LIFE CYCLE ASSESSMENT

31 MARCH 2023

WP6 REGULATORY, TOXICOLOGY, ENVIRONMENTAL AND SOCIAL LIFE CYCLE ANALYSIS.

DELIVERABLE D6.1

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DELIVERABLE REPORT

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LIST OF ABBREVIATIONS

Abbreviation	**Definition**
CLR	Closed-Loop Recycling
DOD	Depth of Discharge
EF	Environmental Footprint impact assessment methods
FU	Functional unit
GSA	Global Sensitivity Analysis
ISO	International Standards Organisation
LCA	Life Cycle Assessment
LIB	Lithium-ion battery
OLR	Open-Loop Recycling
ORFB	Organic Redox-flow battery
RTE	Round-Trip Efficiency
S-LCA	Social Acceptance Asessment
VRFB	Vanadium Redox-flow battery
YC	Yearly Cycles

1. Introduction

Together with deliverable 6.2, this deliverable report fulfills one of the objectives of WP6 Task 6.1, namely to *study the environmental suitability & impact of the target battery components by a Life Cycle Sustainability Assessment (LCA) and Social Acceptance Assessment (S-LCA).* As set out in the project proposal, this Life Cycle Assessment considered the entire life cycle of the proposed BALIHT Organic Redox-flow Battery (ORFB) to assess the environmental impacts associated with all the stages of the battery's life from-cradle-to-cradle (i.e., from raw material extraction through material processing, manufacture, distribution, use, maintenance, and recycling of battery and its components at their end-of-life). Recognizing that LCA results are only meaningful in a relative/comparative context, we took well-documented Vanadium Redox-flow Battery (VRFB) and Lithium-ion Battery (LIB) designs previously reported in literature as a benchmark[1].

This LCA was performed in adherence to relevant aspects of the ISO 14040 standard[2] and related methodological guidances such as the EU JRC's International Life Cycle Data System[3] and the more recent EU Product Environmental Footprint recommendations[4]. We also adhered to the relevant indications for carbon footprint calculations proposed in the current draft EU Batteries Regulation[1]. "Background" data for the supply chain of raw materials and intermediate products was obtained from the Ecoinvent database v3.8 which was updated in 2021.[5] "Foreground" data - that which involves processes developed by the consortium- was obtained directly from project partners over the course of the project. This study recognized that many products/processes in the battery's manufacturing are still being developed and optimized from an economic point of view as well as from a sustainability point of view. The assessment was therefore of a forward-looking nature (i.e., *ex- ante*)[6], which implies that the LCA was modelled initially based on lab and pilot-scale processes and extrapolated to better reflect battery deployment at industrial scale. This constitutes a *scenario exploration* rather than a predictive exercise, thus quantifying the uncertainties associated with upscaling to market-readiness was a central part of the assessment. The main goal with this report is to inform forthcoming ORFB battery designs, allowing for optimal upscaling of the processes, rather than reflecting an absolute indicator of the batterys' future environmental impacts.

This report briefly summarizes the 4-steps of the LCA framework applied to the BALIHT battery (Goal & scope definition, Life cycle inventory, Life cycle impact assessment, Interpretation). The detailed descriptions of the underlying models, data sources, calculations and assumptions are provided in a supplementary Annex, along with complementary results and figures. Furthermore, the implementation and results of this study will be combined with those from Deliverables 6.2 and 6.7 in a scientific paper on Safe and Sustainable-by-Design Organic Redox-flow Batteries which is to be submitted to a peer-reviewed journal.

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[1] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CONSIL:ST_5469_2023_INIT&qid=1675069045839&from=EN

2. Methods

2.1. Goal and scope definition

Functional unit. Life cycle impacts in LCA are calculated on the basis of the service provided by a product system, i.e., the *function* of the sytem.[7] This function is quantified in a *functional unit* which for batteries, following the latest definition put forth in the draft EU Batteries Regulation, is *one kWh of the total energy provided over the service life by the battery system*. The total energy provided over the BALIHT battery's lifetime was calculated as (see Annex for VRFB and LIB calculations):

$$E_{total} = C_{max} * C_{loss-factor} * DoD * yearly\ cycles * lifetime * \sqrt{\eta_{RTE}}$$

E_{total}	Total electricity delivered back to grid over battery's lifetime	870 MWh
C_{max}	Storage capacity of battery	200 kWh
$C_{loss-factor}$	Factor that incorporates electricity losses of battery over lifetime	90%
DoD	Depth of discharge	100 %
$yearly\ cycles$	How many cycles each year: currently 300 values, bit less than 1 cycle every day	300 cycles/year
$lifetime$	Years of operation	20 years
η_{RTE}	Round trip efficiency (the square root is taken to account only for losses during discharging and not during charging)	65 %

