Analysis of durable battery technologies for industrial stationary application

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Introduction

With an ever-increasing amount of renewable energy being produced, the necessity for batteries to store this energy increases as well. The production of these stationary batteries is linked to a larger demand for certain metals, the mining of which possibly causing their own environmental and social negative impacts. The aim of the study w to investigate the sustainability (environmental & social) of different batteries with a sufficiently high TRL ('Technology Readiness Level', at least 6) to deduce, after integration of these aspects, which one is the most sustainable.

The Environmental aspects are studied based on a life cycle assessment with a focus on the categories Mineral Resources, Climate Change and Human Health. The Social aspects will focus on child labor.

The investigated battery technologies are:

- Li-ion NMC
- Li-ion LFP
- Na-ion
- Lead-acid (PbA)
- Vanadium redox flow battery (VRFB)

Scope of this study

The **Functional Unit** is the quantified performance of a product system for use as a reference unit.

One of the primary purposes of a functional unit is to provide a reference to which the input and output data are normalized (in a mathematical sense). Therefore, the functional unit shall be clearly defined and measurable. [Source: ISO 140 44:2006]

In this study, the functional unit is:

To store and to deliver electricity in a stationary battery for 20 years, with a net storage capacity of 250 kWh over one complete charge-discharge cycle

The capacity of the stationary battery is normalized at 250 kWh. The choice to include the period of 20 years in the functional unit allows to consider the different amount of life cycles, and to normalize results over the same lifetime. This is done to have a fair comparison between the different assessed technologies.

The period of 20 years is selected as it is the lifetime of the container that houses the stationary battery. Two locations are studied where the stationary battery is used, the difference in climate between these two locations has an impact on the F.U. in the following manner:

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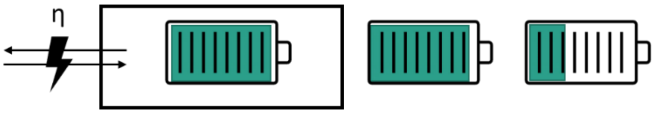
- Belgium: an assumed 300[1] cycles/year, this is a total of 6000 cycles over 20 years
- Dubai: an assumed 365[2] cycles/year, this is a total of 7300 cycles over 20 years

An example to illustrate the number of batteries needed to fulfil the functional unit.: If a stationary battery, located in Dubai, has a lifetime of 3 000 cycles, 2,4 (= 7 300 / 3 000) battery cells are used.



Amount of battery cells over 20 years is defined as:

Location	Li-ion NMC	Li-ion LFP	Na-ion	PbA	VRFB
Belgium	3	1,9	3,8	7,6	0,8
Dubai	3,7	2,3	4,6	9,3	0,9

System boundaries

The following stages are considered:

- Production/mining of raw materials
- Transport of raw materials to the plants producing stationary batteries
- Production of the stationary battery, and its housing
- Transport of the manufactured battery to the place of use
- Use phase of the stationary battery, which is charged with solar energy
- End-of-Life of the stationary batteries and their housing

The following steps are excluded as they are supposed to be negligible based on the literature and RDC Environment experience:

- Maintenance of the stationary battery
- Flows tied to R&D
- Flows tied to employee transport from home to work and back
- Flows tied to services allied to a product, such as advertising, canvassing, and marketing

The system boundaries define all stages that are included in the selected LCA scope. The system is described below using a process flow diagram showing the unit processes and their inter-relationships.

