Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows

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Highlights

1. Methods are needed for the environmental assessment of using electric vehicle batteries in second-use applications.
2. An adapted life-cycle assessment method is presented based on a comparison of scenarios.
3. The parameters used in the method can be adapted to assess second-use applications.
4. A case study of the increase of photovoltaic self-consumption proved the method's usefulness.
5. Primary data need to be used to model the energy flows of the system in each case.

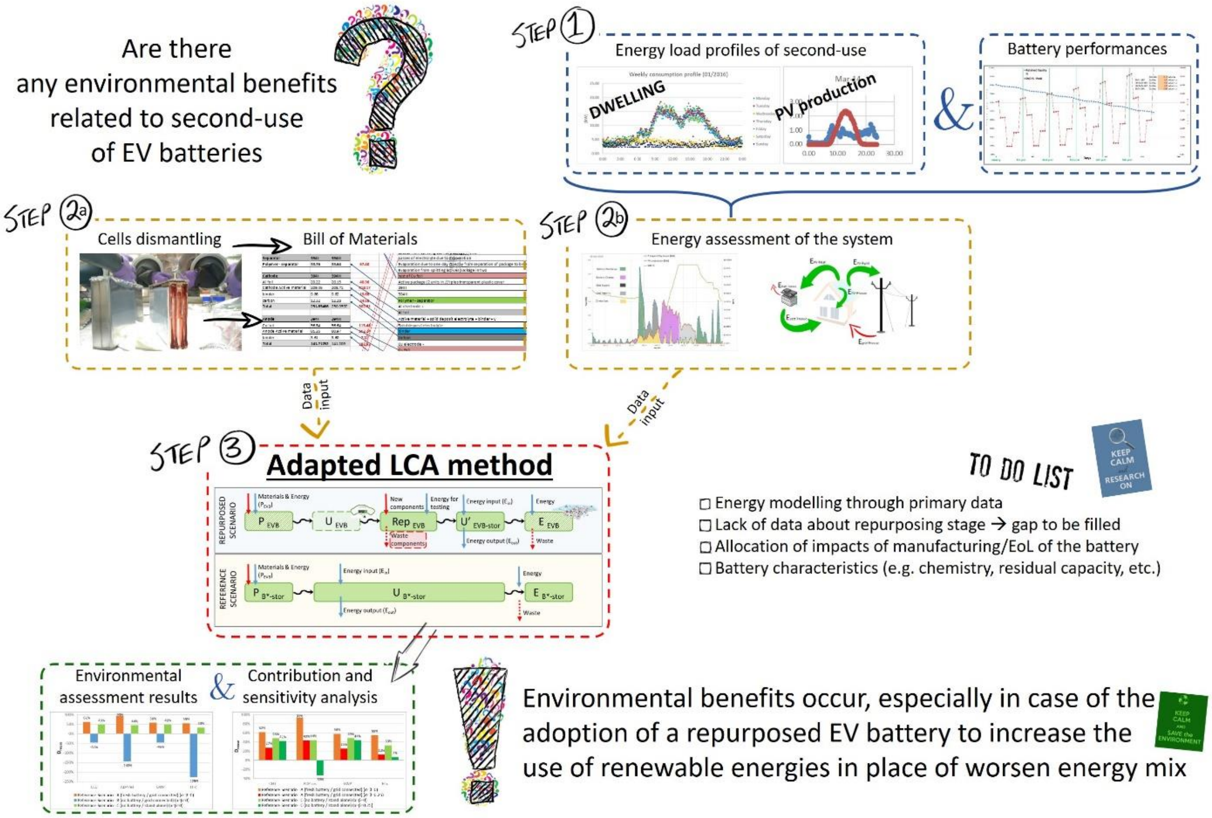
Abstract

After their first use in electric vehicles (EVs), the residual capacity of traction batteries can make them valuable in other applications. Although reusing EV batteries remains an undeveloped market, second-use applications of EV batteries are in line with circular economy principles and the waste management hierarchy. Although substantial environmental benefits are expected from reusing traction batteries, further efforts are needed in data collection, modelling the life-cycle stages and calculating impact indicators to propose a harmonized and adapted life-cycle assessment (LCA) method.

To properly assess the environmental benefits and drawbacks of using repurposed EV batteries in second-use applications, in this article an adapted LCA is proposed based on the comparison of different scenarios from a life-cycle perspective. The key issues for the selected life-cycle stages and the aspects and parameters to be assessed in the analysis are identified and discussed for each stage, including manufacturing, repurposing, reusing and recycling.

The proposed method is applied to a specific case study concerning the use of repurposed batteries to increase photovoltaic (PV) self-consumption in a given dwelling. Primary data on the dwelling's energy requirements and PV production were used to properly assess the energy flows in this specific repurposed scenario: both the literature search performed and the results obtained highlighted the relevance of modelling the system energy using real data, combining the characteristics of both the battery and its application. The LCA results confirmed that the environmental benefits of adopting repurposed batteries to increase PV self-consumption in a house occur under specific conditions and that the benefits are more or less considerable depending on the impact category assessed. Higher environmental benefits refer to impact categories dominated by the manufacturing and repurposing stages. Some of the most relevant parameters (e.g. residual capacity and allocation factor) were tested in a sensitivity analysis. The method can be used in other repurposing application cases if parameters for these cases can be determined by experimental tests, modelling or extracting data from the literature.

Graphical Abstract



Keywords:

Environmental impact; Life Cycle Assessment (LCA); Battery second-use; Reuse; Repurposing; Electric Vehicles (EVs)

1. Introduction

A rapid increase in the worldwide stock of electric vehicles (EVs) is expected in the near future [1–3]. Lithium-ion (Li-ion) chemistry is recognized as the dominant battery technology available for EVs [4]. Therefore, an increased demand is expected for high-energy density traction Li-ion batteries. Due to the lifetime of batteries, this trend will inevitably lead to an increase of flows of waste batteries that need to be collected and treated [4,5] and to a substantial modification of the battery value chain (e.g. collection schemes and end-of-life treatment).

Although current experience is still very limited, once such used batteries are collected, recycling is presently the most common end-of-life (EoL) treatment for used EV batteries. However, a new EoL option concerning the reuse of such batteries is emerging worldwide. This is because the remaining capacity of the batteries after their use in EVs ranges from 60% to 80% of their initial capacity and it can be potentially exploited in sectors other than the automotive sector [6–8]. Recent studies and pilot projects state that extending the lifetime of EV batteries by using them in other types of application can lead to various benefits, including economic, environmental and social. However, because of the novelty of the topic and the limited availability of data, more investigations are needed to confirm and quantify such benefits [6,9].

In Europe, the relevance of reuse as a waste management strategy to prevent wastage and contribute to the EU's jobs and social agenda has been acknowledged by both the waste management hierarchy, defined in 2008 by the Waste Framework Directive [10] and in 2015 by the European Commission's Circular Economy Action Plan [11]. The End-of-life vehicles (ELV) and the Batteries Directives [12,13] support the recycling of batteries after they have been used in EVs. However, several stakeholders currently support the inclusion of a “reuse” option in the EU Batteries Directive (e.g. the European Association for Advanced Rechargeable Batteries, the European Portable Battery Association, the Association of European Automotive and Industrial Battery Manufacturers), as shown, for instance, during a panel discussion at the 22nd International Congress for Battery Recycling (ICBR 2017). Moreover, in the framework of the Circular Economy Action Plan [11], the Innovation Deal concerning the reuse of EV batteries, recently launched by the European Commission[1] [14], demonstrates that legislators and innovators have increasing interest in this field.

A wide-ranging analysis of the scientific and technical literature suggests that the absence of a clear framework for the second use of EV batteries can result in imprecise or interchangeable terminology, such as “reuse”, “repurpose” or “refurbish” [15–17]. However, some terminology proposals exist: for example, according to Ardente et al. [18], “reuse” implies that a product is being utilized for the purpose for which it was conceived, and “repurposing” refers to utilizing products in other, different applications (often referred to as “second-use” applications). Therefore, consistent with the aim of the study, in this paper “repurposed EV batteries” refer to EV batteries that, after their use in EVs, are tested and prepared for use for energy storage in a second-use application.

Existing international and European industrial activities, research and development (R&D) projects, and demonstration projects indicate that the second use of Li-ion batteries is of great interest to several actors in the value chain [19]. Nevertheless, several barriers were identified in

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[1] “The Innovation Deal focuses on propulsion batteries and will assess whether existing EU legal provisions and the transposition to national or regional law hamper the use of batteries in a second-life application or otherwise discriminate any technology that might be necessary for second-life applications” [14].

different studies: 1) regulatory barriers, mainly relating to the absence of a clear framework for definition of battery reuse [20–25]; 2) technical barriers, related to the lack of data about battery performance and degradation [9,20]; 3) economic barriers, such as uncertainty with regard to economic returns and the market for EV batteries, and the absence of economic incentives [20–22,25–27], and 4) safety barriers, such as hazards and fire risks associated with removing and handling Li-ion batteries [9,25].

From a complementary economic perspective, several authors have studied the benefits of reusing EV batteries, especially in relation to decreases in EV costs as a result of longer battery service lives [9,28,29]. From a legal perspective, more efforts are required to provide "an adequate legal framework for second-life applications", for example in the forthcoming review of the Batteries Directive [30].

To support the EV second-use regulatory framework, the sustainability of extending the lifetime of EV batteries to second-use applications should be demonstrated. Thus, the three sustainable development pillars – economic, social and environmental – should be assessed[2], but only a few studies in the literature integrate an economic assessment with social and environmental aspects related to the second-use of batteries [31]. In the scientific literature, an increasing number of studies are available concerning environmental aspects; however, they show major differences in the environmental analysis methodology adopted (see Section 2).

