Powering electrification sustainability: LCA of repurposing battery systems from automotive to building sector

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Abstract: As the automotive and building sectors continue to embrace electrification technologies, it is imperative to adopt holistic and circular approaches that prioritize environmental stewardship and resource efficiency, especially in the field of battery system management along the entire life cycle. To this end, repurposing offers an innovative and promising avenue for extending the lifespan of batteries, turning Electric Vehicle (EV) batteries into Battery Energy Storage Systems (BESS). The application of Life Cycle Assessment (LCA) of repurposed battery system, based on primary data, contributes to advancing sustainable practices in these sectors, fostering a transition towards a low-carbon and circular economy paradigm.

1. Cross-sectoral cycles to implement CE practice

The electrification of the automotive and building sectors is currently pursued to reduce greenhouse gas emissions and combat *Climate Change*. To this end, continued technological advancements, development policies and government incentives are supporting the setting up (EU Regulation 2023/1542) and the further driving of this transition in the coming years.

In the automotive sector, the adoption of Electric Vehicles (EVs) has been steadily increasing, with many major automakers investing heavily in EV battery technology and many governments implementing policies to accelerate the transition, such as vehicle emissions standards, zero-emission vehicle mandates and financial bonus for EV buyers. Accordingly, the expansion of charging infrastructure is in action for the widespread adoption of EVs, with considerable investments by administrations, business and utilities in building more charging stations, including fast chargers to address range anxiety and encourage EV adoption. In parallel, in the building sector, there is a growing trend towards the electrification of heating, ventilation, and air conditioning (HVAC) systems. As a results, technologies like electric heat pumps are becoming increasingly popular for both residential and commercial buildings, matched with renewable energy sources such as solar panels to reduce their reliance on grid electricity and improve energy efficiency.

With the shift towards electric vehicles and the integration of renewable energy sources in building design (EP, 2024), the demand for energy storage solutions such as batteries is rapidly escalating, posing environmental concerns specifically relate to their production and disposal. In this context, the repurposing of battery systems emerges as a crucial strategy for enhancing the sustainability of electrification initiatives and improving Circular Economy (CE) practices and cost savings (Heymans at al., 2014; Horesh at al., 2021), linking up and synergising automotive and building sectors (Khowaja et al., 2022; Philippot at al., 2022). Indeed, by extending the lifespan of batteries through repurposing, the aim is to reduce the environmental footprint associated with manufacturing new batteries but also alleviate pressure on raw material extraction and waste management systems.

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This is exactly the case of a photovoltaic company founded in Amsterdam - involved in the Horizon research project "RE-SKIN Renewable and Environmental-Sustainable Kit for building Integration" - that traditionally offers lithium-ion batteries in all its applications both for off-grid and on-grid photovoltaic systems and it is now taking advantage of battery cells coming from the automotive sector. Operating in close collaboration with the supplier who demounts the batteries from cars in The Netherlands, the company performs in-house the demanded industrial processes to put the batteries back on the market. It deals therefore with a repurposed process in order to give a second life to the battery cells extracted from Electrical Vehicles (EV as first life). The specific battery cell type used is the LEV40, sourced from the Mitsubishi Outlander PHEV and originally manufactured by the Japanese company GS-Yuasa. Considering that in Europe there are to date more than 200.000 of such cars (Mitsubishi, 2021), the market volume is estimated more millions of cells per year. Going into detail, cells are taken either from car that has accident or from ones that reach their end of life. The battery pack, namely the set of cells in origin, is discarded from a car when it goes below 70% of its nominal capacity, opening up the chance to being easily repurposed as a Battery Energy Storage System (BESS as second life). Figuring that 2% of cars reach the end of life due to accidents, and 50% of those cars have still a reusable battery, it means that a first estimation is of 1% of 200.000 cars each of which contain 80 cells, resulting for a total of 160.000 cells/year. On top of this figure, it is possible to add the cells recovered from batteries that are depleted under the 70% warranted capacity.

In this framework, the paper provides insight of battery repurposing, applying LCA to evaluate the environmental impacts of battery system at various stages of their life cycle, focusing in particular on production (meant as repurposing) and transport to the marketplace. By combining repurposing with LCA (Ardente et al., 2018), the goal is to substantiate the resource use optimization and waste minimization thanks to cross-sectoral battery flows, identifying hotspots to potentially mitigate the most significant impacts and improving collective awareness on repurposed products. This helps in the assessment of the environmental performance of circular economy initiatives and in supporting informed decision-making about resource management for maximizing the benefits of repurposing practice.

