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Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB)

JRC Exploratory Research (2016-2017)
Final technical report
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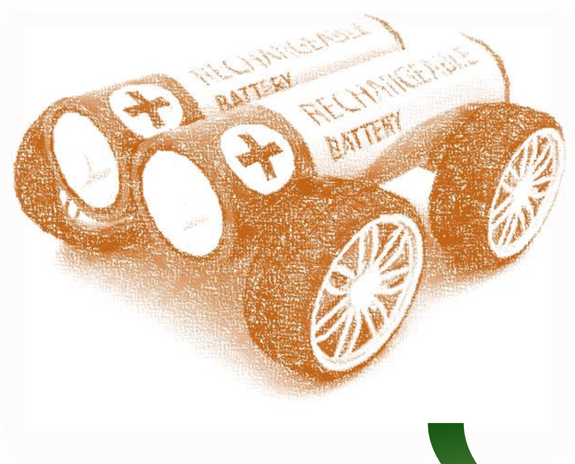

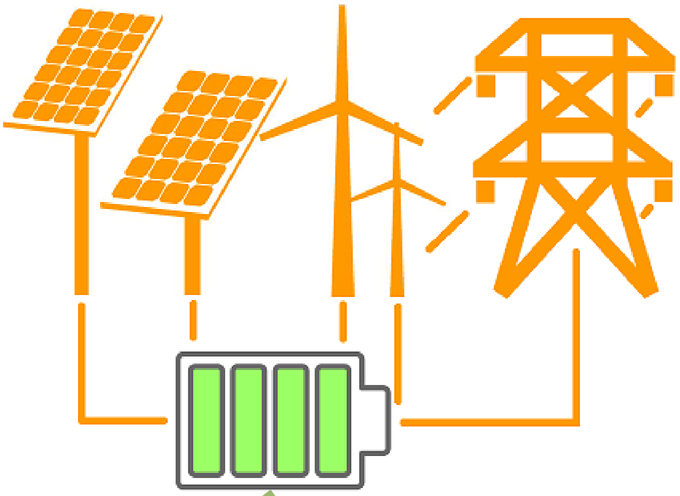

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- page 41, Figure 7, Source: Spotnitz (2003)

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Acronyms

ADP-res	Abiotic Depletion Potential - resources
AP	Acidification Potential
ARN	Auto Recycling Netherlands
BDBT	Bidirectional Battery Tester
BEV	Pure Battery Electric Vehicle(s)
BMS	Battery Management System
BoM	Bill of Materials
BoT	Begin of Test
CC	Constant Current
CCCV	Constant Current Constant Voltage
CED	Cumulative Energy Demand
CEN-CENELEC	European Committee for Standardization (CEN), and European Committee for Electrotechnical Standardization (CENELEC)
CMU	Cell Monitoring Unit
CV	Constant Voltage
DC	Direct Current
DoD	Depth of Discharge
DoE	U.S. Department of Energy
EC	European Commission
EIS	Electrochemical Impedance Spectroscopy
ELV	End-of-Life Vehicles
EoL	End-of-Life
EPf	Freshwater eutrophication
EPm	Marine eutrophication
EPR	Extended Producer Responsibility
EPt	Terrestrial eutrophication
ER	Exploratory Research
ESS	Energy Storage System(s)
EUROBAT	Association of European Automotive and Industrial Battery Manufacturers
FET	Freshwater ecotoxicity
GWP	Global Warming Potential
HEV	Hybride Electric Vehicle(s)
HT-C	Human toxicity, cancer effects
HT-nC	Human toxicity, non-cancer effects
IEC	International Electrotechncal Commission
IR	Ionizing Radiation
ISO	Independent System Operators

LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFP	Lithium Iron Phosphate
LIB	Lithium-Ion Batteries
LMO	Lithium Manganese Oxide
LMO-NMC	Lithium Manganese Oxide - lithium Nickel Manganese Cobalt oxide
NEDC	New European Drive Cycle
NMC	Lithium Nickel Manganese Cobalt oxide
OCV	Open Circuit Voltage
ODP	Ozone depletion
OEM	Original Equipment Manufacturers
PHEV	Plug-In Hybrid Electric Vehicle(s)
PM	Particulate matter
POFP	Photochemical ozone formation
SEI	Solid Electrolyte Interface
SoC	State of Charge
SoH	State of Health
TSO	Transmission System Operators
USABC	US Advanced Battery Consortium
VUB	Vrije Universiteit Brussel
WEEE	Waste Ellectrical & Electronic Equipment Directive
WLTC	World-wide harmonised Light-duty Test Cycle
xEVs	Electrified Vehicles (i.e. BEV, HEV, PHEV)

Abstract

The fast increase of the electrified vehicles market will translate into an increase of waste batteries after their use in electrified vehicles (xEV). Once collected, batteries are usually recycled; however, their residual capacity (typically varying between 70% and 80% of the initial capacity) could be used in other applications before recycling. The interest in this topic of repurposing xEV batteries is currently high, as can be proven by numerous industrial initiatives by various types of stakeholders along the value chain of xEV batteries and by policy activities related to waste xEV batteries.

SASLAB (Sustainability Assessment of Second Life Application of Automotive Batteries), an exploratory project led by JRC under its own initiative in 2016-2017, aims at assessing the sustainability of repurposing xEV batteries to be used in energy storage applications from technical, environmental and social perspectives.

Information collected by stakeholders, open literature data and experimental tests for establishing the state of health of lithium-ion batteries (in particular LFP/Graphite, NMC/Graphite and LMO-NMC/Graphite based battery cells) represented the necessary background and input information for the assessment of the performances of xEV battery life cycle. Renewables (photovoltaics) firming, photovoltaics smoothing, primary frequency regulation, energy time shift and peak shaving are considered as the possible second-use stationary storage applications for analysis within SASLAB.

Experimental tests were performed on both, new and aged cells. The majority of aged cells were disassembled from a battery pack of a used series production xEV. Experimental investigations aim at both, to understand better the performance of cells in second use after being dismissed from first use, and to provide input parameters for the environmental assessment model. The experimental tests are partially still ongoing and further results are expected to become available beyond the end of SASLAB project.

To obtain an overview of the size of the xEV batteries flows along their life cycle, and hence to understand the potential size of repurposing activities in the future, a predictive and parametrized model was built and is ready to be updated according to new future data. The model allows to take into account also the (residual) capacity of xEV batteries and the (critical) raw materials embedded in the various type of xEV batteries. For the environmental assessment, an adapted life-cycle based method was developed and applied to different systems in order to quantify benefits/drawbacks of the adoption of repurposed xEV batteries in second-use applications. Data derived from laboratory tests and primary data concerning energy flows of the assessed applications were used as input for the environmental assessment. Under certain conditions, the assessment results depict environmental benefits related to the extension the xEV batteries' lifetime through their second-use in the assessed applications. In the analysis, the importance of using primary data is highlighted especially concerning the energy flows of the system in combination with the characteristics of the battery used to store energy. A more comprehensive environmental assessment of repurposing options for xEV batteries will need to look at more cases (other battery chemistries, other reuse scenarios, etc.) to derive more extensive and firmer conclusions. Experimental work is being continued at the JRC and the availability of further data about the batteries' performances could allow the extension of the assessment to different types of batteries in different second-use applications.

A more complete sustainability assessment of the second-use of xEV batteries that could be useful to support EU policy development will also require more efforts in the future in terms of both the social and economic assessment.

Executive summary

Context

The commercialisation of electrified (road) vehicles (xEVs), including battery, hybrid and plug-in hybrid electric vehicles (BEV, HEV, PHEV) is forecasted to increase worldwide in the next years, responding to the global concerns on CO_2 emissions, on air quality in urban areas and on energy security. This, in turn, has led to rapidly increasing demand for density traction Li-ion batteries (LIB). This will also translate into an increase of waste xEV batteries after reaching first use End of Life (EoL) in vehicles. According to European Directives (End-of-Life Vehicles Directive 2000/53/EC and Batteries Directive 2006/66/EC), batteries have to be collected and recycled; however, their residual capacity (typically varying between 70% and 80% of the initial capacity) could be used in other applications before recycling.

The Research & Innovation (R&I) targets related to Key Action 7 *"Become competitive in the global battery sector to drive e-mobility forward"* of the Integrated European Strategic Energy Technology Plan (C(2015)6317) (EC, 2015a) that falls under the European Energy Union Package (COM(2015)80) (EC, 2015b), among other subject matters also take into account the topic of **''Second Life''** and recycling, with the core focus being Li-ion batteries.

Even though the term **''second use[1]''** is not currently defined in the Batteries Directive, nor in any of the various Waste Directives[2], the second-use of xEV batteries is aligned with both the waste management hierarchy (i.e. prevent, preparation for reuse, recycle, other recovery, disposal) as established by the Waste Framework Directive 2008/98/EC (EU, 2008) and the 2015 Circular Economy action plan of the European Commission (EC, 2015c), especially concerning actions on lifetime and improved raw materials flows. In fact, this EoL option can keep the added value in products for as long as possible and minimizes waste. Resources are kept within the economy when a product has reached the end of its life, so that they can be productively used again and hence create further value. It should be noted that refurbishing (i.e. reuse of a product in the original application such as reuse of a battery in an electric vehicle after refurbishing) can be especially beneficial for optimal exploitation of resources. The recently signed Innovation Deal on "From E-Mobility to recycling: the virtuous loop of the electric vehicle"[3] will explore the extent to which the current regulatory framework contains unnecessary barriers. In this case, the barrier would be the absence of a clear definition and consideration of "repurposing" in existing pieces of legislation.

Existing R&D activities and projects underline the relevance of the topic: automakers in partnership with power equipment companies are actively exploring possible second-use applications and testing the technical feasibility of repurposing xEV batteries, already demonstrating stationary storage systems employing such batteries. Applications being studied range from home or neighbourhood back-up power systems, to more advanced grid power buffering strategies (smart grid). However, the sustainability of the adoption of xEV batteries in second-use application needs to be further demonstrated from different perspectives (technical, environmental, economic and social).

SASLAB project

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[1] Second-use and Re-use are two different terms: Re-use, is defined (legal definition) and mentioned in a number of Waste Directives (i.e. ELV, WEEE, WFD but not in BD) as any operation by which components of e.g. end-of-life vehicles are used for the same purpose for which they were initially conceived. Definitions about relevant terms for the reuse of products, e.g. remanufacturing, refurbish, repurpose, are described in (APRA Europe, 2012).

[2] Neither in the Waste Framework Directive 2008/98/EC and/or other daughter Directives, such as the Waste Electrical & Electronic Equipment Directive 2012/19/EU (WEEE) and the End-of-Life Vehicles Directive 2000/53/EC (ELV) (EU, 2000) "second-use" is defined

[3] http://ec.europa.eu/research/innovation-deals/index.cfm?pg=emobility

The **SASLAB (Sustainability Assessment of Second Life Application of Automotive Batteries)** project is a JRC exploratory research project[4] (duration January 2016 until December 2017) that aims at assessing the sustainability of employing xEV batteries in second-use applications, and at filling in some of the existing knowledge gaps in this respect. SASLAB particularly aims at better formalising and defining a realistic second-use battery system, testing performances of some of its elements (using experimental facilities and physical modelling), developing relevant performance indicators for the foreseen system (adopting a life cycle thinking approach) and finally discussing results also considering potential future policy-relevant research needs. This final report illustrates the main accomplishments of the project, discussing the most relevant conclusion and potential developments.

Overall, both the performed literature review and the contacts with stakeholders confirmed the novelty and relevance of the SASLAB project. Visits to several relevant actors of the xEV batteries value chain complemented the information gathering and allowed to enlarge and strengthen the networking established during the SASLAB project. A clear understanding of the current value chain of the xEV batteries, identifying the most important aspects and possible future second-use scenarios, allowed the creation of a predictive and parametrized model: this model is able to estimate the size of the xEV batteries flows along their value chain in Europe in the next future. Data concerning (residual) capacity of xEV batteries, their lifetime and embedded materials (e.g. cobalt, lithium) could be used also in the model in order to enhance the assessment and enlarge the analysis also focusing on flows of specific materials along the xEV batteries value chain.

The performed mapping of recent European and international industrial activities, R&D projects and research studies, using second-life xEV LIBs, revealed that applications related to grid integration of renewable energy and to reserve capacity are mostly studied and seem the most promising second-life options. The identified second-use applications to be tested and assessed during the SASLAB project are: peak shaving, PV firming, PV smoothing and primary frequency regulation.

The environmental assessment model must be fed with parameters expressing the expected performance of a battery dismissed from an EV. Such parameters can be extracted from experimental tests assessing this battery performance and how battery performance degrades with time and cycling. For this purpose an experimental campaign was designed for investigation of fresh and aged cell samples under different conditions and duty cycles representing first xEV life and second use utility grid applications. Unfortunately external circumstances lead to delays in the planned experimental activities and several tests had to be postponed or even cancelled. Nevertheless, the experimental tests are still ongoing and results are expected to become available and be used beyond the end of SASLAB project.

Results of the Life Cycle Assessment

From the environmental analysis, an adapted life-cycle assessment (LCA) [5] was developed to assess the environmental performances of the adoption of repurposed batteries. The relevant features of this assessment refer to both methodological aspects of LCA of batteries in specific applications and the data to be used for the assessment.

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[4] Exploratory Research is a direct action for the JRC to pursue scientific excellence. It aims to enable the JRC staff to pursue ambitious research projects and activities, without the requirement to address specific policy requests. It is a bottom-up process, where JRC scientists are invited to propose ideas for research projects and activities with the ambition to build up new scientific competences on emerging research fields and possible upcoming policy demands. Project proposals are assessed and selected by the JRC Scientific Committee following regular calls for proposals.

[5] http://eplca.jrc.ec.europa.eu/

Concerning the methodological aspects, the allocation of the impacts of the products to the first or/and the second life is still an open issue and various approaches co-exist in the scientific literature. In this study, allocation factors are introduced to assess the relevance of allocating impacts of both manufacturing and EOL stages along the life-cycle of the xEV battery. About data, the peculiarity of the systems in which repurposed batteries are used is accounted through the energy modelling of the system: energy requirements, system characteristics (e.g. grid-connected, PV installation) and battery characteristics (e.g. capacity, efficiency) need to be considered in order to model the energy flows of the system and, consequently, the impact of the second-use stage.

In particular, the LCA method was tested in **two different applications**, consistent with the available primary data and the project resources: peak shaving and increase of PV-self consumption. **Primary data** available from tests and the built-up knowledge during the lab analyses were used as input for the environmental assessment. For the LCA, primary data refer to both the Bill of Materials (BoM) of LMO/NMC battery cells and to the second-use stage. The LMO/NMC battery cells were dismantled in the JRC-Petten laboratories and a Bill of Materials is provided for modelling the environmental impact of the cells. Energy data related to real dwellings and PV installations were used for the energy assessment and the calculation of the second-use stage impacts.

Results show that, under certain conditions, environmental benefits occur when extending the lifetime of xEV batteries by repurposing in stationary applications. More in detail, the adoption of a repurposed LMO/NMC battery in place of a fresh one is **beneficial from an environmental point of view** for both assessed second-use applications. Higher yearly benefits are related to the increase of PV-self consumption application. No environmental benefits occur if a repurposed LMO/NMC battery is used without replacing any battery.

The performed **contribution analysis** depicts that all the life-cycle stages play an important role to the life cycle impact; therefore, none of them should be considered as negligible. Moreover, the impacts strictly depends on the characteristics of both the adopted battery (e.g. chemistry, type of battery, performances) and the specific application (e.g. energy flows, geographical location). For both the assessed applications, the performed balance of the systems' energy flows confirmed the importance of **properly modelling the use stage**, if possible through primary data. Data about the degradation of the end-of-first use batteries determined through experiment at JRC-Petten were used to estimate the lifetime of the batteries in the specific applications and for different configurations.

Finally, the performed **sensitivity analysis** shows the relevance of enlarging the analysis considering different options, e.g. chemistry of the battery and energy mix used in the assessment. As a result, the use of a repurposed LMO/NMC battery is always environmentally beneficial as compared to the use of a PbA battery for both assessed applications; moreover, in the increase of PV self-consumption application, the adoption of repurposed LMO/NMC batteries in a stand-alone application, avoiding the use of energy from diesel-electric generator can decrease the yearly impact of the system between 30 % and 40 %.

To complement the environmental assessment, some rough assessments of social assessment of the battery value chain were also developed by SASLAB project using S-LCA methodology. However, to be meaningful, these initial results will have to be adapted to the repurposing context. No economical assessment were carried out since it was not possible to implement a formal cooperation with one or several industrial partners that could have given us access to economic data.

Conclusions

In conclusion, the results obtained during the SASLAB exploratory project shows that the extension of the lifetime of xEV batteries through their adoption in second-use application is a credible and feasible end-of-first use recovery option, which is interesting for various stakeholders and also from a policy perspective. Moreover, significant environmental benefits from the extension of xEV batteries lifetime are generally observed. However, the sustainability of this option needs to be further assessed and the analysis illustrated in this report could be enlarged and complemented with data available in near future (from both laboratory tests and stakeholders consultation).

The repurposing stage of batteries, stage that was modelled in SASLAB with hypothesis, would need to be analysed in more depth since it could heavily affect the second-use of batteries from different perspectives. For this, primary data collection at repurposing plants would be necessary. During repurposing, tests can confirm the suitability of a specific xEV battery to one or more applications. Moreover, this stage could offer some social benefits related to the potential creation of a business case and jobs related to second-use of xEV batteries.

The social assessment should be improved focusing on the whole life cycle of xEV batteries. Industrial partners could play an important role in this aspect, as well as in the assessment of economic benefits/drawbacks of second-use of batteries. Moreover, the established network with industrial stakeholders could be strengthened and developed in order to gather information and data especially about repurposing stage.

In the SASLAB project, a methodology was developed to evaluate different reuse options of EV batteries from both a technical and environmental perspectives. This methodology could be employed in the future to assess potential benefits related to second-use of EV batteries in different applications, considering different scenarios, and even impacts/benefits of potential policy options.

Introduction

Second-use of traction batteries after their use in electrified vehicles (xEV) is aligned with both the Waste Framework Directive 2008/98/EC (EU, 2008) and the 2015 Circular Economy action plan of the European Commission (EC, 2015c). Despite the increasing interest in the topic, ''second use'' is not currently defined in any of the various Waste Directives.

In this context, the goal of the SASLAB (Sustainability Assessment of Second Life Application of Automotive Batteries) project is to explore the emerging area of second-life application of xEV batteries and to develop and apply an adapted methodology to analyse the sustainability of such systems. The technical feasibility and the environmental, economic and social performances of xEV battery second-use need to be assessed, especially considering that the extraction of resources used in batteries, manufacturing and end-of-life management are energy and resource intensive processes. When xEV batteries no longer meet the requirements for being used in a vehicle, they still retain energy storage capacity which can be potentially employed and repurposed e.g. within the electrical grid distribution system.

This project tries to fill-in some knowledge gaps concerning the technical, environmental, economic and social performances of the second-use applications of xEV batteries. The project in particular aims at better formalising and defining realistic second-use battery systems, testing performances of some of its elements (using experimental facilities and physical modelling), developing relevant performance indicators for the foreseen system (adopting a life cycle thinking approach) and finally discussing results. Of course, such a discussion should also address the questions of policy implications and research needs.

The project was jointly proposed by Directorate C (Energy, Transport and Climate Directorate, Petten) and by Directorate D (Sustainable Resources Directorate, Ispra) in the context of the JRC Exploratory Research call 2015, and it was selected by the JRC Scientific Committee. The project was executed from January 2016 to December 2017.

JRC.C.1 (Energy Storage Unit) in Petten (The Netherlands) mainly dealt with the assessment of battery degradation by performing experiments on xEV batteries and modelling of performance of the battery system in first xEV use and selected second-use applications in order to device reliable and accurate life time predictions to be employed in the LCA modelling exercise.
The activities conducted by JRC C1 include a mapping of existing European and international industrial activities, research and innovation projects and research studies, using second-life xEV LIBs, along with an overview of the reported results on energy storage applications and use cases. The considered second-use application(s) within SASLAB, the experimental assessment of LIB’s ageing in first- and second-use, the literature review on degradation data and durability testing for the selected LIB chemistries to be examined within SASLAB are also described and discussed in this report.

JRC.D.3 (Land Resources Unit) in Ispra (Italy) mainly dealt with the formalization of the xEV batteries value chain and the development / application of adapted life-cycle based assessments in order to assess the sustainability of the LCA system’s performance.
More in detail, the activities conducted by JRC.D.3 dealt with the definition of the value chain of xEV batteries and the reuse system. Aiming at defining and formalizing the battery system (especially for repurposing and second-use of batteries), the analysis of the current practices of repurposing and reuse of xEVs batteries was performed through both a literature review and contacting specific stakeholders. With this purpose, JRC.D.3 developed specific questionnaires. Moreover, visits to representative actors of the value chain of second-use of xEV batteries were organized. Through the available information from both the stakeholders, the literature and the JRC.C.1 tests outcomes, the environmental performances of the adoption of repurposed xEV batteries in second-use applications were assessed through tailored life-cycle based methods.

Maarten Messagie, expert from the VUB University (Brussels, Belgium), supported the project by establishing new contacts, in gathering information about xEV batteries modelling of performance, in the definition of the first steps of the environmental analysis, in reviewing the final deliverables and more in general in giving feedback on the approach adopted.

Collaboration within the multidisciplinary research team represented an added value for enlarging the scientific knowledge on the topic and to network with different stakeholders of the xEV batteries value chain. The collaboration and the knowledge of different aspects related to batteries permitted to base the environmental assessment on robust data and built-up knowledge during the project development. Finally, JRC.C.1 and JRC.D.3 participated in two successful Horizon 2020 project proposals, which cover aspects of second-use applications[6].

The experience developed in the SASLAB project supported tasks not directly forecasted at the beginning of the project, e.g. participation in the process of the Batteries Directive Review during the ISG meetings and invitation to contribute to the Innovation Deal on "From E-Mobility to recycling: the virtuous loop of the electric vehicle"[7].

This report summarises the outcomes of the SASLAB project. It should be pointed out that adjustments of staffs allocations were to be made in the course and not all initially planned activities were implemented. However, some lab tests are still ongoing and results could be beneficial in further development of JRC's competences in the field.

This report is organised into the following major chapters. **Chapter 1** contains an analysis of the current value chain of xEV batteries. This analysis is largely based on interviews of key stakeholders representing various stages of the value chain. A mapping of recent European and international industrial activities, R&I projects and research studies, using second life xEV batteries, along with an overview of the reported results on energy storage applications and use cases are presented. **Chapter 2** describes the implications of the findings presented in Chapter 1. In particular, specific aspects (e.g. selected second-use applications and better understanding of the batteries value chain) relevant for the SASLAB project deriving from both the performed literature and the stakeholders contacts are pointed out. **Chapter 3** describes the experimental assessment of LIB's ageing in first- and second-use, along with a literature review on degradation data and durability testing for the selected LIB chemistries and second use applications. The environmental assessment of a repurposed lithium-ion xEV batteries in different second-use applications is described in **Chapter 4**, taking a life cycle perspectives. Finally, some insights of social aspects related to xEV batteries are reported in **Chapter 5** of this report. Concluding considerations about the sustainability of xEV batteries second-use are discussed in **Chapter 6**.

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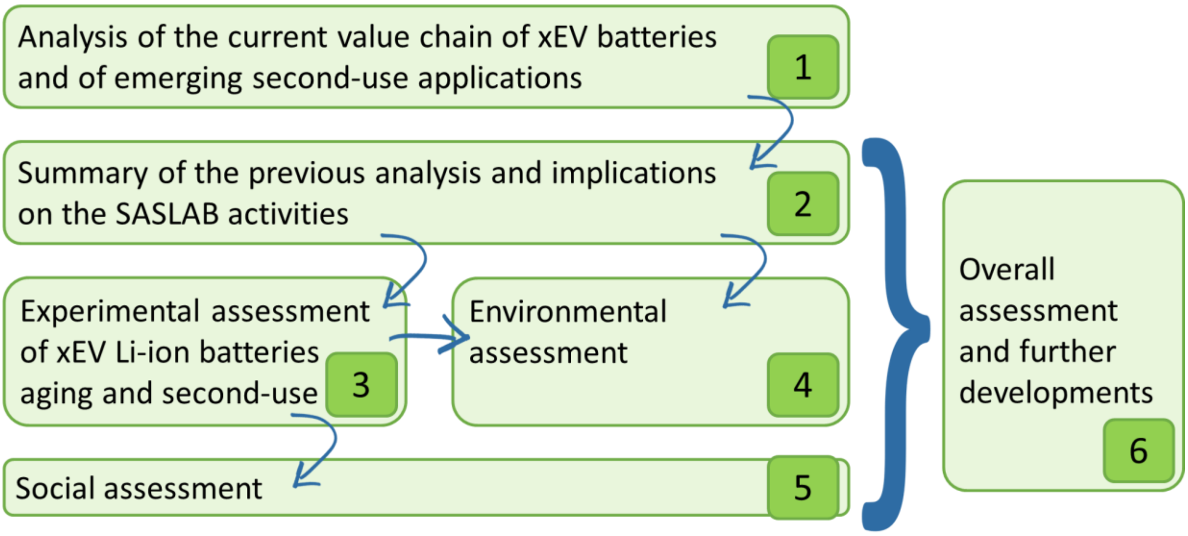
[6] CarE-Service (Circular Economy Business Models for innovative hybrid and electric mobility through advanced reuse and remanufacturing technologies and services) and LiBforSecUse (Quality assessment of electric vehicle Li-ion batteries for second use applications)

[7] http://ec.europa.eu/research/innovation-deals/index.cfm?pg=emobility

Figure 1: Schematic representation of the report and the links between chapters



CHAPTER 1

Analysis of the current value chain of xEV batteries and of emerging second-use applications

In this section, the main findings derived from the contacts with stakeholders involved in the xEV batteries value chain are reported (section 1.1). Then, section 1.2 describes the performed analysis of second-use applications of xEV batteries through a mapping of international and European industrial activities, research and development (R&D) projects, and demonstration projects. Further learnings from the on the field visits during the SASLAB project are summarized in section 1.3. Finally, further learning from literature about various aspects of second-use of xEV batteries are reported in section 1.4.

1.1 Consultation of the stakeholders of the value chain

To understand better the emerging system of electric vehicles batteries repurposing, it is necessary to analyse the xEV battery value chain as a whole. With this purpose, a set of questionnaires (ANNEX I) was developed and addressed to stakeholders belonging to the whole value chain of xEV battery, with special focus on potential reuse of xEV batteries. In second-use applications. Building on previous experiences from JRC Dir. D staffs (cf. e.g. (Mathieux and Brissaud, 2010)) and on the performed literature review supported the creation of the SASLAB questionnaires.

The stakeholders of the value chain of xEV batteries were grouped as following:

1. questionnaire for car companies;
2. questionnaire for waste batteries collectors;
3. questionnaire for repurposing companies;
4. questionnaire for actors using repurposed batteries;
5. questionnaire for experts

The following table lists several stakeholders which were contacted in order to gather information through the questionnaires.

Table 1: List of the identified and contacted stakeholders

	Actors		Website	Feedback
1	Battery manufacturer	**EUROBAT** - Association of European Automotive and Industrial Battery Manufacturers	www.eurobat.org	Contacted - questionnaire sent
2	Car company	**RENAULT**		Contacted - questionnaire sent
3	Car company	**FCA**		Answered questionnaire
4	Car company	**PEUGEOT/CITROEN**		Answered questionnaire
5	Car company	**HYUNDAI MOTOR**		Answered questionnaire
6	Car company	**MITSUBISHI**		Answered questionnaire
7	2nd use project	**Bosch/BMW/Vattenvall** (pilot project: Second Life for electric-vehicle batteries)	http://www.bosch-presse.de/presseforum/details.htm?txtID=7067	Answered questionnaire
8	Waste batteries collectors	**Battery Foundation** (Stichting Batterijen) in NL (Advised by Wecycle instead because they work in cooperation with ARN)	https://www.stibat.nl/	Contacted

	Actors		Website	Feedback
9	Waste batteries collectors	**ARN -** centre of expertise for sustainability and recycling in the mobility sector.	http://www.arn.nl/en/	Answered questionnaire
10	Expert	**EGVIA** - European Green Vehicles Initiative Association	http://www.egvi.eu/about-egvia/organisation	Contacted - questionnaire sent
11	Expert	**IKERLAN** - Spanish knowledge transfer centre - Project Battery 2020	http://www.ikerlan.es/en/	Contacted
12	Expert	**VUB** - The Vrije Universiteit Brussel	http://www.vub.ac.be/en/	Contacted - questionnaire sent
11	Expert	**ENEA** - National Agency for New Technologies, Energy and Sustainable Economic Development	http://www.enea.it/it	Contacted - questionnaire sent

In general, answers to questionnaires highlight an increasing interest in second-use of xEV batteries, even if some barriers were identified for this EoL option. More in detail, a suitable regulatory framework seems to be most relevant since the term "reuse" is not mentioned in the Batteries Directive. However, movements in this direction are already occurring (e.g. the Innovation Deal on second-use of batteries[8]).

Even though some pilots and research projects are ongoing, currently there are few examples of the reuse of batteries. An example of xEV batteries' repurposing is implemented by Autobedrijf Peter Ursem[9]. Through an environmental permit, Autobedrijf Peter Ursem, that is initially a car dealer, became also a "recycler" and consequently a manufacturer of new products. This means that collected batteries could be tested and used for other purposes (see the ARN questionnaire, 2016). A visit to this repurposing centre was organized and it permitted to better understand how collection, testing and repurposing of batteries are managed.

Another example is Vattenfall, a Swedish utility electric company providing services both at the Utility-side-of-the-meter and Behind-the-meter level in Germany, Netherlands, Sweden and Finland. In 2013, an agreement was reached between Vattenfall and the car manufacturer BMW for setting up pilot projects to assess the feasibility of electric vehicle battery second-use. Negotiation with BMW on price and conditions were the key element of the agreement, but warranties were not included since they cannot be properly quantified as the system behaviour is not well known. According to Vattenfal, the simplification of the hardware/software integration is the key cost factor for the second-use business case. This is achieved limiting the battery packs remanufacturing process and using packs coming from a unique provider. Also the value for money can be justified only if as many services as possible run on the same installation (e.g. trading, primary frequency regulation and household-PV energy storage).

Hyundai Motor, in case of accidents, removes the battery pack from the xEV and checks it for possible reuse. If usable, the battery pack will enter a remanufacturing program for complete battery packs or it could be used in a second-use application. The most promising applications seem to be residential household applications, especially in combination with solar energy.

From an economic perspective, almost all the interviewed stakeholders highlight the potential relevance of governmental incentives on battery reuse. Some economic issues to be faced are the price of second life batteries, the absence of a clear OEM business

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[8] https://ec.europa.eu/research/innovation-deals/index.cfm?pg=emobility

[9] http://www.peterursem.nl/

strategy for EVs and the fact that the second-use battery packs are more expensive in terms of €/kWh/n.cycle compared to first use packs.

Knowledge about the application of reuse xEV batteries is quite limited due to the limited available experience. However, the most suitable applications identified by stakeholders could be stationary applications in which renewable sources are involved and a multipurpose application for a single installation (trading, frequency regulation, etc).

Finally, a general issue underlined by the interviewed stakeholder is the absence of a clear definition of "second life application". According with interviewed stakeholders, a standardised and recognised definition of "second life application" within the regulatory framework could support the future strategies in extending batteries' lifetime and creating new investments opportunities.

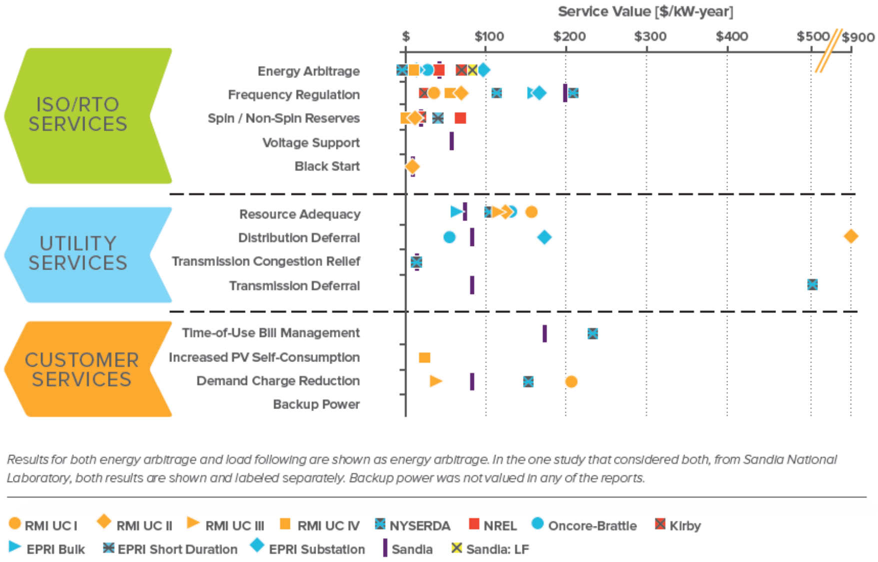
1.2 Analysis of emerging second-use activities

International and European industrial activities, research and development (R&D) projects, and demonstration projects were mapped within SASLAB. This mapping is based on peer-reviewed scientific publications and technical reports by research laboratories, agencies, consultants, and industry analysts. Since automotive and energy storage are fast-moving industries, this second set of documents contain a larger part of the available up-to-date information with respect to developments in second-use battery applications.

1.2.1 Second-use applications

Nowadays, Lithium-ion batteries (LIBs) are receiving a growing attention as they can be employed to provide one or several services in modern electricity systems. (Fitzgerald et al., 2015) illustrated that energy storage is capable of providing up to thirteen services to the electricity system (Figure 2) to three stakeholder groups: customers, utilities, or independent system operators / regional transmission organizations (ISO / RTOs) in the U.S. Customer-sited, behind-the-meter energy storage are presented as the energy storage that could technically provide the largest number of services to the electricity grid at large (Fitzgerald et al., 2015; Reid and Julve, 2016).

Figure 2: Energy storage values ($/kW-year) in the U.S. for three stakeholder groups

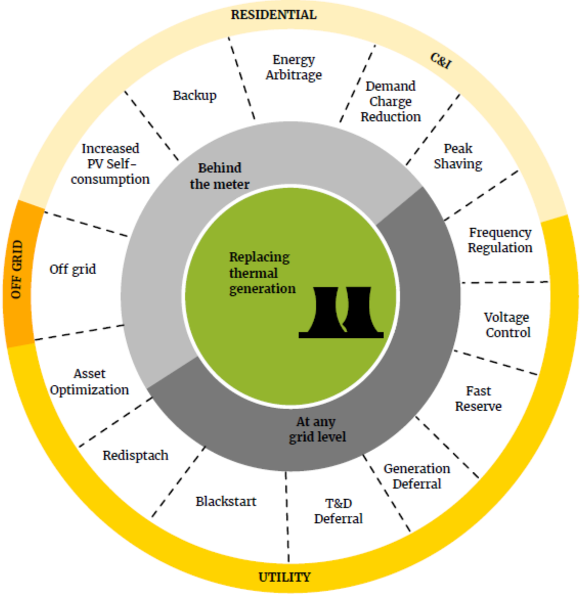


Results for both energy arbitrage and load following are shown as energy arbitrage. In the one study that considered both, from Sandia National Laboratory, both results are shown and labeled separately. Backup power was not valued in any of the reports.

Source: Rocky Mountain Institute and the Reidy as the source (Fitzgerald et al., 2015)

In Germany, ''the automotive industry is entering into the energy area by offering batteries to both household and commercial users, as well as, providing services to utilities and the grid'' (Reid and Julve, 2016). Fourteen identified services batteries can be provided to four stakeholder groups (Figure 3).

Figure 3: Fourteen services batteries can provide to four stakeholder groups in Germany at four levels: off grid, behind the meter, at the distribution level, or at the transmission level (TSO: Transmission System Operators)



Source: (Reid and Julve, 2016)

In ANNEX II, a summary of studies, pilots and/or industrial activities assessing the second-use of xEV Li-ion batteries for different applications is given. In the analysed reports, applications related to grid integration of renewable energy and to reserve capacity were most studied (15 and 10 out of 35 assessed studies, respectively). Of the 10 industrial activities reviewed, 5 are taking place in the EU and another 5 internationally (4 out of 5 in the U.S.). Again, applications related to grid integration of renewable energy are dominating. Finally, 4 out of the 7 EU-funded R&D projects focused on second-use of aged xEV batteries are currently running, including our exploratory research - SASLAB - project.

1.2.2 Inventory of industrial initiatives

xEV batteries repurposing and second-use of batteries in stationary storage systems is object of different pilots and activities in which xEV manufacturers and power equipment companies are collaborating.

Europe

Stakeholders: Daimler, The Mobility House[10], GETEC[11], REMONDIS[12]

Aiming at demonstrating a "complete sustainable lifecycle" for automotive batteries, batteries used in Daimler's plug-in vehicles were repurposed by The Mobility House and GETEC to be used at the site of REMONDIS (a recycling, service and water company in Lünen, Germany). This storage unit is the largest in the worlds and has a total capacity

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[10] http://www.mobilityhouse.com/en/energy-storage/

[11] http://www.getec-energie.de/

[12] http://www.remondis.com/en/home/

of 13 MWh (Morris, 2015a). In this respect, reuse of electric vehicle batteries improves environmental performance and the lifecycle costs of e-mobility.

Stakeholders: Bosch, BMW, Vattenfall[13]

In service since 22.09.2016 in Hamburg (Germany), "Battery 2nd Life" project[14] aims at balancing the grid though used BMW batteries (Bosch, 2016; Kane, 2016). 2600 battery modules from over 100 BMW's electric cars (ActiveE and i3 models), with a power output of 2 MW and an installed capacity of 2.8 MWh, were adopted in an already existing Vattenfall virtual power plant. A multipurpose application combining Trading (Arbitrage), Frequency Regulation, Peak Shavings for Utilities, and, as a particular case, household-PV energy storage is Vattenfall's second life applications choice (Bosch, 2016; SASLAB Project, 2016). The project would allow the three partners to gain new insights into potential areas of application for such batteries, their aging behaviour, and their storage capacity.

Stakeholders: Nissan, Eaton[15]

Nissan and Eaton have partnered to introduce a residential energy storage unit (xStorage) using second life batteries from the Nissan Leaf EV, designed to enable customers to take advantage of time-of-use pricing, and to provide back-up power (EATON, n.d.; Morris, 2016a). xStorage Home units will be priced competitively starting at €3,500 (excluding VAT and installation costs) for a power capacity of 3.5kW rising to just €3,900 for 6kW. Units powered by new Nissan batteries will start from €5,000 rising to €5,580 for the highest capacity and will come with an extended warranty period of ten years.

Moreover, in combination of Eaton power conversion units and new xEV batteries, second-life Nissan Leaf batteries are adopted in the Johan Cruijff ArenA (Amsterdam) in order to provide back-up power (total capacity of 3 MW)[16].

Stakeholders: Renault, Connected Energy[17]

E-STOR is a modular storage product which uses reused xEV batteries to store electricity for a variety of purposes[18]. Applications include: storing energy generated from intermittent renewable resources; charging at off-peak times, enabling users to reduce energy costs; and enabling rapid xEV charging without overloading the local electricity supply (Morris, 2016b). The first E-STOR product is nominally rated at 50 kW/50 kWh, but the system is fully scalable, and higher capacity units are to follow.