The equivalent amount of battery required to satisfy the functional demand of 1 kWh is then equal to:

$$\frac{1\ kWh}{E_{total}} = 1.44\ \times 10^{-6}\ battery\ units$$

Scope. The geographical scope of the assessment is for a battery manufactured in Germany, installed and operated in the south of Spain, and subjected to different End-of-Life treatment options in Europe. Supply chains span the globe and are modelled as national/regional markets in the ecoinvent[5] database. The temporal scope reflects data from ca. 2006-2021 for the background supply chain (ecoinvent) and current data for the foreground processes reported by the consortium partners. Where possible, extrapolations were made to reflect feasible industrialization pathways in the near future. The technology scope includes all components, activities and materials required by the battery's life cycle. The types of environmental emissions, natural resource consumptions and environmental impact categories considered are those covered by the EU's Environmental Footprint impact assessment methods (EF), version 3.0.[4] This LCA takes an attributional approach (as opposed to a consequential approach) where impacts are attributed to a marginal increase in demand for the BALIHT battery (whereas the consequential approach calculates the environmental burdens that are expected to occur, directly or indirectly, as a consequence of the decision to displace one technology for another).[8] To this end, the *cutoff* version of the ecoinvent database[5] was used.

2.2. Inventory analysis

A flowchart of interconnected activities involving manufacturing, transport, operation, decommissioning and end-of-life treatment of the battery and its components was prepared in consultation with consortium partners (Figure 1). For each activity, the economic products and services required were quantified along with the environmental emissions and natural resource consumptions incurred. As per standard LCA calculations, these quantities were then scaled to the specific amounts needed to provide the functional unit of 1 kWh. LCA calculations were performed in the *Brightway* open-source LCA software supported by the *Activity-Browser*[9,10].

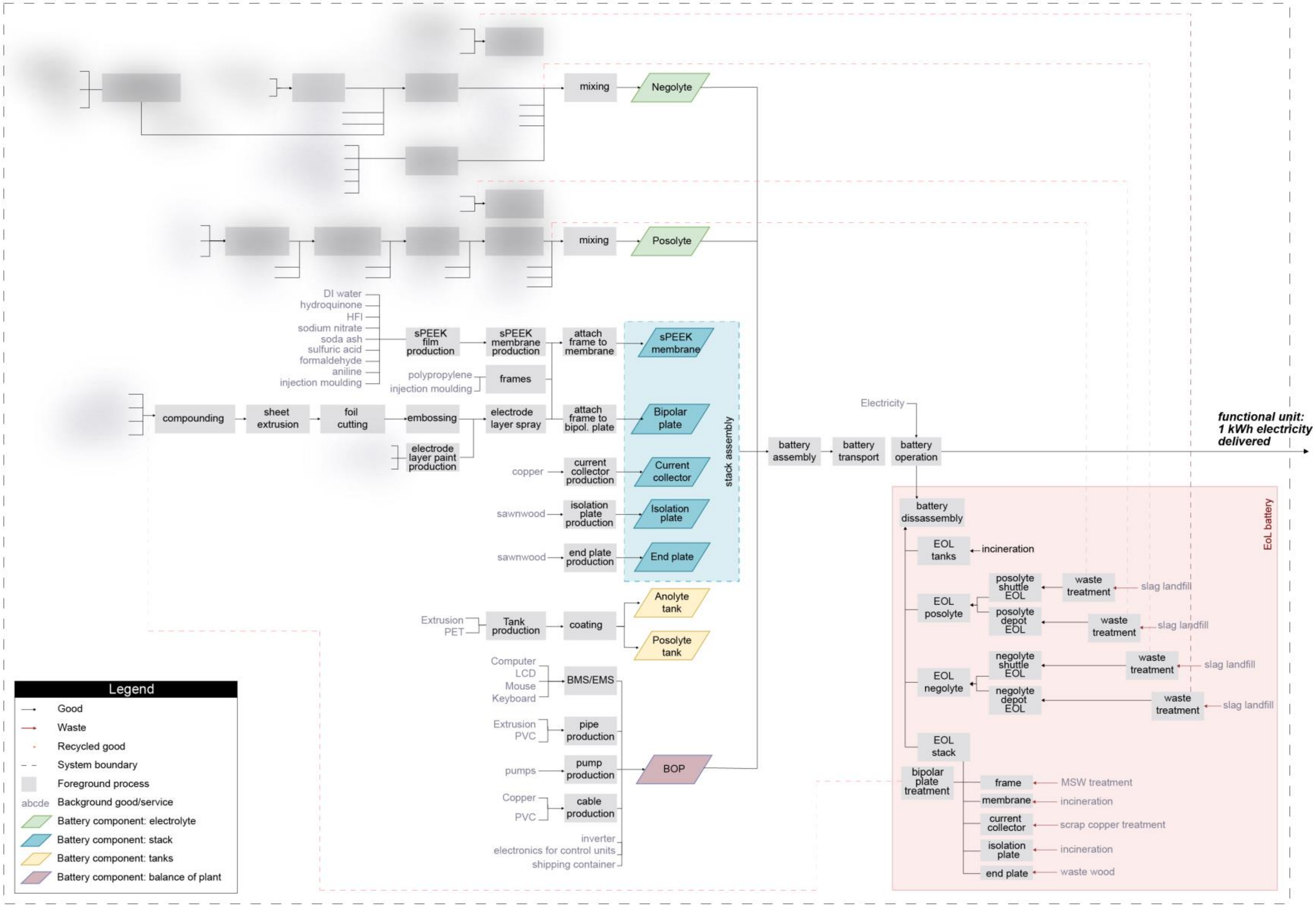

Figure 1 - Flowchart of BALIHT Organic Redox Flow Battery life cycle (commercially sensitive details blurred).

