École polytechnique de Louvain

Sustainability assessment and perspectives for battery storage in a solar home system in Cameroon.

Made in close collaboration with Solarly

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Lastly thank you to my family and all the friends I must have bored with the details of environmental impacts for a year.

Louvain-la-Neuve, August 19, 2022

Olivier Ryelandt

« *There is surely nothing quite so useless as doing with great efficiency what should not be done at all.* »

Peter Drucker,
1963.

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Acronyms

B2U	Battery second-use
BLL	Blood lead levels
DALY	Disability adjusted life years [1]
DoD	Depth of Discharge
EoL	End-of-Life
EROI	Energy Return on Investment
EV	Electric vehicle
GHG	Greenhouse Gases
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LABs	Lead-acid batteries
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LFP	Lithium ion iron phosphate battery
LIB	Lithium ion batteries
MW	Metallic waste
NMC	Lithium-ion nickel manganese cobalt battery
SB	Solarly Box
SK	Solarly standard kit
PK	Solarly premium kit
PAYG	Pay-as-you-go[2]
RoHS	Restriction of Hazardous Substances in Electrical and Electronic Equipment
S-LCA	Social Life Cycle Assessment
SDGs	Sustainability Development Goals [3]

[1] Used as a unit to determine the impact of something as a number of healthy year lost
[2] Payments by instalments
[3] set up in 2015 by the General Assembly of the UN as targets to reach by 2030

SHS	Solar home system
SSA	Sub-Saharan Africa
ST	Solidarité Technologique[4]
UCLouvain	Université catholique de Louvain
ULAB	Used lead acid batteries
UNFCCC	United Nations Framework Convention on Climate Change
WEEE	Waste from electrical and electronic equipment

[4]Non-profit active in the collection and treatments of WEEE in Cameroon

Introduction

The motivation behind this thesis was a desire of Solarly's executive to know if their activity was good and how to improve it. Despite its status of a for-profit company, it aims to have a positive impact. Behind the simple notion of good hides a world of complexity. Therefore, a significant part of the reflection was dedicated to finding where to start.

The discussions covered all kinds of impacts the company had: economic, environmental, social, etc. The sustainability and resilience of the system were also in question. However, those aspects are vast, and conducting a useful assessment is quite a challenge. We tried to find a framework to assess a system as holistically as possible. But this field is in its infancy, and it was hard to find something concrete. A set of criteria considered was the ESG (Environnement, Social and Governance) framework, which has become popular in finance. However, after some time trying to pursue a holistic approach, considering environmental, social, and economic factors, it became clear that the scope had to be reduced to derive any useful conclusions.

The focus was set on environmental impact. Again in an effort to derive useful and specific conclusions, it was decided to focus on the part of the system considered a hot spot in terms of impact, namely the battery that we identified with a mini-LCA. The idea was to characterise the environmental impact and assess alternatives and opportunities to reduce it. To characterise it, the tool selected was an LCA. It allows for a broad assessment of the product's environmental impact. However, given the lack of data for the end-of-life, the quantitative assessment was limited to the production phase. The alternatives assessed along the current solution (LAB) are NMC and LFP. The life cycle assessment is covered in the first chapter.

The second chapter focuses on the end-of-life of batteries. Given the lack of reliable data on the material flows of batteries in Cameroon and the lack of studies treating the impacts of battery disposal, it was considered pointless to make a quantitative assessment. However, a review of the technologies available and the current situation has been conducted. It can be used to define better strategies for end-of-life management of the batteries.

After these two chapters on the current solution's impact and two alternative chemistries, the third chapter concerns the supplies of metal needed to manufacture batteries. It was considered a vital aspect of the sustainability of the system. The mineral resources for each essential element are covered.

The last chapter covers alternatives to reduce the impact of batteries. These include methods to limit the impact of the current solution and exploration of second use as a solution to reduce impact.

This analysis aims to give specific data and conclusions to the studied company to help them make informed decisions. It has forced a reduction in the scope of the study. However, this thesis is part of a more extensive effort to characterise the company's impact and develop its product and operations. It still leaves many areas that deserve to be studied more thoroughly. The scope could be expanded by building upon this study. Environmental impacts could also be refined by gathering more data. Economic and social aspects would also deserve scrutiny.

1 Life Cycle Assessment

This thesis aims to provide information and perspectives for Solarly to improve their solutions' environmental impact. Different tools exist to assess the environmental impact of this solution. In order to get the clearest picture, an LCA was selected. It allows to assess the full extent of the impact of a solution, and as we will see further, it is made more accessible by the vast existing body of research in the field.

It is an important tool for assessing the environmental impacts of all products and services. The method has guidelines defined by various norms [57][58] [37] that allow for replicable results. It also allows for comparison between different products if they use equivalent scopes.

The method consists of 4 main steps that can be reiterated multiple times. The first step consists in defining the goals and the scope of the assessment. The scope is used to set a boundary to the studied system. The second step consists in modelling the life cycle by inventorying all the material and energy flows involved. This step is the Life Cycle Inventory or LCI. Then the impacts of all elementary flows must be determined. Given the extensive range of products in the elementary flows, we typically use existing methods to determine their respective impacts. This step is called Life Cycle Impact Analysis or LCIA. The final step consists in interpreting the results. The steps are illustrated in figure 1.1. They will be detailed in the following sections.

As the system is composed of multiple components (batteries, solar panels, electronics, cables, etc.), concentrating on a "hot-spot" was considered more valuable to get a more precise picture of a specific component instead of getting blurrier results of the whole system.

To identify a "hot spot", the system was modelled with a very basic LCA. It identified the batteries as the component with the worst environmental impact. We then proceeded with a more thorough LCA of the battery and compared it with alternatives.

The current system uses lead-acid batteries, and they are compared to alternative lithium-ion chemistries. We selected NMC (Nickel-Manganese-Cobalt) because it is the current

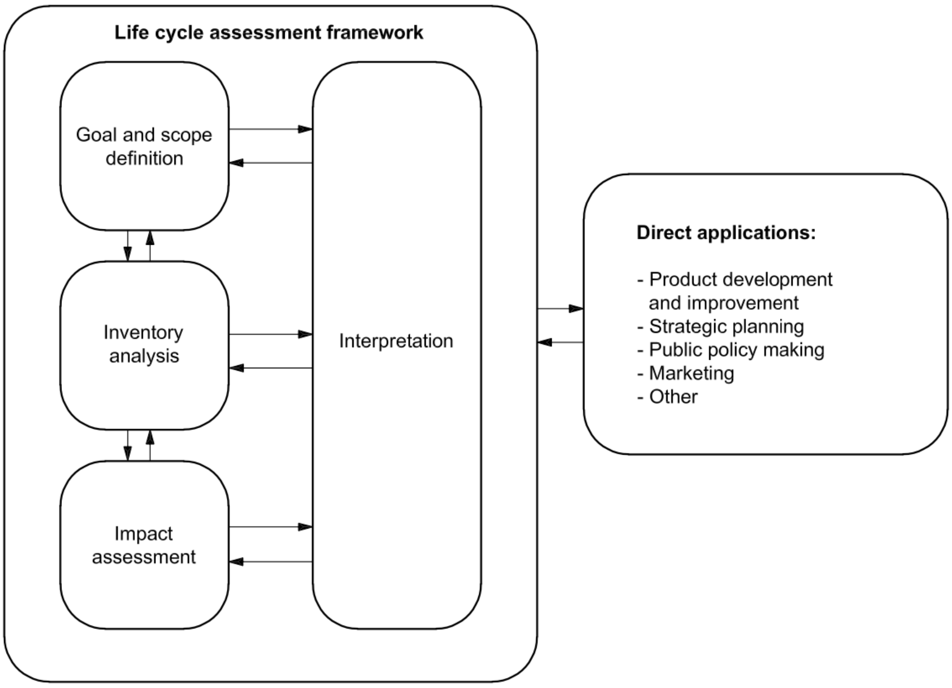


Fig. 1.1.: Steps of a life cycle assessment according to ISO14040 [57]

market leader and LFP (Lithium-ion-phosphate) as it is a rising alternative and the most widely available lithium-ion chemistry on the local market in Cameroon.

This assessment relies exclusively on data from existing literature. As demonstrated in the literature review, the literature concerning the LCA of batteries is abundant. It is fortunate as, given the lack of direct access to industrial actors, the material used for this study does not include any new primary data for the cradle-to-gate processes. Thus, this study's added value is not in the modelling of battery manufacturing. It is, however, in tailoring published data to this specific case. The added value also lies in the study of the end of life in Cameroon. The complete lack of empirical data makes an accurate assessment of the end of life currently impossible. However, we will address it through a qualitative assessment of the situation.

1.1 Mini-lca

This LCA of the whole Solarly premium kit from cradle to gate only identifies the system's most environmentally harmful components for further investigation.

The inventory is based on weight measurements taken from the different elements in Cameroon and the bill of materials supplied by Solarly. For the SolarlyBox, we based our inventory on a dismantling conducted at ST. The processes used to translate this inventory in SimaPro were exclusively sourced from the EcoInvent 3.8 database processes.

No functional unit was defined for this study. Instead, impacts were measured for a given reference flow, namely the Solarly premium kit. The components were only weighted according to their expected lifetimes. It was assumed that the Solarlybox and solar panels have lifetimes ten times superior to the battery (20 years and 2 years, respectively). The cables were assumed to have a longer lifetime of 40 years. It contributes massively to the relatively higher impact of the battery compared to other elements. We see that the solar panel is the only other element that has a significant impact. It would be interesting to investigate his impact and alternatives in further research.

Without surprise, the heaviest elements of the system had a significantly higher impact. The following table displays weighted impact computed with ReCiPe LCIA method [55].

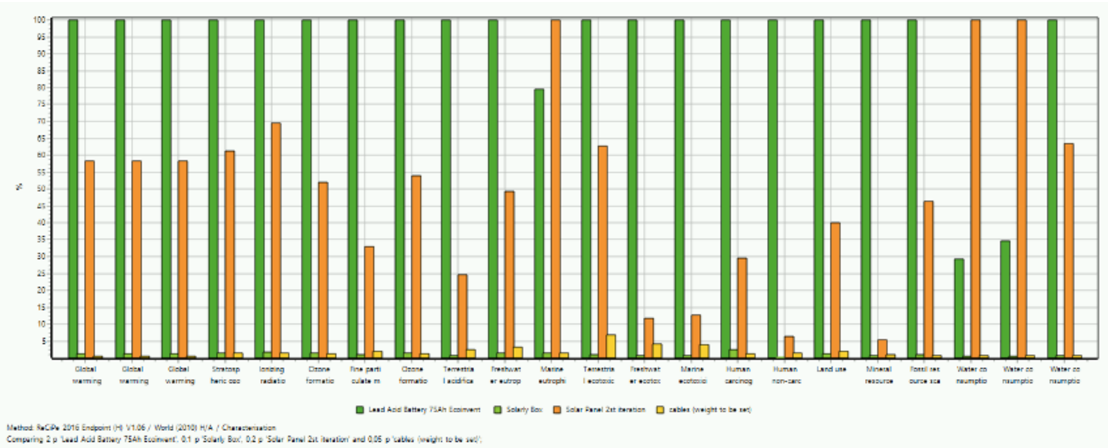


Fig. 1.2.: Impact comparison of the solarly premium kit elements for the 17 midpoint indicators of the LCIA method ReCiPe

Of the 17 midpoint indicators defined in the LCIA by Recipe, marine eutrophication and water consumption are the only categories where solar panels generate higher impacts than batteries.

The first LCA is basic and is only used to find hot spots but should not be used as reference information. This first assessment showed that the battery could be considered an impact "hot spot". Furthermore, plenty of alternatives are available for it, and it is thus interesting to explore variations for this element. Exploring alternatives for all components would be interesting but was considered out of the scope of this thesis. Solar panels seem particularly interesting for a second component to assess in further research.

1.2 Literature review

Batteries are a hot topic in research. As illustrated in the following figure 1.3, significant research is conducted on lead-acid batteries, with a peak in research papers published in 2013. Nevertheless, research efforts in batteries are dramatically more abundant for lithium-ion technologies. Since the sixties, lithium-ion batteries have seen an exponential rise in publications and have significantly outpaced lead-acid ones. The number of documents referenced in Scopus mentioning lithium-ion published in 2021 alone surpasses all the documents mentioning lead-acid (11790 papers and 11,054 documents, respectively).

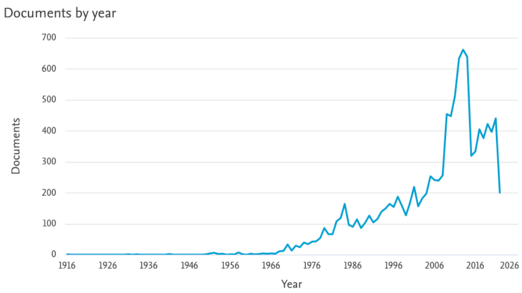
Research in LCA has also steadily risen, and it can be observed in Figure 1.3 the rise of different combinations of keywords in scientific documents on the Scopus database.

Those increases are fueled by an increasingly environmentally conscious public and the rising importance of batteries. The car industry has always used lead-acid as power storage for auxiliary services, and lithium-ion has risen with its use in consumer electronics. More recently, the latter's rise has steepened with their implementation in electric mobility solutions.

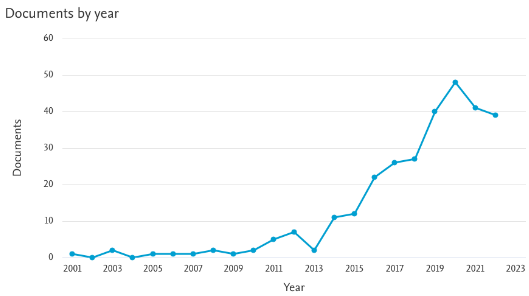
Those two factors, more care towards environmental impact and increased battery demand, have fuelled research at the crossroad of these fields. Hence, the abundant literature treating life cycle assessment of batteries (74 articles published in 2021 for 566 articles total).

LCA for all the most popular technologies have been conducted and even some for more niche chemistries. NMC, LFP, and Lead-acid all have consequent bodies of publications.

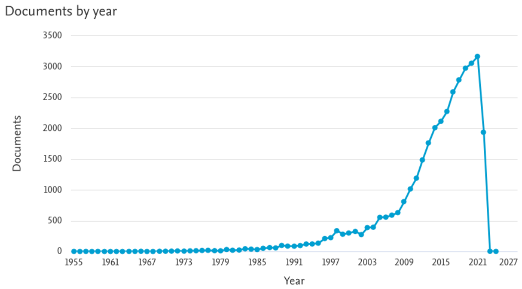
Most studies are focused on the cradle to gate phase of lithium-ion batteries as it is the easiest to measure [123] [25] [100] [23]. Some papers include later stages of life,



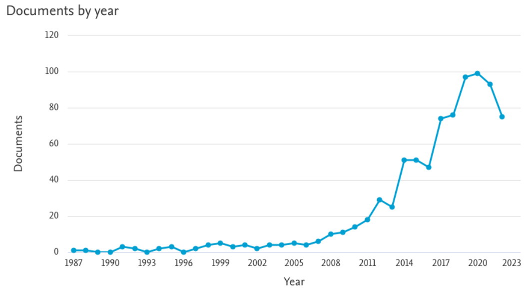
(a) lead-acid



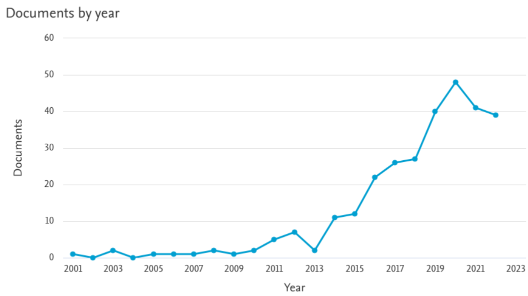
(b) lca, batteries, lithium



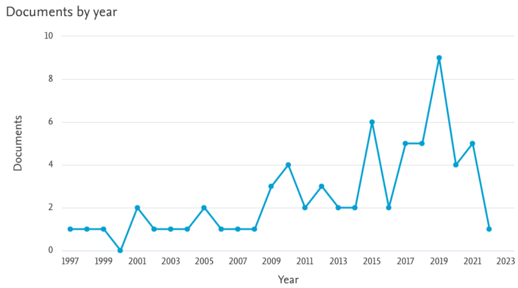
(c) lca



(d) lca, batteries



(e) lca, batteries, lithium



(f) lca, batteries, lead-acid

Fig. 1.3.: Evolution of the number of papers published each year corresponding to given keywords indexed in the Scopus database. The keywords are given below each figure. If multiple keywords are used a virgule separates them.

mostly of EV batteries. [56][106] The end of life is assessed in different ways. The options explored are second use for a different application [56][106] and recycling (both pyro-metallurgic and hydro-metallurgic processes, although the recycling processes offer far more variety inside and across these two categories.) [106]. Unfortunately, the disposal of batteries in landfill or the wild is never modelled. It is not advised but is bound to happen until recycling becomes profitable worldwide. It is thus a shortcoming of current research.

One of the main problems concerning LCA of lithium-ion batteries is the homogenisation of LCI data. Indeed to be able to compare different products, their scope must be similar. The level of details of the assessment should also be similar, and identical processes should be modelled identically. Efforts have been made by Peters and Weil to provide "a common base for life cycle assessments of Li-Ion batteries". They point out the discrepancies in the existing literature and recompile the available data to get a common LCI that is coherent between technologies. [100]. Their work do not include new primary data and is instead based off data from different previously published papers [12][33] [71][92][150].

More recently, a master thesis by Yudhistira expanded on the work of [100] to include the use phase and the end-of-life of those batteries for stationary use [149]. It also included lead-acid batteries in the comparison. The data for the lead-acid batteries were taken from a study conducted by Spanos [123]. This paper is implemented in the Ecoinvent database. This thes will use it as a reference for modelling lead-acid batteries.

The work of Peters and Yudhistira would have represented a well-suited source for this work. Unfortunately, it was impossible to implement. The LCI data of Peters is available at the following link: `https://zenodo.org/record/4574576#.YtEQiS8itQI`. Unfortunately, the education SimaPro licenses do not allow for the import of outside data. Therefore the implementation could not be based on those. Implementation was tried but ended up being too tedious given the number of subprocesses and their inaccessible documentation.

Similarly to Peters, other authors have also contributed to improving flexibility and transparency in LCI, such as Crenna et al. compiling data for NMC(811 and 111) and NCA [23]. Nevertheless, a need for more homogeneous and transparent LCI data remains.

The papers cited above and their respective approach are summarised in table 1.1.

The data published by Dai [25] will be used for this thesis's cradle-to-gate modelling of LIBs. Those LCI data are implemented in the GREET database (dedicated to car environmental impacts) for LFP and Ecoinvent for NMC111. [25] They reevaluated impacts with primary data. The processes modelled have been refined from previous work because they have evolved significantly with their deployment at scale, while some papers based their assumptions on manufacturing at the lab scale [71]. Those LCI data are selected because a single author implemented in a single database, namely GREET, two of our target technologies, NMC and LFP. It offers a better guarantee that similar approaches have been taken. This data also offers a more straightforward implementation

Paper	Technology	Comparison	Application	Scope	functional unit	Assembly
Spanos (2015) [123]	Lead-acid, NiZn, MnO2/Zn	Yes	stationary grid	C2gate	kWh of energy delivered	Battery pack
Dai (2019) [25]	NMC	No	Automotive	C2gate	kWh of capacity	Battery pack
Yudistira [149]	NMC, LFP, NCA, lead-acid	Yes	stationary grid	C2grave	kWh of energy delivered	Battery pack
Peters (2018)[100]	NMC, LFP, NCA	Yes	Not defined	C2gate	1kWh of capacity, 1kg	Battery pack
Crena (2021) [23]	NMC111, NMC811, NCA	Yes	Not defined	C2gate	kWh of capacity	Battery pack
Arshad (2022) [4]	Lithium-ion (many variations)	No	Not defined	Not defined	Not defined	Not defined
Ioakimidis (2019) [56]	LFP	No	EV and Second use	C2grave (second use)	4000 days	Battery pack
Quan (2022) [106]	NMC & LFP	Yes	EV and second use	C2grave (second use & recycling)	kWh of capacity	Battery pack

Legend : C2gate stands for Cradle-to-Gate and C2grave for Cradle-to-grave

Tab. 1.1.: Overview table of studies published concerning the LCA of batteries

as the NMC batteries are available in Ecoinvent 3.8, and the data for LFP can be extracted from the GREET database publications.

1.3 Goals and scope definitions

1.3.1 Goal

The goal of the LCA is to compare the environmental impact of different energy storage options for the Solarly premium kit. As explained in the introduction, such an assessment aims to inform Solarly's executives better so they can make thoughtful decisions concerning their impact. We chose to compare the current solution, lead-acid batteries, with lithium-ion alternatives. At first, three chemistries were singled out, LFP, NCA and NMC. However, NCA was excluded from the assessment to limit the number of options to assess. Its composition also has similarities with NMC and has a lower market share. The author could not identify NCA batteries used for stationary applications.

1.3.2 Scope

Battery lifetime can be separated into three main phases: cradle-to-gate, use phase, and end-of-life. The scope of the assessment conducted in this chapter is limited to the cradle-to-gate phase. The use phase is considered irrelevant, and the end-of-life will be the subject of a broad assessment in the following chapters.

Many studies have been published with a scope limited to cradle-to-gate as manufacturing processes are well defined and easily measured given proper access.

Here the use phase is excluded from the scope. Usually, it is measured for LCA of EV batteries. Indeed the energy mix used to charge EV batteries can impact the impact of an EV. In this case, the energy mix charging our batteries is considered fixed (composed of solar panels). And, because the energy supply is not a factor that varies in this assessment, the use phase does not require attention. Installation and maintenance could be included in the use phase, but the transport is considered part of the cradle-to-gate.

The maintenance is considered negligible as the battery is supposed to be maintenance-free. The system requires very little maintenance, with the solar panels only requiring regular cleaning with a wet cloth during the dry season. The after-sale service conducted by technicians in case of technical issues might be considered in further studies.

Allocation method

LCA practitioners have long debated ways to attribute the impact of given products and services. Although it might seem trivial at first, when considering the multiple actors involved, the integrated processes and recycling or re-using, the matter can be very thorny. Until now, no method has been found to satisfy everyone, and one might never be found as this decision is partly arbitrary.

Every process involved in manufacturing a product is not necessarily only used to produce one product. It can produce multiple co-products simultaneously, each having varying importance and economic value. Therefore, attributing the impact of a specific product can be challenging. The examples that complicate this are numerous. Recycling and end-of-life management can also be essential in the attribution debate. It is hard to draw a line to define to whom and to what degree the impact should belong for a given product. Should the impact of recycling be attributed to the company manufacturing the original product, the recycler or the company manufacturing goods out of recycled material?

LCA practitioners have come up with multiple methods. Pré, the editor of SimaPro, lists 6 of them on its website and explains them shortly. [101] However, Ecoinvent 3.8 offers only 3 different options

1. Allocation, cut-off by classification
2. Allocation at the point of substitution
3. Substitution, consequential, long-term

The logic between each approach is detailed on their website [127]. The consequential approach is the most advanced method but is ruled out because it requires making too many assumptions and is thus considered too susceptible to approximations. The two other methods, the first and second option being similar, are described as attributional methods.