In the context of the sustainability assessment, this paper contributes to developing a method for assessing the environmental impacts of adopting repurposed EV batteries for other applications. In particular, the method develops an indicator based on the life-cycle impacts of the system in which repurposed batteries are used, considering all of the value chain stages affecting second use.

In line with this goal, Section 2 summarizes some relevant results from the literature, identifying the key aspects of repurposed EV batteries and their use in the specific second-use applications that are considered in the assessment. Section 3 describes the proposed method, the specific scenarios used to develop it and the relevant analysis parameters. The method is then used to assess the performance of a repurposed EV battery in specific housing configurations (Section 4) for which the energy and the environmental aspects are discussed in detail.

2. Literature review on environmental assessment of reuse

Although the second use of batteries has been studied less often than recycling [32], environmental benefits are generally expected [6,9,32,33].

Several studies in the literature have estimated the environmental performances of the systems in which batteries have been used, based on a life-cycle approach. However, comparisons of these studies are difficult because of major differences in scope (e.g. different second-use applications and different product systems analysed), system boundaries (e.g. different life-cycle stages and different geographical boundaries), life-cycle inventory data used for the life-cycle stages (e.g. energy flow of the use stage, battery degradation patterns and expected battery lifetime), and impact assessment methods considered. Despite the efforts dedicated to developing a life-cycle assessment (LCA) in this area, guidelines or harmonized approaches do

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[2] https://ec.europa.eu/environment/efe/content/long-term-vision-sustainable-future_en

not yet exist [34]. This is a major barrier to identifying when the repurposing of EV batteries brings environmental benefits. The next paragraphs further analyse each of these diverging practices in the literature.

Repurposed Li-ion batteries could be used in several applications (e.g. utility operations, commercial and residential buildings) depending on their characteristics [35]. An analysis of recent European and international industrial activities, research and innovation projects and research studies, using repurposed EV batteries, revealed that the most frequently reviewed applications are those for integrating renewable energy into the grid. Examples are smoothing for renewable energy systems [27,29,36,37]; energy storage of a single wind turbine/photovoltaic (PV)/battery system [36]; off-grid PV vehicle charging system [38]; and diurnal energy shifting, allowing intermittent renewable energy sources to be used more widely (e.g. wind and solar) [39]. Other applications relate, for example, to transmission and distribution upgrade [6,40,41], regulation services [6,28,40] and supplemental reserves [26,33,36,39,42]. Depending on the type of second use being analysed, repurposed EV batteries for storage applications could substitute non-Li-ion batteries (e.g. lead-acid batteries) or other energy sources (e.g. fossil fuels) and support a shift to renewable energy [21,26,27,39].

The use phase of energy storage is generally recognized as extremely important [26,27], and consequently it is relevant to properly defining both the application in which the storage is used and the associated system boundaries. The lifetime of a battery should take into account battery degradation, which depends on both the battery's initial characteristics (e.g. first life, residual capacity, efficiency) and the specific second-use conditions (e.g. load profile, temperature). The lack of data in this field is reflected by the fact that, in other studies, the estimated life of a battery during its second use is based on manufacturer warranties [9,43] or assumptions and average data [6,26,27,39].

Sizing storage systems, together with renewable energy sources, requires an assessment of the energy flows of the system through the daily production and demand curves of the renewable system; furthermore, the system configuration strongly affects battery lifetime [44]. For instance, in the case of repurposed EV batteries utilized in a residential building that has renewable energy sources, the effects of user behaviour are important for the changes in the proportion of renewable household energy and, therefore, on the energy flows of the system [45]. From the performed literature review, it emerged that modelling the energy flows of the second use of a battery in a specific application often uses average data (e.g. Ahmadi et al. [9]) or is based on previous studies (e.g. Richa et al. [26]).

The life-cycle stages included when assessing the environmental performance of EV batteries repurposed for second use should be clearly identified according to the scope of the study and the application being assessed [46]. To assess how different applications of repurposed EV batteries affect the whole life cycle, Canals Casals et al. [27] and Richa et al. [26] considered all life-cycle stages of the EV battery (car manufacturing, using the battery both in a car and in second use, and recycling). Similarly, Ahmadi et al. [9] performed a from-cradle-to-grave analysis, excluding recycling of the battery since this is the same in all of the scenarios analysed; the second use of the battery was considered through the impacts of the system's energy sources. Differently, Faria et al. [43] and Sathre et al. [39] included only the stages directly related to the second use of the EV battery; therefore, only the energy impacts of battery charging were considered in the environmental assessment of the second use, whereas the impacts of the manufacturing and EoL stages were fully considered for the first use.

Another relevant aspect of the system boundaries that emerged from the literature analysed is that regional conditions could affect a battery's lifetime and also its overall impact [43,47,48]. For instance, the results of these studies confirmed that the energy mix used in the assessment has a large influence on the life-cycle impacts.

Regarding the Life Cycle Inventory (LCI) of EV batteries, Li-ion batteries with different chemistries are available (e.g. lithium-nickel-cobalt-manganese-oxide, lithium-manganese-oxide). Detailed inventory data of Li-ion batteries are usually lacking and authors often refer to a limited sample of previous publications, although this approach can affect the reliability of results [49].

The repurposing stage entails collecting the battery after it has been used in an EV, and may involve disassembling the battery to the module/cell level and testing the health of the battery/modules/cells [9,33]. Since many variables can affect the health of a battery pack (e.g. charging/discharging rate, state of charge, ambient temperature, driving patterns and style), testing during the repurposing stage aims to assess how suitable the battery/modules/cells are for second use in specific applications [48]. Even though testing battery performance is expensive and time-consuming [21,50], a detailed knowledge of the ageing model of the battery is needed to establish the suitability for a given second-use application and the potential battery lifetime [29].

The absence of a clear analysis of and quantitative data about battery repurposing also heavily affects the modelling of this stage. Faria et al. [43] did not assess any impacts related to repurposing. Canals Casals et al. [27] considered the impacts of materials for repurposing negligible, whereas Sathre et al. [39] did not take into account the energy for testing, since tests are already carried out at local car dealerships. Other studies assumed both the substitution of some components and the energy needed for tests [26], or specific cell failure rates and pack recovery rates [9].

In a life-cycle impact assessment (LCIA), the impacts of complex systems such as vehicles should not be captured by a single-score indicator or aggregated indicators [51–53]. Moreover, a low-emission mobility transition implies that it is increasingly important to assess the impacts of resources due to specific materials in powertrains [52,54–58], among which are Critical Raw Materials [59] (e.g. cobalt) and other materials characterized by an exponentially increasing demand (e.g. lithium). Since "resource-related impacts are very complex" and difficult to capture using simple methods [58], the use of a broad set of environmental impact categories is recommended.

This literature review highlights the complexity and novelty of the topic. To assess the environmental performance of second-use repurposed EV batteries, multiple aspects should be considered to provide a complete assessment and to allow a comparison of EV batteries for use in different applications. Moreover, the lack of available data strengthens the need to improve data collection at all the life-cycle stages, focusing especially on the use stage.

3. Method for the environmental assessment of repurposed batteries in a life-cycle perspective

Within the aim of assessing the potential environmental benefits of using a repurposed battery in a specific system, it is considered that the battery, at the end of its life in an EV, could be used in applications with less-demanding electrical requirements (e.g. storage in residential applications) [6–8].

The proposed method is based on comparing the impacts of different scenarios. The impacts of the scenarios are assessed based on LCA, a methodology standardized by the International Organization for Standardization (ISO) [46] and further elaborated by the Joint Research Centre (JRC), Directorate D (within the European Product Environmental Footprint methodology) [60]. Section 3.1 details the description and system boundaries of the scenarios assessed, the energy assessment and the impacts of the life-cycle stages of the assessment of all scenarios. Section 3.2 describes the most relevant parameters included in the assessment and details of how scenario impacts were calculated. Finally, Section 3.3 describes considerations about some specific factors related to the method.

3.1. Description of the Scenarios for modelling

The assessment of repurposed EV batteries in second-use applications is based on comparing the environmental impacts of different scenarios from a life-cycle perspective. Figure 1 shows the life-cycle stages of the scenarios defined using this method.

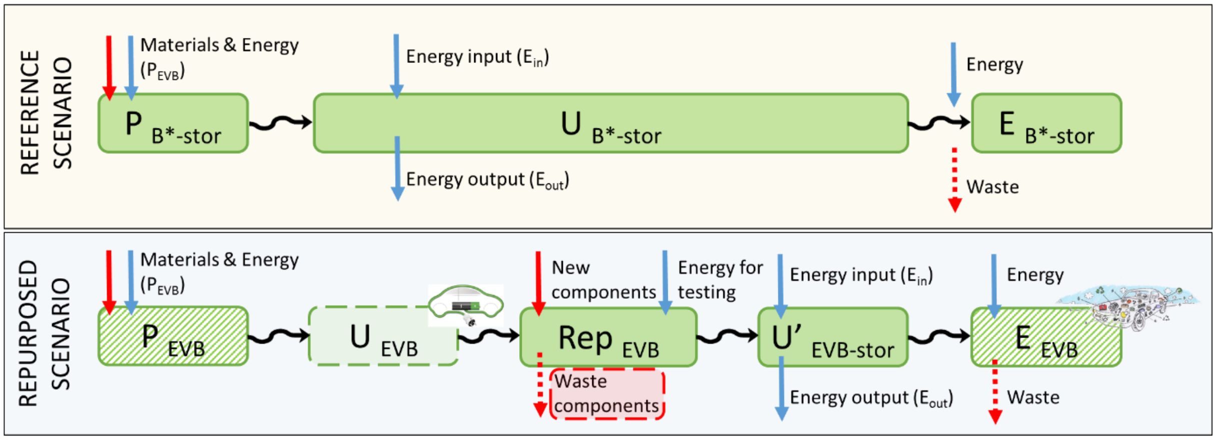
The “Reference Scenario” (Figure 1 top panel) assumes that a fresh battery is used in a storage application and that, after its use, it is recycled. The environmental impact of the Reference Scenario relates to all life-cycle stages relevant to the EV battery, i.e. battery manufacturing ($\mathrm{P}_{\mathrm{B*-stor}}$), using the battery in the system ($\mathrm{U}_{\mathrm{B*-stor}}$) and battery EoL ($\mathrm{E}_{\mathrm{B*-stor}}$).