Stakeholders: EDF (Électricité de France)[19], Forsee Power[20], Mitsubishi Motors Corporation, Mitsubishi Corporation, PSA Peugeot Citroën

In September 2015 at Forsee Power's new Headquarters near Paris (France), a project aiming at delivering an optimised smart grid and Energy Management System, combining solar, xEVs, stationary storage, using new and reused batteries, in bi-directional mode was launched (Forsee Power, 2015). A high voltage (330 V) Energy Storage System made of Peugeot Ion, Citroen C-Zero and Mitsubishi iMiEV reused

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[13] https://corporate.vattenfall.com/

[14] https://boschenergystoragesolutions.com/en/blog/-/blog/4335273/batteries-of-electric-cars-for-a-robust-electricity-grid-bosch-cooperates-with-bmw-and-vattenfall

[15] http://www.eaton.com/Eaton/index.htm

[16] http://www.johancruijffarena.nl/default-showon-page/amsterdam-arena-more-energy-efficient-with-battery-storage-.htm (2016); http://www.johancruijffarena.nl/default-showon-page/the-3-megawatt-energy-storage-system-in-johan-cruijff-arena-is-now-live.htm (2018)

[17] https://www.c-e-int.com/

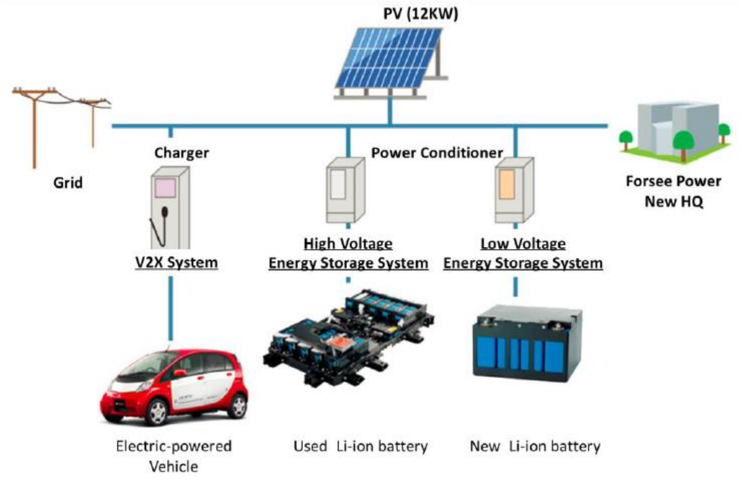
[18] https://chargedevs.com/newswire/renault-and-connected-energy-collaborate-on-e-stor-energy-storage-product/

[19] https://www.edf.fr/

[20] https://www.forseepower.fr/en

automotive battery pack is used. New Li-ion batteries are used for the low voltage (48 V) Energy Storage System. A new business model with energy storage system utilizing such used batteries represents one of the project's outcomes.

Figure 4: EDF, Forsee Power, Mitsubishi Motors Corporation, Mitsubishi Corporation and PSA Peugeot Citroën reused xEV batteries demonstration project schematic



Source: (Forsee Power, 2015)

<u>Stakeholders</u>: Peter Ursem Autobedrijf B.V., ARN (Auto Recycling Nederland)

As of 20/06/2016 all xEV batteries, which are/will be dismissed from vehicles circulating in the Netherlands, are being transferred to and treated at Peter Ursem's installation. Peter Ursem's customers are manufacturers of new products using second-use battery cells. This activity demonstrates that in this stage of market development also other approaches might be feasible: Peter Ursem Autobedrijf B.V. became a "recycler", collecting batteries that could be tested and used for other purposes (section 1.1).

<u>**Outside Europe (or International)**</u>

<u>Stakeholders</u>: GM (General motors), ABB (Asea Brown Boveri)

Reuse application for xEV batteries was demonstrated by GM and ABB since 2013[21]. Five used Chevrolet Volt batteries were repackaged into a modular unit (providing 25 kW of power and 50 kWh of energy) which is used for uninterruptible power supply and grid power balancing system. New tests and activities are ongoing (Starke, 2015)

<u>Stakeholders</u>: Nissan, Sumitomo

Nissan and Sumitomo partnered with '4R Energy' and 'Green Charge Networks'[22] to repurpose used electric car battery packs in large commercial-scale grid-tied energy storage systems - ''Second-Life Grid-Tied Storage Program for Electric Car Battery Packs''. After their use in Nissan LEAF and Nissan e-NV200 EV, the battery packs are teste, repackaged and combined with other used battery packs into a large grid-connected system designed to offset peak electricity demand. The first of these combined storage units will be installed and commissioned at a Nissan North America facility in the U.S. (Gordon-Bloomfield, 2015).

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[21] https://www.linkedin.com/pulse/gm-abb-reused-chevy-volt-batteries-energy-storage-andreas-sur%C3%A1nyi/

[22] Green Charge Networks specialises in the manufacture and supply of grid-connected energy storage systems that help large companies manage and mitigate their peak power uses throughout the day to ensure that they are not hit with large, expensive peak-use charges.

4R Energy Corporation (Yokohama, Japan), was founded in September 2010 as a joint venture between Nissan and the Sumitomo Corporation to conduct research and repurpose second-life Nissan Leaf battery packs. Sumitomo established the world's first large-scale power storage system on Yume-shima Island, Osaka (Sumitomo, 2014). A 600kW/400kWh prototype system that consists of sixteen used xEV batteries is used to test the smoothing effect on the power output from a nearby wind farm.

Stakeholders: BMW, Beck Automation[23]

A stationary storage solution that integrates BMW's i3 vehicle high-voltage batteries was developed in partnership of BMW with BECK Automation (announced at EVS29 in Montreal). The system includes a voltage converter and power electronics to manage the energy flow between renewable energy sources, a home interface, and the battery. It's designed to be stored in a basement or garage, and has a capacity of 22 or 33 kWh, which BMW says should be sufficient to operate a variety of appliances and entertainment devices for up to 24 hours (Morris, 2016c).

Stakeholders: FreeWire Technologies[24] (California), Siemens

The Mobi Charger is a portable charging station powered by second-life xEV batteries from the Nissan Leaf that can charge five cars per day, using lower-cost, off-peak energy stored in repurposed xEV batteries. It uses Siemens' eCar Operation Center, a cloud-based interface for managing large-scale xEV charging. The system is currently in use by several large utilities, enabling them to use xEV charging as a resource to support grid stability. The adoption of the Mobi Charger could save charging costs for customers and create value through grid storage, load levelling, and demand response (Morris, 2015b).

Stakeholders: Spiers New Technologies (SNT)[25]

SNT, a U.S. newly created company, is an aggregator of EoL battery packs and modules with an EPA aggregator number. SNT is HAZMAT 9[26] certified and can design and build energy storage systems for multiple non-vehicle applications, including lower cost stationary electricity energy storage, vehicle recharging stations, solar support and UPS systems (Ruoff, 2016; Technologies, 2015).

1.2.3 R&D projects

This section proposes an inventory and a brief analysis of the most relevant R&D project for SASLAB. Not all the existing activities are reported and it is highlighted that more H2020 projects working on second-use applications within the Green Vehicles, Low Carbon Energy and Smart City calls (for instance GV06 2017[27], SCC01 2017[28] and LCE 01 2017[29]) are expected to start in the near future.

Europe

Batteries2020[30]

The project (completed at the time of writing this report) aimed to improve performance, lifetime and total cost of ownership of batteries for xEVs by the simultaneous

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[23] http://www.team-elektro-beck.de/

[24] https://freewiretech.com/

[25] http://www.spiersnewtechnologies.com/

[26] Miscellaneous hazardous materials not covered by Classes 1-8

[27] https://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/gv-06-2017.html

[28] https://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/scc-1-2016-2017.html

[29] https://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/lce-01-2016-2017.html

[30] http://www.batteries2020.eu/

development of high-performing and durable cells, reliable lifetime prediction, understanding ageing phenomena and assessment of second life in renewable energy applications. As it was pointed out in the project's expected achievements, one of the main methods to potentially reduce the total cost of ownership of batteries is to reuse them in second life applications, especially in the field of renewable energy sources, such as photovoltaics, where Europe has a leading position.

Within Batteries2020 an LCA task was delivered, whereas two main applications were considered for the second life battery testing: (a) A Spanish residential household, which was composed of residential loads, a roof-mounted photovoltaic (PV) system and a second life battery energy storage system, representing a low-demand application, in which low current rates (C-rate) and low depth of discharge (DoD) cycles are mostly recorded (Saez-de-Ibarra et al., 2015), and (b) a second life battery energy storage system to mitigate the power variability of a grid-scale PV plant, representing a high-demand application, especially in terms of C-rate, DoD and number of cycles-per-year (Koch-Ciobotaru et al., 2015).

Energy Local Storage Advanced system (ELSA)[31]

The 10-partner project (ongoing 36-month project that began in April 2015) objective is to enable integration of distributed storage solutions into the energy system and their commercial use. ELSA addresses existing development needs by combining 2nd use batteries with an innovative local ICT-based Energy Management System in order to develop a low-cost, scalable and easy-to-deploy battery energy storage system. ELSA is also developing service-oriented business models, whereas sustainability and social acceptance are both taken into consideration through life-cycle and socio-economic impact assessments. ELSA's energy storage systems (ESS) are foreseen to be applied in 6 demonstration sites in 5 EU countries, that include buildings, districts and grids[32], covering services such as grid congestion relief, local grid balancing, peak shaving, voltage support and frequency regulation. ELSA's work is supported by an Advisory Board composed of key actors of the EU energy sector as well as key users of future ESSs.

ELSA focuses on decentralised small and medium-size ESSs, because the consortium considers they provide much greater operating flexibility than today's large, centralised energy distribution systems, as decentralised ESSs ensure a reliable energy supply for buildings and districts and thus enable the integration of a high share of intermittent renewable energy sources (RES). Yet, few such storage solutions are technically mature and economically viable at this stage, since widespread application is hindered by the EU's existing legal and regulatory framework, according to ELSA consortium (ELSA, 2017).

The storage systems will be directly connected to feeders or substations and will include solutions for autonomous storage management and also to interface the storage system with wider scale energy managers. This storage management installed in commercial and industrial buildings will be able to interact with the Building Energy Management Systems (BEMS) and with local storage of different natures (e.g. thermal) by using standard communication protocols. The BEMS will coordinate generation, storage and loads to provide a building storage system (including demand response) able to interface with other energy managers (e.g. aggregators, markets or substations)[33].

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[31] http://www.elsa-h2020.eu/

[32] http://www.elsa-h2020.eu/Pilots.html

[33] First results of the ELSA project (Jahn et al., 2016) can be found at http://www.elsa-h2020.eu/Results.html

ABattReLife[34]

The consortium gathered automotive industry players and academic institutions, in order to address the technological barriers for a better battery life cycle, as well as the most appropriate technologies to ensure a reuse of the xEV batteries at the end of the first use. The consortium will study the LIBs' behaviour and degradation phenomena and develop methods to determine the battery state of health for potential reuse in other applications. The results of this work will allow to evaluate the options to use xEV batteries in second life applications and determine the technical specifications of second life batteries while also focusing on the recycling technologies solutions at the EoL of the battery from the separation to the valorisation of its different components. Based on the second life and recycling solutions identified, a mapping of the actors of the value chain and development of business models will also be developed. Furthermore, the implementation and feasibility of second life and recycling solutions will be studied in technological and industrial demonstration projects. Subsequently, small scale pilot will be built based on the most promising demonstration projects, thus enabling to close the loop by validating results of the scientific and technological analysis performed at a previous stage.

AlpStore[35]

xEVs will be integral elements of the future energy system. According to AlpStore project, their batteries can be charged with excess power from intermittent energy sources and electricity can be fed into the grid to meet peak loads. Beyond short term balancing with xEVs, stationary batteries can serve long term balancing needs. They can give xEV batteries a "second life” and improve overall economy of electric mobility. The project has closed on April 30, 2015. However, it is mentioned that the web site allows for approaching the project partners.

Netfficient[36]

It is an ongoing EU-funded project, which aims at demonstrating the feasibility of local small scale storage technologies covering low voltage and medium voltage scenarios and a wide range of applications and functionalities. The following storage technologies (that will be implemented and demonstrated on the German island of Borkum in the North Sea with direct involvement of citizens) are foreseen to be integrated: Super Capacitors, Li-ion batteries, Second Life Electric Vehicle Batteries, Hydrogen, and Home Hybrid technologies as a combination of the above.

Through various use cases, such as homes, public buildings, street lighting and others, the project aims at demonstrating the application in the real environment. This is expected to result in the identification of viable business models and propositions for changes in regulations, thereby reducing the barriers for deployment and increasing societal acceptance.

2Bcycled[37]

The project ‘2Bcycled’ launched in the Netherlands investigates possible applications for LIBs at the end of their first life on the road (it is a feasibility study into the deployment of end-of-life HEV batteries). It is a storage system - made from used xEV batteries - installed on the island of Pampus (Ijsselmeer)[38]. The project and related study are carried out by network operator Alliander, ARN, Stichting Forteiland Pampus, DNV GL, the University of Applied Sciences in Arnhem and Nijmegen, the University of Technology in Eindhoven and Amsterdam Smart City. The final goal of the Pampus project is the

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[34] http://www.abattrelife.eu/

[35] http://www.alpstore.info/

[36] http://netfficient-project.eu/

[37] http://www.arn.nl/en/news/2bcycled-investigating-second-life-for-li-ion-batteries/

[38] http://www.pampus.nl/

reduction of CO_2 emissions by reducing diesel consumption. On the island micro wind turbine and solar panels are available, together with a diesel generator. The island receives 20-40.000 visitors per year. The connection of the island to the inland electric grid is too expensive (1 M€). The repurposed energy storage system was installed by DNV GL (Det Norske Veritas Germanischer Lloyd) (former KEMA; KEMA now belongs to DNV GL and Alliander N.V.), in cooperation with the HAN University of Applied Sciences (Hogeschool van Arnhem en Nijmegen in Dutch). The new installation is covering the energy needs for the whole winter and the summer nights obtaining a 28 % saving on diesel consumption and a more stable network. In the new application the BMS had to be replaced and rebuilt completely.

Outside Europe (or International)

The U.S. Department of Energy's Vehicle Technologies Office has funded the National Renewable Energy Laboratory (NREL) to investigate the feasibility of and major barriers to the second-use of modern lithium-ion PEV batteries[39, 40]. The resultant research identified and answered several "high-level" questions critical to understanding the viability of battery second-use (B2U):

“When will used automotive batteries become available, and how healthy will they be?”

“What is required to repurpose used automotive batteries, and how much will it cost?”

“How will repurposed automotive batteries be used, how long will they last, and what is their value?”

The conclusions drawn from NREL's analysis are strongly sensitive to the battery degradation predictions therein - results of NREL's battery lifespan and degradation project[41] were transferred into the B2U project to estimate how long a battery would last with a new duty cycle. It was revealed that the second-use of PEV batteries is both viable and valuable.

To validate NREL's predicted first and second life performance, battery life testing has been conducted in NREL's laboratories. NREL has also partnered with the Center for Sustainable Energy (CSE) and the University of California, San Diego (UCSD) to install a flexible second-use field testbed on a microgrid. In this framework, researchers of the CSE studied the baseline health of four xEV batteries and developed a long-term testing protocol to track battery performance over time under second-use application cycling. Secondary uses (suitable grid application) for reused xEV batteries, such as demand charge management, renewable energy integration and regulation energy management were examined.

While NREL's analysis does not suggest that B2U will significantly reduce the upfront cost of PEVs, it does show that B2U can eliminate costs at end of first use for the automotive battery owner and provide low- to zero-emission peaking services to electric utilities reducing cost, use of fossil fuels and greenhouse gas emissions. Thus, the overall benefit to society may be quite large (Personal communication of A. Pfrang (JRC, C.1) with A. Pesaran (NREL, DOE)). Further details on NREL's studies can be found in (Neubauer et al., 2015a, 2015b, 2015c, 2012).

1.3 Further analysis of a few selected initiatives

During the SASLAB project, the performed interviews permitted to establish a network between some stakeholders along the xEV batteries’ value chain. Thanks to these contacts, especially ARN (Auto Recycling Netherland), visits in the field were organized to develop the networking, to gather data and information.

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[39] https://energycenter.org/program/secondary-use-applications-plug-ev-lithium-ion-batteries

[40] http://www.nrel.gov/transportation/energystorage/use.html

[41] http://www.nrel.gov/transportation/energystorage/lifespan.html

In particular, visited realities are the following:

- Autobedrijf Peter Ursem (The Netherlands) (section 1.1). Autobedrijf Peter Ursem is a car dealer who became also a recycler. Consequently, he collected xEV batteries to be tested and used for other purposes;
- Pampus Island[42]. In the Pampus Island, one of the two batteries used for energy storage is a Li-ion battery derived from 2 xEV battery packs that were dismantled at the cell level, tested and re-assembled to be used in the island. Together with batteries, the energy requirement is covered by a PV system and a diesel generator. The visit permitted to have a clearer knowledge about the sizing of the system, of the main difficulties to be faced in a real second-use applications and to establish contacts potentially useful for the next step of the modelling;
- Van Paperzeel (Lelystad - The Netherlands). Main expertise of Van Peperzeel concern the safe handling of waste batteries along the value chain (reverse logistic, sorting, and packaging for logistics). The company has developed new solutions for handling (storage/transport/packaging) Li-ion batteries especially in relation to their safety issue, solutions to prevent and extinguish fires in containers for waste batteries. Van Peperzeel has also some manual sorting activities and then they send sorted batteries to several recyclers in Europe;
- ARN training centre plant (Tiel - The Netherlands). ARN invited JRC to visit the training centre where ARN regularly trains dismantling and shredders operators on how to safely extract batteries from end-of-life EVs. Challenges related to the batteries extraction were discussed also in view of their second-use (except for vehicles that had an accident).

1.4 Literature analysis

Most of the consideration arisen by the analysis of current practices through questionnaires (section 1.1) are aligned with the results obtained from the literature review.

Due to the fast increase of the worldwide xEV penetration, Bloomberg New Energy Finance (BNEF) forecasts that a 95 GWh of LIBs are expected to come out of xEVs by 2025. Moreover, considering the reuse of xEVs batteries as a viable option, BNEF estimated that about 26 GWh of them could get a second-life and be converted (repurposed) to operate in stationary systems (Bloomberg, 2016).

According to a 2014 report by the UCLA School of Law and UC Berkeley School of Law (Elkind, 2014): "Assuming 50% of the battery packs on the road in 2014 can be repurposed, with 75% of their original capacity, these second-life batteries could store and dispatch up to 850 MWh of electricity (1 MWh is roughly equivalent to the amount of electricity used by about 330 homes over one hour)."

Definition of repurposing

However, a clear definition of repurposing of battery is not available in literature. This is an open issue for stakeholders as stated in section 1.1.
(Canals Casals and Amante García, 2016) distinguished between two different strategies: 1)the battery pack is not dismantled, it is tested and, if suitable for second-use, directly reused, 2) the battery pack is dismantled at the module level, and a new battery pack is created. This second strategy is identified as 'battery repurposing', while the first one as 'direct reuse'. The battery repurposing will requires new materials/components, and consequently an increase of costs related to the repurposing step, but the repurposed battery will be more flexible and fitted for specific uses.

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[42] https://www.pampus.nl/en/

(James Paul et al., 2015) define the battery repurposing as a process involving "the breakdown of packs into modules, inspecting the hardware of the modules, performing inspection and health benchmark tests on the modules, and certifying that the modules meet a market-defined second-life standard. Once the modules have been certified, the second process, repackaging, takes place. The repackaging process involves putting modules deemed "good enough" for second-use into subpacks and packs that can be shipped for use in stationary systems". In this process, it is possible that very good modules can be used again for EVs[43]. Note that the analysis performed by (Neubauer et al., 2015b) identified the technician labour as the major cost element of repurposing.

(Hartwell and Marco, 2016) discuss the ambiguity deriving by the absence of an exact meaning of "related circular economy activities" among which refurbishment and remanufacturing are included. 'Warranty' and 'design-life' were identified as concepts able to provide a clear definition of remanufacturing and, consequently, to propose definitions also for refurbishment of battery packs.
RECHARGE, the European Association for Advanced Rechargeable Batteries[44], aiming at defining 're-use and second-use' of batteries, proposed to establish a set of minimum requirements that need to be fulfilled before authorising the reuse or the second-use of batteries after a first service life. A non-exhaustive list of minimum requirements, as shown in Table 2, shall be met in order for RECHARGE to facilitate the reuse. RECHARGE only supports the second-use of batteries when the battery remains under the responsibility of the producer acting as the first entity placing the battery on the market. In absence of a legal basis and clear minimum requirements, second-use is not supported by RECHARGE, as there are too many unknown factors that could impact the reliability of the product and safety of the end user (Recharge, 2014).

Table 2 Indicative list of minimum requirements to be considered for allowing re-use or second-use of batteries (adapted from (Recharge, 2014))

Proposed Minimum Requirements for	
Re-use (identical use)	**Second-use**
Application - Re-furbishment or re-conditioning by qualified professional - Control of equivalent performances, e.g. through the BMS - Quality, Safety and Performance standards to be observed - Etc…	In absence of a legal basis, additional criteria might be required – e.g. - Compatibility issue between 1st and 2nd application
Producer Responsibility - Producer identified - Warranty offered by producer	- Responsibility for the technical performances - Producer responsibility to be defined: technical and EoL
Safety - Technical requirements maintained - Safety standards respected (tests)	- Compliance with safety testing requirements before second-use

Collection of waste xEV batteries

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[43] https://chargedevs.com/features/second-life-spiers-new-technologies-develops-advanced-battery-classification-techniques/
[44] www.rechargebatteries.org

The first step of the potential reuse of xEV batteries is the collection after their removal from xEV and their sorting. As declared by (EC, 2014), the collection rate of both automotive and industrial batteries in Europe is nearly 100%. Therefore, a high availability of xEV batteries after their use in xEV is expected also in the future.

It is underlined that the expected increase of the xEV market results in an increasing waste batteries flow to be managed. A "reverse logistics"[45] effort could optimize the retailer supply chain and minimize the operational and environmental costs (Klör et al., 2014; Pourmohammadi et al., 2008; Roghanian and Pazhoheshfar, 2014; Schultmann et al., 2003), strength the system effectiveness and decrease costs (CEC, 2015; Groen, 2016).

Concerning Li-ion xEV batteries, an appropriate and safe removal, handling and transport of such batteries is needed (Van Paperzeel communication, section 1.3) and could minimize the failure rate of repurposing operations (Ahmadi et al., 2014b; Canals Casals and Amante García, 2016; CEC, 2015). Then, both specialization of operators who can safely manage batteries (Groen, 2016) and strengthening of stakeholders network (CEC, 2015; IHS Consulting, 2014) are two relevant aspects for potentially ease the second-use of xEV batteries.

(Ruiz et al., 2016) identified car manufacturers as key players in this process due to their access to technical information and their interest in the topic as they might be owner of the battery pack and obtain economic advantages from the batteries reuse.

Repurposing stage

Before being reused in second-use applications, xEV batteries should be tested in order to check their State of Health (SoH) and remaining capacity to identify the best fitting second-use application (Ahmadi et al., 2014b). Some important information arise from their operational history of the battery pack, e.g. operating temperature, average driving distances, and the habits of individual drivers (Nenadic et al., 2014; Reid and Julve, 2016).

From both an economic and technical point of view, the possibility of reusing the whole battery pack without dismantling it is the preferable option (Ahmadi et al., 2014b; Mudgal et al., 2014). If not possible, the battery pack can be dismantled and the modules/cells could be tested and reuse in a new battery pack with new materials/components, e.g. BMS (Ahmadi et al., 2014b; Canals Casals and Amante García, 2016). For instance, (Cready et al., 2003) describes the testing of used xEV batteries considering the testing of modules, whereas (Nenadic et al., 2014) highlights that for big battery packs, failure in the battery system would entail the discarding of the whole pack; therefore, methods to assess the SOH (State Of Health) of cells are required to permit sustainable decisions.

If the perspective is the reuse of the xEV battery after its use in EV, a more flexible BMS could ease its use for a potential second-use; in this sense, "design for disassembly" becomes a relevant issue (Ahmadi et al., 2014b; Kampker et al., 2017; Sathre et al., 2015). This concept also emerged from (Ruiz et al., 2016), (Herrmann et al., 2012) and (Kampker et al., 2017) as the battery should be designed in order to maximize its value during its whole life cycle, including also potential second-uses. As an example, to reduce the repurposing costs of second-life LIBs and ease the adoption of repurposed xEV batteries, the establishment of a BMS in xEVs with the ability to store all data at individual battery cell level (especially temperature, voltage, depth of discharge (DoD), state of charge (SOC) and, if occurred, short circuits) is of outmost importance (Reid and Julve, 2016).

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[45] The reverse logistics is defined as "the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal" (American Reverse Logistics Executive Council)

Economic aspects

Several studies (Ahmadi et al., 2014b; Chmura, 2016; García and Miguel, 2012; ISO, 2007; MacDougall, 2015; Marques et al., 2013; Neubauer and Pesaran, 2011; Proff and Kilian, 2012; Roland Berger Strategy Consultants, 2012; Saez-de-Ibarra et al., 2015; Tamiang and Angka, 2014; Viswanathan and Kintner-Meyer, 2011; Wood, 2016) highlight the potential reuse of xEV batteries as an interesting option to decrease the cost of EVs since the battery represents the most relevant cost item, especially due to the cell production. In this context, profitability and liability are two relevant challenges (Ruiz et al., 2016), and the creation of a stronger partnership network between actors and stakeholders along the whole battery value chain can ease the viability of the second-use of EVs batteries from an economic point of view. Note that a networking is also emerging between different sectors, e.g. automotive and energy sectors and a multi-stakeholders perspective should be considered for the potential reuse of xEV batteries in different applications (Reinhardt et al., 2017).

The batteries' repurposing should be economically viable in order to ease the business case related to second-use of batteries. (Neubauer et al., 2015b) identified as relevant cost items both the cost of purchasing used batteries and the technician labour cost of the repurposing step.

Reused batteries could be adopted in different second-use application depending on their performances and also economic benefits related to their reuse. Specific parameters of the assessed system could affect the profitability of the repurposed battery in the system, e.g. electricity tariff, battery selling price, feed-in tariff (e.g. for photovoltaic installations), therefore models for assessing economic advantages/disadvantages of using repurposed batteries in second-use applications should be flexible (Kirmas and Madlener, 2017).

Narula et al. (Narula et al., 2011) conducted an economic analysis of PEV batteries, assuming a fixed (either 5- or 10-year) service life. They found marginal economic benefits for single-use second-use applications, although results improved with multiple simultaneous applications, e.g. area regulation, transmission and distribution upgrade deferral, and energy time shifting.

Neubauer & Pesaran (Neubauer and Pesaran, 2011) assessed the economic impact that second-life batteries use may have on initial PEV costs. They found the upfront cost reductions to be relatively minor, and strongly dependent on the battery degradation profile and specific second-life application.

Williams & Lipman (Williams and Lipman, 2011) examined the potential economic impacts of second-life battery use, finding modest but positive economic benefits of second-life battery use. Benefits depended largely on whether multiple services could be obtained from the batteries, and on costs associated with power conditioning equipment.

Neubauer et al. (Neubauer et al., 2012) estimated the selling price of repurposed PEV batteries, and found them to be cost-competitive with established lead-acid battery technology.

Ambrose et al. (Ambrose et al., 2014) considered the potential for retired PEV batteries to provide electricity storage for rural micro-grids in developing regions, concluding that second-life lithium-ion batteries may be price competitive with new lead-acid batteries and deliver improved performance.

Since the adoption of batteries in residential ESS entails the increase of the use of energy in the system, financial incentives promoting the renewable energy and a more aware behaviour of energy users (e.g. reducing the energy demand in typical peak periods) should be adopted to enhance the adoption of second-use xEV batteries in houses (Heymans et al., 2014).

(Schmidt et al., 2017) underlined the relevance of the lifetime of the xEV battery both in the xEV and in the second-use application. In general, profitable reuse of LIB is to be preferred to recycling of batteries, even if the second-use application and the initial cost of the battery are two parameters to be determined to validate this statement.

Fewer studies have considered the environmental or energetic implications of second-life battery use. Main outcomes of the literature are reported in section 4.1.

Table 3 gives an example of important factors influencing the potential reuse on xEV batteries in second-use applications.

Table 3: Indicative list of factors influencing the potential reuse on xEV batteries in second-use applications as identified in a few reports(non exhaustive).

Reference	Regulatory barriers	Technical barriers	Safety issues	Economic barriers	Responsibility issues
(Deloitte, 2015)	X				
(Kempener and Borden, 2015)	X	X (Performance issues)	X	X (Lack of monetary compensations schemes available for the benefits of battery storage system)	
(Elkind, 2014)	X (Complex and adverse regulatory structures that limit market opportunities and increase costs (difficulties in transporting batteries as classified as hazardous waste; existence of incentives that indirectly discourage the second-use of batteries; uncertainty about safety issues of second-use of batteries))	X (Lack of data about battery performance in both first and second life applications)		X (Uncertain economic return and market for many energy storage applications Potential future competition between repurposed batteries applications and new energy storage technologies Potentially expensive repurposing or redesigning of the battery pack for new applications High repurposing costs may limit opportunities for financing. Economic uncertainty about second-life battery value translating to reduced upfront costs for electric vehicle consumers)	X (Liability concerns about which entity is responsible for second-life batteries once they complete their first life in the vehicle)
(Neubauer et al., 2015b)	X (Utilities and regulators should develop policies that encourage the use of ESS)			X (No economic incentive to replace a PEV battery prior to the end of the original vehicle's service life (approximately 15 years) Technician labour is a major cost element of repurposing operations that must be minimized)	
(Richa et al., 2015)				X (Second-life batteries are currently ineligible for incentive programs or federal investment tax credits for grid storage, onsite, or residential energy storage systems in the USA)	
(Canals				X (The best possibility to	

Casals et al., 2015)				reach a positive economic balance is the direct reuse of the batteries without module manipulation)	
(Ahmadi et al., 2014b)		X (Difficulties and uncertainties in establishing specific parameters for the analysis (e.g. lifetime, capacity of batteries in the future, driving patterns, etc.) Customers attitudes affect some technical aspects of xEV batteries (driving attitude, perception of costs, batteries retirement, etc.))	X (Battery removal poses hazards associated with high voltage safety and handling of liquid coolant)		
(Reinhardt et al., 2017)	X (Unclear and undefined legislation)	X (High volumes of waste xEV batteries)		X (Profitability of recycling processes)	

Note: “X” means that the barriers / issues are found relevant in the study. More explanations, when relevant, are given between brackets.

CHAPTER 2

Summary of the previous analysis and implications on the SASLAB activities

Based on the general learning from the literature review and interviews with stakeholders (section 2.1), the major implications for the SASLAB project were identified (section 2.2). The formalization of the waste xEV batteries value chain and the second-use applications considered along the project are respectively described in sections 2.2.1 and 2.2.2.

2.1 General learning

The relevance of the topic of repurposing xEV batteries in stationary applications is clearly demonstrated by the literature review, by the existence of several R&D/industrial activities and the outcomes of the stakeholders' interviews, as reported in the previous sections. Meanwhile, the sustainability of reusing xEV batteries in second-use applications needs to be assessed from different perspectives and more efforts in this direction are needed. Moreover, second-use of xEV batteries could be also aligned with the ongoing revision of the Batteries Directive and the Innovation Deal on second-use of batteries[46].

Contacts with stakeholders revealed the interest in second-use of xEV batteries, even though the existence of some **barriers to be faced**. One of the most relevant barriers is represented by the absence of a clear definition of "second-use application" and of a legal framework supporting this option. Furthermore, available knowledge about the adoption of xEV batteries in second-use applications is still limited and more efforts are required to demonstrate their suitability in various applications and their sustainability from the economic, environmental and social perspectives.

The expected worldwide increase of the xEV will necessarily imply the adaptation of the different steps of the **xEV batteries value chain**, e.g. collection schemes, testing infrastructures and waste batteries treatment (e.g. size and technologies of recycling plants). The collection after the xEV batteries removal from EV, their sorting and testing are important steps related to the potential second-use of xEV batteries, e.g. amount of big size batteries and safety issues related to their proper handling, missing waste batteries flows, etc.

Based on literature and according to some stakeholders, the most promising applications are residential household applications, especially in combination with solar energy. However, available literature and existing projects focus of **various second-use applications**.

2.2 Implications in the SASLAB projects

In the SASLAB project, **different perspectives** (technical, environmental, economic and social) were considered to assess the sustainability of the adoption of xEVs batteries in second-use applications.

In order to obtain an overview of the **xEV batteries flows in Europe**, the value chain of xEV batteries was better formalized. Moreover, based on the performed literature review and to the information gathered by stakeholders, a predictive and parametrized model was developed to estimate the size of the flows along the xEV batteries value chain in Europe In the next future (section 2.2.1).

Due to complexity of the system and the limited knowledge, four **specific different scenarios** described in section 2.2.2 were identified in the SASLAB project. Thanks to

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[46] https://ec.europa.eu/research/innovation-deals/index.cfm?pg=emobility

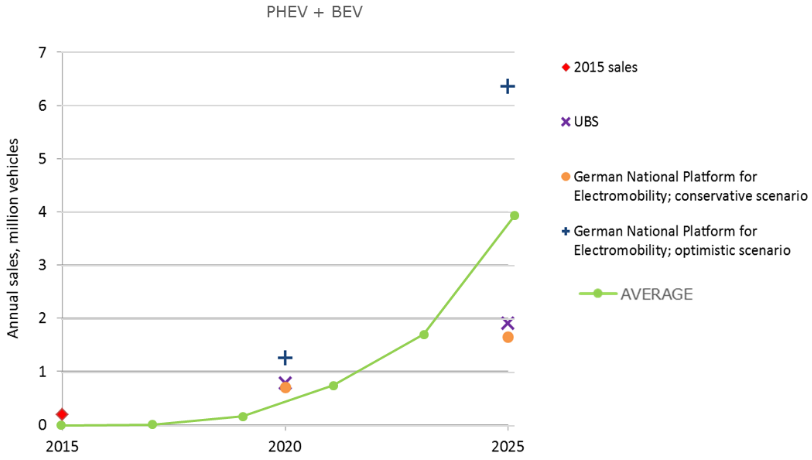
the contacted stakeholders and the created network, fresh xEV batteries and xEV batteries no more usable in xEVs were provided and tested in the JRC-Petten laboratories. Some tests on batteries were performed in 2016 and 2017, and some are still ongoing. This allowed to adopt the available **primary data and tests results** as input data/information for the subsequent environmental assessment.

2.2.1 Formalization of the xEV batteries value chain in Europe

According to literature and information gathered through the stakeholders' interviews, data about xEV were collected with the purpose of creating a model to estimate the amount of spent batteries available from xEVs in Europe.

The recent report published by the European Commission (EC, 2016) asserted that the European market share of new PHEVs and BEVs will reach 0.7-0.8 million in 2020 and 1.65-1.9 million in 2025, which means about 25-50% of the global sales. Accordingly, the Paris Declaration on electro-mobility and climate change (2015) affirmed that xEV should represent the 35% of the global cars sales in 2030, which means that about 20% of the vehicles on the road will be electrically driven (UNFCCC, 2015). Different sources forecasting the xEV sales were considered and the results of the analysis are depicted in Figure 5.

Figure 5: Projected European sales of new PHEV and BEV vehicles for 2015-2025 (adapted from (EC, 2016))



Within the worldwide rechargeable battery market, the Li-ion batteries in the last 15 years increased faster than the NiCd and MiMH batteries and its penetration rate within the HEV it is forecasted to increase from 15 % to 90 % between 2010 and 2025 (Pillot, 2014, 2013). Several sources confirmed that Li-ion batteries as the most promising technology for the electric traction and that the majority of the EVBs are Li-ion Batteries (Chmura, 2016; Gasparin, 2015; Hays, 2008; Kahl, 2013; Lebedeva et al., 2016; Navigant Research, 2016; Richa et al., 2014; RSEview, 2011; Vallis et al., 2012). The competitiveness growth of Li-ion batteries compared to nickel-based and advanced lead-acid batteries is expected in battery cost reduction, energy and power density increase, longer lifetime and increased charge acceptance (EUROBAT, 2014).

The amount of deployed battery in a specific year was calculated based on the xEV lifetime and the xEV battery lifetime. EUROSTAT data show that 43.90 % of passenger cars in 2013 had a lifetime higher than 10 years, whereas the 27.37 % of European cars has a lifetime lower than 5 years (EUROSTAT, 2015)[47]. The xEV battery lifetime ranges

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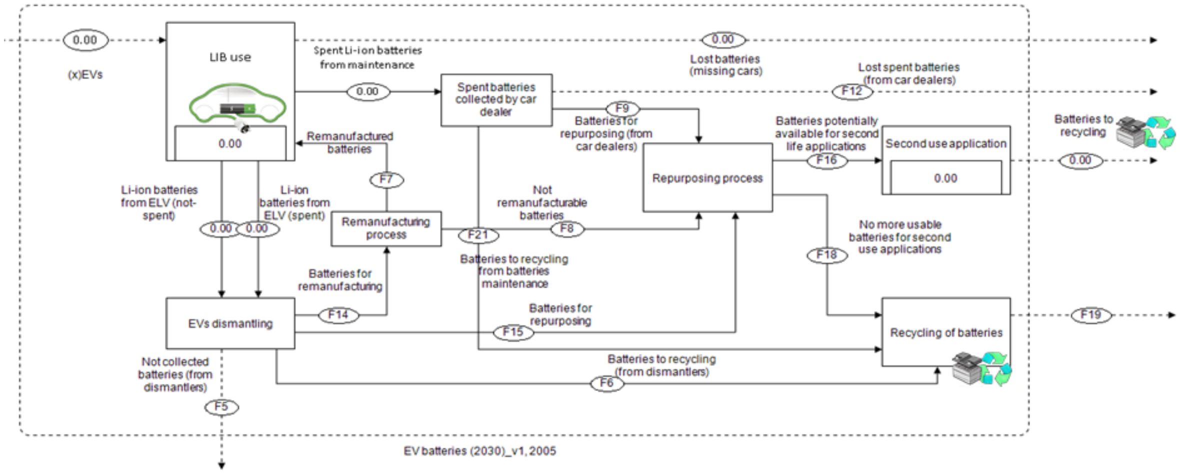
[47] http://ec.europa.eu/eurostat/statistics-explained/index.php/Passenger_cars_in_the_EU

between 5 and 15 years depending of several factors, e.g. driving style, frequency of charging (Ahmadi et al., 2014a; Canals Casals et al., 2015; Daimler, 2015; Neubauer et al., 2015b; Richa et al., 2015, 2014; Sathre et al., 2015). This is consistent to the Nissan warranties for the Leaf's battery[48] (8 years/100,000 miles) as it is supposed that the battery can live at least 10 years.

After their removal from the xEV, batteries are collected and addressed to recycling. As declared by (EC, 2014), the collection rate of both automotive and industrial batteries in Europe is nearly 100% and a high availability of xEV batteries after their use in xEV is expected also in the future. There are already examples of very high collection rate (e.g. 91 % for Toyota and Lexus)[49], also confirmed by (Mudgal et al., 2014). For instance, concerning the automotive lead-based batteries, their collection and recycling rate is 99 % in Europe (IHS Consulting, 2014; Mudgal et al., 2014). Note that in Europe, about 30 % of the vehicle waste flow is "missing" (Oko Institute, 2016) (ProSUM Meeting, 2016).

Based on the above illustrated considerations and thanks to the information collected from stakeholders (section 1.1), Figure 6 depicts the model of the value chain of xEV batteries and the batteries flows in Europe[50].

Figure 6: Value chain model of xEV batteries in Europe according to the stakeholders information and the performed literature review



The model is parametrized in order to allow the assessment of different scenarios along time according to the input data and assumption (e.g. amount of batteries used in second-use applications, missing cars, amount of batteries remanufacture and/or directly reused in xEVs, etc.). Then, the xEV batteries flows in the system (e.g. waste batteries, recycled batteries, available batteries for repurposing, etc.) can be quantified. As soon as detailed data would be available, the model could be run in order to increase the robustness and the reliability of results based on secondary data and assumptions. Parameters can vary in order to identify their relevance for the overall system.

Similar estimations could be carried-out also in terms of materials embedded in batteries. The extension of the batteries lifetime through their second-use results in a decrease of secondary raw materials (SRM) available in the market, e.g. recovered cobalt/nickel/…. Meanwhile, extending the lifetime also translates into an increase of materials productivity and decreasing of demand of batteries e.g. for storage systems.

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[48] http://www.hybridcars.com/how-long-will-an-evs-battery-last/

[49] http://www.autoblog.com/2015/02/10/toyota-mirai-most-innovative-honor/

[50] The software use for modelling the waste flow is STAN 2.5

For such analysis, the Urban Mine Platform[51], developed by the ProSUM H2020 project[52], represents a relevant source of data for batteries flows and materials content (e.g. batteries placed on the market, stocks and waste flows, amount of Co in batteries).