The remaining categories of methods are "allocation at the point of substitution" and "allocation, cut-off by classification". We select "allocation, cut-off" because it is the one recommended for first-time practitioners. Allocation at the point of substitution is ruled out because it presents "some theoretical advantages, but in practice, it is very complex and sometimes leads to strange results. For example, recycled metals may have higher impact scores than their virgin equivalents." [101]

Impact assessment method

A vital step of the LCA is the translation of the life cycle inventory into impacts. The life cycle inventory records every material and energy flow coming in and out of the systems. At this stage, the impacts of those flows are not characterised. LCIA methods are built to translate those fluxes into impact. It is done by characterising each flux for its impact on given indicators. It can be done in multiple steps, with material flows first converted to midpoints indicators. Those midpoints indicators can then be used to determine endpoint indicators.

A general structure of this process is displayed in the following figure.

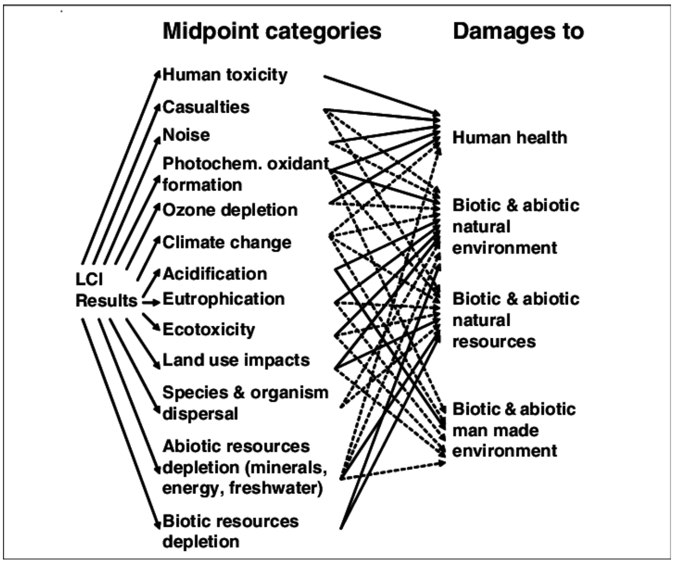


Fig. 1.4.: General structure of an LCIA framework [122]

Numerous methods have been developed: USEtox, CML1996, CML 2011, Eco-indicator 95 Eco-indicator 95RF, TRACI 2.0, EDIP 2003, Impact 2002+, and ReCiPe 2016, to name a few. For this study, ReCiPe, developed in 2008 by RIVM, CML, PRé Consultants and the Radboud University Nijmegen on behalf of the Dutch Ministry of Infrastructure and the Environment, was selected. It has a worldwide scope, has plenty of material characterised, is well documented, and is widely used in the literature. It is also available on the license of SimaPro from UCLouvain.

ReCiPe uses 17 midpoint indicators and 3 endpoint indicators. Its structure is represented in figure 1.5

ReCiPe offers three different options in terms of timeframe for the impacts. The options are individualist, hierarchist and egalitarian, which correspond respectively to 20, 100 and 1000 years timeframes. A typical example to demonstrate the influence of this choice is the case of methane. It is a far more potent gas than CO_2 in terms of greenhouse effect. However, its lifetime in the atmosphere is much smaller than CO_2. Depending on the timeframe, its relative impact will not be constant with the one of CO_2. Measured over a

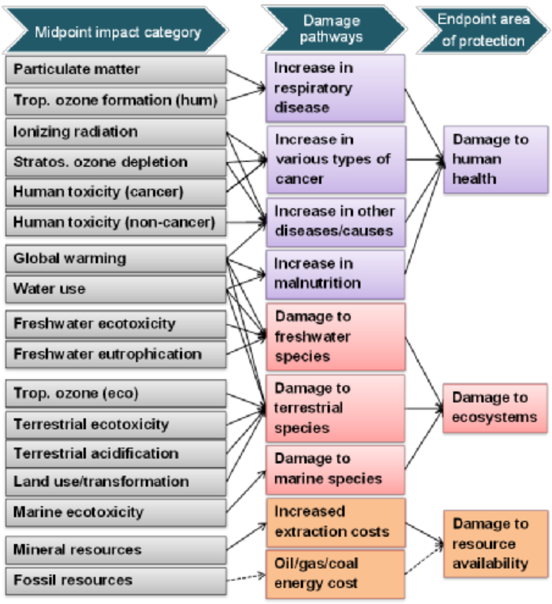


Fig. 1.5.: LCIA method ReCiPe impact pathways illustrated.[55]

period of 20 years, it is 56 times more potent than CO_2, but if we measure its effect over 500 years, it is only 6,5 times more potent than CO_2. [74]

Here we select a hierarchist perspective. It is an arbitrary decision that seems like a good compromise between the other options.

It must be stated that the LCIA results are only as strong as the framework used. It is easier to characterise some categories, primarily with global effects. For example, GHG disperses in the atmosphere and have an even impact no matter where it is emitted. Nevertheless, some impacts are much harder to characterise through standardised frameworks like ReCiPe. For example, in Cameroon, we find a lead-acid recycling facility in the middle of its biggest city (Douala, with more than 4 million inhabitants). Its lead emissions will likely have a more substantial impact on human health than if it was located in a sparsely populated population. As going further would be tedious, we will limit ourselves to the ReCiPe method. However, it must be understood that local circumstances are often ignored despite having a considerable impact on the final results.

Functional unit

In any LCA, a functional unit is defined. It is defined in the ISO14044 norm as the "quantified performance of a product system for use as a reference unit". When comparing different products, the functional unit selection is crucial as products can only be compared for equivalent services given. As two solutions often differ in the outcome they offer, the choice of the functional unit can influence results. We deal here with a battery delivering an energy storage service. Kg and kWh of capacity are great functional units for comparing technologies as those are very well defined. They are used in numerous studies, as shown in table 1.1. However, these functional units lack the lifetime factor, which is a massive blind spot. Indeed some studies use kWh of energy delivered. It is a more accurate way to measure the impact of a given service. However, because many variables influence the energy delivered over its lifetime, the results are more uncertain.

This study aims to measure battery impact for a specific use. Namely, operating our solar home system with identical performances than currently. What is meant by identical performance is that it must be able to store and deliver an equal amount of energy than the current solution. Duration of use is also specified. The current solution is used as a benchmark for this function. It comprises a pair of 12 volts 75Ah lead-acid batteries with a combined storage capacity of 1800Wh which operate with a maximal Depth-of-Discharge, DoD, of 50%. As we also want to capture the lifetime of the batteries, we define the functional unit as delivering this service for two years. It is an arbitrary value that matches the warranty of the product.

This functional unit is specific to this study and will allow us to compare different solutions properly. However, it has the downside of being harder to compare with other studies. Conversion factors should be applied. Although, given the hypothesis, it is a matter of factor to make the conversion to more conventional functional units (mass, capacity, energy delivered over the lifetime) used by the literature [123]. They all have significant advantages, such as having a fixed inventory when choosing mass. Capacity provides a balance between use and an accurate inventory. The energy delivered is far harder to measure as it varies greatly depending on the conditions of operation[103]. As a result, the inventory will scale in response.

However, the functional unit described above was selected because the goal is to compare the three technologies for our specific use. Because of the critical role, DoD and cycle life play when comparing such different technologies, using energy capacity seemed less appropriate. Because we compare different uses, we will include DoD and Cycle life in the approach. They have considerable impact, as we will see in the reference flow.

Reference flow

We will use data from published LCA. As they often use mass as a functional unit, we will need to convert our functional unit to a given mass. This allows the definition of a reference flow which differs for each technology. Including DoD and cycle life massively impacts the results as they vary considerably between technologies. However, they are tough to determine. DoD and cycle life are tightly linked, but other factors also impact the results. Temperature and cycling conditions (charging current, discharge current, etc.) are critical. The assessment is further complicated by the difference in the behaviour of the different technologies relative to these factors. It is thus relatively hard to define exact values. Hypotheses had to be made, and data was selected to determine them.

Hypothesis

Lifetime and depth-of-discharge We have gathered values from datasheets from manufacturers and the literature. A battery is considered spent once its state-of-health, SoH, reaches 80%. It means that its current capacity is only 80% of what it was at the beginning of use. It is the standard used in the industry. However, some batteries might remain operating long past that arbitrary threshold, although with lower performances, but it is not taken into account here. The DoD currently used is 50% for lead-acid batteries. However, LIBs can hold much higher DoD, and we will thus use values approaching 100%, namely 95%. The data gathered is transcribed in table 1.2

Lead-acid cycle life will be directly obtained from the current supplier, Sunmaster, at the current DoD implemented in the system. However, it is to be noted that better performance can be obtained from different suppliers having better-performing lead-acid batteries, like Ultracell. LFP data are taken from felicity solar, as they are the main supplier in Cameroon for Solarly for lithium-ion batteries. However, no supplier of NMC batteries for stationary use could be identified with certainty [1]. The author could not find

[1] the Tesla Powerwall is described as using NMC by some online media [126] but the spec sheet made available by Tesla does not specify the technology used. The data sheet also lacks crucial information on testing temperature and DoD.

Technology	DoD	Number of cycle	Wh/kg	Temperature	Source
NMC	/	3650	108,00	25	Tesla powerwall
LFP	95%	3000	95,69	25	Felicity 2kwh
LFP	95%	3000	117,92	25	Felicity 2,5kwh
LFP	50%	5000	121,90	25	Ultracell 40Ah
LFP	100%	2000	121,90	25	Ultracell 40Ah
LFP	100%	2000	133,12	25	Ultracell 78Ah
Lead-acid	100%	985,5	40,36	26	Mekkonen
Lead-acid	100%	748,25	40,36	37	Mekkonen
Lead-acid	50%	1200	40,36	25	Ultracell 75Ah
Lead-acid	50%	500-700	45,00	/	SunMaster
Lead-acid	80%	1200	27,00	25	Spannos

Tab. 1.2.: Characteristics of batteries of different chemistries extracted from manufacturer's spec sheets

specific data for the cycle life of NMC as all suppliers seem to use LFP. Nevertheless, NMC batteries have a cycle life similar to LFP, and we will thus use the same specs as for both. This similarity in behaviour is illustrated in figure 1.6

One paper identified describes a superior performance of the LFP [103] but contradicts other sources stating the opposite [102]. Variation of quality and technology in the batteries might explain it as NMC can have different compositions, for example, NMC111 and NMC811. Even in a single technology, different performances can be observed depending on the specific battery model, as each manufacturer has its manufacturing secrets.

The value and sources selected are displayed in figure 1.3.

Techno	DoD	Cycle life	Wh/kg	Temperature (°C)	Battery mass [kg]
Lead-acid	50%	700	45,00	25	40,00
LFP	95%	3000	95,69	25	9,90
NMC	95%	3000	108,00	25	8,77

Tab. 1.3.: Technical characteristics of LFP, NMC and LABs

This selection presents shortcomings. Most notably, the value are given for a standard temperature of 25 degrees Celsius. However, operating temperature would vary in actual use and can significantly impact the cycle life and performance of the batteries [103][90]

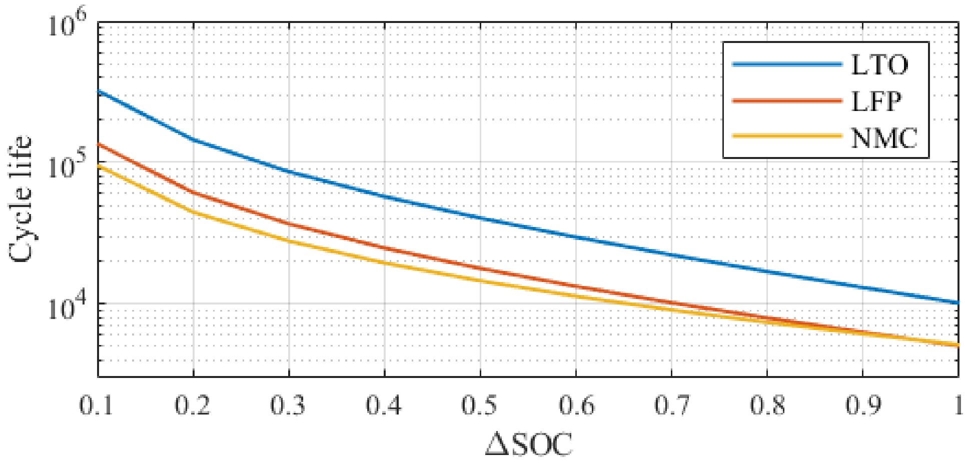


Fig. 1.6.: DoD vs cycle life for three battery chemistries [46]

The ambient temperature depending on climate and time of the day, will vary significantly. Operating temperatures are usually higher than the ambient air as the batteries are isolated and can heat up with electrical losses. They are enclosed and sealed in textile to avoid clients manipulating them uselessly. The climates of Cameroon are generally warm but particularly varied; thus, generalities are hard to make. Climate change promises to raise the region's temperature and move the operating conditions further from the standard conditions of 25°. [74]

To further complicate the predictions, real use cycles are more complex than linear charge and discharge cycles up to a given DoD. The SolarlyBox is programmed to avoid discharging the battery lower than 50%. However, the batteries might not reach 50% in state of charge every night and 100% every night. The cycles are more complex and thus harder to model.

Without more data, our selection was the best approximation available. A more accurate method for estimating the cycle life under a given DoD would be to conduct empirical research on the existing fleet of SHS. Unfortunately, only one technology, lead-acid, is currently deployed. Even for this technology, the data is currently lacklustre. Indeed most systems are relatively young. Failure cases are thus rare. Data collection on the failure rate is lacking at the time, but precious data might be gathered from analysing after sale data further down the road when batteries will reach the end of their lifetime.

Specific capacity Specific capacity for the lead-acid batteries is calculated based on data from the spec sheet of the Ultracell battery, as it is the only one that has been verified in Cameroon. Specific capacity for NMC is included in the sources used for the inventory and is thus directly used here. [25] Data concerning specific capacity is not available from the GREET database. However, we have the specs from an available supplier in Cameroon. The mean of the different options was calculated. They are listed in the following table:

	Specific capacity (Wh/kg)	Source
Lead-acid	40,36	Ultracell
NMC	143	Dai (2019)[25]
LFP	118,11	Ultracell, Felicity

Tab. 1.4.: Specific capacity of LAB, NMC and LFP

These are specific capacities of whole battery packs. Battery cells alone would have higher values.

With all the following data, the computation of reference flows for every technology become possible. The reference flow and the data used to compute them are available in the following table 1.5.

Techno	DoD	Number of cycle	Wh/kg	Temperature	Battery mass
Lead-acid	50%	700	40,36	25	44,60
LFP	95%	3000	118,11	25	8,02
NMC	95%	3000	143,00	25	6,62

Tab. 1.5.: Reference flow as battery mass, and the related parameters.

1.4 Inventory

1.4.1 Cradle-to-gate

As stated in the introduction of this chapter, the best option would have been to rely on the harmonised data of Peters and Yudhistira [100][149]. However, due to the limited tools available, their use was deemed impossible and it was decided to rely on an available database, namely Ecoinvent 3.8. We used secondary data from the Ecoinvent database to model the system. For the lead acid batteries, we relied on data published by Spanos [123]. For the LIB chemistries, we relied on data from the EV industry and the research published by Dai in 2017, 2018 and 2019. NMC data are made available in Ecoinvent [25], and LFP data are included in the GREET model developed by Dai [25] and reused by [106].

1.4.2 Transport

We assume that the batteries are manufactured in China in the industrial region of Guangzhou and transported via sea freight to Douala. Then we include transportation to Solarly's headquarters in Yaoundé by truck and delivery to the client with a light-duty vehicle for 200km. All transport is modelled with standard processes of the EcoInvent database.

	reference flow [kg]	Sea freight	Truck	Light duty vehicle	Total
Distance [km]	/	17344	260	200	17804
NMC [tkm]	2,13	36,94272	0,5538	0,426	37,92252
LFP [tkm]	2,41	41,79904	0,6266	0,482	42,90764
lead acid [tkm]	41,71	723,41824	10,8446	8,342	742,60484

Tab. 1.6.: Transport calculations based on reference flows and distance

1.4.3 End-of-Life phase

The end-of-life is an integral part of the life cycle of any product. However, it is far harder to model. The next chapter will develop a qualitative assessment of the current situation and levers to improve end-of-life management. In the absence of studies concerning the impacts of degradation of batteries in the environment and in statistics concerning waste management of batteries, any quantitative assessment would be hazardous at best.

1.5 LCIA - Life Cycle Impact Assessment

The result displayed in figure 1.8 and figure 1.7 represent the impact of each technology for every midpoint indicator weighted. The weighting is calibrated to have the worst

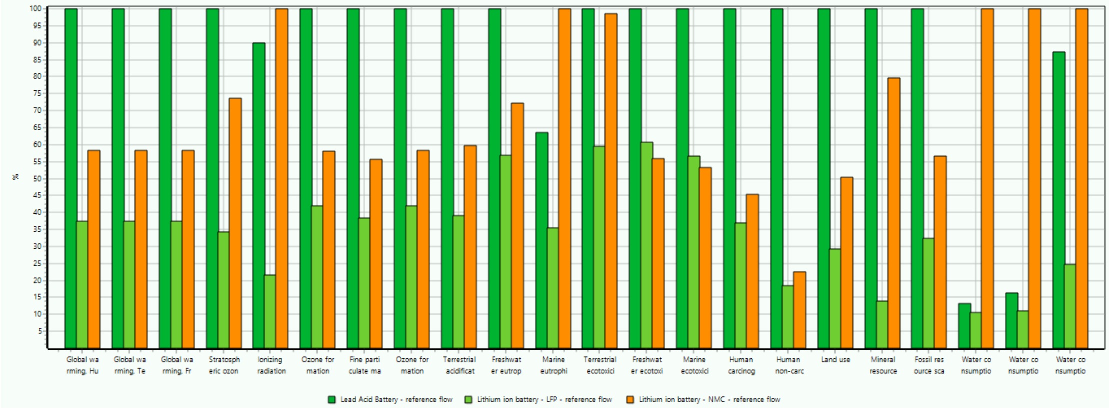


Fig. 1.7.: Weighted impact of the three assessed technology (NMC, LFP, lead-acid) for every Recipe midpoint indicator, scenario not including transport

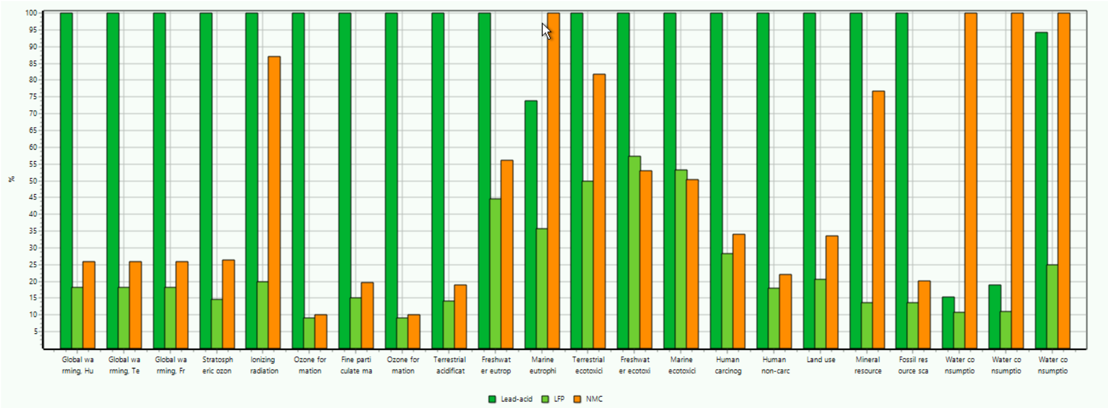


Fig. 1.8.: Weighted impact of the three assessed technology (NMC, LFP, lead-acid) for every Recipe midpoint indicator, scenario including transport

performing technology for that indicator with a relative impact of a hundred. It explains that every midpoint indicator gets a technology with 100 of impact.

More detailed results, including a breakdown of integrated impacts for each battery type, are available in the annexe.

1.6 Interpretation

We observe net differences between the technologies. LFP has the lowest impact of the technologies analysed, followed by NMC, while LAB has the highest impact in most categories, with or without transport accounted. A significant reduction in the impacts can thus be achieved by switching to LIBs, LFP being the best LIB option.

In the annexe, it can be observed that ship freight has the highest impact of all processes. The weight of lead-acid batteries causes them to be even more significant than the other technologies. However, although lithium-ion batteries are mainly produced in China, Lead-acid are manufactured worldwide. Shortening the supply chain for LABs seems crucial and doable.

The assessment can still be refined. For example, Spanos did not consider pollutants emissions in the batteries' manufacturing process. As is described in section 2.1.1, technologies to reduce them extensively exist and might make measuring them almost irrelevant. It is, however far from the case in informal operations and for some operations in developing countries.[48]

Another shortcoming is that the homogenisation of data sources was not perfect. Data from 2 overlapping databases (NMC and Lead acid in Ecoinvent, NMC and LFP in GREET) allowed for some coherence in the scope and modelling. However, the manufacturing of LFP batteries in GREET is less detailed than the NMC process included in Ecoinvent.

Changes in the reference flow because of differences in the performance of batteries can also directly impact the results. Empirical data collected from the field would be invaluable for more accurate results.

2 End-of-life

The end of life of any product has long been seen as not worthy of much interest. In a cradle-to-grave approach, any product is destined to be manufactured, used, and discarded. This model shows signs of weakness through the pollution it generates and the precious resources it wastes. Those significant weaknesses have led to more circular alternatives (cradle-to-cradle).

In this case, the assessment covers solar home systems, focusing on batteries. SHSs and all their components fall under the WEEE category. Parts of those (batteries, for example) are classified as "hazardous" by the Basel convention because they represent major environmental and health concerns. It is thus vital to treat those wastes appropriately.

From the work of Yudistira [149] we observed that the EoL could play a significant role in reducing the overall impact of the solution. That is only if proper treatment is used. There are particular concerns about the end of life of batteries because they contain toxic metals. Lead-acid batteries are, as their name suggests, made out of lead. The devastating effect of lead will be developed further in section 2.4. Lithium-Ion batteries also contain dangerous substances that, if released into the environment, can cause severe damage. [81] The end-of-life should thus be considered carefully to avoid contamination of the environment.

Through circular approaches, the end of life can also be viewed as an opportunity. Indeed, any product contains materials that have the potential to be reused through reuse, repairs, repurposing or recycling. It allows to reduce the extraction need of new materials. They also represent an energy economy as recycling is often less energy-intensive than the mining and refinement process.

End-of-life also presents a challenge in modelisation. It is a crucial step to assess the environmental impact, but it is more challenging to measure than the production and use phase. If products were tracked from their inception until their eventual recycling or grave, measuring their impact would be easy. Even though assessing the pollution generated by the product at the grave might be challenging too.

Unlike production, end-of-life is often less straightforward to measure. We often rely on financial streams for production and use phases as reasonable proxies for physical flows. We also have explicit transformation processes than can be analysed.

For the EoL phase, unfortunately, we do not have nearly as much detail because it is not necessarily tracked. Determining the final destinations of the product, their relative importance and the impact that derives from those is not always feasible because of a lack of data.

This chapter will not model the end of life of the batteries as in an LCA. The data is considered too scarce for Cameroon to derive any valid conclusions. So instead of modelling the exact situation, this chapter reviews the technologies available for both LABs and LIBs. It identifies the current situation in Cameroon and the world and allows identifying the main challenges and the processes available for Solarly. This overview can guide further actions to improve the EoL of SHS.

Although we will further develop the recycling methods that exist for lead-acid batteries and LIBs, it should be mentioned that the two processes are very different and differ in complexity.

Lead-Acid recycling is a relatively straightforward process and mature technology. It has been used for decades and involves relatively simple machinery. It can be done at an artisanal scale, although this comes at a tremendous environmental cost, as we will see further. The technological complexity is limited, and it can thus be executed all over the world. Spent lead-acid batteries still have economic value because their recycling is easy, and the lead they contain can be resold as raw material or directly repurposed into new batteries.