2. Repurposing process for battery system second life

The repurposing process focuses on battery cells of LEV40 type as assembled during the first life on all Mitsubishi Outlander cars, in which the battery system is composed of 10 battery packs of 8 cells each, for a total of 80 cells. As appropriate over lifetime, the car battery system reach the company partner that checks on them, mainly inspecting if there are damages on the cells and the age of the cells. If the cell is already quite old, it will be directly discarded, as well as if the cell is damaged, it is destined for disposal. In this way, the battery packs that do not pass this primarily inspection are disposed of by grinding them and later separating the different elements. Conversely, the cells that surpass the inspection are either sent back to the car company (Mitsubishi in this instance) or sold by the company that disassembled the car after the accident. The company that receives the car battery system deconstruct it and disassembly it into packs (Rallo et al. 2020), keeping the metallic case and other cablings for their business purposes.

At this stage, the battery packs (set of 8 cells) are properly delivered at the process plant to be subject to repurposing, aimed at giving them a new life as BESS. Here some process loss occurs, by considering for example that out of 160 cells received by the company, only 144 cells are used for a new battery pack. Indeed, it is on record that 2 of them are usually mechanically broken while disassembly (from battery packs to single cells) due to bolts that were too stiff, some of the other 12 cells are used to more aggressive testing to push them to the limit, while a few of them are kept as spare parts. Once the remaining cells are collected, they are affected to the repurposing process which mainly consists of the charging and discharging of the single cells to check the quality. This procedure is executed twice, dissipating the energy as heat during both discharges. In the second round, the battery system is tested as a whole by discharging and charging it at 80%. Besides the energy consumed for performing the battery charging and discharging, during the test an additional share is used to power the tools. In the near future, the repurposing company has planned to install an energy recovering system to recover 50-70% of the energy used in the testing phase (energy recover is not considered in the present paper).

In addition, during repurposing, a new Battery Management System (BMS) is integrated into the battery bank. In this way, the original BMS communication cable that connected the cells to their original BMS in the car battery pack is removed and disposed as well as the original BMS of the battery pack coming from the car. The new BMS is made of plastic and has a motherboard inside, namely a printed circuit board dedicated to the oversight of the battery packs, enabling the delivery of targeted range of voltage and current for a duration of time against expected load scenarios. Indeed, the battery system managed by the BMS serves as an essential electrical energy storage solution for powering various electrical equipment. In practice, when applied to building sector, its primary function is to store photovoltaic (PV) electricity, to be used for instance to power heat pump, fan coils and other auxiliaries.

After the trial process, the battery system is supplied to the construction site in association with a cabinet meant for outside usage. In fact, it has been established that, where technically feasible, the outdoor installation of the battery pack is preferred for safety reasons. For this reason, a specific cabinet is chosen to make sure that the battery pack can be installed outdoor, ensuring proper operational conditions. The cabinet is made of sheet steel and aluminium and include the mounting sleeves. Note that the spot on which is located the cabinet with the battery system inside affects the placement of the external cabling to connect it to the grid. However, the provision of that service is outside the scope of the repurposing company.

This is in brief the repurposing process to give a second life to the battery cells extracted from Electrical Vehicles turned into a Battery Energy Storage System for building applications. The cells in origin are manufactured by Japanese company, with a nominal cell voltage of 3.75 V and enclosed in a plastic tray in group of 8 battery cell in series, forming together a battery bank with a nominal voltage of 30 V. The repurposed battery system connects in parallel multiple battery packs to satisfy the unique storage needs of each building, resulting in the case at issue composed of 18 battery banks for a total of 144 cells (Table 1), installed in a cabinet and managed by a Battery Management Systems (BMS).

Technical features	**Repurposed battery system**	**New battery system**
Nominal capacity	16,2 kWh from full charge	16,2 kWh from full charge
Number of cells	144 p	101 p
Weight (including BMS, excluding cabinet)	208,6 kg	147,1 kg

Table 1. Technical features of battery systems (primary data from Solartechno Europe B.V.)