If the (residual) capacity of xEV batteries is known, the available capacity in waste batteries could be estimate according to the batteries' types[53]. Then, the energy savings related to the second-use of batteries could also be estimated.

2.2.2 Second-use applications assessed in the SASLAB project

2.2.2.1 Peak shaving and self-consumption of renewable energy

It is an energy storage service used to shift electricity demand from on-peak to off-peak periods. It requires a duration of discharge of the ESS during the on-peak period on the order of 2 to 12 hours and is intended to recharge in the off-peak period to be available again the following day (Schoenwald and Ellison, 2016a). Within this time frame (day), the peak shaving service can be used for shifting electricity demand to relieve peak demand charges, thus ensuring a saving for the customers. Also the peak shaving service can be used to increase the self-consumption of renewable energy. In this case the PV energy that is exceeding the permitted feed-in limit is stored in the battery avoiding the loss of such energy (Litjens et al., 2016; Weniger et al., 2014).

2.2.2.2 Renewables (photovoltaics (PV)) firming application

The purpose of renewables firming is to provide energy (or conversely, to absorb energy) when renewable generation falls below some threshold (or conversely, exceeds this threshold). This service is performed to provide a renewable steady power output over a time window between the 15-minute to several-hour time (Schoenwald and Ellison, 2016a).

2.2.2.3 PV smoothing

PV smoothing is a power service performed by an energy storage system (ESS) to mitigate rapid fluctuations in photovoltaic (PV) power output that occur during periods with transient cloud shadows on the PV array. The ESS is adding power to or subtracting power from the output of a PV system in order to smooth out the high frequency components of the PV power. The purpose of PV smoothing is to mitigate frequency variation and stability issues that can arise at both the feeder and transmission level in high penetration PV scenarios to help meet ramp rate requirements (Schoenwald and Ellison, 2016b).

2.2.2.4 Primary frequency regulation

Frequency regulation is primarily a power service. Grid must maintain balance between load and generation especially with the increasing penetration of small-scale intermittent distributed energy resources such as solar/wind that poses frequency regulation problems due to the reduced system inertia. Regulation of electric power frequency is provided by increasing or decreasing the amount of energy injected into the grid or the amount of load on the grid in a time frame that range between fraction of seconds to few minutes.

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[51] http://www.urbanmineplatform.eu/homepage

[52] http://www.prosumproject.eu/

[53] Batteries sed in BEVs have a higher energy density than batteries use in PHEV

2.2.3 Final remarks and main constraints

According to the literature review and the information collected from stakeholders, the value chain of xEV batteries was formalized and the second-use application to be tested in the SASLAB project were identified.

Technical aspects related to the use of repurposed xEV batteries in second-use applications were derived from fresh/used LIB. Due to the time consuming required for tests, some tests are still ongoing.

The method for assessing the environmental assessment of second-use application of xEV batteries was initially based on the available literature data. Available data from test were used to perform the environmental assessment of the peak shaving and the increase of PV self-consumption applications. In these cases, primary data about both the energy flows and the battery characteristics were adopted.
Concerning the PV firming and the PV smoothing, sizing of the system are already available, and the environmental assessment could be carried-out once the tests results will be available. Hence, this report does not contain any results on the environmental assessment of the two latter applications as well as for frequency regulation applications, for which the sizing of the system is also required.

Once data will be available, the method for assessing the environmental performances of xEV batteries in second-use applications could be applied to other applications not yet included in this report.

Despite the contacts, it was not possible to set-up a strong partnership with industrial stakeholders dealing with xEV batteries' repurposing and this resulted in the absence of a detail modelling of the repurposing stage, as initially planned. Moreover, no economic analysis is provided in the report due to the absence of real data and the reduction of human resources allocated to the project.

CHAPTER 3
Experimental assessment of xEV Li-ion batteries aging and second-use

The environmental assessment model must be fed with parameters expressing the expected performance of a battery dismissed from an xEV. Such parameters can be extracted from experimental tests assessing battery performance. For this purpose, an experimental campaign was designed for investigation of performance of fresh and aged cells and its degradation with time and cycling under different conditions and duty cycles for first xEV life and second use utility grid applications.

3.1 Investigated battery samples

All examined LIB cells contain a graphite anode. But cells with different types of cathodes were investigated. The cells were received in our facilities at different stages in their cycle life:

- composite (blended) cathode, based on lithium manganese oxide $LiMn_2O_4$ and lithium nickel manganese cobalt oxide $LiNiMnCoO_2$, (LMO-NMC)
    - Fresh (declared nominal capacity: 38 Ah) and aged (average measured capacity: 30.9 Ah)
    - Nominal Voltage: 3.75 Volts
- lithium iron phosphate $LiFePO_4$ cathode (LFP)
    - Aged
- lithium nickel manganese $LiNiMnCoO_2$ cathode (NMC)
    - Aged

The aged (LMO-NMC/graphite) cells were disassembled from a battery pack of a used series-production xEV after it had driven 136,877 km and at this point in time, the capacity recorded by the battery management system (BMS) was 30.91 Ah. From the same provider, also the same fresh cells were acquired (LMO-NMC/graphite) with a rated capacity of 38 Ah. The aged LMO-NMC/graphite cells were initially screened based on the voltage/temperature recorded by the cell monitoring unit of the xEV just before disassembly took place. Three different locations were identified in the battery pack according to the registered temperature in the vehicle last ride. Cells located in location 1 (L1) were at 25 °C, in L2 at 24 °C and in L3 at 23 °C, respectively.

The other cells (LFP/graphite and NMC/graphite) were already aged when received in our laboratory.

3.2 Degradation/ageing process

A systematic behaviour for the degradation mechanism of Lithium ion cell is reported in literature, although it is not always observed. A simplified pattern was proposed by Spotnitz (Spotnitz, 2003), see Figure 7.

When the cell reaches the knee point (point D in Figure 7), this marks the beginning of a non linear, accelerated degradation pattern. From that point on, the cell has to be considered technically not viable for further use, marking its End of Life.

Although this pattern shows only the degradation related to capacity fade, a similar, simplified visualisation can be used to map the first use mileage and the number of years of second use together (see Figure 8).

Usually, the capacity of electrical vehicle battery cells in their first life decays linearly. Then, the severity and demands in terms of power and energy of the second use application will determine when (e.g. second use duration in years) the knee point will be reached.

Figure 7: Schematic of Li-ion capacity fade with cycle numbers (Spotnitz, 2003)

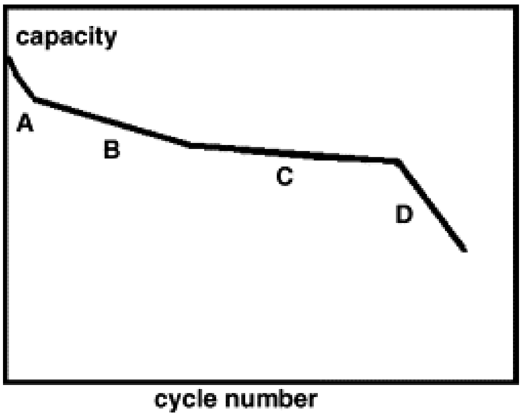
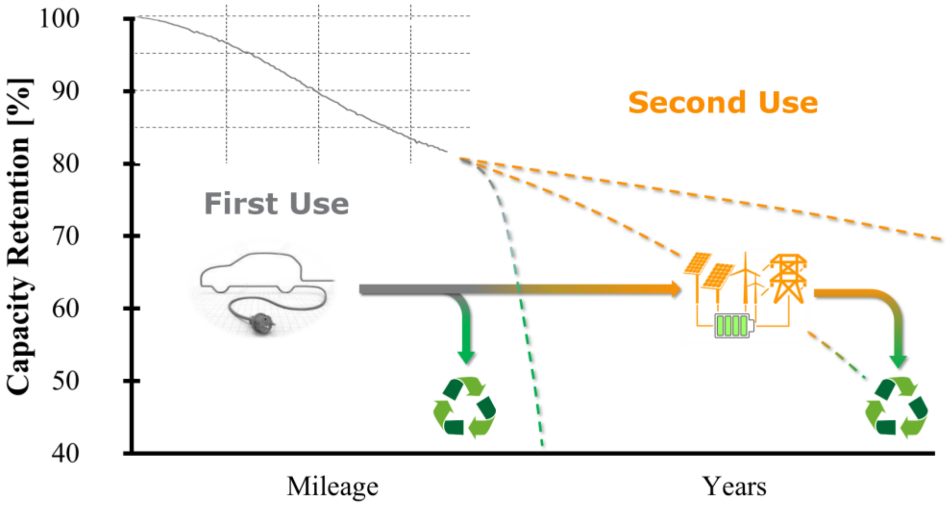


Figure 8: Capacity retention with First Use mileage and Second Use duration



The experimental campaign is designed to determine performance degradation during second use and potentially identify the knee point and to retrieve relevant data to be used as input for the environmental assessment of the second use option.

3.3 Experimental procedure

3.3.1 Planned test matrix

The aged and fresh (LMO-NMC/graphite) cells have to be assessed towards a better understanding of their extended lifetime, beyond the 70% to 80% capacity automotive EoL criterion. Both, calendar ageing and cycling ageing considering the possible second-use applications and standard cycling ageing should be assessed. Also automotive use of fresh and aged (LMO-NMC/graphite) cells should assessed to outline the possible reuse or continued use of the battery pack in the automotive sector. Finally, the degradation of the pre-aged LIB cells (LFP) and (NMC) should be also examined under duty cycles that simulate those of second-use grid-scale applications.

3.3.2 Actual Situation

However, the reduced availability of human resources in Unit C1 led to several limitations and delays in the planned experimental activities. As results several tests had to be postponed and 'possibly to be cancelled. Table 4 reflects the status at the time when this final report has been published (July 2018). The colour code will help to understand how severely the planned activities were affected.

Table 4: Test matrix reflecting the situation at July 2018

Type of test	Scope of the test	Chemistry and number of samples	Conditions	Expected duration	Situation (July 2018)
Calendar Ageing	Assess the degradation of cells without charging or discharging	6 aged and 6 fresh LMO-NMC/graphite cells	Temperature: 25° and 45° C SOC: 100 % and 50 %	As long as possible	Completed as planned. Still running for long term assessment. Results employed in LCA analysis
Cycle ageing (Charge/Discharge at CC-CV/CC)	Assess the degradation of cells with 100% DoD at C/5 and 1C rate	2 aged and 2 fresh LMO-NMC/graphite cells	Temperature: 25° and 45° C	6 months	The C/5 series is not completed as planned. 3 months performed. The 1C series not running
Automotive use cycle ageing *(WLTC driving **duty cycle**)*	Assess the degradation of cells for automotive applications	2 aged and 2 fresh LMO-NMC/graphite cells	Temperature: 25° C	3 months	Not running. Possibly to be cancelled
Second use cycle ageing *(**Duty cycles**: PV firming; PV smoothing; primary frequency regulation; peak shaving)*	Assess the degradation of cells for second use applications	28 aged LMO-NMC/graphite cells	Temperature: 25° C , 45° C and 5° C	6-9 months	• Almost 2 months performed and still running (Since November 2017) for 25° C and 45° C (23 samples) • Not running the 5° C (5 samples) Preliminary results partially adopted in the LCA analysis
Second use cycle ageing *(**Duty cycles**: PV Power smoothing)*	Assess the degradation of cells for second use applications	2 aged LFP/graphite and 2 aged NMC/graphite cells 2+2 aged (EV+Lab) LMO-NMC/graphite cells	Temperature: 25° C	6 months	Not running. Possibly to be cancelled

3.3.3 Calendar ageing

LMO-NMC aged and fresh Mitsubishi cells were kept under different conditions to assess the calendar ageing process: at a temperature of 25 °C or 45 °C and at 100% or 50 % SOC following IEC 62660-1:2010, 2011.

3.3.4 Duty cycles

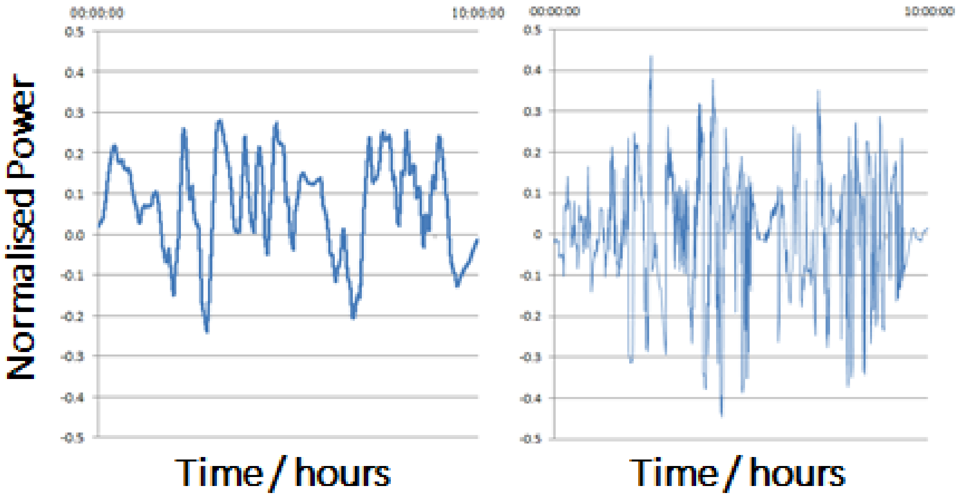
For designing the experimental procedures to assess the ageing process associated to cycling several standards were consulted, such as the IEC62660-1 (IEC 62660-1:2010, 2011), ISO 12405 (ISO 12405, 2010) and (IEC61427-1, 2013) and (IEC61427-2, 2015), and protocols, such as the one for uniformly measuring and expressing the performance of ESSs, prepared by Pacific Northwest National Laboratory (PNNL) and Sandia National Laboratories (SNL) (Conover et al., 2016), and another developed in the EU-funded research project Helios (Mettlach et al., 2012).

For the first, automotive life the chosen duty cycle is the World-wide harmonised Light-duty vehicles Test Cycle (WLTC) (Tutuianu et al., 2013).

For the second use case the following grid-scale applications were selected: PV firming (PVf), PV smoothing (PVs), primary frequency regulation (PFR) and peak shaving (PS). For each of these applications a duty cycle was selected to simulate the charge/discharge power profiles and so to generalize the demands placed on an ESS by the specific application.

See paragraph 2.2.2 for general description of the applications and hereafter for a short description of the correspondent duty cycles.

Figure 9: Duty cycles as power normalised by ESS rated power over a 10-hours period of time: PVf (left); PVs (right)



Source: Adapted from (Bray et al., 2012; Schoenwald and Ellison, 2016a, 2016b)

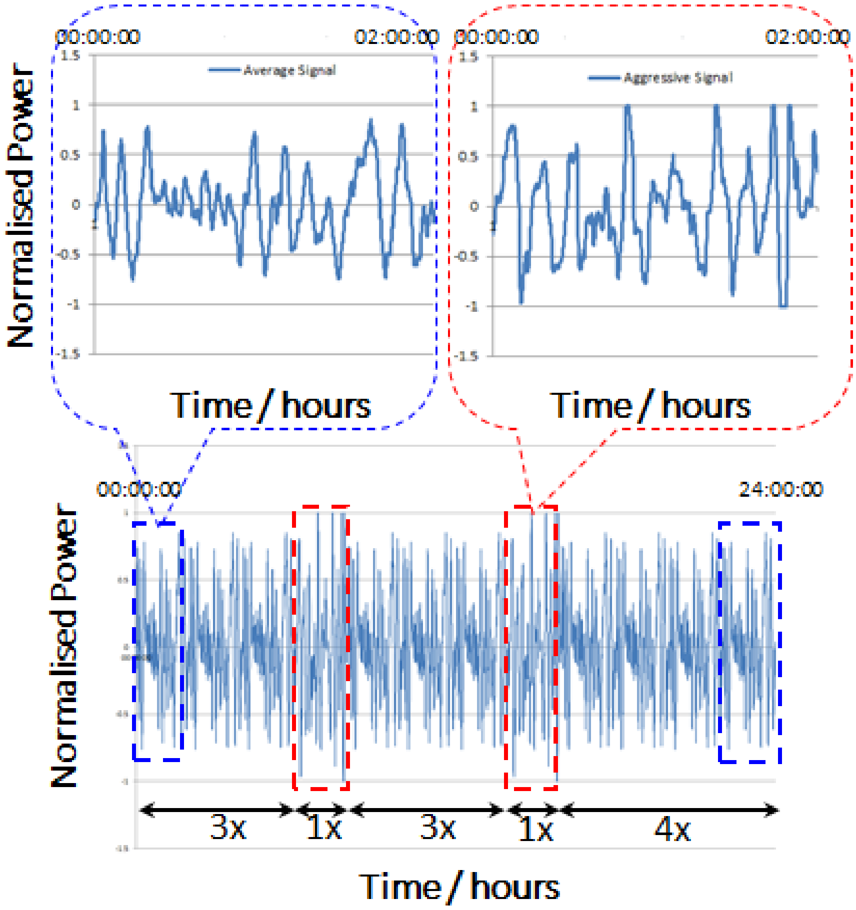
Duty cycles for PVf (an energy smoothing application), and PVs (a power smoothing application), as adapted from (Bray et al., 2012; Schoenwald and Ellison, 2016a, 2016b) are depicted in Figure 9. The duty cycle is obtained by normalising the PV power time-series to the rated power of the smoothing battery (here battery cell) over a 10-hour time period. The construction process of the PVf duty cycle (cf. Figure 9-left) is similar to PVs except that the time windows of interest are in a minutes to hours range, rather than seconds to minutes.

The PFR duty cycle, as described in detail in (Conover et al., 2016), consists of three 2-hour average standard deviation (SD) power signals, followed by one 2-hour high SD (aggressive) signal, three 2-hour average SD signals, one 2-hour aggressive signal, and four 2-hour average SD signals (Figure 10), with the SD over a 24-hour period being the chosen metric for the aggressiveness of the signal analysed (Conover et al., 2016): the representative 2-hour average and 2-hour high SD signals were chosen to compose the duty cycle in such a way that they were energy neutral and had the same SD as the average and aggressive signals over a one-year time frame).

In the PS duty cycles, charge, rest, and discharge time windows (Figure 11: -1, 0, and 1 correspond to charge, rest, and discharge, respectively) are defined. This allows the duty cycle profile to be applied in the same manner to different battery technologies regardless of system size, type, age and condition (Conover et al., 2016).

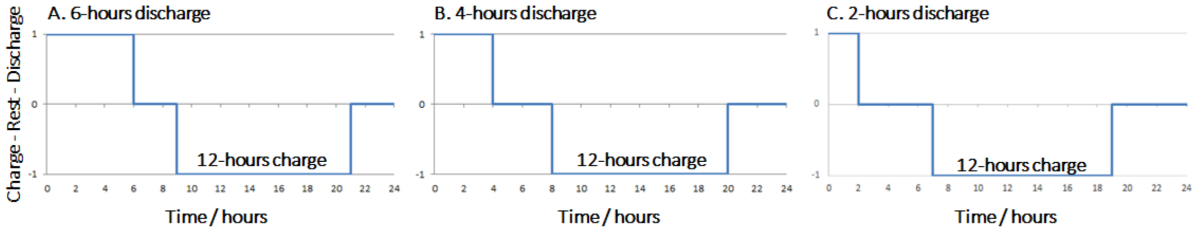
Due to the different characteristics of those duty cycles, for sake of comparison performance and degradation parameters retrieved from those tests will be compared on a basis of test duration in hours, rather than number of cycles.

Figure 10: PFR duty cycle as power normalised by ESS rated power. Representative average SD signal (top-left), and representative aggressive SD signal (top-right) over a 2-hour period of time (X-axis). PFR duty cycle, composed of 3 average, 1 aggressive, 3 average, 1 aggressive and 4 average signals over a 24-hours period of time (bottom)



Source: Adapted from (Conover et al., 2016)

Figure 11: Example of PS duty cycle over a 24 hours period of time (X-axis) for each one of the duty cycles (A, B, C). Charge duration is 12 hours. Discharge duration is 6, 4, and 2 hours, and rest period is 6, 8, and 10 hours for duty cycle A, B, and C respectively



Source: Adapted from (Bray et al., 2012)

3.3.5 Degradation assessment

During ageing testing (calendar ageing and cycle ageing), a set of tests is performed at periodic intervals to establish the condition and rate the performance and degradation of cells under test. The periodicity is of every 42 days during calendar ageing testing, and every 210 hr during cycle ageing testing.
Those baseline cell performance tests are used to assess any changes in the condition of the cell and rate performance degradation over time and as a function of use. The reference performance test includes quasi-open circuit voltage (quasi-OCV) vs. state-of-charge (SoC) relationship determination, capacity determination and EIS (at different SoC: 50% and 100%) determination at 25 °C according to (IEC 62660-1:2010, 2011). To ensure thermal equilibrium, prior the beginning of the reference performance test, the cells were maintained at 25 °C in the temperature chambers for at least 12 h or up to when the temperature change is lower then 1°C/1 hr.

The degradation of the cells is assessed in terms of capacity retention through the ICA (Incremental Capacity Analysis) technique utilising post-processed charging / discharging data over lifetime ageing testing, and in terms of impedance growth as tracked via EIS. The internal impedance of a cell is closely associated with its state of health (Abarbanel et al., 2015). The EIS measurement can be represented on Nyquist and Bode plots allowing a qualitative and quantitative analysis of ageing processes correlating the impedance growth with the changes of SEI (Solid-Electrolyte Interface) and electrode surface behaviour of lithium ion batteries (Schuster et al., 2015; Wang and Rick, 2014).

For each duty cycle (second-use cycle) the RTE (Round Trip Efficiency) is calculated. It is expected that the degradation process will reduce the RTE (Crawford et al., 2018). The RTE is determined as the total energy output (at discharge) divided by the total energy input (at charge). The RTE is a relevant input for the environmental assessment of the second use option.

3.3.6 Employed equipment

Maccor Series 4000 bidirectional battery testers - cyclers (Maccor, Tulsa, USA) have been used for the ageing studies (current and voltage accuracy: 0.025 % and 0.02 % of full scale, respectively). These cyclers also control the (12) BiA MTH 4.46 temperature chambers (BiA, Conflanse Saint Honorine, France) with a temperature accuracy in the centre of working space of ± 0.5 K and a homogeneity in space relative to the set value of ± 1.5 K (the specified max. temperature rate is 2.0 K/min for both heating and cooling), and the (2) Vötsch VCS3 7060-5 climate chambers (Vötsch Industrietechnik GmbH, Balingen-Frommern, Germany) with a temperature accuracy in the centre of working space of ± 0.5 K or below and homogeneity in space relative to the set value of ± 2.0 K or better (the specified max. temperature rate is 6.0 K/min for both heating and cooling). All temperature (BiA MTH 4.46) and climate chambers (Vötsch VCS3 7060-5) maintain the ambient temperature at a similar specific and constant value (cf. tables 3a, b). A thermocouple, positioned (and secured) on the cell surface as described in (Pfrang et al., 2016), was placed in the centre of one side of each cell to monitor surface temperature variations.

The impedance spectra are measured in galvanostatic mode over a frequency range of 10 kHz to 10 mHz using a Maccor FRA 0355 (Maccor, Tulsa, USA) or 30 (or 50) kHz to 1 mHz using the ModuLab XM (Solartron Analytical, AMETEK Advanced Measurement Technology, Farnborough, Hampshire, United Kingdom) at the respective temperature and SoC, with the FRA equipment being connected to the Maccor cyclers; when FRAs were not connected to the Maccor cyclers (which was the case for the measurements after 135 days), experiments were paused and cells were disconnected from the cyclers for EIS to take place.

The World-wide harmonised Light-duty vehicles Test Cycle (WLTC) (Pfrang et al., 2016) is performed with a four-channel, BDBT Bidirectional type Battery Test bench (Digatron

Power Electronics GmbH, Aachen, Germany), which has a current range of 0 to 200 A (for one channel) and a voltage range of 0 to 100 V. Both the voltage accuracy and the current accuracy are ±0.1 % of full scale.

3.4 Results and experimental outputs used as modelling parameters in the environmental assessment

In this section results and experimental outputs are discussed and analysed. Results that are relevant inputs to the environmental assessment model are especially highlighted.[54]

3.4.1 Calendar ageing

Table 5 summarises exemplarily discharge capacity, discharge energy and ohmic resistance determined during calendar ageing of an aged LMO-NMC/graphite cell at 45 ° C and at 100% SoC. Results are compared with nominal performance of a new cell.

The charge / discharge capacity at 25 °C directly after the start of the calendar ageing test was 28.76 Ah and 28.78 Ah, respectively. After 135 days, the remaining capacity at discharge (at 25 °C) was reduced to 24.14 Ah (63.5 % of the initial rated capacity of 38 Ah provided by the manufacturer and 83.4% of capacity of 28.95 Ah measured in the reference cycle at the start of the calendar ageing test). The energy content of the cell on discharge was 92.3 Wh after 135 days (and 64.8 % of the initial rated cell energy content of 142.5 Wh specified by the manufacturer and 81.9 % of the reference energy content of 112.77 Wh measured in the reference cycle at the start of the calendar ageing test, respectively). Table 5 shows the ohmic resistance, which was determined as the intercept of the Nyquist plots with the real axis. This ohmic resistance is composed of ohmic resistances of active materials, current collectors and electrolyte resistance, also within the separator and increased with ageing time.

Table 5: Retained discharge capacity, discharge energy and ohmic resistance of an aged LMO-NMC/graphite cell over calendar ageing at a temperature 45 °C and at 100% SoC (the measurements of the shown data is performed at 25 °C). Nominal values of a new cell are shown for comparison

.Cell status	New cell (nominal values)	2 days	46 days	90 days	135 days
		after start of calendar ageing			
Discharge capacity / %	100	75.7	71.2	67.5	63.5
Discharge energy / Wh	142.5	109.7	103.3	98.0	92.3
Ohmic resistance from EIS / mΩ	n.a.	1.10	1.19	1.27	n.a.

Charge-discharge curves (cell voltage vs. capacity (Ah) on charge and discharge), as recorded every 42 days during the intermediate characterisation cycles (of 55 hours duration), over a total of 135 days of calendar life ageing for a pre-aged LMO-NMC/graphite cell at 45 ˚C and 100% SoC are depicted in Figure 12.

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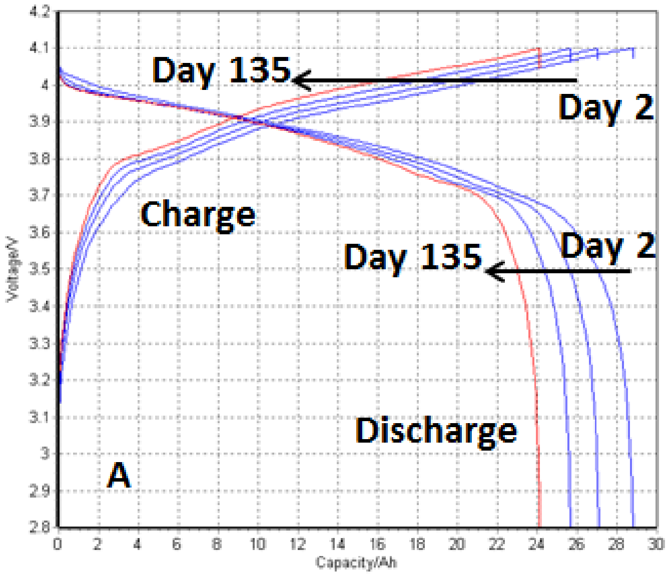
[54] Only a selection of calendar ageing results is shown here and it is the intention to make all results available in a peer-reviewed publication.

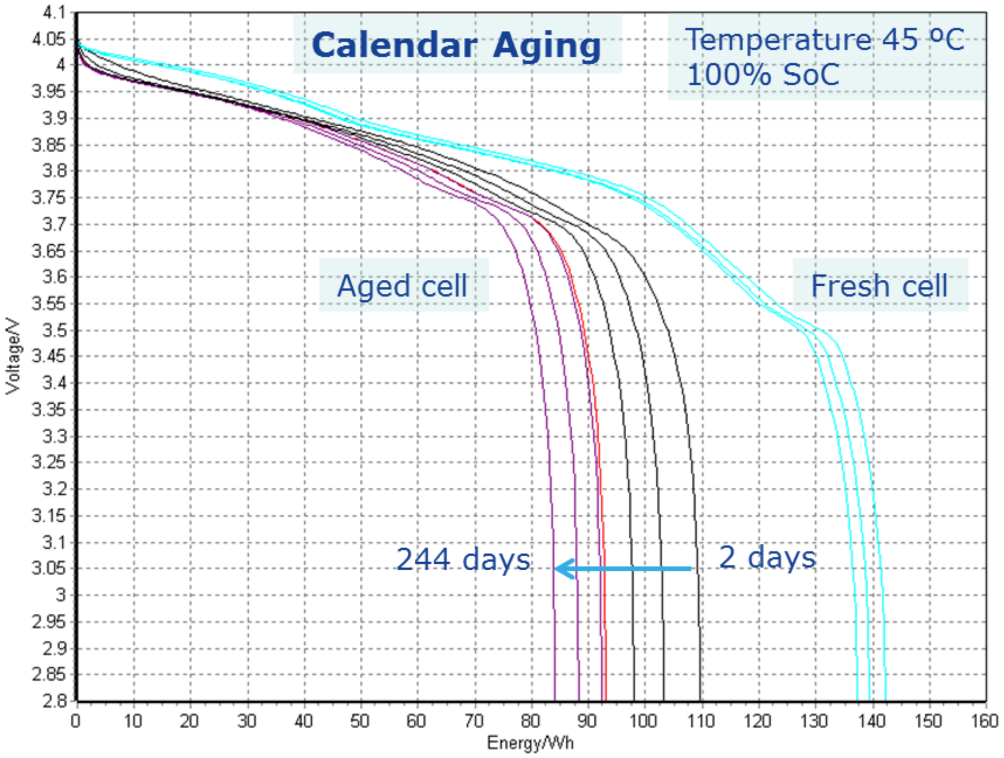
Figure 12: Charge-discharge profiles from reference cycles as a function of calendar ageing (temperature 45 °C, 100% SoC) of a pre-aged LMO-NMC/graphite cell: (A) voltage vs. capacity



In general, for a Li-ion cell, one expects the charge behaviour to be similar to the discharge behaviour - this is also the case here, where for the applied current rate, the cell is able to recharge to completion for every characterisation cycle during the calendar life testing so far.

After 244 days the same behaviour is observed with a consistent further reduction of discharged capacity, in figure iv expressed in terms of energy (Wh).

Figure 13: Discharge (voltage vs. energy) profiles from reference cycles as a function of calendar ageing (temperature 45 °C, 100% SoC) of a pre-aged LMO-NMC/graphite cell and fresh cell



The average energy capacity degradation for the cells calendar aged at temperature of 45°C and 100% SOC is of - 0.11 Wh/day.

3.4.2 Cycling ageing

Although the cycling ageing tests based on standard Charge/Discharge at CC-CV/CC have been running since three months, they will become more valuable when their results can be compared to the second-use cycle ageing tests results.
Tests are running on the second use applications following the PV firming, PV smoothing, primary frequency regulation and peak shaving protocols (but only started recently). Only a limited preliminary set of data is available (e.g. allowing evaluation of Round Trip Efficiency at the beginning of the second life: around 98%), but it is expected that the analysis of the degradation assessment tests will be soon capable to provide a complete set of inputs necessary for the environmental impact analysis. For each of the second use applications a list of experimental output will be retrieved to fed the LCA model and to answer the following questions.

- What is the final capacity at the end of the cell second life? Is 60 % (coming from literature) a realistic value?
- After how many cycles (e.g. days, hours) is the final capacity reached ?
- How does the capacity decrease during testing and what is the relation with the evolution of impedance?
- How much do temperature and DoD (Depth of Discharge) affect the ageing process of the cell?
- What is the Round Trip Efficiency (RTE) of the cells under study and how does it evolve with ageing?
- What will be the best way to compare different applications degradation? In terms of FEC (Full Equivalent Cycle) or expected lifetime?

The second-use cycle ageing tests are planned to be continued beyond the end of the SASLAB project, especially considering the relevance of the results and methodology to be applied in the new CarE-Service H2020 project[55] due to start in June 2018.

3.4.3 Cell opening and Material breakdown

One LMO-NMC cells was disassembled in a glove box under inert argon atmosphere and a material breakdown analysis was performed. During all the disassembling steps weights of detached elements and of the leftover material were recorded in order to keep track of evaporated electrolyte and any materials lost during the dismantling operation.

Free electrolyte was firstly poured out and weighted and then current collectors and metal case were removed. Inside the hard metal case, there are two packages connected in parallel. Each of the two packages is made of three layers (cathode, anode and separator) rolled in a prismatic shape (jelly roll), wrapped with a soft plastic cover. The package was then opened and unrolled to separate the three layers.

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[55] Call topic: Systemic, eco-innovative approaches for the circular economy: large-scale demonstration projects (http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/circ-01-2016-2017.html)

Figure 14: Left - Components of a fresh LMO-NMC/graphite cell after opening and removal of the cell casing in a glove box. Right - Unfolding of one of the two prismatic jelly rolls.

The dismantling process and the subsequent analysis was performed reaching a material break-down to the following level: steel (external case, connectors, tabs), aluminium and copper (current collectors, and electrode foils), polymer (wrapping, separator, and tapes), cathode and anode active material, binder (for the anode and the cathode), carbon black (in the cathode) and finally electrolyte. Based on the measured weights and on the available information from the manufacturer and averaged value from literature (ANL; Li, Daniel, & Wood, 2011; Liu et al., 2014), the average weight of all those elements is estimated (% in weight) including an error estimation (+/- g) (Table 6).

Table 6: Material breakdown of a fresh LMO-NMC/graphite cell as determined by cell opening and further analysis

Cell #394 (total weight before opening: 1396.2 g)	% in weight	**Fraction/ g**	Accuracy / g
Steel: external case, connectors	21.47%	299.8	+/- 2
Al: current collectors, electrode foils	3.74%	52.2	+/- 2
Cu: current collectors, electrode foils	10.03%	140.0	+/- 6
Polymer: wrapping, tapes, separator	5.99%	83.6	+/- 2
Anode active material: graphite	10.17%	142.0	+/- 12
Binder	2.68%	37.4	+/- 6
Cathode active material: LMO-NMC	27.47%	383.5	+/- 20
Carbon black in the cathode	3.38%	47.2	+/- 32
Electrolyte	13.75%	192.0	+/- 20
Uncounted materials lost in cutting/drilling/handling (steel, polymer, Cu, Al, active materials)	1.32%	18.4	+/- 5

This material bill will support the formulation of an inventory data set for a Li-ion battery cell that can be employed in the life cycle inventory analysis and subsequent LCA.

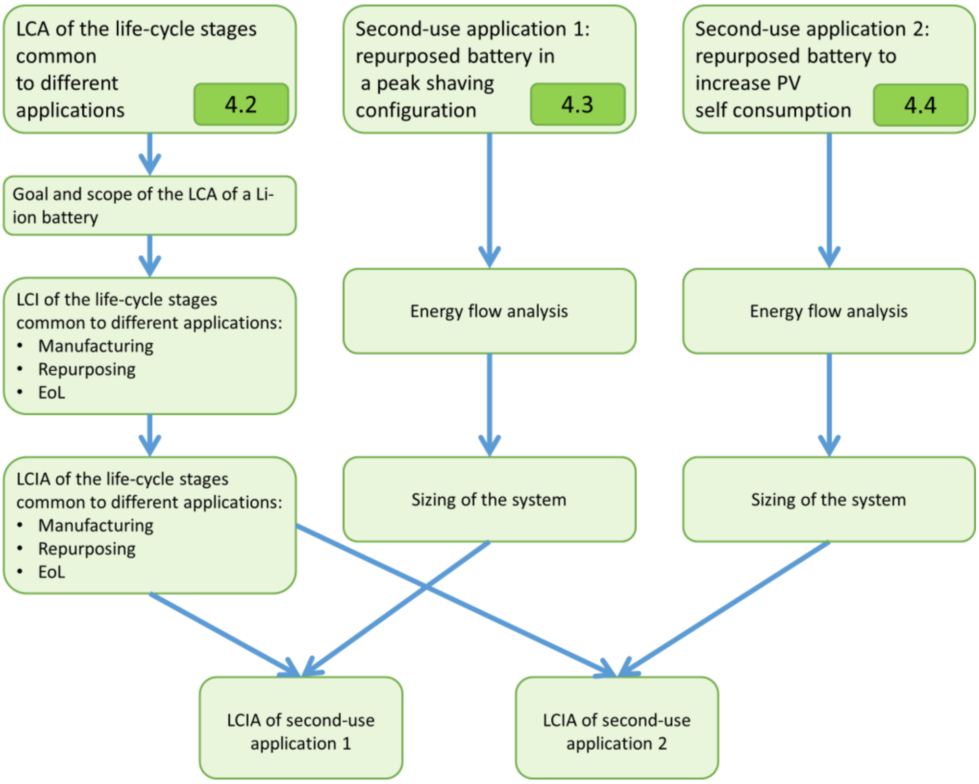
CHAPTER 4
Environmental assessment

Among the existing methodologies for assessing the environmental performances of products and systems, the Life Cycle Assessment (LCA) methodology, standardized by ISO and further elaborated by JRC Directorate D (e.g. Product Environmental Footprint methodology (Manfredi et al., 2015)), has demonstrated its potential. Even though a few LCA studies are already available in the scientific literature in the area, life cycle based analysis of xEVs and of their components is a rather new subject. Moreover, very few studies focus on reuse of xEV batteries and the potential environmental benefit/burden related to their adoption for second-use applications.

Despite the existing efforts for the LCA development within this topic, unified guidelines or harmonized approaches do not exist yet (Ruiz et al., 2016). In the framework of the SASLAB project, an adapted method to assess the environmental performances related to the adoption of a xEV repurposed battery was developed. Detailed description of this novel method can be found in a recently submitted journal paper (Bobba et al., 2018b).

In section 4.1 the main literature outcomes useful for the environmental assessment of a repurposed xEV Li-ion battery in different second-use applications are reported. Then, the Life Cycle Assessment of the manufacturing, the repurposing and the EoL a xEV Li-ion battery are illustrated (section 4.2). Since the environmental impact of the use of the repurposed battery depends on the application, for each application the system sizing and the environmental impact is reported separately. Then, section 4.3 describes the energy flow analysis of the adoption of a xEV battery in a peak shaving configuration. Similarly, section 4.4 describes the energy flow analysis of the adoption of a xEV battery to increase the renewable (PV) self-consumption of a house. The overall environmental impact is finally presented for both configurations in sections 4.3.2 and 4.4.2, respectively. To ease the reading, Figure 15 schematizes the structure of the above-mentioned sections. Conclusions derived from the performed assessment and opportunities of further development are discussed in section 4.5.

Figure 15: Schematic representation of the structure of chapter 4



4.1 Relevant environmental aspects of xEV batteries repurposing coming from literature

In this section, the most relevant findings arising from the performed literature review are summarized. More details are reported in Bobba et al. (2018) and (Cusenza et al., 2018).

Despite the availability of some LCAs of second-use of xEV batteries, guidelines or harmonized approaches do not exist yet and the comparison between the LCA results are often complicated due to major differences in the studies, especially concerning differences in the assessed applications, different life-cycle stages included in the assessment, lack of inventory data to model the impacts of the life-cycle stages and the impact methods used to assess the impacts of the system.

In the scientific literature, various papers focus on the **environmental impact of second-use applications** of xEV batteries[56]. The adoption of batteries in combination with renewable energy installation in buildings sounds the most promising application (ADEME, 2011; Canals Casals et al., 2015; Koch-Ciobotaru et al., 2015; Tamiang and Angka, 2014). The use stage of batteries is recognised as an important stage to be assessed (Canals Casals et al., 2015; Richa et al., 2015). The performance of the battery in a specific system depends on both the batteries characteristics (e.g. battery chemistry, capacity, efficiency) and the system in which they are adopted (grid-connected, stand-alone, power/energy application) (Koch-Ciobotaru et al., 2015; Weniger et al., 2014b). Due to the absence of primary data, in place of data reflecting real energy systems, often average data, estimations and assumptions are used (Ahmadi et al., 2014b; Richa et al., 2015).