LIBs recycling is a less mature technology, although already implemented in some plants. It has, for example, been deployed at scale by Umicore in Hoboken, Belgium (7000 T/year).[67] It requires a higher technological level than lead-acid. The recycling rates vary with the process but are usually much lower than LABs recycling rates. It means all the materials cannot be recovered, and some will be lost.

2.1 Recycling a review

2.1.1 Recycling processes for Lead Acid Batteries

This part describes the different processes that are used to recycle ULABs effectively.

The well-known and stable composition facilitates the processes. LAB comprise 4 main elements: [152]: metallic lead (grid plates and connectors), lead or lead paste (lead sulfate, lead-oxide and metallic lead), Sulfuric acid ($H2SO_4$) diluted in solution for the electrolyte and organic matter (polypropylene, polyethylene, ABS, fibres,...). The first two represent the most important part of the battery's mass. Table 2.1 shows a detailed composition from Prengaman.

Lead grids and poles	–
Lead grids and poles	25%
Lead paste	38%
PbSO4	50–60%
PbO2	15–35%
PbO	5–10%
Metallic lead	2–5%
Other	2–4%
Polypropylene cases	5%f
Separators, hard rubbers, etc.	10%
Sulfuric acid (about 15%)	22%

Tab. 2.1.: Detailed composition of lead-acid batteries [104]

Two prominent families of technologies exist for recycling: pyro-metallurgy and hydro-metallurgy. It must be understood that each encompasses a variety of processes. We can not be exhaustive in their descriptions without making this document excessively long. The traditional method uses pyro-metallurgy. It is the most widely deployed technology by far and is also used by the informal sector. Hydro-metallurgy is more recent. Although research projects on the matter have existed for some time now, it has only recently been deployed at scale. Some recycling processes involve both pyro- and hydro-metallurgy.

Despite the difference in the processes, ULABs recycling typically follows four steps [104].

- Battery Breaking and components separation

- Sulfur removal
- Smelting
- Refining

The following description of the recycling processes will use the book's chapter by R.D. Prengaman and A.H. Mirza as a reference. [104]

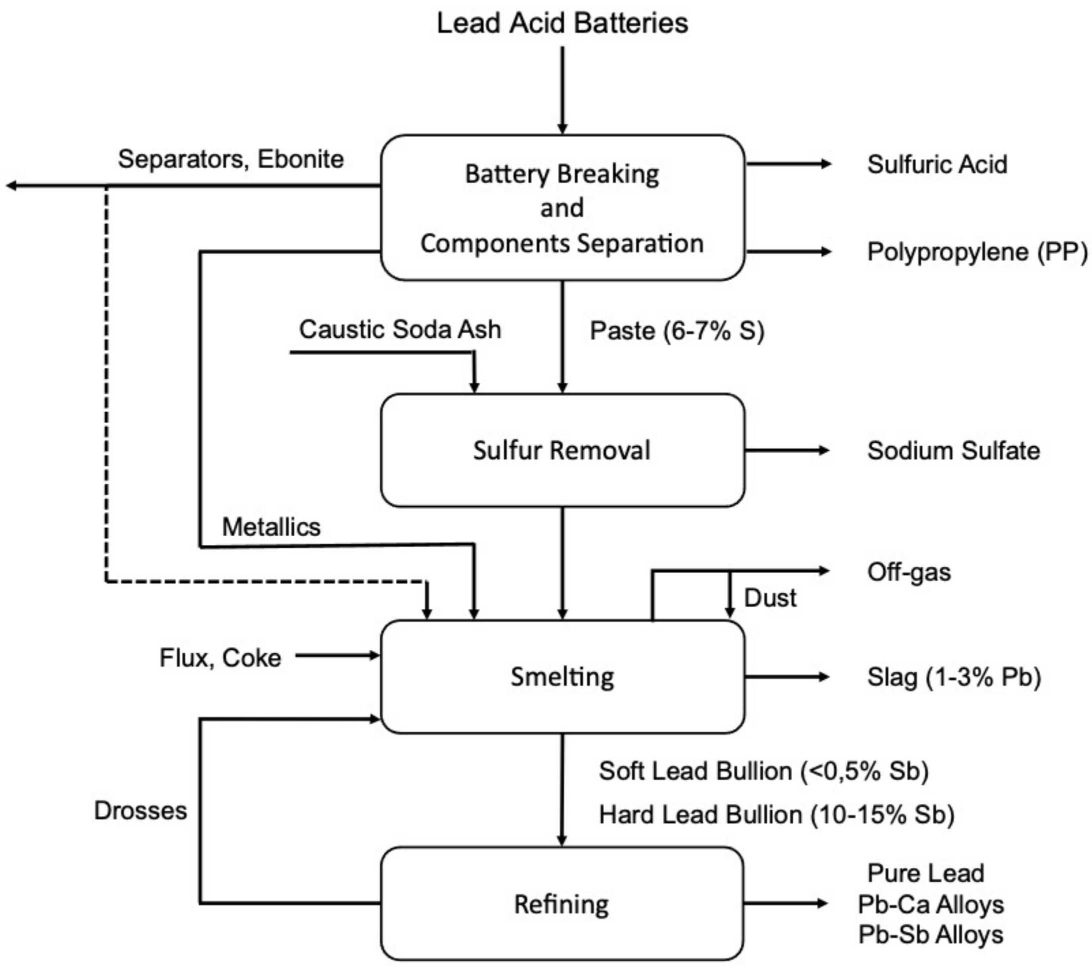


Fig. 2.1.: Material flows of a lead-acid battery recycling process according to Prengaman [104]

Pyro-Metallurgy

Battery crushing The battery is first mechanically crushed either with a hammer or a toothmill. The resulting small pieces are segregated by density by passing through a sink/float operation. The dense metals sink while the casings and separators composed chiefly of plastics rise.

The lead paste is then separated from the other lead compounds as it is loaded with SO_2 and requires special treatment. The sank components are screened to isolate the paste through a rotation drum or a vibrating screen.

At this stage, the four main parts of the batteries are separated.

Plastics The plastics, mainly polypropylene, need to be washed and can then be recycled. Until the mid-eighties, it was impossible because of the large concentration of ebonite in the casings. They were disposed of in landfills. ABS is currently becoming more common for its better mechanical properties and allows for recycling.

Sulfuric acid The sulfuric acid is usually first neutralized with caustic soda ($NaOH$) or soda ash (Na_2CO_3). Then after treating to remove heavy metal contaminants, it can be used for other applications or disposed of in the public sewage system. This procedure must be done according to rules set by the competent authorities. In the case of informal operations, it is often dumped unneutralized and untreated straight into the neighbouring sewer. The acid can also be used for other phases of recycling. Its acidic properties allow regulating the PH of water treatment reactors of the scrubber-oxidation system. [104] AGM batteries cause problems at this step. As the name suggests, it is equipped with an Absorbent Glass Mat, composed of glass fibres, that trap sulfuric acid. As a consequence, more sulfur remains to be treated in other processes.

If the plant is directly remanufacturing new batteries, the sulfuric acid can be reused after treating it by solvent extraction. That step removes the impurities in the spent acid (iron, antimony, organics and particulates).

Lead paste Lead paste comprises refractory lead sulfate.[147] It is problematic because it can lead to dangerous emissions. To eliminate the $PbSO_4$, we rely on a carbothermic reduction of $PbSO_4$. It is performed by heating in the presence of coal to temperatures over 1500°C.[104] although lower temperature might be usable [52]. The sulfur dioxide,SO_2, generated is then recuperated through scrubbing. The sulfur dioxide then passes through the oxidation system to form sulfate that gets neutralized, either as sodium sulfate in a crystalizer or as gypsum,$CaSO_4 \cdot 2H_2O$. For gypsum to be obtained, the scrubbing needs to be done with lime, $Ca(OH)_2$.

Lead Smelting is a two-stage process with the slag requiring more treatment. The first stage of smelting can take place in a reverberatory furnace. In a second phase, a blast or electric furnace can be used. The reverberatory furnace is loaded with battery scrap, lead scrap, drosses and internally recycled dust combined with coke and operates at a higher than atmospheric oxygen concentration (25% to 40%). Coke is used to reduce the PbO content of the slag. The oxidizing condition evolves the sulfur as SO_2 and oxidizes the undesired metals Ca, Al, Sb, As, Sn, etc. Oxides concentrate in the slag phase leaving a low impurity bullion. 1 kg of slag is produced from every 3 to 7 kg of lead bullion. The slag is further treated either in an electric furnace still in a molten state or a reduction furnace after solidifying.

Other types of equipment and processes exist for the smelting phase. We can mention rotary furnace smelting and top-submerged lancing. Some methods also smelt full batteries (when casings are not recyclable).

Pollution control equipments Crushing, smelting and refining operations emissions emit harmful pollutants. These include CO SO_2 and metal emissions (Lead, arsenic, nickel and cadmium). Thermal oxidizers reduce CO, and SO_2 is captured by scrubbers. Historically, the metal particulates were taken care of with bag filters.

Currently, industries include a more efficient measure to limit emissions, for example, Wet Electrostatic Precipitator (WESP). [27] It separates particles from a gas stream through electromagnetism. It consists of charging the particles of the stream and then passing it close to charged plates of the opposite polarity that will attract the charged particles. The plates are continuously washed with water to clean them and gather the pollutants.[79] The stream can also be prequenched to cool and saturate the gases before entering the electrical fields. [1].

Another measure set in place is the use of negative pressure enclosures. It ensures that all the contaminated flows go through the pollution control equipment. [9]

Hydro-Metallurgy

Hydro-metallurgic processes only take place after the separation of the principal elements. Indeed they only replace the Pyro-metallurgic processes. Crushing the battery and separating the principal parts are done similarly. Plastics and sulfuric acid are also reserved the same fate. The difference concern the treatment of the leady components. These technologies address the main environmental problems of Pyro-metallurgic methods, namely the intense use of energy and the emissions of pollutants above all SO_2 and lead compounds. However, they require heavy means for water treatment. [81]

Paste A classical application of hydrometallurgy is the desulfatation of the lead paste. The concentration of lead sulfate can be reduced through leaching. The process uses the difference in solubility of lead carbonates and oxides compared with lead sulfates. It allows to dissolve the sulfur compounds selectively. To use this difference, it must first convert lead sulfates into lead carbonates and hydro carbonates.

Lead More recent applications allow avoiding the use of pyro-metallurgy altogether. Indeed new processes proceed with hydro-metallurgic electrowinning methods. The lead is extracted with solvents and then reformed through electro-deposition.

These methods have been developed for years but have long remained a researcher's dream. However, the technology is now effectively deployed by Aqua metals™. Since 2017, they have had a plant up and running. [104] However, the profitability of the process remains to be proven as the company has not made any profit. The company is not limited to this process as it invests in R&D and new processes for Lithium-Ion batteries, so we can not have an exact picture of the financial details. Nevertheless, it puts the technology's profitability in question. As the company is publicly traded on the NASDAQ, its financial information is public and can be consulted on the NASDAQ website.

Plenty of research is being done to increase the potential of hydro-metallurgy by researching new, more efficient, less polluting solvents. [9][152][128]

This process avoids the smelting refining phase. It drastically reduces the production of SO_2 and the energy use. Given that it uses electricity, it can also be decarbonised if the electricity mix is too.

Conclusion

The traditional pyro-metallurgical has some significant drawbacks with dangerous emissions and massive energy use. Nevertheless, the processes are constantly refined and improving. Implementing pollution control methods has allowed for significant reductions in emissions, and energy use can also be reduced. Hydro-metallurgy is a promising technology. It is already in use for the treatment of lead paste. However, the electrowinning solution allowing to bypass pyro-metallurgy does not seem ready for full industrialisation. Given the existing infrastructure in Cameroon, the author thinks that priority should be given to improving the operating conditions of the recycling plants through better safety practices for workers and implementing effective pollution control equipment.

2.1.2 Recycling of Lithium

Through an interview of a recently retired executive of Umicore, Ghislain Van Damme, information was gathered on the current state of LIB recycling. It offers an insider's view of the industry and its perspective. The following chapter is essentially based on the exchange. The information mainly concerns Umicore, but as they are one of the only historical actors, it offers precious information on the industry's operations.

Process

In this chapter, the recycling supply chain is described in three steps: gathering, disassembly of the battery packs and finally, the recycling process.

Gathering As stated before, automakers are currently leveraging their distribution network in an effort to recover their batteries. Apart from that, players like Umicore rely on public partners like Bebat. They also try to gather from any partner they can find to supply materials for their recycling facilities. The supply chain is worldwide as only a few players have the required plants, and the batteries are used worldwide. However, battery shipping is not a straightforward operation. Therefore, a dismantling step before shipping is often prefered.

Dismantling Dismantling is not a very technical process. It consists in disassembling the battery packs to extract the battery cells from the rest and separate the remaining fractions to valorise them separately. The remaining fractions mainly consist of the BMS, some plastics and common metals like copper and stainless steel. They are resold on the local markets as recycling capacities for these materials are widespread around the globe. The dismantling is a manual operation, so the costs are almost exclusively labour costs. They are, on average, offset by reselling the non-cell fractions on local markets. Before any dismantling is operated, the battery is fully discharged for safety reasons [141].

Dismantling operations are only conducted for big batteries such as EV batteries. For each model of battery, a complete assessment need to be performed. That assessment is used to set up a dismantling procedure and inform the following recycling process. It provides essential information to refine the recycling process to the particular battery cell and increase the recycling rate. Recycling rate of 95% to 98% even up to 99% can be reached.

This assessment is performed on 2 to 3 packs representing battery generation. The first pack is dismantled very carefully while documenting the whole process. The second pack is dismantled following the procedure set up with the first pack, and the dismantling time is measured. Based on these tests, a contract is prepared with the battery supplier and the recycler.

Dismantling operations are motivated by the difficulty surrounding the shipping of batteries. From an EV battery, only around 70% of the mass is of interest to Umicore (essentially the battery cells). As they are a specialised recycling industry, they are not interested in sourcing commonly recycled materials from around the globe. The rest of the battery pack can be taken care of locally, which is the privileged option. Dismantling operations also allow for packing the batteries more efficiently for shipping. Instead of 3,5 tons of battery packs per container, they can reach up to 15 tons of battery cells per container. It is imperative as used batteries are considered as toxic waste and fall under stringent regulation, for example, worldwide under the Basel convention. The consideration surrounding such waste makes shipping very costly, and any superfluous material is thus better kept locally. The battery cells dismantled are shipped to the plant.

Recycling At Umicore, a closed loop approach is taken. The batteries are processed, and materials are refined until they can be reused in other parts of the company, for example, for re-manufacturing cathodic materials. The process focuses on recovering critical materials like cobalt, copper, lithium and nickel. Security is critical during the whole process as LIB cells are very reactive and represent a hazard. Depending on the kind of batteries, the process will differ. For EV cells, the process is tailored to the specifications given by the supplier to increase recovery rates. For smaller batteries, they are loaded in bulk inside the oven. No pre-treatment is applied.

The process used by Umicore is based on pyro-metallurgy. They use a continuous process where materials are continuously fed and extracted from an industrial oven. Slag is extracted, and new materials are added. Once started, the process has the advantage of being self-sustained because the reactions of the element of the batteries are exothermic. The reaction of aluminium is particularly exothermic. Energy must be extracted from the process to maintain it at the right temperature. In the second Umicore plant in Sweden, the excess heat produced by the process was used to heat the neighbouring village.

The slag from the oven concentrates the aluminium and lithium. It is very similar to spodumene. The lithium can then be extracted with similar processes used to mine it from spodumene. Spodumene is one of the two primary mining sources of lithium with salars. It is principally mined in Australia.

The alloy is processed into pellets and dissolved to isolate cobalt from nickel.

The copper precipitates in the slurry. That slurry is very interesting as it as the particularity to concentrate precious metals (Au, Pt, etc). The slurry is refined in Hoboken to extract those precious metals.

The pyro-metallurgic process present the inconvenient of emitting large amount of CO_2. Umicore is working to reduce them by using carbon capture technologies. However it allows to process significantly more material than hydrometallurgy (*trop bizarre cette phrase sans contexte, faut d'office un élément de comparaison, genre à prix égal ou un autre paramètre parce que sinon ça n'a pas de sens*)

A hydrometallurgical process also exists. It involves the following preparing steps before using metallurgic processes:

1. Calcination: They are calcined at 600 to 700°C
2. Crushing: Then crushed to generate a blackmass in the form of a powder
3. Screening: The powder is passed through a sieve, and the ferrous metals are removed with magnets

Only then is the blackmass put into solution in a dissolution bath, and the metals of interest are selectively precipitated. Specialised hydro-metallurgic firms run this process. The process is less expensive than pyro-metallurgy, but the recovery rate of metals is lower by about 10%.

2.2 Current situation in Cameroon

This section describes the current system for waste management of WEEE and batteries. Cameroon has adopted a series of principles that regulates the management of waste in general [1]. Although in effect, they are not widely respected. WEEE also falls under specific regulations. A decree jointly signed by the Minister of the environment, nature protection and sustainable development and the Minister of commerce sets out the specific conditions for the management and disposal of WEEE[2]. The rules specify that every company operating in Cameroon should treat its WEEE. In practice, the laws are not well enforced, and only some multinational companies and international development agencies comply. The paper of Tchoupou mentions that these regulations are often: "simply ignored or even misunderstood by the actors in the management chain of such waste." [130]

However, the WEEE legislation does not apply to private citizens. Solarly is not the end user of the solution, but their clients are, so those rules do not apply. Nevertheless, even as a for-profit organisation, Solarly executives show great interest in having the most beneficial impact. Improving the EoL of their products would indeed contribute to reducing their environmental impact.

The only recognised actor handling WEEE in Cameroon is Solidarité Technologique, ST. It is a french non-profit founded in 2001 and active in Yaoundé since 2004. Its mission is multifaceted, and one of those facets is the recycling and valorisation of WEEE.

They participate in the WEEECAM project. The goal is to derive value from WEEE. It must demonstrate the feasibility and viability of such activities in developing countries. More specifically, its goal is to implement a viable and replicable model of waste collection and treatment of WEEE in large urban areas. The project is to last for five years until

[1] Defined in the "Loi N°96/12 du 05 août 1996 portant loi cadre relative à la gestion de l'environnement"
[2] Defined in the "Arrêté conjoint n°005/Minepded/ Mincommerce du 24 octobre 2012 Fixant les conditions spécifiques de gestion des équipements électriques et électroniques ainsi que de l'élimination des déchets issus de ces équipements."

the end of 2022 with a budget of 6 million €. At the end of the project, it should have created 112 full-time jobs and be able to treat 2000T of WEEE per year. The author had the opportunity to visit the site of operations of ST. Concretely it is a logistical centre with operations of dismantling and reparations. They allow for the repair of repairable appliances and the separation of the different fractions of waste. They do not have recycling capabilities in-house but rely on partners to whom they send the fractions they have separated at their facilities (in Yaoundé). Most recycling national partners are located in Douala, the economic and industrial capital of the country.

ST it is the only known actor with the capacity to treat WEEE in Cameroon. Analysing its partners confirms that it is primarily multinational companies and international development agencies that are engaged in treating their WEEE.

ST is currently an exception in Cameroon. Other sources were needed to define the current situation better. Although the studies on the treatment of WEEE in Cameroon are scarce, some exist. We found a few studies on the subject. The treatment of metallic waste (including batteries) has been covered by Djoussi for Yaoundé [83]. Bidoung assessed, in 2007, the situation for metallic waste in Cameroon, but his assessment seems to be dated and does not mention specifics about WEEE [14]. We also have two studies providing information on the treatment of WEEE. Tchoupou assessed the behaviour of citizens towards WEEE in Douala [130], and Tsamo observed behaviour of professionals managing the EoL of WEEE in Maroua (Extreme-North) in 2014 [133].

They all point to either a lack of awareness or a lack of action towards WEEE. Nevertheless, they also describe a functioning informal sector, at least for metallic waste. Together they provide a good picture of the situation.

2.2.1 Waste collection

WEEE

Parts of the Solarly kits can be assimilated to WEEE. Most notably the charge controller, solar panels and appliances. Although part of the WEEE, lead-acid batteries and cables are assimilated to metallic waste.

Concerning the behaviour of citizens towards WEEE, we observe that, in the city of Douala, a large majority of people (76%) threw their DEEE with their household waste.

Even though a similar proportion (77%) affirm to be aware of those waste's impact [130]. No other study on the behaviour of consumers in Cameroon was found. We can assume it to be worse in the rest of Cameroon as Douala is part of the country's most developed regions.

We have some information on the handling of E-waste by the informal sector as it has been studied in the city of Maroua (Extreme-north). They studied workshops that handled EEE. Out of all the items brought to those shops, 6% got repaired. 87.9% of workers handling these WEEE did so without any protection, and only 12% were aware of the toxicity of these wastes. Most of the waste is stored in the workshops, and parts are recycled when necessary. We do not have further information on the future of these wastes. Those results show the poor current management of waste. [133] denounces the absence of an e-waste management plan by the public authorities. The data gathered by Tsamo might not be representative because they only include the part of WEEE brought to workshops for reparations. [133]

ST is the formal actor acting in Yaoundé. It collects waste in the streets on a small scale with motored tricycles, but they compete with the informal sector. Their operations will be detailed in the next section, section 2.2.1. Because of this competition, ST is operating at a loss in this activity.

Our exchange with ST and those papers show that WEEE not recovered by ST follows a path which consists of first being repaired if possible. If not, the devices are taken apart to recover valuable metallic fractions. Only easily recoverable metals are considered. It leads to a partial valorisation of electronic waste, limited to the metallic elements (iron, copper, aluminium and lead). Glass, plastics and internal components tend to be disposed of in Nature. [130]

Batteries and metallic fractions

It should be noted that the information concerning the collection of metallic waste has only been documented in Yaoundé [83]. There are hints that they apply in the rest of Cameroon, at least in cities. Indeed, executives from lead-recyclers said they were receiving supplies from all the major urban areas [80] [3]. The transport cost might make the system unfeasible or unprofitable in the remotest part of the country. SHS, being

[3] 58% of Cameroonians live in urban areas according to data from the world bank. https://donnees.banquemondiale.org/indicator/SP.RUR.TOTL.ZS?locations=CM

adapted for off-grid and "off-on" grid use, is particularly suited for the countryside. A more thorough investigation would be needed to assess the system in the rest of Cameroon as it might vary significantly from the reality in the capital. However, given the lack of other sources, we will assess the situation based on the information available for Yaoundé.

A very different dynamic than for WEEE is at play for metallic parts. It concerns all sorts of traditional metal parts (iron, copper, aluminium, lead) and includes lead-acid batteries. Indeed all of these wastes have a commercial value.

The metallic waste collection, including lead-acid batteries, is an almost exclusively informal activity. Waste collection systems exist in the big cities but are limited to household waste (where approximately 60% of all waste gets collected). For metals, the collection rate is far higher, although not characterised. Yaoundé, for example, has an efficient metallic waste collection system, as evidenced by the almost absence of those on the streets [83].