Compared to a new battery system with equal performances, it is worth stressing that the repurposed battery system requires more cells to provide the same effective energy storage capacity, specifically 144 cells instead of 101 cells. Indeed, it is estimated a residual capacity of 70%, as attested by the warranty provided by the automotive manufacturer. This change in the number of cells also results in a reproportioning of the management system, installed in both cases as a single master BMS regardless of cell type and capacity with the number of BMS slaves proportional to the total number of cells. In particular, it is considered that the BMS of the new battery system is composed of 8 units rather than 10 of the repurposed battery system. It follows a significant final weight difference between the two BMS systems and as well as for the cabinet that is 70% less heavy than for the repurposed battery system. In both cases, the set of battery accessories, such as thermostat, heater, fan, filter, monitoring device, contactors, fuses, DC switch, AC circuit breaker, resistor and battery connectors, are excluded from the study.

3. LCA modelling of repurposed battery system

In line with Level(s) (EC, 2024) – the EU framework for sustainable buildings – and in compliance with the related LCA requirements, the environmental profile of the repurposed battery system under study follows the EN 15804 +A2 standard, selecting characterisation results to evaluate potential impacts. In particular, the focus is on the Global Warming Potential (GWP) of the greenhouse gases emitted, expressed in terms of kgCO_2 equivalents and broken down into the different *Climate change* subcategories: *Fossil*, *Biogenic*, *Land use and LU change*. Moreover, with the aim to go a step further, other additional indicators than GWP has been considered, for providing an overview of the most significant LCA environmental hotspots and limiting the risk of burden shifting: *Ozone depletion*, *Acidification*, *Eutrophication* (*Freshwater*, *Marine*, *Terrestrial*), *Photochemical ozone formation*, *Resource use* (*Fossils*, *Minerals and metals*) and *Water use*. Note that the project RE-SKIN does not properly face with the application of the new Regulation (EU 2023/1542) on batteries and waste batteries, which sets out novel obligations for manufacturers, such as: carbon footprint declaration, requirements on recycled content, performance, durability, removability and replaceability, all included in digital product passports to enhance transparency along the entire life cycle supply and value chains of batteries for all stakeholders. Nevertheless, the manufacturer of the repurposed battery system is aware that in the next few years it will have to carry out the conformity assessment procedure, clearly labelling all batteries with the carbon footprint calculated based on Product Environmental Footprint (PEF method required for the new battery EU Regulation but not for the ongoing EU Horizon project “RE-SKIN”).

The LCA modelling is performed using SimaPro 9.0.0.49 software and Ecoinvent 3.6 database, from which all background data were selected. The Functional Unit (FU) is one repurposed battery system (UF = 1 p), with the distinct technical and performance features provided by the repurposing company (Table 1), and the mainstay is that the study includes primary data retrieved directly by the company in charge of repurposing process. The assessment thus evaluates all processes from the raw material extraction phase to the exit from the production plant (A1-A3), providing a higher granularity of data especially during the core phase of repurposing and including primary data for the transport of all input materials/products (Table 2). The output comprises both the li-ion battery cells that that fail the texts, broken during the repurposing process and used as spare parts (16 in total) as well as the original BMS contained in the automotive battery (mass 2,3 kg), properly breakdown into the different materials/sub-system. In compliance with the cradle-to-gate analysis, the potential capacity loss of the battery over time is out of scope since referred to the use phase. However, by evaluating the environmental benefits derived from repurposing (comparison between new battery system and repurposed battery system), it is estimated the critical distance eligible for downstream transport (A4). According to the principal means of transportation, the outreach within which operating to effectively be a sustainable practice are mapped out.

INPUT	Transport	Packaging	Energy	OUTPUT
Li-ion battery cell 201,6 kg*	50 km truck	Pallet 2 pz Cardboard 1,5 kg Packaging film 0,5 kg	Electricity low voltage 141,2 kWh	Used li-ion battery 22,4 kg
BMS metallic base 3 kg	1278 km truck			Original BMS plastic base 0,55 kg
BMS plastic cover 1 kg	1278 km truck			Original BMS plastic cover 0,82 kg
BMS motherboard 2,5 kg	1278 km truck			Original BMS motherboard 0,94 kg
Data cable 0,12 kg/ml x 4 m	10 km truck			Original cable 0,88 kg
Cabinet 120 kg	75 km truck			Waste packaging product 0,5 kg
Mounting shelves 25 kg	5 km truck			

*not considered due to cut-off allocation method (reused battery cells from automotive sector)

Table 2. LCA inventory of repurposed battery system (primary data from Solartechno Europe B.V.)