The Reference Scenario is the term of reference for comparing a “Repurposed Scenario” (Figure 1 bottom panel) in which an EV battery is reused in a second-use application, after its first application in an EV. The environmental impact of the Repurposed Scenario relates to all life-cycle stages involved in the second use, i.e. battery manufacturing ($\mathrm{P}_{\mathrm{EVB}}$), battery repurposing ($\mathrm{Rep}_{\mathrm{EVB}}$), battery use in the storage application ($\mathrm{U'}_{\mathrm{EVB-stor}}$) and battery EoL ($\mathrm{E}_{\mathrm{EVB}}$).

The use of a battery in an EV affects its characteristics and lifetime in the second-use application (e.g. its residual capacity and efficiency after the use in the EV); the impact of this stage ($\mathrm{U}_{\mathrm{EVB}}$) is not included in the assessment, since this is not directly related to the second-use application (dashed box in Figure 1). Nevertheless, the first use of the battery affects its second use, especially in terms of performance and lifetime. During the repurposing stage, some components of the battery pack can be replaced (e.g. casing). In this case, the impact of the waste components (dashed box in Figure 1) is not included in the assessment of the Repurposed Scenario, since this waste is assumed to relate exclusively to the first application of the EV battery, and therefore is out of the system boundaries of the analysis of the repurposed battery. Consistently, the impacts of the manufacture and EoL of the new components used during repurposing are fully allocated to the battery’s second use.

Regarding the manufacture and EoL of the battery in the Repurposed Scenario (striped boxes in Figure 1), the environmental impacts of these two stages ($\mathrm{P}_{\mathrm{EVB}}$ and $\mathrm{E}_{\mathrm{EVB}}$) should be allocated to the different applications over the whole life cycle, since they relate to both the first application in the EV and the second application in the storage system. Therefore, not every impact of these two stages should be fully allocated to the battery’s second use.

It should be noted that the method can be adapted to different configurations. The adoption of different batteries (e.g. in terms of capacity or chemistry) in a system will affect the overall energy flows of the system. Since the aim of the analysis is to assess the potential environmental benefits of using a repurposed battery in a specific system, in both Scenarios the impacts related to the use of the battery in the system ($\mathrm{U'}_{\mathrm{EVB-stor}}$ and $\mathrm{U}_{\mathrm{B*-stor}}$) refer to the impacts of all input and output energy flows (E_{in} and $\mathrm{E}_{\mathrm{out}}$) of the system during the battery's lifetime. This aspect is highly dependent on the system characteristics, including geographical (e.g. local grid mix, temperature) and technical (e.g. residual capacity of the battery, driver's behaviour, load profile of the building) considerations. A more detailed description of the modelling of the energy flows of the system and of the impacts of the use stage for both Scenarios is provided in Section 3.2.1.



Note that $U'_{EVB-stor}$ denotes the second use of the EV battery, after it has been repurposed. "B*" denotes a battery not specifically identified as used in EVs but still usable in storage applications.

Figure 1: Schematic presentation of the scenarios compared to assess repurposed EV batteries using a life-cycle perspective. The dashed boxes represent stages/processes not included in the analysis, and the striped boxes represent stages partially included.

3.2. Environmental assessment of Scenarios

As the lifetime of fresh batteries in stationary applications is usually longer than that of repurposed batteries, a more meaningful comparison between Scenarios requires a consistent functional unit [46]. The lifetime of a battery and, consequently, the energy flows of the assessed system depend on both the battery's characteristics and its applications (see Section 2). Therefore, the functional unit in both Scenarios is represented by the average yearly energy balance of the system in which the battery stores energy, and this is used for the comparison. For this purpose, the life-cycle impacts of both the Repurposed and the Reference Scenarios are divided by the lifetime of the battery in the application assessed.

The benefits and drawbacks of adopting a repurposed EV battery in a specific application are assessed through the difference in the life-cycle impacts between the Reference and Repurposed Scenarios:

$$\Delta_{reuse,n} = I_{Reference\ Scenario,n} - I_{Repurposed\ Scenario,n} \qquad (1)$$

Where:

- $I_{Reference\ Scenario,n}$ = impact of category "n" for the Reference Scenario [unit/time];
- $I_{Repurposed\ Scenario,n}$ = impact of category "n" for the Repurposed Scenario [unit/time].

The environmental benefits of replacing a fresh battery with a repurposed battery occur when $\Delta_{reuse} > 0$, i.e. $I_{Reference\ Scenario,n} > I_{Repurposed\ Scenario,n}$. Details of how $I_{Reference\ Scenario,n}$ and $I_{Repurposed\ Scenario,n}$ were calculated are illustrated in Section 3.2.2.

To aid the interpretation of results and assess the relevance of the impacts in the different scenarios, the ratio of Δ_{reuse} to the impacts of the Reference Scenario is calculated as:

$$D_{reuse,n} = \frac{\Delta_{reuse,n}}{I_{Reference\ Scenario,n}} \cdot 100\ \ [\%] \qquad (2)$$

For example, a value of $D_{reuse,GWP}$ of 10% means that reusing the EV battery in energy storage systems would allow a reduction of 10% of the life-cycle global warming potential (GWP) compared with the Reference Scenario.

3.2.1. Impacts of battery use

In line with the main goal of the proposed method, the impact of battery use in a storage application is assessed through the input/output energy flows of the system. As introduced in Section 3.1 and highlighted by the case study (Section 4), for both the Repurposed and the Reference Scenarios the impacts of the use stages ($\mathrm{U'_{EVB-stor}}$ and $\mathrm{U_{B*-stor}}$) differ depending on the battery characteristics and the configuration of the system in which the battery is used. Differences relate to, for instance, energy losses related to the battery, energy requirements of the system and energy exchanges with the grid. This requires an assessment of the energy flows to allow an evaluation of the overall input and output flows ($\mathrm{E_{in}}$ and $\mathrm{E_{out}}$) of the specific system.

The environmental impacts of the use stages of the two Scenarios are calculated as the difference between the impacts of these flows:

$$U_n = (E_{in} - E_{out}) \cdot u_n \qquad (3)$$

Where:

- E_{in} = energy entering the system (e.g. from the grid) [kWh];
- E_{out} = energy leaving the system (e.g. to the grid) [kWh];
- u_n = environmental impact of category “n” per kWh of energy [unit/kWh].

According to the specific system characteristics, Formula (3) refers to both the Reference ($\mathrm{U_n} = \mathrm{U}_{B^*-\mathrm{stor}}$) and the Repurposed ($\mathrm{U_n} = \mathrm{U'_{EVB-stor}}$) Scenarios.

3.2.2. Life-cycle impacts of the Scenarios

The average yearly impacts of the Reference Scenario ($I_{Reference\ Scenario}$) are calculated as:

$$I_{Reference\ Scenario,n} = \frac{P_{B^*-stor,n} + U_{B^*-stor,n} + E_{B^*-stor,n}}{T_{B^*-stor}} \qquad (4)$$

Where:

- $P_{B^*-stor,n}$ = impact of category “n” for the battery manufacturing [unit];
- $U_{B^*-stor,n}$ = impact of category “n” for the energy use in the storage system in which the battery is used [unit];

- $E_{B^*-stor,n}$ = impact of category “n” for the battery EoL [unit];
- T_{B^*-stor} = lifetime of the battery storing energy in the storage system [time].

In the Repurposed Scenario, the allocation of the environmental impacts of both the manufacturing (P_{EVB}) and the EoL (E_{EVB}) of the repurposed EV battery along the whole life cycle is modelled by adopting two allocation factors (“α”and “β”) (Section 3.3.1). The average yearly impacts of the Repurposed Scenario ($I_{Reuse\ Scenario}$) are calculated as follows:

$$I_{Repurposed\ Scenario,n} = \frac{\alpha \cdot P_{EVB,n} + Rep_{EVB,n} + U'_{EVB-stor,n} + \beta \cdot E_{EVB,n} + E_{EVB\ new\ components,n}}{T_{EVB-stor}} \qquad (5)$$

Where:

- $P_{EVB,n}$ = impact of category “n” for the EV battery manufacturing [unit];
- $Rep_{EVB,n}$ = impact of category “n” for the EV battery repurposing [unit];
- $U'_{EVB-stor,n}$ = environmental impact of category “n” for the energy use in the storage system in which the EV battery is used [unit];
- α = allocation factor considering the impact of the EV battery manufacturing to be allocated to the second use [–];
- β = allocation factor considering the impact of the EV battery EoL to be allocated to the second use [–];
- $E_{EVB,n}$ = impact of category “n” for the EV battery EoL [unit];
- $E_{EVB\ new\ components,n}$ = impact of category “n” for the EoL of the new EV battery components [unit];
- $T_{EVB-stor}$ = lifetime of the EV repurposed battery storing energy in the storage system [time].