More than 800 ragmen operate the collecting system. "They go from door to door, furrow the streets of the city, the garages, the construction sites and public works, the dumpsters... to gather through picking, giving or paying the desired metallic waste. On the other hand, some individuals collect MW to make a profit. It is the case in households where children and even sometimes adults set aside part of the MW to resell them to ragmen." [83]

Once a ragman has gathered more than he can carry, he will sell those MW to collection sites of various sizes around the city, usually in the Muslim neighbourhoods. Depending on their size, they might resell the metal to bigger collection sites. Finally, the MW is shipped to the metallurgic industries in Douala, although a small part is recycled locally in an artisanal way. [83]

The system relies on hundreds of ragmen that rely on it to make money. It is their principal motivation. Some actors stated, « what attracts us is money above all ». It is attractive for them because they have the guarantee that they will sell what they gather. The activity does not require specific skills as the interesting fractions are easy to identify and separate manually from other fractions. The abundant workforce is fueled by the social context of low-income families, unemployment and low education levels. [83]

Prices are fixed by the recyclers downstream and vary throughout the year. Djoussi estimates a vehicle battery to be worth between 1000 FCFA and 2500 FCFA at the collection site [83]. Considering a car battery to be about 18kg, we find a price per kg ranging from 55 to 139 FCFA. Through phone calls with the recyclers, we obtained a price of 150 to 200 FCFA/kg depending on the quantity of batteries supplied (in tons). A doubling of value between the collection point and the recycler seems coherent, given that the transporter must take a margin. It fits the margins observed in [14] for other metals.

The collection of lithium-ion batteries is more challenging because recycling is not a profitable activity. A study from Djoussi is aimed at drawing inspiration from the efficient informal sector for household waste [83]. If Solarly is to switch to LIBs over Lead-acid batteries, it might do the same. It definitely should ensure that a collection system is in place. The design of that system could be the topic of a whole thesis.

2.2.2 Recycling actors in Cameroon

Statistics

LABs are a leading example of a circular economy. In some countries, like the US, the recycling rate of lead-acid batteries reaches 99% [50]. The recycling rate is defined here as the ratio between the amount of lead recycled from LABs and the amount of lead from LABs reaching the end of their lifetime. Furthermore, in 2015, secondary lead is estimated to cover 85% of total US lead production. [104]

Although the picture is bright in most countries, the statistics are unavailable for some countries. The author could not find reliable data concerning recycling rates in Cameroon. Nevertheless, we can try to form a general comprehension of it. A study aimed to calculate the annual production of waste LABs in various countries of Africa. For Cameroon, the total yearly production of ULAB was estimated at 7423 tonnes in 2016 [134]. We can also estimate the yearly recycling production. Testimonies gathered from battery recyclers in Douala [80] mention a monthly capacity of all formal recyclers at 1000 tons per month. That number is stipulated as a minimum flow required to make the industries function that used to be reached (before the Nigerian concurrence picked up). It puts Cameroon's total formal recycling capacity at 12 000 tonnes a year. However, those two data are incoherent.

We can make hypotheses to explain those discrepancies. The recycling plants might have been over-dimensioned and never functioned at total capacity or the ULAB flow is not well characterised and underestimated. As illustrated by the Nigerian competition, the borders are permeable to ULABs and thus do not allow for rigorous statistics to be collected. Because of those discrepancies, it seems pointless to estimate a recycling rate for the country. Further research must address this lack of information as it is harder to solve a problem that is not adequately measured.

Formal sector

ST is the only formal actor for the collection of WEEE. However, ST does not take care of the recycling of their waste. They only collect, repair, and disassemble. Then they rely on industrial partners, often in Douala, the economic capital of the country and the only city with significant industrial capacities, for recycling their fractions.

Lead Acid batteries For lead-acid batteries, ST has an industrial partner in Douala, which, although confidential, is suspected to be BOCOM recycling.

Three factories processing old lead-acid batteries were identified in Cameroon, all based in the Douala area. From the limited information we could gather, they seem to use a basic pyrometallurgic process to generate lead ingots. No direct recycling into batteries is taking place at the factory level. They also recycle the plastic into new objects or plastic granulates that can be reused later. [80]

Despite efforts to contact them to have more information on the processes, the conversations always fell short. At some point, a visit to their installation was programmed. But, the contacts proved unreliable, and our meeting never fell through. We could not access the facilities and get more precise information on their processes, scale and recycling rate.

Two sources of information were identified. One assessed the pollution of lead-acid recycling plants. It is a study conducted in multiple African countries, which gathered samples for 2 of the three plants in Douala.[48] Another one is a journal article describing the current situation, which includes the interview of an executive from one of the plants. [80]

The analysis of Gottesfeld covered two plants from the companies Metafrique, and Bocom Recycling [48]. They measured the lead concentration in topsoils near the plant (max 500m). The GPS coordinates are mentioned to be recorded in the paper despite not being published. Gathering them would be helpful for a more specific study of their impact. The author has been contacted, but our request remained unanswered.

Meanwhile, through a quick investigation on Google maps, The two installations can be identified with relative confidence.

Company	GPS Coordinates	Annual Capacity in T
Metafrique	4.030030, 9.744874	$\approx$ 3000T
Bocom Recycling	4.0655215702119945, 9.67925919455779	3000T
Ganesha	4.13535125983697, 9.57277025279298	$\approx$ 3000T

Tab. 2.2.: Identification of the lead recycling facilities in Douala

The recycling capacities of Bocom Recycling are provided by Yomim [8]. CREPD encountered similar problems to those encountered during this thesis and could not get exact numbers from the two other actors. Only Metafrique and Bocom Recycling were analyzed by Gottesfeld [48] but the third actor, Ganesha, could also be located (at the outskirt of the city). Their location matters because they determine which kind of neighbouring land is being polluted.

Prevailing winds are a crucial factor in the dispersion of lead pollution [36]. In Douala, the dominant winds are from the South-West [125]. We should thus expect the neighbouring terrains and communities North-East of the sites to be particularly affected. Without the GPS coordinates, we could not confirm this hypothesis.

The Cameroonese results of the study conducted by Gottesfeld are contained in table 2.3.

Company	Lead battery Plant	Sample #	Lead (mg/kg)
Cameroon	Metafrique	M001	170
Cameroon	Metafrique	M002	240
Cameroon	Metafrique	M003	170
Cameroon	Metafrique	M004	19000
Cameroon	Metafrique	M005	320
Cameroon	Metafrique	M006	240
Cameroon	Metafrique	M007	<40
Cameroon	Metafrique	M008	550
Cameroon	Bocom recycling	B001	260
Cameroon	Bocom recycling	B002	15000
Cameroon	Bocom recycling	B003	2300
Cameroon	Bocom recycling	B004	1200

Tab. 2.3.: Lead concentration in samples of topsoils gathered around listed lead recycling plants [48]

We observe concentrations reaching up to 19000 and 15000mg/kg of topsoils, respectively.

Those concentrations are superior to international norms. In the US, here are the applicable standards:

- 1200mg/kg at industrial sites according to the EPA.
- 400mg/kg for residential areas according to the EPA.
- 80mg/kg is the soil screening level criteria used by the California Department of Toxic Substances Control, CDTSC, for residential site remediation.

All but one sample respects the standard of the CDTSC for residential site remediation. Three of the four samples taken near the Bocom Recycling plant are past the threshold for industrial sites. More positive is that 6/8 of the measurements taken near Metafrique respect residential limits defined by the EPA. One nearly exceeds it, but the worst sample shows signs of severe contamination, with lead levels exceeding the industrial site limit set by the EPA more than 15 times over. Those results are concerning and are further aggravated by the presence of incompatible activities nearby. "One of the two facilities included in Cameroon is located within approximately 100 m of a High School and residential district with 30,000 inhabitants." and "Animal herding has been observed in the direct vicinity of plants in Cameroon" states [48]. We suspect these statements to concern respectively Metafrique and Bocom Recycling, given the direct surroundings of the plants. They are depicted in figure 2.2

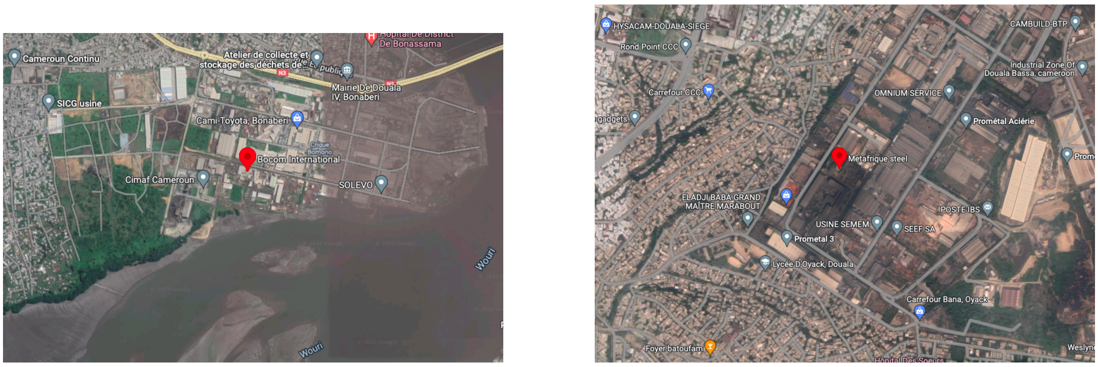


Fig. 2.2.: Location of Bocom and Metafrique lead recycling plant in Douala

This dangerous pollution level can be attributed to a global context that does not favour limiting lead pollution. Indeed similar results are observed elsewhere in Africa. [48]

There is a lack of industry-specific regulations to limit emissions or force the adoption of pollution control technology. "Most countries rely on general provisions within environmental laws to oversee LAB recycling plants performance and operational requirements."

Another key factor is the plant size in Africa compared to other countries. African plants tend to be smaller than developed countries. For example, the industrial capacity per plant reaches approximately 4000 tons/year in Cameroon [4]. This relatively small size hinders the deployment of pollution control equipment by making such installations more challenging to install, operate and control. On the other hand, China requires new plants to have a capacity of at least 50 000T/year and does not allow plants below 10 000T to continue operating. [48][104]

Those two issues contribute to the absence of sufficient pollution control equipment. Nevertheless, investment in adequate equipment is necessary to reduce the exposure of neighbouring populations. These include bag-house technology, Wet Electrostatic Precipitator (WESP), High Efficient Particulate Air filters and negative pressure enclosures.

The situation is far from optimal with the current plant but could get direr if the plants had to close down and be replaced with informal operations [108]. Their future is in question as all the plants are running below capacity. They suffer from intense competition from Nigerian buyers who take those batteries over the border. It is illegal according to Cameroonian law and goes against the Basel Convention that both Cameroon and Nigeria have signed. [84]

Of the 1000 tons that the combined three companies usually need to operate, they barely manage to gather 300 tons, says Godvind Prasad, an executive of Metafrique. He estimates that approximately 1000 tons pass the border every month with the complicity of the customs officials. Most traffic passes through the border of the southwest and northwest regions. [80] Since the article's publication, the zone has known an armed insurrection (anglophone crisis) which probably makes the situation even harder to regulate. We could not gather more recent information on the situation.

That situation might worsen the environmental impact as the recycling conditions of those batteries leaving for Nigeria are unknown. Whether they use artisanal furnaces or

[4] Total capacity of 1000 T/month for three functioning plants assumed to be of equal size

industrial plants with necessary safety precautions could greatly influence the environmental and sanitary impact. The situation also has social repercussions as it puts "900 jobs of the three companies in jeopardy." according to Godvind Prasad [80].

End-of-life management of LIB in Cameroon Lithium-ion batteries are currently not appropriately managed in Cameroon. It has no value for recyclers, and thus the informal sector does not collect them.

At the time of visit, in November 2021, Solidarité Technologique stored LIBs safely in containers waiting for a solution. They stored small batteries of pico-solar solutions and phones, but nothing on the scale of SHS comparable to Solarly's. They had identified only a handful of industrial partners capable of recycling LIBs in the developed world. None of them was already under contract with ST.

Recycling LIBs still represents a cost as recyclers currently ask to be paid for processing LIBs. Given the technical complexity of the process and the fact that recycling technologies are proprietary, relying on international partners is inevitable in the short term. Given the few plants currently existing, the chances of seeing one spawn in Cameroon are slim. Although SSA is gonna need lithium-ion recycling capacities for their consumer electronics, EV have not made a real breakthrough there, and it will be years before the supply of spent LIBs is comparable to developed countries.

LIBs, at the end of their lives, present an environmental hazard. Indeed, they will not be collected unless companies or the government takes action. The informal sector could be leveraged if given proper incentives. Nevertheless, given Cameroon's lack of infrastructure, a system must be set in place to ship those. It is entirely possible as CTL has already done it in Nigeria, most likely in partnership with the site of Umicore in Hoboken as the batteries were shipped to Antwerp [3].

Informal sector

The informal sector plays a major role in collecting but also plays a part in transforming used lead-acid batteries. Batteries are taken apart and the acid is discarded in the drains while the Lead is melted in hazardous conditions in artisanal foundries. No precautionary measures are taken while processing the batteries. Different kinds of objects are manufactured with the recycled lead. Objects range from dumbbells to fence decorations. A hazardous use that needs to be pointed out is the manufacturing of cooking pots, commonly called "macocote", with a mix of aluminium and lead. [8] Those pots will inevitably cause human exposition through the food cooked in them. [143]

Fig. 2.3.: recycling conditions and processes in the informal sector as illustrated by Yomim [8]

The consequences of artisanal lead recycling are dire and will be treated in a dedicated chapter.

As described in section 2.2.2, recyclers are not interested in paying for LIBs. The situation might change in the coming years, but the process is complex, and the few international plants available are in high demand. The technological complexity probably precludes informal recycling of LIB [61]. They also present a significant fire hazard, and even industrial plants encounter difficulty managing them[140]. As sole actors, industrial recyclers determine the market price. with prices currently being negative, the informal sector cannot provide an answer without proper external incentives.

We deplore the lack of data assessing the size of the different fluxes from figure 2.4.

2.3 International

This section was included to develop the international situation for battery recycling. The LAB case is less interesting and has already been covered and will thus be glossed over. Nevertheless, the recycling of LIBs deserves attention as it is still wholly international. All the recycling chain after collection is expected to take place outside Cameroon. The following sections are written with the help of the interview with Ghislain Van Damme.

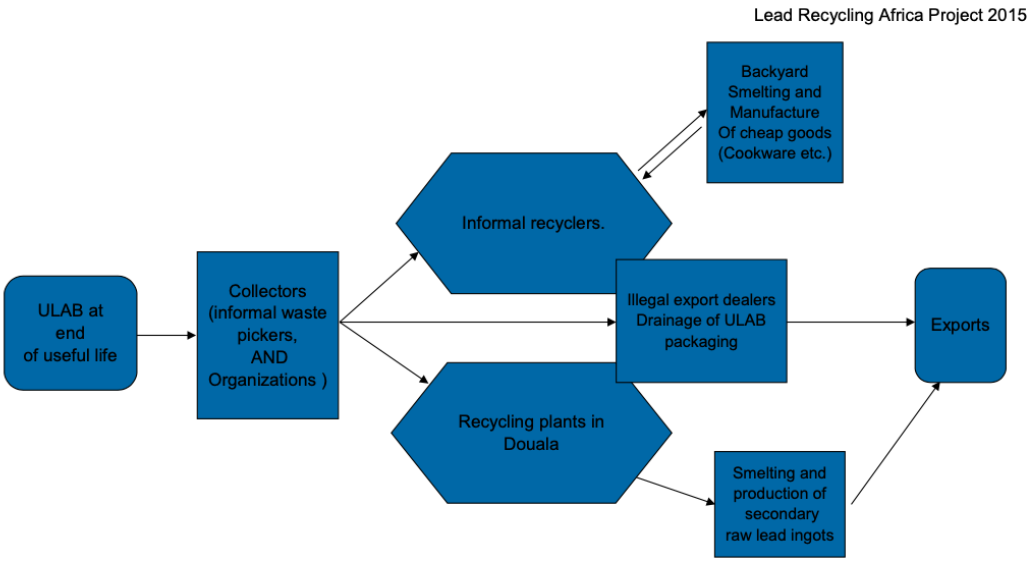


Fig. 2.4.: End-of-Life LAB material flow chart [8]

2.3.1 International situation for recycling of lead-acid batteries

LABs are a leading example of a circular economy in the developed world. In some countries, like the US, the recycling rate of lead-acid batteries reaches 99% [50]. The recycling rate is defined here as the ratio between the amount of lead recycled from LABs and the amount of lead from LABs reaching the end of their lifetime. Furthermore, in 2015, secondary lead is estimated to cover 85% of total US lead production. [104]

Although the picture is bright in most countries, the picture is bleaker in other countries, mostly LIMC. [108] As much as half of the lead-acid battery recycling in the world might end up in the informal sector.

2.3.2 International situation for recycling of lead-acid batteries

Historic context

Recycling LIBs is a relatively recent development as the first commercialised battery dates back to 1991 [107]. At Umicore, it started in 2003 with a pilot installation with an annual capacity of 200T. The operation was scaled up to 2000T/year with a plant in Sweden in 2006 and finally a small industrial plant with a capacity of 7000T/year in Hoboken, Belgium, around 2011.

The creation of such battery recycling facilities stems from the larger WEEE recycling operations of Umicore in Hoboken. They noticed a rise of LIB in small electronic devices that they processed and decided to build specific capacities to process them. At first, the goal was primarily to retrieve precious metals such as cobalt that comprised 18 and 24% of the total battery mass.

The current plant has been running for over a decade without capacity increases. However, things are changing as they just announced, on the 22d of June, plans for the world's largest battery recycling facility. With an annual capacity of 150 000T and a price tag of 525 million dollars. The plant is scheduled to open in 2026. [16][139]

This massive increase in planned capacity can be observed in the other market players. The sector is developing at breakneck speed, and numerous projects are in the works. This interest can be easily explained by the rise in LIB production, particularly for EVs that require massive batteries compared to other uses [97]. Stationary use can also be expected to this rise, although it is currently not at the same scale. All those batteries are expected and will eventually reach the end of their life. Managing their end-of-life thus becomes crucial. With increasing environmental awareness and concerns regarding material supply, recycling LIB becomes very appealing.

The auto industry, which is expected to supply most of the batteries to this new recycling industry, is getting more involved in the end-of-life management of their batteries. They used to be uninterested in it as battery recycling was costly as opposed to every other car component that could be sold for scraps. However, more and more automakers are interested in recycling LIB. This involvement stems from a desire for control over their whole supply chain. They need it to secure their supply of critical materials, exploit used batteries, and avoid scandals over non-ethical sourcing (conflict minerals).

In practice, automakers are stepping up to recover their cars at the end of their life. For this, they are leveraging their distribution network. After recovery, they can collaborate with recyclers to recycle their current park of EVs. Recycling players like Umicore are increasingly asked to play the role of recycler without ever owning the material recycled. The automakers wish to supply batteries from their EV to Umicore, rely on Umicore to recycle and refine the battery's metals, and get those raw materials back to manufacture new vehicles. Umicore would only be paid for the recycling operations and would not have to rely on the profits from reselling recycled materials.

This very circular approach is seen as attractive because it shields the manufacturer from price fluctuations of batteries. Because cell prices are tightly linked with metal prices on the international markets, they are very volatile. Battery cell's listed prices are usually valid for three months when automakers need more stability. They usually list car prices minimum for a year. Given the high fraction of the batteries' price in an EV (40-50%), shielding themselves from those variations is very important. By keeping ownership of the materials throughout their lifetime, they become essentially insensitive to price fluctuations with some significant caveats. That only applies if recycling costs do not vary if recycling rates reach almost 100%, and production is kept at a constant rate.

The second beneficial aspect of recovering EV is the ability to re-purpose their battery for second use. We will develop this promising method later.

This circular loop also shields them from potential scandals over conflict minerals. As they are customer-facing and the industry suffered from a big scandal with the diesel gate, there is pressure to display an ethical image. Sourcing their materials through recycling allows them to avoid conflict minerals and traceability problems.

All those elements could be applied to stationary use, most importantly shielding against price variations. We could imagine big energy storage players adopting similar practices as the giant automakers in the future.

Legislation The EU has edicted rules to regulate the production of batteries sold in the EU. Although the EU only has oversight over the EU market, these rules could have impacts worldwide. The EU is considered a worldwide regulatory powerhouse as the European market is too important to be overlooked by multinational companies. To streamline their processes, they often use one specification for all markets. It forces their whole production to comply with the EU standards, which often have the stringiest requirements. Chinese manufacturers will thus probably end up following EU regulations for all of their production.

The said rules form a directive [38]. A proposal to update said regulation would require minimum recycled contents in batteries by 2030 and 2035. Each metal has a different requirement, and the threshold increases with time. By 2030, the recycled content must reach 12 % cobalt, 85 % lead, 4 % lithium and 4 % nickel. By 2035, the recycled content must reach 20 % cobalt, 85 % lead, 10 % lithium and 12 % nickel. This will force industries to raise recycling rates.

Economics The economics of battery recycling is not optimal yet. Recycling companies operate at a loss and need to sell their services. It means that other players need to pay for recycling for the recycling plants to be profitable. They are not yet at the breaking point of generating enough revenue through reselling recycled materials. This assumption is currently valid for every player except those treating scraps directly from the manufacturing process. This matters as until the operation generates profits, recycling will be seen as a mandatory burden and not as an opportunity.

However, once the volume of waste grows enough economies of scale are anticipated to bring the costs down. With the current investments and the scaling of business, it can be expected that LIB recycling will become profitable. The current plant of Umicore has a yearly capacity of 7000T. Their Business plan estimated that the break-even point was around 15000 to 20 000T. With a new 150 000T plant announced, the break-even point should be passed, making recycling profitable.

This prediction depends on the material composition of batteries and their selling prices. Small electronics tend to have batteries with high densities of cobalt which has a high market value. However, their market share is decreasing compared to LIBs powering EVs. Furthermore, compositions of EV batteries are usually far less favourable, with 2% to 4% of cobalt. Certain automakers are even making efforts to get rid of cobalt in their batteries altogether. The reduction is also motivated by the concerns surrounding mineral resources.

The industry is putting efforts toward cathodes with higher nickel content to increase energy density. By trying to reduce raw material costs, they are also developing LFP, which relies on cheaper iron and phosphate. It affects the viability of recycling as in LFP, only lithium and copper are interesting to extract. [141] For EVs, NMC and NCA are still the favoured chemistries, but for example, Chinese EVs often rely on LFP batteries which threatens LIB recycling profitability. It also depends massively on metal prices, which can be volatile.

As stated before, recycling actors get paid to process spent LIBs. Ghislain Van Damme could give us an idea of the prices at Umicore. The prices vary significantly for each battery model and are fixed after the dismantling procedure is carried out and the battery is analysed. Of course, a battery pack costs more than cells to recycle, so the form in which they are delivered will impact the price. The current prices for EV batteries vary from 1,5€ to 5-4 € per kg in Europe and from 1$ to 2,2-2,3$ per pound in the US. For smaller batteries, where no assessment is carried out, the price lies between 300 and 1500$ per ton.

2.4 Lead

2.4.1 Impacts on populations

Health impacts

It is well known that lead is toxic. It is therefore very regulated, and worldwide efforts have been made to reduce exposure [113]. However, it is still a significant and often under-publicised public health problem. [108] In practice, how does it affect human health? First, a distinction must be made between children and adults who suffer differently, the first being particularly exposed. The main consequences of lead exposure are the following. Children have their neurocognitive development affected, while adults are susceptible to cardiovascular disease. The mechanisms of this toxicity are beyond the scope of this report. Further information can be found in this review on lead toxicity. [142]

The health impacts depend on the BLL and the age of the patient. The WHO has compiled a table of known effects for different BLL [95]. They are given in figure 2.5

It is to be noted that no safe blood lead level, BLL, is known. [86][116] WHO and CDC have not defined a safe level. For reference, we can mention that the CDC now uses 3,5 $\mu g/dL$ as their Blood Lead Reference Value which is used to detect children with higher levels of lead in their blood compared to most children [18].

A ruthless fact of lead exposure impact is that it affects children disproportionally in the general population. A few reasons explain that fact. First, they are more susceptible to have higher concentrations because their tissues are softer [142]. Indeed, for the same amount of ingested lead, they absorb 4 to 5 times as much as adults [94]. They also ingest relatively more lead. Indeed they ingest and breath more relative to their size than adults. As the main contamination pathway is through ingestion of water and food, their exposition is increased. Another factor is children's behaviour. Children are more susceptible to playing on the ground, engaging in hand-to-mouth behaviour, eating dirt and displaying pica. [108].