Dealing with repurposing, the challenge of the present LCA study is to measure the environmental benefits of implementing CE strategies, since repurposing is generally identified as a cascaded multi-functionality problem in LCA. This is because the product in question serves additional functions after its original primary function in the first life cycle (Richa et al., 2015), allowing different methodological approach for allocating manufacturing and End-of-Life (EoL) impacts among multiple life cycles. The literature review on lithium-ion battery fields of use – EV battery in the first cycle and BESS systems in the second cycle – shows the application of the following approaches to handling multi-functionality (Schulz et al., 2020):

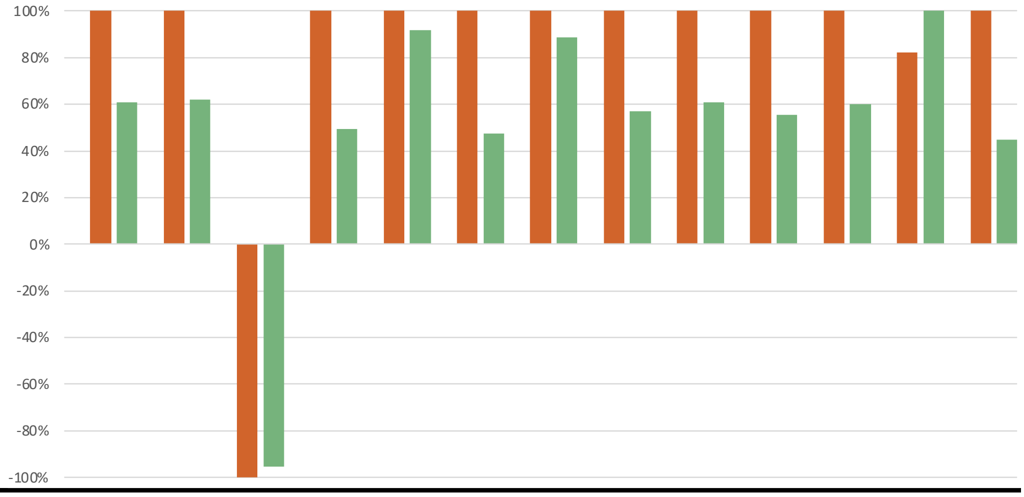
1. system expansion, expanding the system boundaries of EV battery first life to include repurposing, BESS and second life application (Ahmadi et al., 2017; Casals et al., 2017);
2. cut-off allocation, fully assigning manufacturing and EoL impacts to the first life within the automotive sector, and exclusively assessing the impacts of what occur during the second life (Faria et al., 2014; Sathre et al., 2015);
3. allocation based on allocation factors, focusing on BESS and second life application, considering to partly allocate battery manufacturing and EoL impacts to the second life according to different criteria: i) quality-based (e.g. battery capacity); ii) market-based (e.g. market value); iii) equally divided (50/50) (Cusenza et al., 2019; Bobba et al., 2018).

The first two approaches turn out to be spread to the same degree among the sample of analysed studies, while the third is applied to a lesser extend (the multi-functionality handling strictly depends by the purpose of the study). Here, the choice to run the LCA modelling of repurposed battery system following the cut-off allocation method is in compliance with the specific standards for the construction sector, as established by both EN 15804 (at product level for Environmental Product Declarations), and by EN 15978 (at building level for the assessment of whole environmental performance). In particular, the cut-off is an input-oriented method, which assess the impacts occurred within the system boundary under study, by allocating impacts directly to the product generating them. In this way, the cut-off method fully assigns to the first life of battery cells (automotive sector): the extraction of raw material, the production process, the first use phase and the waste disposal. It allocates instead to the second life (construction sector) the impacts of repurposing process, second use phase and disposal, when covering the full life cycle. Accordingly, the LCA analysis rewards to the second life the reduced environmental impact in this case due to materials reuse (but potentially also recycling). Reused (or recycled) materials generally imply lower impacts than the original production because only the impacts of transport and reprocessing are considered, without the raw materials. Consistent with this, the LCA inventory of the repurposed battery system under study does not account cells production.