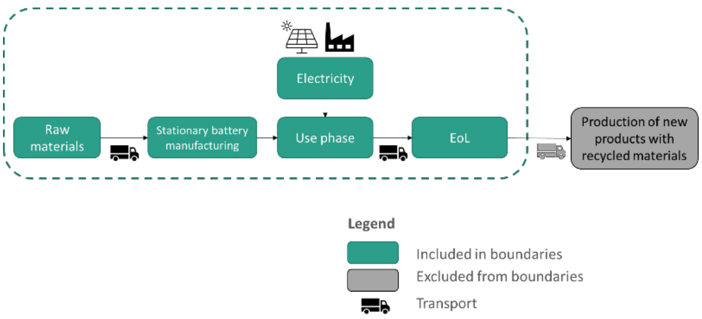


Figure 1: Boundaries of studied system

In LCA practice, it is not always possible to achieve data for each flow or process of the life cycle due to lack of information, time, or resources. Some flows or processes were excluded from the study in accordance with ISO 14044:2006, which defines

[1] Same assumption used in *Life cycle assessment of lithium-ion batteries and vanadium redox flow batteries-based renewable energy storage systems, Da Silva, 2021* where a stationary battery in Belgium is modelled

[2] Assumption: the climate allows for the battery to be charged daily

criteria based on mass, energy, and environmental significance to assess whether a flow or process can be neglected.

The Pareto principle is applied for this study. Modelling and data collection efforts are therefore focused on the elements that most influence the results.

In practice, RDC Environment have proceeded iteratively for data collection as recommended in the ILCD Handbook and ISO 14040/44:2006.

First iteration: we use default values (value intervals) provided by actors with a global vision of the problem and secondary databases or with conservative assumptions to identify, automatically and exhaustively, important modelling parameters.

Second iteration: we refine the data that have a significant impact through contacts with actors in the field. To the extent possible, the gaps identified in the first study will also be addressed.

Third iteration: final validation and data search.

This system makes it possible not to waste time in the search for data without influence on the balance, and thus to set up the emphasis on the search for sensitive data. Thus, more reliability can be achieved for these sensitive data.

The cut-off criterion is satisfied according to the following rules:

- **Mass:** inclusion in the study of all inputs that cumulatively contribute more than 5% to the mass input of the product system being modelled.
- **Energy**: inclusion in the study of all inputs that cumulatively contribute more than 5% of the product system's energy inputs.
- **Environmental significance:** inclusion in the study of all inputs that contribute to more than 5% of the environmental impact indicators studied

Data quality requirements

In accordance with ISO 14 044 an assessment of the quality of the data is carried out according to the following criteria:

- Temporal representativeness,
- Geographical representativeness,
- Technological representativeness,
- completeness of the inventory,
- Methodological consistency and reliability of the data

The bill-of-materials and the manufacture of the different batteries studied are based on a literature review. Seven different battery technologies are investigated in this literature study, of which five were chosen to assess in the environmental and social analysis. The literature study recommends certain studies to be used for the modelling of these technologies, due to their extensive and reliable LCI. The main studies upon which the LCI for the environmental analysis is based, are from this literature study.

Other data has been supplied by John Cockerill:

- Weight of container
- Auxiliary consumption to keep the stationary battery operational
- Information on geographical distribution of mining sites and manufacturing

The inventory database used is Ecoinvent v3.7.1, published in 2020.

In addition to Ecoinvent, road transport is modelled using the COPERT tool. COPERT is a reference database for Europe for modelling road transport air emissions.

The reliability of the study is examined from three different aspects:

- **Primary data**: plausibility checks are carried out by cross-checking and comparison.
- **Consistency of the LCA model**: cross-checks on the mass and energy flows are carried out.
- **Methodological consistency:** only the Ecoinvent v3.7.1 database is used for the background data. This ensures avoiding any methodological inconsistency associated with the use of multiple LCA databases.

Treatment of multi-functionality

If a process or facility provides more than one function, i.e., it delivers several goods and/or services ("co-products"), it is “multifunctional.” In these situations, all inputs and emissions linked to the process must be allocated among the product of interest and the other co-products in a principled manner.

Treatment of multi-functionality in production processes: Allocations may be required for the extraction and production of some jointly produced minerals. The database Ecoinvent is used for these background processes and therefore the allocations are the ones performed by Ecoinvent.