Blood Lead Levels in µg/dL (micrograms per deciliter)	Effects
Children & Adults	
<5 µg/dL	Decreased IQ, cognitive performance and academic achievement; increased incidence of problem behaviours and diagnosis of attention deficit/hyperactivity disorder; reduced fetal growth (based on maternal blood concentration); impaired renal function; reduced synthesis of aminolevulinic acid dehydratase (ALAD), contributing to anaemia
<10µg/dL	Delayed puberty; developmental toxicity
<20 µg/dL	Increased level of erythrocyte protoporphyrin; decreased vitamin D metabolism; decreased calcium homeostasis
>20 µg/dL	Anaemia
>30 µg/dL	Reduced nerve conduction velocity; increased vitamin D metabolism; increased risk of hypertension in adulthood
>40 µg/dL	Decreased haemoglobin synthesis
> 50 µg/dL	Severe neurological feature
> 60 µg/dL	Abdominal coli; features of acute poisoning but no encephalopathy
> 90 µg/dL	Encephalopathy
> 105 µg/dL	Severe neurological features
150 µg/dL	Death
Adults	
<5 µg/dL	Impaired renal function; reduced synthesis of delta-aminolevulinic acid dehydratase, contributing to anaemia
<10 µg/dL	Hypertension, increased cardiovascular-related mortality, spontaneous abortion, preterm birth
> 40 µg/dL	Peripheral neuropathy, neurobehavioural effects, abdominal colic
> 50 µg/dL	Decreased haemoglobin synthesis

Fig. 2.5.: Association of subclinical and clinical effects with blood lead concentrations [95]

Lead exposure leads to a decline in cognitive capacity, attention troubles and impaired visual, motor and reasoning abilities. It also impacts social behaviour. These effects have been measured on individuals, and the global effects on populations have been studied.

Even very low levels of BLL have been shown to impact cognitive ability negatively. Children with BLLs as low as 5 $\mu g/dL$ show significant differences with children with lower BLLs [68]. For a single individual, IQ decrease is estimated to be 6,9 points over the BLL range of 2,4 to 30 $\mu g/dL$ [13]. Although the impact on the individual is relatively small, on a population, the effects are terrible [95]. Bellinger studied this disproportionate impact and describes the effects of lowering BLL: "The prevention paradox predicts that the benefit to the population would be substantial in terms of reducing the prevalence of IQ scores associated with a need for remedial academic services, reduced lifetime earning

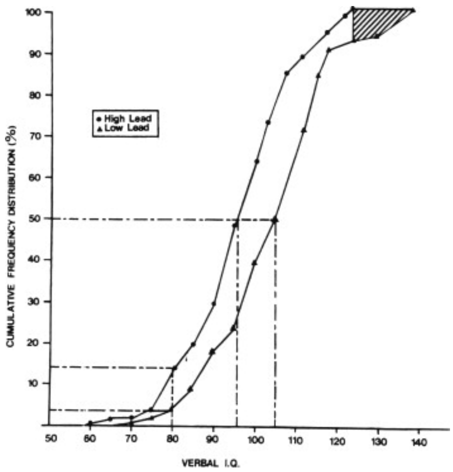


Fig. 2.6.: Observed cumulative frequency distributions of verbal IQ for school-aged children stratified by dentin lead level [87]

potential, etc. What is sometimes overlooked, moreover, is that if a distribution retains its shape and variance, an increase in the area of the lower tail will be accompanied by a mirror image decrease in the area of the upper tail, in this case a reduction in the prevalence of high IQ scores." [13] Empirical studies illustrate this effect. [87]

We observe that: "While the median verbal IQ scores of the two groups differed by fewer than 10 points, the proportion of children in the high lead group with scores below 80 was threefold higher than the proportion in the low lead group. Similarly, no child in the high lead group had a score above 125, while 5% of children in the low lead group did. Thus, the modestly lower median score in the high lead group was associated both with a large increase in the percentage of children with scores in the range of clinical concern and with a truncation of the distribution at the upper end." [13]

However, lead does not only lower intelligence. It has also been linked to increases in violence levels in society. According to UNICEF, juvenile delinquency, violence and crime have been associated with preschool lead exposure. [108] This link could be observed in the US with the rise and reduction in lead exposition. According to Reyes: "A large portion of the decline in the US violent crime rate between 1992 and 2002 may be attributable to reductions in gasoline lead exposure."[110] She estimated the elasticity of violent crime with respect to lead exposure to be around 0.8.

This relationship has also been demonstrated by Nevin, which went further and linked it with IQ, Violent Crime, and Unwed Pregnancy [89]. A powerful illustration is given in his article (figure 2.7). It relates murder rate and lead exposition in the US:

EFFECTS OF CHILDHOOD LEAD EXPOSURE

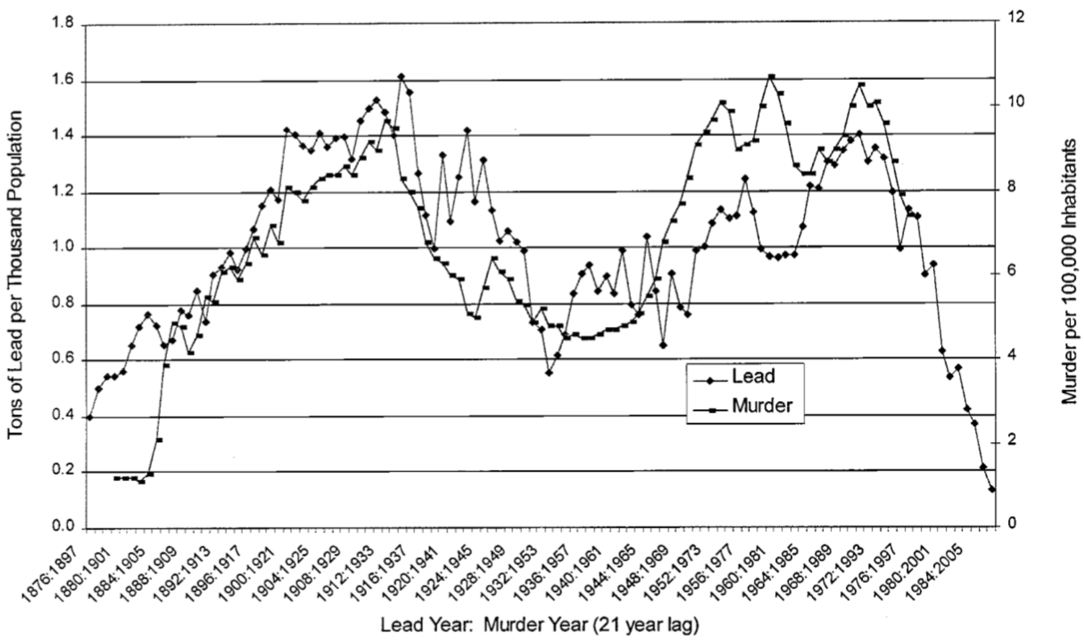


FIG. 12. Gasoline and white lead versus murder.

Fig. 2.7.: Evolution of murder rate and lead exposition (with a 21-year delay) in the US [89]

The two lead spikes observed can be attributed to the use of lead in paint and then in gasoline.

Economic impact

Those effects on health, cognitive ability, and behaviour impact the economic activities of affected communities and countries. Measuring the economic impact of lead is not as straightforward as measuring health costs. There are direct and indirect costs. Direct costs encompass every cost associated with health costs (medical treatment, screening) and the provisions for adapted education and management of violent behaviours. Indirect costs consider factors like reduced intelligence and their consequence on productivity. [95] The overall impact can be modelled with a cost-of-sickness approach. [10]

It has been done for multiple regions of the world. For the US and the EU, the impact is evaluated for 2008 at around 0,5% of the GDP [10][131]. It must be noted that this estimate is an upper bound as it takes into account more pollutants and consequences than lead (lead exposure, methylmercury exposure, developmental disabilities, asthma and cancer [10]. Lead poisoning, prenatal methylmercury exposure, childhood cancer, asthma, intellectual disability, autism, and attention deficit hyperactivity disorder [131])

The impacts have also been estimated for Low and low-middle income countries, LIMC. Their total cost has been estimated at nearly a trillion dollars ($977 billion). The burden is unequally spread. It represents 4.03% of GDP in Africa, 2.04% in Latin America and the Caribbean and 1,88% in Asia. [5] Figure 2.8 displays the disparity.

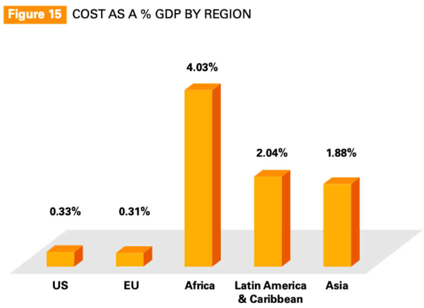


Fig. 2.8.: Cost of lead exposure as a % of GDP by region [108]

DALY and Death

The total annual tally of death attributed to lead exposure is estimated at 902 000, on par with HIV/AIDS (864 000) [29].

Another perhaps more interesting unit when it comes to measuring the impact of an industry is the DALY. It is the abbreviation of Disability Adjusted Life Years. It means that every DALY represents a year of life in good health lost. [144] Unfortunately, lead is responsible for millions of DALY each year. According to Pure Earth, ULAB recycling is the most polluting industry on earth with 2,000,000 - 4,800,000 DALY [105]. The Institute for Health Metrics and Evaluation (IHME) puts a higher tally at 21,7 million but includes all lead exposure-related DALY. Like the economic burden, deaths are not spread uniformly over the world.

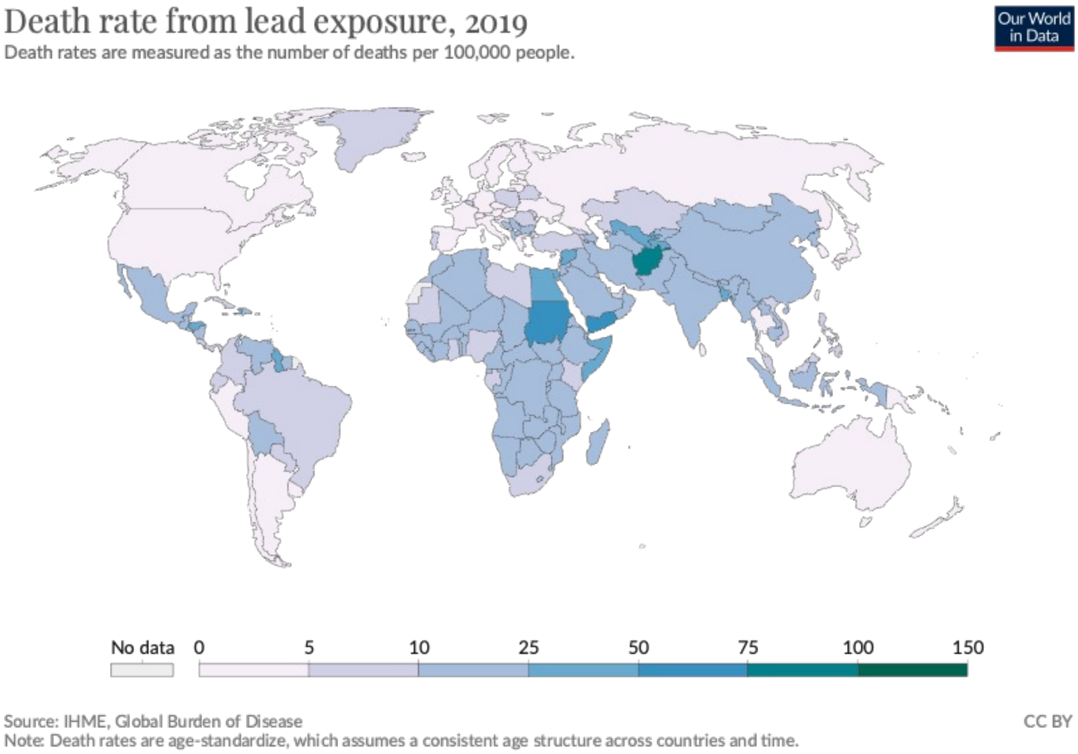


Fig. 2.9.: Death rate lead exposure

2.4.2 Exposition levels in Cameroon

The data of IHME [29] published in the report of [108] and those in the study of Ericson[35] offers information on the situation in Cameroon in 2019. They are summarised in figure 2.4[5]. Although numerous international publications have published numbers for

Cameroon	# of people [108]	# of people [35]
Number of Children with BLL $> 5\mu g/dL$	7 534 476 (68,7%)	6 574 477
- (lower-bound estimate)	4 030 583	1 265 141
- (upper-bound estimate)	11 048 855	8 072 622
Number of Children with BLL $> 10\mu g/dL$	1 620 490 (14,8%)	4,588,727
- (lower-bound estimate)	534 307	492 446
- (upper-bound estimate)	3 586 082	6 404 146
Total Number of Children (0 to 14 years old)	10 961 789	9 991 800

Tab. 2.4.: Statistics on the exposure to lead of Cameroonian children

Cameroon, [35][114][108] we should be careful with them.

Indeed, the author could only find one study that has ever been done on BLL in Cameroon. This study is supposed to be the only one ever conducted on the matter in Cameroon [66]. A systematic review of blood lead levels in low-income and middle-income countries relies on that one study for Cameroon [35]. Although no definitive answer could be found, the IHME numbers seem based on this same study.[29]

The study is not the problem, but the lack of other data and the generalisation of its results was probably never intended by its author.

The study was conducted on 147 children aged between 12 months and 6years. The results are summarised in table 2.5.

Data	Result
geometric mean	$8,0\mu g/dL$
arithmetic mean	$8,7\mu g/dL$

Tab. 2.5.: BLLs of children in Yaoundé

It also states that 88% of the children tested had lead levels greater than $5\mu g/dl$. The only major shortcoming in the methodology pointed out by the author is the lack of a random sample, as the children were not sampled with a random survey. [78]

[5] the percentages are computed with Worldbank data for population in Cameroon in 2019. `https://data.worldbank.org/indicator/SP.POP.0014.TO?locations=CM`

So although the study is precious to get an understanding of the situation in Yaounde and a first glimpse at the situation of Cameroon, its generalisation seems fanciful. There is only one sample of people without any sub-sample. The study was limited to children one to 6 years old and all living in Yaounde. It seems perilous to extend the assessment to the whole country (adults included) as the dynamics in the countryside or smaller cities might vary considerably. The only comparable city in terms of population is Douala. Moreover, Douala presents significant differences that might impact BLL in its population. Heavy Industries are concentrated there, and crucially, all the ULAB recycling industries in the country are there. Cameroon is also famous for its diversity of terrain and climates, which are all parameters for the spread and persistence of pollution. The rain regimes vary tremendously, with annual rainfall varying from 3174 mm in Douala (Littoral) to 1727 mm in Yaoundé (Centre) and even 581 mm in Maroua (Extreme-North).[20]

Nevertheless, no better study exists, so we will not be able to make a better assessment of the situation. The uncertainty should be kept in mind when interpreting the results.

2.4.3 Estimated impact in Cameroon

The study, which analysed the Economic Costs of Childhood Lead Exposure in Low-Middle-Income Countries, also offered numbers for individual countries. [5] The results are displayed in the following figure:

This study was published in 2013 before Monebenimp (2017) published his result, and the sources used are not specified for Cameroon. The credibility to give to those result are thus hard to determine.

For context, Our World In Data, based on the data from IHME [29] displays the death rate from lead exposure in the world in figure 2.11.

2.4.4 Sources of exposure

This part of the thesis took a broader view of the impacts of lead. An essential of the problem is to define where the problem comes from. However, with current data, it is virtually impossible to distinguish between pollution from Lead-acid batteries' lifecycle and pollution from other sources. Moreover, because lead is highly recyclable, the lifecycles of multiple sources can be linked. LABs can be informally recycled, and the lead

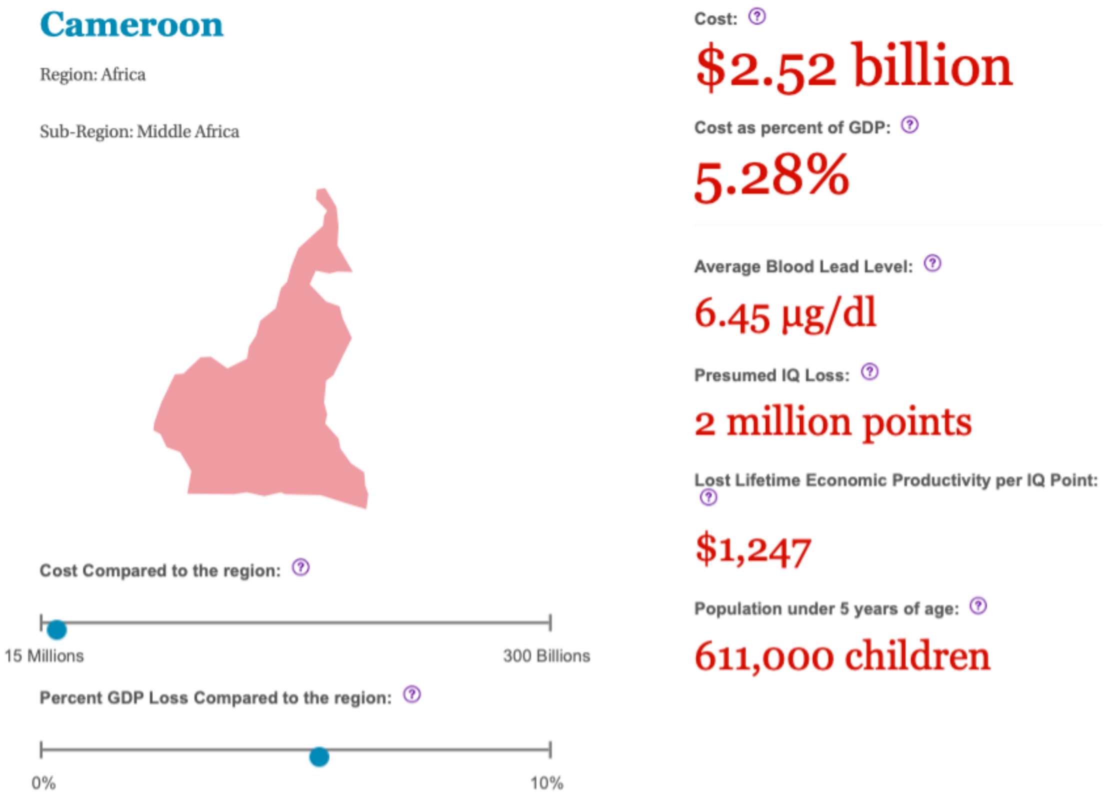


Fig. 2.10.: Impact of lead exposure in Cameroon as estimated by Attina [5]

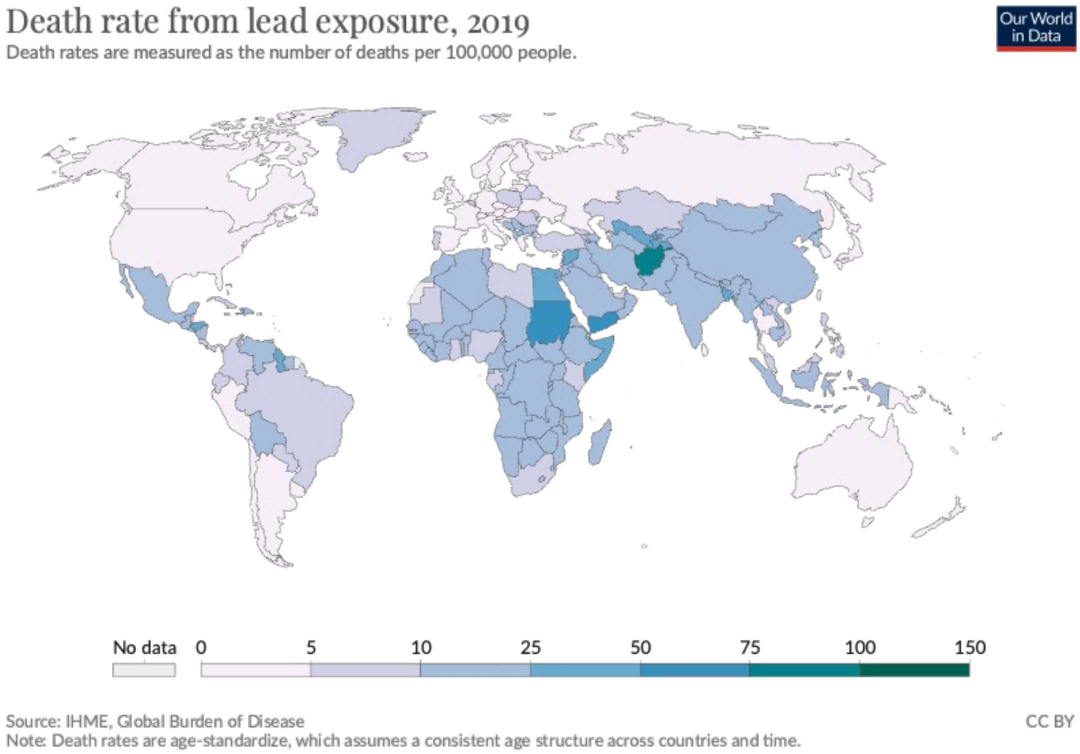


Fig. 2.11.: Deathrate from lead exposure across countries in 2019 [29]

they contain could harm the population once transformed into another form (cookware, paint, etc.). However, their inclusion in the impact of lead-acid batteries is subject to debate. It shows the importance of setting boundaries for any life cycle assessment. Nevertheless,

With these caveats set, we can identify different pathways of lead pollution. On a quantitative basis, it is almost impossible. There are multiple possible sources. One key number we have is that the primary use of lead is batteries for the transport sector. They represent over 85% of lead use. However, attributing 85% of lead contamination to lead-acid batteries is not correct. As explained before, recycling rates for ULAB are very high, probably even in Cameroon. The main question surrounds the conditions of this recycling as virtually no lead leaks into the environment during the use phase. However, the absence of leaks during the use phase and a high recycling rate does not apply to other lead applications. In the absence of objective quantitative measures, we will thus take a qualitative approach and describe the documented path of exposure. It allows to understand and devise policies for each path. Implementing them and measuring their effect would allow to adjust them for better results.

Besides lead-acid batteries, a potential source of contamination is lead paint. Lead helps to accelerate drying, increase durability, maintain a fresh appearance, and resist moisture that causes corrosion. However, it presents a risk for the population exposed to it, and economical substitutes exist. It is particularly dangerous for children because of its sweet taste [108]. To preserve their population, many countries have implemented a regulatory limit of 90 parts per million (ppm) or 600ppm per weight of dry paint [88].

The problem of lead paint in Cameroon is surprisingly well documented, with four studies published recently. Three of them by the Cameroonese NGO CREPD in 2011, 2015 et 2017 [24] and one in 2013 by another group of researchers. [47]. They all bought a representative sample of paint available on the market and analysed the lead content.

Their results are synthesised in table 2.6.

Threshold	CREPD 2011	Gottesfeld (2013) [47]	CREPD 2015	CREPD 2017
90ppm	67%	66%	47%	43%
10 000 ppm	25%	/	17%	15%

Tab. 2.6.: Statistics of paint samples over given thresholds of total lead content sold in Cameroon

The results are worrying as lead paint continues to be sold. Information on the packaging is still often lacking, and the problem with paint is that they have a long-lasting effect as it will be applied and stay in place for decades. However, the evolution is encouraging as we see a net positive progression. The proportion of sold paint over internationally recognised thresholds is diminishing with each study. On the legal side, there is currently no legislation to limit lead concentration in paint. However, the authorities are aware of the problem for which they set up a governmental comity charged ad hoc with elaborating national regulations for lead paint [24]. The action of this comity should be monitored, given the high level of corruption in the country.