The overall impact of the repurposing stage comprises the impacts of the different operations, such as the transport required to collect the battery (TR_{B-car}), testing the battery, implying some energy consumption ($U_{testing}$), and checking the battery, including possibly substituting some components ($P_{new\ components}$). The impact of EV battery repurposing is calculated as:

$$Rep_{B-car,n} = TR_{EVB-car,n} + U_{EVB\ testing,n} + P_{EVB\ new\ components,n} \qquad (6)$$

Where:

- $TR_{EVB,n}$ = impact of category “n” for the EV battery collection [unit];
- $U_{EVB\ testing,n}$ = impact of category “n” for the EV battery testing [unit];
- $P_{EVB\ new\ components,n}$ = impact of category “n” for the replacement of components of the EV battery [unit].

3.3. Specific factors and modelling options

The proposed method allows to consider different factors that could affect the environmental impact of both the Reference and the Repurposed Scenarios, for instance allocating the impacts of the manufacturing and EoL of the battery to its second use (Section 3.3.1), and assessing different configurations of the system (Section 3.3.2).

3.3.1. Allocation rules

The energy and environmental assessments of reusing products imply that some life-cycle stages (e.g. production and EoL) affect both the first and the second applications. This issue is solved by allocating impacts [46,61]. In general, different criteria could be adopted to determine allocation factors, including physical parameters (e.g. energy content, mass) and economic considerations (e.g. market price) [62]. Allacker et al. [63] have discussed the available allocation solutions for modelling the environmental performance of a product's EoL stage to assess their suitability in the framework of EU product policies. Although reuse is recognized as relevant to all of the methods assessed, there remains no clear definition of how to address the environmental modelling of reuse and solve multi-functionality in LCA, and this currently depends on the allocation decisions of the LCA practitioners [26,63,64].

According to current European legislation, after their first use in an EV, batteries are classified as "waste", i.e. a market has not yet developed for reusing EV batteries in second-use applications in Europe. In addition, according to AFNOR (*Association française de normalisation*), as cited in Allacker et al. [63], "if the raw materials market is in disequilibrium because producers are demanding secondary raw materials which are in short supply, then there are grounds for offering incentives to producers of recycled products in order to pull the market. All of the EoL impacts are allocated to the producer". In this case, the environmental impact of manufacturing and EoL should be fully allocated to the battery's first life (i.e. $\alpha = \beta = 0$). However, with the potential future development of a business case, as some authors have stated [9,21,34], the battery could be manufactured with an additional focus on its potential second-use application, so that the "α" and "β" coefficients may not be null once a market for repurposed batteries has been established.

3.3.2. System configurations

Specific scenarios could be defined depending on the assessment goal. For example, a repurposed EV battery could be adopted in a system that uses no batteries. In this case, the impacts of the Reference Scenario ($I_{Reference\ Scenario}$) do not include those related to both the manufacture and the EoL of the battery (i.e. $P_{B^{*}-stor} = E_{B^{*}-stor} = 0$), and will be equal to the impact of the energy use in the system ($U_{B^{*}-stor,n}$) (Figure 2).

Moreover, the repurposed battery could be adopted in a system that is not connected to the grid (e.g. in a stand-alone building). In this case, the environmental impact per kWh of energy (u_n) relates to an energy source that is different from that of the grid mix (e.g. diesel or natural gas).

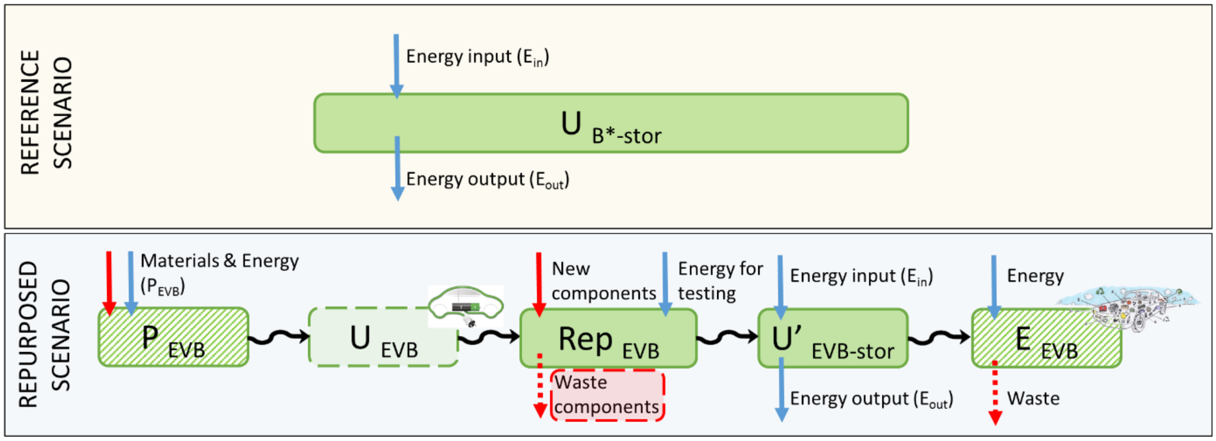


Figure 2: Schematic presentation of the two Scenarios in a stand-alone building without batteries.

4. Case study: analysis of second-use application in the case of increasing photovoltaic (PV) self-consumption

The method proposed in Section 3 is applied to a specific case study (Section 4.1). Data and assumptions of each life-cycle stage are described in Section 4.2. The impact assessment results and the sensitivity analysis performed are then described and discussed in Sections 4.3 and 4.4.

4.1. General presentation of the case study

In several renewable systems, such as PV systems, the utility consumer does not directly use a significant amount of the energy produced. As a consequence, this energy enters the grid network or is lost. Energy storage is one of the principal approaches to balancing an electric power system with a high penetration of time-varying renewable resource. With a storage battery, the surplus of PV energy (i.e. the energy not directly consumed by the system) can be stored for use when the PV system cannot produce energy (i.e. at night) or is unable to satisfy energy demand [65]. At the European level, PV installations are expected to grow further in the next decade and to play a key role in increasing the proportion of renewable energy sources at a local level [66]. Meanwhile, the cost of energy storage is expected to decrease [67] and renewable integration is expected to be one of the most relevant applications of storage batteries [25,68].

Therefore, a house with a PV installation has been selected for the application of the method described in Section 3. A repurposed EV battery could potentially replace a fresh battery storing energy in a building or could be adopted in a stand-alone house, avoiding the need to use a less environmentally friendly energy source, such as a diesel-electric generator. To capture all of these aspects, different Reference and Repurposed Scenarios were assessed, as shown in Table 1.

Table 1: Main characteristics of the examined scenarios

Configuration	Reference Scenario	Repurposed Scenario

Configuration A	• Grid-connected house • PV installation • Fresh Li-ion battery storing PV energy	• Grid-connected house • PV installation • Repurposed Li-ion battery storing PV energy
Configuration B	• Grid-connected house • PV installation • No battery storage system	• Grid-connected house • PV installation • Repurposed Li-ion battery storing PV energy
Configuration C	• Stand-alone house • PV installation • Diesel-electric generator used to satisfy the energy requirements not satisfied by the PV installation	• Stand-alone house • PV installation • Repurposed Li-ion battery storing PV energy

The case study has been selected based on the available real data gathered during the research. The system assessed is in the Netherlands (EU); a repurposing plant was visited and an EV battery was tested after its first use. Because in Europe there is no developed market for reusing EV batteries (Section 3.3.1), and because real data are available on a PV installation in the Netherlands, it has been assumed that a repurposed battery has been used in a second-use application in that country.

4.2. Models, data and assumptions used over the life cycle of batteries in the case study

This section aims to present all the data and assumptions considered for all relevant stages of the battery life cycle. Primary data are used both for assessing the environmental impact of EV battery manufacturing and for calculating the energy flows of the system.

4.2.1. Manufacturing stage

Different types of battery could be suitable for an energy storage system (e.g. sodium-sulphur, lead-acid, Li-ion, vanadium redox-flow, sodium-nickel chloride) [69,70]. In 2013–2014, Li-ion was the most relevant chemistry in terms of installed capacity, and its market price is quickly decreasing [25]. After consulting stakeholders during our research, it emerged that there are examples of Li-ion EV traction batteries also being used for energy storage in buildings (e.g. lithium-manganese-oxide/nickel-manganese-cobalt (LMO/NMC), the battery used in the BMW i3). Although a battery's material composition may be expected to change over time, for simplification, in this study the same composition of Li-ion batteries is considered for both the Reference and the Repurposed Scenarios.

The impacts of manufacturing the EV battery were based on a commercial Li-ion battery used in a plug-in hybrid EV (the Mitsubishi Outlander) that reached the end of its life in 2016. At the end of the battery's first use, the EV had driven 136,877 km and the capacity estimated by its battery management system (BMS) was 81.31% of the nominal capacity (11.4 kWh – 300 V, 38 Ah). At the JRC laboratories for battery testing in the Netherlands, such a LMO/NMC battery was disassembled and the cells were dismantled to identify the bill of materials [19]. Therefore, primary data were used for the Life Cycle Inventory (LCI) of battery cells, and the additional components (e.g. BMS) delivered in Europe were taken from the literature [71–73]. Information on battery degradation and specific parameters was derived from laboratory tests performed by the JRC and, when necessary, complemented by data from the literature. Table 2 summarizes the battery characteristics.