In LCA, the **system boundaries** characterizing the study should be clearly defined (ISO, 2006). According to the goal of the study, different approaches can be observed in the literature. For instance, aiming at assessing the whole life-cycle of the xEV battery, all the life-cycle stages on the xEV battery, i.e. car manufacturing, use of the battery in both the car and in the second-use application, the battery recycling (Canals Casals et al., 2015; Richa et al., 2015). Other authors consider only the life-cycle stages directly affecting the second-use of the xEV batteries (Faria et al., 2014; Sathre et al., 2015). Furthermore, the regional condition are recognised as relevant in assessing the environmental performances of batteries in different systems (DeRousseau et al., 2017; Erkisi-Arici et al., 2017; Faria et al., 2014).

The reviewed LCA studies address different Li-ion chemistries (e.g. lithium-nickel-cobalt-manganese-oxide, lithium-manganese-oxide, lithium-iron-phosphate). However, most of the studies refer to the same **inventories for modelling** both the manufacturing and the EoL of the battery, as also stated by (Peters et al., 2017) (see section 4.2.2).
Due also to the novelty of the topic, few data about the **repurposing stage** are available and LCA studies often resort to assumptions or consider it as negligible from an environmental perspective (e.g. in Canals Casals et al. (2015) and Faria et al. (2014)). Even though battery testing is expensive and time consuming (Nenadic et al., 2014; Neubauer et al., 2015b), a detailed understanding of the battery behaviour is needed (DeRousseau et al., 2017; Koch-Ciobotaru et al., 2015). The lifetime of the battery is in fact a relevant parameter in the assessment of the environmental impacts related to repurposed batteries. This data gap is usually solved through assumptions based on warranties (Ahmadi et al., 2014b; Faria et al., 2014) or average data (Canals Casals et al., 2015; Richa et al., 2015; Sathre et al., 2015). This is why data on expected lifetime

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[56] Examples of applications assessed in the literature are: smoothing for renewable energy systems, energy storage of a single wind turbine/photovoltaic/battery system, off-grid photovoltaic vehicle charging system; diurnal energy shifting, allowing expanded use of intermittent renewable energy sources such as wind and solar, load shifting and peak shaving.

coming from testing campaign (like the ones carried out by JRC-Petten for this SASLAB project) are extremely important.

Concerning the **Life Cycle Impact Assessment** (LCIA), in order to capture the complexity of systems like vehicles, a multi-criteria analysis is recommended in place of single or aggregated indicators (ACEA, 2012; Bauer et al., 2015; Messagie et al., 2014a). Moreover, impacts related to resources used for vehicles and their components should be assessed especially concerning xEVs: the transition to the e-mobility translated also in a variation of the resources used for xEV. Relevant quantities of Critical Raw Materials (CRM) can be contained in Li-ion batteries, depending on the battery chemistry (Mathieux et al., 2017). Therefore, material efficiency and analysis of critical raw materials are very important elements to be considered in a complete environmental / sustainability assessment of EVs batteries after their use within EVs.

Finally, **sensitivity and uncertainty analysis** performed by different studies permitted to assess the relevance of specific parameters in the analysis. From the performed literature review, it emerged that the energy mix adopted for assessing the impacts is a relevant issue (e.g. in (Ahmadi et al., 2014b; Canals Casals et al., 2015; Erkisi-Arici et al., 2017)). Other significant parameters are: the repurposed xEV battery lifetime; avoided technology thanks to the adoption of deployed xEV batteries; repurposing effort (cell conversion rate, BMS dismantling, etc.); round-trip efficiency; DoD in a specific application; residual capacity and SOH of the xEV battery when removed from the EV.

Concluding, the environmental assessment of repurposed xEV batteries requires the **clear definition of the system** in which batteries are adopted. Primary data to model the system are recommended, especially concerning system energy flows in combination of the battery characteristics. Due to the complexity of the system, a sensitivity analysis could reveal the relevance of some relevant parameters for the environmental assessment.

4.2 Life Cycle Assessment of the Li-ion battery

4.2.1 Goal and scope

The aim of the LCA is the environmental assessment of the adoption of xEV batteries in second-use applications. In this chapter the manufacturing, the repurposing and the EoL steps are hereinafter illustrated and discussed (section 4.2.2 and sub-sections), whereas sections 4.3 and 4.4 refer to the use phase of specific second-use applications.

The study applies the LCA methodology as regulated by the international standards of series ISO 14040 (ISO, 2006; ISO 14044:2006, 2006), considering the life cycle by depicting the existing supply-chain of the product.

The analysed product is the Mitsubishi Outlander Plug-In Hybrid Electric Vehicle (PHEV) battery pack (Figure 16). It weighs 175 kg and consists of 10 modules, each made up of 8 battery cells. Each cell has a nominal voltage of 3.75 V and a capacity of 38 Ah. The 80 cells are connected in series providing a nominal voltage of the battery pack of 300 V and a total nominal capacity of 11.4 kWh. The cell has a cathode based on 0.52 $LiMn_2O_4$ + 0.48 $LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$ (LMO/NMC lithium - ion battery)[57] and an anode based on graphite. The functional unit (FU) of the study is an LMO/NMC Lithium-ion battery pack for PHEVs.

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[57] Coefficients refer to the weight fraction

Figure 16: Mitsubishi Outlander PHEV battery pack

Source: visit to the Peter Ursem plant (The Netherlands)

The most relevant characteristics for sizing the configuration assessed in the environmental assessment are summarized in Table 7.

Table 7: Battery characteristics

Parameter	**LMO /NMC Repurposed battery**	**LMO /NMC Fresh battery**	**Source of the information**
Chemistry	LMO/NMC: 0.52 $LiMn_2O_4$ + 0.48 $LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$		Derived from lab tests
Nominal capacity of the battery [kWh]	11.40 (300V - 38Ah)		Manufacturer
Number of cells per modules / per battery	8 cells/module; 80 cells/battery		Manufacturer
Initial RTE (Round-trip efficiency)[58] [%]$^+$	98%	>98%	Based on (Görtz, 2015) and own measurement (see 3.4.2)
Initial capacity for the assessment [%]	81.31%	100%	Derived from lab tests
End-of-second-use Retained Capacity [%]	60%		Based on (Canals Casals et al., 2015; Lacey et al., 2013; Oliveira, 2017)
Battery degradation	-3 Wh/cycle (cycling aging); -0.13 Wh/day (calendar aging)		Based on (Faria et al., 2014) Derived from lab tests

+ a linear decrease of the battery efficiency is considered (5 percentage points in 5 years)

According to the goal of the project, the system boundaries if the study include the following phases:

- manufacturing stage;
- repurposing stage;
- second-use stage;
- end-of-life (EoL) stage.

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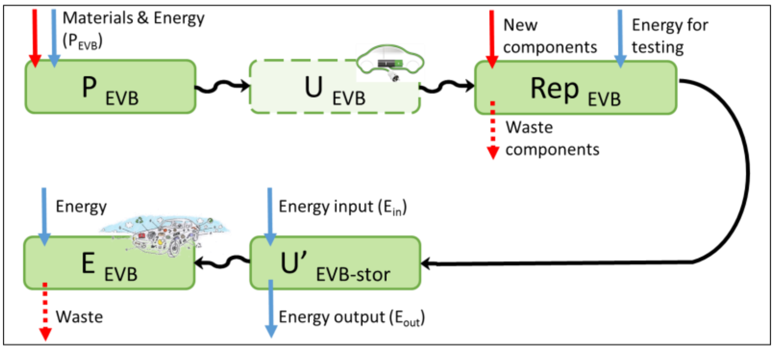
[58] RTE is represents the total energy output (at discharge) divided by the total energy input (at charge) measured between the same state-of-charge (SoC) end points associated with the application of the duty cycle during the test. It is expected that it may fade during the life test

The impacts of the first use in xEV is considered as out of the system boundaries (dashed boards in Figure 17).

Figure 17: Schematic presentation of the system boundaries of the LCA



It is important to note that, assessing the products' reuse, the allocation of the environmental impact of both manufacturing and EoL phases represents an unresolved issue to be addressed at a later stage. If reused, the lifetime of the xEV battery is extended and not all the impacts of both manufacturing and EoL of the xEV battery should be allocated to the second life since the xEV battery already provided function for which it was built (i.e. to be used in EV). In this LCA, it is proposed to use two allocation factors ('α' and 'β') are used, respectively, as further explained in (Bobba et al., 2018b).

The LCA of the case-study product is performed through SimaPro 8.3 software and the database used is Ecoinvent 3. All material components are modelled as 100% of primary production.

The recommended ILCD/PEF recommendations (EC - JRC, 2012) are used for the LCIA. Note that, according to previous JRC studies, the land use, the water resource depletion and ionizing radiation impact categories have been excluded due to limited life-cycle inventory data[59] (Bobba et al., 2015; Latunussa et al., 2016) and the Resource Depletion impacts have been specified into the Abiotic Depletion Potential, mineral resource impact category [60] (Bobba et al., 2015). Finally, Cumulative Energy Demand method (Frischknecht et al., 2007) is also included in the assessment.

Table 8: List of impact categories used in the LCA

Impact categories	**Unit of measure**
Cumulative energy demand (CED)	$MJ_{primary}$
Abiotic depletion potential (ADP-res)	kg Sb_{eq}
Global warming potential (GWP)	kg CO_{2eq}
Ozone depletion (ODP)	kg CFC-11_{eq}
Human toxicity, cancer effects (HT-C)	CTUh
Human toxicity, non-cancer effects (HT-nC)	CTUh
Particulate matter (PM)	kg $PM2.5_{eq}$

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[59] According to the ILCD guidelines the ionizing radiation is classified as "interim" (best among the analysed methods for the impact category, but still not ready to be recommended); land use and water resource depletion are classified as "level III" (recommended, but to be applied with caution)

[60] The abiotic depletion potential - resources - is an impact category that account for the extraction rate of a certain resource (in relationship to the estimated world reserves), compared to a reference resource (antimony).

Impact categories	Unit of measure
Ionizing radiation (IR)	kBq $U235_{eq}$
Photochemical ozone formation (POFP)	kg $NMVOC_{eq}$
Acidification (AP)	mol H^{+}_{eq}
Terrestrial eutrophication (EP_t)	mol N_{eq}
Freshwater eutrophication (EP_f)	kg P_{eq}
Marine eutrophication (EP_m)	kg N_{eq}
Freshwater ecotoxicity (F_{ET})	CTU_e

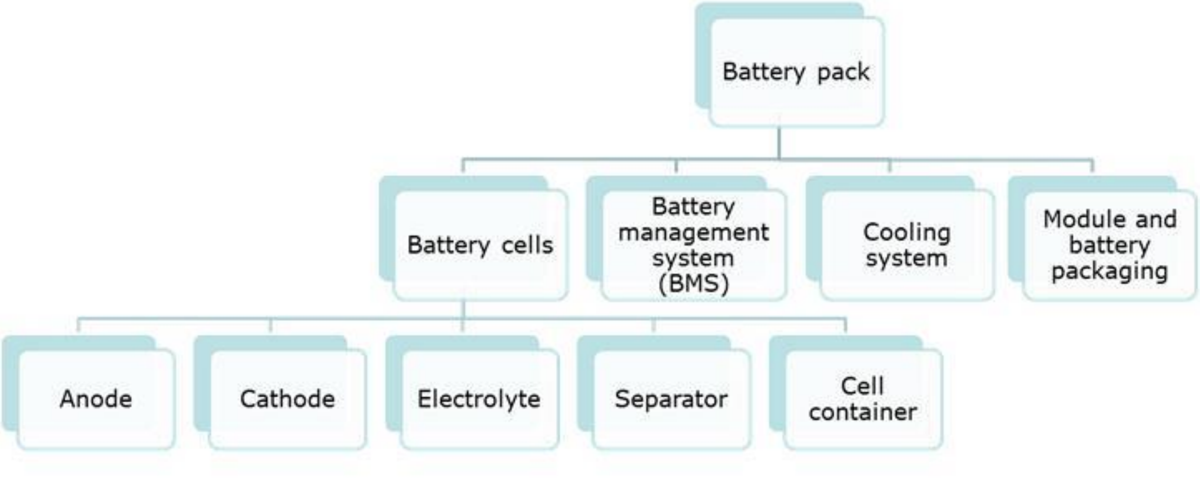
4.2.2 Life Cycle Inventory (LCI)

The Life Cycle Inventory (LCI) take account of the materials/energy inputs and output of each stage included in the system boundaries. In this case, the LCI data collection is based both on primary and secondary data as described in the following sections.

4.2.2.1 Battery manufacturing

To model the manufacturing step, the battery components have been clustered in four main groups: battery cells, battery packaging, battery management system (BMS), and cooling system (Figure 18). In detail, JRC Petten laboratory provided the bill of material (BoM) of the battery cells through their dismantling, weighting and classification of materials. The upstream materials and the energy required to manufacture the components were derived from literature data (Ellingsen et al., 2014; Majeau-Bettez et al., 2011; Notter et al., 2010). Battery components not included in the cell (BMS and the cooling system) are modelled based on literature data. Transport and infrastructure required for the battery components are based on (Ellingsen et al., 2014). It is assumed that the assembly of the battery occurs in Europe, and thus the European electricity mix, at medium voltage is used.

Figure 18: Battery pack components as clustered for the LCA modelling



Source: own elaboration

Battery pack

Table 9 reports the LCI of one battery pack of 175 kg. The battery cells represent approximately 64% of the total weight.

Table 9: Inventory data for one battery pack

Components	Unit of measure	Mass	Source
Battery cells (80 cells)	[kg]	111.73	JRC Petten
Battery packaging	[kg]	49.59	JRC Petten/(Ellingsen et al., 2014)
BMS	[kg]	6.49	JRC Petten/(Ellingsen et al., 2014)
Cooling system	[kg]	7.19	JRC Petten/(Ellingsen et al., 2014)
Battery pack	[kg]	175.00	JRC Petten

Battery cell

The Mitsubishi Outlander PHEV battery pack was dismantled at the cell level at the JRC Petten laboratories and each cells component was weighted and classified based on material composition (section 3.4.3)

The detailed inventory of the battery cell and its sub-components is available in ANNEX III.

4.2.2.2 Battery repurposing

The repurposing process consist of a (limited level of) disassembly, testing for degradation and failure, and re-packaging. According to Ahmadi et al. (Ahmadi et al., 2014a), dismantling of the cells within a vehicle battery pack is neither technically nor economically feasible, therefore it is expected that packs will be repurposed at the pack or module level.

In this study, main assumptions for the repurposing stage are:

- battery is disassembled down to modules;
- tests evaluate the state of health (SoH) of the battery pack; the energy consumption to perform a complete charge/discharge cycle for each module is considered[61];
- a new packaging guarantees the safety conditions in the second-use applications; the substitution of both the battery tray (in which battery modules are placed) and the battery retention (that keeps the battery modules in place within the battery tray) is included[62].

Inventory data used for the LCA of battery repurposing stage referred to one repurposed battery pack are shown in Table 10.

Table 10: Inventory data for the battery repurposing stage

Components	Unit of measure	Mass	Source
Battery tray	[kg]	14.88	(Ellingsen et al., 2014)
Battery retention	[kg]	5.45	(Ellingsen et al., 2014)
Electricity consumption	[kWh]	8.72	Own calculation based on JRC Petten data
* for the analysis, only the electricity consumption of testing is considered; the disassembly is assumed to be a manual disassembly since repurposing is not yet an industrial operation			

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[61] The overall losses (cycler + battery) during a charge/discharge cycle are considered to be 15%

[62] The detailed inventories for the battery tray and battery retention are derived from (Ellingsen et al., 2014)

4.2.2.3 Use stage

As illustrated in section 4, the discussion about the use stage depends of the considered applications. Therefore, the use stage of the peak shaving application is illustrated in section 4.3 and the use stage of the increase of PV self-consumption application is illustrated is section 4.4.

4.2.2.4 Battery End-of-Life (EoL) stage

Consistently with the provisions of the Batteries Directive, the LCA considers that the battery was properly collected and addressed to recycling.

Before the recycling process, it is assumed that the BMS, the cooling system and the battery packaging are separated from the cell and treated separately. Specific EoL processes were created based on Ecoinvent data; the amount of material recoverable from cells are calculated considering the recycling rate reported in (Chancerel et al., 2016).

Most of the recycling processes for spent lithium-ion batteries in Europe are currently based on pyro-metallurgical process (Chagnes and Pospiech, 2013; Swain, 2017), which is highly effective at recovering nickel, cobalt, copper and steel (Kushnir, 2015; Mancini et al., 2013); aluminium, lithium and manganese are lost in the sludge since it is not economic or energy efficient to recover (Dunn, J B; Gaines, L; Barnes, M; Sullivan, J; Wang, 2013). The LCI for the recycling process is based on Ecoinvent database[63] and the amount of material recoverable from the cells are calculated considering the recycling rate reported in (Chancerel et al., 2016).

4.2.3 Life Cycle Impact Assessment (LCIA)

All the impacts illustrated in this section were calculated for the manufacturing of one battery pack as defined in section 4.2.1.

4.2.3.1 Battery manufacturing

LCIA results show the environmental impacts of the manufacturing, the repurposing and the EoL of the assessed LIB[64]. Figure 19 shows the percentage contribution of the battery components, infrastructure, transports and electricity consumption for assembly. These results demonstrate that the battery cells manufacturing is responsible for the major contributions in almost all the examined environmental impact categories (always higher than 50% except for the ADP). The packaging and the BMS are also relevant for all the impact categories, exceeding 50% of the overall impact bot ADP, HTc, HTnc and FET. The cooling system has a contribution lower than 5% for all the impact categories, with an exception for HT-C. Finally, the facility, the transport and the electricity consumption for assembly contribute for less than 2% for all analysed impact categories.

A more in depth contribution analysis was performed in order to identify the most relevant processes contributing to the overall impact. For more details, please refer to annexes.

Focusing on the cells manufacturing (Figure 20), the anode, the cathode and the energy needed for the cells production contribute for more than 70% for all the assessed categories.

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[63] The output flows are adapted to match the input of materials specific to the specific composition of the analysed battery cells

[64] Quantitative assessment is available in annexes

Figure 19: Battery pack manufacturing (175 kg) - contribution analysis

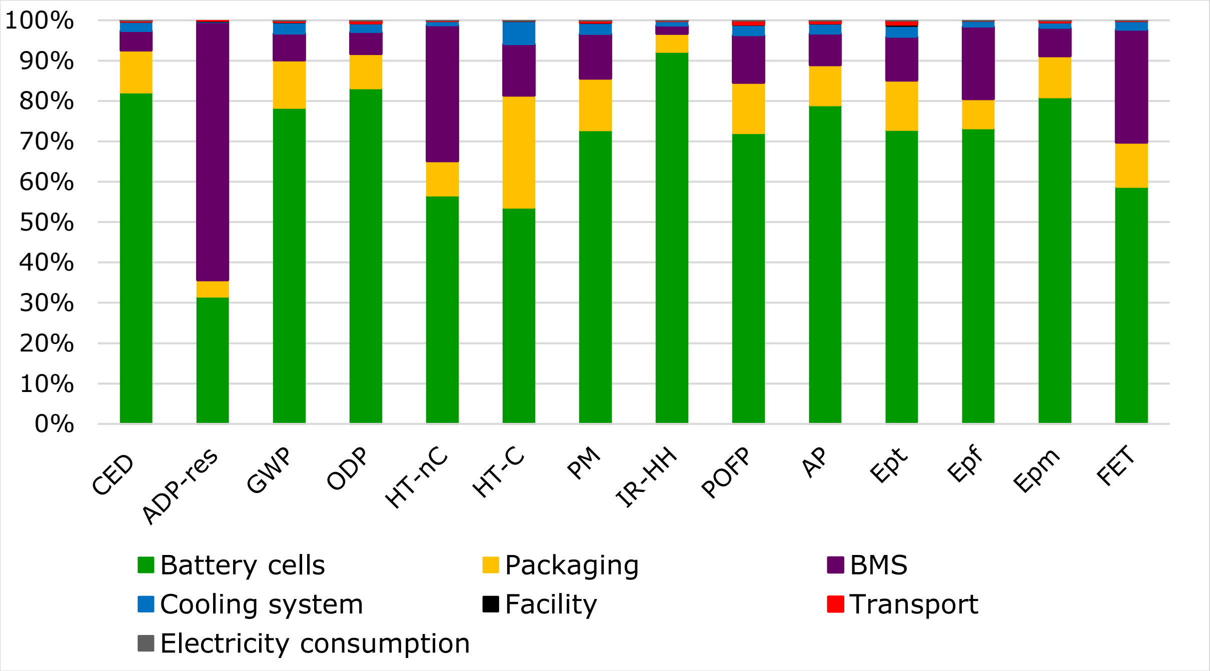
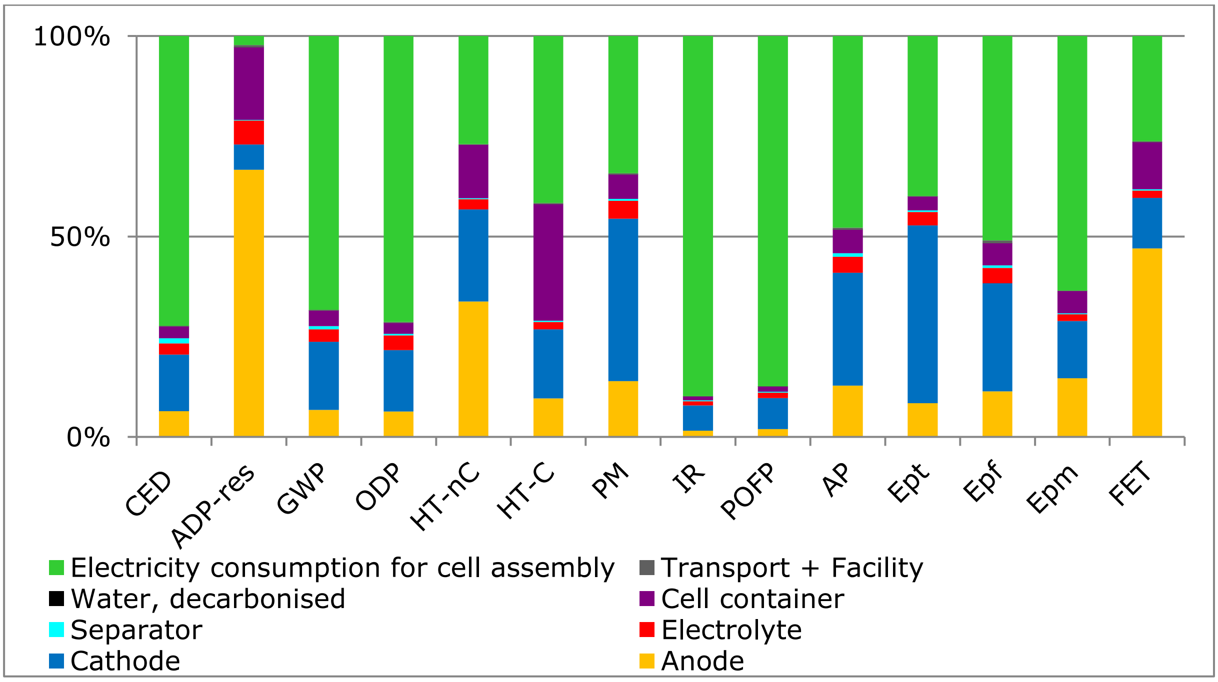


Figure 20: Battery cells manufacturing (111.73 kg) - contribution analysis



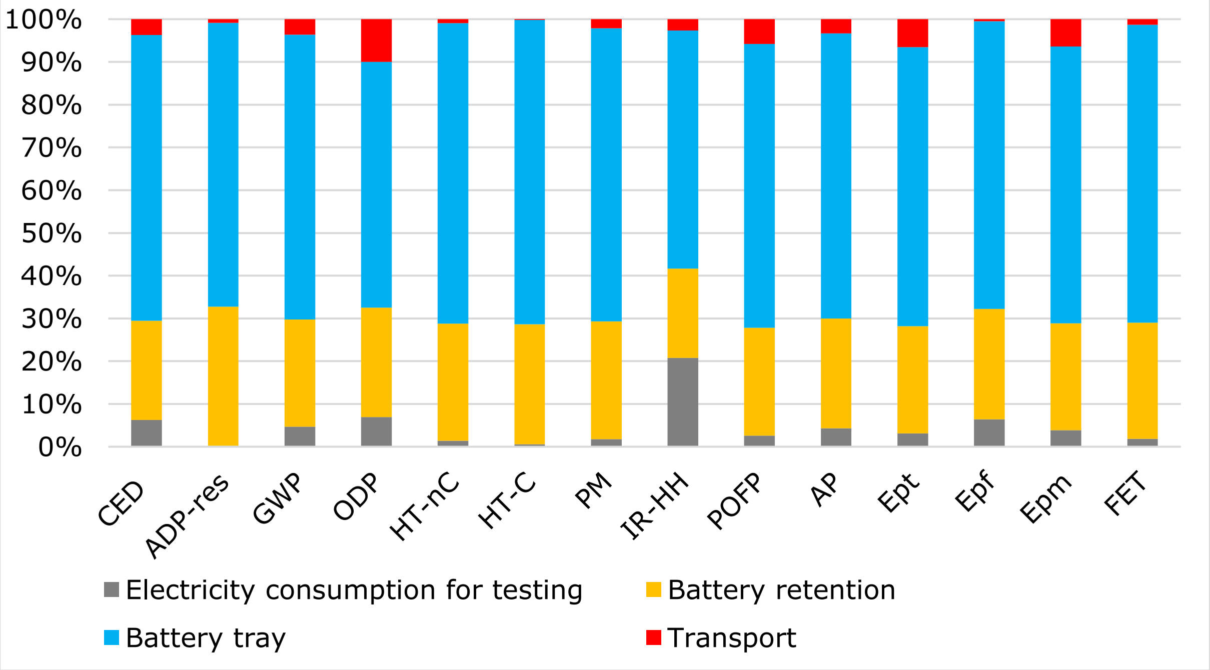
4.2.3.2 Battery repurposing

Results reported in Figure 21 depict the relevance of manufacturing of the battery new components: battery tray and battery retention. Their contribution ranges between 76.60% and 99.25% for respectively the IR and the HT-C impact categories.

The electricity consumed for testing the battery pack is always lower than 21% for all the other assessed impact categories and the contribution of transports could be considered as negligible (maximum contribution for the ODP category).

Note that, according to (Cready et al., 2003), 4 charge/discharge cycles are needed for testing the SoH of battery packs whereas only 1 is considered in the LCI (Section 4.2.2.2). However, the performed sensitivity analysis shows that the contribution on the tests will not heavily affect the overall environmental impact. The impact categories mainly affected by this change is the AP (+5.77% of the overall impact), whereas for all the other assessed impact categories the variation can be considered as negligible (it never exceeds 0.70%).

Figure 21: Repurposing stage of the LMO/NMC battery - contribution analysis



4.2.3.3 Use stage

As illustrated in section 4, the discussion about the use stage depends of the considered applications. Therefore, based on the specific LCI of the use stage of the two assessed application, the environmental impact of the adoption of a repurposed xEV battery in a peak shaving application is illustrated in section 4.3.2. Similarly, the environmental impact of a repurposed xEV battery to increase PV self consumption of a house is illustrated is section 4.4.2.

4.2.3.4 Battery End-of-life (EoL) stage

In Table 11 are reported the overall impacts and the percentage contribution of EoL of the battery pack. The recycling and then the avoided primary production of copper, aluminium and steel determine an avoided impact (i.e. <0) in almost all the impact categories. The only exceptions (positive values, i.e. environmental impacts) are represented by the ODP and FET impact categories (grey cells in Table 11) due to the "sodium hydroxide" used for the pyrometallurgical process and the aluminium in the treatment of the casing.

More detailed LCIA results are reported in ANNEX IV and the performed LCA Interpretation phase is reported in ANNEX V.

Table 11: Environmental impact assessment of the EoL of one battery pack

Impact categories	Unit of measure	Treatment of the BMS	Treatment of packaging	Treatment of cooling system	Treatment of battery cells	Total
CED	MJ	-7.61E+01	-3.01E+03	-9.31E+01	5.30E+02	-2.65E+03
ADP-res	kg Sb $_{eq}$	-7.74E-04	-1.50E-03	-1.56E-04	-2.16E-02	-2.41E-02
GWP	kg CO2 $_{eq}$	-4.08E+00	-1.90E+02	-8.06E+00	3.61E+01	-1.66E+02
ODP	kg CFC-11 $_{eq}$	-3.30E-07	-1.14E-05	-6.21E-08	2.57E-05	1.38E-05
HTnc	CTUh	-1.29E-05	-1.05E-04	-1.71E-05	-4.98E-04	-6.33E-04
HTc	CTUh	-6.72E-06	-9.99E-05	-1.56E-05	-6.21E-05	-1.84E-04
PM	kg PM2.5 $_{eq}$	-8.44E-03	-1.70E-01	-1.50E-02	-1.10E+00	-1.29E+00
IR	kBq U235 $_{eq}$	-1.21E-01	-2.22E+01	-2.82E-01	1.13E+01	-1.13E+01
POCP	kg NMVOC $_{eq}$	-2.91E-02	-6.13E-01	-4.98E-02	-1.78E+00	-2.47E+00
AP	molc H+ $_{eq}$	-6.13E-02	-1.66E+00	-7.29E-02	-2.47E+01	-2.65E+01
EP_t	molc N $_{eq}$	-9.26E-02	-2.02E+00	-1.34E-01	-1.22E+00	-3.47E+00
EP_f	kg P $_{eq}$	-9.18E-03	-1.22E-01	-1.13E-02	-2.30E-01	-3.72E-01
EP_m	kg N $_{eq}$	-1.11E-01	-3.40E-01	-1.25E-02	-2.25E+00	-2.72E+00
FET	CTUe	1.63E+03	7.31E+04	3.03E+04	-1.14E+04	9.37E+04

4.3 Second-use application 1: repurposed battery in a peak shaving configuration

As stated in Figure 15, this section summarises the necessary information related to assess the environmental impacts related to the adoption of a repurposed LMO/NMC battery in a peak shaving application.

In section 4.3.1 the most relevant information for the impact assessment are summarized, whereas the detailed analysis of the energy flows of the system is illustrated in ANNEX VI.

Finally, based on this analysis and on the environmental impacts of the manufacturing, repurposing and EoL of the LMO/NMC battery as illustrated in the previous sections (4.2.3), the environmental impact of the adoption of a LMO/NMC battery in a peak shaving application along the whole lifetime of the battery is described in section 4.3.2. The main outcome of the performed sensitivity analysis are also provided at the end of the section.

4.3.1 Energy flow analysis

The analysed system is an office building at JRC - Ispra (Building 6) with a total area of 1,444 m^2, a volume of 4,706 m^3 without any PV system and without any lab area. Therefore, energy consumption is related only to offices. For the environmental assessment, the input/output energy flows are calculated according to the battery's and the system's characteristics (note that the energy delivered by the batteries is covering the peak during the day while batteries are charged during the night).

Data of the daily consumption profile of the building were available on yearly base with 5 minutes resolution. Data of 4 representative months are processed to obtain the average energy requirement for each season (January for winter, April for spring, July for summer and October for autumn). Results of the analysis show that the maximum peak occur during winter (23.16 kW). Considering the load profile of the worst day was considered (Wednesdays during winter) and an assumed contracted power of 8 kW, the peak to be shaved is calculated for each representative month. Since data refer to one month per season, the maximum energy requirement is increased of 10% in order to oversize the battery system and be sure to cover all the peaks.

Table 12: System energy requirements

	January (winter)	April (spring)	July (summer)	October (autumn)
Max peak power [kW]	23.16	19.55	14.43	18.89
Required energy [kWh/day]	202.78	174.66	129.39	153.46
Peak to be shaved [kWh/day]	50.40	34.54	7.55	20.13
Peak to be shaved (+10%) [kWh/day]	55.44	37.99	8.31	22.15

If **repurposed batteries** are adopted, a minimum of 8 batteries are required in the system. Note that only the working days are considered for the assessment, i.e. 240 days per year[65].

The lifetime of such batteries is estimated about 4 years; then, batteries are no longer able to satisfy the energy requirement by the peak due to their low capacity, and the DoD exceed 80%. The total amount of energy provided by such 8 batteries in 4 year to the system is 27.03 MWh. The corresponding energy required for charging the batteries is calculated based on the roundtrip efficiency (RTE) of the battery as in Table 7 (31.80 MWh).

Similarly, if **fresh batteries** are adopted in the system, minimum 7 fresh LMO/NMC batteries can provide the required energy during the peak hours for 1,473 working days (i.e. about 6 years). After this period, even though the batteries' capacity does not yet reach its EoL, the DoD of the batteries exceeds 80% during all winter days. The total amount of energy provided to the system is 42.20 MWh. The corresponding energy required for charging the batteries is calculated based on the roundtrip efficiency (RTE) of the battery as in Table 7 (46.89 MWh).

4.3.2 LCIA of the adoption of repurposed xEV batteries to the peak shaving application

In order to assess the environmental performances related to the adoption of repurposed batteries, different configurations of the system were considered:

A. adoption of a fresh battery charged during the night and able to cover the peak during the working days;

B. adoption of a repurposed battery charged during the night and able to cover the peak during the working days;

C. no batteries are used.

According to these configurations, the most relevant information for the modelling the impacts of the use phase are reported in Table 13.

Table 13: Summarize of the system energy flows needed for the environmental assessment

Energy requirement		Fresh battery (A) [kWh]	Repurposed battery (B) [kWh]	No battery (C) [kWh]
Energy between 08:00 and 19:00	from the grid	102,770	109,527	102,770
	from the battery	6,757	-	6,757
Energy between 19:00 and 08:00	from the grid	48,942	48,942	48,942
	for charging the battery	7,508	-	7,949
Total energy requirement		159,219	159,661	158,469

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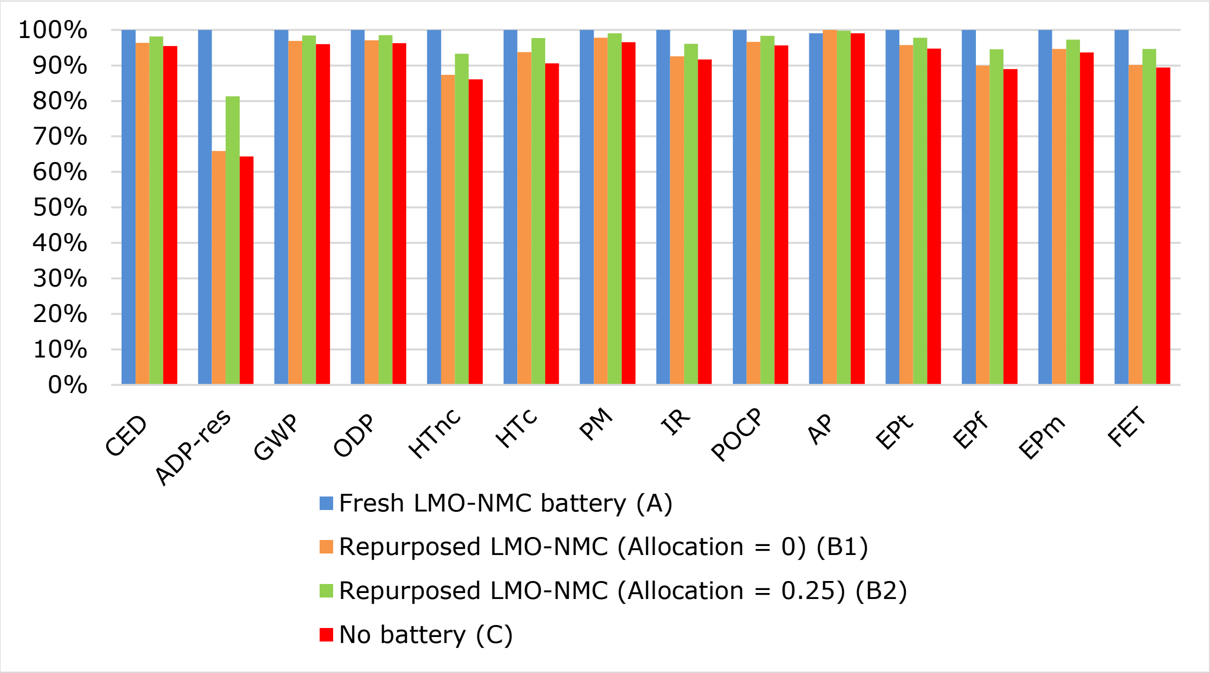
[65] The energy requirement of the building during weekends never exceed 8 kW all over the year.

Note that, according to the allocation considerations in Section 4.2.1, two different allocation factors, $\alpha = \beta = 0$ (case B1) and $\alpha = \beta = 0.25$ (case B2) are considered for the assessment[66]. Quantitative data are detailed reported in ANNEX VI, whereas in the followings, the most relevant outcomes from the LCIA are described.

In order to permit the comparison between the different assessed systems, the same timeframe is considered, i.e. the yearly impact of all the assessed configurations (Figure 22). With exception for the AP impact category, the adoption of a LIB (either fresh or repurposed) to cover the energy peak of the office building does not entail environmental benefits. Results also show that, if repurposed LMO/NMC batteries are used in the building in place of fresh LMO/NMC batteries, the yearly impact of the system is lower. This is true also in case 25% of the manufacturing/EoL impacts are allocated to the second-use of the battery (Case B2).

In general, differences between the yearly impacts of different configurations are limited, with the only exception of the ADP-res impact category. In this case, the high impact of the configuration with the fresh LMO/NMC battery (A) is related to the contribution of the battery manufacturing. Note that the ADP-res impact category is dominated by the manufacturing/EoL impacts (Bobba et al., 2015). It is to be noticed that the energy mix used for the assessment is the same for both day and night. For some Countries, e.g. Belgium, the difference between the energy mix during the peak hours and the off-peak hours is relevant and different mix should be considered according to (Messagie et al., 2014b).

Figure 22: Comparison between the different peak shaving systems (for 1 year)



According to the main outcome of the literature review (section 4.1), a sensitivity analysis is performed in order to estimate the relevance of the energy mix used in the assessment and the relevance of the battery chemistry to the overall impacts (ANNEX VI).

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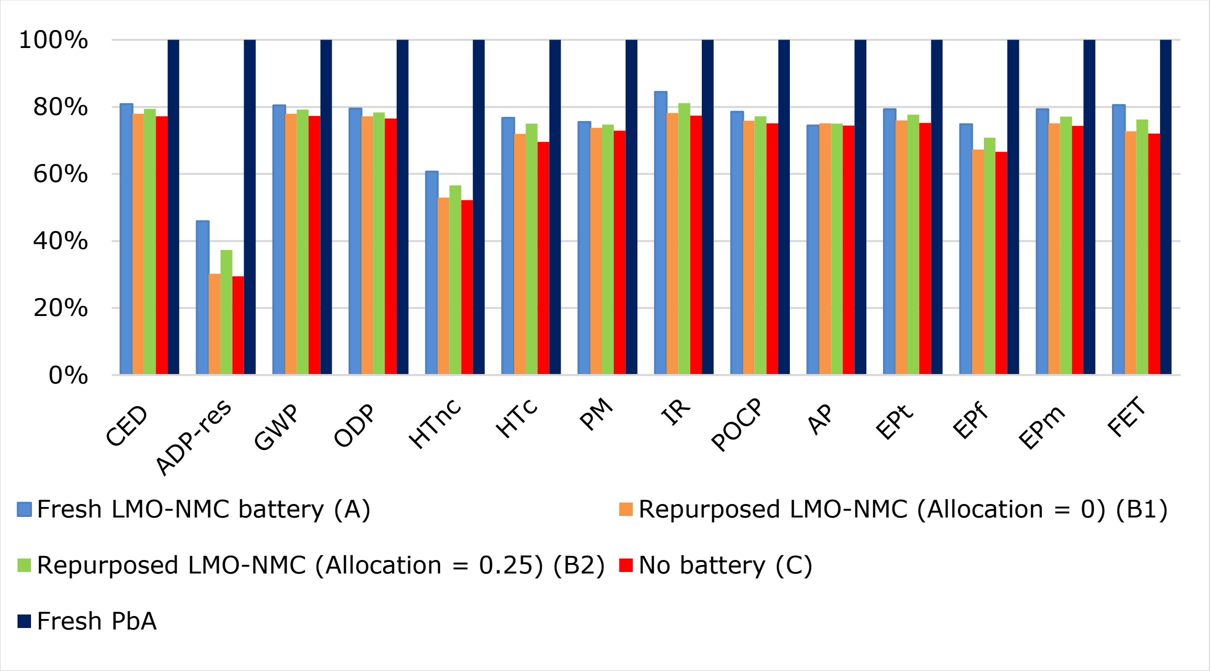
[66] $\alpha = \beta = 0$ means that all the environmental impacts related to both the manufacturing and the EoL of the xEV battery are allocated to the first use in the EV. Therefore, these stages does not affect the impacts of the second-use of the xEV battery.

