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Repurposing of electric vehicle batteries for second life stationary applications in residential photovoltaic systems: an environmental and economic sustainability assessment

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Repurposing of electric vehicle batteries for second life stationary applications in residential photovoltaic systems: an environmental and economic sustainability assessment

List of acronyms

BEV: Battery Electric Vehicle

DOD: Depth of discharge

ESU: Energy Storage Unit

EV: Electric vehicle

LCA: Life Cycle Assessment

LCC: Life Cycle Costing

LCEV: Light Commercial Electric Vehicle

LET: Lifetime Energy Throughput

LFP: Lithium Iron Phosphate (batteries)

NMC: Nickel Manganese Cobalt (batteries)

PHEV: Plug-in Hybrid Electric Vehicle

PV: photovoltaic

SOC: State of charge

SOH: State of health

1. Introduction

Responding to a growing environmental awareness from part of the civil society and the need to decarbonize the European economy and become increasingly independent from foreign fossil fuel imports, the electric vehicle (EV) market is booming. This market has been growing strongly in Europe, overtaking the Chinese market by the end of 2020 (1.4 vs. 1.34 million vehicles) (Perkins 2021). One of the main barriers to the widespread adoption of EVs is the high price of batteries (Neubauer et al. 2015a). Provided that EVs are charged with renewable energy sources to effectively lower the environmental burden of such transport means compared to internal combustion engine vehicles (Bobba et al. 2018a), the main environmental hotspot for most impact categories would be the battery (Ahmadi et al. 2017). The reuse, repurposing and (where these options are not available) recycling of batteries is, therefore, a critical aspect of the economic feasibility and environmental sustainability of EVs. Some experimental projects have been tested to

demonstrate such examples of circular economy, since battery packs at the end of their traction life still have 50-80% of residual capacity and could therefore be used later in selected static applications, e.g. as power storage unit in a solar photovoltaic (PV) system (Neubauer et al. 2012; Lacey et al. 2013; Bobba et al. 2018b).

The European Union (EU) is trying to relocate battery cells production to Europe, in order to become independent from Asian suppliers in the coming years. It is paramount to understand what factors determine the environmental sustainability of battery reuse and refurbish processes, as well as the parameters that influence their economic viability. This is necessary to close the open material loop system of the current battery life cycle, which is the main goal behind the recent Battery Regulation (European Commission 2023).

Several initiatives for repurposing batteries have been tried, such as Eaton's xStorage, a residential Energy Storage Unit (ESU) built from automotive batteries of the Nissan Leaf EV[1]. The domestic version, xStorage Home, is sold at € 3,500 (price without VAT or installation costs) for a nominal capacity of 4.2 kWh. The company Forsee Power developed a similar business model, reusing its 'spent' batteries sold for electromobility solutions in stationary second-life applications[2]. Other similar pilot projects have been undertaken by car manufacturers such as BMW and Tesla, described in the European SASLAB project report (Bobba et al. 2018b).

A number of life cycle assessment (LCA) studies and energy analyses on battery repurposing performance for different stationary applications have also been carried out (Ahmadi et al. 2017; Bobba et al. 2018a; Yang et al. 2020). Case studies of repurposed batteries applied to the residential PV sector in Spain have investigated an optimal storage size that could reduce the cost of electricity for users through linear programming (Saez-de-Ibarra et al. 2015; Alfaro-Algaba and Ramirez 2020). An economic analysis for battery repurposing based on laboratory tests has been published too, where the testing and disassembly times of a battery pack of a commercial electric car are reported (Rallo et al. 2020). Another study performed a life cycle costing (LCC) analysis to investigate the potential of Lithium Titanium Oxide batteries for industrial applications, comparing them with conventional lead-acid batteries (Cicconi et al. 2019). In the US Renewable Energy Laboratory, the ageing of batteries used in EVs have been simulated taking into account climatic conditions and different driving styles, to estimate the sustainability of repurposing batteries for

[1] www.eaton.com
[2] https://www.forseepower.com/press-release/forsee-power-signs-mou-with-stationary-storage-specialist-connected-energy-to-extend-the-use-of-transport-battery-systems-into-second-life-applications-15-11-2021/

stationary second life applications (Neubauer and Pesaran 2011; Eyer et al. 2012). These models were subsequently used to map the most cost-effective potential applications, to identify the main limitations and barriers, and then to assess the economic viability of such a business model in the US (Neubauer et al. 2015b).

Here are the main limitations and issues for adequate EV battery repurposing as found in the performed literature review:

- great variability and heterogeneity of batteries for EV on the market, in terms of configurations, anode-cathode chemistry, electronics and communication protocols (Canals Casals and Amante García 2016);
- absence of legislation standardising testing protocols to minimise health risks (safety protocols);
- batteries designed as a single block for one purpose, i.e. they are not designed for a potential secondary use after their automotive lifetime is over. This requires ad hoc disassembly lines with trained and specialized technicians (high disassembly costs);
- until the new regulation on batteries approved last year (European Commission 2023), there was an important legislative void that facilitate dthe reuse of batteries. The new EU law forces producers to ease identification and traceability of batteries put in the market through a Battery Passport, which should streamline repurposing and reduce costs;
- absence of a scientific consensus to unambiguously define and measure the health status of used batteries, more commonly called State of Health (SOH). It is one of the most important parameters to determine the full sustainability of repurposing and it is very difficult to estimate a priori without information on batteries' operating conditions during their first lifetime (Ahmadi et al. 2014; Casals et al. 2017).
- lack of data or lack of access to existing battery data registries to determine the SOH; most of the necessary battery functioning data is either not recorded or it is not available to other stakeholders than the battery manufacturer for confidentiality reasons. This has been addressed by the new battery regulation as well (European Commission 2023).

In this study, both the economic and the environmental sustainability (through LCC and LCA, respectively) of modern automotive battery repurposing for second life applications has been investigated. This allowed i) to identify the key parameters that drive the repurposing costs and the main economic barriers for a widespread repurposing of EV batteries in a European context, and ii) to evaluate the environmental performance of a repurposed EV pack versus a new battery system in a specific stationary application.

In section 2 the overall methodology is presented, with the definition of the goal and scope and the description of the inventory analysis and the impact assessment phases. Results are presented and discussed in section 3, first the economic ones (section 3.1), then the environmental ones (section 3.2), together with a sensitivity analysis. The paper ends with the main conclusions and limitations of the study (section 4).

2. Material and methods

2.1. Methodology

In the last years, LCA has become the most internationally recognized and widespread methodology for carrying out comprehensive environmental sustainability assessments of commercial products and services. LCA has also gone mainstream in many industrial applications for product footprinting and environmental product declarations used in business-to-business and business-to-consumer communications. LCA is also the backbone and reference methodology in key European policies, such as the renewable energy directive (European Commission 2018), the recommendations on product environmental footprint communications (European Commission 2013), the green taxonomy for sustainable investments (European Commission 2020) and in the proposal for a directive on green claims[3]. Most standards and policies typically refer to and follow the principles and requirements set out in the main LCA standards (ISO 2006a, b). These define four steps to carry out an LCA study: i) Goal and scope definition, ii) Life Cycle Inventory, iii) Life Cycle Impact Assessment, and iv) Interpretation and recommendations.