The last major documented contamination pathway in Cameroon is cooking. Both the food and the cookware can be culprits. Informal lead recycling can be used to manufacture aluminium tainted with recycled lead scraps. Although the concentrations of lead in the pots are relatively low (measured under 1000ppm by X-ray fluorescence), "Potential lead exposures per serving are estimated as high as $260\ \mu g$."[143] A study commissioned by the CREPD documented their manufacturing by the informal sector [8]. Unfortunately, such cookware is widespread and used everywhere in Cameroon, both in professional kitchens, and personal settings [72]. Food and spices can also be significant sources by themselves [45][78].

2.5 Recommandations for reducing lead exposure

As we have seen, we lack reliable data on the problem. A priority should be made to conduct more studies to get a more accurate view of the problem. It is much harder to solve a problem which is not well defined. Similar studies to that of Monebenimp [78] should be made in different settings (location, age group, socio-economic) to get a fuller picture of the problem and its scale. Repetition through time would also be beneficial to track any progress of efforts made. Efforts to identify the contamination pathways quantitatively would help to set up tailored regulation. Those efforts can be made in parallel as regulations take effect.

There are many dimensions to that problem. To tackle the problem holistically, a report by UNICEF and Pure Earth [108] suggests a 6-pronged approach:

1. Monitoring and Reporting Systems: building up blood level testing capacity and monitoring, set up a procedure to act upon these informations

2. Prevention and Control Measures: mitigating the risks at the sources, limiting exposure of sensitive populations, lower lead emissions of emitting processes
3. Management, Treatment and Remediation: Intervention when dangerous levels are observed
4. Public Awareness and Behavior Change: Educate people on the matter to create real change with the help of the population
5. Legislation and Policy: State use legislative powers to regulate the pertinent sectors (battery recycling, paint, food, etc.)
6. Global and Regional Action: Create global standard units of measure (to monitor exposure) and international standards and norms around recycling and transportation of used lead-acid batteries.

More specifically, for batteries, the World Health Organization suggests working on different axes [95]. They suggest to follow the best practices of the industry which are available in public documents [19] [11] [118] [34].

1. Battery collection, storage and transportation systems
2. Battery recycling (pollution control and protection of working staff)
3. Informal recycling: Due to the incompatibility of an environmentally and socially acceptable treatment of ULAB waste and informal processes, informal recycling must be prevented. Only a holistic approach can help to achieve that. They recommend using the documentation of the Basel Convention, which dedicates a full chapter on this [118]
4. Dealing with legacy pollution (already polluted area) through environmental remediation
5. Setting up policies and a competent administration to enforce them

The situation might seem dire, but there are reasons to be hopeful, as a reduction in lead exposure is one of the successes in the IHME study [29]. The worldwide death rate linked to lead exposure has steadily declined since 1990, showing that lead exposure can be curbed. Some significant successes have been had along the way, most notably the recent worldwide ban on lead gasoline, Algeria being the last country to follow suit in 2021 (Cameroon discontinued the use of lead in petrol in 2004). These changes can be quick, as reflected by the fast phasing out that happened in most African countries [113][85].

The policies and technologies are known and available. They have been applied efficiently in many countries and have proven profitable ($ 3.10 return for every dollar invested) [132][108]. Nevertheless, an effort remains to be made. With a high priority in LMIC as they are the most affected by this burden, to reduce exposure to the poison that lead is.

2.5.1 Socio-economic factors impeding collection

Despite the overall positive impact of recycling and EoL management, collecting is not always easy. Education in environmental preservation is not developed in the country. It is simply not a priority or even something taken into consideration at all.

With this in mind, environmental preservation is not a valid argument to convince people to give back their WEEE. Return of experience from upOwa showed that people are unwilling to give back broken items. There is a sense of entitlement to the product, and in the absence of other incentives than the environment, they are usually opposed to the recovery of their WEEE. People are attached to what they paid even though no direct value is derived from owning the product once it is broken. In order to organize an efficient collection, it should be kept in mind. As we saw earlier, the informal sector already takes care of collecting lead-acid batteries. However, it is not the case with lithium-ion batteries, which are considered worthless and discarded in nature.

2.5.2 Concrete actions for Solarly

In practice, what is recommended for Solarly to manage the end of life of its products? The recommendation will be centred on the current situation using LABs, but a paragraph will be dedicated to LIBs.

System design

End-of-life starts with the design of the product. In a cradle-to-cradle approach, the product should be taught with its end of life in mind so it can be repurposed. Concretely for Solarly it will involve the choice of battery technology. Solarly does not manufacture batteries, so the control over battery design and composition is low.

More actionable advice gathered concerned the system as a whole and plastics. Feedback from technical workers in Solidarité Technologique mentioned that plastic pieces of the SolarlyBox should have the distinctive logo of their material. It facilitates the work of the recyclers to distinguish between plastic types. A plastic that can not be identified will be classified as non-recyclable to avoid ruining the recycling process of the recyclable fraction.

Discussions with upOwa also raised the issue of traceability. They have an interesting system in place from which Solarly should inspire itself. Concretely every piece of their system has a serial number which is tracked. Therefore they know how old and to which client each piece belongs. It becomes crucial when some pieces are faulty and must be repaired or replaced. If a complete system returns and a single piece needs to be changed, the rest of the system can be repurposed. This discussion is also linked with the system's repairability and the proper tools to ensure it is repaired in practice. Because this does not apply to batteries, we will not develop it further here.

Collection

Given the efficiency of the informal sector, inspiration should be drawn from it. It might also be actively leveraged. The main reproach to the informal sector concerning lead-acid batteries is the poor handling of the ULABs and, most importantly, the recycling conditions, which are unknown.

Here are three options that should be explored.

First, the informal sector could be trusted for the collection. The main problem would be to avoid the informal recycling that may follow. The formal recycling industries could be made more attractive by raising market prices for used batteries once collected. It could be done through subsidies. That unfair competition should drive informal recycling out of business. Fixing the right price and other incentives would not be as straightforward as it might seem. We have no information on the collection rates in the countryside. Moreover, since batteries are heavy, high transport costs might make collection unprofitable. Another drawback of a system based on the informal sector is that it, by definition, does not allow for traceability. It is an important argument for investors, so it should be kept in mind.

The second option is to leverage the informal sector by directly offering to buy back our batteries for a higher price than normal recyclers. This would be done at the micro-scale of the company. It presents the advantage that Solarly does not need to carry out the collection operations except for the final payment and centralisation step. Unfortunately, Solarly might not have the scale for such operations. It seems fanciful to educate the 800 ragmen. ST might have a more adapted scale to do so.

Finally, the work could be done directly with the clients. Setting up the right incentives could encourage or force the collection of ULABs. The system deserves to be well designed. Direct financial compensation, reduction on the next battery bought, contractual bond, etc. Designing the system can be tricky, and each option has its advantages/drawbacks. Education can not be relied upon entirely but is also part of the solution. With this option, the collection would have to be done by Solarly, probably relying on its technician network. Although this option offers the best perspective regarding control and traceability, it is not the most efficient. Indeed, in a worst-case scenario, a technician team would collect each battery individually.

Recycling

Recycling is the heart of the solution and the problem of ULABs' end-of-life. The lack of information on the matter is unfortunate. The conditions of operations of industries in Douala are hard to characterise. They are, however, almost certainly better than informal operations. Solarly does not have another option but to work with current actors as it does not have the scale to manage its own operations.

Nevertheless, it should work towards ameliorating the recycling conditions and cracking down on informal recycling. The role of the state is paramount in this matter. They should draw up regulations on the allowed emissions of recycling plants and set up a competent administration to regulate it. Lobbying the competent authorities is highly recommended and could be done with other actors (development agency, ST, solar actors, environmentalists, etc)

Ashok Sharma, director of Ganesha Sarl, one of the three recycling companies, mentions the "tracasseries policières" in an interview [80]. Although they are not described, it usually means corrupted officials abuse their power and try to extort money from businesses for personal gain. It can jeopardise operations and diminish the operating margin, which can lower the formal sector competitiveness against informal actors. On the contrary, subsidies might help improve recycling as simulated by Indian researchers [62].

For all the other parts of the Solarly system, Solarly should rely on Solidarité Technologique. The amount of work such an operation requires is significant, and Solarly would benefit from relying on a more prominent partner.

Lithium-ion batteries

Collection and recycling of lithium are challenging activities. Choosing lithium-ion batteries implies that it is imperative to set up collecting and recycling systems if any batteries are to be recycled. There is nothing in Cameroon to deal with it except ST, which stores small LIBs for now. The lessons of the informal sector still apply here, and with proper incentives, it might be leveraged. Working together with other actors of solar energy in Cameroon would be highly recommended as many of them use LIBs. It would allow to operate a system at a bigger scale and thus make it more efficient.

3 Resilience

3.1 Ressource availability

Any product requires resources and materials to be manufactured. In this chapter, we will analyse the resource availability of the materials required to build batteries of the different technologies analysed in precedent chapters. Resources tend to be overlooked when talking about sustainability when it is a critical parameter that influences the feasibility of any solution. We will also look at the price evolution of the different elements.

The resources needed for this work can be identified based on the LCI. Lead-acid, LFP and NMC all have different compositions, but we will address each of the significant metals and materials involved and then draw a conclusion for each technology. We will assess hereafter Aluminum, Cobalt, Iron, Lead, Lithium, Manganese, Nickel and Phosphate rock.

Assessing the availability of any material is an arduous task, given the uncertainties and the numerous parameters that influence it. The factors influencing the availability of materials are at the macro-level. We assume that given the small size of Solarly, they are a micro-level player that does not influence the market and availability of any resource.

A critical layer for the availability of batteries is further in the supply chain in the manufacturing step. We will not cover it in this chapter, but it must be noted that China has taken a preponderous position in the market. It creates dependencies with it, given the critical role of batteries in the energetic transition.

3.1.1 Definitions

To talk about resource availability, we first need to define three key notions that tend to be mixed in the vernacular language but have distinct definitions for the mining world.

- Abundance: Abundance is defined as the fraction of a given element in a given environment. We often use relative abundance in Earth's upper continental crust for minerals.[145]

- Resource: The resource for a given mineral are composed of all the potential deposits that are potentially exploitable. They include both discovered and undiscovered deposits. By definition, it is only an estimation.[77][111]

- Reserve: The reserve is a subset of the resource. Reserve is only applied to the fraction of resources that has been identified, measured and is assessed to be viably economically exploited currently. [111][44]

Abundance can be estimated for various systems: universe, earth, earth crust, etc. However, for mining, the only currently available environment is Earth's upper continental crust [1].

The widely used reference seems to be the USGS report from the sixties on the matter. Earth's crust abundance approximates the potential resources [75], but it is not a sufficient indicator. The accessibility, concentration and chemistry of the mineral's element influence the potential for exploitation.

Fortunately, we have data points for resources and reserves. We could think that back-of-the-envelope calculations would be enough to determine resource availability. A classic mistake is to compare current production to the current reserve and define a year where this specific element would be spent from that ratio. However, the mistake is in the statement. We can not base predictions on a ratio on fixed current values that are bound to evolve through time. Meinert, Robinson and Nassar concluded that neither peak production or exhaustion could be accurately modelled from reserves. [76]

Resource and reserve also have significant shortcomings. Indeed resources are but an estimation which leaves much room for error. It also is partially arbitrary as the deposits must be deemed eventually exploitable in the future, but this depends on technological and economic hypotheses.

Reserves are more accurately defined as they are based on feasibility studies for given deposits at a given time. However, reserves are not definitive numbers as, with time, conditions change. Technology, legislation, energy supply, and price can all impact what

[1] Oceanic floor is a solution explored for some minerals but it is not developed on an industrial scale

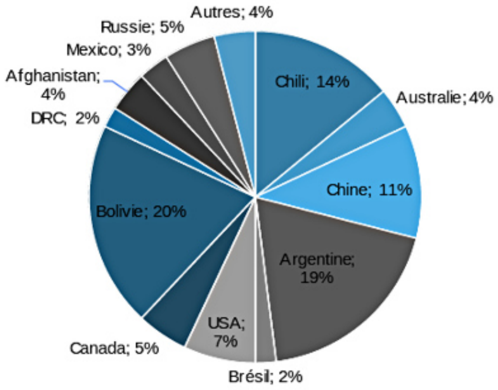
deposits are characterised as a reserve. Furthermore, the price can also drive exploration up or down, causing the stock of discovered deposits to grow more or less.

We can make a few observations on the evolution of the production and reserves. Optimists argue that we underestimate when we will run out of any element. The scarcity of a given mineral will drive up its price. These higher prices would drive the market to invest more in exploration and innovation, leading to higher reserves available at a lower cost. Regulation might also play a role with a current push to make ocean mining a reality despite serious environmental concerns. This optimistic stance has held strong for most commodities as humanity has never extracted more materials than currently. However, that is a classical problem of induction, and alarmists take the opposite stance. They argue that in a finite world and one where any mining actor is encouraged to exploit the easiest sources first. The newly exploited deposits are bound to be of poorer quality. That is, of lesser concentration, harder to refine chemistries or inaccessible places. All these factors mean that the capital and the energy required to access them will be higher. The idea is tightly linked with EROI. The more we exploit a resource, the lesser quality the future resources are and thus the higher effort required to exploit it. It is also linked with the real definition of EROI as mining is an energy-intensive activity, most notably crushing. Coupled with the diminishing EROI observed in oil extraction and other fossil fuels, material extraction is predicted to get harder fast.[111]

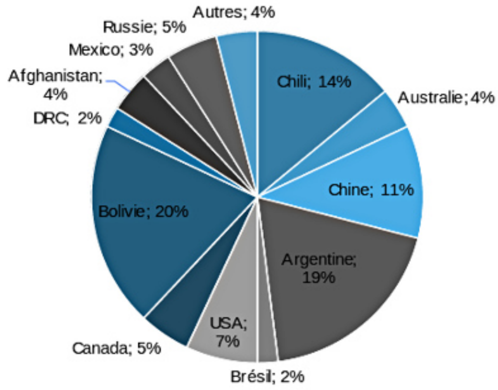
Another observation is that no exploitation will follow a linear production until the end. Total production will probably display a sigmoid, with yearly production reaching a peak well before the end of production. Any current production and reserve ratio are limited and insufficient to make predictions. [111]

Recycling, legislation, geopolitics, the concentration of actors, diversity of technology and combined exploitation of different elements are other factors that also play a part.

These factors make predicting any future prices or availability hazardous. Price in a free market is supposed to reflect all current information about a given financial product, including commodities like raw materials. Because of the inherent difficulty of predicting prices, we will not risk ourselves to predict it. We will, however assess individual risks associated with each resource.



(a) Geographic repartition of lihtium reserves



(b) Geographic repartition of lihtium resources

Fig. 3.1.: Resources and reserves distribution of lithium

3.1.2 Assessment per resources

Here each resource is assessed by characterising current reserves and production while identifying the main concerns associated with the availability of the material.

Lithium

Crucial because of the meteoric rise of lithium-ion chemistries. As their name suggests, they all use this element in their cathode design and the electrolyte despite using different chemistries. The resources in 2017 have been estimated at 53MT by USGS [137]. However, it seems too low given many estimates of reserves that hover around 100Mt. Deutsche Bank estimates global resources to amount to 273Mt. The global reserves are estimated by the same source at 102Mt [31].

The resource and reserves are spread around the world in the proportions given in figure 3.1.

As can be observed, there is a supply domination by the lithium triangle composed of Chile, Argentina and Bolivia. They account for 53% of resources, 60% of reserves [31] and 45% of production in 2017 [137]. Other significant players are China and Australia. Together with Chile, they account for 85% of production in 2017 [7].

Lithium deposits have different profiles depending on the region, and extraction techniques will thus vary. In the triangle of lithium, lithium is extracted from salted brines. In

Australia, lithium is extracted from rock, usually spodumene. China uses both kinds of deposits, brine accounting for 80% of Chinese reserves and rock the rest [7].

Extraction from spodumene was considered more expensive, but it is changing as lithium hydroxide takes a more important place in battery manufacturing than lithium carbonate. The path to lithium hydroxide is cheaper from spodumene lithium. [31] That is fortunate as spodumene is more spread out and found on every continent, while the specific salt flats needed for lithium brine are much rarer.

Back of the envelope calculation show that at the 2017 rate of extraction (82 000t in 2017 according to USGS) and with current reserves, it would take more than a thousand year to run out of lithium. Suppose that 0,2kg of lithium is needed to make a battery storing 1kwh, which is in phase with EV standards [31]. In that case, we can calculate that all the lithium reserves could theoretically [2] store 500TWh of electrical energy. That represents approximately a week's worth of worldwide electricity production. [3]

As demonstrated here above, worries concerning lithium mineral reserves are pretty low. Even with the increase in demand, decades will be necessary to change this status quo. More worrying is the concentration of actors, with currently only eight producing countries and only four companies controlling most of the output. [7].

Cobalt

Cobalt is a fare more problematic mineral than lithium USGS does not provide a figure for the worldwide resource of Cobalt. However, it provides data for the reserve, estimated at 7 000 000t [137] and 7100 000t in 2020. The production meanwhile was at 120 000t in 2017 [137] and 140 000t in 2020.

The production to reserve ratio of 2020 predicts 50 years until the depletion of the reserve. However, reserves increased between 2017 and 2020 despite the production that had taken place. The reserve might still rise, but consumption is also promised to rise two-fold according to McKinsey from 2017 to 2025 [7]. As LIB production increases, availability problems might present themselves in the medium term. It is more limiting than lithium.

[2] if turned entirely into lithium-ion batteries
[3] assuming annual production of 26,823 Twh [21]

It also presents the challenge of being a hitchhiker mineral [111]. It is often mined as a by-product of another element's extraction. Cobalt tends to be extracted alongside Copper(55%) or Nickel (35%). [7] The profitability of cobalt mining operations is thus also dependent on the prices of other minerals. Beyond the technical problems, other problems arise.

First, the production (70%) and reserves (50%) are concentrated in the DRC, Democratic Republic of the Congo. The country is politically unstable and has a record of human rights abuse, most notably child labour in the cobalt mines. Furthermore, the refining operations are also regionally concentrated in China. Gulley states that: "China's global production share increases as cobalt material moves downstream (i.e. mine, 14%; intermediate, 33%; refined, 50% in 2016)" [51]. These concentrations in the supply chain are quite concerning for other players. However, efforts are being made to reduce the dependence on Cobalt in batteries by reducing its fraction or even making cobalt-free batteries.[91][93][49][63] NMC batteries, for example, have evolved from NMC111 to NMC811 (with variations along the way). The numbers represent the proportion of atoms of the respective letters in the cathode (NMC811 = 8 Nickel, 1 Manganese, 1 cobalt)

Besides a potential reduction in cobalt content in batteries, other deposits have been identified. They can limit the monopoly of China and the DRC. Both onshore (United States, Canada, Australia, the DRC, Zambia and Madagascar) and off-shore sites have been identified [65]. Off-shore deposits have their own environmental problems and might be inadequate.

Recycling is crucial as it supplies approximately 10% of the world's production. Its high price is a key factor in making recycling attractive. [7] The higher price also means that price fluctuation impacts the prices of batteries more significantly than lithium [7].

Phosphate rock

Phosphate rock is the only significant source of phosphorus, according to USGS. In 2014, They estimated resources at 290 000 Mt and reserves at 67 000 Mt. [137] The reserve rose to 71 000 Mt in 2020. Both resources and reserves have increased significantly by raising estimates for Morocco. Researchers have contested these conclusions. They find that "... the report most likely presents an inflated picture of global reserves, in particular those of Morocco, ..." They encourage further research and more transparency in methodology and terminology used. [32] Despite these shortcomings, no better estimation was found.

The global production in 2020 reached 223Mt of phosphate rock which amounted to 30 Mt of phosphorus. [124].

The material still seems plentiful as the ratio of production to reserve guarantees three centuries of supply. However, numbers might be inflated, and the resources are concentrated in Morocco (70% of world reserves). Moreover, this material is not a traditional battery material. 85% of the supply is currently used for fertilisers and 10% for animal feed supplements, the last 5% being used for various products. [124]

A paper has estimated that developing LFP batteries for EVs would require upwards of 3 Mt of yearly phosphorus supply. Including stationary use would further grow this demand. The paper also states that demand in the agricultural sector could almost double by 2050, putting more strain on the supply [124]. However, if the reserves estimates are to be trusted, it still leaves plenty of supply in the short and medium term. It is vital to manage this properly as phosphorus plays a key role in our food production systems, and its biogeochemical cycle is identified as essential. [115]

Iron

Iron is the most mined metal on Earth by far. Ores exploited have higher concentrations than other elements, and the scale of exploitation is massive. Battery manufacturing would not represent a significant demand for a commodity with such immense supply. It is estimated that 5,63% of Earth's upper crust is composed of iron. Nevertheless, like the other metals, it requires energy to be mined. It is found almost exclusively in oxide form. The construction sector, which is far more price sensitive than battery manufacturing, depends on it as a pillar of modern construction techniques. Therefore its use in batteries should not pose a problem.

Manganese

Manganese is an abundant metal. It is the twelfth most abundant element in Earth's upper crust [117]. Its reserve, according to USGS, was at 810 Mt in 2020 [137]

That reserve is mainly found in four countries that concentrate almost 80% of the total reserves (South Africa, Ukraine, Brazil and Australia with respectively 32%, 17.2%, 17.2% and 12.3%). The total production reached 16,000,000 T in 2016. Given the new nickel-rich composition of NMC batteries, the Manganese supply might become less important. Currently, manganese is mainly used in the steel industry, with only 10% of the production dedicated to other uses. It is not a particularly critical metal.[54]

Lead

A review has been conducted to assess lead and zinc mineral resources.[82] They are usually found together, which justifies this joint study. It makes lead a hitchhiker element.

They conclude that sufficient resources exist with 226,1Mt of lead identified [82]. USGS gave world production at 4820 000 tons in 2016 and reserves at 88 000 tons in 2017. [137]

They conclude that: "Economics, environmental impacts and social concerns are the real constraints to Pb-Zn's future – not just how much is left" [82]

Recycling, as we have seen before, also reduces demand for mineral resources and thus ensures that supply should not be a problem for a long time.

Nickel

The reserves were estimated at over 95 Mt in 2021. With 2/3 in four countries (Indonesia, Australia, Brazil and Russia). The total world production reached 2,7Mt in 2021 [138].

The ratio of production to reserve is less favourable than other elements. The supply will be a challenge if no other reserves are identified in the coming years because of the new nickel-rich chemistries and the rise in demand for EVs.

In 2019, stainless steel consumption accounted for 80% of nickel use, and batteries, electroplating and alloys accounted for 9%, 5% and 4%, respectively. [54] The part dedicated to batteries is expected to rise. This element will be one of the most critical ones. It has been defined as critical in 2021 by the Biden administration.

A potential way to increase reserves would be to account for nickel resources found on the ocean floor. If land deposits were to run out, new deposits on the seafloor would have substantial potential [22]. However, they are currently not economically viable [54].

3.1.3 Conclusion

As we have observed, despite numerous uncertainties surrounding such predictions, material supply seems ensured at medium term at least. Lead benefits from high lead recycling rates. It also benefits from the fact that no other significant application for lead exists. Lithium, present in all LIBs, has sufficient reserves. Nevertheless, ramping up production is going to be necessary. For NMC batteries, the most critical elements seem to be Cobalt and Nickel. Cobalt importance is promised to be reduced with newer chemical formulations for cathodes. Nevertheless, the uncertainties surrounding its supply should be taken seriously as it is still necessary for NMC formulations. Nickel is also a critical metal and represents supply risk in the future. LFP have the advantage of relying on material with substantial reserves and is less exposed to material availability issues than NMC.