4. Repurposing LCA impacts and benefits

Narrowing the LCA analysis to the production phase, the aim is to assess the environmental impacts of a repurposed battery system compared to a new battery system with the same effective energy storage capacity, accounting the performance loss of repurposed batteries from the first cycle (automotive sector) to the second cycle (construction sector). Note that either way, the term "battery system" is intended in a broader sense, namely the finished set of products offered by the business company to the market and so complete with BMS, cabinet and packaging for transport. However, while due to the change in the number of cells the BMS and the cabinet with mounting shelves varies between the models (multiplication factor of about 0,7), they include equal data cable and packaging used for the supply/delivery. As claimed by the surveyed company, the packaging material usage is optimized in practice, since the pallets and cardboard on which they received the input materials/products are the same used for delivery the finished battery system to the construction site, thus limiting the waste treatment apart from cellofan. In this way, the differences in the modelling rely in particular to the inclusion of the impacts derived by cells production in the new battery system, excluded in the other model due to cut-off allocation method. Conversely, the repurposed battery system considers additional contributions in terms of energy consumption and waste. In addition, the difference in terms of weigh between the two systems, due to the variation in the number of cells and thus BMS and cabinet, affects the related transport from suppliers to production plant.

LCA results prove how the repurposed battery system allows to make environmentally-sound choices in respect of the new battery system for all environmental indicators, except for *Climate change Biogenic* and *Resource use Minerals and metals* (Figure 1).



	Climate change	Climate change Fossil	Climate change Biogenic	Climate change Land use and LU change	Ozone depletion	Acidification	Eutrophication Freshwater	Eutrophication Marine	Eutrophication Terrestrial	Photochemical ozone formation	Resource use Fossils	Resource use Minerals and metals	Water use
	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CO2 eq	kg CFC11 eq	mol H+ eq	kg P eq	kg N eq	mol N eq	kg NMVOC eq	MJ	kg Sb eq	m3 depriv.
🟧 **NEW battery system**	2,13 E+03	2,21 E+03	-8,16 E+01	3,49 E+00	9,51 E-05	1,77 E+01	1,40 E+00	2,66 E+00	2,66 E+01	8,56 E+00	2,95 E+04	2,74 E-01	4,43 E+02
🟩 **REPURPOSED battery system**	1,29 E+03	1,37 E+03	-7,79 E+01	1,72 E+00	8,73 E-05	8,39 E+00	1,24 E+00	1,51 E+00	1,62 E+01	4,75 E+00	1,77 E+04	3,33 E-01	1,97 E+02

Figure 1. Comparison of LCA production impacts between new and repurposed battery systems

In particular, it is possible to emphasise two different degrees of reduction achieved in terms of environmental impacts. High-impact reductions, namely with the potential to decrease by about half the impacts ranging from 38% to 55%, are displayed for the majority of indicators (9 out of 13), including *Climate change*, *Climate change Fossil* and *Land use and LU change*, *Acidification*, *Eutrophication Marine* and *Terrestrial*, *Photochemical ozone formation*, *Resource use Fossils* and *Water use*. Low-impact reductions are obtained in the indicators *Ozone depletion* and *Eutrophication Freshwater*, with emissions savings attested at 8% and 11% respectively. This is mainly caused by the provision of BMS proportional to the number of cells and therefore more impactful in case of repurposed battery system (144 cells) than in case of new battery system (101 cells). In *Eutrophication Freshwater*, major contribution derived primarily by the BMS, notably for the printed wiring board, and secondly by the cells modelled for the new battery system.