Like LCA, LCC allows identifying the economic hotspots in the life cycle of a product or service. Here a conventional cradle to gate LCC was performed, covering all costs (without considering externalities) associated with the repurposing of used EV batteries. The calculated potential environmental impacts (LCA) and costs related to the repurposing of batteries were then compared to those associated with the production of an equivalent new battery system for the selected stationary application.

2.2. Goal and scope definition

2.2.1 Goal

The study focuses on automotive Lithium-Nickel-Manganese-Cobalt (NMC) batteries which are then repurposed as stationary batteries for domestic solar PV systems. The study pursues a double goal: to assess if such a business model is economically feasible and environmentally sound, when compared to a new energy storage system for the selected application.

[3] https://environment.ec.europa.eu/publications/proposal-directive-green-claims_en

2.2.2 Assessed batteries

The reference system is a new NMC battery designed for a grid-connected domestic PV system. This system design is meant to increase the self-consumption capacity of households, thereby increasing energy production from renewable sources and reducing the demand for electricity production from the grid (Bobba et al. 2018b). On the other hand, the repurposed system consists of used EV battery modules that still hold a pre-defined energy storage capacity. Considered batteries for repurposing come from different commercial EV models: Battery Electric Vehicles (BEV), Plug-in Hybrid Electric Vehicles (PHEV) and Light Commercial Electric Vehicles (LCEV). Their technical specifications can be seen in Table *1*. Used batteries are tested, discarding the packs and modules that do not fulfil minimum SOH requirements. Reusable batteries are disassembled to their modules and re-assembled with additional parts into new battery systems of different sizes for the selected stationary application.

Table 1. Characteristics and technical specifications of the batteries and modules considered taken from publicly available information. They represent batteries used in popular EVs on the market. Brand names and models have been anonymized.

	BEV	**PHEV**	**LCEV**
Battery capacity [kWh]	52	10.7	74
Number of battery modules	12	5	16
Number of battery packs	1	1	2
Battery weight (kg)	326	94	260
Length (cm)	162	139.6	85
Width (cm)	129	35.2	70
Height (cm)	33.1	31.4	30
Battery chemistry	NMC	NMC	NMC
Average capacity per module (kWh)	**4.3**	**2.1**	**2.3**

2.2.3 Geographical and temporal scope

The study focuses on Italy and uses national battery sale statistics (2010 to 2019) and EV sale projections to 2030[4] to estimate the total volume of intercepted batteries for repurposing. This is used during the LCC to estimate the repurposing site dimension and related fixed costs.

[4] Provided by COBAT

2.2.4 System boundaries

The system boundaries for both battery systems end at the factory gate. However, the use and final disposal stages of both battery systems are expected to be very similar in terms of costs and impacts, since the functional unit has been defined in a way to make both the repurposed and the new battery systems equivalent in terms of the energy service provided to households (see section 2.2.5). Moreover, the domestic energy demand, the PV system with its electrical installation and the national grid where the batteries are installed are assumed to be identical in both systems. Likewise, the costs and impacts of the end of life of both battery systems are expected to be similar, since the materials and components are the same, or similar, as well as the country where the batteries are installed and disposed of. Hence, despite both the LCC and LCA are, strictly speaking, "cradle-to-gate" analysis, the results of the study can be considered representative of the full life cycle of such energy storage systems, i.e. "cradle-to-grave" (see Figure *1*).

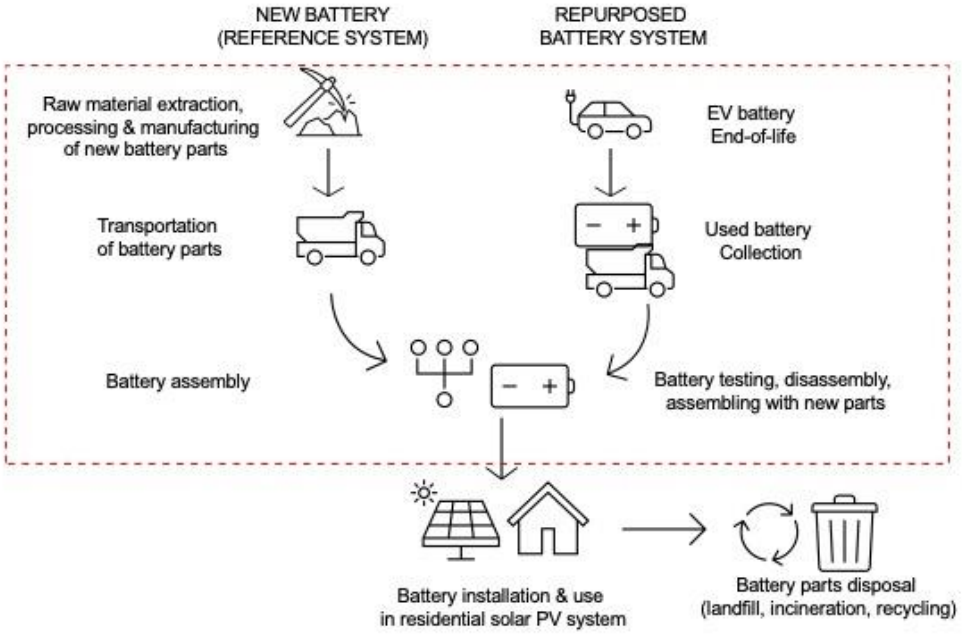


Figure 1. System boundaries of the analysed energy storage systems: raw material extraction and processing (reference system), used battery collection and transport to facility (repurposed system); new battery parts manufacturing and assembly (refererence system), used battery testing, disassembly, module selection and assembly with new parts (repurposed system).

2.2.5 Functional Unit

To compare the reference system with the repurposed system, we define the functional unit through two energy performance indicators. This is necessary to cover two basic requirements of the energy service that such battery systems must fulfil (i.e. total energy provided to the household) during a

day and during their lifetimes. The first parameter is the effective storage capacity (K_{eff}) of the battery systems at the start of the stationary application and covers the energy service that these provide on a daily basis:

$$K_{eff} = K_0 \cdot SOH_{initial} \cdot DOD \quad \text{(Equation 1)}$$

Where K_0 is the nominal storage capacity (kWh), $SOH_{initial}$ is the battery's initial state of health and DOD is the depth of discharge. For new batteries (reference system), SOH_i is set at 97% and the DOD is assumed to be 100% for every cycle. For repurposed batteries, SOH_i is a key technical prerequisite for their usability in second life applications and it is set at 80% (it is checked during the testing phase), while the DOD is capped at 80% through the new battery management system. This is necessary to have a prolonged secondary lifetime that is equivalent, or as close as possible, to the new battery in terms of duration and total cumulated energy (Neubauer et al. 2012).