Concerning the **energy mix**, it is assumed that the electricity delivered by the batteries to the building (covering the energy peaks) avoids the production of an equal amount of electricity provided by a natural gas peak power plant. Results show that the differences of the yearly impacts can be considered as negligible for all the assessed impact categories.

Concerning the **battery chemistry**, a PbA battery is considered to be used to the peak shaving application. Results show that the yearly impact of the adoption of repurposed batteries to cover the peaks of the system is always lower than the adoption of a PbA battery for all the assessed impact categories (Figure 23).

Figure 23: Comparison between the different peak shaving systems (for 1 year)



To conclude, the adoption of a repurposed LMO/NMC battery in place of a fresh one has environmental benefits for all the assessed impact categories. No environmental benefits were observed comparing configurations with no batteries and repurposed LMO/NMC batteries.

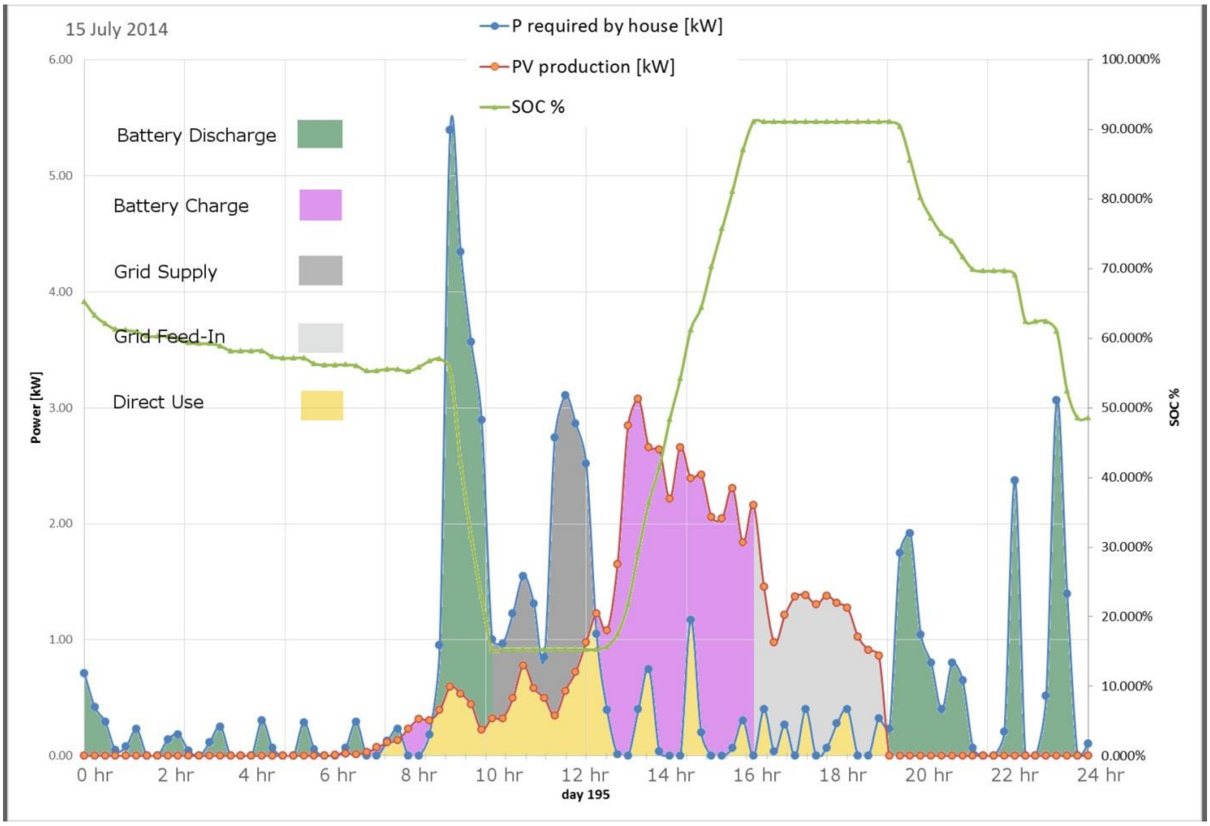
Negligible environmental benefits emerged when the avoided energy production refer to a less environmentally-friendly energy source (i.e. natural gas peak power plant) compared to the average energy mix.

Finally, the adoption of PbA battery in place of fresh of repurposed LMO/NMC battery shows negative impacts for all the assessed impact categories. Note that, since the data used to model the PbA battery derived from the literature, a more detailed analysis is recommended.

4.4 Second-use application 2: repurposed battery to increase photovoltaic self consumption

For several renewables system, e.g. photovoltaic systems, a significant amount of produced energy is not directly consumed by the utility consumer. As a consequence, this energy enters in the grid network or it is lost. The adoption of batteries connected to these sources of renewable energy can increase the use of local (PV) electricity. Therefore, the surplus of PV energy (i.e. energy not directly consumed by the system) is stored and used where the PV system could not produce energy (i.e. night) or it could not answer to the energy demand of the system (Eyer and Corey, 2010). Figure 24 illustrates the energy flows of the the system for one representative day. The energy flows of the system are the direct energy used by the house and provided by the PV installation (yellow), the energy provided by the battery (green), the energy used for charging the battery (pink), the energy provided to the house from the grid (black) and the energy produced by the PV installation not directly used by the hous, i.e. fed into the grid (grey).

Figure 24: Energy flows of the system for 1 day (day 195 of own data base)

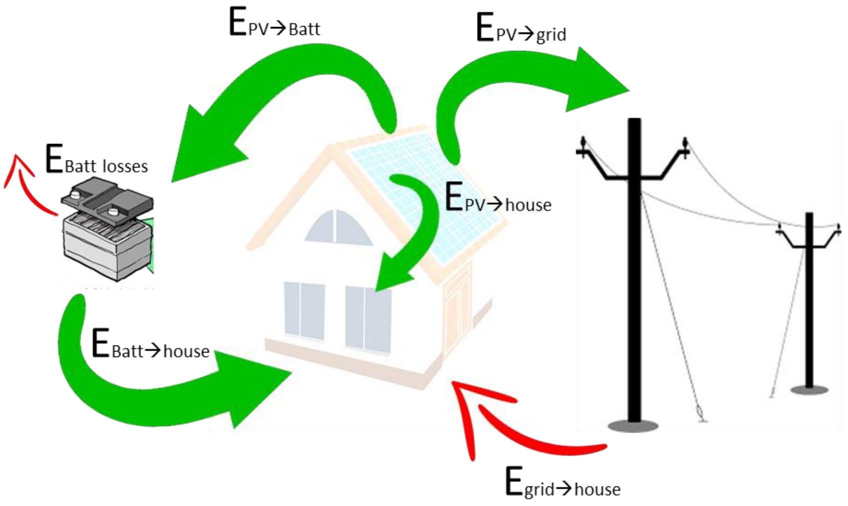


Source: own elaboration

In Europe, the increase of the PV system in residential and commercial buildings entailed also challenges in predicting power and voltage fluctuations, that can disturb the low voltage grid (e.g. ramps and peaks of injected PV power and hence power reversal, reactive power control) (Aziz and Ketjoy, 2017; Weniger et al., 2014a). Therefore, new policies for managing the PV self-consumption arose in several European Countries and depending on several factors (geographical area and weather conditions, PV penetration level, network characteristics, etc.). An example is the feed-in curtailments, which means the limitation of the feed-in power to a specific value, e.g. 70% (0.7 kW/kWp) in Germany for PV systems below 30 kWp (Aziz and Ketjoy, 2017; Weniger et al., 2014a). However, the Renewable Energy (RES) Directive 2009/28/EC requests the minimization of the use of curtailment, this means the increase of the share of consumer load covered by RES and the decrease of fuel use and generation related emissions of the conventional power plants (Winkler and Regawitz, 2016).

The configuration considered for the environmental assessment of second-use batteries to increase the PV self-consumption in a house is schematized in Figure 25.

Figure 25: Schematic representation of the energy flows of the system



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

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

4.4.1 Energy flow analysis

The household load profile is provided by the ResLoadSIM software[67] (time resolution of 1 minute). The system configuration refers to a residential building located in Amsterdam, with 4 residents and a yearly consumption of 5.15E+03 kWh. Available primary data (15 minutes resolution) for the PV production refer to a real PV installation in a JRC site in The Netherlands[68]. Based on a real case, for the analysis the energy provided by 21 PV panels is considered[69]. Based on (Ciocia, 2017) and on the battery characteristics, the energy flows of the system (schematized in Figure 25) were assessed for one year, every 15 minutes. Further information on how the capacity model is used to calculate relevant parameters can be found in (Bobba et al., 2018a).

Consistent with the above illustrated calculation, after about 4 years, one **repurposed battery** is no longer able to satisfy the house energy requirement since its capacity reaches 60% of the nominal capacity. The total amount of PV energy stored by the battery during its operational life is about 6.77 MWh, 83% of which are directly used for covering the energy requirement of the house.

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[67] https://ses.jrc.ec.europa.eu/our-models-portfolio
[68] The system is characterized 2 PV converters connected to 96 modules of 250 W, totalling 24 kWp. The orientation of all the modules is SSE with a slope of 10° (Vandenbergh, 2014).
[69] This evaluation Is based on a real case-study for which primary data are being collected.

If a **fresh battery** is used in the same system, it can be used in the house for increasing the renewable consumption. The nominal capacity decreases until 60% of the nominal capacity of the battery after 7 years.

4.4.2 LCIA of the adoption of repurposed xEV batteries battery to increase photovoltaic self consumption

To assess the potential benefits related to the adoption of a repurposed xEV battery to increase the PV self-consumption of a house, different configurations were considered:

A. adoption of a fresh battery in a grid-connected house;

B. adoption of a repurposed battery in a grid-connected house;

C. no batteries are used. In this last configuration,
    i. no feed-in curtailments are considered;
    ii. feed-in curtailments of 70 % kW/kWp are considered;
    iii. feed-in curtailments of 50% kW/kWp are considered.

Table 14 summarises the energy flows of the system for all the above listed configurations.

Table 14: Energy requirement for the configuration without and with a repurposed/fresh battery

Parameter	Fresh Battery(A)	Repurposed battery (B)	No battery (C.i)	No battery (C.ii)	No battery (C.iii)
Lifetime [year]	7.4	3.6	1	1	1
Electricity required by house [kWh]	3.81E+04	1.85E+04	5.15E+03	5.15E+03	5.15E+03
Direct electricity consumption from PV [kWh] - $E_{PV \rightarrow house}$	1.24E+04	6.02E+03	1.68E+03	1.68E+03	1.68E+03
Electricity provided by batteries [kWh] - $E_{Batt \rightarrow house}$	1.11E+04	5.14E+03	0.00E+00	0.00E+00	0.00E+00
Electricity needed for charging batteries [kWh] - $E_{PV \rightarrow Batt}$	1.17E+04	5.51E+03	0.00E+00	0.00E+00	0.00E+00
Electricity from the grid [kWh] - $E_{grid \rightarrow house}$	1.46E+04	7.29E+03	3.47E+03	3.47E+03	3.47E+03
PV production [kWh]	3.57E+04	1.73E+04	4.83E+03	4.83E+03	4.83E+03
Electricity potentially to be fed in the grid [kWh] - $E_{PV \rightarrow grid}$	1.16E+04	5.78E+03	3.15E+03	3.15E+03	2.99E+03
Energy losses due to fee-in curtailments [kWh]	---	---	0.00E+00	3.24E+00	1.66E+02

As for previous repurposing application, note that, according to the allocation considerations in Section 4.2.1, two different allocation factors, $\alpha = \beta = 0$ (case B1) and $\alpha = \beta = 0.25$ (case B2) are considered for the assessment.

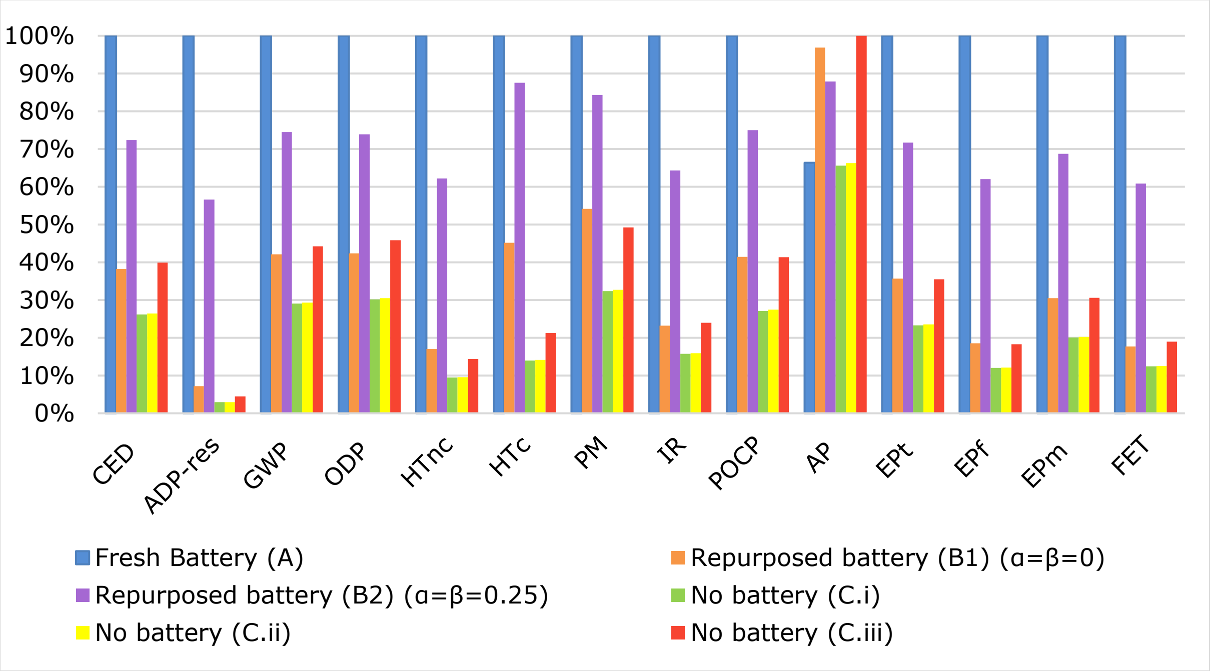
Quantitative data are detailed in ANNEX VII, whereas in the following paragraphs, the most relevant outcomes from the LCIA are described.

In order to compare the different scenarios, the yearly environmental impact was calculated (Figure 26). It is observed that the adoption of a repurposed battery revealed environmental benefits compared to the use of a fresh LMO/NMC battery for all the assessed impact categories.
The only exception is the AP impact category for which, even if the allocation of the

manufacturing and EoL impact of the battery pack are fully allocated to the first life ($\alpha = \beta = 0$), the adoption of a repurposed battery is not beneficial from an environmental perspective.

The configurations in which no batteries are used (C.i, C.ii and C.iii) have the lowest impacts for all the assessed impact categories. Environmental impacts also depend on the design of the system: the increase of local use of renewable energy is beneficial from an environmental perspective. Considering the potential existence of curtailments for the energy fed into the grid, it is observed that the configuration with high curtailments (i.e. C.iii) has a higher impact than the configuration in which a repurposed battery replace a fresh battery. Note that the considered PV installation is sized according to the energy requirement of the house. Results could be different in case of oversized installation.

Figure 26: Comparison between the different scenarios (for 1 year)

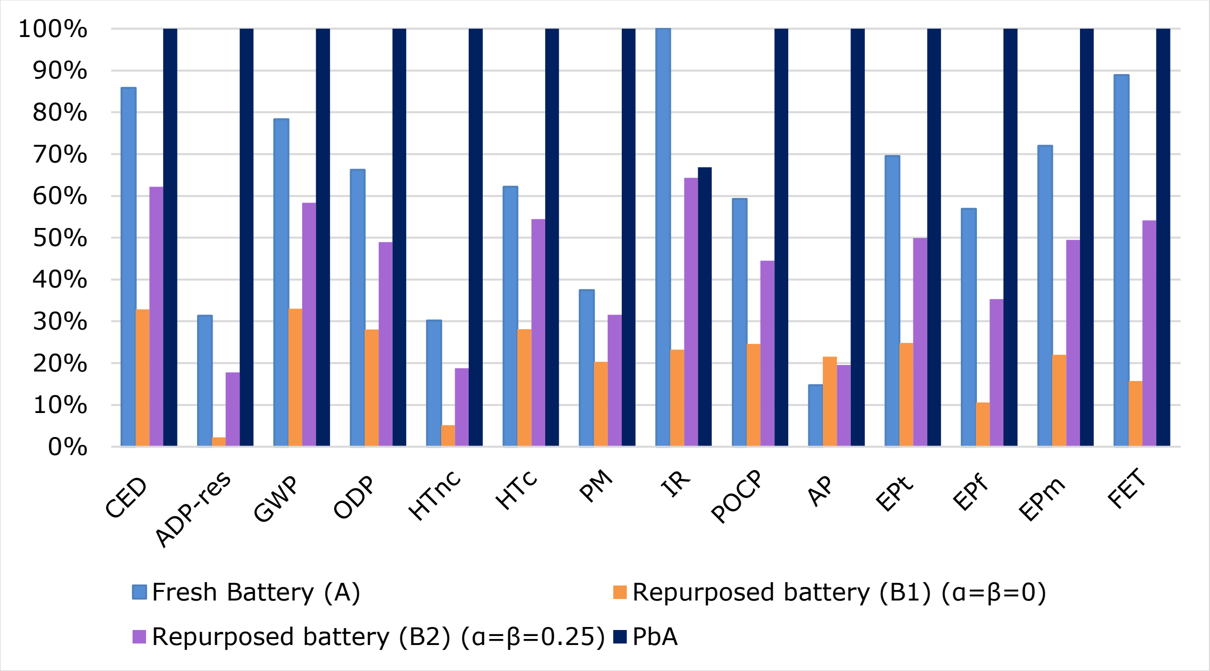


According to the main outcome of the literature review (section 4.1), a sensitivity analysis was performed in order to estimate the relevance of the energy mix used in the assessment and the relevance of the battery chemistry to the overall impacts (results are presented in ANNEX VII).

Concerning the **energy mix**, it is assumed that the house is stand-alone (e.g. on an island or in a remote location) and the energy not supplied by neither the PV installation nor the battery, is provided by a diesel-electric generator of 18.5 kW. The surplus of the energy generated by the PV is lost. Results depict that the adoption of a repurposed battery in a stand-alone configuration compared to its adoption in a grid-connected one is beneficial from an environmental perspective. The energy mix heavily affects the impacts of the assessed configurations and the . The adoption of a battery (either fresh or repurposed) revealed important environmental advantages compared to stand-alone configuration without any battery (C.i, C.ii and C.iii).

Concerning the **battery chemistry**, a PbA with a lifetime of 4 years (Rydh and Sandén, 2005) is considered. LCIA results show that the substitution of a PbA battery with a repurposed LMO/NMC is beneficial for all the assessed impact categories. This difference is mainly related to the losses related to the lower performance of PbA batteries compared to the LMO/NMC battery.

Figure 27: Comparison between the different increase of PV self-consumption systems (for 1 year)



To conclude, the environmental benefit of reusing a battery for the increase of PV-consumption, in this case, is beneficial to increase the self-consumption of a house in which a fresh LMO/NMC battery is substituted.

The adoption of repurposed batteries in stand-alone houses is beneficial according to the avoided energy mix (e.g. diesel-electric generator).

Finally, the adoption of PbA battery in place of repurposed LMO/NMC battery shows negative impacts for all the assessed impact categories. Note that, since the data used to model the PbA battery derived from the literature, a more detailed analysis is recommended.

4.5 Interpretation/Final remarks

The environmental assessment of the second-use application of an LMO/NMC battery was performed for two different applications: peak shaving and increase of PV-self consumption.

Work carried out:

In order to assess the benefits/drawbacks of second-use of LMO/NMC battery, the LCA was performed for both fresh batteries and repurposed batteries in such applications. The life-cycle stages directly affecting the impacts of the second-use of the battery are included in the assessment[70].
To model the impacts of the battery manufacturing, both primary[71] and secondary data were used. The repurposing stage was modelled through literature data and entailed the testing of the state-of-health of the LMO/NMC battery and the substitution of two components of the battery pack. According to the literature, it is assumed that the LMO/NMC battery is recycled through a pyrometallurgical process.
Concerning the use of the battery, the impacts of this stage strictly depends on the specific application. Therefore, the impacts of this phase were modelled separately and through the analysis of the energy flows of the two systems. Primary data concerning the energy requirement of the dwellings and PV production were combined with the LMO/NMC battery's characteristics in order to model the energy flows in both applications. Primary data from lab tests were used to model the degradation of the LMO/NMC battery.

The yearly impact of the adoption of repurposed xEV batteries is calculated for each application and for different configuration of the systems[72]. To enlarge the analysis, a PbA battery and a different energy mix are considered for assessing the relevance of some aspects affecting the LCA results.

Results of the performed assessment:

Concerning the adoption of a repurposed battery for a **peak shaving application** in a grid-connected office building in Italy, the LCA results showed that a repurposed LMO/NMC battery is environmentally beneficial *only* if it replaces a fresh battery (either a LMO/NMC or a PbA battery). The addition of a repurposed battery in a building in which no batteries were previously used does not entail benefits. .
Note that results of the LCA are affected by the energy mix used in the assessment, in particular to the feedstock providing the energy during the peak hours. In specific Countries, where differences in feedstocks are relevant, this is a relevant aspect to be assessed in the LCA (Messagie et al., 2014b).

If repurposed batteries are used to **increase the PV self-consumption** of a residential dwelling, *higher benefits* are observed compared to the previous application. The adoption of a repurposed battery in place of a fresh one (either LMO/NMC or PbA battery) entails environmental benefits due to the avoided battery manufacturing (in case of fresh LMO/NMC battery) or the higher performance of the Li-ion battery (if compared to a PbA battery). Moreover, in case of stand-alone houses, where the energy not provided by the PV installation is provided by generators, the adoption of a repurposed battery is *even more convenient*.

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[70] Impacts of the use of the xEV battery in the xEV is considered out of the system boundaries of this study

[71] The cells dismantling in the JRC Petten laboratories provided the bill of material used to model the environmental impact of the LMO/NMC battery cells

[72] A) fresh LMO/NMC battery is adopted in the system; B) repurposed LMO/NMC battery is adopted in the system; C) no batteries are adopted in the system.

Lessons learnt from the performed assessment:

Overall, the results of the assessment confirmed the findings of the literature. Importantly, results of the specific analysis helped us to identify the following relevant parameters to be considered in assessing the environmental performances of second-use of xEV batteries:

1) Along the study, the need of a detailed model of the use stage emerged as a relevant aspect of the assessment since this stage could importantly affect the overall impact. The clear understanding of this stage depends on the characteristics of both the system and the battery, and their relation.
    a. The system characteristics entail e.g. the load profile of the dwelling in which the battery is used, the energy sources of the system (e.g. PV installation, energy from the grid, generators).
    b. The battery characteristics refer, for instance to battery efficiency, battery (nominal/residual) capacity, etc. Batteries have different performances according to their first life, e.g. the energy density of batteries to be used in BEV is higher than the energy density of batteries for PHEV. Their capacity, at the end of the first life is also different and it should be considered when assessing the suitability of such a battery in a specific second-use application
    c. Characteristics of both the battery and the system should be complemented in order to identify the energy flows of the system and to estimate the lifetime of the battery according to the specific energy requirements of the system. The modelling of the real energy flow of the system could offer a better understanding of the system and real data could offer a more realistic overview of the real benefits related to the adoption of repurposed batteries.
2) Another relevant parameter to be considered in the assessment is the battery chemistry. There are different type of chemistries already available on the market, and their materials content, the production process and their size is relevant in terms of environmental impact. Moreover, changes in batteries' technology should be considered in the future when assessing the impacts of batteries second-use. In both the assessed applications, the impacts of the battery manufacturing, repurposing and EoL are not negligible for all the assessed impact categories in the study; environmental benefits are observed if repurposed batteries avoid the adoption of fresh batteries.

Environmental results may considerably vary at varying the above mentioned parameters. According to the LCA results and the above mentioned considerations, further analyses are needed to enlarge the assessment considering different case-studies (especially if renewable energy sources are used to charge the batteries).

Other findings:

Allocation of the impacts of manufacturing and EoL stages along the first and the second life of products is still an open issue and several approaches coexist in the scientific literature. This issue was addressed by introducing two allocation factors and assessment results pointed out their relevance in terms of changes of the environmental impact. This methodological aspect should be addressed more in-depth, also because the creation of a market for second-use applications of xEV batteries could affect the choice of the value of these allocation factors and, consequently, the environmental benefits/drawbacks of second-use of xEV batteries.

Further work

Although some preliminary results were obtained on some specific cases, more efforts in this research field are needed to fully grasp the environmental performances of second-use applications, taking into account parameters listed above.

Literature data adopted to build the energy and the LCA models should be substituted by lab and real data in order to obtain more robust results. Once the results of the lab test for the PV firming and PV smoothing applications will be available, the method developed during the SASLAB project could be applied to these two applications. Furthermore, it may be applied also to frequency regulation, especially considering that the TSO (Transmission System Operators) stakeholders shows especially high interest on frequency regulation ancillary services for relatively high potential revenues (Thien et al., 2017).

Finally, if second-use of xEV batteries will occur in Europe, the technological developments related to batteries should be considered in assessing the potential environmental benefits/drawbacks of their second-use. New technologies are expected to enter in the market (Berckmans et al., 2017; Lebedeva et al., 2016); as an example, the investigated chemistry LMO/NMC is last generation as compared to e.g. NMC 622 which is currently used in Chevrolet Bolt (with higher energy density). In general, the higher density of the next generation batteries will potentially result in higher lifetime and potential opportunities of reuse in different applications.

CHAPTER 5
Social Assessment

5.1 Qualitative assessment

This section introduces some insights concerning social performances of the start of the value chain (from extraction of raw materials to production of materials) of xEV batteries.

Battery electric vehicles are developed with the awareness that conventional fossil fuelled vehicles are not sustainable in the long term and will yield a collapse of the whole economic, environmental and social system. The roll-out of battery electric vehicles can solve pertinent environmental impacts (for instance urban air quality and climate change) when managed properly. However, the development of the battery electric vehicle ecosystem also requires great quantities of key raw materials and might imply relevant social implications in the supply chain. This is why it is important that social impacts are considered (and when possible avoided) from a whole system perspective. The main remaining question is what the social impacts are linked to battery production. Social supply chain risks are becoming pertinent for vehicle manufacturers as inability of full accountability of impacts induced at supplier side can harm their business.

In principle, a lithium battery exists out four main subcomponents, being the anode, cathode, separator and electrolyte. Many different chemistries exist, influencing the performance of the battery. The production of the various materials for the four main subcomponents will have different impacts. In line with findings of chapter 4 for the environmental assessment, resource extraction also contributes significantly to social impacts of batteries. The first focus for social impacts is on the mining of the metals for the cathode, as the cathode of a lithium battery has been proven to be the most impactful component when it comes to environmental impacts and material criticality (Oliveira et al., 2015).

The cathode contains several metals in an alloy. The most frequently used are: lithium, nickel, manganese and cobalt (Gopalakrishnan et al., 2017).

Based on the four metals - lithium, nickel, manganese and cobalt - a first screening of social impacts induced by the mining sector in various countries of origin has been conducted.

The geographical dispersion of the metal ores is of relevance as poorer countries with abundance of resources have worse development indexes than those well-endowed. Mineral extraction activities can be related to corruption and armed conflicts and the specific national and/or local labour conditions differ greatly and therefore have a strong influence on the social impact (Oliveira et al., 2015). Following list of countries of origin are identified for the different materials.

Lithium resources are found in countries like Argentina, Australia, Austria, Afghanistan, Brazil, Bolivia, Canada, Chile, China, Finland, Russia, U.S., Congo, and Zimbabwe. However, three countries, Argentina, Bolivia and Chile, together hold 70% of the mining market (Chung et al., 2015). **Manganese** is one of the main materials in use in NMC and LMO batteries for battery electric vehicles. South Africa is by far the world's largest producer of manganese followed by China (Steenkamp and Basson, 2013). **Cobalt** is mined in Canada, Australia, Russia and Brazil but the most important mining nation is Democratic Republic of Congo which accounts for 50% of global production. The principal **nickel** mining nations in the world today are Russia, Brazil, Australia and Canada.

The main identified social supply chain risks of resource extraction of the four selected metals are: bad labour conditions, conflicts between small-scale and large- scale miners, water scarcity and contamination, and resettlement of local communities.

The presence of artisanal mining is largely practised in Africa. The sector of artisanal mining is often unregulated and based on manual labour and hand tools yielding bad labour conditions. In Democratic Republic of Congo, where around 110.000 miners are involved, a large part of the artisanal liners are children working in cobalt mines lacking basic protection equipment and assistance (Amnesty International, 2016; The Washington Post, 2016; Zubi et al., 2018). Conflicts can arise between artisan at small-scale miners and large-scale mining companies when competing for the same resources and land (Liskowich, 2016).

Different environmental and social impacts are involved during the lithium extraction process. Highlighted impacts that harm communities, ecosystem, soil and food production are water pollution, depletion and the release of toxic chemicals. The extraction of lithium can cause conflicts with local communities when it limits access to water.

Involuntary resettlement can occur when a new mining site is developed, creating a large impact on local communities. To avoid conflicts, a strong coordination is needed between local authorities and mining companies. The inability of some local authorities to coordinate the interests of the local communities is often a weak point.

Companies also need to be proactive in identifying the social risks and implement management structures to avoid them.

From this short scan of social impacts it is very clear that a further detailed analysis is needed to pinpoint the specific social impacts during mining and manufacturing lithium batteries. In order to map potential burden shifts throughout the supply chain it is recommended to use the Social Life Cycle Assessment framework as proposed by SETAC (UNEP Setac Life Cycle Initiative, 2009).

5.2 Initial quantitative Social Life Cycle Assessment (SLCA) of Lithium-ion batteries

This section aims at providing an overview about the SLCA methodology used to evaluate the social impacts related to the extraction and mining phases of the main raw materials involved in the production of positive electrode (cathode) in LIB: lithium, cobalt, nickel and manganese. The section also contains some initial rough assessments with SLCA, adapted from (Eynard, 2017).

For this purpose, we used the Product Social Impact Life Cycle Assessment (PSILCA) database (Eisfeldt, 2017)[73]. The underlying reasons for this choice are that PSILCA is the most updated available data source with transparent documentation of original data sources and risk assessment. The software used for calculations was openLCA v 1.6.3.

In order to select the relevant impact categories for the evaluation of social risks from those present in PSILCA, we used a selection of indicators developed for the assessment of social risks in the raw materials industries, as in (Mancini et al., 2018). Table 15 shows the list of impact categories and indicators selected for this work.

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[73] A. Ciroth and F. Eisfeldt, "PSILCA - A Product Social Impact Life Cycle Assessment database. Documentation." 2016.

Table 15: Selected impact categories and indicators to be considered in SLCA according to Mancini et al. (2018)

Impact category	Indicators	Unit of measurement	Sector-specific
Child labour, total	Children in employment, total	% of children	No
Contribution to economic development	Contribution of the sector to economic development	% of GDP	Yes
	Illiteracy rate, female	%	No
	Illiteracy rate, male	%	No
	Illiteracy rate, total	%	No
	Public expenditure on education	%	No
	Youth illiteracy rate, female	%	No
	Youth illiteracy rate, male	%	No
	Youth illiteracy rate, total	%	No
Corruption	Active involvement of enterprises in corruption and bribery	%	No
	Public sector corruption	# per 10000 employees	No
Fair salary	Living wage, per month	USD	No
	Minimum wage, per month	USD	No
	Sector average wage, per month	ratio	Yes
Frequency of forced labour	Frequency of forced labour	‰	No
Freedom of association and collective bargaining	Right of Association	score	Yes
	Right of Collective bargaining	score	Yes
	Right to Strike	score	Yes
	Trade Union density	%	No
Health and Safety (Workers)	DALYs due to indoor and outdoor air and water pollution	DALY rate	No
	Presence of sufficient safety measures	DALYs	Yes
	Rate of fatal accidents at workplace	# per 100'000 employees	Yes
	Rate of non-fatal accidents at workplace	# per 100'000 employees	Yes
	Workers affected by natural disasters	%	No
Gender wage gap	Gender wage gap	%	Yes
Industrial water depletion	Level of industrial water use (related to total withdrawal)	%	No
Migration	International Migrant Stock	%	No
	International migrant workers in the sector	%	Yes
	Net migration rate	‰	No
Respect of indigenous rights	Presence of indigenous population	yes/no	No
	Human rights issues faced by indigenous people	score	No
Working time	Hours of work per employee, per week	h of work per employee and week	Yes

For a reliable SLCA study, country-, sector- as well organization- and site-specific data are needed. In this study, the purpose is to provide a basis for more specific investigations. Therefore, we used data provided by PSILCA database for the comparison, and we did not dispose of primary social data.

The amount of materials composing the cathode was taken from the bill of materials developed within SASLAB and according to the available inventory data (section XXX). We assume that processes take place in the major world producer countries. Production data and prices are for example available in raw material profiles (to be) provided by the Raw Materials Information System (RMIS) developed by European Commission[74].
We used generic PSILCA sectors datasets due to the lack of primary data. Table 16 resumes the main information on the LC inventory.

Figure 28 shows the results of the social impact assessment of the main cathode materials[75]. Results of the SLCA are measured in "medium risk hours" (according with the methodology guidelines, (UNEP Setac Life Cycle Initiative, 2009)). LCIA results refer to the extraction phases (and upstream processes) of selected materials. In this case, results are relative, as normalized values: for each indicator, the maximum result is set to 100% and the results of other options are displayed in relation to 100%.

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[74] http://rmis.jrc.ec.europa.eu/ (Section Raw Materials' flows / Raw Material Profiles)

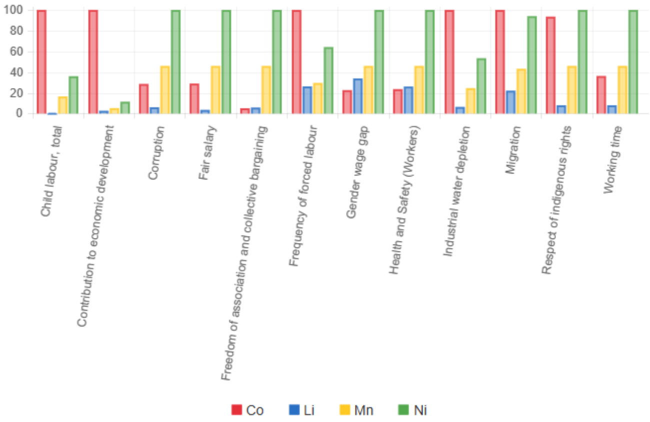
[75] Results are calculated applying a cut-off criteria of 10^{-4}.

Table 16: Social Life Cycle Inventory (S-LCI) for selected materials

	Major World producers*	PSILCA sector	Material / battery [kg]	Price [USD/kg]	Price Source	Notes
Cobalt	DRC	Mining and Quarrying	2.3	25.7	Data from Cobalt Development Institute (2016)	Proce for Co high grade; average on the period December 2015 - November 2016
Lithium	Chile	Other minerals	2.7	7.1	Data from DERA (2016)	Price for Lithium carbonate; average on the period December 2015 - November 2016
Manganese	China	Non-ferrous ore mining	25	2	InfoMine website (2016)	Global Mn prices
Nickel	China	Non-ferrous ore mining	6.5	16.8	Data from DERA (2016)	Average price of primary Ni (> 99.8 %) between 2011 and 2015

*Data for production from BGS World Mineral Statistics database

Figure 28: Relative impact category results of the respective materials contained in a cathode (screenshot from openLCA)



Impact category	Co [medium risk hours]	Li [medium risk hours]	Mn [medium risk hours]	Ni [medium risk hours]
Child labour, total	733.39	3.01	119.79	261.62
Contribution to economic development	2,341.98	67.79	38.30	83.64
Corruption	774.11	124.07	1,224.28	2,673.83
Fair salary	832.31	73.57	1,300.74	2,840.82
Freedom of association and collective bargaining	155.32	139.73	1,359.81	2,969.82
Frequency of forced labour	7.86	2.04	2.29	5.00
Gender wage gap	12.95	25.27	25.94	56.65
Health and Safety (Workers)	137.64	124.33	264.91	578.56
Industrial water depletion	70.05	3.14	16.96	37.03
Migration	9.28	1.75	3.96	8.64
Respect of indigenous rights	56.83	2.97	27.52	60.10
Working time	1.44	0.24	1.80	3.92

Results depend to a large extent on prices of components, on the quantity of materials used in the processes and on the countries where the production is located, according the methodology. Nevertheless, results allow highlighting social risks for the materials involved in the cathode production.

As shown in Table 15 some indicators are based on data provided only on country level but they are not sector-specific (e.g. child labour). Results highlight that the occurrence of negative social impacts strongly depends on the socio-economic and political situation of the country.
Cobalt and nickel mining have the highest risks among selected impact categories. As mentioned in the previous section (5.2), in the DR Congo, labour conditions are very critical and results of the study confirm high risks of children in employment and forced labour.
As for nickel mining, high impacts are linked to the high amount of material involved in the cathode production.
It is underlined that the modelling of Mn and Ni mining (in China) refers to the same PSILCA sector (i.e. "Non-ferrous ore mining, China"). However, the social impact of Mn is lower than Ni due to its very low price (2 USD/kg compared to 16.8 USD/kg for nickel).

Results underline lithium extraction as the process with the lowest risk in almost all categories. Contrary to expectations (Buratovic et al., 2017), the impact category industrial water depletion shows a very low impact for lithium extraction. The reason is that data available for this impact category does not refer to a specific mining sector.

Results from the SLCA shows that the methodology can confirm in many cases qualitative previsions about social impacts and give quantitative results. The interest about SLCA is increasing and many studies have been carrying out so far even if it is in its first stages and international standards are not available yet.
This overview aims at giving some insights on the potentiality of performing a SLCA in the battery sector and it is used as a first screening and overview for future analyses. In fact, data related to social impacts are often missing or affected by uncertainty and, as previously stated, more efforts are needed in terms of both data quality and data availability. For this reason, the first step for a more detailed study could be to start creating a survey specifically adapted to that kind of companies and mining or industrial processes.

A further possible development of the study could be the inclusion of the end-of-life phase of the battery cathode, in particular considering the potential benefits/drawbacks of recycling the assessed materials. Indeed, illegally shipped batteries to developing countries from Europe, and/or a not proper collection and treatment of Li-ion batteries could entail risky social and environmental conditions in some specific countries. This phase is therefore a potential source of several social impacts that due to the informal nature of these processes are often overlooked by statistics.

This section introduced some insights and initial assessments concerning social performances of the production of materials contained in xEV batteries. Considering all the shortcomings and hypothesis presented above, these initial results should be handled with great care. Of course, to better serve the purpose of SASLAB, and in order to be consistent with the LCA study presented in chapter 4, this preliminary SLCA assessment should be further enlarged and should also cover collection, repurposing and reuse stages. For this, primary data should be collected from industrial partners and this would require specific efforts in potential follow-up initiative.