4 Alternatives

This thesis has focused on the impact of batteries and, more specifically, comparing three different chemistries. However, this is not an exhaustive list of storage technologies. It is essential to keep an open mind as those two options are in direct or indirect competition with several alternatives. This chapter will introduce alternative storage solutions not assessed in this thesis, methods allowing to reduce the consumption of batteries and explore second-use batteries.

This chapter seemed important as it highlights measures on which the company can have an impact. Solarly is not a battery manufacturer and has little leverage to change manufacturing operations. However, they can choose the storage technology it uses and/or influence the operating conditions of these storage systems.

4.1 Competing storage technologies

The most direct competitors of LAB and LIB are other battery technologies. It would be pointless to list them all as numerous existing chemistries exist. Nevertheless, at an industrial scale, the number of alternatives is reduced. Only Nickel Metal hydride, Nickel-cadmium have a significant market share. This situation is illustrated in figure 4.1 for the US market.

Nickel-cadmium is being phased out in developed countries for toxicity concerns. It has already been banned in the EU [98]. Moreover, their performance has been matched and surpassed by their nickel hydride counterpart. [129]

It should be mentioned that sodium-ion batteries are also a technology to watch out for as it has promising perspectives. They offer an alternative to lithium-ion batteries for stationary use by requiring less of the critical metals needed for the anode and cathode. Depending on the price fluctuations of metals, they might become more competitive in the short term [99]. CATL, the biggest battery manufacturer in the world, is already betting on it. They started industrial deployment of the technology and plan to have a

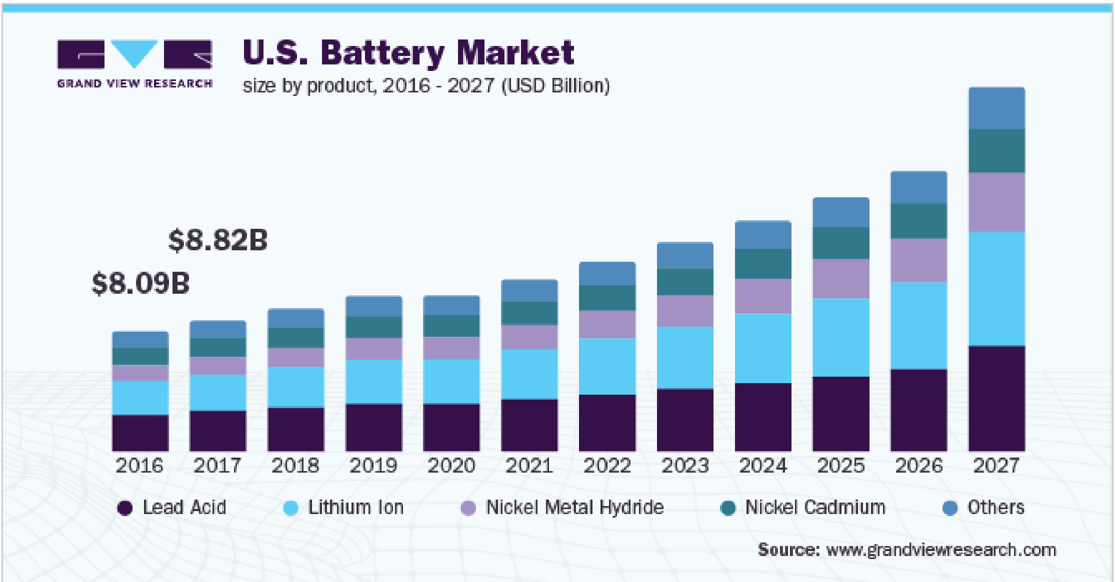
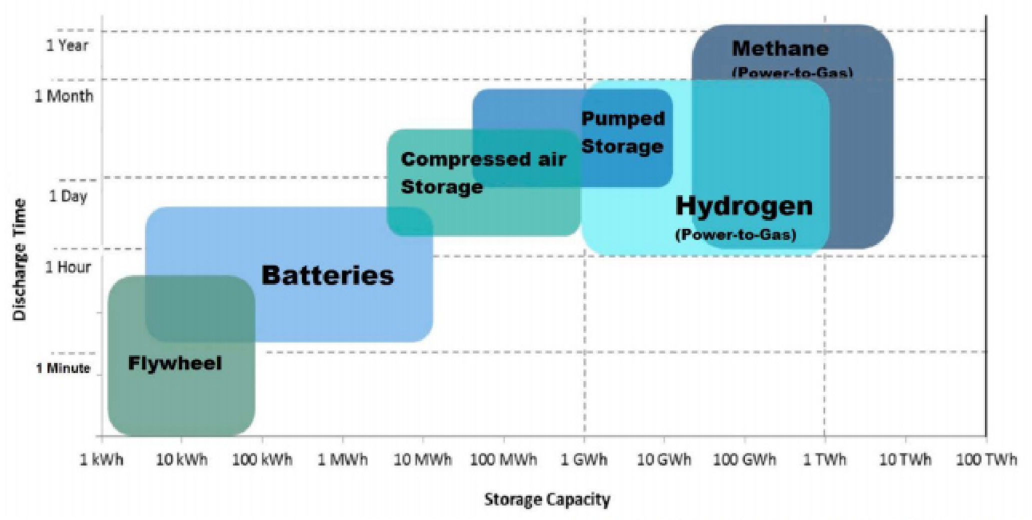


Fig. 4.1.: Market evolution of battery technologies in the US Market [109]

basic industrial chain by 2023. The manufacturing processes for sodium-ion batteries are compatible with existing lithium-ion infrastructure, according to Dr Qisen Huang, deputy dean of the CATL Research Institute [17]. It will allow for fast scaling of the manufacturing capacities and makes it a credible alternative that would benefit from being investigated once it is available at scale.

Apart from batteries, there are also countless other options to store energy. Pumped hydro currently dominates all the other technologies in terms of capacity and power. [112] But it is hardly the only solution. Flywheel, Compressed air, electro-fuels, thermal,... The list of alternatives is never-ending and shows that energy can be stored in many forms. However, they are not all adapted to individual home systems as they often require significant infrastructure, unique terrain, and a specific scale.

A specific system seems worth mentioning because it is often overlooked and particularly adapted for the current market of Solarly. That system is phase change energy storage for refrigeration. Behind this impressive name hides a simple principle. It relies on the energy stored in the phase change of a specific chemical species (for example, water). The system works by using available energy to power a refrigeration system. That system is used to freeze water in a fridge. When the energy supply runs out, the system is maintained at the freezing temperature by the melting block of ice. Until the block is completely melted, the temperature is maintained at a freezing temperature. It allows bypassing the need for battery storage for refrigeration needs entirely. This application would allow for efficient use of electricity as the time of abundant supply correspond with the hottest external temperature of the day. The higher temperature differential leads to a higher coefficient of performance for the refrigeration cycle [69]. It is a crucial application for health, and food conservation for developing countries [148]. However, it is not versatile as it is only effective for this use. Nevertheless, it is an interesting use that can be combined with batteries in a system to reduce the required battery capacity. [96]



Source: School of Engineering, RMIT University (2015)

Figure 3. Available storage technologies, their capacity and discharge time.

Fig. 4.2.: capacity and discharge time of various alternative storage technologies [145]

Despite the numerous alternatives available, no better option for our system could be identified. As shown in figure 4.2, batteries are a perfect match for our use case (capacity of 900Wh and discharge time reaching from hours to a day). With the lack of moving parts, almost non-existent maintenance cost and an existing supply for a system this size, batteries are an obvious choice. We can not rule out alternatives, but batteries seem to be the logical choice for this specific case. However, they should be reconsidered if the scale of the system changes, for micro-grids or small-scale industries, for example.

4.2 Reducing battery consumption

4.2.1 Lifetime maximization

The product's lifetime is key in determining how many products (and underlying material flows) will be required to provide a given service. The amount of product needed is inversely proportional to its lifetime. Those are obvious statements, but they are essential as it means that lengthening the lifetime of products can have a significant positive impact on the environmental impact of a solution. That is even more true for batteries that do not generate significant direct impacts during their use phase. They are not supposed to emit pollutants into the environment as they are closed systems.

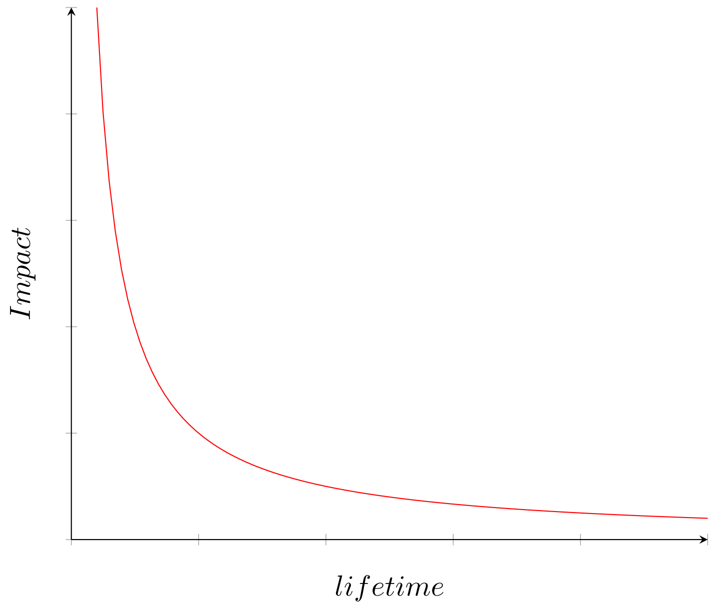


Fig. 4.3.: Inverse relationship between environmental impact and lifetime of a given product

Unfortunately, everlasting batteries are but a dream. No technologies are everlasting, and no methods allow to prolong the life of LABs or LIBs forever. However, by identifying the parameters affecting the lifetime of batteries, we can devise strategies to maximise the lifetime of operation and/or reduce the reference flow of batteries.

The lifetime of lead-acid batteries has been modelled with different methods. [43] [15] They involve many different parameters. We can encompass them in two main categories, condition of operation, which comprises mainly the temperature of operation and cycling conditions, which is the conditions of charge and discharge that the battery experiences.

The degradation mechanisms are quite complex. The physicochemical processes have been identified and involve corrosion, acid stratification, gassing, sulfatation and sulfate crystal growth and degradation of active material.[64]

With proper temperature control and optimisation of the cycling conditions, a battery's lifetime can be significantly raised. The advice to technicians for the installation should thus be researched further. The packaging should be rethought to allow for better aeration and better thermal management. The cycling conditions are harder to influence except through the maximal DoD tolerated by the charge controller. Lower DoD can lead to a higher lifetime but also reduces a battery's capacity.

Victron, a reputable electrical equipment manufacturer, published recommendations for managing LABs to maximise their lifetime. Here are the actions they recommend to avoid [135]:

- Running a battery flat and failing to re-charge
- Persistent Undercharging
- Overcharging
- Charging too quickly
- Ignoring temperature considerations

Desulfatation

The batteries can also benefit from active measures to prolong their lifetime. A specific method allows them to regain some lost capacity through desulfatation. That method mitigates the impact of the sulfatation and sulfate crystal growth mechanisms. It tends to happen when a battery remains at a low SoC for an extended period.

It consists in sending high-frequency electric pulses to destroy the sulfate crystals at the interface of the lead plates and the sulfuric acid. The frequency chosen must match the resonating frequency of the sulfate molecule. It provokes their separation from the plate and subsequent dissolving in the acid. Finding this frequency requires systems that analyse the given battery.[59]. What was described here is one of the different existing methods: pulse width modulation, pressure feedback, resonant frequency, by chemical reaction [121]. Heating the battery to 50-60°C can also help to dissolve the crystals. [121]

The result of desulfatation is a battery with lower internal resistance and higher capacity. The potential remains limited as other degradation mechanisms are irreversible, and sulfatation can also be irreversible if the SOC remains too low for too long [121]. Still, the method has potential as, in some cases, the recovery in capacity can be as significant as 41% [120].

This method is directly applicable in after-sale service as Solarly is equipped with Victron chargers with a desulfatation function.

4.2.2 Reducing battery size

The logic behind reducing the size of the batteries is the same as lengthening their lifetime. It allows to reduce the material flows and thus the environmental impacts linked to it. However, the battery serves a fundamental purpose in our system, allowing us to use electricity throughout the day despite relying on an intermittent energy source. This reduction in the need for storage can be made through demand-side management. However, reducing its size can not be made without compromise.

Nevertheless, it seems like an interesting perspective to explore as it is a novel hot topic for smart grids in developed countries. The idea is to manage demand to reduce the mismatch between regular demand and intermittent energy sources. By aligning energy consumption with moments of energy production, we might reduce the need for batteries. A study on microgrids with a mixed solution of diesel and solar found that the reduction in LCOE could reach 20%. [6] However, for a system like ours depending on batteries and on a smaller scale, it remains to be seen if demand-side management could deliver promising results.

By treating energy as a precious resource, we can dedicate it to the most important needs. However, it requires educating the customers about the energy consumption of their different devices and the optimal way to manage their energy demands throughout the day. However, current consumption with Solarly systems could hardly be considered oversized in the light of consumption standards in developed countries. A paternalistic view should be avoided as reducing energy consumption is not a priority in such cases, but maximising the return for the available energy might well be.

4.3 Second use

Recently, a new option has become promising. It is not a new technology but a new supply of available storage solutions. As the electric vehicle market share is expanding and expected to rise further in the coming years, the idea of repurposing used EV vehicles for stationary uses has become appealing. Three options exist for the battery of an EV at the end of its life: discarding, recycling, or second use [73]. The last option is very interesting for less demanding applications like stationary applications that do not require top-of-the-line energy densities. Depending on the manufacturer and the application, batteries are replaced even though their capacity is between 70-80%.[40]

The interests of second use are both economics and the environment. Currently, second-use batteries are between 30% and 70% cheaper than new ones. As second-use batteries use existing batteries, they do not require the extraction and manufacturing process and allow to minimise environmental impact. Given that the supply of second-use batteries could exceed 200 gigawatt-hours per year by 2030 because of the rise of the EV market, the potential is enormous. That supply could outpace the predicted demand for BESS [53]. Although this option has real potential to be deployed at an industrial scale, it still needs to overcome some economic, technological and regulatory barriers. The current situation is auspicious economically, but prices of new batteries are predicted to go down significantly. By 2040, the gap between new batteries and second-use ones might be reduced to 25% [53].

In terms of technology, the main problems lie in repurposing batteries for a use they were not conceived in the first place and coordinating multiple second-use batteries in a system. It poses major challenges for battery management systems. Lastly, regulations must be updated to deploy second-use batteries at scale. Mandatory labelling for the different chemistries is not even yet in place. It makes end-of-life management complicated. Furthermore, the process would benefit from standardising battery packs, modules and cells. It would allow for automation in the recycling and repurposing processes. Lastly, a body of legislation must be built to frame the process and define responsibilities for the safety and performance of the secondary use batteries. Fortunately, states are working on the matter. For example, the EU commission is already committed to modernising its legislative arsenal surrounding batteries [39].

Cameroon might prove a perfect ground for repurposing used batteries as the process is labour intensive and labour is relatively cheap compared with developed economies. Local engineers are not in short supply. The safety standards are also lower, which might benefit a pioneer industry like this. There is also probably a local market for those second-use batteries.

Given the problem of waste surrounding lithium-ion batteries, second use would offer a great solution. If the formal sector does not develop, the informal might and the safety standards might be even lower. It should be mentioned that because EVs are still near nonexistent in Cameroon, the supply for an eventual informal market is probably not present; thus, the risk is low at present.

Conclusion

This thesis explored the sustainability of the batteries of the SolarlyBox and options to improve it.

The first chapter demonstrated that LIBs, particularly LFPs, have a smaller environmental impact than LABs, for the cradle-to-gate phase.

The second chapter has been the occasion to understand the different dynamics surrounding LIBs and LABs. The first poses less of a threat to the environment [1] but lacks any collection structure that would allow for proper management. The second is a circular economy model but presents significant public health concerns given the high toxicity of lead and the poor recycling conditions in the informal and formal sectors. It has also shown that efforts are needed to characterise the lifecycle from disposal to recycling better. The recycling conditions also need to be improved for LABs, and the collection must be set up for LIBs.

The third chapter treated the critical topic of resources. It gave a positive outlook for practically all chemistries. The field has significant challenges to overcome to increase production, but they do not seem insurmountable. LFP is particularly promising as it depends less on critical metals than NMC. However, LFP presents less potential for recycling given its lack of precious metals. LABs are a model for recycling and benefit from it to ensure long-term supply, while the recycling of NMC is expected to become profitable in the short term.

The fourth chapter showed the importance of the management of the batteries for minimising impact and showed a promising opportunity in second-use batteries from EVs that are expected to be available in great numbers in the future.

Although the conclusions should be nuanced for academic work, and the entire thesis is essential to understand the conclusion reached, the thesis aimed to give specific conclusions to Solarly. Those conclusions are that a shift towards LFP seems to be the best

[1] compared to LABs

option in terms of technology. It would limit the environmental impact of the cradle-to-gate phase and does not present a risk as high as lead for its end-of-life. The resources are abundant and pose less risk than Nickel-based chemistries. However, this shift must be accompanied by proper battery management to maximise its lifetime, as recommended for any battery technology. Extra care must also be taken with the end-of-life management as the economics of recycling are worse than for the other chemistries. Active measures must be taken to ensure proper collection and treatment. Second-use batteries were also identified as an auspicious opportunity that should be pursued.

Further research deserves to be conducted to broaden the scope of the assessment. The scope of the system assessed could include the rest of the Solarly kit or even the whole operation of the company. The impacts analysed could also be extended to other fields, such as fields in the humanities. Besides analysis, research could also be conducted to devise better systems, for example, by designing a proper incentive structure to leverage the informal sector for battery recycling or by conceiving better battery management systems to maximise lifetime.

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Context and Motivations

A

A.1 Global Context

In 2020, there are 759 million people living without access to electricity, three quarter of those living in Sub-Saharan Africa. And even for those connected to the grid, the energy source might not be reliable. The situations vary widely from country to country, but network instability still plagues sub-Saharan Africa. A situation of partial connection described as "off-on". [2] [41]

Progress in the field is being made. The part of the global population having access to electricity grew from 83% to 90% between 2010 and 2019. But despite those progress universal energy access is still far from being achieved with 660 million people forecast to still be without access in 2030 at the current pace. [60] The vast majority of those will be in Africa (9 out of 10) where the challenge remains daunting.

The lack of access to the grid or the off-on grid is a truly important issue for the affected populations. It precludes their development opportunities, their quality of life and often it is paired with great poverty. It is thus a challenge of great importance to bring electricity to the maximum of those and reach a better global welfare. This lack of access to clean and affordable through energy also poses a problem in terms of the alternatives (diesel generator, wood burning) put in place which can have dire consequences on health and finance for the users. On a more global level it hurts efforts to mitigate climate change.

Efforts to make clean and affordable energy access universal are under way. And the objective has most notably been set as one of the 17 sustainable development goals (SDG) of the UN as part of the 2030 Agenda for Sustainable Development [136]. They set clear targets for economic, social and environmental development to reach by 2030. Those goals are meant to ensure a better future for all.

Despite the hurdles of the pandemic, a lot of progress has been made towards reaching them. But a lot of work remains. And particularly towards the SDG of concern, the seventh. It is directed toward energy access and is thus of particular interest for electrification. The goal is to:" Ensure access to affordable, reliable, sustainable and modern energy for all" [136].

As mentioned before, humanity is off-track to reach this goal and an increase in activity, involvement and investment of all actors involved is required to be able to meet it faster.

The 7th SDG has been set in accordance with the spirit of the SDGs to offer a better life for all. But it does not state why it matters and how it impacts those affected. The SDGs encompass economic, social, and environmental impacts. Energy access, and more specifically electrification has both direct and indirect impact on all of them.

On the socio-economic implications of electrification, it seems intuitive that energy access plays a key role in the standard of living of populations, but the causality relation between electrification and standards of living is not exactly straightforward. Although electricity access seems to play a role in socio-economic development [151] correlation is not always causation. They have shown that "that access to finance, education, economic development, infrastructure, and industrialisation are positively related to electricity access in the long-run". But the conclusion of their study also suggest that electricity access requires "not only economic, educational and infrastructural development, but also private sector participation, governments' commitment and political will, and integration with poverty reduction and other development schemes." Not taking all the other aspects of development into account will result in poor results. Another study conducted in Kenya suggest that extending electricity access does not have "meaningful medium-run impacts on economic and non-economic outcomes" because of a lack of demand. [70] It must be kept in mind to not be blinded by the objective of electrification which by itself is not a guarantee of a better life for those concerned. It can make a difference and impact other SDG (4, 8, 10, 16)[119] but must necessarily be combined with other factors.

Besides socio-economic impacts, we also have massive environmental implications for energy use. Energy use is by far the most greenhouse gas emitting activity at 76% of all emissions [26]. Not all energy use is linked to electricity although there is a tendency for electrification which broadens the use of electricity to sector which classically used other energy sources. [28]. It raises the production of electricity but is supposed to reduce the emissions by using less carbon intensive electricity production methods.

Impacts are not limited to GHG emissions and climate change. They include local and global pollution like air pollution, water pollution, thermal pollution, and solid waste disposal. Those impacts are wide ranging and can be analysed through different tools one being a Life Cycle Assessment.

Bringing affordable and sustainable energy to population off grid represents a huge potential but also involves environmental impacts and that is why it must be well thought as to avoid an environmental disaster that could contribute significantly to climate change. “In physics, energy is the quantitative property that must be transferred to a body or physical system to perform work on the body, or to heat it.” [146] The more energy, the more capacity to transform a system. And thus by definition, energy corresponds to impact in the sense of transforming the system.

The scale and implications of electrification are clear, but the means are also of particular interest. Technical and financial means are needed to reach universal access, but which are to be privileged and how much capital is required? The numbers that will be given here are projections sourced from expert institutions, but they cannot be considered definitive answers. The technical innovations and economical evolution influencing those predictions are unpredictable.

According to the IEA, investments of $723 billion are required to reach universal access between 2017 and 2030. [42] Currently the trajectory is far below this objective.

The methods used to bring access to clean, reliable and affordable energy can also be discussed. Linking everyone to the grid is probably not be the most efficient plan. Off-grid electricity systems have a role to play. Affordability of mini-grids and off grid systems are increasing with the development of renewable energy and energy storage.

According to the IEA: “Detailed geospatial modelling suggests that decentralized systems, led by solar photovoltaic in off- grid systems and mini-grids, are the least-cost solution for three-quarters of the additional connections needed in sub-Saharan Africa.” [42]

We can see that electrification of SSA remains a daunting challenge. It will require massive investments and off-grid systems has a great role to play in this electrification.

A.2 Company Context

The thesis has been written in collaboration with the studied company. It allowed the author to do a field trip in Cameroon to gather data and direct insights on the ground. That has been invaluable to this thesis by giving me a direct access to the company’s activities and environment. I have had the privilege to encounter employees, clients, and suppliers. Furthermore, the field trip was beneficial to understand the context of the company, which operates in a developing country, Cameroon.

A.2.1 Presentation of the company Solarly SPRL

Solarly is a Belgo-Cameroonian company operating in Cameroon in the energy sector. Its social mission is to « Promote the development of populations with little or no access to electricity through sustainable and affordable energy solutions. »

The mission is translated into acts by bringing solar energy to On-grid and Off-grid houses. Its sells solar energy kits which are comprised of solar panels, batteries, a smart charge controller, and various appliances.