Ecoinvent prefers economic allocations (allocations based on the revenues generated by the different co-products). This reflects the position of RDC Environment in the choice of relevant allocations for an LCA study.

Treatment of multi-functionality in waste treatment, Incorporation of recycled materials and recycling at end-of-life: An allocation is necessary between the supplier and the user of secondary material to allocate the recycling benefits.

The following allocations are applied in accordance with the Circular Footprint Formula of the Joint Research Centre of the European Commission for PEF studies[3]

- Metal: 20% incorporator / 80% supplier,
- Plastic: 50% incorporator / 50% supplier,
- Cardboard: 20% incorporator / 80% supplier.

Heat surplus from incineration: Export of heat surplus from plant (incineration): the heat surplus (heat produced but not used) can be sold to external grid or converted in electricity. In this case, the sold heat or electricity is modelled via a substitution approach because it avoids an equal heat production somewhere else (based on the energy content) or an equal electricity production (average national grid avoided).

Impact categories

The choice of the LCIA methods aims at giving an overall view of environmental impacts of the products modelled. Total results are presented for all the 16 impact categories (EF 3.0) recommended by the PEF (product Environmental Footprint by the European Commission).

The list of those impact categories is as: Climate change; Ozone depletion; Human toxicity, cancer; Human toxicity, non- cancer; Particulate matter; Ionizing radiation, human health; Photochemical ozone formation, human health; Acidification; Eutrophication, terrestrial; Eutrophication, freshwater; Eutrophication, marine; Ecotoxicity,

[3] Zampori, L. and Pant, R., Suggestions for updating the Product Environmental Footprint (PEF) method, EUR 29682 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76- 00654-1, doi:10.2760/424613, JRC115959.

freshwater; Land use; Water use; Resource use, minerals, and metals; Resource use, fossils.

The associated characterisation models are classified into three levels according to their quality

- Level I - recommended and satisfactory
- Level II - Recommended, but in need of some improvements
- Level III - recommended, but to be applied with caution

Sensitivity analysis

Sensitivity analysis is performed:

- Adjusted impact category 'resource use, minerals & metals'
- on the characteristics of the battery technologies, on the main characteristics of the battery technologies, these are the energy density, amount of life cycles and efficiency, with the impact categories Climate change, Resource use, minerals and metals
- Second-life batteries (SLB) from mobile application, Once EV batteries degraded to 70–80% of their initial capacity, EV owners will have to replace the EV's batteries as the residual capacity becomes insufficient for automotive use. As a result, more batteries will be discarded from EVs. These batteries could be re-purposed in other applications, where they are known as the EV Second Life Batteries (SLB)[4].

Social analysis: child labor

Batteries might contain certain metals that originate from countries/regions where child labor is still a major issue. One such example is cobalt, an element often used in batteries. More than half of the world's cobalt originates from the Democratic Republic of Congo (DRC), where child labor is very frequent.

Thus, to be consistent with the principles of sustainable development, particularly regarding the social aspect, it is essential to take this aspect into account in the sustainability assessment of batteries.

The social aspect is assessed via the child labor risk indicator. The child labor risk indicator is based on the mineral resource and the respective country of origin.

Child labor is a well-defined and a relatively well documented social indicators (compared to forced labor, corruption, etc.).

The child labor indicator encompasses the following sub-indicators:

- children in employment, male,
- children in employment, female
- children in employment, total.

In the context of this study, there are 20 countries of concern. These are the main countries of origin of the studied mineral resources.