The second energy performance indicator defines the reference flow of the functional unit and it is based on the present value of throughput method to cover the lifetime aspect of the energy service of batteries (Neubauer et al. 2012). We define the lifetime energy throughput (LET) as the effective storage capacity over time to estimate the cumulated energy that batteries can provide over their lifetimes (see Equation 2):

$$LET = \int_{c_0}^{c_{max}} SOH_{initial} \cdot DOD \cdot K_{eff}(c) \cdot dc \quad \text{(Equation 2)}$$

The LET encompasses the total amount of energy that batteries can accumulate and give back to the households during their lifetime, depending on their respective SOH, technical specifications like nominal capacity and design aspects, e.g. DOD. Simplifying the storage capacity over time $K_{eff}(c)$ as a function of the number of charge-discharge cycles (Ellingsen et al. 2014):

$$K_{eff}(c) = K_0 - K_0 \cdot (\delta \cdot c) \quad \text{(Equation 3)}$$

Where δ is the battery degradation index, we can now combine Equation 2 and 3 to get the LET. Given the technical difficulties of modelling batteries' LET with greater accuracy, this linear model is deemed sufficient to approximate the LET of the batteries used in the current assessment, as similarly done in other studies (Neubauer et al. 2012). The degradation index and the amount of maximum cycles that the batteries can perform are determined by the operating conditions, such as DOD and discharge power, which are controlled by the battery management system. Hence, by integrating Equation 3 with the application conditions (i.e. DOD and $SOH_{initial}$ of 80%,), we obtain the formula that defines the LET of repurposed batteries as a function of K_0, δ, c_{max} and c_0:

$$LET = SOH_{initial} \cdot DOD \cdot K_0 \cdot \left[\left(c_{max} - \frac{\delta \cdot {c_{max}}^2}{2}\right) - \left(c_0 - \frac{\delta \cdot {c_0}^2}{2}\right)\right] \quad \text{(Equation 4)}$$

Where c_0 is the number of cycles performed at the beginning of the application (this is assumed to be 0 for new batteries and 1500 for used ones) and c_{max} is the number of maximum cycles that the battery,

new or used, is expected to perform at the design DOD. The degradation index δ is approximated linearly as:

$$\delta = \frac{(SOH_{initial} - SOH_{final})}{c_{max} - c_0} \qquad \text{(Equation 5)}$$

In Table 2 an overview of the energy performance indicators used for the functional unit of the assessed batteries is presented. As it can be seen in the Table 2, there are significant differences in LET among the assessed batteries, which form the reference flow of the functional unit around which the comparison is made. These differences in performance are addressed by:

i. Applying a correction factor to repurposed battery selling prices proportional to the gap between the assessed battery systems and the reference LET of the new battery following the approach of Neubauer et al. 2015 (see 3.1.1);
ii. Carrying out the environmental impact assessment of repurposed batteries over the total LET of each battery system (impact per kWh_{LET}), since LET is the defined reference flow of the functional unit.

Table 2. Key energy performance indicator values used in the functional unit of the new and the repurposed batteries: BEV, PHEV and LCEV.

Repurposed & New batteries	**Modules**	***K₀* (kWh)**	***K*$_{eff}$ (kWh)**	***K*$_{eff}$ gap to Ref.**	**LET (MWh)**	**LET gap to Ref.**
Repurposed BEV	1	4.3	2.9	10%	7.9	24%
Repurposed PHEV	2	4.3	2.8	11%	7.8	25%
Repurposed LCEV	2	4.6	3.1	4%	8.5	19%
New Battery	1	3.3	3.2	-	10.4	-

The electricity consumption of an average Italian residential unit is 2,154 kWh $year^{-1}$, or 5.9 kWh day^{-1}, ranging from 3.2 to 9.4 kWh day^{-1} (Besagni et al. 2020). Based on this range of measured household consumption for Italy, repurposed batteries are reconfigured into ESUs of different sizes by combining several modules to get an effective storage capacity within that range and as close as possible to existing commercial batteries. For additional details see section 1.4 in the Supplementary Materials and Tables therein for all the technical characteristics and parameter values used for all batteries.

2.2.6 End of life modelling approach

A cut-off modelling approach was followed for the reused battery modules, i.e. repurposed batteries are free of any upstream environmental burden. This modelling choice is tested in the sensitivity analysis (section 3.2.1), through the circular footprint formula for the LCA part, while a used battery price is calculated for the LCC part (section 3.1.1) and tested in a separate sensitivity analysis (section 3.1.3).

2.3.Life Cycle Inventory

The main characteristics of the batteries and modules considered for this study are shown in Table *1* and Table *2*. Furthermore, the study is based on the following assumptions:

i) The volume of intercepted batteries in the Italian market for repurposing is considered to be 75% of the total available each year in the period analysed (2020-2030)[5]. Batteries that could be damaged are labelled as dangerous by the dealer and not collected for repurposing. Furthermore, a 10% of the collected batteries are assumed to be discarded after the testing phase. Discarded batteries are assumed to go directly to disposal and are not paid to the owners.

ii) Repurposed batteries are limited to a DOD of 80% to ensure the longest possible second life (Lacey et al.; Neubauer and Pesaran 2011; Ellingsen et al. 2014)[6]. This allows the number of cycles to be extended and the degradation rate of used batteries to be reduced.

iii) Used batteries have 1500 charge-discharge cycles at the start (approximately 5 years of life), which corresponds to a SOH of 80%. Repurposed batteries are at the end of their second life when they reach a SOH of 60%, which is assumed to occur after 5000 full cycles at the design DOD.

iv) New batteries have a SOH of 97% and 0 cycles at the start. They are at the end of their life when they reach a SOH of 60%, which is assumed to occur after 4000 full cycles at full DOD.

v) If the repurposing of batteries is profitable, the value of used batteries is greater than zero and therefore they are purchased from the owners at a designated price (to be estimated).

vi) To estimate the purchase price of used batteries, the capital costs are amortized over 5 years, considering an internal rate of return (IRR) of 5%.