Table 2: Battery characteristics

Parameter	LMO/NMC Repurposed battery	LMO/NMC Fresh battery	Source of information
Chemistry	LMO/NMC: 0.52 $LiMn_2O_4$ + 0.48 $LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$		Laboratory tests
Chemistry	LMO/NMC: 0.52 $LiMn_2O_4$ + 0.48 $LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$		Manufacturer
Nominal capacity of the battery [kWh]	11.40 (300V – 38Ah)		Manufacturer
Number of cells per modules/per battery	8 cells/module; 80 cells/battery		Manufacturer
Initial RTE (round-trip efficiency)* [%]+	95%	98%	Based on Görtz [74] and own assumptions
Initial capacity for the assessment [%]	81.31%	100%	Laboratory tests
End-of-second-use retained capacity [%]	60%		Based on Canals Casals et al., 2015; Lacey et al., 2013; Oliveira, 2017 [27,80,79]
Battery degradation	–3 Wh/cycle (cycling ageing); –0.13 Wh/day (calendar ageing)		Based on Faria et al., 2014 [43] Laboratory tests

+A linear decrease of battery efficiency is considered (5 percentage points in 5 years).

* RTE is the total energy output (at discharge) divided by the total energy input (at charge) measured between the same state-of charge (SoC) end points associated with the application of the duty cycle during the test. It is expected that this may fade during the life test.

4.2.2. Repurposing stage

According to Richa et al. [75] and based on analyses of real practices, repurposing includes disassembling the main components of the battery pack (e.g. casing and BMS) down to module level to test the battery's state of health (SoH) [9,33]. Also considered are: an average transport distance of 100 km to collect the battery, the disassembly of the battery pack down to module level and the testing of one charge/discharge cycle. According to Ellingsen et al. [71], the battery modules are kept together on a battery tray using straps, restraints and foam. For LCA modelling, it is assumed that a new battery tray is used after the battery pack has been dismantled (Table 3).

Table 3: Data used for the repurposing stage

Parameter	LMO/NMC repurposed battery	Source of information
Transport [km]	100	Own assumptions
Battery tray [kg]	14.88	Ellingsen et al. [71]
Battery retention [kg]	5.45	Ellingsen et al. [71]
Electricity consumption [kWh]	8.72	Own assumptions, considering one charge/discharge cycle

4.2.3. Use stage

As discussed in Section 3.2.1, the calculation of the impacts of the use stage require an assessment of the energy flows of the system in which the battery is used, according to the battery's characteristics and the system configuration. To assess the environmental benefits and drawbacks of increasing PV self-consumption through using one battery, PV production data and the house load profile are needed. In the case study, primary data (15 minutes' resolution for 1 year) are available from a PV installation in the Netherlands [76][3]. Since data of PV energy production and of energy requirements relate to the same building, they should also relate to the same geographical area thus allowing site-specific conditions to be considered (e.g. solar irradiation and energy requirements depending on climate conditions). Therefore, the house load profile is provided by ResLoadSIM software[4] (time resolution of 1 minute), and it relates to a fictitious residential building in Amsterdam (the Netherlands), with four residents and a yearly consumption of 5.15 MWh.

Data were elaborated considering a time resolution of 15 minutes for 1 year. Taking into account Ciocia [77], expert considerations and the battery's characteristics (Table 2), a model was built to calculate the input/output energy flows ($\mathrm{E_{in}}$ and $\mathrm{E_{out}}$) of the system (consisting of home, PV and battery) along the lifetime of the battery with varying the input parameters. The model takes into account PV production, the house's energy requirements ($\mathrm{E_{requirement}}$), depth of discharge (DoD), battery capacity ($\mathrm{C_n}$), battery efficiency and battery degradation.

Therefore, all of the system's energy flows (Figure 3) are calculated every 15 minutes: the PV energy directly consumed by the house ($E_{PV\rightarrow house}$); the PV energy used for charging the battery ($E_{PV\rightarrow Bat}$); the surplus of PV energy ($E_{PV\rightarrow grid}$); the energy provided by the battery ($E_{Batt\rightarrow house}$); the energy loss due to battery efficiency ($E_{Batt\ losses}$); and the energy not covered by the PV installation ($E_{grid\rightarrow house}$).

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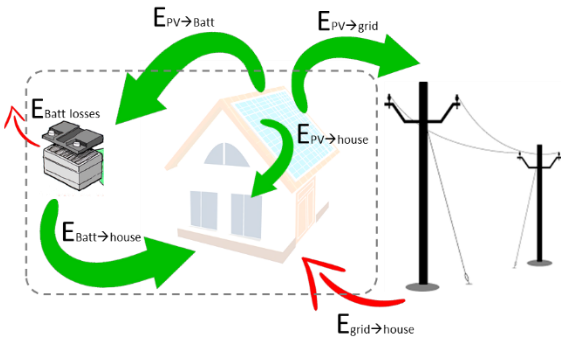
[3] The system is characterized by two PV converters connected to 96 modules of 250 W, totalling 24 kWp. The orientation of all of the modules is south-southeast (SSE) with a slope of 10° (Vandenbergh, 2014). Based on a real case, the energy provided by 21 PV panels is considered for the analysis.

[4] https://ses.jrc.ec.europa.eu/power-system-modelling



$E_{PV\rightarrow Batt}$ = energy provided to the battery from the PV installation
$E_{PV\rightarrow grid}$= energy provided to the grid from the PV installation
$E_{Batt\ losses}$ = energy lost due to the battery efficiency
$E_{PV\rightarrow house}$ = energy provided to the house from the PV installation
$E_{Batt\rightarrow house}$ = energy provided to the house from the battery
$E_{grid\rightarrow house}$ = energy required by the house from the grid

$$E_{in} = E_{PV\rightarrow grid} = E_{requirement} - E_{PV\rightarrow house} - E_{PV\rightarrow Batt}$$
$$E_{out} = E_{grid\rightarrow house} = E_{requirement} - E_{PV\rightarrow house} - E_{Batt\rightarrow house}$$

Figure 3: Energy flows of the system.

The battery's ageing at specific intervals is estimated taking into consideration both the calendar ageing and the cycling ageing according to the literature and laboratory tests (Table 2). For simplicity, calendar ageing and cycling ageing are assumed to occur independently (i.e. they are not interdependent). Cycling ageing is considered proportional to the cycles performed (Formula (7)).

$$C_n = C_{n-1} - \left(Calendar\ ageing + Cycling\ ageing \cdot \frac{DoD_{n-1}}{DoD_{max}}\right) \qquad (7)$$

Where:

- C = capacity of the battery [energy];
- n = timeframe interval [–];
- $Calendar\ ageing$ = degradation of the battery's capacity due to calendar ageing during one time step [energy];
- $Cycling\ ageing$ = degradation of the battery's capacity due to its use based on a 80% DoD_{max} (Faria et al., 2014) [energy];
- DoD = depth of discharge of the battery [–].

The model assumes that the DoD does not exceed 80% (DoD_{max}) to prevent the battery degrading faster (considering a maximum of one cycle per day) [6,9,43]. Moreover, the battery's efficiency is assumed to linearly decrease by 5 percentage points in 5 years [78].

The model was run for each Scenario until the battery capacity reached 60% of its nominal capacity. If the capacity is lower, the battery should be discarded, since it is no longer able to satisfy the system requirements [27,79,80].

The sum of the system energy flows during the battery's lifetime provides the input/output energy flows (E_{in} and E_{out}) needed for the environmental assessment (Table 4). The results suggest that the repurposed LMO/NMC battery can be used for about 3.6 years before its capacity reaches 60% of its nominal capacity and it is transferred to recycling. If a fresh LMO/NMC battery is adopted, the battery's lifetime is about 7.4 years.

Table 4: Energy flows for the Reference and the Repurposed Scenarios and the corresponding battery lifetimes

Parameter	**Reference Scenario A**	**Reference Scenario B**	**Reference Scenario C**	**Repurposed Scenario**

Lifetime [years]	7.4	1	1	3.6
Electricity required by house [kWh]	38,070	5,148	5,148	18,453
Direct electricity consumption from PV [kWh]: $E_{PV\rightarrow house}$	12,417	1,679	1,679	6,019
Electricity provided by batteries [kWh]: $E_{Batt\rightarrow house}$	11,051	–	–	5,143
Electricity needed for charging batteries [kWh]: $E_{PV\rightarrow Batt}$	11,706	–	–	5,514
Electricity from the grid [kWh]: $E_{out} = E_{grid\rightarrow house}$	14,602	3,469	3,469	7,291
PV production [kWh]	35,727	4,831	4,831	17,318
Electricity potentially to be fed into the grid [kWh]: $E_{in} = E_{PV\rightarrow grid}$	11,604	3,152	–	5,785

In the environmental assessment, an EU average grid mix is considered when calculating the impacts of electricity used in the grid-connected house. The surplus of the energy not directly consumed is considered sold to the grid. It is assumed that a Dutch grid mix would have been possible but that the authors preferred to adopt an EU grid mix, since various repurposing scenarios throughout Europe will be studied in the future and the comparison is easier with an average grid mix.

In the stand-alone house, the energy requirement not satisfied by the PV production is supposed to be provided by a diesel-electric generator of 18.5 kW. In this case, the surplus of the energy not directly consumed is considered lost (i.e. $E_{PV\rightarrow grid} = 0$).