[4] Feasibility of utilising second life EV batteries: Applications, lifespan, economics, environmental impact, assessment, and challenges, Haram et al., 2021

Conclusions

The Lead-acid (PbA) battery has the largest impact for 12 of the 16 impact categories. The VRFB has the lowest impact for 7 of the 16 impact categories. The PbA battery often has an impact multiple (2 – 5) times larger than the other battery technologies on a certain impact category. The VRFB on the other hand usually has the best score with the lowest impact found in 7 of the 16 impact categories, only in one impact category (land use) this battery technology has the largest impact of all assessed technologies. The VRFB has the lowest impact on among others 'climate change', 'resource use, fossils', 'ecotoxicity, freshwater' and the second lowest impact on 'resource use, minerals and metals'. Although the difference in impact on this last impact category between the Na-ion and VRFB is too small to make a statement on which of these two batteries will have the lowest impact on this impact category.

The impact category 'resource use' (minerals and metals) is the most relevant impact category to the total environmental impact with regards to the normalization and weighing. There are six impact categories causing > 80% of the total environmental impact, these are: resource use (minerals and metals), ecotoxicity freshwater, climate change, resource use (fossils) and eutrophication freshwater. For all battery technologies the most contributing impact category is resource use (minerals and metals), causing between 30 – 55% of the environmental impact. The top three main impact categories are completed by climate change and ecotoxicity freshwater on second and third place for all technologies.

The conventional Li-ion and Na-ion battery technologies gives similar results on relevant impact categories.

When comparing technologies, the uncertainty of the results must be considered. Uncertainty occurs at several levels: the activity data (composition and manufacturing impacts), the secondary data (LCA database) and depending on the impact category. In this study, the composition of the batteries is derived from different sources, resulting in a high degree of uncertainty in extrapolating to the reality that John Cockerill will encounter on the batteries that will be installed. Therefore, the results for li-ion and Na-ion batteries can be considered similar on the relevant impact categories.

For the conventional battery technologies, batteries manufacturing is the main contributing phase to the environmental impact; for the flow battery, it is the use phase. The conventional batteries have a smaller number of life cycles compared to the flow battery (1000 to 3000 vs 8000), but a larger efficiency (80 to 90% vs 80%). This causes the cradle-to-gate impacts to be higher for the conventional batteries, while the operation of the battery is less impactful. The opposite is true for the flow battery (although for some impact categories, the manufacturing phase can have a similar impact as the operation). The PbA battery has the smallest amount of life cycles and the second lowest efficiency, largely explaining the large environmental impact of this technology compared to the other assessed technologies.

The production of the anode/electrodes causes a large part of the cradle-to-gate impacts for the conventional batteries, except for the Na-ion battery. The production of the electrolyte generates most of the cradle-to-gate impacts for the flow battery. The impact category resource use, minerals and metals, is the most contributing impact category to the total environmental impact, and within this impact category most of the cradle-to-gate impact is caused by the anode (Li-ion technologies) and electrodes (PbA). The elementary flow analysis indicates this impact on resource use, minerals and metals is due to:

- Li-ion technologies: the production of the copper current collector, which is the current collector used in the anode

- PbA: the production of lead

For the flow battery, the electrolyte causes most of the environmental impacts during cradle-to-gate, even though it does not cause most of the impact on the impact category resource use, minerals, and metals. It does however have by far the largest impact on the other 4 impact categories that together with resource use, minerals, and metals form more than 80% of the total environmental impact.

Energy consumption to manufacture the battery cells is another important contributor to the cradle-to-gate impacts for the conventional batteries. Especially the two Li-ion technologies and the PbA battery see a large contribution on certain impact categories due to energy consumption, mainly on climate change and resource use, fossils. This means the country of manufacturing has a large influence on the overall environmental impact; the batteries are modelled to be manufactured in China, where most of the electricity is generated through coal.

The end-of-life of batteries is highly uncertain. Except for lead-acid batteries, battery recycling is still in the industrial development stage. For example, lithium is not yet recovered because it is not economically viable. Furthermore, databases on the impact of battery treatment facilities are poorly documented. The hydrometallurgical and pyrometallurgical processes come from a single plant in Europe. The additional processes for the recovery of ores (not Fe-Co metals) are approximated by mining processes.