[5] Source: COBAT data

[6] According to the modelling of Casals et al., 2017, for a used battery with an initial SOH of 80%, a maximum DOD of 50%, and a final SOH of 60% (in stationary application as an battery in a PV system), such an ESU would have a second life of 8 years, while in Bobba's model, Podias et al., 2018, it is estimated a second life of 4 years for a second life battery with a DOD of 80%. In Ellingsen et al. (2014) the change is reported on the maximum cycles depending on the DOD of work, provided by an NMC battery manufacturer (1000 cycles at 100% DOD, 5000 cycles at DOD 50%)

For the collection phase of the used batteries, it is considered that the new plant will be located in the area of Bologna (centre north) and that the trucks will cover an average distance of about 300 km (average distance between Bologna and the main Italian cities, such as Genoa, Turin, Milan, Rome). The system has been designed parametrically, i.e. based on the volume of incoming batteries. Due to feasibility constraints, the system was designed for an initial battery volume equivalent to 150,000 kWh $year^{-1}$ of storage capacity, i.e. 75% of the total flow expected for 2026. The expected volume of batteries for 2030 is an order of magnitude greater than expected for 2026; the size of the plant, and therefore of the business, is multiplied by 10 in just 5 years[7]. To calculate the plant size, the parametric model of Neubauer et al. (2015) was followed. The plant area is calculated from the number of offices needed (for managers), the area needed for workstations for testing, assembly and disassembly, the area for the conveyor belt, the storage shelves for batteries and ESU and a space to manoeuvre forklifts. Thus, the size of the plant will be approximately 3000 m^2, with 44% of the area destinated to the BEV production line, 21% to PHEVs and 35% to LCEVs. The plant has a land cost of 100 €/m^2 and a cost of 350 € /m^2 for the construction of the site. Taking 2030 as reference year, and according to the volume of batteries estimated, the plant would have a size of 22,570 m^2 (and a cost of 6.9 M€). The required staff is calculated based on the times from Rallo et al. (2020) and 252 annual working days. The salaries for each category and contractual level were taken from ISTAT[8]. Full details of the life cycle inventory

All the inventory data has been normalized to the reference flow (1 $kWh_{_LET}$) defined in the FU. All the processes related to the Collection, and Testing & Disassembly of the batteries used for repurposing are calculated based on the nominal capacity. This is because these processes are designed according to the size and weight of the used batteries and modules. The available inventory data from Rallo et al. (2020) is referred to the nominal battery capacity too.

The life cycle inventories for the environmental impact assessment of the NMC batteries have been taken from Majeau-Bettez et al. (2011) and Ellingsen et al. (2014), integrating the data from Bobba et al. (2018) where necessary and using Ecoinvent 3.7 as the main database for all background processes. For the full details of costs and resources inventory calculation of each life cycle stage and battery type, we refer to the life cycle inventory Section S1 in the Supplementary Materials.

[7] Specifically, the estimated flow is equal to 146,052 kWh/year for 2026.
[8] https://www.istat.it/it/archivio/retribuzioni

2.3.1. Calculation of ESU's selling prices

A key cost of repurposing is related to the purchase of used batteries, which in turn represent the potential cost reduction (and added value from a second life application business model) of the EV value chain. This cost results from the fact that used batteries will have a positive value in a viable repurposing business model, provided that a minimum SOH and LET are guaranteed by the dealer. The selling price of the ESU is calculated following the "battery salvage value" approach of Neubauer et al. 2015, as shown in Equation 6:

$$P_{repurposed} = \frac{LET_{used}}{LET_{new}} \cdot P_{new} \qquad \text{Equation 6}$$

where the P_{new} factor is the price of a stationary battery of similar performance and characteristics. The price of stationary batteries for the period 2026 – 2030 was estimated from 2020 and 2024 market price data and extrapolating linearly until 2030 the seen price decrease. Future price estimates from other sources have proven to be too optimistic, as demonstrated by 2024 data, which contrasts with ambitious projections reported by Bloomberg and others (Logan Goldie-Scot 2019, Steen et al. 2017). Thus, an average market price for 2024 of about 493 € kWh^{-1} for stationary batteries was considered, which goes down to 397 € kWh^{-1} for 2030. Selling prices were differentiated among battery size, according to market prices retrieve for 2024 and were considered to derive the plant revenues from 2026 to 2030. For a summary of the selling prices, please refer to Supplementary Materials (section S2.1, and tables therein).

2.3.2. Calculation of purchase prices of used batteries

The purchase prices for used batteries were calculated iteratively through the net present value (NPV) of the plant, as the acquisition costs of used batteries were the only unknown in the equation that represents the financial ambition of the project (see equation 7):

$$\sum(CapitalCosts_{t=0}) = \sum_{t=1}^{t=5}(Revenues_t - Expenses_t) \cdot (1 + IRR)^{-t} \qquad \text{Equation 7}$$

Where the IRR is the Internal Rate of Return and "t" is the amortization period, assumed here to be 5% and 5 years, respectively (premise viii). On the left side of the equation are capital costs, i.e., the initial investment needed for the year 2026 (equipment, land, facility). On the right is the sum of the net cash flow for a period of 5 successive years (2026 – 2030).

To obtain the maximum purchase prices of used batteries implies satisfying:

i) A positive NPV;

ii) a final repurposed ESU cost lower than the calculated selling price in the previous step.

With the battery salvage values calculated, the total cost of repurposing is obtained by adding indirect costs to cover insurance costs (3% of direct costs), general and administrative costs (5% of direct costs), ESU guarantee costs (5% of revenues), and Research and Development (3% of revenues), as suggested in Neubauer et al. (2015). All the details on ESU's repurposing costs (unit costs in €/kWh,

total costs in €/ESU and selling prices in €/ESU) for all battery types can be seen in section S2.2 of the Supplementary Materials and tables therein.

2.4.Impact Assessment

The Life Cycle Impact Assessment (LCIA) is finally carried out to characterize the modelled inventories for each battery system in terms of contributions to a recognized set of environmental impact categories. In this study, the Environmental Footprint v3 method was chosen. The assessment was carried out using the Simapro Analyst 9.1 software with Ecoinvent 3.7 as the main background database.

3. Results and discussion

3.1. Life Cycle Costing results

3.1.1. EV batteries' salvage value

Table 3 shows the battery salvage values for the three analysed battery types (BEV, PHEV and LCEV). These represent the potential cost reduction in the battery value chain (Neubauer and Pesaran 2011). Battery salvage values were calculated iteratively, maximizing their value by calculating ESU's selling price with projected new stationary battery prices from 2026 to 2030 and expected LET performance (see Section 2.3.2).

Table 3. Maximum purchase price of used batteries. Iteration results computed to get to a near-zero project NPV (IRR of 5%, t = 5 years) with integer battery salvage values (no decimals considered in the iterations).

	BEV	**PHEV**	**LCEV**
Used battery salvage value (€ kWh^{-1})	120	100	110
Buying price, whole battery	€ 6,240	€ 1,070	€ 8,140[§]
NPV	€ 102,352,387	€ 12,504,926	€ 90,977,965

[§] Includes 2 battery packs

As shown in Table 3, BEV and LCEV batteries seem to retain a considerable economic value at the end of their automotive life. Calculated NPV for each battery type show that such repurposing business has still a great margin to further adjust ESU (and purchased used battery) prices according to market evolution. With the considered price estimates and assumptions on used batteries' SOH and LET, repurposing of EV batteries as residential energy units could reduce the total cost of a BEV by as much as € 6,240, and by € 8,140 for LCEV. Repurposing of PHEV batteries show lower profitability, as the repurposing process does not change depending on the capacity of the battery

pack. Therefore, the production cost weighs more on packs with low capacities. In other words, the smaller the batteries and their modules, the more expensive the unit costs of repurposing gets.