4.2.4. EoL stage

According to the Batteries Directive and the ELV Directive [12,13], automotive and industrial batteries must be collected and recycled. In both the Reference and the Repurposed Scenario, a pyrometallurgical process is considered for the LMO/NMC cell recycling, since it is currently the most commonly used in Europe and recycling data were derived from the literature [37,79,81]. The recovery of other components, such as the casing and BMS, which are sorted before the pyrometallurgical process, are modelled using the recovery rates reported by Chancerel et al. [82]. More details about the EoL stage are described in the study by Cusenza et al. [83].

4.3. Life-cycle impacts of the battery

The LCIA of the life-cycle stages of the fresh and repurposed batteries used in the storage application assessed was calculated using SimaPro software, Ecoinvent 3.1 database; the impact categories recommended by the European Product Environmental Footprint were adopted [84][5]. The life-cycle impacts for each stage of all of the Scenarios assessed are reported in the supplementary material (Table S1), i.e. manufacturing a LMO/NMC battery ($P_{EVB,n}$ and $P_{B^{*}-stor,n}$), repurposing the battery ($Rep_{EVB,n}$), the EoL of both the battery ($E_{EVB,n}$ and $E_{B^{*}-stor,n}$)

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[5] The land use and water resource depletion impact categories were excluded (because of limited life-cycle inventory data), while the resource depletion impact was divided into "abiotic depletion potential, mineral resources" and "cumulative energy demand".

and the new components ($E_{EVB\ new\ components,n}$) and the impacts of energy not provided by either the PV installation or the battery ($E_{in} = E_{generator\rightarrow house}$ and $E_{out} = E_{grid\rightarrow house}$). Negative values in Table S1 refer to environmental credit, e.g. savings made because new materials were not used.

According to the LCIA results, the impact categories can be grouped into clusters depending on the contribution of the life-cycle stage to the overall impact. A first cluster comprises the impact categories largely affected by the use stage (i.e. CED, GWP, ODP, PMF, AP and EPf, Table S1); a second cluster comprises the impact categories for which manufacture and EoL are most relevant (i.e. ADP, POCP and FET, Table S1). HTnc, HTc, IR, EPt and EPm (Table S1) are the impact categories influenced by both the use and the manufacturing stages. In the following sections, for simplicity, the results of the energy and environmental assessments are reported for one representative impact category in each cluster. For the first cluster, GWP is selected because of its relevance to society and policy (e.g. the Paris Agreement) [85]. For the second cluster, ADP-res (abiotic depletion potential, mineral resources) is selected because of the relevance of natural resource availability to economic development and also because of increasing political interest in resource consumption [86,87]. For the third cluster, HTc (human toxicity cancer effect) is selected, as it is recognized as one of the most reliable methods of assessing toxicity in LCA [88]; moreover, unlike the other impact categories in this cluster, HTc is recommended for assessing the protection of human health [89,90]. Furthermore, since the assessment relates to an energy system, the cumulative energy demand (CED), which accounts for primary energy inputs over the whole product life cycle, is also considered.

4.4. Assessment of environmental benefits

The difference between the scenarios (Δ_{reuse}) was calculated following the method described in Section 3 for all of the impact categories presented in Table S1 (supplementary material). The LCIA results for four representative impact categories, together with the necessary information for the environmental assessment of reusing batteries for increasing PV self-consumption, are summarized in Table 5. It should be noted that, in the case study, the impact of the use phase is calculated as the difference between the electricity input and the output of the system, as stated in Section 3.1.

Table 5: Summary of the data used to calculate the difference between scenarios (Δ_{reuse})

Parameter	CED	ADP-res	GWP	HTc
α	0	0	0	0
P_{EVB}	5.57E+04	7.56E–02	2.76E+03	4.29E–04
Rep_{EVB}	1.48E+03	6.92E–04	8.81E+01	4.68E–05
β	0	0	0	0
E_{EVB}	–2.65E+03	–2.41E–02	–1.66E+02	–1.84E–04
$E_{EVB\ new\ components}$	–5.40E+01	1.58E–04	–1.14E+01	–8.06E–06
$T_{EVB-stor}$	3.6	3.6	3.6	3.6
P_{B^*-stor}	5.57E+04	7.56E–02	2.76E+03	4.29E–04
E_{B^*-stor}	–2.65E+03	–2.41E–02	–1.66E+02	–1.84E–04
T_{B^*-stor}	7.4	7.4	7.4	7.4
Reference Scenario A* (grid-connected house)				
$U_{B^*-stor,n}$	2.79E+04	2.12E–03	1.60E+03	5.56E–05

Reference Scenario B* (grid-connected house)				
$U_{B^*-stor,n}$	2.82E+03	2.14E–04	1.62E+02	5.62E–06
Reference Scenario C* (stand-alone house)				
$U_{B^*-stor,n}$	4.96E+04	4.07E–03	3.27E+03	5.71E–05
Repurposed Scenario*				
$U'_{EVB-stor,n}$ (grid-connected house)	1.34E+04	1.02E–03	7.70E+02	2.67E–05
$U'_{EVB-stor,n}$ (stand-alone house)	1.04E+05	8.56E–03	6.88E+03	1.20E–04

[+] As explained in Section 3.3.1, in this study the environmental impact of EV battery manufacturing and EoL is fully allocated to the first life (i.e. α = β = 0). The sensitivity analysis performed considers other values (Section 4.4.1).

*Use stage impacts (U) refer to the difference between the electricity input and output of the system, as stated in Section 3.1.

It should be noted that, as stated in Section 3.3, no impacts of a battery's manufacture and EoL are allocated to the second-use application (α = β = 0); therefore, the Repurposed Scenario considers only the environmental impacts of the production/EoL of the new components and the impacts of the energy flows in the second-use application.

According to the method proposed in this paper, the index D_{reuse} is calculated for all impact categories (Table S1) and for the Reference and the Repurposed Scenarios described in Section 4.1. Figure 4 shows the resulting indexes for four representative impact categories. It can be observed that:

- Replacing a fresh LMO/NMC battery with a repurposed EV battery that has a residual capacity of 81.31% after its first life (Configuration A) is beneficial for all the impact categories, i.e. $D_{reuse} > 0$. Moreover, the environmental benefits are greater for the impact categories mainly affected by the manufacturing stage (i.e. ADP-res). In detail, using a repurposed battery in a grid-connected house to increase PV self-consumption allows a reduction of 93% of the life-cycle ADP-res, compared with a Reference Scenario in which a fresh battery is used.
- When adopting a repurposed battery in a grid-connected house that has no batteries to be replaced (Configuration B), environmental drawbacks are observed for all of the assessed impact categories. For instance, even if the adoption of the repurposed battery allows local electricity consumption to be maximized, the life-cycle GWP increases by 46% compared with the life-cycle GWP in the Reference Scenario. This is mainly due to repurposing the EV battery, the need for new battery components and the energy losses due to the battery's efficiency.
- In a stand-alone house with a diesel generator (Configuration C), adopting a repurposed battery shows benefits for all of the assessed impact categories even if the repurposed battery does not substitute a fresh battery. In detail, a life-cycle GWP reduction (49%) is observed if a repurposed battery is used in a stand-alone house where a generator is used for energy requirements.

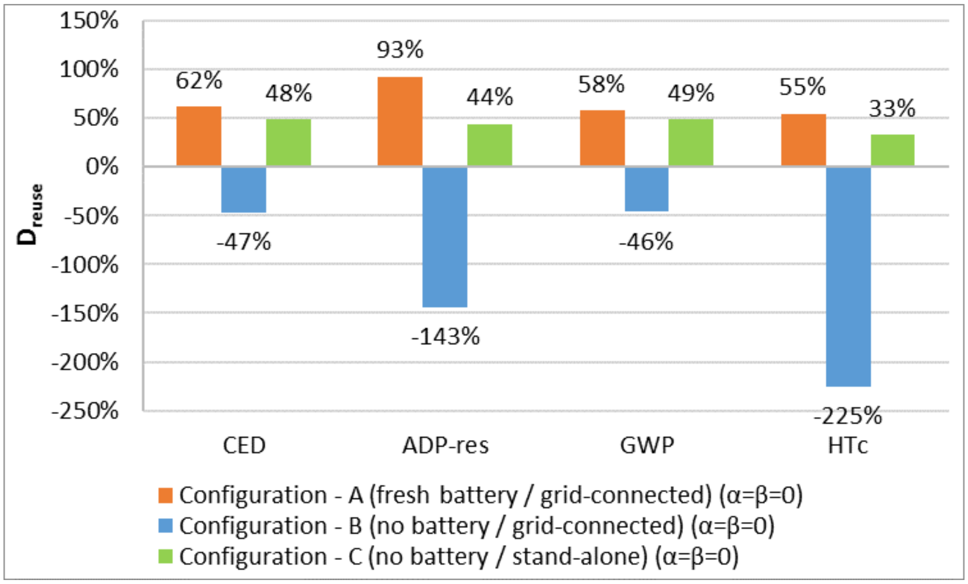

Figure 4: Index assessing the energy and environmental assessments of adopting a repurposed EV battery to increase a house's PV self-consumption.

4.4.1. Sensitivity analysis

Because the system is complex and some parameters are uncertain, a sensitivity analysis was run to assess the relevance of the allocation factor and the residual capacity of EV batteries. Based on the environmental assessment results, a sensitivity analysis for "Configuration B" was not undertaken, since no environmental benefits were identified in Section 4.4. The details of the sensitivity analysis performed are reported in the supplementary material, and the main conclusions are discussed in this section.