A remarkable inversion, namely the environmental indicators in which the new battery system appears a winning practice over the repurposed battery system, is evidenced for the indicators of *Climate change Biogenic* and *Resource use Minerals and metals*. With reference to *Climate change Biogenic*, both battery systems account the same packaging materials that turn out to be extremely beneficial due to the wood-based share of pallets, for which it is considered the absorption of CO_2 during the growing stage of plants. That, in combination with the different mass of battery systems that weight more when repurposed (208,6 kg including BMS) rather than as new (147,1 kg including BMS), allows to report 5% reduction in the new battery system. Instead, the impacts of *Resource use Minerals and metals* are strictly related back to the integration of BMS which reaches almost 100% of impacts in the case of repurposed battery system, limited to 97% in the new battery system due to the 3% derived by cells production. Here, despite the much lower mass of BMS compared to cells, the BMS turns out to be the principal contributor to this indicator, especially due to the gold used in the production of the integrated circuit, as also confirmed by other literature studies (Ahmadi at al., 2017; Cusenza et al., 2019). In addition, the key determinant relies once again in the different number of cells to get the same nominal capacity between the new and repurposed battery systems, accounting for the latter the performance loss over time (from automotive to construction sectors). Accordingly, also the BMS is resized, lowering the mass of BMS for new battery system and thus abating the related environmental impacts. As a result, the new battery system turns out to achieve 18% reduction compared to the repurposed battery system. Except for these two environmental indicators, note that the new battery system discloses the significant contribution of cells production, responsible for a share of 30% to 68% of the total impacts for all other indicators.

With the aim to provide detailed insight of total GWP impacts expressed in terms of $kgCO_2eq$, it is important to highlight that they are closely linked to *Climate change Fossil*, to a negligible extent to *Climate change Land use and LU change* and just partly attributable to *Climate change Biogenic*. To provide the order of magnitude, concerning the repurposed battery system, the *Climate change* impacts are 1366,3 $kgCO_2eq$ associated to *Fossil*, -77,9 $kgCO_2eq$ to *Biogenic* (negative emissions) and only 1,7 $kgCO_2eq$ to *Land use*, resulting in total 1290,1 $kgCO_2eq$. Similarly happens in the case of new battery system but getting the total impacts of 2127,9 $kgCO_2eq$ and showing an increase of 39% compared to the repurposed battery system.

Looking into *Climate change* impacts, the key hotspots of the battery system at issue are the BMS (light-blue coloured) and the metallic cabinet (red-coloured), along with cells (blue coloured) in the new battery system (Figure 2). In the repurposed battery system, they are responsible for 62% and 35% respectively, excluding cells impacts because of the cut-off method. The BMS appears especially critical due to the *Printed Circuit Board* and thus for the electronic components necessary for the battery operation, which corresponds to 99% of BMS impacts, assigning the rest to the metallic part, plastic case and data cables. The matter is that during the repurposing process the original BMS derived from automotive sector is replaced by a new BMS suitable for the new function of BESS. In this way, the repurposed battery system does not take any advantage of the existing BMS, but rather it is penalized of it because it contributes to the output flows of the process, being considered as a waste.

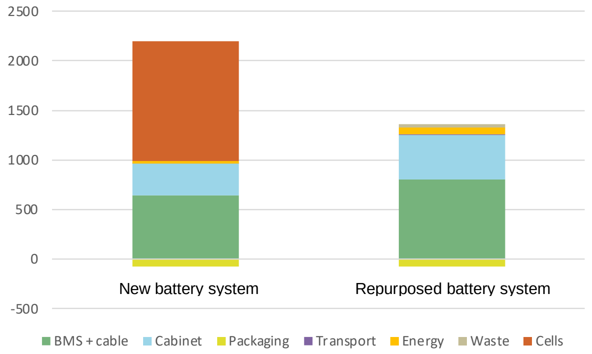


Figure 2. GWP hotspot analysis (A1-A3) of new and repurposed battery systems

In overall terms, the waste as well as the energy consumption at the core process of repurposing are minute compared to other impacts, respectively with a share of 2% and 6% of total GWP. In particular, the waste assessment encompasses the used li-ion battery damaged during the testing phase, the original printed wiring boards, the original cable and plastic waste. However, as declared by the operators in the field, all these wastes are intended for recycling, thus allocating with the next life the related impacts and here including only minor intermediate treatments and transport to the recycling facilities. Concerning the energy, the repurposing usage is modelled with the specific energy mix of The Netherlands, since the production plant at issue is located in the countryside surrounding Amsterdam. Despite the estimate of charging and discharging operations, conducted twice, firstly at 100% and secondly at 80%, and the additional tools power, the consumption of electricity during the repurposing process represents a low value of total impacts. Even more negligible are the impacts associated to transport, that on the total GWP are of 0,4% in the case of repurposed battery system and of 0,2% in the case of new battery system. Although the two models differ in the cargo transported (finished battery system with related packaging of 0,40 tons if repurposed, while 0,30 tons if new), the distances travelled from component suppliers to product manufacturer are equally evaluated based on primary data and local supply apart from BMS that is sourced from Slovenia. In the case of new battery system, more than half of *Climate change* impacts derives from cells production, achieving a rate of 57% of total GWP impacts.