CHAPTER 6
Overall assessment of second-use application for xEV batteries and further work

6.1 Summary of the work

The increase of xEV in the worldwide market will translate in an increase of waste batteries to be treated at the end of their use in vehicles. After their use in xEVs, batteries have to be recycled according to the Directives in force (Batteries Directive and ELV Directive). Second-use of batteries can represent an interesting and viable option to face the global concerns on the CO_2 emissions and on energy security. Moreover, reuse of batteries before their recycling is also aligned with both the Waste Framework Directive 2008/98/EC (EU, 2008) and the 2015 Circular Economy action plan of the European Commission (EC, 2015c). However, this EoL option is challenged by the existence of some barriers, e.g. regulatory/economic/technical barriers, safety and responsibility issues. In this context, more efforts are required to provide "an adequate legal framework for second-life applications", for example in the forthcoming review of the batteries Directive (EC, 2017).

SASLAB project contributed to fill-in some of the existing knowledge gaps in assessing the sustainability of second-use of xEV batteries, especially according to the skills of the partners involved in the project[76]. The development of the SASLAB project proved the relevance of assessing second-use of xEV batteries from different perspectives. The analysis focused on both the technical and environmental assessment of second-use application of xEV batteries. Moreover, initial assessment about social aspects of specific materials embedded in batteries was carried out.

The better understanding of the **xEVs batteries value chain**, according to both the performed literature review and the contacted stakeholders, allows to identify the most relevant barriers to second-use application of xEV batteries: be the absence of a clear definition of "second-use" and a legal framework allowing second-use of batteries. The expected growth of xEV batteries in Europe was captured through the creation of a predictive and parametrized model to estimate batteries flows in Europe up to 2030. Through the model, specific aspects of Li-ion batteries and their potential second-use, e.g. the (residual) capacity of xEV batteries at different step of their value chain, the batteries' characteristics (e.g. SoH and energy density), the embedded materials (CRMs, lithium, etc.). Availability of SRMs along time could be estimated and positive/negative impacts related to the extension of the xEV batteries lifetime in terms of resources and energy could be assessed.

Used and fresh Li-ion batteries were tested in the JRC-Petten laboratories in order to identify the **technical suitability** of such batteries to be adopted in different second-use applications. Results so far proved that second-use of xEV batteries is feasible from a technical point of view, even though more results are expected. Moreover, an LMO/NMC battery cell was dismantled in order to provide a Bill of Materials based on primary data to be used for the environmental assessment.

Concerning the **environmental assessment**, an adapted Life Cycle Assessment (LCA) method was develop to assess the environmental performances of second-use of xEV batteries. This method was applied to two different case-studies: peak shaving of an office building located in Ispra (IT) and increase of photovoltaic (PV) self-consumption of a residential house located in The Netherlands. For both case-studies, the energy flows

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[76] The project was jointly proposed by Directorate C (Energy, Transport and Climate Directorate, Petten) and by Directorate D (Sustainable Resources Directorate, Ispra) in the context of the JRC Exploratory Research call 2015. Maarten Messagie, from the VUB University (Brussels), supported both JRC C1 and JRC D3 as an LCA expert in the automotive sector.

of the system were estimated through the adoption of primary data concerning the energy load profile of the dwellings in which batteries are adopted. This permitted to model real energy flows considering both the battery characteristics[77] and the system characteristics[78].

For the peak shaving application, results pointed out that a repurposed LMO/NMC battery is environmentally beneficial *only* if it replaces a fresh battery (either a LMO/NMC or a PbA battery). The addition of a repurposed battery in a building in which no batteries were previously used does not entail benefits.

Environmental benefits are observed also in case of increase of PV self-consumption of a residential house: a repurposed battery in place of a fresh one (either LMO/NMC or PbA battery) entails environmental benefits due to the avoided battery manufacturing (in case of fresh LMO/NMC battery) or the higher performance of the Li-ion battery (if compared to a PbA battery). Furthermore, if the residential house is a stand-alone houses (i.e. the energy not provided by the PV installation is provided by generators), the adoption of a repurposed battery is *even more convenient* from an environmental perspective.

In order to have a more complete **overview of the sustainability** of the adoption of xEV batteries in second-use applications, technical, environmental, social and economic assessments should be performed[79]. In this report, the economic assessment is not provided due to the lack of industrial data from stakeholders and reduction of human resources allocated to the project; however, existing studies on economic aspects revealed that there are opportunities to create new business cases. An overview on social aspects related to the extraction and mining of some of the embedded materials in xEV batteries was provided in the report. Results give some insights on the potentiality of performing a Social LCA in the battery sector and it is used as a first screening and overview for future analyses.

6.2 Further work: what's needed to have a more robust analysis?

A more in-depth analysis of the batteries flows along their value chain could offer relevant opportunities for tracking flows of materials through the supply chain of batteries. This is potentially relevant also to estimate the availability of specific secondary raw materials and to quantify the flows and stocks of CRMs embedded in batteries.

According to the built-up knowledge along SASLAB, the results of the **technical assessment** will contribute to develop a model for a SoH assessment of xEV batteries at the end of their first life to facilitate the choice for sending the batteries at the appropriate destination (e.g. Recycling, second life in a grid application for specific purposes, reuse in automotive applications). The developed methodology should be consolidated through future researches on batteries coming from different manufacturers and of different chemistries

From the **environmental assessment**, some relevant aspects to be considered in future analyses emerged. In particular: 1) the need of primary data concerning the energy flows of the system since the behaviour of batteries strictly depends on the specific conditions in which it is adopted, 2) the chemistry of the battery since it could affect the impacts of the manufacturing and the EoL, and therefore the life-cycle impact. According to the obtained results, environmental results may considerably vary at varying the above-mentioned parameters. Then, further analyses are needed to enlarge the assessment considering different case-studies (especially if renewable energy

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[77] e.g. battery efficiency, state of charge, battery capacity

[78] e.g. energy demand, renewable/grid energy sources

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

sources are used to charge the batteries) and to address some LCA methodological issues still open[80].

Economic and social aspects related to second-use of xEV batteries should be further explored in order to identify (and possibly quantify) the benefits/drawbacks of this emerging EoL option. In general, such information are often missing or affected by uncertainty. Then, in order to strength both the data quality and data availability, economic and social data need to be gathered along the whole batteries value chain and in strict collaboration with stakeholders.

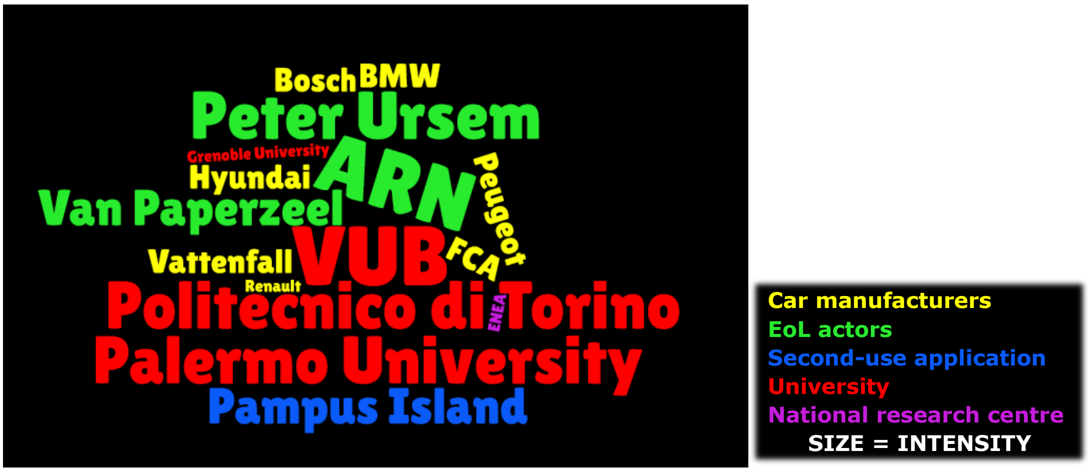
Finally, it is underlined that the technological development expected for the xEV batteries will affect the sustainability of their adoption in second-use applications from different perspectives (i.e. technical, environmental, social, economic). The market development of second-use of batteries will entail the next batteries generation, with higher energy density compared to those currently available in the market and also with different materials for their manufacturing. These aspects are crucial and should be taken into account when assessing the sustainability of xEV batteries second-use.

6.3 Further analysis and policy implications

The multidisciplinarity of the research team represented an added value in the SASLAB project. The collaboration and the knowledge of different aspects related to batteries permitted to adopt primary data to model the environmental performances of second-use of batteries. Finally, JRC.C.1 and JRC.D.3 participated in two successful Horizon 2020 project proposals, which cover aspects of second-use applications[81] and are now working together for the further developments of this research field.

The established **network** between different stakeholders (Figure 29) of the xEV batteries value chain could be an added value to further development and fill-in gaps, as above mentioned. For instance, the network could be strengthened and developed in order to contact relevant stakeholders dealing with repurposing of xEV batteries in order to better understand the processes of the repurposing stage, for which information are still lacking.

Figure 29: Representation of diversity and intensity of the established SASLAB network



Source: own elaboration)

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[80] E.g. the allocation of the manufacturing and EoL impacts to the first and second lives is addressed in the developed model through the adoption of specific parameters.

[81] CarE-Service (Circular Economy Business Models for innovative hybrid and electric mobility through advanced reuse and remanufacturing technologies and services) and LiBforSecUse (Quality assessment of electric vehicle Li-ion batteries for second use applications)

In the picture, the size of words represents the intensity of the relations between JRC teams and the stakeholders. Colours refer to the stakeholder "category", i.e. Car manufacturers, EoL actors, Users of second-life batteries, Universities, national research centres.

6.4 Policy implications

The policy interest in this topic was also underlined by the fact that the experience developed in SASLAB project already supported several policy activities that had not been foreseen at the beginning of the project: in particular, JRC teams participated in the process of the Batteries Directive Review during the ISG meetings and they were invited to contribute to the Innovation Deal on "From E-Mobility to recycling: the virtuous loop of the electric vehicle"[82].

Moreover, building on SASLAB work, reuse of batteries has been cited in two Commission staff working documents, "Report on Critical Raw Materials and the Circular Economy" (SWD(2018)36 final) and "Report on Raw Materials for Battery Applications" (SWD(2018) 245).

Current (and future) policy interests in the field of battery repurposing were actually discussed with several policy DGs of the European Commission during a workshop at JRC headquarters in June 2018. The main technical and environmental results of the SASLAB project as well as the lessons learnt on EV batteries reuse were discussed with DG RTD, DG ENV DG GROW and DG ENER. Some outcomes and further work opportunities of the workshop are illustrated in the following list:

- SASLAB results could be useful for: the on-going Waste Battery Directive review (that should strengthen the collection rate for industrial batteries, and should include recycling-reuse provisions), for the future end-of-life vehicles Directive review, for possible preparation of Ecodesign regulation on batteries, for raw material policy (including Battery Alliance) and for Innovation Deals;
- Further work opportunities to better support policies to be considered include:
    - how much of battery capacity available for repurposing can be absorbed by society?
    - do multiple services at the same time make sense (i.e. EV providing other services such as Vehicle-to-grid)?
    - what are the technical measures for improved business case (e.g. universal BMS, gathering info from first use to minimise effort for repurposing)?
    - How can safety during transport of used batteries be improved (EV battery in car may be transported, but EV battery alone is considered hazardous good)?
    - How could the analysis be enlarged to consider other applications (e.g. mobile second life charger; stationary battery off shore to quickly charge ships / storage in combination with fast charging installation) and batteries chemistries. Also, how could specific system characteristics (e.g. regulations related to electricity) be taken in account?
    - How relevant aspects (e.g. technological development (e.g. solid state batteries, fast chargers); mobility patterns (car sharing, automated

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[82] http://ec.europa.eu/research/innovation-deals/index.cfm?pg=emobility

  - vehicles, etc.) and their consequences in EV batteries lifetime) could be better considered in the assessment? ;
  - How could economic performances be assessed in order to identify the potential barriers/drivers for second-use of EV batteries.

6.5 Conclusions

In conclusion, the report describes the activities and the main results developed during the exploratory research SASLAB project. The high level of interest is highlighted for different actors (both industrial and policies bodies), and results show that the extension of the lifetime of traction batteries after their use in xEV could be a sustainable EoL option.

Along SASLAB project, an assessment framework (including both experimental and modelling aspects) of an emerging EoL option has been developed and it is now ready to be used for enlarging the assessment further.

Results of the assessment pointed out that second-use of xEV batteries could be technical viable and environmental benefits exist, even though more efforts to include more applications, chemistries and system are needed.

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SASLAB Publications

Scientific papers

S. Bobba, A. Pfrang, F. Ardente, G.A. Blengini, A. Podias, F. Mathieux, M.A. Cusenza, Life Cycle Assessment of repurposed electric vehicles batteries: an adapted method based on modelling of energy flows, Journal of Energy Storage (2018), 19,2013-225, doi: 10.1016/j.est.2018.07.008

M.A. Cusenza, S. Bobba, F. Ardente, F. Di Persio, M. Cellura, Energy and environmental assessment of a traction lithium-ion battery pack for plug-in hybrid electric vehicles, submitted to Journal of Cleaner Production

A. Podias, A. Pfrang, F. Di Persio, A. Kriston, S. Bobba, F. Mathieux, M. Messagie, L. Boon-Brett, Sustainability Assessment of Second Use Application of Automotive Batteries: Ageing of Li-Ion Battery Cells in Automotive and Grid-scale Applications, World Electric Vehicle Journal (2018), 9(2), 24, doi: 10.3390/wevj9020024

Presentations at conferences

F. Di Persio, A. Pfrang, A. Podias, S. Bobba, F. Mathieux, M. Messagie, Sustainability Assessment of Second Life Application of Automotive Batteries, Batteries 2020 workshop (Brussels, 2016)

F. Di Persio, A. Pfrang, A. Podias, S. Bobba, F. Mathieux, M. Messagie, Sustainability Assessment of Second Life Application of Automotive Batteries (SASLAB), ICBR International Congress for Battery Recycling 2016 (Antwerp, 2016)

A. Podias, A. Pfrang, F. Di Persio, A. Kriston, S. Bobba, F. Mathieux, M. Messagie and L. Boon-Brett, Sustainability Assessment of Second Life Application of Automotive Batteries: Preliminary results on ageing of Li-ion cells in automotive applications and power grid support, Advanced Battery Power 2017 conference (Aachen, 2017)

A. Podias, A. Pfrang, F. Di Persio, A. Kriston, S. Bobba, F. Mathieux, M. Messagie and L. Boon-Brett, Sustainability Assessment of Second Life Application of Automotive Batteries: Ageing of Li-Ion Battery Cells in Automotive and Grid-scale Applications, EVS30 Symposium (Stuttgart, 2017)

S. Bobba, G. A. Blengini, F. Di Persio, A. Podias, A. Pfrang, M. Messagie, F. Mathieux, Second use of traction Li-ion batteries: an investigation of environmental performances based on material flow analysis, ICBR International Congress for Battery Recycling 2017 (Lisbon, 2017)

S. Bobba, F. Mathieux, A. Pfrang, G. A. Blengini, Environmental assessment of potential second use of traction Li-ion batteries, Circular economy perspectives for future end-of-life EV batteries (Brussels, 2017)

A. Pfrang, A. Podias, S. Bobba, F. Di Persio, M. Messagie, F. Mathieux, Second Life Application of Automotive Li-Ion Batteries: Ageing During First and Second Use and Life Cycle Assessment, Transport Research Arena (Vienna, 2018)

S. Bobba, F. Ardente, F. Mathieux, G. A. Blengini, F. Di Persio, A. Pfrang, M. Messagie, Life Cycle Assessment (LCA) of repurposed traction Li-ion batteries in storage second-use applications, ICBR International Congress for Battery Recycling 2018 (Berlin, 2018)

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Annex I – Questionnaires

1. Questionnaire for the chain of processes - Car companies -

General information on the company

1. Brief description of the company activity
2. What kind of battery chemistries is mainly adopted by the company (NiMH vs. Li-ion: LFP / NMC / …)?

Batteries after EV use.

1. Please describe the current flow of batteries after being dismissed from the EV (Electric Vehicle): storage, collection, second-hand exports, main reuse/recycle/recovery routes.
2. How many tons of waste EV batteries (if any) does the company produce annually? Alternative: How many cars (which size/mass of battery per car)?
3. Where do waste EV batteries (if any) go when leaving the company?
4. What is the ownership model for EV batteries (owned by the company or by car owner?)
5. How the producer responsibilities, as set in the "End of Life Vehicle" Directive, apply to the EV battery?

Final considerations and future developments

1. Do you expect in the near future any changes in the batteries usage (including changes in the amount and type of batteries)?
   ☐YES ☐NO
   If yes: what change? why?
2. What are the main difficulties observed in the adopting different batteries typologies (technical and/or economic aspects)?
3. What are the second life applications that you consider most attractive for EV batteries (frequency regulation, other grid services, residential household applications e.g. in combination with solar, enabling EV charging at limited grid connectivity, others)?
4. Please specify these applications in more detail (current rates, calendar life, other requirements)
5. May you suggest some other representative actors of batteries repurposing/second life applications in the EU?
6. Do you have some collection/handling systems in place?

2. Questionnaire for the chain of processes

- Waste batteries collectors -

General information on the company

1. Briefly describe your activity and the main steps during the collection of batteries (from the reception to the sorting of each fraction)? How is the battery collection done (organized collection system / purchase of batteries / …)?
2. Have you any management system (quality, environment) implemented in your company? (if yes: Can you provide additional information on what data you monitor?)

Collection system of waste batteries – general understanding

1. Please describe the current flow of batteries after being dismissed from the EV (Electric Vehicle): storage, collection, second-hand exports, main reuse/recycle/recovery routes?
   ☐YES ☐NO
   If yes, can you briefly describe the batteries flows?
2. How many tons of waste batteries do you collect annually? Of which type (chemistry) of batteries?
3. Is this amount growing annually?
   ☐YES ☐NO
   If yes, what is the annual growth?
4. Where are the waste batteries from (is the collection based in your Country / in the EU)?
5. From what actors the waste batteries are mainly collected?
   ☐citizens;
   ☐car companies;
   ☐________________
6. While leased batteries remain ownership of an OEM, often the car owner also owns the battery. How to deal with different EV battery ownership models? How this can affect the batteries collection system?
7. Do you have information about the origin of batteries (e.g. exhausted batteries, accidents, …)?
8. Do you consider the characteristics of collected batteries for further treatment or do you collect all the exhausted batteries (chemistry / residual capacity…)?
   ☐YES ☐NO
   If yes,
    a. how these characteristics influence the batteries collection system (e.g. selection of batteries, particular procedures, …)?
    b. Is there any difference in the collection of different type of batteries?
9. Can you share any experience on possible circumstances beyond stakeholder control that may affect the cost of collection?

..before the repurposing of batteries

1. Are you involved in repurposing of batteries?
2. Are there some tests performed for assessing the state of health before the next step of the chain?

   ☐YES ☐NO

   If yes,

   a. which kind of tests?
   b. once the tests are performed, on which level (cell, module or pack level) are components discarded?
3. What is the share of collected batteries going to recycling? To repurposing? Are there any collected batteries which are not delivered to any recyclers or repurposing plants?
4. Where are they “treated” (place and duration of storage / where are they sent / …)?
5. Who are the customers for the collected batteries? Are they based in your Country?

   ☐YES ☐NO

   If no, where to?

Final considerations and future developments

1. What are the main difficulties observed and faced within the collection of batteries (technical and/or economic aspects)?
2. Is the collection of the used batteries organized? How the collection system could be organized and/or improved?
3. Do you expect in the close future any changes in the batteries collection system (including changes in the amount of waste treated)?

   ☐YES ☐NO

   If yes: what change? why?
4. Can you share any best practices to be recommended about the collection of waste batteries?
5. May you suggest some other representative actors of batteries repurposing in the EU?

3. Questionnaire for the chain of processes - Repurposing companies -

General information on the company

1. Briefly describe your activity and the main steps of the repurposing of batteries (from the reception to the sorting of each fraction)? How the batteries repurposing occur (organized collection system / purchase of batteries / …)? To what extent it is applied manual/automated extraction, sorting, testing?
2. Have you any management system (quality, environment, safety) implemented in your company? (if yes: Can you provide additional information on what data you monitor?)

Collection system of waste batteries – batteries delivery

1. Do you have a clear understanding about the flows of batteries storage, collection, second-hand exports, main reuse/recycle/recovery routes?

   ☐YES ☐NO

   If yes, can you briefly describe the batteries flows?
1. How many tons of batteries are delivered in the repurposing plant annually? Is this amount growing?

   ☐YES ☐NO

   If yes, what is the annual growth?
2. Where are the waste batteries from (is the collection based in your Country / in the EU)?)?
3. From what actors the waste batteries are mainly delivered?

   ☐citizens;

   ☐car companies;

   ☐Collectors;

   ☐________________
4. While leased batteries remain ownership of an OEM, often the car owner also owns the battery. How to deal with different EV battery ownership models? How this can affect the batteries repurposing?
5. What are the main differences between the batteries delivered by different collectors (type, amount, age, conditions, …)?

Collection system of waste batteries – repurposing process

1. What are the characteristics of the input batteries treated in the plant (amount, age, type, dimensions, origin, and status of the waste at the reception)? In how far could this information reduce the effort for refabrication?
2. What is the share of delivered batteries going to repurposing process? Are there any delivered batteries which cannot be repurposed?
3. How much is the residual capacity of the batteries after the retirement from automotive service (e.g. 80%)?

4. Which tests are performed for assessing state of health before proceeding to refabrication? Please describe the tests:
    a. Test:
    b. Key parameters:
5. What technologies do you use in the plant for the repurposing of batteries? If innovative technologies are used in your processes can you mentioned them?
6. Is there any difference in the treatment of different type of batteries?

Collection system of waste batteries – after the repurposing process

1. In how far does the wide variety of chemistries (supposing a Lithium-ion technology) impede second life applications (for the recycling industry different chemistries are an issue)?
2. Can you describe the destination of repurposed batteries after their treatment in your plant?
3. Which are the applications that you consider most interesting for second life batteries (frequency regulation, other grid services, residential applications e.g. in combination with solar, enabling EV charging at limited grid connectivity, others)?
4. Please specify these applications in more detail (current rates, calendar life, other requirements)
5. How can a sufficient level of safety for second life applications be ensured?
    a. Which safety tests would be required (e.g. on aged batteries)?
    b. Which organizational measures are required?
6. What the most relevant economic aspects concerning the potential second life applications?
7. Where do waste batteries (if any) go when leaving the company?

Final considerations and future developments

1. What are the main difficulties observed in the repurposing of batteries (technical and/or economic aspects)?
2. What are the current problems faced within the repurposing of batteries? What should be improved?
3. Do you expect in the close future any changes in the batteries repurposing processes (including changes in the amount of waste treated)?
   ☐YES ☐NO
   If yes: what change? why?
4. Can you share any best practices to be recommended about the repurposing of waste batteries?
5. May you suggest some other representative actors of batteries repurposing in the EU? And of second life batteries applications?

4. Questionnaire for the chain of processes - Actors using repurposed batteries -

General information on the company

1. Briefly describe your activity
2. Have you any management system (quality, environment, safety) implemented in your company? (if yes: Can you provide additional information on what data you monitor?)

Collection system of waste batteries – purchased repurposed battery

1. Do you have a clear understanding about the flows of batteries storage, collection, second-hand exports, main reuse/recycle/recovery routes?
2. How many batteries do you install/use annually? Is this amount growing annually?
   ☐YES ☐NO
   If yes, what is the annual growth?
3. Where are the waste batteries from (is the collection based in your Country / in the UE)?
4. Since when does your company use repurposed batteries?
5. While leased batteries remain ownership of an OEM, often the car owner also owns the battery. How to deal with different EV battery ownership models? How this can affect the second life batteries market?
6. Are there any characteristics/tests you need to know before purchasing a repurposed battery?
   ☐YES ☐NO
   If yes, can you describe these characteristics/tests?
7. How can a sufficient level of safety for second life applications be ensured?
   a. Which safety tests would be required (e.g. on aged batteries)?
   b. Which organizational measures are required?

Collection system of waste batteries – second life application

1. What are the most relevant economic aspects concerning the potential second life applications?
2. What is the typology of batteries (e.g. chemistry) you mostly install/use? Why?
3. In how far does the wide variety of chemistries (supposing a Lithium-ion technology) impede second life applications (for the recycling industry different chemistries are an issue)?
4. Which are the applications that you consider most interesting for second life batteries (frequency regulation, other grid services, residential applications e.g. in combination with solar, enabling EV charging at limited grid connectivity, others)?
   Which are the applications that you actually use second life batteries for?
5. Please specify these applications in more detail (current rates, calendar life, other requirements)

6. Do you combine different batteries in the same application or do you only use a specific type of battery for a specific application?
7. Who are the customers for the collected batteries? Are they based in your country? If not, where to?
8. Do you directly deal with the EoL of batteries after their second life application? Can you describe the EoL chain (disassembly, recycling, recovery, disposal..)?

Final considerations and future developments

1. What are the main difficulties observed in the second life batteries application (technical and/or economic aspects)?
2. What are the current problems faced within the second life application of batteries? What should be improved?
3. Do you expect in the close future any changes in the second life application of batteries (including changes in the amount of installed/used batteries)?
   ☐YES ☐NO
   If yes: what change? why?
4. Can you share any best practices to be recommended about the second life application of batteries?
5. May you suggest some other representative actors of batteries repurposing in the EU?

5. Questionnaire for the chain of processes
- Experts -

General understanding of the process

1- Do you have a clear understanding about the flows (also from a geographical point of view) of batteries: storage, collection, second-hand exports, main reuse/recycle/recovery routes? Can you describe it?

Collection system of waste batteries

1- What are the most important factor affecting the waste batteries collection?
☐ leased batteries;
☐ chemical characteristics;
☐ organized collection;
☐ actors network;
☐________________
☐________________
☐________________
☐________________
☐________________
☐________________

2- What are the main difficulties for an organized waste batteries collection system (technical and/or economic aspects)?

3- Can you mention any best practices to be recommended for improving the waste batteries collection system?

Repurposing process waste batteries

1- What are the most important factor affecting the repurposing process of batteries?
☐ leased batteries;
☐ market, collection system;
☐ chemical characteristics;
☐ actors network;
☐ need of tests
☐ available technology
☐ process efficiency
☐ potential second life application
☐________________
☐________________

2- Are there any specific characteristics/tests (if any) necessary before the repurposing process?
☐YES ☐NO

If yes, can you briefly describe them?

4- What are the main difficulties for the repurposing process of batteries (technical and/or economic aspects)?

3- Can you mention any best practices to be recommended for improving the repurposing process of batteries?

☐YES ☐NO

If yes, do you know any important actor within the repurposing process chain (in terms of treated quantities) who is already carrying out these best practices?

Second life application

1- What are the most important characteristics/tests (if any) necessary for identifying the potential use of a repurposed battery for a second life application?

2- Which are the applications you consider most interesting for second life batteries? Please specify these applications in more detail (current rates, calendar life, other requirements)

3- Please specify these applications in more detail (current rates, calendar life, other requirements)

4- Do you think that combining different batteries into the same application makes sense or is it advantageous to use only a specific type of battery for a specific application?

5- Where do waste batteries (if any) go after the second life application?

5- What are the main difficulties for the second life application of batteries (technical and/or economic aspects)?

4- Can you mention any best practices to be recommended for second life application of batteries?

☐YES ☐NO

If yes, do you know any important actor of the second life application of batteries who is already carrying out these best practices?

Final considerations and future developments

6. Do you expect in the close future any changes in the repurposing of batteries (including changes in the amount of waste treated and new second life applications)?

   ☐YES ☐NO

   If yes: what change? why?

7. May you suggest some representative actors of batteries repurposing in the EU?

-

Annex II – Existing second use activities

Table II.1 Recent activities and studies using second-life xEV LIBs for several second use applications

			Second Use Applications								
Paper Actors [Reference]	**Transmission & Distribution upgrade deferral**	**Energy arbitrage / energy time-shift**	**Area regulation / regulation service / frequency regulation)**	**Reserve capacity / Supplemental reserve / Backup supply**	**Grid System**	**Load levelling / Load shifting**	**Peak shaving/smoothing**	**Power quality**	**Demand charge management**	**Renewable Energy Sources (RES) Integration (e.g. PV Firming, power smoothing)**	**EV charging**
Peer-reviewed scientific publications and other studies											
ADEME (ADEME, 2011)				X						X	
Neubauer (Neubauer and Pesaran, 2011)			X		X			X			
Viswanathan (Viswanathan and Kintner-Meyer, 2011)			X								
Tong (Tong et al., 2013)										X	
Ahmadi (Ahmadi et al., 2014b)						X					
ELIBAMA (Tamiang and Angka, 2014)				X						X	
Faria (Faria et al., 2014)						X	X				
Heymans (Heymans et al., 2014)						X					
Koch-Ciobotaru et al. (Koch-Ciobotaru et al., 2015)										X	
Casals (Canals Casals et al., 2015)		X								X	
Neubauer (Neubauer et al., 2015c)							X				
Richa (Richa et al., 2015)				X							

Saez (Saez-de-Ibarra et al., 2015)				X							
Sathre (Sathre et al., 2015)										X	
Cready et al. (Cready et al., 2003)				X	X	X					
Narula et al. (Narula et al., 2011)	X	X	X								
Neubauer & Pesaran (Neubauer and Pesaran, 2011)	X		X					X			
Williams & Lipman (Williams and Lipman, 2011)	X	X	X	X		X			X	X	
Industrial activities											
European (EU)											
Daimler, The Mobility House, GETEC, REMONDIS (Morris, 2015a)					X					X	
Bosch, BMW, Vattenfall (Bosch, 2016; Kane, 2016)			X		X						
Nissan and Eaton (EATON, n.d.; Morris, 2016a)		X		X							
Renault and Connected Energy (Morris, 2016b)		X								X	
EDF, Forsee Power, Mitsubishi Motors Corp., Mitsubishi Corp. (Forsee Power, 2015)										X	
International											
GM and ABB, and Nissan with Sumitomo/ABB (Williams, 2011)				X							
4R Energy (joint venture between Nissan and Sumitomo Corporation) (Gordon-Bloomfield, 2015) (Sumitomo, 2014)		X					X				
BMW and BECK Automation (Morris, 2016c)										X	
FreeWire Technologies and Siemens (Morris, 2015b)											X
Spiers New Technologies (Ruoff, 2016; Technologies, 2015)				X			X				
R&D activities											
EU-funded projects											
ABattReLife (ABattReLife, n.d.)	No specific application was defined										
AlpStore (Alpstore, n.d.)					X						
Batteries2020 (Batteries2020, n.d.)									X	X	
Energy Local Storage Advanced system (ELSA) (ELSA, 2017)	X	X	X	X	X	X	X	X	X	X	

Netfficient (NETfficient - Storage for Life, n.d.)	No specific application is currently defined (at the moment this report was written)										
2Bcycled (ARN, 2014)										X	
International											
Batteries Second Use (B2U) – NREL (Center for Sustainable Energy, 2016; NREL (National Renewable Energy Laboratory), 2015)			X						X	X	
	4	**7**	**8**	**10**	**6**	**6**	**5**	**3**	**4**	**15**	**1**

Annex III - Life Cycle Inventory (LCI) of the battery pack and its components

Anode

The anode is composed of a copper current collector with a coat of negative electrode paste. The negative electrode paste consists mainly on graphite, small amounts of binder and solvent. Graphite can be divided into natural graphite and synthetic graphite. Based on Ellingsen et al. (Ellingsen et al., 2014) in this study it is assumed that the anode consists on synthetic graphite. Battery grade graphite from Econivent 3 is used as inventory for the synthetic graphite (Notter et al., 2010). With reference to the binder the most common are polyvinylidene fluoride (PVDF), polytetrafluoroethylene (PTFE), poly acrylic acid (PAA) and carboxymethyl cellulose (CMC) (Majeau-Bettez et al., 2011) (Ellingsen et al., 2014). In this inventory, the binder is assumed to be PAA and CMC. However, a sensitivity analysis is carried out in order to assess the influence due to the variation of the type of binder in the obtained impacts. N-methyl-2-pyrrolidone (NMP) solvent is applied to give the mixture a slurry texture. After the negative paste has been applied to the current collector, the solvent evaporates. The inventory data used for the anode of one cell are synthetized in Table III.1.

Table III.1: Inventory data for the anode of one battery cell

Components	Unit of measure	Mass	Source
Cu current collector	[g]	137.13	JRC Petten
Synthetic graphite	[g]	153.36	JRC Petten
Binder (PAA)	[g]	3.08	JRC Petten/Ellingsen et al. (2014)
Binder (CMC)	[g]	3.08	JRC Petten/Ellingsen et al. (2014)
Solvent (NMP)	[g]	149.54	Ellingsen et al. (2014)

Cathode

The cathode is composed of an aluminium current collector with a coat of positive electrode paste. The positive electrode paste is composed of the positive active material, the binder, and carbon black to improve the conductivity. Similarly to the negative electrode paste, NMP solvent is applied. The positive active material consist of 0.52 $LiMn_2O_4$ + 0.48 $LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$ (the mass proportion between the LMO and the NMC part was provided by JRC Petten laboratories). The corresponding upstream materials required to manufacture the positive active material are inferred from literature data (Majeau-Bettez et al., 2011)(Ellingsen et al., 2014). The binder is assumed to be PVDF (Ellingsen et al., 2014). Also, in this case a sensitivity analysis is carried out considering the employment of PTFE in order to assess the influence in the obtained results.

As in the anode manufacturing, after the positive paste application into the current collector, the solvent evaporates. Table III.2 show the inventory data used for the cathode.

Table III.2: Inventory data for the cathode

Components	Unit of measure	Mass	Source
Al current collector	[g]	48.73	JRC Petten
$LiMn_2O_4$ (LMO)	[g]	235.90	JRC Petten
Lithium nickel cobalt manganese hydroxide ($LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$) (NMC)	[g]	170.83	JRC Petten
Binder (PVDF)	[g]	17.25	JRC Petten/(Ellingsen et al., 2014)

Carbon black	[g]	22.18	JRC Petten/(Ellingsen et al., 2014)
Solvent (NMP)	[g]	182.93	(Ellingsen et al., 2014)

The inventory for the production of 1 kg of $LiMn_2O_4$ is taken from Econivent 3 database, while the inventory for the production of 1 kg of $LiNi_{0.4}Co_{0.2}Mn_{0.4}O_2$ is taken from Majeau-Bettez et al. (Majeau-Bettez et al., 2011).

Electrolyte

The electrolyte is made of lithium salt (lithium hexafluorophosphate – $LiPF_6$) and solvent, typically ethylene carbonate ($C_3H_4O_3$) (Notter et al., 2010). The amount of electrolyte per battery cell provided by the JRC Petten laboratories is 170.61 g. The corresponding amounts in terms of $LiPF_6$ and $C_3H_4O_3$ are estimated base on Ellingsen et al. (Ellingsen et al., 2014). The inventory data used for the anode are synthetized in Table III.3.

Table III.3: Inventory data for the electrolyte

Components	**Unit of measure**	**Mass**	**Source**
Lithium hexafluorophosphate ($LiPF_6$)	[g]	20.47	JRC Petten/Ellingsen et al. (2014)
Ethylene carbonate ($C_3H_4O_3$)	[g]	150.14	JRC Petten/Ellingsen et al. (2014)
Total	[g]	170.61	JRC Petten

Separator

The separator has the role of separating the cathode from the anode. It is a porous membrane based on polypropylene (PP) and sometimes includes a polyethylene (PE) middle layer (Nelson et al., 2011). According to Nelson et al. (Nelson et al., 2011) it is assumed that the separator is composed of PP (80%) and PE (20%) (Table III.4).

Table III.4: Inventory data for the separator

Components	**Unit of measure**	**Mass**	**Source**
Polypropylene (PP)	[g]	54.04	JRC Petten/(Nelson et al., 2011)
Polyethylene (PE)	[g]	13.51	JRC Petten/(Nelson et al., 2011)
Total	[g]	67.55	JRC Petten

Cell container

The cell container consists of the two aluminium and copper tabs and a multilayer assemblage made of the external steel metal case plus other polymeric components. According to the bill of material provided by the JRC Petten laboratories and to LCI published by Ellingsen et al. (Ellingsen et al., 2014) the cell container is modelled as shown in Table III.5. Table 6 shows the detail of the multilayer assemblage sub – components.