2.3. Impact assessment

All environmental emissions and natural resource consumptions that result from the delivery of 1 kWh by the ORFB, VRFB and LIB were then translated and aggregated into 16 impact categories determined by the EU-recommended Environmental Footprint (v3.0) method[4], including climate change, acidification, eutrophication, human toxicity (carcinogenic and non-carcinogenic), ecotoxicity and ozone depletion. Three toxicity categories are further subdivided into 3 subcategories each (for metals, inorganic and organic substance emissions), and climate change is further subdivided into 3 subcategories (biogenic, fossil, and land use change related emissions). Emissions are translated to impacts by *characterization factors* which are calculated according to best available methods determined by the EU in the EF (v 3.0)[4] methodology.

2.4. Interpretation

Three analyses were conducted in the interpretation stage. First, environmental hotspots were identified by means of a *contribution analysis*, which calculates the contributions of specific life cycle stages, (groups of) battery components and/or related processes, environmental emissions or natural resource consumptions to the overall LCA impact scores (e.g. as a percentage). This allowed us to pinpoint specific elements in the battery's life cycle that can be targeted for substantial improvement of the overall environmental profile.

We also conducted an *uncertainty analysis*, in which uncertainty and variability in the LCA model's parameters was propagated via Monte Carlo simulations[11], giving a probability distribution curve for each of the impact scores rather than a fixed score. The uncertainty analiysis ensures a full range of plausible conditions -including extremes - are accounted for while weighed according to their expected probabilities of occurrence. The probabilistic impact scores can then be interpreted using conventional statistics such as means, modes, percentiles and interquartile ranges.

Finally a *global sensitivity analysis* (GSA)[12] was conducted. As opposed to *local* sensitivity analysis, where model parameters are changed one at a time to see how the impact score is affected, a GSA simultaneously varies all parameters along their possible ranges of values and then determines which parameters are more influential. The most influential parameters offer the most effective avenues of action to improve the battery system's design in terms of environmental impacts. To measure sensitivity we chose the delta moment-independent sensitivity measure proposed by Borgonovo[13] and estimated its value for all uncertain and variable parameters using the *sensiFdiv* package in the statistical software *R*.[14]. The most influential parameters were then selected and fixed at their best-case values to propose a roadmap for optimization of the environmental sustainability of the BALIHT battery.

3. Results

3.1. Life cycle impacts: BALIHT ORFB vs. VRFB and LIB

Table 1 presents the resulting indicator scores for the three battery systems assessed when charged from a photovoltaic ground-mounted plant in the south of Spain. The scores reflect average values (base case) for all variable and uncertain model parameters (see Annex for a full list of the model's parameters, their base case value and their assumed probability distributions). To inform on the environmental burdens associated exclusively to the battery, the impact scores reported herein include the impacts from electricity losses during discharge, while the impacts of electrictiy generated and ultimately delivered to the grid are discounted.

Table 1 Impact indicator scores for BALIHT ORFB, LIB and VRFB batteries.*

Impact category indicator	**ORFB**	**LIB**	**VRFB**
acidification | accumulated exceedance (ae)	**5.48E-04**	**1.08E-03**	**1.18E-03**
climate change | global warming potential (GWP100)	**8.16E-02**	**8.92E-02**	**9.02E-02**
Biogenic	*6.87E-04*	*7.22E-04*	*2.66E-04*
Fossil	*8.07E-02*	*8.82E-02*	*8.98E-02*
land use and land use change	*1.85E-04*	*2.47E-04*	*1.78E-04*
ecotoxicity: freshwater *Total* | comparative toxic unit for ecosystems (CTUe)	**5.24E+00**	**7.82E+00**	**6.95E+00**
Inorganics	*1.18E+00*	*1.05E+00*	*1.06E+00*
Metals	*3.84E+00*	*6.75E+00*	*5.86E+00*
Organics	*2.17E-01*	*1.98E-02*	*2.92E-02*
energy resources: non-renewable | abiotic depletion potential (ADP): fossil fuels	**1.10E+00**	**1.14E+00**	**1.11E+00**
eutrophication: freshwater | fraction of nutrients reaching freshwater end compartment (P)	**4.53E-05**	**8.08E-05**	**6.24E-05**
eutrophication: marine | fraction of nutrients reaching marine end compartment (N)	**4.23E-04**	**1.64E-04**	**1.79E-04**
eutrophication: terrestrial | accumulated exceedance (AE)	**9.17E-04**	**1.25E-03**	**1.41E-03**
human toxicity: carcinogenic | comparative toxic unit for human (CTUh)	**2.05E-10**	**6.03E-10**	**5.95E-09**
Metals	*1.22E-10*	*4.84E-10*	*1.60E-09*
Organics	*8.27E-11*	*1.19E-10*	*4.35E-09*
human toxicity: non-carcinogenic | comparative toxic unit for human (CTUh)	**3.79E-09**	**1.04E-08**	**2.06E-07**
Inorganics	*6.28E-10*	*1.25E-09*	*7.24E-08*
Metals	*2.96E-09*	*8.71E-09*	*1.34E-07*
Organics	*2.13E-10*	*4.69E-10*	*2.58E-10*
ionising radiation: human health | human exposure efficiency relative to u235	**7.88E-03**	**1.45E-02**	**7.88E-03**
land use | soil quality index	**3.81E+00**	**2.78E+00**	**4.07E+00**
material resources: metals/minerals | abiotic depletion potential (ADP): elements (ultimate reserves)	**5.42E-06**	**1.81E-05**	**9.42E-06**
ozone depletion | ozone depletion potential (ODP)	**1.62E-08**	**2.65E-07**	**2.06E-07**
particulate matter formation | impact on human health	**4.88E-09**	**6.58E-09**	**4.81E-05**
photochemical ozone formation: human health | tropospheric ozone concentration increase	**2.93E-04**	**3.83E-04**	**4.42E-04**
water use | user deprivation potential (deprivation-weighted water consumption)	**6.43E-02**	**1.79E-01**	**7.90E-02**