3.1.2. Total repurposing costs

Once the battery salvage values are calculated, total repurposing costs can be derived, which are shown in Figure 2. As can be seen, the most important costs are consumption costs (68%), mainly due to the costs of purchasing used batteries (44% of total). This is followed by indirect costs (16%), collection and personnel costs (7% each). Capital costs are last in order of importance (2% of total annual costs). Further graphs and tables on consumption and costs can be in the Supplementary Material (section S2.2 "Summary of repurposing costs" and tables therein).

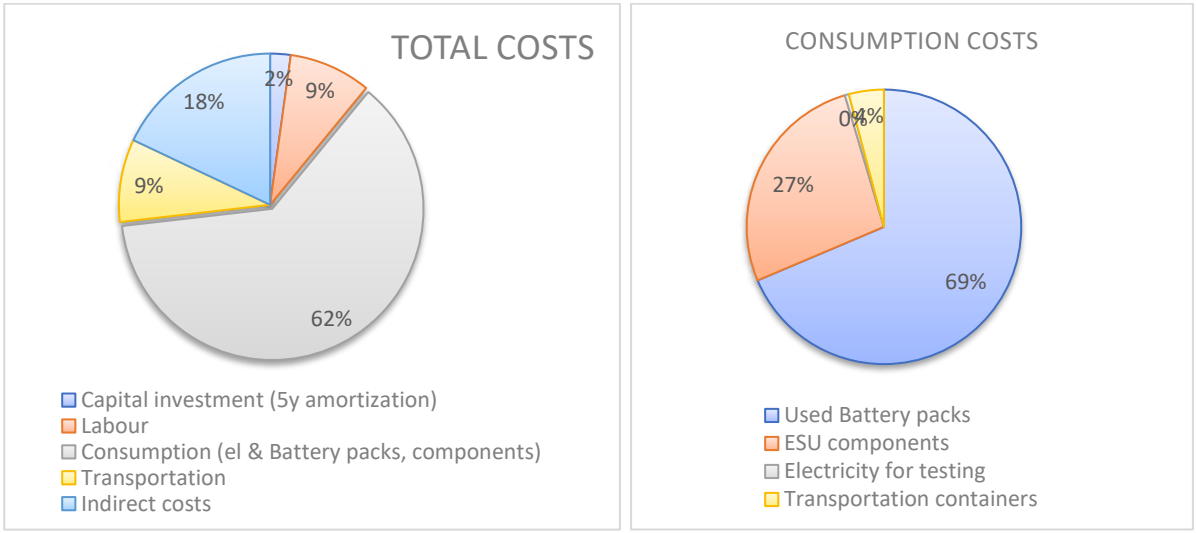


Figure 2 Breakdown of total costs and consumption costs for battery repurposing

3.1.2.1. Benchmarking of repurposed ESU to market batteries

The characteristics of the repurposed ESUs from BEV batteries are presented below according to the number of modules assembled and the LET. Similar tables for PHEV and LCEV can be consulted in Tables S15 and S16 in the SM. As can be seen in Table 4, the results of the analysis indicate that there is a possibility to start a repurposing business model. For PHEV battery types the selling price of some ESU would remain below the battery cost, which means that the profitability of repurposing also follows economies of scale, being low or inexistent for batteries with small modules. The price would still be around 25% of the selling price of the new similar battery (the new 3.3 without VAT, inverter, or installation). Considering also the possible drop in the prices of new batteries reported here in the near future, the repurposed ESUs still maintain a good margin to remain competitive in the field of residential storage for domestic PV systems. Alternatively, Table 4 and Tables S15 and S16 show that there is margin to reduce the selling prices to make repurposed batteries more attractive

to consumers, since they are less performative in terms of LET. Nevertheless, the prices reflect already the lower LET performance potential of repurposed batteries.

Table 4 Comparison of performance and selling prices ESU – BEV with market prices for similar batteries for similar new batteries (estimated prices for 2026 of 220 € kWh^{-1}). In red are the costs of ESUs that would not be profitable (costs > selling price)

ESU - BEV configurations	**Nameplate capacity (kWh)**	**Usable energy (kWh)**	**Unit Cost (€/kWh)**	**Total ESU Cost (€)**	**2026 selling price (€)**	**LET (MWh)**	**Price difference**
2 modules	4.3	3.5	259	1124	1822	7.9	7.9
4 modules	8.7	6.9	232	2012	2349	15.8	15.8
6 modules	13.0	10.4	223	2901	3085	23.8	23.8
8 modules	17.3	13.9	219	3790	4020	31.7	31.7
New 3.3	3.3	3.2	*712*	-	*2286*	10.4	10.4
New 6.5	6.5	6.3	*459*	-	*2857*	20.6	20.6
New 9.8	9.8	9.5	*406*	-	*3792*	31.0	31.0
New 13	13.0	12.6	*395*	-	*4891*	41.1	41.1

The competitiveness of the final ESU prices depends strongly on the final price of new similar batteries and the size of the packs and modules. The BEV and LCEV business scenarios, with bigger battery packs and modules, are more likely to be profitable while PHEV battery repurposing remains more problematic.

To illustrate the application of the LCC performed, two ESU from repurposed BEV were chosen, considering the size needed by an average Italian family, which according to the recent analysis by Besagni et al. (2020) should cover an average daily consumption of 5.9 kWh. The energy needs could therefore be covered with a PV system connected to a new battery with a nominal capacity of 6.5 kWh (the actual capacity is 90%), or a first ESU – BEV of 4 modules (17.3 kWh nominal, 6.2 kWh useful) for the first 10 years and a second ESU – BEV of 3 modules (13 kWh nominal and 4.7 kWh useful) for the second decade (Table 5). Under the assumed conditions and assumptions, the two ESUs would have an overall price (LCC) slightly lower, but very similar, to the new reference battery considered.

Table 5 Price comparison and performace of ESU and reference battery

Battery characteristics	**ESU – BEV**	**ESU – BEV**	**Reference** (new 6.5 kWh)

	(4 modules)	(6 modules)	
Nominal capacity (kWh)	8.7	13.0	6.5
Usable energy at initial SOC (kWh)	6.9	10.4	6.3
Usable energy at design DOD (kWh)	5.5	8.3	6.3
Estimated LET (MWh)	15.8	23.8	20.6
Pack weight (kg)	54.3§	81.5§	52
Cost, at factory gate (€)	2,012	2,901	-
2026 selling price (without VAT, inverter and installation)	**€ 2,349**	**€ 3,085**	**€ 2,857†**

§ Linearly extrapolated from original battery pack weight.