Table III.5: Inventory data for the cell container

Components	**Unit of measure**	**Mass**	**Source**
Tab aluminum	[g]	11.84	JRC Petten
Tab copper	[g]	25.21	JRC Petten
Multilayer assemblage	[g]	329.89	JRC Petten

Table III.6: Inventory data for the multilayer assemblage sub – components

Components	Unit of measure	Mass	Source
Steel	[g]	301.01	JRC Petten/(Ellingsen et al., 2014)
Polyethylene terephthalate, granulate	[g]	4.48	JRC Petten/(Ellingsen et al., 2014)
Packaging film	[g]	6.03	JRC Petten/(Ellingsen et al., 2014)
Polypropylene, granulate	[g]	18.38	JRC Petten/(Ellingsen et al., 2014)

Annex IV – Life Cycle Impact Assessment (LCIA) of the battery pack and its components

Table IV.1: Environmental impact assessment of one LMO/NMC battery pack manufacturing and contribution of the battery components, infrastructure, transports and electricity consumption for assembly

Impact categories	Unit of measure	Battery cells	Packaging	BMS	Cooling system	Facility	Transports	Electricity	TOT
CED	MJ	4.57E+04	5.86E+03	2.65E+03	1.26E+03	4.41E+01	1.58E+02	4.68E-01	5.57E+04
ADP-res	kg Sb $_{eq}$	2.39E-02	2.47E-03	4.83E-02	8.14E-05	2.05E-04	1.51E-05	7.63E-09	7.56E-02
GWP	kg CO2 $_{eq}$	2.16E+03	3.27E+02	1.81E+02	7.71E+01	4.02E+00	9.81E+00	2.09E-02	2.76E+03
ODP	kg CFC-11 $_{eq}$	2.10E-04	2.16E-05	1.36E-05	5.43E-06	2.44E-07	1.69E-06	2.12E-09	2.53E-04
HTnc	CTUh	1.33E-03	1.95E-04	7.92E-04	2.44E-05	2.29E-06	1.80E-06	5.09E-09	2.35E-03
HTc	CTUh	2.30E-04	1.19E-04	5.45E-05	2.45E-05	6.43E-07	2.93E-07	1.36E-09	4.29E-04
PM	kg PM2.5 $_{eq}$	1.52E+00	2.68E-01	2.30E-01	5.64E-02	3.73E-03	1.07E-02	7.36E-06	2.08E+00
IR	kBq U235 $_{eq}$	8.01E+02	3.94E+01	1.76E+01	1.01E+01	1.77E-01	8.57E-01	1.02E-02	8.69E+02
POCP	kg NMVOC $_{eq}$	6.01E+00	1.05E+00	9.76E-01	2.14E-01	1.42E-02	7.93E-02	4.07E-05	8.34E+00
AP	molc H+ $_{eq}$	1.97E+01	2.49E+00	1.94E+00	6.09E-01	3.25E-02	1.71E-01	1.11E-04	2.49E+01
EP$_t$	molc N $_{eq}$	1.98E+01	3.31E+00	2.95E+00	7.23E-01	9.88E-02	2.79E-01	1.43E-04	2.72E+01
EP$_f$	kg P $_{eq}$	2.00E+00	1.96E-01	4.88E-01	4.08E-02	1.03E-03	1.14E-03	1.80E-05	2.73E+00
EP$_m$	kg N $_{eq}$	4.52E+00	4.72E-01	3.90E-01	7.46E-02	4.63E-03	2.51E-02	1.68E-05	5.59E+00
FET	CTUe	3.91E+04	7.17E+03	1.85E+04	1.39E+03	9.47E+01	5.23E+01	1.90E-01	6.64E+04

Table IV.2: Environmental impact assessment - contribution of the battery cells manufacturing

Impact categories	Unit of measure	Anode	Cathode	Electrolyte	Separator	Cell container	Water, decarbonised	Transport + Facility	Electricity consumption for cell assembly
CED	MJ	6.39E+00	1.41E+01	2.85E+00	1.21E+00	2.97E+00	8.58E-03	1.56E-01	7.23E+01
ADP-res	kg Sb $_{eq}$	6.66E+01	6.33E+00	5.95E+00	1.65E-01	1.81E+01	7.67E-03	5.66E-01	2.26E+00
GWP	kg CO2 $_{eq}$	6.75E+00	1.69E+01	3.18E+00	7.72E-01	3.83E+00	1.61E-02	2.33E-01	6.83E+01
ODP	kg CFC-11 $_{eq}$	6.32E+00	1.54E+01	3.61E+00	4.36E-01	2.72E+00	1.08E-02	2.49E-01	7.13E+01
HTnc	CTUh	3.38E+01	2.29E+01	2.52E+00	2.56E-01	1.33E+01	1.05E-02	1.55E-01	2.70E+01
HTc	CTUh	9.60E+00	1.72E+01	1.82E+00	3.39E-01	2.90E+01	3.12E-02	2.70E-01	4.17E+01
PM	kg PM2.5 $_{eq}$	1.39E+01	4.05E+01	4.49E+00	4.90E-01	6.07E+00	1.92E-02	2.63E-01	3.43E+01
IR	kBq U235 $_{eq}$	1.57E+00	6.30E+00	1.00E+00	2.50E-01	9.86E-01	2.26E-03	6.71E-02	8.98E+01
POCP	kg NMVOC $_{eq}$	1.28E+01	2.81E+01	3.95E+00	9.37E-01	5.89E+00	1.85E-02	4.59E-01	4.78E+01
AP	molc H+ $_{eq}$	8.45E+00	4.43E+01	3.35E+00	3.97E-01	3.37E+00	8.14E-03	1.98E-01	3.99E+01
EP_t	molc N $_{eq}$	1.13E+01	2.70E+01	3.81E+00	6.65E-01	5.50E+00	1.78E-02	6.59E-01	5.10E+01
EP_f	kg P $_{eq}$	1.46E+01	1.43E+01	1.70E+00	2.53E-01	5.54E+00	5.61E-03	7.34E-02	6.35E+01
EP_m	kg N $_{eq}$	4.70E+01	1.26E+01	1.86E+00	2.81E-01	1.18E+01	7.83E-03	2.04E-01	2.63E+01
FET	CTUe	2.66E+01	2.44E+01	2.42E+00	2.86E-01	1.17E+01	2.50E-02	2.04E-01	3.43E+01

Table IV.3: Environmental impact assessment of the repurposing of one battery pack and the percentage contribution of the included processes

Impact categories	**Unit of measure**	**Electricity consumption for testing**	**Battery retention**	**Battery tray**	**Transport**	**Total**
CED	MJ	9.23E+01	3.42E+02	9.87E+02	5.42E+01	1.48E+03
ADP-res	kg Sb $_{eq}$	1.50E-06	2.25E-04	4.60E-04	5.91E-06	6.92E-04
GWP	kg CO2 $_{eq}$	4.12E+00	2.21E+01	5.86E+01	3.18E+00	8.81E+01
ODP	kg CFC-11 $_{eq}$	4.18E-07	1.55E-06	3.48E-06	6.05E-07	6.06E-06
HTnc	CTUh	1.00E-06	1.93E-05	4.94E-05	6.78E-07	7.03E-05
HTc	CTUh	2.67E-07	1.31E-05	3.33E-05	8.51E-08	4.68E-05
PM	kg PM2.5 $_{eq}$	1.45E-03	2.28E-02	5.68E-02	1.79E-03	8.28E-02
IR	kBq U235 $_{eq}$	2.01E+00	2.02E+00	5.38E+00	2.53E-01	9.66E+00
POCP	kg NMVOC $_{eq}$	8.01E-03	7.67E-02	2.02E-01	1.76E-02	3.05E-01
AP	molc H+ $_{eq}$	2.19E-02	1.30E-01	3.38E-01	1.67E-02	5.07E-01
EP$_t$	molc N $_{eq}$	2.82E-02	2.28E-01	5.95E-01	5.94E-02	9.10E-01
EP$_f$	kg P $_{eq}$	3.54E-03	1.43E-02	3.73E-02	2.62E-04	5.54E-02
EP$_m$	kg N $_{eq}$	3.32E-03	2.13E-02	5.52E-02	5.44E-03	8.52E-02
FET	CTUe	3.74E+01	5.57E+02	1.43E+03	2.68E+01	2.05E+03

Annex V. Life cycle interpretation

This section illustrates a more detailed processes contribution in the manufacturing, repurposing and EoL phases performed for some exemplary impact categories as:

- GWP, dominated by the energy consumption;
- ADP, dominated by the consumption of mineral resources;
- HT-C, equally influenced by both energy and mineral resource consumption.

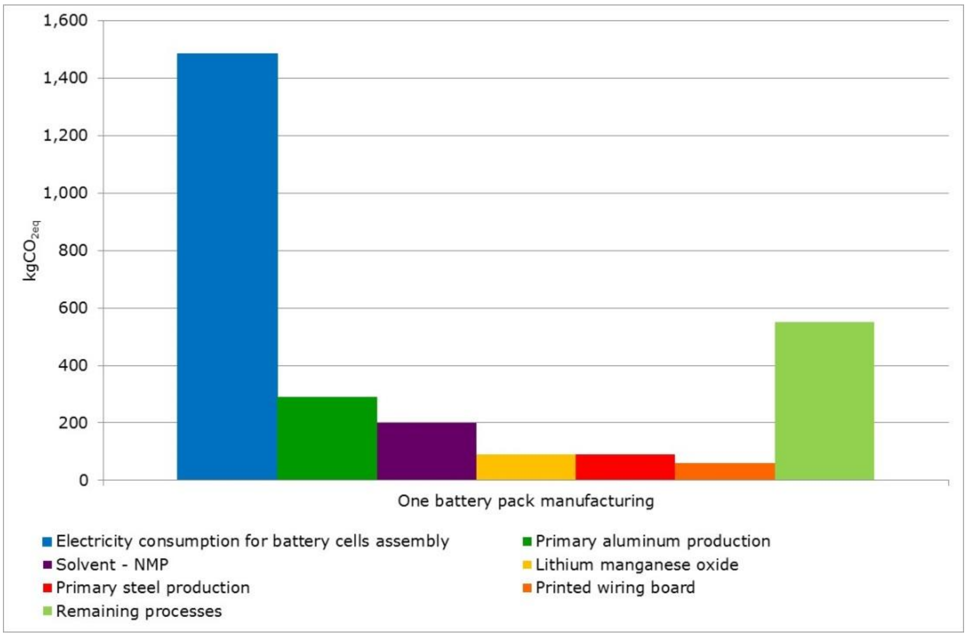
Further, as the cell manufacturing is responsible for the main contribution in the impact a detailed analysis is carried out for this process.

Manufacturing phase – contribution analysis

Figures V.1, V.2 AND V.3 show, respectively, the process contribution of the manufacturing phase in the GWP, ADP and HT-nC impact categories. The processes with a percentage contribution lower than 2% are grouped in the "remaining processes".

With reference to the GWP, the electricity consumed for the battery cell assembly determines the highest impact (53.7%). The primary aluminium production, used in battery cells, BMS, packaging and cooling system, follows it with a contribution equal to 10.5%.

Figure V.1: GWP - battery pack manufacturing contribution analysis



In the ADP impact category the process responsible for the highest impact is the production of the electronic component, it is responsible for the 35% of the overall impact. The primary copper production used in the anode and in the packaging and the printed wiring board in the BMS follow it with percentage contribution equal, respectively, to 28% and 19%.

Finally, in the HT-nC impact category the primary copper and the electronic components productions and the electricity consumption during the battery cells assembly are the processes responsible for the highest impacts. In detail, they represent, respectively, a percentage equal to 22%, 16% and 15% of the overall impact.

Figure V.2: ADP - battery pack manufacturing contribution analysis

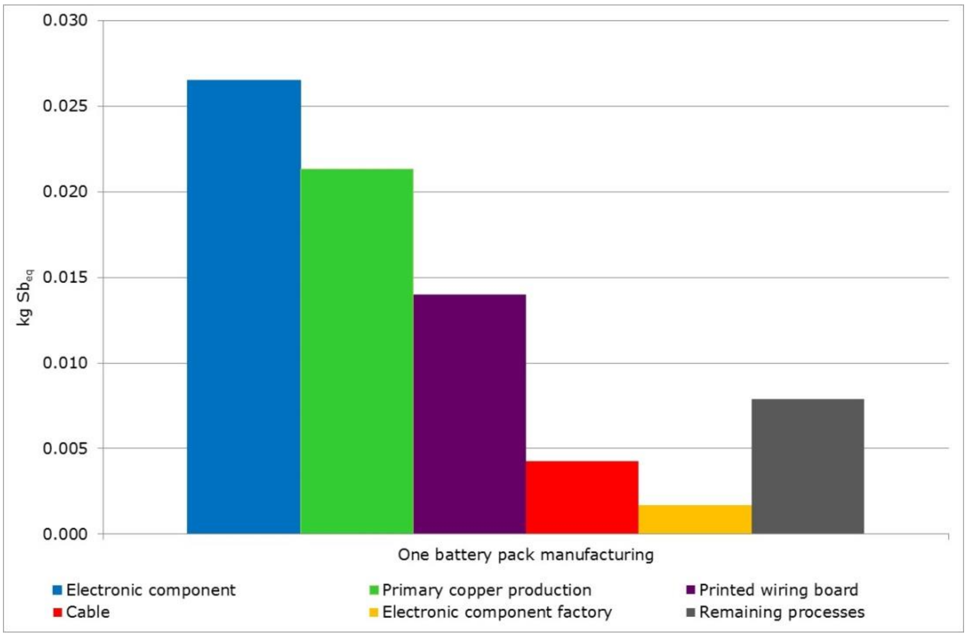
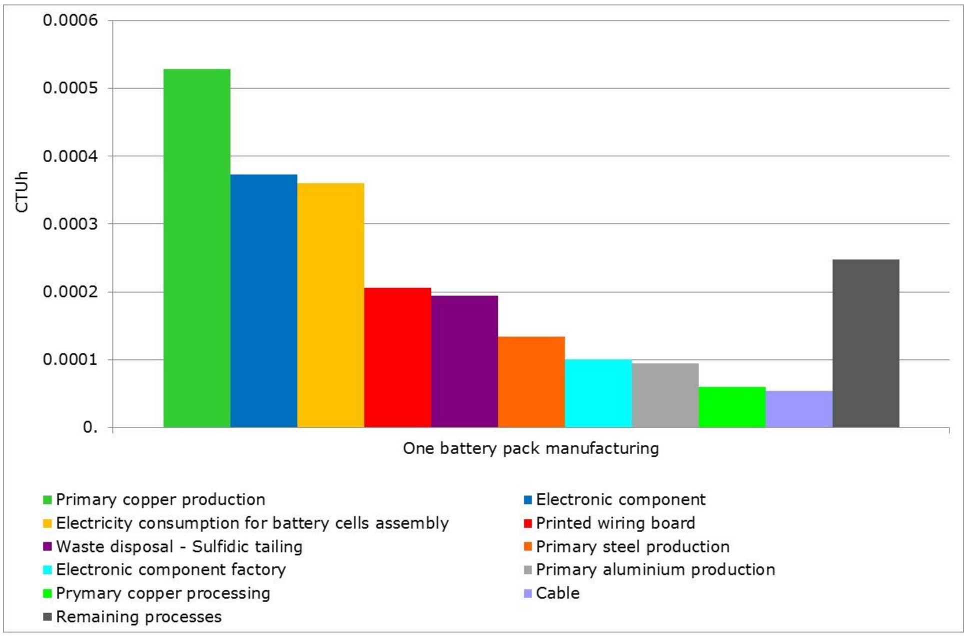


Figure V.3: HT-nC - battery pack manufacturing contribution analysis



Manufacturing phase – Sensitivity analysis

Due to some uncertainties in the BoM of the battery pack, a sensitivity analysis is performed for some relevant processes occurring during the manufacturing phase. Hereinafter, the sensitivity analysis of the binder is reported.

As the type of binder used in the anode and in the cathode of the analysed battery is unknown, a sensitivity analysis is carried out in order to assess the variation in the battery cells manufacturing impacts resulting from the adoption of different kind of binder. With reference to the binder the most common are polyvinylidene fluoride (PVDF), polytetrafluoroethylene (PTFE), poly acrylic acid (PAA) and carboxymethyl cellulose (CMC) (Ellingsen et al., 2014; Majeau-Bettez et al., 2011). In the following, the compared configurations are illustrated:

- Base case (BC): Anode binder PAA and CMC; Cathode binder: PVDF;

- Case 1 (C1): Anode binder PVDF; Cathode binder: PVDF;
- Case 2 (C2): Anode binder PTFE; Cathode binder: PTFE.

The results of the analysis, shown in Table V.1, highlight that the percentage variation of the impacts in the C1 configuration compared to BC configuration is negligible for all the environmental categories. In detail, it range from +0.11% (EP$_m$) to 0.43% (PM).

The analysis of the C2 configuration shows that the use of PTFE as binder causes higher impacts in GWP and ODP impact categories. In the other environmental categories, the percentage variation of the impacts is lower compared to BC scenario. It ranges from -0.1% (EPf and PM) to +0.93% in ADP.

Table V.1: Percentage variation of the impacts between different binders

Impact categories	Unit of measure	BC	(BC – C1)/C1	(BC – C2)/C2
CED	MJ	4.58E+04	0.19%	0.15%
ADP-res	kg Sb $_{eq}$	2.39E-02	0.36%	0.93%
GWP	kg CO2 $_{eq}$	2.17E+03	0.38%	31.05%
ODP	kg CFC-11 $_{eq}$	2.10E-04	0.18%	9673.30%
HTnc	CTUh	1.33E-03	0.16%	0.49%
HTc	CTUh	2.30E-04	0.15%	0.25%
PM	kg PM2.5 $_{eq}$	1.52E+00	0.43%	-0.01%
IR	kBq U235 $_{eq}$	8.01E+02	0.12%	0.04%
POCP	kg NMVOC $_{eq}$	6.01E+00	0.26%	0.41%
AP	molc H+ $_{eq}$	1.97E+01	0.25%	0.31%
EP$_t$	molc N $_{eq}$	1.98E+01	0.25%	0.32%
EP$_f$	kg P $_{eq}$	2.00E+00	0.20%	-0.01%
EP$_m$	kg N $_{eq}$	4.53E+00	0.11%	0.12%
FET	CTUe	3.91E+04	0.16%	0.38%

Repurposing phase – contribution analysis

Figure V.4, V.5 and V.6 show, respectively, the processes contribution in GWP, ADP and HT-NC impact categories referred to the repurposing phase. The processes with a percentage contribution lower than 2% are grouped in the "remaining processes".

In all the three impact categories, the primary steel production and processing used in the manufacturing of the new battery tray and new battery retention for the second life application are responsible for the highest impact. In detail, their percentage contribution is equal to 76% in GWP, to 80% in the ADP and to 93% in HT-nC.

Figure V.4: GWP - battery pack repurposing contribution analysis

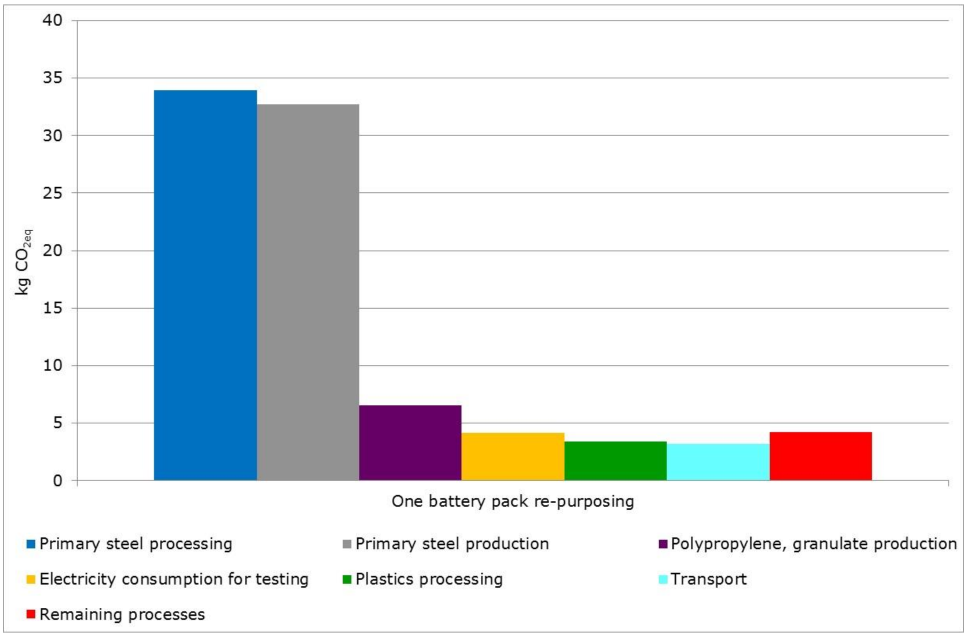


Figure V.5: ADP - battery pack repurposing contribution analysis

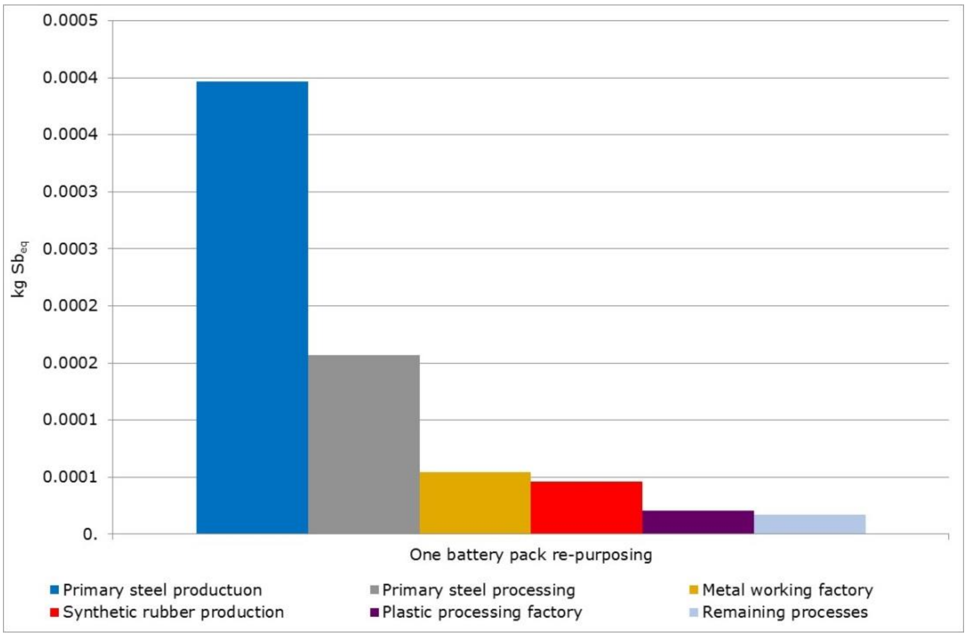
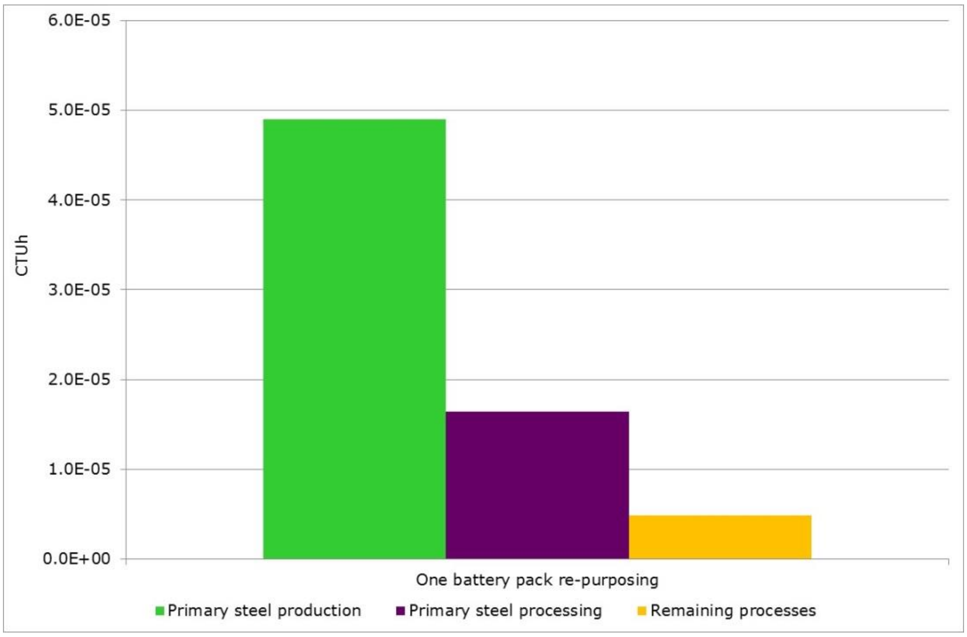


Figure V.6: HT-nC - battery pack repurposing contribution analysis



End – of – Life phase – contribution analysis

Figures V.7, V.8 and V.9 show, respectively, the process contribution of the EoL phase in the GWP, ADP and HT-nC impact categories. The processes with a percentage contribution lower than 2% are grouped in the "remaining processes". For the examined environmental categories, credits for the avoided impacts, due to the avoided production of primary copper, cobalt, nickel, aluminium, and steel recycled, are attributed to the EoL stage.

In the GWP impact category, the electricity and sodium hydroxide consumption in the pyro-metallurgical process are responsible for the highest impact. They represent, respectively, the 41% and 30% of the overall impact.

In the ADP impact category the highest impact is determined by the preparation of copper scrap for recycling, however this process contributes for less than 2% and it is included in the "remaining process" in Figure V.8.

Finally, in HT-nC impact category the preparation of copper scrap for recycling, the production of the sodium hydroxide used in pyro-metallurgical process and the preparation of aluminium scrap for recycling are responsible, respectively, for 52%, 30% and 20% of the overall impact.

Figure V.7: GWP - battery pack EoL contribution analysis

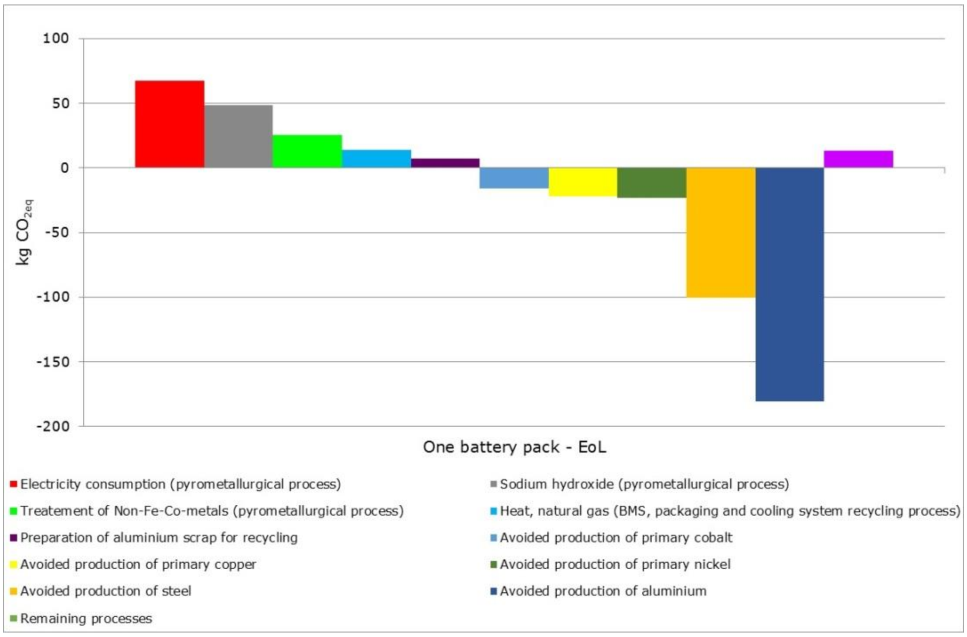


Figure V.8: ADP - battery pack EoL contribution analysis

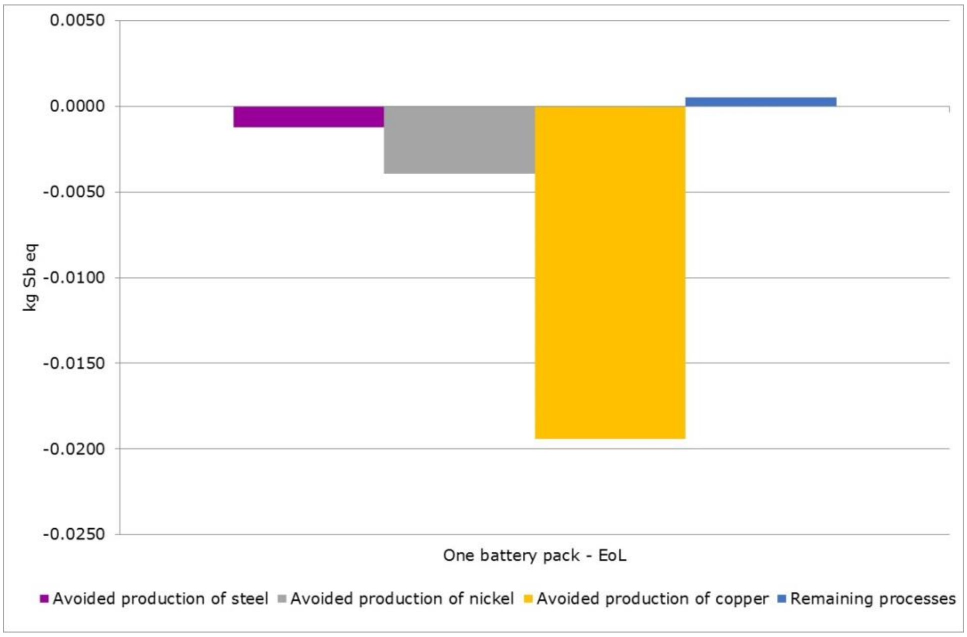
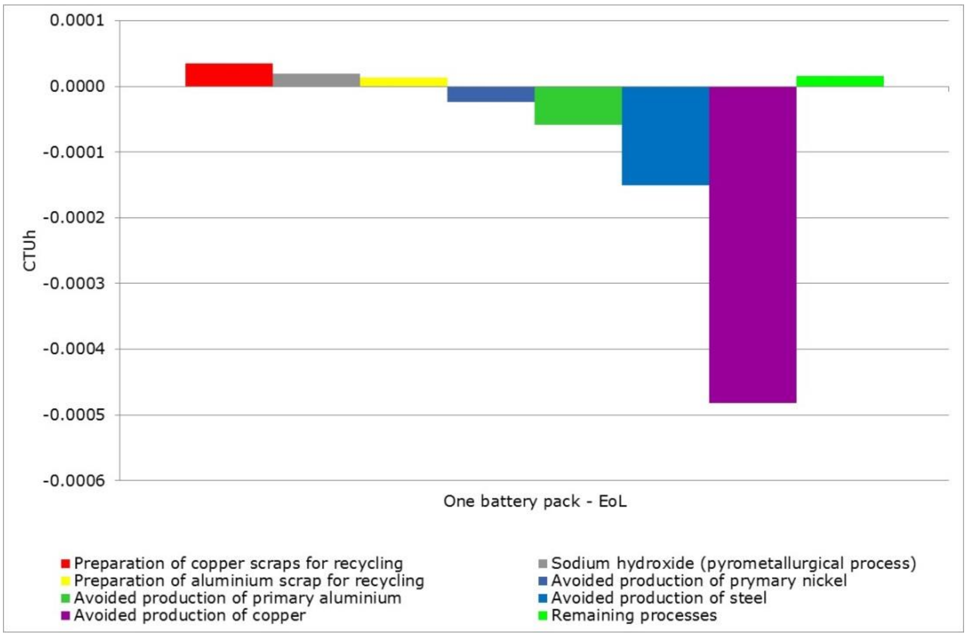


Figure V.9: HT-nC - battery pack EoL contribution analysis



Annex VI - Peak shaving

Energy flows of the system

System description

The analysed system is an office building at JRC – Ispra (Building 6) with a total area of 1,444 m^2, a volume of 4,706 m^3 without any PV system and without any lab area. Therefore, energy consumption is related mainly to offices.

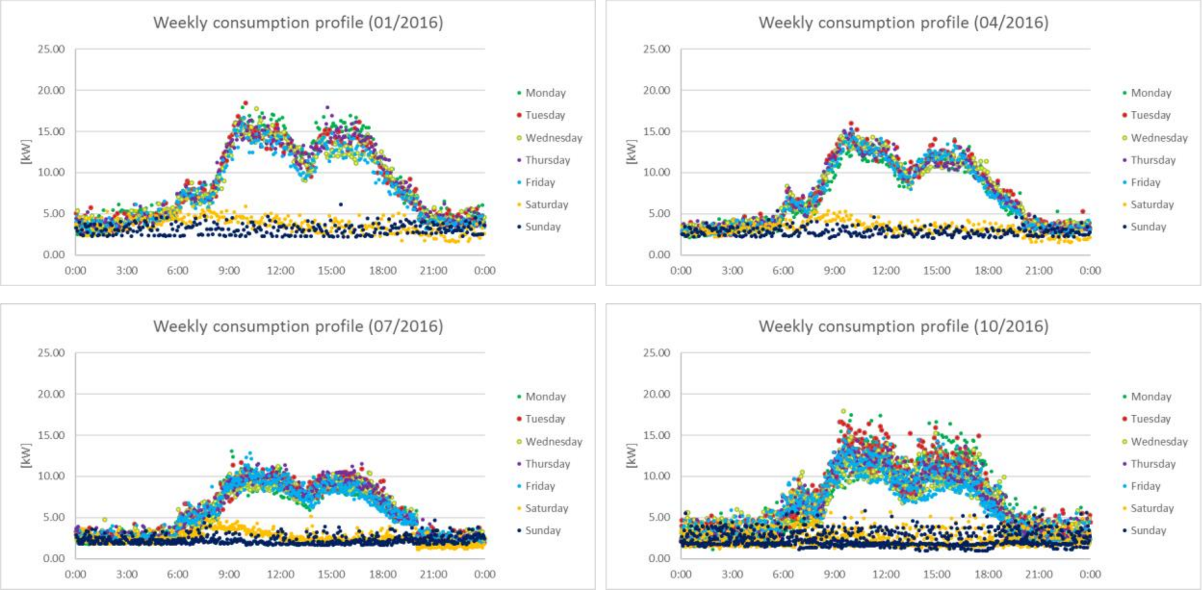
Energy data analysis

The daily consumption profile of the building was given by the unit "R.I.4 – Maintenance and Utilities" on yearly base with 5 minutes resolution. In order to consider the variation of the energy requirement along the year in a simplified way, data of 4 representative months are processed in order to obtain the average energy requirement for each season (January for winter, April for spring, July for summer and October for autumn).

Data were elaborated in order to obtain the daily consumption, to identify the worst day for each month and to calculate the maximum peak for each season.

For each month, the average load profile of each weekday in a month is calculated, including weekends. The weekly consumption profile shows that electricity peaks occur only during the working days for all the 4 seasons, and that the maximum peak occurs during winter (23.16 kW) (Figure VI.1).

Figure VI.1: Average daily load profile of the assessed building for each season



Source: own elaboration

For sizing the system and define the number of batteries needed for peak shaving, the load profile of the worst day was considered (Wednesdays during winter). Therefore, considering a contracted power of 8 kW, the peak to be shaved is calculated. For each representative month, the energy requirement of the building and the peak to be shaved is estimated; since data refer to one month per season, the maximum energy requirement is increased of 10% in order to oversize the battery system and be sure to cover all the peaks.

Table VI.1: System energy requirements

	January (winter)	April (spring)	July (summer)	October (autumn)
Max peak power [kW]	23.16	19.55	14.43	18.89
Required energy [kWh/day]	202.78	174.66	129.39	153.46
Peak to be shaved [kWh/day]	50.40	34.54	7.55	20.13
Peak to be shaved (+10%) [kWh/day]	55.44	37.99	8.31	22.15

The number of batteries needed to cover the peak in the considered building is calculated accordingly considering both the batteries characteristics and their degradation (Table VI.1). The main assumptions for the assessment are hereinafter listed:

- each battery performs no more than 1 cycle/day;
- when the battery reaches 60% of its nominal capacity it should be substituted (Canals Casals et al., 2015; Lacey et al., 2013; Oliveira, 2017); this means that the capacity of the considered battery at its EoL is 6.84 kWh;
- to guarantee a longer lifetime of the Li-ion batteries, it is assumed that the DoD does not exceed 80% (Lacey et al., 2013; Neubauer and Pesaran, 2011; Wood et al., 2011).
- Change of battery performance is taken into account through both the cycling and the ageing degradation;
- Despite the variation of the energy requirement according to the season, thanks to the BMS all the batteries are similarly used, guarantying a similar degradation level along their use in the building.

Due to the absence of a degradation model for repurposed batteries, for the calculation a linear degradation of the battery including both the calendar and the cycling aging is considered. As such, the available capacity of the battery at the end of each cycle is calculated and the timeframe after which the repurposed battery should be substituted is estimated.

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

As a first assumption, the battery degradation is considered based both on literature data (Faria et al., 2014) and JRC-Petten laboratory tests. A linear degradation of -3 Wh/cycle is assumed as in Faria et al. (2014) and a calendar ageing of -0.13Wh/day as resulted from JRC-Petten calendar ageing experiments so far for 45°C and 100% SoC.

Further information on how the capacity model is used to calculate relevant parameters can be found in (Bobba et al., 2018b).

Sizing of the system using a repurposed battery

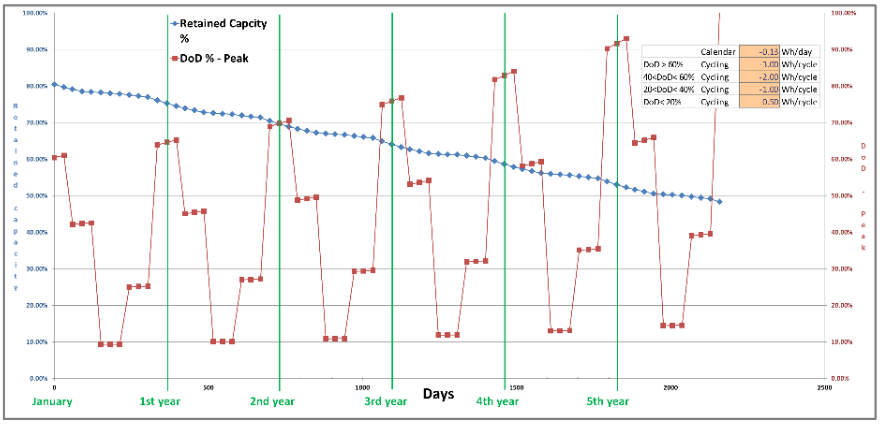
Based on the load requirement and on the degradation of the battery, the amount of batteries needed to cover the peak and their lifetime before reaching 60% of the nominal capacity are calculated.

$$Available\ battery\ capacity\ after\ first\ use = \frac{Residual\ capacity}{Nominal\ capacity}\ [\%] \cdot Nominal\ capacity\ [kWh]$$

$$\text{Number of batteries} = \frac{Max\ peak\ to\ be\ shaved\ [kWh]}{Available\ battery\ capacity\ after\ first\ use\ \left[\frac{kWh}{battery}\right] * DoD\ [\%]}$$

Since the maximum peak to be covered is 55.43 kWh (Table VI.1), minimum 8 batteries are required in the system[83]. Note that, since the energy requirement of the building during weekends never exceed 8 kW all over the year, only the working days are considered for the assessment, i.e. 240 days per year). After about 4 years, batteries are no longer able to satisfy the energy requirement by the peak due to their low capacity, and the DoD exceed 80% (Figure VI.2).

Figure VI.2: DoD and residual capacity of the repurposed battery during the peak shaving service



For the environmental assessment, the input/output energy flows are calculated (note that the energy delivered by the batteries is covering the peak during the day while batteries are charged during the night).

The total amount of energy provided by such 8 batteries in 4 year to the system is 27.03 MWh. The corresponding energy required for charging the batteries is calculated based on the roundtrip efficiency (RTE) of the battery (31.80 MWh).

$$\text{Energy required for charging} = \frac{\text{Delivered energy}}{\text{RTE}}\ [\text{kWh}] = \frac{\text{Retained capacity } \times \text{DoD}}{\text{Roundtrip efficiency}}\ [\text{kWh}]$$

Table VI.2: Yearly energy delivered/required by the repurposed batteries for each season

Energy requirement	Winter	Spring	Summer	Autumn	TOT
Energy delivered by the batteries	3,024	2,072	453	1,208	**6,757**
Energy required for charging the batteries	3,557	2,438	533	1,421	**7,949**

Table VI.3: Yearly energy requirement for the configuration without and with the repurposed batteries

Energy requirement		Without battery [kWh]	With battery [kWh]
Energy between 08:00 and 19:00	from the grid	109,527	102,770
	from the battery	-	6,757
Energy between 19:00 and 08:00	from the grid	48,942	48,942
	for charging the battery	-	7,949
Total energy requirement		**158,469**	**159,661**

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[83] According with experts, a DoD = 75% is considered for this calculation

Sizing of the system using a fresh battery

The same calculation procedure is used to define the system configuration illustrated in previous section but considering a fresh Li-ion battery with the same characteristics as the repurposed one.

In this case, minimum 7 fresh LMO/NMC batteries can provide the required energy during the peak hours of the working days along about 6 years). After this period, even though the batteries' capacity does not yet reach its EoL, the DoD of the batteries exceeds 80% during all winter days.

Figure VI.3: Capacity trend of the repurposed battery during the peak shaving service

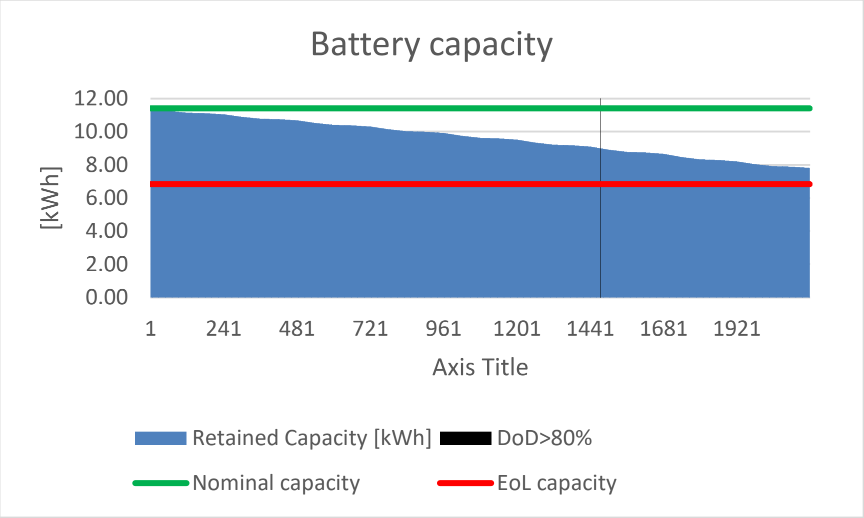
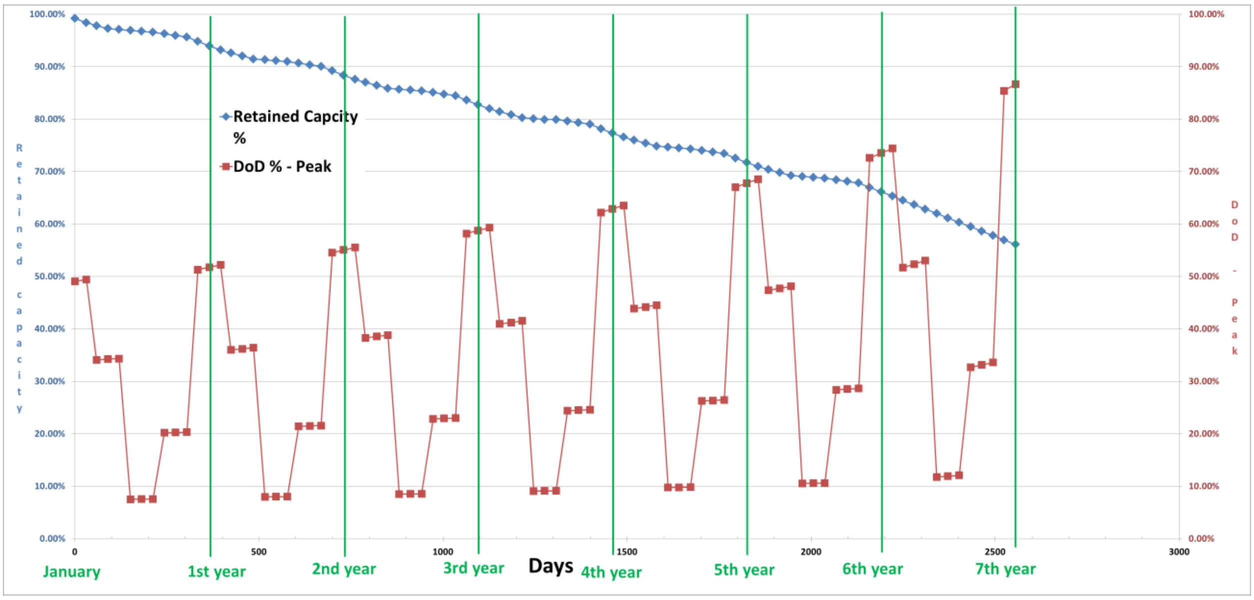


Figure VI.4: DoD of the repurposed battery during the peak shaving service



The total amount of energy provided by the 7 batteries in 6 years to the system is 42.20 MWh. The corresponding energy required for charging the batteries is calculated based on the roundtrip efficiency (RTE) of the battery (46.89 MWh).