**Numbers in italics indicate subcomponents of the total impact score (in bold) for those categories that are subdivided by type of emission in EF3.0. Colours indicate best (green), yellow (middle) and worst (red) performing battery in each impact category.*

Figure 2 shows how the impacts of the BALIHT battery in the Monte Carlo simulation compare to those of the lithium-ion battery (LIB, blue) and a vanadium redox-flow battery (VRFB, green). It can be seen, for example, that the BALIHT battery's (median) acidification impact score is only around 50% that of LIB and slighly less than that of VRFB. In terms of climate change, the (median) impact score of the BALIHT battery is ca. 10% lower than that of LIB and VRFB. For other types of impacts except land use, the BALIHT battery's impact score is only a fraction (<1.0) of the other batteries' scores, indicating a much better overall environmental performance, even when considering variabilities and uncertainties in the model.

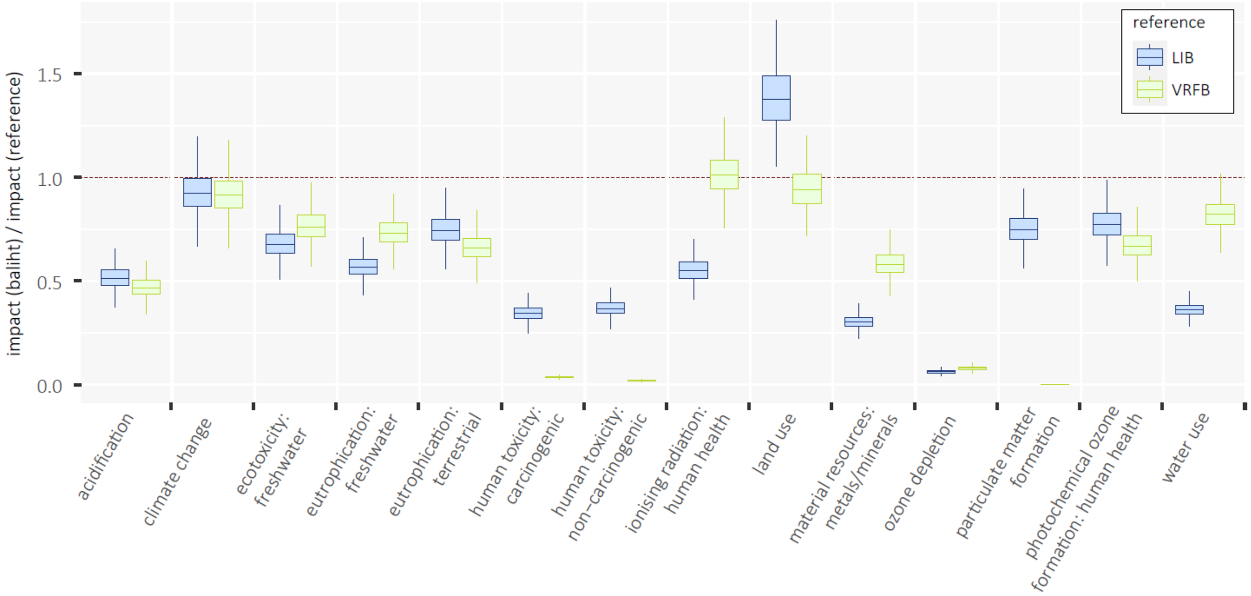

Figure 2 - Ratio of impact score of BALIHT battery vs. reference batteries: LIB (blue) and VRFB (green).

Land use is an exeption when the battery is charged from a PV installation; because of its lower roundtrip efficiency than LIB, the BALIHT ORFB incurrs in larger losses of PV generated electricity which has a considerable land footprint.

3.2. Environmental hotspots in the BALIHT ORFB

The contributions of different battery components and activities to climate change impacts are illustrated by the thickness of the branches in the Sankey diagram in Figure 3. For illustration purposes, elements that contribute less than 5% to the total impact score are not shown. In the battery components, the key hotspots are in the negolyte and posolyte constituting chemicals. An interesting outcome from the analysis is that two non-related processes contribute substantially, i.e. battery transport to installation facility and the steel container structure to house the system. The electricity losses are a result of the battery's roundtrip efficiency and reflect the impacts of the electricity generated by the PV installation but which is ultimately lost.