The weight of battery per cycle strongly influences the environmental impact of the battery. The battery's weight per cycle is determined by the efficiency, energy density and number of cycles. In the sensitivity analyses, the point clouds have a steep slope indicating the strong influence of this parameter on the results. The VRFB has a significantly less steep slope compared to the other conventional batteries, which means this parameter is less of importance for this battery technology. This is in accordance with the conclusion that the VRFB's main contributing life cycle stage is the use phase, and not the manufacturing stage.

A sensitivity analysis does not change the conclusion that the VRFB has the lowest environmental impact. The point clouds that result from the assessed ranges on energy density, efficiency and amount of life cycles do not overlap with the VRFB's base case result. Only in one instance there is a small overlap: the Li-ion NMC does have a few data points which score better on the impact category 'climate change' than the VRFB's base case results. However, there is never any overlap between the VRFB and the other battery technologies for the impact category 'resource use, minerals and metals'.

Important remarks:

- The true ranges for the Na-ion battery are not known since too little literature is available. The current range for the Na-ion battery leads to some overlap with the VRFB although this is due to a high amount of life cycles (5000) which has been claimed by one supplier. If this lifetime could be achieved, the Na-ion battery could be a serious contender for the VRFB.
- The sensitivity analysis was performed using the unaltered impact category 'resource use, minerals and metals', meaning the elementary flow Tellurium is assessed as well.

Giving discarded EV batteries a second-life application in a stationary battery could yield to a decrease in climate change impact but a potential increase in the impact of mineral resource depletion. This prospective sensitivity analysis shows the first trends in the environmental impacts of the use of second-hand batteries. This work should be extended with real data to confirm or refute these first trends. Thus, it can be concluded that:

- the use of second-hand batteries avoids the production and end of life of new batteries in proportion to their remaining life
- the use of less efficient batteries requires more solar energy production to compensate for the decrease in efficiency. Solar energy requires the production of significant mineral resources, which would offset the benefits associated with avoiding the production of new batteries. However, the overall climate change impacts appear to be reduced (i.e., there is a transfer of impacts).

Two of the assessed materials pose a high risk for child labor, cobalt, and manganese. For five materials there is at least a medium risk for child labor. Most of the global production (71%) of cobalt occurs in Congo (RDC), where a very high risk for child labor is found. Manganese is for a large part mined in two African countries; South Africa (29%) and Gabon (13%). Here as well, a large risk for child labor is found. This is especially of relevance for the Li-ion NMC technology which uses a paste made up of Cobalt, Manganese and Nickel. Also, the Na-ion technology makes use of a paste which consists partly of Manganese. For five other materials a medium risk for child labor is found, these are: graphite, lead, nickel, phosphate, and vanadium. These results are mainly explained by the large share of China in the global production of these materials, and the medium risk for child labor found in China.

Recommendations

If the technology is regarded as sufficiently mature, the flow battery (VRFB) should be selected from an environmental viewpoint. The flow battery has the best score (lowest impact) for most of the impact categories, among the assessed battery technologies. Thanks to its large number of life cycles, the cradle-to-gate impacts are greatly reduced and much smaller than those for the other battery technologies. This battery has the lowest efficiency of all technologies, which increases the impact during operation but still this battery achieves better results than the other technologies.

As cell production is the main source of impacts, increasing lifetime (number of cycles) and recycling are priority development areas. As battery production is the main source of impacts, the number of batteries needed to fulfil the functional unit is a key parameter. Actions leading to a longer lifetime (maintenance, managing the discharge level, improved design…) should be implemented.

From a social standpoint, the Li-ion NMC battery should be avoided due to the large risk for child labor for two of its elements. The mining of cobalt and manganese pose a very high-risk regarding child labor, these elements are used in the Li-ion NMC battery as part of the positive active material. To avoid the possibility of child labor, the sourcing of these elements should be carefully assessed. If it is not possible to track the origin of these elements, it is better to avoid using this technology.