Table VI.4: Energy delivered/required by the fresh batteries for each season

Energy requirement	Winter	Spring	Summer	Autumn	TOT
Energy delivered by the batteries	3,024	2,072	453	1,208	**6,757**
Energy required for charging the batteries	3,360	2,302	503	1,342	**7,508**

Table VI.5: Energy requirement for the configuration without and with the fresh batteries

Energy requirement		Without battery [kWh]	With battery [kWh]
Energy between 08:00 and 19:00	from the grid	109,527	102,770
	from the battery	-	6,757
Energy between 19:00 and 08:00	from the grid	48,942	48,942
	for charging the battery	-	7,508
Total energy requirement		**158,469**	**159,219**

LCIA

Table VI.6: Environmental impact of different scenarios for the peak shaving application along the batteries' lifetime

Impact categories	**Unit of measure**	**Fresh battery (A)**	**Repurposed battery (B1)** $(\alpha = \beta = 0)$*	**Repurposed battery (B2)** $(\alpha = \beta = 0.25)$	**No battery (C)** (PV 100% fed in the grid)
Considered timeframe		6.14 years	4 years	4 years	1 year
Number of batteries		7	8	8	0
CED	MJ	9.08E+06	5.70E+06	5.81E+06	1.41E+06
ADP-res	kg Sb$_{eq}$	1.02E+00	4.38E-01	5.42E-01	1.07E-01
GWP	kg CO2$_{eq}$	5.18E+05	3.27E+05	3.32E+05	8.11E+04
ODP	kg CFC-11$_{eq}$	5.64E-02	3.57E-02	3.62E-02	8.84E-03
HTnc	CTUh	8.92E-02	5.08E-02	5.42E-02	1.25E-02
HTc	CTUh	1.91E-02	1.16E-02	1.21E-02	2.81E-03
PM	kg PM2.5$_{eq}$	1.87E+02	1.19E+02	1.21E+02	2.95E+01
IR	kBq U235$_{eq}$	7.64E+04	4.61E+04	4.78E+04	1.14E+04
POCP	kg NMVOC$_{eq}$	1.06E+03	6.67E+02	6.79E+02	1.65E+02
AP	molc H+$_{eq}$	2.51E+03	1.65E+03	1.65E+03	4.09E+02
EP$_t$	molc N$_{eq}$	3.45E+03	2.15E+03	2.20E+03	5.32E+02
EP$_f$	kg P$_{eq}$	1.56E+02	9.11E+01	9.59E+01	2.25E+01
EP$_m$	kg N$_{eq}$	3.44E+02	2.12E+02	2.18E+02	5.25E+01
FET	CTUe	1.10E+07	6.46E+06	6.78E+06	1.60E+06

* results consider an allocation factor equal to 0, which means that no manufacturing/EoL impact of the LIB are allocated to the second-use application. However, manufacturing and EoL of new components used for repurposing the battery are fully allocated to the second life of the battery.

Sensitivity analysis

Energy mix

In order to assess the relevance of the energy mix adopted in the assessment, it is assumed that the electricity delivered by the batteries to the building (covering the energy peaks) avoids the production of an equal amount of electricity provided by a natural gas peak power plant[84]. In this case, benefits related to avoid the production of energy by a natural gas peak power plant compared to avoid grid mix energy are higher, with the only exception of ADP-res impact category (Table VI.7). However, the differences of the yearly impacts can be considered as negligible for all the assessed impact categories

Table VI.7: Percentage difference between the yearly environmental impacts of the adoption of a repurposed battery avoiding grid mix electricity and avoiding energy provided by a natural gas peak power plant

Impact categories	**Unit of measure**	**Repurposed battery (B)** $(\alpha = \beta = 0)$* electricity provided by the grid mix	**Repurposed battery (B)** $(\alpha = \beta = 0)$* electricity provided by a natural gas peak power plant	**Percentage difference**
CED	MJ	1.43E+06	1.42E+06	-0.16%
ADP-res	kg Sb $_{eq}$	1.10E-01	1.11E-01	0.89%
GWP	kg CO2 $_{eq}$	8.18E+04	8.16E+04	-0.32%
ODP	kg CFC-11 $_{eq}$	8.92E-03	8.89E-03	-0.30%
HTnc	CTUh	1.27E-02	1.27E-02	-0.07%
HTc	CTUh	2.91E-03	2.91E-03	-0.13%
PM	kg PM2.5 $_{eq}$	2.99E+01	2.98E+01	-0.21%
IR	kBq U235 $_{eq}$	1.15E+04	1.15E+04	-0.34%
POCP	kg NMVOC $_{eq}$	1.67E+02	1.66E+02	-0.28%
AP	molc H+ $_{eq}$	4.13E+02	4.12E+02	-0.29%
EP_t	molc N $_{eq}$	5.38E+02	5.36E+02	-0.28%
EP_f	kg P $_{eq}$	2.28E+01	2.27E+01	-0.23%
EP_m	kg N $_{eq}$	5.30E+01	5.29E+01	-0.28%
FET	CTUe	1.62E+06	1.61E+06	-0.16%

* results consider an allocation factor equal to 0, which means that no manufacturing/EoL impact of the LIB are allocated to the second-use application. However, manufacturing and EoL of new components used for repurposing the battery are fully allocated to the second life of the battery.

Battery chemistry (PbA battery)

According to literature, different batteries' chemistries can be used in stationary applications, e.g. the PbA chemistry. Similarly, to the LMO/NMC battery, a PbA battery is considered in the assessment. The LCA model for the manufacturing and the EoL of the PbA battery was realized according to (Richa et al., 2015).

The mass of the PbA battery is derived according to (Richa et al., 2015) and the assessed application. Therefore, the PbA nominal capacity is calculate according to the following formula, considering a DoD equal to 50% and a residual capacity at the end of the battery life equal to 80%.

$$\text{PbA Nominal capacity } = \frac{\text{Max peak to be shaved in winter season increased by 10\% (worst case) [kWh]}}{\text{DoD(maximum allowable before EoL)} \times \text{Residual Capacity EoL (e.g. 80\%)}}$$

$$= \frac{55.437\ \text{kWh}}{50\% \times 80\%} = 138.59\ \text{kWh}$$

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[84] This assumption is aligned with the (Neubauer et al., 2015b) study

As a results, the mass of the PbA battery is considered as proportional as to its nominal capacity. In detail, in Richa et al., a PbA battery with an energy density of 34,5 Wh/kg. Then, the weight of a PbA battery with a nominal capacity of 138.59 kWh is obtained as:

$$PbA\ weight = \frac{138.59\ kWh}{34.5\ Wh/kg} = \ 4{,}017.2\ \mathrm{kg}$$

In Table VI.8 the battery parameter used to model the use phase are synthetized.

Table VI.8: PbA battery parameters

Battery parameters	Vlaue and Source
Roundtrip efficiency of the battery	77.5% (Richa et al., 2015)
PbA_DoDmax (maximum allowable before EoL)	50% (Richa et al., 2015)
Battery Lifetime [year]	4 (Rydh and Sandén, 2005)
PbA_Cf (Residual Capacity EoL)	80% (Bindner et al., 2005)

The energy requirement for the peak shaving configuration with a PbA battery are reported in Table VI.9.

Table VI.9: Energy requirement for the configuration with a PbA battery

Energy requirement		Fresh PbA battery [kWh]
Energy between 08:00 and 19:00	from the grid	102,770
	from the battery	6,757
Energy between 19:00 and 08:00	from the grid	48,942
	for charging the battery	8,719
Total energy requirement		167,188

LCIA outcomes show that the yearly impact of the adoption of repurposed batteries to cover the peaks of the system is always lower than the adoption of a PbA battery for all the assessed impact categories (Table VI.10).

Table VI.10: Yearly environmental impact of the adoption of a PbA battery VS a repurposed LMO/NMC for the peak shaving application

Impact categories	Unit of measure	PbA	Repurposed battery $(\alpha = \beta = 0)$*
CED	MJ	1.83E+06	1.43E+06
ADP-res	kg Sb $_{eq}$	3.63E-01	1.10E-01
GWP	kg CO2 $_{eq}$	1.05E+05	8.18E+04
ODP	kg CFC-11 $_{eq}$	1.16E-02	8.92E-03
HTnc	CTUh	2.40E-02	1.27E-02
HTc	CTUh	4.05E-03	2.91E-03
PM	kg PM2.5 $_{eq}$	4.05E+01	2.99E+01
IR	kBq U235 $_{eq}$	1.47E+04	1.15E+04
POCP	kg NMVOC $_{eq}$	2.20E+02	1.67E+02
AP	molc H+ $_{eq}$	5.50E+02	4.13E+02
EP_t	molc N $_{eq}$	7.08E+02	5.38E+02
EP_f	kg P $_{eq}$	3.39E+01	2.28E+01
EP_m	kg N $_{eq}$	7.06E+01	5.30E+01
FET	CTUe	2.22E+06	1.62E+06

* results consider an allocation factor equal to 0, which means that no manufacturing/EoL impact of the LIB are allocated to the second-use application. However, manufacturing and EoL of new components used for repurposing the battery are fully allocated to the second life of the battery.

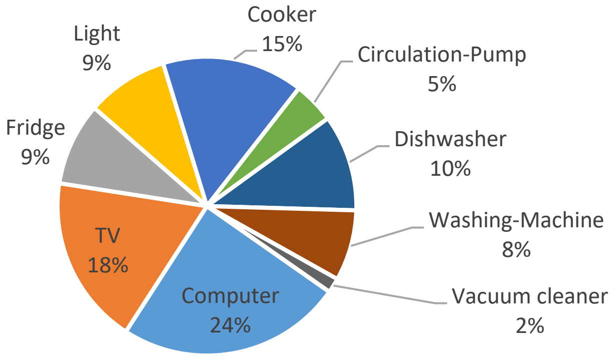
Annex VII - Increase of photovoltaic (PV) self consumption

Energy flows of the system

System description

The household load profile is provided by the ResLoadSIM software[85] (time resolution of 1 minute). The system configuration refers to a residential building located in Amsterdam, with 4 residents and a yearly consumption of 5.15E+03 kWh.

Figure VII.1: Yearly energy consumption of household appliances used for the modelling (Total consumption of the household appliances = 2,140.23 kWh/y)



Source: own elaboration based on ResLoadSIM simulation

Available primary data (15 minutes resolution) for the PV production refer to a real PV installation in a JRC site in The Netherlands[86]. Based on a real case, for the analysis the energy provided by 21 PV panels is considered[87].

Energy data analysis

Figure VII.2 shows the monthly average energy requirement/production for the assessed case-study for the year 2014. Data were elaborated in order to obtain the load profile of the building and the PV production every 15 minutes.

Based on (Ciocia, 2017) and on the battery characteristics, the energy flows of the system (schematized in Figure 25) were assessed for one year with a time resolution of 15 minutes.

The main assumptions for the assessment are hereinafter listed:

- the battery performs no more than 1 cycle/day;
- when the battery reaches 60% of its nominal capacity it should be substituted (Canals Casals et al., 2015; Lacey et al., 2013; Oliveira, 2017); this means that the capacity of the considered type of battery at it EoL is 6.84 kWh;
- to guarantee a longer lifetime of the Li-ion batteries, it is assumed that the DoD does not exceed 80% (Lacey et al., 2013; Neubauer and Pesaran, 2011; Wood et al., 2011).

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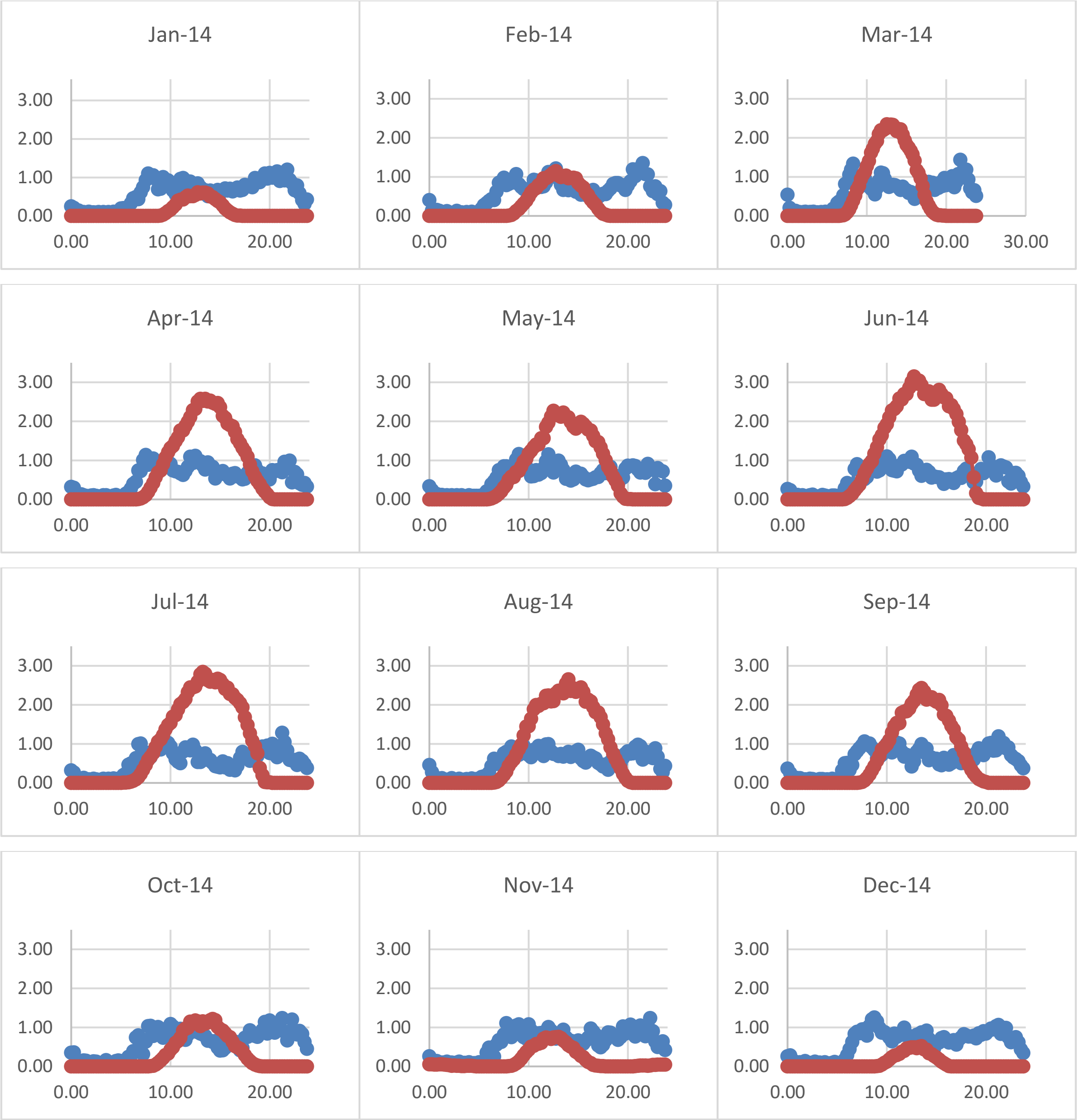
[85] https://ses.jrc.ec.europa.eu/power-system-modelling

[86] The system is characterized 2 PV converters connected to 96 modules of 250 W, totalling 24 kWp. The orientation of all the modules is SSE with a slope of 10° (Vandenbergh, 2014).

[87] This evaluation Is based on a real case-study for which primary data are being collected.

- Change of battery performance is taken into account through both the cycling and the ageing degradation;
- The battery efficiency is assumed to linearly decrease of 5 percentage points in 5 years;
- Despite the variation of the energy requirement according to the season, thanks to the BMS all the batteries are similarly used, guarantying a similar degradation level along their use in the building.

Figure VII.2: average daily load profile and PV generation for each month along 1 year



Due to the absence of a degradation model for repurposed batteries, for the calculation a linear degradation of the battery including both the calendar and the cycling aging is considered. As such, the available capacity of the battery at the end of each cycle is calculated and the timeframe after which the repurposed battery should be substituted is estimated.

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

As a first assumption, the battery degradation is considered based both on literature data (Faria et al., 2014) and JRC-Petten laboratory tests. A linear degradation of -3 Wh/cycle is assumed as in Faria et al. (2014) and a calendar ageing of -0.13Wh/day as resulted from JRC-Petten calendar ageing experiments so far for 45°C and 100% SoC.

Further information on how the capacity model is used to calculate relevant parameters can be found in (Bobba et al., 2018b).

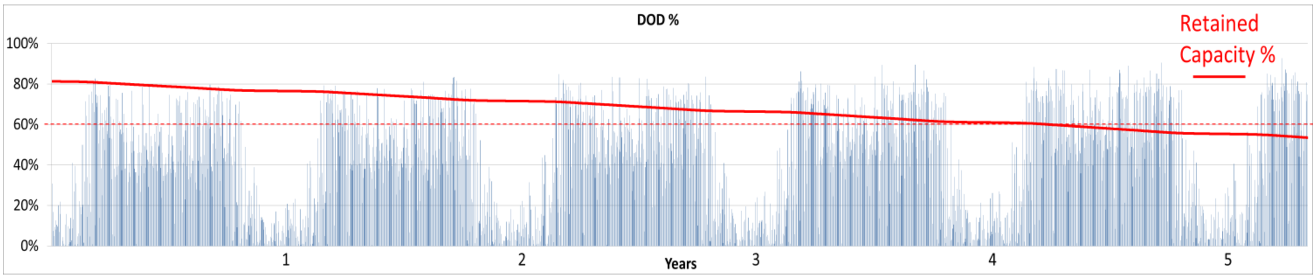
Sizing of the system using a repurposed battery

Based on the PV energy not directly used by the house, 1 repurposed battery is required by the system[88].

$$\text{Number of batteries} = \frac{Average\ daily\ consumption\ non\ covered\ by\ PV\ production\ [kWh]}{Available\ battery\ capacity\ after\ first\ use\ \left[\frac{kWh}{battery}\right] * DoD\ [\%]}$$

Results (Figure VII.3) shows that after about 4 years the repurposed battery is no longer able to satisfy the house energy requirement since its capacity reaches 60% of the nominal capacity. The total amount of PV energy stored by the battery during its operational life is about 6.77 MWh, 83% of which are directly used for covering the energy requirement of the house.

Figure VII.3: Decrease of the battery capacity (red line) and DOD (blue bars) along the battery lifetime



Sizing of the system using a fresh battery

The same calculation procedure is used to define the system energy flows of a system in which a fresh Li-ion battery is adopted. The considered battery is a new LMO/NMC with the same characteristics as the battery described in the report.

Also in this case, one fresh battery can be used in the house for increasing the renewable consumption. The nominal capacity decreases until 60% of the nominal capacity of the battery after 7 years.

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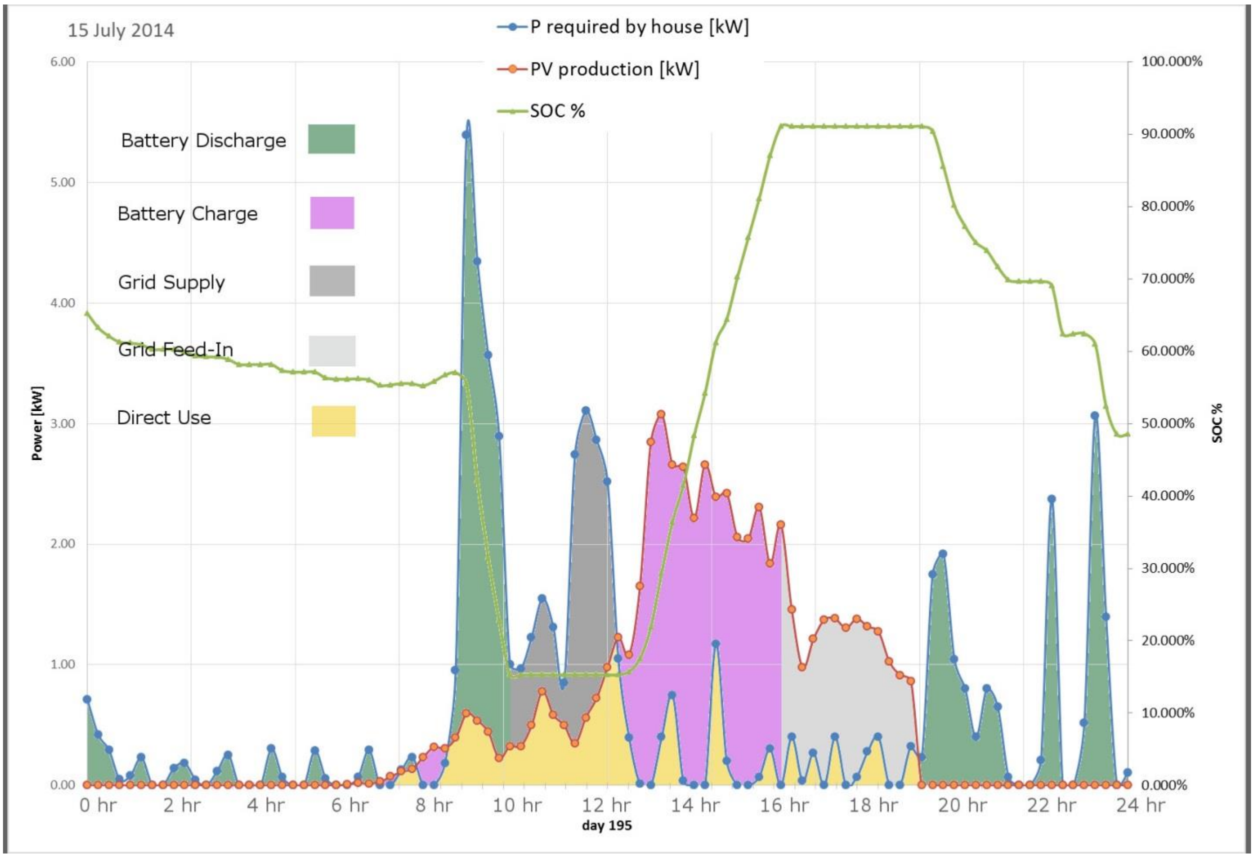
[88] Note that according with experts, a DoD = 75% is considered for this calculation

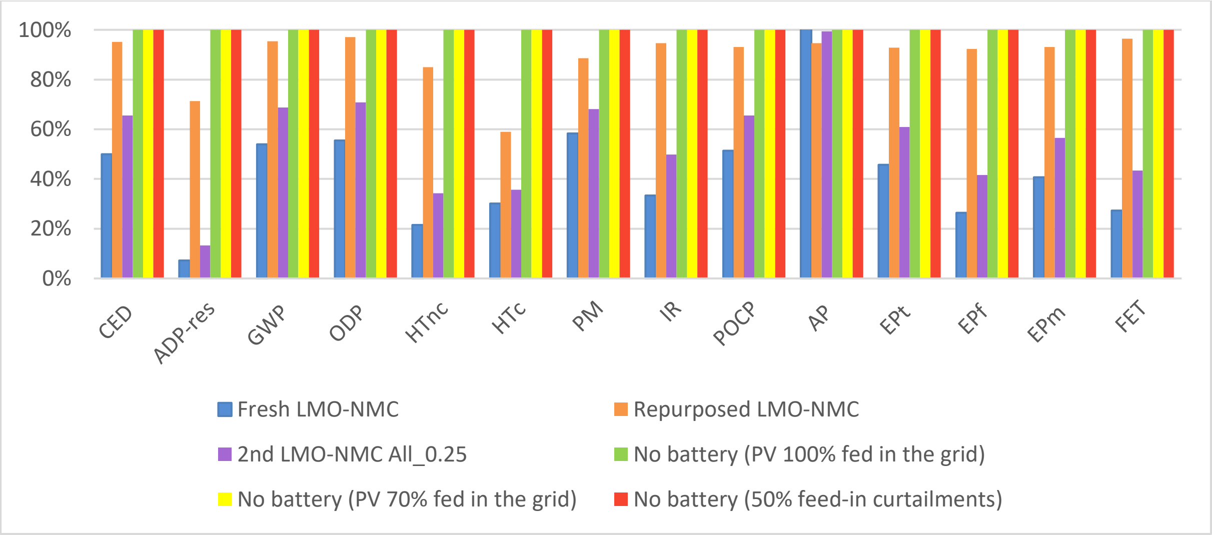
Figure VII.4: Daily energy flows of the system



LCIA

Finally, the LCIA highlights that the environmental impact related to the impact categories dominated by the manufacturing phase is not negligible. Figure VII.5 depicts that the yearly contribution of the use phase is always lower than 71%, with exception for the AP impact category.

Figure VII.5: Contribution of the use phase to the yearly environmental impact (for 1 year)



Sensitivity analysis

Energy mix

In order to assess the relevance of the **energy mix** adopted in the assessment, it is assumed that the house is stand-alone (e.g. on an island or in a remote location); therefore, the energy not supplied by neither the PV installation nor the battery, is provided by a diesel-electric generator of 18.5 kW and the surplus of the energy generated by the PV is lost.

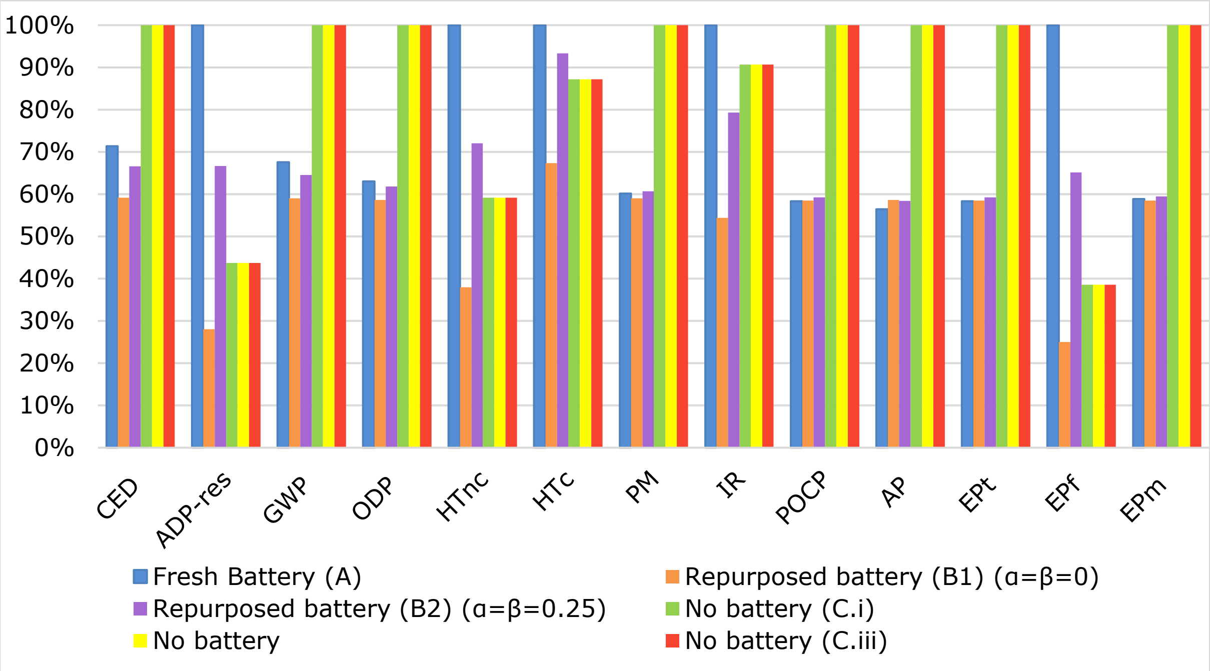
Results (Table VII.1) show that the adoption of a repurposed battery in a stand-alone system compared to its adoption in a grid-connected system is always beneficial from an environmental perspective, with exception for the EP_f impact category.

The comparison based on the early assessment (Figure VII.6) depicts that 8 out of 14 impact categories, stand-alone configuration without any battery (C.i, C.ii and C.iii) has higher impacts compared to the stand-alone configuration in which a battery is adopted ((A) and (B)).

Table VII.1: Percentage difference between the yearly environmental impacts of the adoption of a repurposed battery in a grid-connected configuration and in a stand-alone system

Impact categories	**Unit of measure**	**Repurposed battery (B)** $(\alpha = \beta = 0.25)$ **grid-connected configuration**	**Repurposed battery (B** $(\alpha = \beta = 0.25)$ **stand-alone configuration**	**Percentage difference**
CED	MJ	2.81E+04	1.18E+05	-76%
ADP-res	kg Sb $_{eq}$	1.48E-02	2.22E-02	-34%
GWP	kg CO2 $_{eq}$	1.50E+03	7.55E+03	-80%
ODP	kg CFC-11 $_{eq}$	1.56E-04	1.29E-03	-88%
HTnc	CTUh	5.92E-04	9.00E-04	-34%
HTc	CTUh	1.27E-04	2.19E-04	-42%
PM	kg PM2.5 $_{eq}$	5.53E-01	7.07E+00	-92%
IR	kBq U235 $_{eq}$	3.36E+02	6.76E+02	-50%
POCP	kg NMVOC $_{eq}$	3.28E+00	1.19E+02	-97%
AP	molc H+ $_{eq}$	3.94E+00	9.61E+01	-96%
EP_t	molc N $_{eq}$	1.18E+01	4.63E+02	-97%
EP_f	kg P $_{eq}$	8.40E-01	9.41E-01	-11%
EP_m	kg N $_{eq}$	1.29E+00	4.25E+01	-97%
FET	CTUe	5.64E+04	7.42E+04	-24%

Figure VII.6: Comparison between the different scenarios for a stand-alone configuration with a diesel-electric generator (for 1 year)



PbA battery

According to literature, PbA batteries can be used in storage system to increase the PV self-consumption. In order to assess the relevance of the battery chemistry, a PbA with a lifetime of 4 years (Rydh and Sandén, 2005) is considered.

In this case, the PbA nominal capacity is calculated as:

$$\text{PbA Nominal capacity} = \frac{\text{capacity of the } \frac{\text{LMO}}{\text{NMC}} \text{ battery at the end of its life [kWh]}}{\text{DoD(maximum allowable before EoL)} \times \text{Residual Capacity EoL (e.g. 80\%)}}$$

$$= \frac{11.4\ \text{kWh} * 80\%\ (\text{DOD}) * 60\%}{50\% \times 80\%} = 13.68\ \text{kWh}$$

As a results, the mass of the PbA battery is obtained as:

$$PbA\ weight = \frac{13.68\ kWh}{34.5\ Wh/kg} = 396.52\ \text{kg}$$

The energy flows of the system using a PbA battery are summarize in Table VII.2.

Table VII.2: Energy requirement for the configuration with the PbA battery

Parameter	PbA battery
Lifetime [year]	4
Electricity required by house [kWh]	2.25E+04
Direct electricity consumption from PV [kWh] - $E_{PV\rightarrow house}$	7.12E+03
Electricity provided by batteries [kWh] – $E_{Batt\rightarrow house}$	5.76E+03
Electricity needed for charging batteries [kWh] - $E_{PV\rightarrow Batt}$	7.40E+03
Electricity from the grid [kWh] - $E_{grid\rightarrow house}$	9.63E+03
PV production [kWh]	2.04E+04
Electricity potentially to be fed in the grid [kWh] - $E_{PV\rightarrow grid}$	5.89E+03

LCIA results shows that the substitution of a PbA battery with a repurposed LMO/NMC is beneficial for all the assessed impact categories (Table VII.3 and Figure VII.7). This is mainly related to the losses related to the lower performance of PbA batteries compared to the Li-ion batteries.

Focusing on the configuration in which the PbA battery is adopted, the contribution analysis depicts that the contribution of the use phase never exceeds 70% of the overall impact (highest contribution correspond to the IR, CED and GWP impact categories).

Table VII.3: Yearly environmental impact of the adoption of a PbA battery VS a repurposed LMO/NMC for the increase of PV-self consumption

Impact categories	**Unit of measure**	**PbA**	**Repurposed battery (B)** $(\alpha = \beta = 0)$*
CED	MJ	1.26E+04	7.81E+03
ADP-res	kg Sb $_{eq}$	2.31E-02	4.10E-03
GWP	kg CO2 $_{eq}$	7.13E+02	4.16E+02
ODP	kg CFC-11 $_{eq}$	8.85E-05	4.33E-05
HTnc	CTUh	8.76E-04	1.64E-04
HTc	CTUh	6.48E-05	3.53E-05
PM	kg PM2.5 $_{eq}$	4.86E-01	1.54E-01
IR	kBq U235 $_{eq}$	9.70E+01	9.33E+01
POCP	kg NMVOC $_{eq}$	2.05E+00	9.11E-01
AP	molc H+ $_{eq}$	5.60E+00	1.10E+00
EP$_t$	molc N $_{eq}$	6.56E+00	3.28E+00
EP$_f$	kg P $_{eq}$	6.61E-01	2.33E-01
EP$_m$	kg N $_{eq}$	7.26E-01	3.60E-01
FET	CTUe	2.89E+04	1.57E+04

Figure VII.7: Comparison between the different increase of PV self-consumption systems (for 1 year)

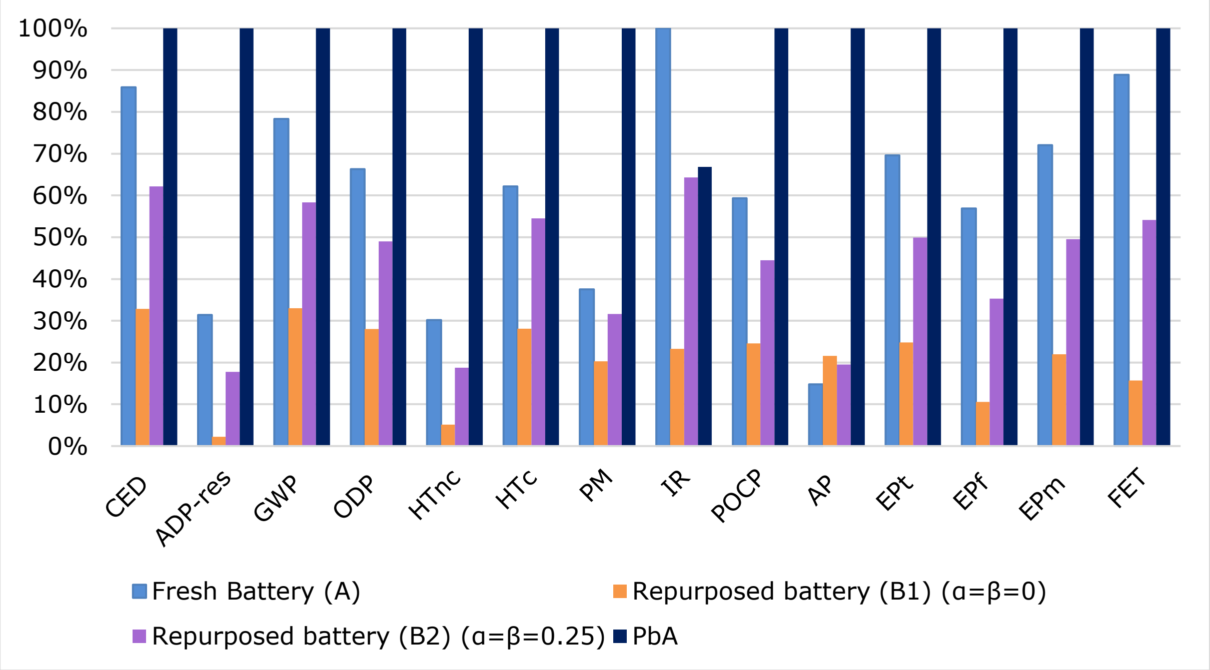
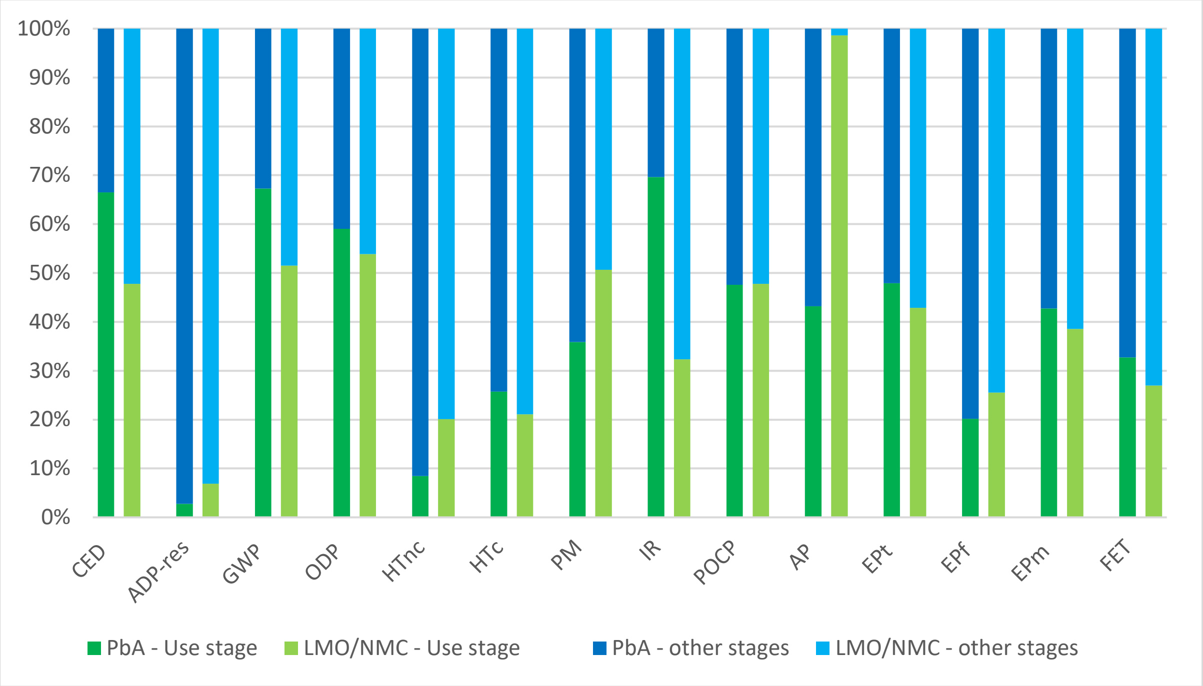


Figure VII.8: Manufacturing/EoL and use stages contribution to the yearly impact of both the PbA and the LMO/NMC batteries



Therefore, the environmental benefit of reusing a battery for the increase of PV-consumption, in this case, is beneficial for such application in which a fresh battery is substituted. Note that the assessed batteries have the same chemistry, and different results could occur depending on the batteries characteristics (e.g. batteries for BEVs, different chemistry life LIB vs PbA, etc., climate conditions, etc.).

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