† Taking a 2024 market price of € 2,982. The 2020 price of this battery was € 3,409

Assuming a € 2,000 inverter cost that is included in the original price (€ 3,900).

3.1.3. Sensitivity analysis of LCC

Having considered three different battery types, each with different module and pack sizes, a good range of variability has already been covered in terms of scenario analysis. The most critical parameters for the economic profitability of a repurposing business are:

a. The dimensions of the battery packs and their modules;

b. Future prices of new reference batteries;

As argued by cited references, used batteries for repurposing should have a SOH > 0.8 to be economically viable. As the analysis of this study showed, battery packs' capacity should be greater than 30 kWh and modules' capacity over 2.3 kWh. Regarding the future prices of new batteries, given the increasing importance of electromobility and the battery market in general, several studies and surveys have estimated the selling prices (or production costs) of batteries for the next 10 years. For the sensitivity analysis, future prices for new automotive batteries are taken from a Bloomberg study (Logan Goldie-Scot 2019). Taking a EV battery cost target of 150 $ kWh^{-1} for 2030, Table 6 shows how the economic performance of the repurposing would change to these new battery prices (much more ambitious than used values).

Table 6 Changes in economic performance of BEV battery repurposing plant with lower (more ambitious) price projections for new batteries.

ESU - BEV configurations	**Nameplate capacity (kWh)**	**Usable energy (kWh)**	**Unit Cost (€/kWh)**	**Total ESU**	**2026 selling price (€)**	**LET (MWh)**	**LET difference**

				Cost (€)			
2 modules	4.3	3.5	148	641	635	7.9	76%
4 modules	8.7	6.9	121	1047	1290	15.8	77%
6 modules	13.0	10.4	112	1453	1925	23.8	77%
8 modules	17.3	13.9	107	1859	2580	31.7	77%
New 3.3	3.3	3.2	*712*	-	*726*	10.4	-
New 6.5	6.5	6.3	*459*	-	*1430*	20.6	-
New 9.8	9.8	9.5	*406*	-	*2156*	31.0	-
New 13	13.0	12.6	*395*	-	*2860*	41.1	-

Table 7. New battery salvage value estimates based on lower new battery prices.

	BEV	PHEV	LCEV
Used battery salvage value (€ kWh^{-1})	30	0	20
Buying price, whole battery	€ 1,560	-	€ 1,480[§]
NPV	€ 4,345,387	€ - 445,704	€ 16,622,965

[§] Includes 2 battery packs

As it can be seen, selling prices would decrease dramatically, and so the repurposing unit costs (as the acquisition of used batteries is one of the main cost drivers). For PHEV batteries the business would not be profitable anymore. BEV and LCEV results show a good margin to run viable repurposing businesses for these battery types, although the cost reduction of for EV would be limited. for The reduction in the profitability of repurposed batteries due to a significant decrease of new batteries, could be offset by efficiency improvements in the form of economies of scale (e.g. reduced transport and component costs). Further cost reductions could be expected from standardization of communication protocols, disassembly safety protocols, battery design that eases disassembly, robotization and general improvements from learning. A protocol for a fast and safe disassembly could substantially reduce the time involved through automation with modular robotic systems with artificial intelligence. In addition to reducing disassembly and assembly times (from 20% to 50%, depending on the complexity of the process), automation would also lead to further savings in personnel costs because it would reduce the number of technicians needed (a 49% of the labour cost in this study). Finally, a CO_2 tax could also give an additional incentive to such repurposing battery

systems, as they would become more competitive than the new ones and would support solar energy storage (which is CO_2 free).

3.2.Life Cycle Assessment results

The environmental footprint results for the reference system vary, decreasing with the storage capacity of new NMC batteries. This means that the environmental performance of new batteries, i.e. the sum of impacts per kWh of storage, decreases with their size. The main reading of the results obtained, also in line with other studies in the literature, is that the environmental footprints of repurposed battery systems remain significantly lower than the baseline ones for practically all the impact categories analysed (see graphs in Supplementary Material). This means that second life ESU have multiple and significant environmental benefits compared to new batteries. The battery type with a better environmental performance is the BEV (i.e. the largest battery pack with larger modules), followed by the LCEV and the PHEV (which is still better than the new more performing NMC battery, the 13 kWh). Figure 3 graphically illustrates the Climate Change impact results for the storage systems analysed. Repurposed battery impacts vary according to the battery type but, unlike new storage systems, their impacts are constant in terms of battery size (see Figure 3).

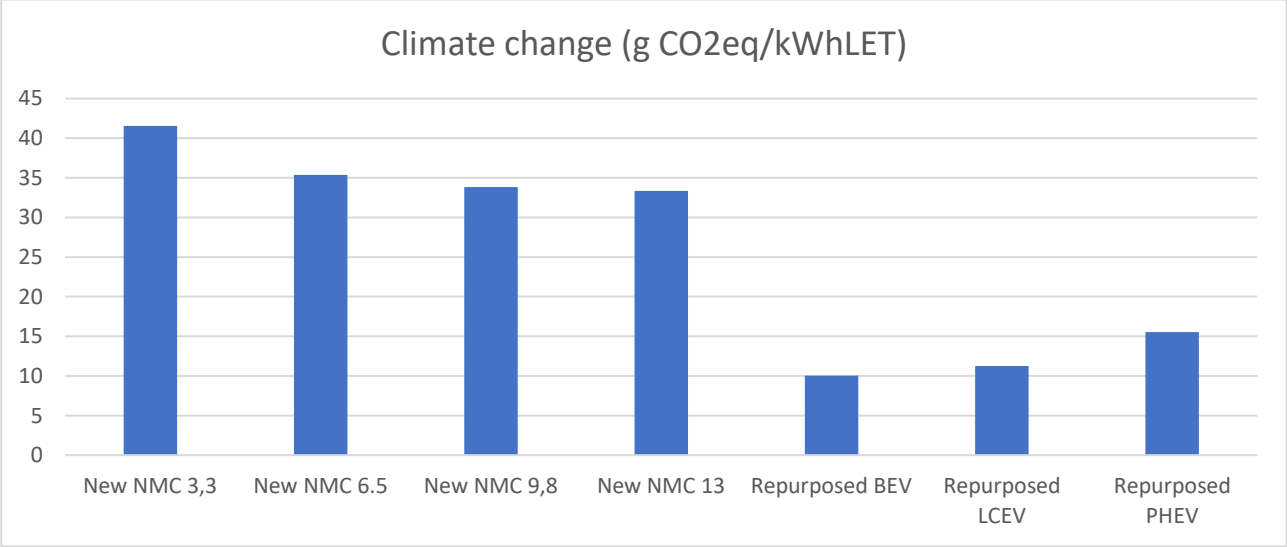


Figure 3 Results of the calculation of the climate-altering impact of the storage systems analysed

Considering the borderline cases of the two systems compared (i.e. the PHEV, the least performing, and the new NMC of 13 kWh, the best performing of the new ones), the repurposing of the batteries would in any case be an excellent alternative from an environmental point of view, under the conditions and assumptions described above. Further results concerning the comparison of environmental performances of batteries in other categories are shown in Supplementary Material, Section S3.