5. Transport LCA impacts and trade-off

Starting from the impact saving obtained in the production phase of the repurposed battery system compared to the new battery system, it is determined the critical distance viable for downstream transport from the repurposing plant to the building construction site. Consistently with decarbonization goals, the assessment focuses on GWP impacts, setting the environmental benefits of 838 $kgCO_2eq$, equal to 39% of new production, as a reference point on which mapping out the operational boundaries for securing the effective implementation of sustainable practices.

The carried freight of 0,40 tons, comprising both the repurposed battery system with BMS, cabinet and packaging for delivery, is envisioned taking into account the primary modes of transportation, by road, rail, sea and air respectively. Road transports deal with lorries of size of 16-32 metric tons and emission class of both Euro5 and Euro6, by considering the entire transport life cycle and fuel consumption and emissions as for average European journeys. Rail transports encompass good trains with a weight of 1000 Gt, on one side, diesel powered and, on the other, electro powered, esteeming the variation in the geography by classifying European countries into regions (flat, hill, mountain). Sea transports comprise, as appropriate to the potential destination, good barge with a carrying capacity not less than 50 tonnes operating on inland waterways and container ship with a load capacity of 43.000 tonnes. Finally, air transports embrace belly-freight aircraft, namely air carrying both passengers and freight, over a distance of 1500 km and 4000 km (medium haul) and of greater than 4000 km (long haul). As for other vehicles, the selected datasets cover the entire transport life cycle including the production, operation and maintenance of both the transportation means under study and connected facilities, according to the case, such road infrastructure, canal, port, airport.

From an LCA point of view, the trade-off between the environmental benefits achieved from the production of repurposed battery system and the environmental losses generated by transport impacts allow to provide evidence of the market area to be served in view of sustainability. The operation distance depends on the considered means of transport, ranging in ascending order from around 2.400 km when by belly-freight aircraft; about 10.500 km when by lorry; like 33.000 km when by diesel train; near to 40.000 km when by inland barge; around 52.000 km when by electric train and slightly less than 200.000 km when by container ship. In this way, to limit as much as possible CO_2 emissions while expanding to the greater extent the distribution market, it is advantageous to use intermodal sea transport, followed by rail transport but only if electrically powered and to inland waterways transport. As expected, more emitting and thus tolerating short distances are the transport via road and, as a worst-case scenario, via air.

6. Conclusions and outlooks

In light of the current transition towards electrification in the automotive and building sectors, the present LCA of repurposing battery systems versus new battery systems has revealed significant environmental benefits associated with repurposing. Note that the focus is exclusively on the production phase (and distribution), excluding from the system boundary the use phase in which the battery system built with repurposed cells is going to have a shorter life than one built with new cells. The rigorous analysis and primary data collection prove that repurposing batteries reduces the environmental impact of manufacturing new batteries, contributing positively to the overall sustainability of battery systems. The environmental advantage is however limited by the need to replace the BMS, which entails significant impacts and for which finding possible alternative solutions would bring additional benefits. Furthermore, the estimation of the critical distance eligible for downstream transport of repurposed battery systems provides practical insights for the involved stakeholders. It enables informed decision-making regarding the production and logistics of battery systems, ensuring that low-carbon and circular economy strategies are integrated into the planning and implementation of electrification projects. Nonetheless, such advisements on distance covered have to be extended also to upstream transport, favouring local supply chain, as here occur at least for the collector (50 km away from the repurposing plant), but also for all upstream steps of the market network to obtain a comprehensive understanding of the system.