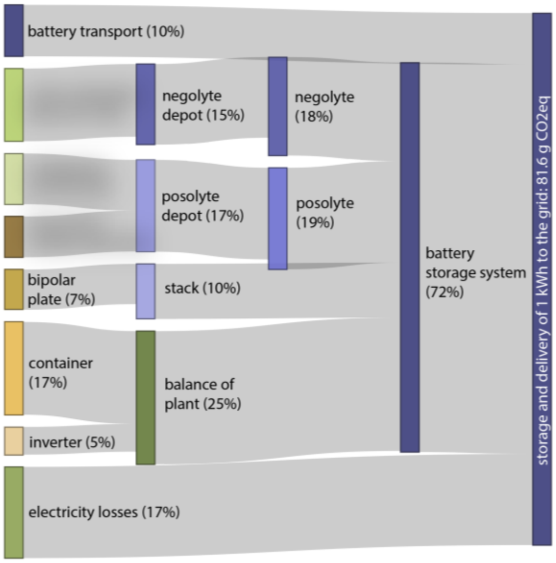

Figure 3 - Contributions of BALIHT battery's components and activities to its total climate change impact score. Commercially sensitive details blurred.

3.3. Sensitivity analysis

The global sensitivity analysis clearly highlighted 3 out of 192 variable and uncertain parameters as having considerable more influence on the uncertainty in the BALIHT battery's climate change impact score; the battery lifetime, the number of yearly cycles and the round-trip efficiency. These are followed by the depth-of-discharge, after which the differences between the subsequent parameters is marginal. (Figure 4)

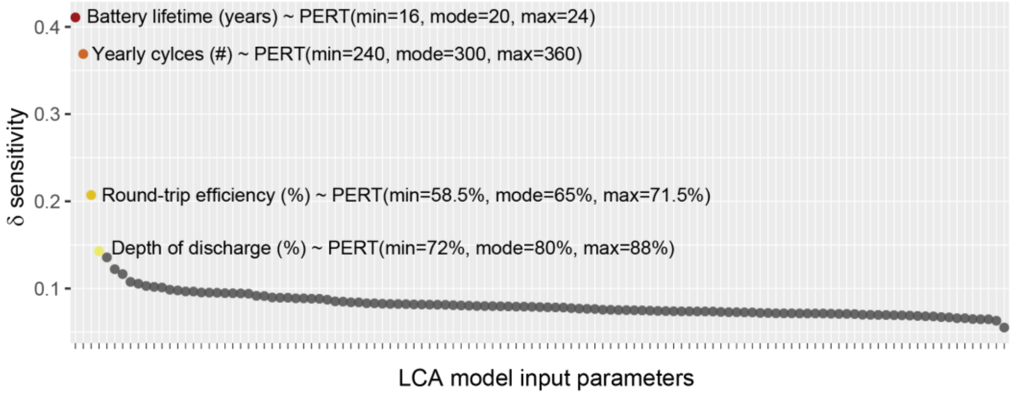

Figure 4 - Sensitivity ranking of model's 192 variable and uncertain parameters, according to Borgonovo's delta sensitivity measure.

Setting the most sensitive factors identified above at their best-case value points towards a roadmap to optimize the environmental sustainability of the battery. In Figure 5, subsequent optimizations are applied by (i) extending the lifetime (LC) of the battery to 24 years; (ii) increasing the yearly cycles (YC) to 360; (iii) increasing the round-trip efficiency (RTE) to 71.5%; (iv) increasing the depth-of-discharge to 88% (DOD); (v) implementing open-loop recycling (OLR); (vi) implementing closed-loop recycling (CLR); (vii) charging the battery with wind power instead of solar (Wind). Together, these measures could reduce the climate change impacts of the BALIHT battery by up to 58% and the land use impacts by up to 93%. In the latter case, the shift to charging from wind energy brings about a considerable reduction given the land use intensity of solar PV.