3.2.1. Sensitivity analysis

Similar to the analysis carried out previously, the study already covers a good range of scenario analysis in terms of battery types, pack and module sizes. Two important additional aspets have been considered for the sensitivity analysis, namely the chemistry (and thus the LET performance) of the new battery system, and the end-of-life allocation of used batteries for repurposing. For the battery chemistry, a LFP one was modelled (more common in stationary applications) as a reference system. The end-of-life allocation was changed from the polluter pays or cut-off modeling approach to the circular footprint formula, which considers the residual economic value of the recycled or reused materials as criterion to allocate upstream and downstream burdens.

3.2.1.1. New LFP chemistry batteries as a reference system

We focus here on an alternative scenario for the reference system, where we model a storage system with new batteries of LFP chemistry instead of NMC. LFP batteries have a lower energy density than NMCs, which are more widely used more used in automotive today, but they have longer longevity and therefore some manufacturers choose this chemistry for stationary applications. The technical specifications from a manufacturer were used for the correct description of the system and to complete the related inventory, adapted from the inventory of NMC batteries. To simplify, the only component modified was the main cathode material, taking LiFePO4 instead of LiNixCoyMnzO2.

Inventory data reported in the previously cited LCA studies (Majeau-Bettez et al. 2011; Ellingsen et al. 2014) were also taken to model the production of the LFP cathode and its supply chain ending with the production of LiFePO4, not present in the Ecoinvent 3.7 database. Figure 4 illustrates the single result of the Climate Change impact category for the analysed storage systems (new NMC and LFP batteries, and repurposed batteries). As it can be seen, the overall conclusions do not change with the new battery chemistry. Additional graphs and tables concerning the sensitivity analysis are shown in Supplementary Materials, Section S3.

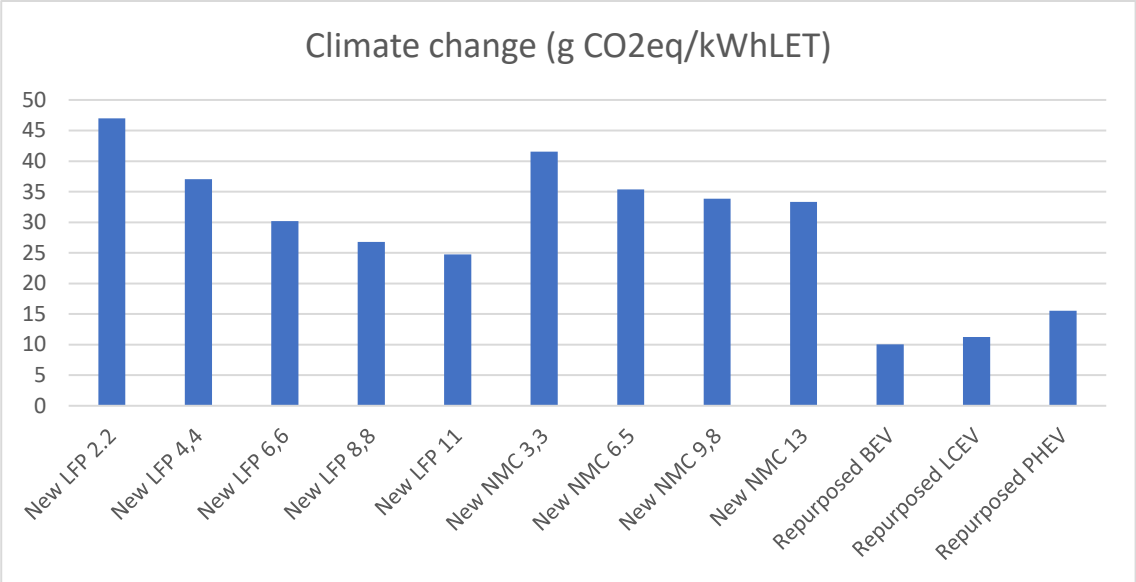


Figure 4 Results of the calculation of the climate-altering impact of the storage systems analysed.

3.2.1.2. *Circular Economy allocation criterion*

Another allocation can be performed using Circular Footprint Formula (CFF) which balances the environmental burdens between primary and secondary products. Following this methodological approach, the environmental burden of the production of the new NMC batteries was distributed between the first useful life (automotive use) and the second life (ESU for PV system) through the A factor. As we have no other indices that can measure the possible quality of repurposed batteries, we took the SOH as an approximation for A[9]. Consequently, the impacts of repurposed batteries are considered there as follows (Equation 1), similar to the approach followed in (Bobba et al. 2018a).

Equation 1 CFF formula to allocate the environmental loads of the production of new batteries (and the virgin raw materials related to them) between new and repurposed batteries

$$I_{repurposing_{TOTAL}} = I_{repurposing_{processes}} + (1 + A) \cdot I_{new} + A \cdot I_{EoL}$$

Where A is equal to the SOH of the batteries in this sensitivity analysis (i.e. 0.8), whereas A = 1 for the analysis performed previously (cut-off results). A selection of the results for the sensitivity analysis with the allocation criterion of "Circular Economy" is presented. As could be expected, and as seen in Figure 5, environmental results increase with this allocation criterion. However, the environmental footprint of repurposed batteries remains lower than that of new NMC 6.5 batteries. In the case of the ESU with PHEV batteries, this would remain similar to the environmental footprint of the new LFP 6.6 battery, and therefore worse than the ESU with new batteries >6.6 kWh of storage. Further results are shown in Supplementary Materials, secton S3.

[9] In the PEF, an A of 0.5 is recommended for unknown situations or where the market situation is balanced.