As discussed in Section 3.3, the allocation factor could be null, since EV battery repurposing remains an emerging strategy for recovering waste batteries. However, a reasonable market could develop in the future, and such batteries could be designed for sequential use in mobile and then stationary applications. Since the 50/50 allocation represents, conceptually, the worst case for reusing EV batteries in storage applications [26], but would still be rather unfair given the emerging market for repurposed batteries (see Section 2.4.1), the analysis was run assuming an average value for both allocation factors (i.e. $\alpha = \beta = 0.25$). In general, it is observed that allocation factors largely affect the results of the assessment, especially for the impact categories dominated by the manufacturing/EoL stages. In "Configuration A", halved benefits are observed for GWP, ADP-res and CED categories. Reduced benefits are also observed in "Configuration C" for all impact categories, with the exception of ADP-res; this reduction is not as relevant as the overall result for the GWP and CED (about 5 percentage points), since these two impact categories are dominated by the use stage and the allocation factors are mainly related to other life-cycle stages (Figure S1 in the supplementary material).

According to Neubauer et al. [6,21], early EV battery replacement could be a strategy to support second-use application. In that case, the residual capacity of the EV battery varies between 70% and 90% of the nominal capacity. The results (Figure S2 in the supplementary material) show that the higher the residual capacity of the battery, the higher the observed benefits, in particular for impact categories dominated by the manufacturing/EoL and repurposing stages (e.g. ADP-res and HTc). This mainly relates to differences in EV batteries' lives (e.g. 1.6 and 5.3 years for the battery corresponding to 70% and 90%, respectively, of the residual capacity).

5. Discussion

As the literature review has highlighted, the inclusion or exclusion of specific life-cycle stages remains a controversial methodology in the LCA of second-use applications. Similar to Faria et al. [43] and Sathre et al. [39], we propose to exclude the first-use stage of EV batteries from the assessment. However, the performance of the battery in its second-use needs to be considered, and this depends on both the battery's characteristics and its applications in first and second uses [6,47]. Thus, the first use of the battery is indirectly taken into account by including some relevant parameters in the model (e.g. the expected lifetime).

Because of the lack of data and the novelty of the topic, some data are highly uncertain or very difficult to determine (e.g. energy requirements due to user behaviour, battery lifetime, battery degradation) and often secondary or average data or assumptions have to be considered [6,9,26,27,39,43,45]. Different scenarios and sensitivity analyses concerning variables used in the assessment are recommended to estimate the significance of specific parameters to the overall environmental benefits and drawbacks of repurposed EV batteries.

According to the literature review, one of the most promising applications for the second use of EV batteries is combining them with renewable energy installations in buildings [27,29,36,37]. Therefore, the method was applied to a case study in which batteries were used to increase PV self-consumption.

Both the literature review and the LCA results emphasize the relevance of properly modelling the use stage, possibly through primary data and combining both the battery and the system characteristics [29,44]. In this study, data obtained from dismantling a LMO/NMC battery were used to model the impact of manufacturing. Moreover, an original energy model was developed that was adapted to specific reuse applications. This model, based on real PV energy data, was used to calculate the life of the battery and the input/output energy flows in a specific application in the Netherlands. Hence, using as many primary data as possible on both first use and potential second use of the battery is an important recommendation from our LCA method.

The results of the case study illustrated in this paper can be used to confirm and quantify some of the most common claims reported in the literature: 1) the environmental benefits obtained are greater when a repurposed EV battery is used in place of a fresh storage battery; and 2) the environmental gains associated with adopting a repurposed EV battery are more substantial as the energy mix worsens when renewable energies are substituted (e.g. diesel generator vs grid mix). In particular, using a repurposed battery in a grid-connected house to increase the rate of PV self-consumption, compared with a reference scenario in which a fresh battery is used in a grid-connected house, allows a reduction of 93% of the life-cycle ADP-res and 58% of the life-cycle GWP. If the repurposed battery is used in a grid-connected configuration without replacing any battery, the results indicate environmental drawbacks. In the case of a stand-alone house with a diesel generator in which a repurposed EV battery is used to increase renewable energy consumption, the life-cycle ADP-res and GWP are reduced by 44% and 49%, respectively. The results align with previous claims about the relevance of the energy mix used in the assessment [43,47,48].

In the study, the lack of data on the repurposing stage was managed by using available secondary data. The results show that the contribution the repurposing stage makes to the overall impact is not negligible, especially for some impact categories (e.g. HTc). The sensitivity analysis confirmed that the variation in HTc impact on a repurposed EV battery's residual capacity is largely affected by the repurposing stage. These results do not correspond to those reported by Canals Casals et al. [27] and Faria et al. [43], in whose studies the repurposing stage was considered negligible and, thus, was not included in the assessments. Therefore, further efforts to gather data about this stage are recommended to confirm the results and provide primary data for future analyses.

Furthermore, the sensitivity analysis highlights that allocating a proportion of the environmental impact related to the battery's manufacture/EoL to its second use decreases the overall level of environmental benefit, especially for the impact categories dominated by these stages (e.g. ADP-res and HTc). However, solving multi-functionality remains an open issue that depends on subjective decisions made by those undertaking a LCA [26,63,64]. Further work in this area is necessary to define a consensual and fair approach.

6. Conclusions

This article presents a method that aims to provide an adapted, clear, comprehensive and flexible framework for assessing the potential environmental benefits of adopting repurposed traction batteries after their use in EVs. Hence, it contributes to harmonizing LCA methodology on the second-use applications of batteries.

The method is based on a life-cycle approach, and the article discusses the most relevant parameters over the life-cycle stages that contribute to the impacts of second-use EV batteries. The method covers different options in terms of both the batteries used (e.g. chemistry, type) and their second-use applications (e.g. grid-connected, stand-alone houses), and it allows a comparison of the different ways in which repurposed batteries could be used. The discussion addresses some key aspects of the assessment that should be considered, e.g. the repurposing and reuse stages.

The environmental benefits of extending an EV battery's lifetime through repurposing and implementing it in a second-use application are confirmed by the assessment results and align with the literature. However, the lack of primary data and the subsequent use of secondary data from the literature, especially on the use stage, inevitably affect the uncertainty of the results. This, along with the significance of specific parameters in the assessment, was addressed through a sensitivity analysis. In further analyses, it is recommended that the use stage is modelled, possibly through primary data (combining both the battery and the system characteristics) and assessing the energy flow of the system. Contribution analysis and sensitivity analysis are recommended, especially if there is a lack of data on the repurposing stage.

The literature review and the analysis of the present study confirm the relevance of the topic for both policy perspectives and potential business cases. However, further research efforts are needed to gather more detailed information and primary data to evaluate battery degradation (and, consequently, battery lifetime) in specific second-use applications. Additional case studies should be carried out to expand the assessment and identify the best options for extending a battery's life during reuse. Finally, technical, economic, social and environmental assessments should be combined to provide a complete overview of the sustainability of reuse.

Disclaimer

The views expressed in the article are personal and do not necessarily reflect an official position of the European Commission.

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Supplementary material

Life-cycle impact assessment (LCIA) results

Table S1: Life Cycle Impact Assessment (LCIA) of the life-cycle stages of the Repurposed and Reference Scenarios

					Use stage ($E_{in} \cdot u_{B*-stor,n}$)				
Impact category	**Manufacturing ($P_{B*-stor,n}$=$P_{EVB-stor,n}$)**	**Repurposing ($Rep_{EVB-stor,n}$)**	**EoL ($E_{B*-stor,n}$=$E_{EVB-stor,n}$)**	**EoL of the new components ($E_{EVB\ new\ components,n}$)**	**Repurposed Scenario** (grid-connected house)	**Repurposed Scenario** (stand-alone house)	**Reference Scenario A** (grid-connected house)	**Reference Scenario B** (grid-connected house)	**Reference Scenario C** (stand-alone house)
Cumulative Energy Demand (CED) [MJ]	5.57E+04	1.48E+03	–2.65E+03	–5.40E+01	6.50E+04	1.04E+05	1.30E+05	3.09E+04	4.96E+04
Abiotic Depletion Potential, mineral resources (ADP-res) [kg Sb eq]	7.56E-02	6.92E-04	-2.41E-02	1.58E-04	4.93E-03	8.56E-03	9.87E-03	2.34E-03	4.07E-03
Global Warming Potential (GWP) [kg CO2 eq]	2.76E+03	8.81E+01	-1.66E+02	-1.14E+01	3.73E+03	6.88E+03	7.47E+03	1.77E+03	3.27E+03
Ozone Depletion Potential (ODP) [kg CFC-11 eq]	2.53E-04	6.06E-06	1.38E-05	-7.05E-07	4.07E-04	1.22E-03	8.15E-04	1.94E-04	5.82E-04
Human toxicity non-cancer effect (HTnc) [CTUh]	2.35E-03	7.03E-05	-6.33E-04	-2.68E-05	5.75E-04	4.35E-04	1.15E-03	2.74E-04	2.07E-04
Human toxicity cancer effect (HTc) [CTUh]	4.29E-04	4.68E-05	-1.84E-04	-8.06E-06	1.29E-04	1.20E-04	2.59E-04	6.16E-05	5.71E-05
Particulate matter /Respiratory inorganics (PMF) [kg PM2.5 eq]	2.08E+00	8.28E-02	-1.29E+00	-7.68E-03	1.36E+00	6.82E+00	2.72E+00	6.45E-01	3.24E+00
Ionizing Radiation (IR) [kBq U235 eq]	8.69E+02	9.66E+00	-1.13E+01	3.23E+00	5.25E+02	4.56E+02	1.05E+03	2.50E+02	2.17E+02
Photochemical Ozone Formation (POCP) [kg NMVOC eq]	8.34E+00	3.05E-01	-2.47E+00	-6.03E-02	7.59E+00	1.17E+02	1.52E+01	3.61E+00	5.59E+01