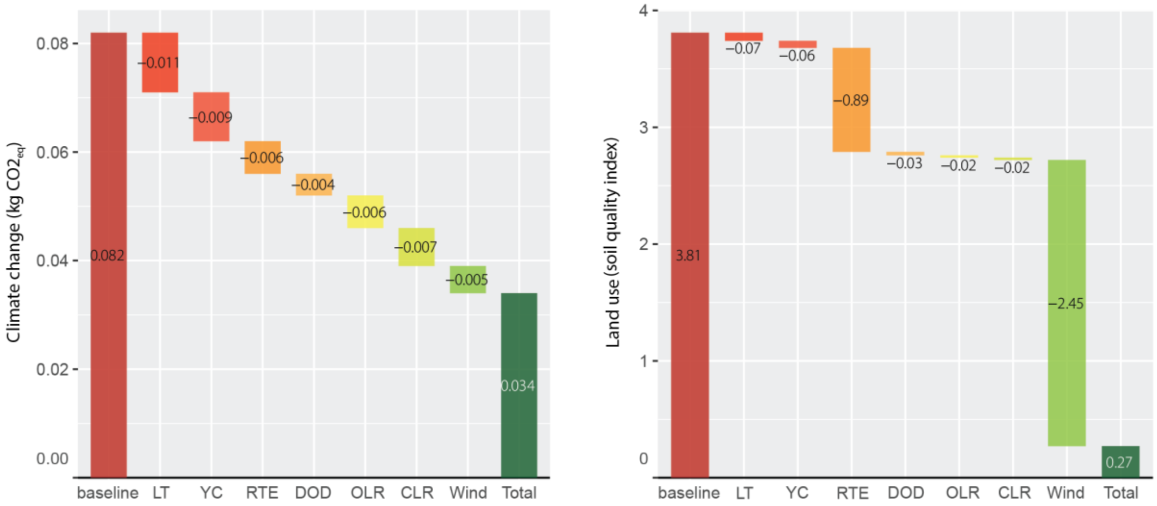

Figure 5 - Roadmap for optimizing the environmental sustainability of the BALIHT battery.

4. Conclusions and recommendations

A key achievement of the proposed BALIHT ORFB design is the fact that not only the climate change impacts appears to be slightly lower than the LIB and VRFB references, but that this is achieved without the use of metals like lithium and cobalt, and even vanadium which may be problematic for environmental, social and supply security reasons (see also Deliverable 6.2). We can thus conclude that, from a sustainability point of view, the switch to organic electrolytes is a direction very much worth pursuing for stationary energy storage applications. The battery's operational performance parameters such as roundtrip efficiency and depth-of-discharge are the most influential to the battery's life cycle impact scores, and any further improvements in this respect will not only enhance the technological and economic competitiveness of the battery but its environmental sustainability as well.

5. References

1. da Silva Lima, L. *et al.* Life cycle assessment of lithium-ion batteries and vanadium redox flow batteries-based renewable energy storage systems. *Sustainable Energy Technologies and Assessments* **46**, (2021).
2. ISO 14044. ISO14044. *The International Journal of Life Cycle Assessment* vol. 2006 Preprint at https://www.iso.org/standard/38498.html (2006).
3. JRC European commission. *ILCD Handbook: Recommendations for Life Cycle Impact Assessment in the European context*. *Vasa* (2011). doi:10.278/33030.
4. European Commission. *Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations*. (2021).
5. Wernet, G. *et al.* The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess* **21**, 1218–1230 (2016).
6. Cucurachi, S. & Blanco, C. F. Practical solutions for ex-ante LCA illustrated by emerging PV technologies. in *Ensuring the environmental sustainability of emerging technologies* (ed. Florin, M.-V.) 149–167 (EPFL International Risk Governance Center., 2023).
7. Rebitzer, G. *et al.* Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International* vol. 30 701–720 Preprint at https://doi.org/10.1016/j.envint.2003.11.005 (2004).
8. Zamagni, A., Guinée, J., Heijungs, R., Masoni, P. & Raggi, A. Lights and shadows in consequential LCA. *International Journal of Life Cycle Assessment* **17**, 904–918 (2012).
9. Mutel, C. Brightway: An open source framework for Life Cycle Assessment. *The Journal of Open Source Software* **2**, 236 (2017).
10. Steubing, B., de Koning, D., Haas, A. & Mutel, C. L. The Activity Browser — An open source LCA software building on top of the brightway framework. *Software Impacts* **3**, 100012 (2020).
11. Rubinstein, R. & Kroese, D. *Simulation and the Monte Carlo method*. (2011).
12. Saltelli, A. *et al. Global Sensitivity Analysis. The Primer*. *Global Sensitivity Analysis. The Primer* (John Wiley and Sons, 2008). doi:10.1002/9780470725184.
13. Borgonovo, E. A new uncertainty importance measure. *Reliab Eng Syst Saf* **92**, 771–784 (2007).
14. Iooss, B., Da Veiga, S., Janon, A. & Pujol, G. Global Sensitivity Analysis of Model Outputs. Preprint at https://cran.r-project.org/web/packages/sensitivity/sensitivity.pdf (2021).

Annex

1. Methods

1.1. Goal and scope definition

Functional unit. For the VRFB and LIB the total energy provided over the lifetime is calculated and reported by da Silva Lima et al. (2021).

Table 2 - Operational parameters for functional unit calculations.

Parameter	***Description***	***ORFB***	***VRFB***	***LIB***
E_{total}	Total electricity delivered back to grid over battery's lifetime	870 MWh	180 MWh	5758 MWh[2]
C_{max}	Storage capacity of battery	200 kWh	37.5 kWh	1300 kWh
$C_{loss-factor}$	Factor that incorporates electricity losses of battery over lifetime	90%		
DoD	Depth of discharge	80 %	100%	85%
$yearly\ cycles$	How many cycles each year: currently 300 values, bit less than 1 cycle every day	300 cycles/year	300 cycles/year	300 cycles/year
$lifetime$	Years of operation	20 years	20 years	10 years
η_{RTE}	Round trip efficiency (the square root is taken to account only for losses during discharging and not during charging)	65 %	83%	90%