Continued research and collaboration with field operators turns out to be essential for realizing the full potential of the electrifying process that is affecting the building sector (but also automotive industry) while minimizing its environmental impact over the entire life cycle and beyond, toward multiple cycles. In this respect, the development of LCA study plays a crucial role, opening up to new practical opportunities but also methodological issues. For instance, considering within the system boundary the first cycle (Electrical Vehicles) and the second life (Battery Energy Storage System), what is the impact gap between battery repurposing and recycling? With reference to transport, how to effectively trace the goods over the entire supply chain and to evaluate the cargo conditions (full/half/empty)? How to deal with the dynamic nature of electrification technologies, such as batteries and renewable energy systems? All this, with the awareness that obtaining comprehensive and accurate data throughout the lifecycle is challenging and need the support of the stakeholders of the entire value chain. Indeed, data on energy consumption, emissions and materials sourcing may be incomplete or inconsistent, impacting the reliability of LCA results. The paper presents a first attempt, based on primary data, to assess the LCA impacts of battery repurposing and to maintain the impacts credits during transportation, providing valuable insights for advancing towards a circular economy paradigm.

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7. Bibliography

Ahmadi, L, Young, SB, Fowler, M, Fraser, RA, Achachlouei, MA, 2017. A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems. Int. J. Life Cycle Assess. 22 (1), 111–124.

Ardente, F, Peiró, LT, Mathieux, F, Polverini, D, 2018. Accounting for the environmental benefits of remanufactured products: Method and application. J. Clean. Prod., 198, 1545-1558.

Bobba, S, Mathieux, F, Ardente, F, Blengini, GA, Cusenza, MA, Podias, A, Pfrang, A, 2018. Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows. J. Energy Storage, 19, 213-225.

Casals, LC, García, BA, Aguesse, F, Iturrondobeitia, A, 2017. Second life of electric vehicle batteries: relation between materials degradation and environmental impact. Int. J. Life Cycle Assess. 22 (1), 82–93.

Cusenza, MA, Bobba, S, Ardente, F, Cellura, M, Di Persio, F, 2019. Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles. J. Clean. Prod., 215, 634-649.

European Commission, 2024. LEVEL(S): A common language for building assessment, https://environment.ec.europa.eu/topics/circular-economy/levels_en

European Parliament, 2024. P9_TA(2024)0129 Energy performance of buildings (recast), https://www.europarl.europa.eu/doceo/document/TA-9-2024-0129_EN.pdf

EU Regulation 2023/1542. Batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC, https://eur-lex.europa.eu/legal-content/IT/TXT/?uri=CELEX%3A32023R1542

Faria, R, Marques, P, Garcia, R, Moura, P, Freire, F, Delgado, J, de Almeida, AT, 2014. Primary and secondary use of electric mobility batteries from a life cycle perspective. J. Power Sources, 262, 169-177.

Heymans, C, Walker, SB, Young, SB, Fowler, M, 2014. Economic analysis of second use electric vehicle batteries for residential energy storage and load-levelling. Energy Policy, 71, 22-30.

Horesh, N, Quinn, C, Wang, H, Zane, R, Ferry, M, Tong, S, Quinn, JC, 2021. Driving to the future of energy storage: Techno-economic analysis of a novel method to recondition second life electric vehicle batteries. Applied energy, 295, 117007.

Khowaja, A, Dean, MD, Kockelman, KM, 2022. Quantifying the emissions impact of repurposed electric vehicle battery packs in residential settings. J. Energy Storage, 47, 103628.

Mitsubishi, 2021. Mitsubishi Motors verkoopt 200.000e PHEV in Europa, viewed April 2024, https://www.mitsubishi-motors.nl/nieuws/mitsubishi-motors-verkoopt-200-000e-phev-in-europa

Philippot, M, Costa, D, Hosen, MS, Senécat, A, Brouwers, E, Messagie, M, 2022. Environmental impact of the second life of an automotive battery: Reuse and repurpose based on ageing tests. J. Clean. Prod, 366, 132872.

Rallo, H, Benveniste, G, Gestoso, I, Amante, B, 2020. Economic analysis of the disassembling activities to the reuse of electric vehicles Li-ion batteries. Resources, conservation and recycling, 159, 104785.

Sathre, R, Scown, CD, Kavvada, O, Hendrickson, TP, 2015. Energy and climate effects of second-life use of electric vehicle batteries in California through 2050. J.Power Sources, 288, 82-91.

Schulz, M, Bey, N, Niero, M, Hauschild, M, 2020. Circular economy considerations in choices of LCA methodology: How to handle EV battery repurposing? Procedia CIRP, 90, 182-186.