Acidification Potential (AP) [molc H+ eq]	2.49E+01	5.07E-01	-2.65E+01	-4.68E-02	1.88E+01	9.63E+01	3.77E+01	8.96E+00	4.58E+01
Terrestrial eutrophication (EPt) [molc N eq]	2.72E+01	9.10E-01	-3.47E+00	-1.05E-01	2.45E+01	4.56E+02	4.90E+01	1.16E+01	2.17E+02
Freshwater eutrophication (EPf) [kg P eq]	2.73E+00	5.54E-02	-3.72E-01	-1.85E-02	1.04E+00	3.30E-01	2.08E+00	4.93E-01	1.57E-01
Marine eutrophication (Epm) [kg N eq]	5.59E+00	8.52E-02	-2.72E+00	-8.89E-03	2.41E+00	4.17E+01	4.83E+00	1.15E+00	1.98E+01
Ecotoxicity for aquatic fresh water (FET) [CTUe]	6.64E+04	2.05E+03	9.37E+04	-8.87E+02	7.37E+04	3.41E+04	1.48E+05	3.50E+04	1.62E+04

Variation of allocation factors

As discussed in Section 3.3, the allocation factors of both the manufacture and the EoL of a repurposed EV battery do not need to be null. Currently, repurposing is an emerging strategy for recovering waste batteries, and hence allocation factors can be null. However, battery repurposing could develop in the future so that a reasonable market exists and EV batteries are actually developed for sequential use in mobile and then stationary applications. In that case, the allocation factors would not be 0. Since the 50/50 allocation represents, conceptually, the worst case for reusing EV batteries in storage applications [26], but would still be rather unfair to the emerging market of repurposed batteries (see Section 2.4.1), an average value is assumed for both allocation factors (i.e. $\alpha = \beta = 0.25$).

Figure S1 shows the results of the sensitivity analysis for “Configuration A” and “Configuration C”, compared with results in Figure 4. In general, it can be observed that non-null allocation factors largely affect the results of the assessment. The results show that the environmental benefits of adopting a repurposed EV battery are reduced for all of the impact categories assessed, especially for those dominated by the manufacturing/EoL stages.

If a repurposed EV battery replaces a fresh battery (Configuration A), the D_{reuse} is positive for all impact categories but the environmental benefits are more than halved for the GWP, ADP-res and CED and even lower for HTc when 25% of the impacts of the manufacture and EoL of the battery are allocated to the second-use application.

If the repurposed battery is used in a stand-alone house that previously used no batteries and a diesel-electric generator (Configuration C), the benefits relate to all of the impact categories with the exception of ADP-res. In particular, the decrease of the D_{reuse} in Configuration C on varying the allocation factor is not as relevant to the impact categories mainly affected by the use stage (i.e. CED and GWP), since the energy provided by the battery prevents or reduces the need to use energy from a less environmentally friendly source (e.g. a diesel-electric generator).

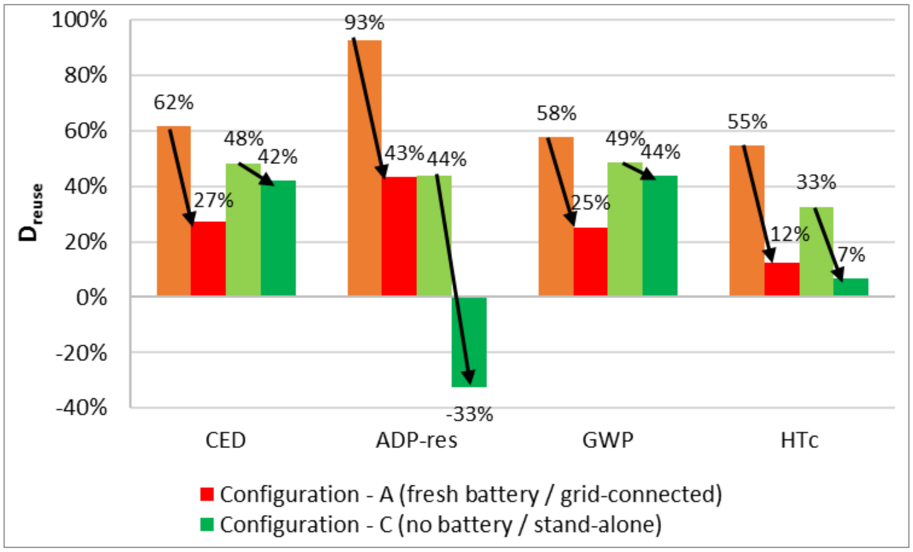

Figure S1: Index of the energy and environmental assessments of adopting a repurposed EV battery to increase PV self-consumption, on varying the allocation factors “α” and “β”.

Variation of residual capacity

According to Neubauer et al. [21], the early replacement of an EV battery could be a strategy for second-use applications. In this case, the residual capacity of the battery after its first use varies between 70% and 90% of the nominal capacity.

Varying the residual capacity of the repurposed EV battery shows that this (Figure S2) is more relevant to impact categories dominated by the manufacturing/EoL and repurposing stages (i.e. ADP-res and HTc). The higher the residual capacity of the EV battery at the end of its first use, the higher the level of benefit observed. The increase in environmental benefits is mainly related to increasing the battery’s life in its second use and, therefore, to decreasing the impacts of the repurposing and EoL of new components every year (in this case $\alpha = \beta = 0$). For instance, with a residual capacity of 70%, the life of a repurposed battery in its second-use application is about 1.6 years and the reduction of the life-cycle GWP compared with the Reference Scenario is about 58%. The option of early replacement with a residual capacity of 90% shows that the repurposed EV battery can be used in the storage application for about 5.3 years and the life-cycle GWP could be reduced by 62% compared with the Reference Scenario.

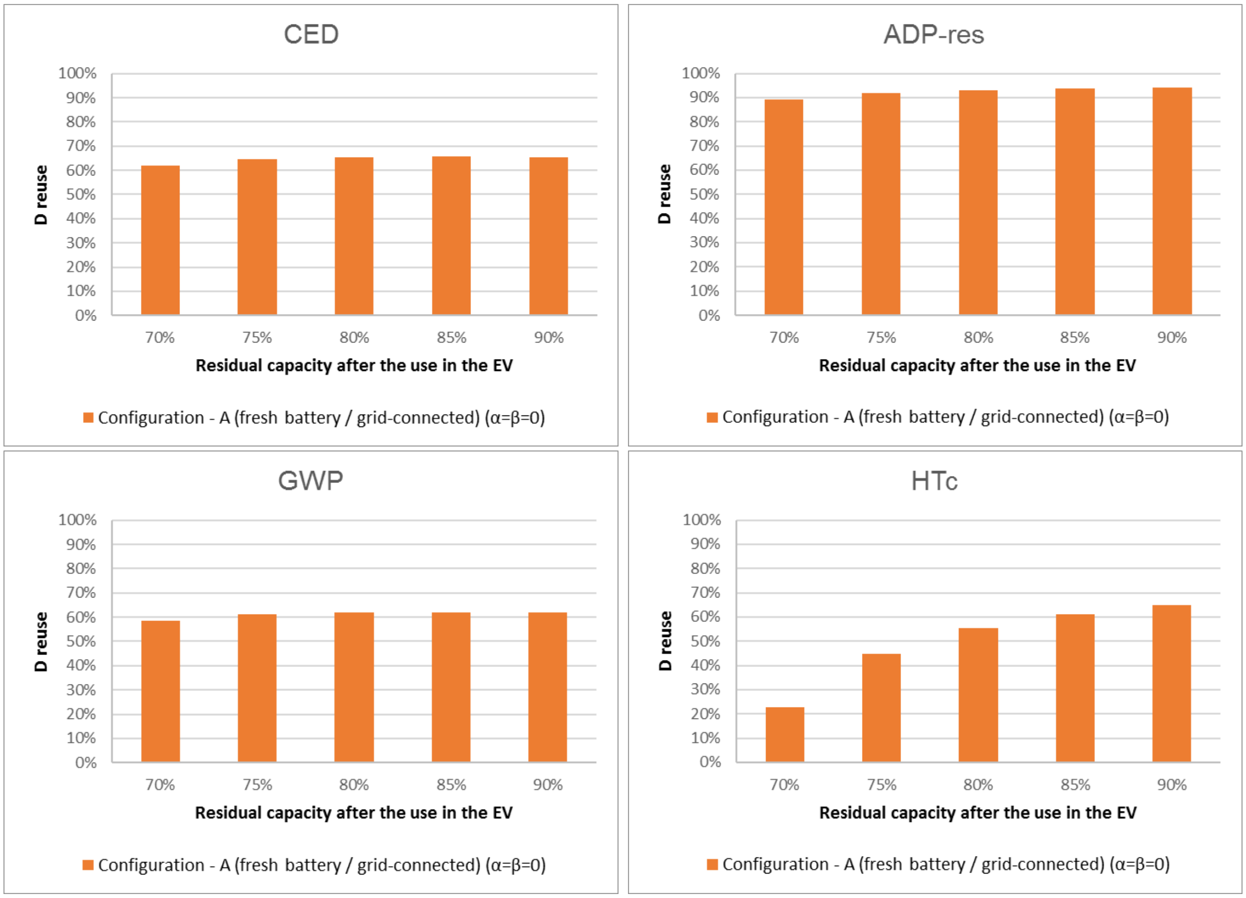

Figure S2: Index of the energy and environmental assessments of adopting a repurposed EV battery to increase PV self-consumption, on varying the battery’s residual capacity.