1.2. Inventory analysis

1.2.1. Overview of processes and modelling principles

All processes modelled are listed below, corresopnding to the flowchart in the main report. The inventory tables containing the input/output data for all processes are provided in the attached Excel spreadsheet, following the coding provided in the list below. Processes listed in itallics are alternatives, e.g. one of them is selected in each scenario. For open-loop recycling scenarios (OLR), recycing efficiencies are assumed (see Parameter list in Excel) and the recovered material is fed back into the battery manufacturing (red dotted lines in the flowchart). Closed-loop recycling scenarios are modelled by also applying recycling efficiencies and subtracting the impacts of the unprocessed virgin materials (avoided burden approach). The "base case" results reported do not consider recycling but waste treatment methods listed below and detailed in the inventory tables in the Excel spreadsheet. For the chemical synthesis processes, energy requirements at industrial scale are calculated following the recommendations of Piccinno et al. (2016). Additional information on data sources and assumptions is provided in the subsections further below.

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    2.1.3 Injection moulding of frame for membrane
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    2.2.2 Sheet extrusion
    2.2.3 Foil cutting
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    2.2.6 Electrode spraying paint
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    2.3.2 Production of sPEEK membrane for battery

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[2] Energy delivered over 20 years. After 10 years the LIB is replaced by a new one.

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End plate
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Isolation plate
    2.6 PET isolation plate
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    3.1.3 Precursors (details ommited due to commercial sensitivity)
    3.1.4 Precursors (details ommited due to commercial sensitivity)
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Battery dissassembly
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        9.1.3.2 Bipolar plate treatment, fenton + flotation
        9.1.3.3 Bipolar plate treatment, leaching + filtration
        9.1.3.4 Bipolar plate treatment, oxygen free roasting
        9.1.3.5 Bipolar plate treatment, air heating
        9.1.3.6 Bipolar plate treatment, calcination + leaching
        9.1.3.7 Bipolar plate treatment, calcination
        9.1.3.8 Bipolar plate treatment, microwave
    9.1.4 Membrane EOL treatment
    9.1.5 Current collector EoL treatment
    9.1.6 End plate EoL treatment
    9.1.7 Isolation plate EoL treatment
    i10.1.1 Posolyte treatment
        i10.1.1.1 Posolyte waste treatment Chlorination
        i10.1.1.2 Posolyte waste treatment Chlorine dioxide
    i10.1.2 Posolyte shuttle treatment
        i10.1.2.1 Shuttle sludge treatment

i10.1.2.2 Closed loop recycling
i10.1.2.3 Open loop recycling
i10.1.2.4 Waste treatment
i10.1.3 Posolyte depot treatment
i10.1.3.1 Posolyte depot closed loop recycling
i10.1.3.2 Posolyte depot open loop recycling
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i10.2.1 Negolyte treatment
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i11.1.1 Negolyte Storage tanks waste treatment
i11.2.1 Posolyte tanks end of life treatment

1.2.2. Production of Electrolytes

Details on electrolyte production are ommitted from this report due to commercial sensitivity.

1.2.3. Production of storage tanks

In total there are 12 tanks for the posolyte and 12 for the negolyte. Last update was that total volume of posolyte is equal to 1500L and negolyte to 750L. Each tank has 10% more volume, leading to a total volume of 1650L for the posolyte and 825L for the negolyte tanks. Given that there are 12 tanks each, this leads to a total volume of 200L per posolyte tank, and 130L per negolyte tank. These numbers have been used to calculate the total volume of material of each tank. V = V(outer cube) – V(inner cube). The inner cube in this calculation is equal to the volume of the tanks, which results in certain dimensions for length, width and height. The length, width and height dimensions for the outer cube are than equal to the dimensions of the inner cube + thickness.

1.2.4. Production of BOP and peripheral components

The balance of plant is a combination of all peripheral components which are needed for a safe operation of the battery. This includes:

- Piping
- Pumps
- Electronics
- Battery Management System
- Inverter
- Intermodal shipping container

1.2.5. Assembly of Cell stack and final battery including transportation

Losses of frames/membranes during the assembly process was assumed to be 3%. Once the battery stack is produced, the complete battery is assembled. It is assumed that this happens at CMBLU and is transported as a whole unit.