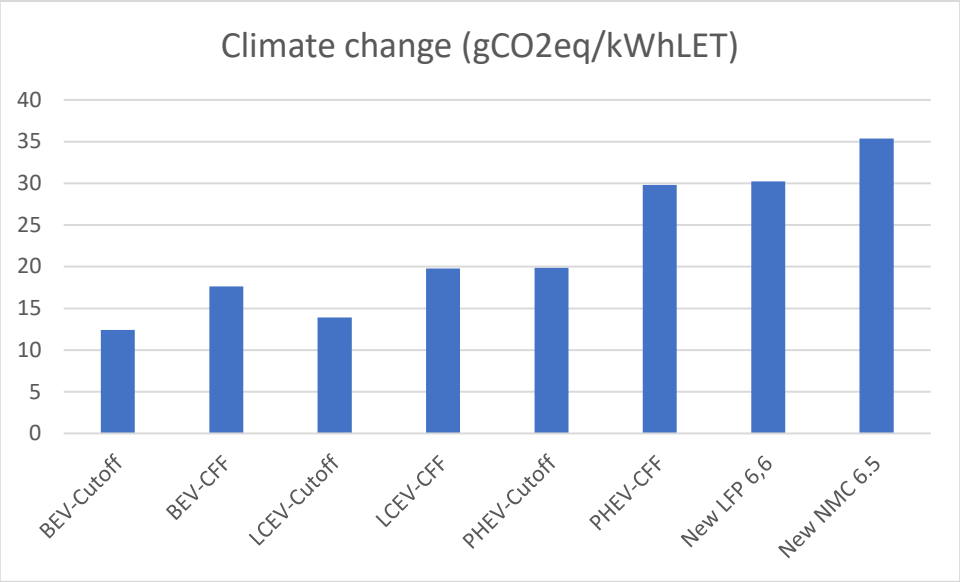


Figure 5 Results of climate changes for the main storage systems analysed

4. Conclusions

Cradle to gate costs and environmental impacts of used EV batteries repurposed for domestic solar photovoltaic systems' were assessed. The equivalence of repurposed energy storage units (ESU) with new ones was carried out through the potential lifetime energy throughput (LET) of both systems as main service provided and defined within the functional unit of the assessment. LET of batteries were calculated with an innovative, simple approach (given the lack of data on used batteries) yet accurate enough to allow the comparison of both storage units. Estimated LET of repurposed ESU were 20% to 25% lower than new systems, even if depth of discharge (DOD) of used modules was capped to 80% to allow for an extended second life and maximize LET. To correct this dissimilarity of the basic energy service provided by both systems, a "battery salvage value" was incorporated to calculate both the purchasing price of used batteries and the selling price of repurposed ESU. The selling price of repurposed ESU were calculated by multiplying the usable capacity (i.e. nominal capacity adjusted with the new DOD) of batteries with the LET ratio (LET_used/LET_new) and the estimated annual market prices for new stationary batteries.

In general, the costs reported here can be considered in line with other literature studies (Neubauer et al. 2012, Steen et al. 2017). From the results of the economic analysis performed it was observed that the repurposing costs are dominated by the purchase of used batteries (battery salvage values), which amount to 44% of the total annual costs for the year 2026. These costs are followed in importance by indirect costs (18% of total), collection and transport costs (9%) and labor costs (9%). The most critical parameters for the economic profitability of a repurposing business are the SOH of used

batteries (SOH > 0.8) and the dimensions of the battery packs and their modules. LCC results showed high positive NPVs for the repurposing plants of all battery types due to estimated high selling ESU prices. These were calculated based on annual estimated market prices (extrapolated from 2024 prices) and their LET performance ratio. Calculated battery salvage values of used EV batteries show a significant potential of repurposing to reduce EV costs – currently one of the main barriers for their widespread adoption. Battery salvage values were estimated at €6,240, €1,070 and €8,340 for BEVs (one pack), PHEVs (one pack), and LCEVs (two packs) batteries, respectively. The price of used batteries though should be based on its real SOH (the higher the SOH, the higher the price). With this approach to calculate the "battery salvage value", the economic feasibility (and profitability) of re-purposing business (NPV value) is strongly linked to assumed minimum SOH of used batteries and estimated market prices of new stationary batteries, since these directly compete with repurposed ESUs and establish the reference price. Comparing the prices of ESU with the xStorage Home (a storage system with repurposed batteries, mentioned in the market analysis of the introductory chapter), these would also be aligned or competitive: sales prices of €3,500 (for a nominal capacity of 4.3 kWh) vs. ESU-BEV cost of €1,120 and a selling price of €1,800 (considering 76% LET ratio and an estimated price of the new equivalent battery of 516 €/kWh). From 2027, according to the new European legislation on batteries, car manufacturers will have to incorporate a digital passport and a registry with the key parameters to determine the SOH of the batteries. In the future it will be possible to save part of the testing phase costs and to derive at delivery the compensation price (salvage value) of used batteries.

From the environmental analysis performed by LCA modelling, it is clear, as expected, that all repurposed battery scenarios (BEV, LCEV and PHEV) demonstrate significantly better environmental profiles than their new NMC and LFP battery reference systems. The environmental footprints calculated using the European Environmental Footprint (EF) v3 methodology, lead to impact reductions in all the categories analyzed ranging from 50% to 90%, which is an order of magnitude of the multiple environmental benefits that such a business could generate. Finally, for the repurposed batteries the environmental hot-spots are concentrated in the new components (the electronic printed circuit board for the battery management system in particular) to be integrated with the modules needed to build the ESU. For the new NMC batteries the hotspots are found in the cathode materials (cobalt extraction and production of the related alloys, such as NiCoMn).

The sensitivity analysis covered two important methodological choices, such as the battery chemistry reference system (LFP instead of NMC) and allocation criterion used for repurposed batteries

(circularity criterion implemented instead of the "polluter pays" criterion. The setting of the study covered different types of batteries, with different module and package sizes, parameters that proved to be key in both environmental and economic performance. The study also covered another critical parameter in LCC and LCA analysis: battery health status (SOH). The investigations made and the results reported in the different Figures and Tables have shown that storage systems with repurposed batteries would entail multiple environmental benefits and for some cases (BEV repurposed vs. NMC new) would also be very significant. Based on the sensitivity analysis done and the wide coverage of critical parameters in the study (such as SOH and module sizes), it can finally be said that the repurposing of EV batteries is environmentally better than acquiring new batteries for stationary applications as domestic photovoltaic systems.

A registry system to record the key parameters in the BMS to characterize the batteries at the end of the first life is fundamental. This would allow to determine quickly and with precision the degradation rate and the overall SOH status of used batteries, which enable an accurate calculation of their LET potential and, thus, their salvage value. BMS communication problems with modules from different manufacturers could be expected. To bypass this barrier, battery manufacturers should be obliged to provide communication protocols to manage the charging and discharging of different modules assembled together in new storage units. The design DOD imposed on repurposed batteries (set at 80%), allows to extend the second useful life and provide reasonable LET that are comparable to new ESU. However, capping DOD limits the maximum usable energy of an ESU, thus requiring a greater nominal storage capacity compared to new storage units with a similar LET. The main problem with this is the greater weight and volume of a repurposed ESU that would be installed in households, which can be problematic as it requires more space than a new ESU.

Declarations and statements

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request

Competing interests

This study was fully funded by Motus-e, an Italian association that gathers industrial stakeholders from the automotive sector, car manufacturers and researchers to foster electric mobility solutions.

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