1.2.6. End of Life of battery stack and other components

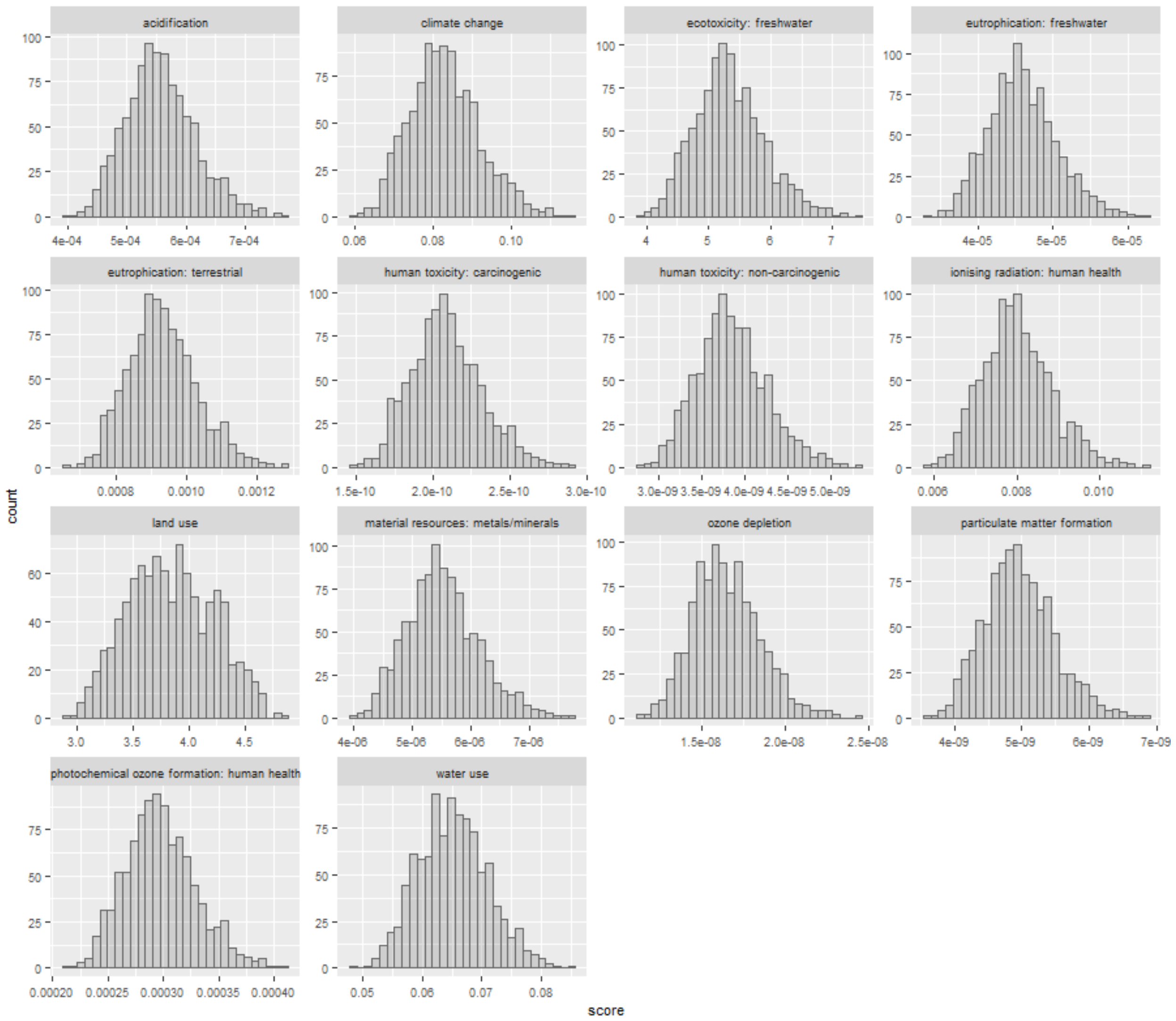
Basic principle is to separate every subpart of the battery and use appropriate End of Life methods for it. The main component in the frame is polypropylene, thus it has been decided to have the amount of polypropylene in the cell frame sent to polypropylene incineration. Scant literature was found about treatment of bipolar plates. Currently the treatment option is based upon a LCA conducted for Lithium Ion Battery electrodes (Rey et al., 2021) . There are differences between the electrodes of the LIB and the ORFB, but we take this process as a proxy for the impact of the treatment. In the paper it is mentioned that pyrolysis and flotation is the best option, and thus this one was chosen for the base case. The recovery rate is equal to 56.38%. The Membrane is sent to incineration, as for sPEEK there is not as treatment option available, but since it has similarities in structure to PET, it is likely to be incinerated. The current collector is sent to market for scrap copper collection, the end plate for wood treatment and the isolation plate is sent to incineration. Tanks are incinerated using the waste PET incineration. EoL of Balance of Plant components is not considered.

1.2.7. End of Life electrolyte

The shuttles are processed using a water treatment process and afterwards the sludge is send towards landfill. The depots can be filtered out and send to landfill.

2. Complementary results and figures

Histograms for the Monte Carlo simulation results are shown in the figure below:



3. References

Piccinno, F., R. Hischier, S. Seeger, and C. Som. 2016. From laboratory to industrial scale: a scale-up framework for chemical processes in life cycle assessment studies. *Journal of Cleaner Production* 135: 1085–1097. http://linkinghub.elsevier.com/retrieve/pii/S0959652616308514. Accessed September 26, 2017.

Rebitzer, G., T. Ekvall, R. Frischknecht, D. Hunkeler, G. Norris, T. Rydberg, W.P. Schmidt, S. Suh, B.P. Weidema, and D.W. Pennington. 2004. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International*. July. http://linkinghub.elsevier.com/retrieve/pii/S0160412003002459. Accessed August 1, 2017.

Silva Lima, L. da, M. Quartier, A. Buchmayr, D. Sanjuan-Delmás, H. Laget, D. Corbisier, J. Mertens, and J. Dewulf. 2021. Life cycle assessment of lithium-ion batteries and vanadium redox flow batteries-based renewable energy storage systems. *Sustainable Energy Technologies and Assessments* 46: 101286. Accessed December 8, 2021.