The company has been founded in 2017 by 4 Belgians and is managed from Belgium where 4 persons work full time for the company. But the operations and clients are in Cameroon where Solarly employs 40 employees at the date of the 12th September 2021. Those employees are divided in 3 main group:

- The managers operating from Yaoundé.
- The technicians tasked with the installations and customer service.
- The salesmen tasked with finding new clients.

The product has been intended for productive use. That is, it was expected that users would use their installations to generate revenue. However, rare are the client corresponding to this use. Solarly also develops higher powered systems that might better correspond to that segment.

A.2.2 The product

As mentioned here above, Solarly sells solar energy kits which always include solar panels, batteries, and a charge controller. Many other appliances can then be added to form a functional and useful system.

The charge controller is developed in house while the other elements of the kit are sourced from external suppliers. The controller is called the SolarlyBox (SB). It is a smart charge controller regulating electric fluxes between the panels, the batteries, and the client's appliances. The SB cannot be acquired alone and is always included in a kit including the solar panels and batteries. Two different configurations exist. Indeed, the photovoltaic production capacity available are 150W to 300W packed with batteries of 75 Ah or 150Ah respectively. The detailed technical specifications of the SB are available in the annexes.

The kit can be sold in two different manners. Either through direct payment or through Pay-as-you-go payments (PAYG). The Pay-as-you-go formula consists of a direct payment of 40% of the total retail cost and then the rest of the price is covered through monthly or bimonthly payments. Those are done through mobile payments. It allows to reduce the upfront cost of the Solarly box kit. By doing so, the kit becomes more affordable to families with small means.

The box is equipped with a SIM card which allows the company to gather live data of the performances of the systems. Every 15 minutes, it sends data about the consumption and production of the solar kit. The SIM also allows them to control the payments of their client opting for a PAYG formula by shutting the box off if the payments stop. It also means that the PAYG option is only available when mobile coverage is sufficient.

Dismantling

With the help of a local dismantling centre, Solidarité Technologique, we dismantled the Solarly box and asked for their recommendation to facilitate recycling. It is an initiative backed by a French non-profit, "la guilde", which aims to develop the end-of-life management of WEEE in Cameroun. Their operations are based in Yaoundé, but they work in cooperation with recyclers in Cameroon and abroad. ST manage the repair and dismantling of WEEE. They are the only actor accredited in Cameroon for the treatment of WEEE from companies. Which are required by law to dispose of their WEEE with an accredited actor. In practice it is not yet the case at all. The companies cooperating with ST must pay them for the service. The price depends on the type of waste and the contracts signed between the parties. Unfortunately, we could not obtain those prices as they are confidential information. They also collect waste from individuals where they must compete with the informal sector. The informal sector pays to collect those wastes because they can repair the collected goods or extract precious parts or material from them. But a large part of the collected wastes ends up in unauthorized dump. Dangerous material can then leak into the natural environment.

Waste type	Mass [kg]
plastique non brômé blanc	0,188
Steels	1
Printed wiring Board (PCB) category DVD	0,276
rubber	0,018
Copper cable	0,088
Cable sheath	0,154
Lithium button cell	0,003
total	1,727

Tab. A.1.: Results of the Solarly box dismantling

The handling of those waste is often an expensive process and ST is not yet financially viable without external financing. They hope to develop the recycling sector and to reach financial stability in the long term.

The dismantling of the box gave us a measurement of the different waste fractions present in the product and the handling necessary to dismantle it. The results are displayed in table A.1 below.

A.2.3 Market

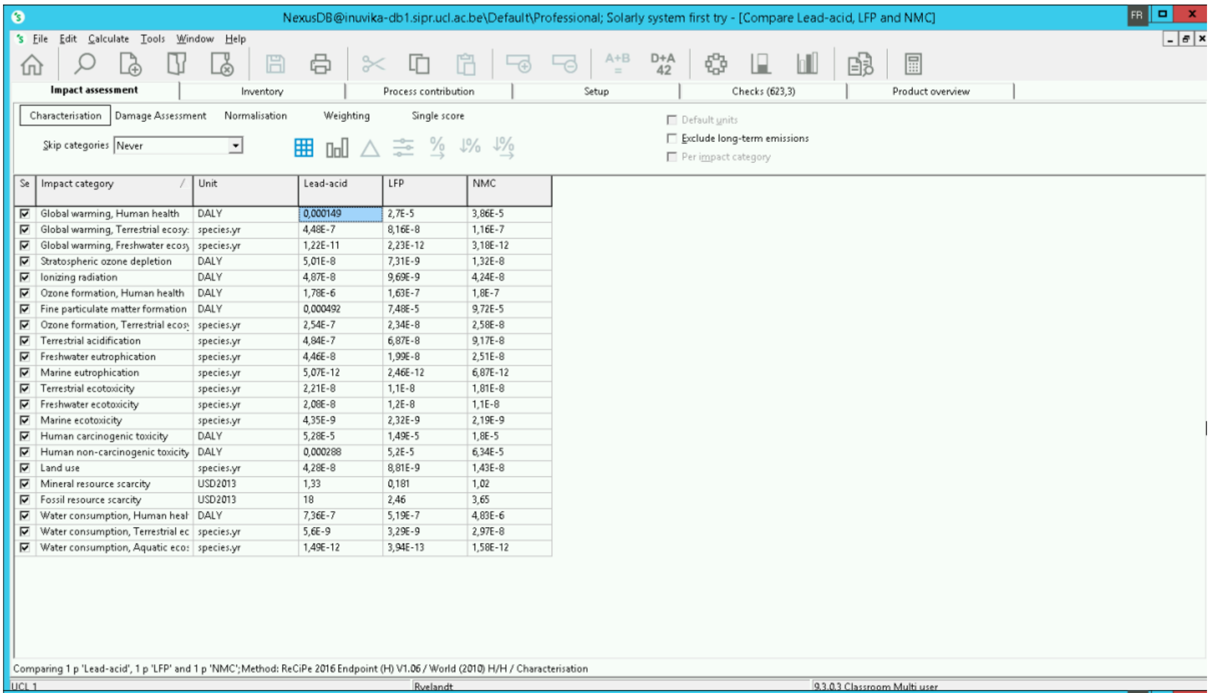
The field of off-grid solar energy solutions in Sub-Saharan Africa is a competitive one with many actors involved. Most of them are positioned on a lower segment than Solarly in terms of power and/or service. Most actors sell power stations between 0 and 50W.

The potential market is very large with the number of sub-Saharan Africans living without electricity estimated to be around 573 million [30]. All of them are potential customers. Their revenues are quite low but are expected to grow.

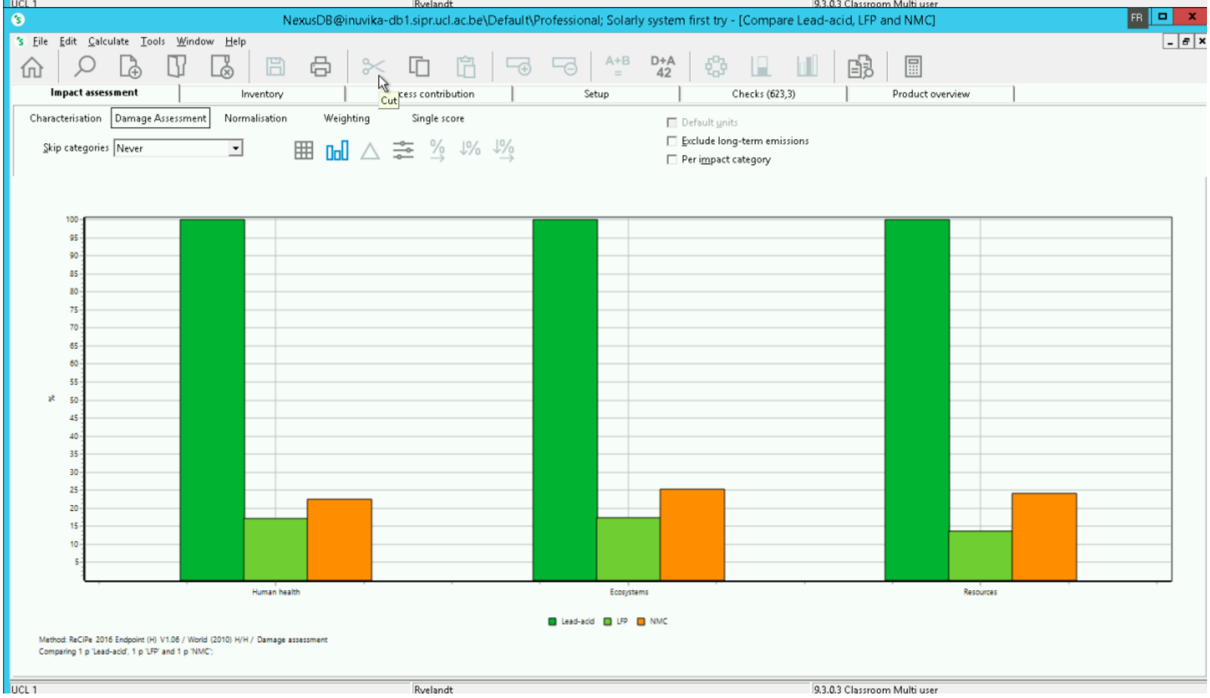
B Resultats LCA

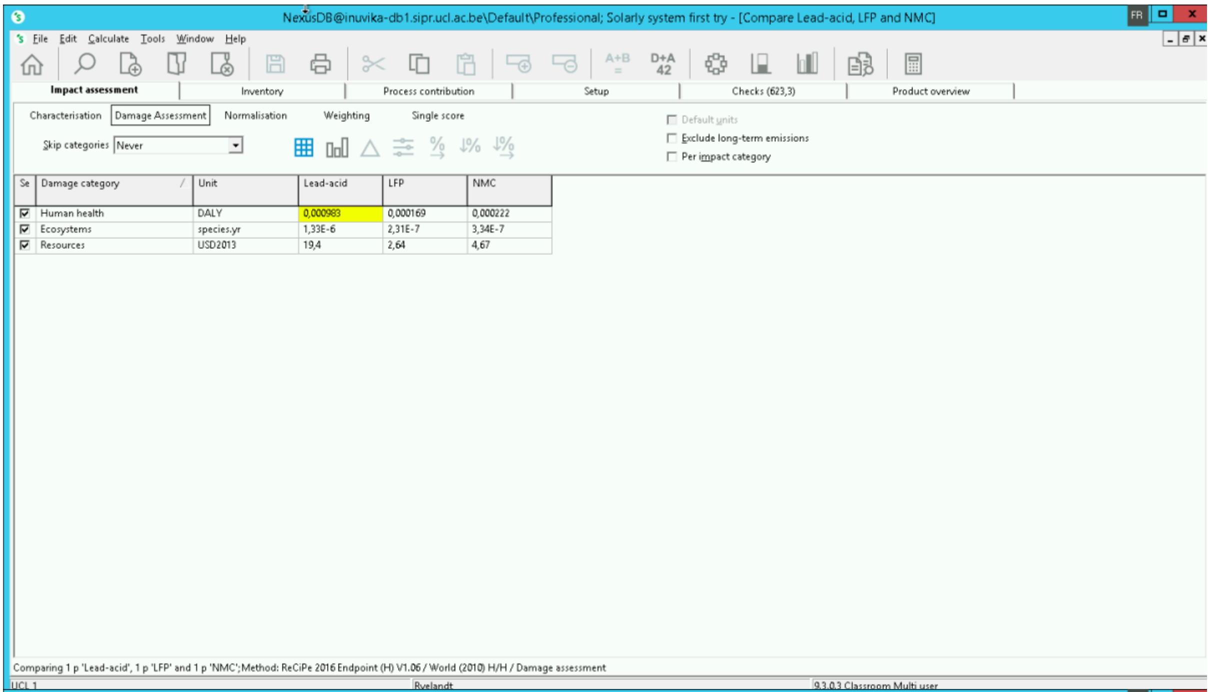
B.1 LCA result

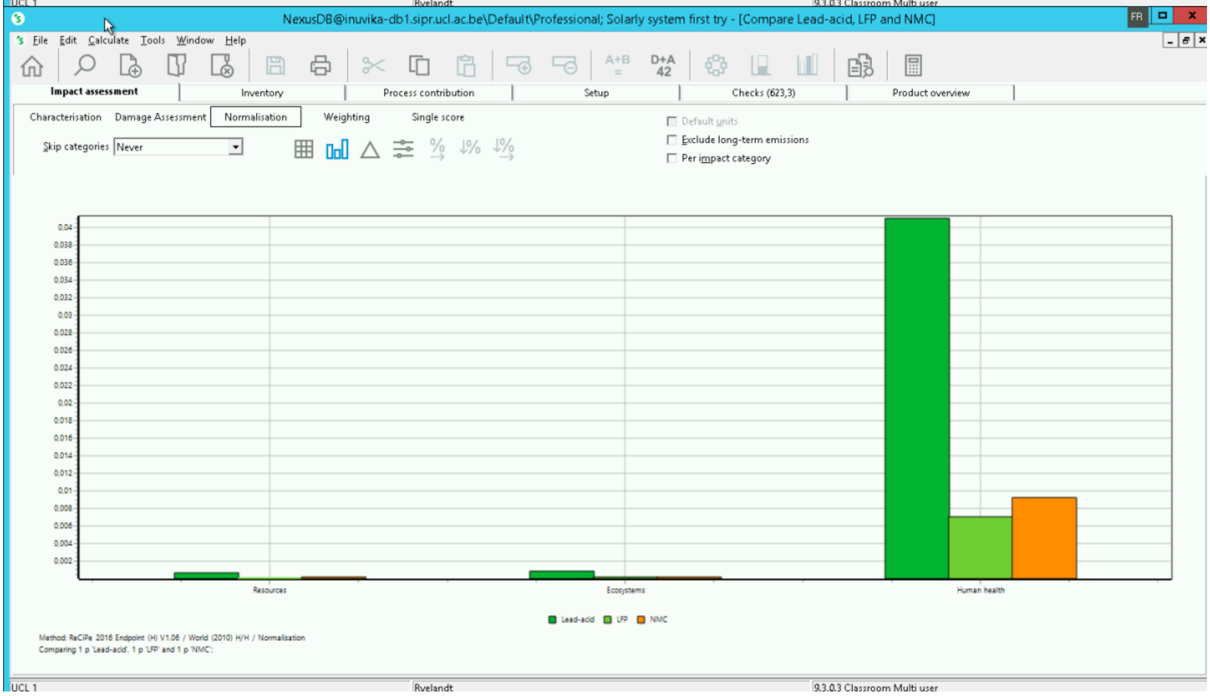
B.1.1 Including Transport



Se	Impact category	Unit	Lead-acid	LFP	NMC
☑	Global warming, Human health	DALY	0,000149	2,7E-5	3,86E-5
☑	Global warming, Terrestrial ecosy:	species.yr	4,48E-7	8,16E-8	1,16E-7
☑	Global warming, Freshwater ecosy	species.yr	1,22E-11	2,23E-12	3,18E-12
☑	Stratospheric ozone depletion	DALY	5,01E-8	7,31E-9	1,32E-8
☑	Ionizing radiation	DALY	4,87E-8	9,69E-9	4,24E-8
☑	Ozone formation, Human health	DALY	1,78E-6	1,63E-7	1,8E-7
☑	Fine particulate matter formation	DALY	0,000492	7,48E-5	9,72E-5
☑	Ozone formation, Terrestrial ecos	species.yr	2,54E-7	2,34E-8	2,58E-8
☑	Terrestrial acidification	species.yr	4,84E-7	6,87E-8	9,17E-8
☑	Freshwater eutrophication	species.yr	4,46E-8	1,99E-8	2,51E-8
☑	Marine eutrophication	species.yr	5,07E-12	2,46E-12	6,87E-12
☑	Terrestrial ecotoxicity	species.yr	2,21E-8	1,1E-8	1,81E-8
☑	Freshwater ecotoxicity	species.yr	2,08E-8	1,2E-8	1,1E-8
☑	Marine ecotoxicity	species.yr	4,35E-9	2,32E-9	2,19E-9
☑	Human carcinogenic toxicity	DALY	5,28E-5	1,49E-5	1,8E-5
☑	Human non-carcinogenic toxicity	DALY	0,000288	5,2E-5	6,34E-5
☑	Land use	species.yr	4,28E-8	8,81E-9	1,43E-8
☑	Mineral resource scarcity	USD2013	1,33	0,181	1,02
☑	Fossil resource scarcity	USD2013	18	2,46	3,65
☑	Water consumption, Human heal	DALY	7,36E-7	5,19E-7	4,83E-6
☑	Water consumption, Terrestrial ec	species.yr	5,6E-9	3,29E-9	2,97E-8
☑	Water consumption, Aquatic eco:	species.yr	1,49E-12	3,94E-13	1,58E-12




NexusDB@inuvika-db1.sipr.ucl.ac.be\Default\Professional; Solarly system first try - [Compare Lead-acid, LFP and NMC]
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (623,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories Never
Default units
Exclude long-term emissions
Per impact category
Se | Damage category | Unit | Lead-acid | LFP | NMC
Human health | DALY | 0,000983 | 0,000169 | 0,000222
Ecosystems | species.yr | 1,33E-6 | 2,31E-7 | 3,34E-7
Resources | USD2013 | 19,4 | 2,64 | 4,67
Comparing 1 p 'Lead-acid', 1 p 'LFP' and 1 p 'NMC'; Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Damage assessment
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user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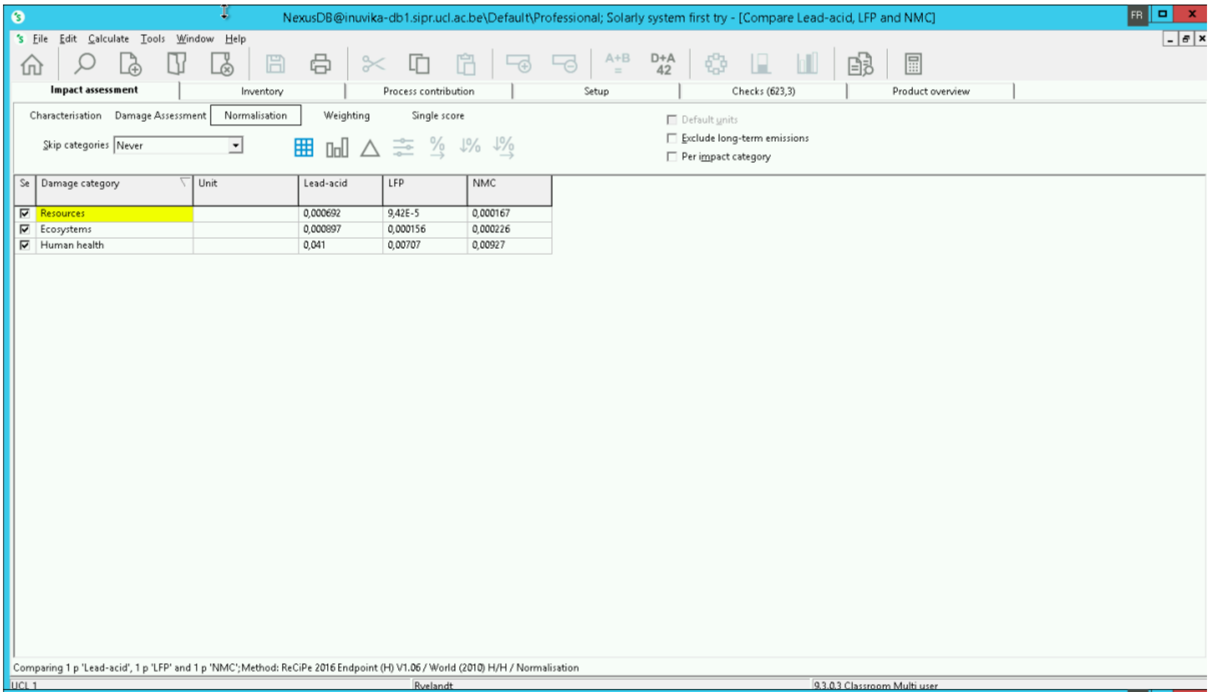
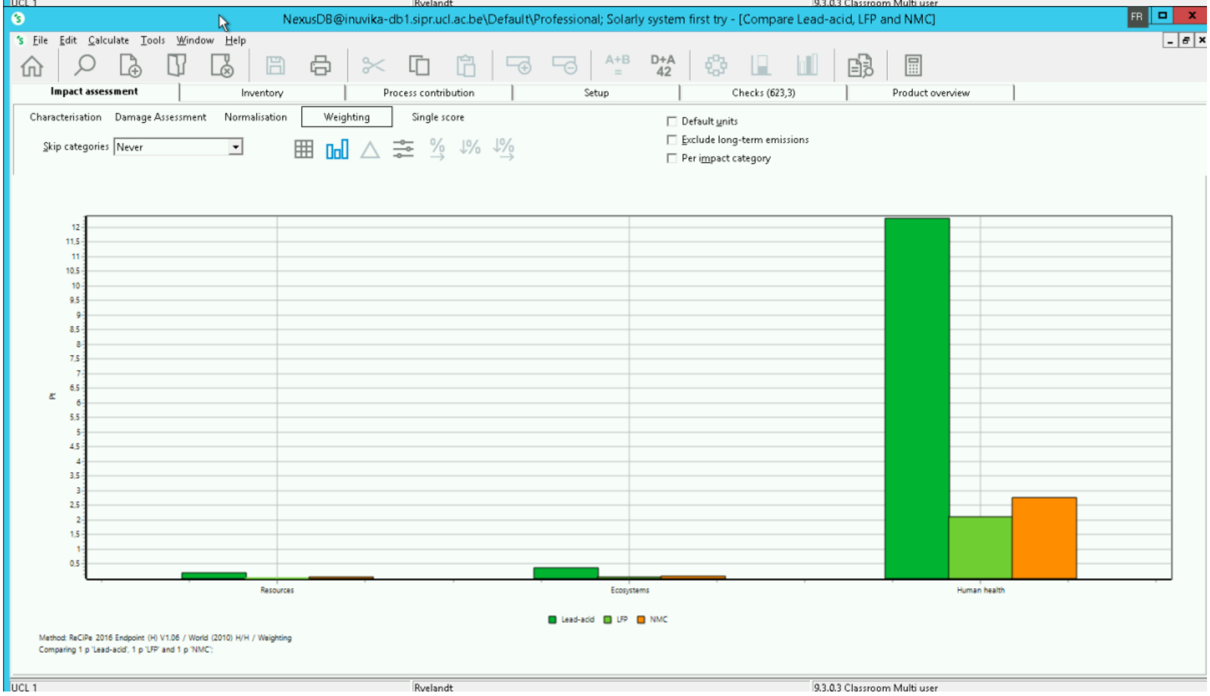
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (623,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories Never
Default units
Exclude long-term emissions
Per impact category
0.04
0.038
0.036
0.034
0.032
0.03
0.028
0.026
0.024
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
Resources
Ecosystems
Human health
Lead-acid LFP NMC
Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Normalisation
Comparing 1 p 'Lead-acid', 1 p 'LFP' and 1 p 'NMC';
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user


NexusDB@inuvika-db1.sipr.ucl.ac.be\Default\Professional; Solarly system first try - [Compare Lead-acid, LFP and NMC]
Impact assessment
Inventory
Process contribution
Setup
Checks (623,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories
Never
Default units
Exclude long-term emissions
Per impact category
Se | Damage category | Unit | Lead-acid | LFP | NMC
Resources | | 0,000692 | 9,42E-5 | 0,000167
Ecosystems | | 0,000897 | 0,000156 | 0,000226
Human health | | 0,041 | 0,00707 | 0,00927
Comparing 1 p 'Lead-acid', 1 p 'LFP' and 1 p 'NMC'; Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Normalisation
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user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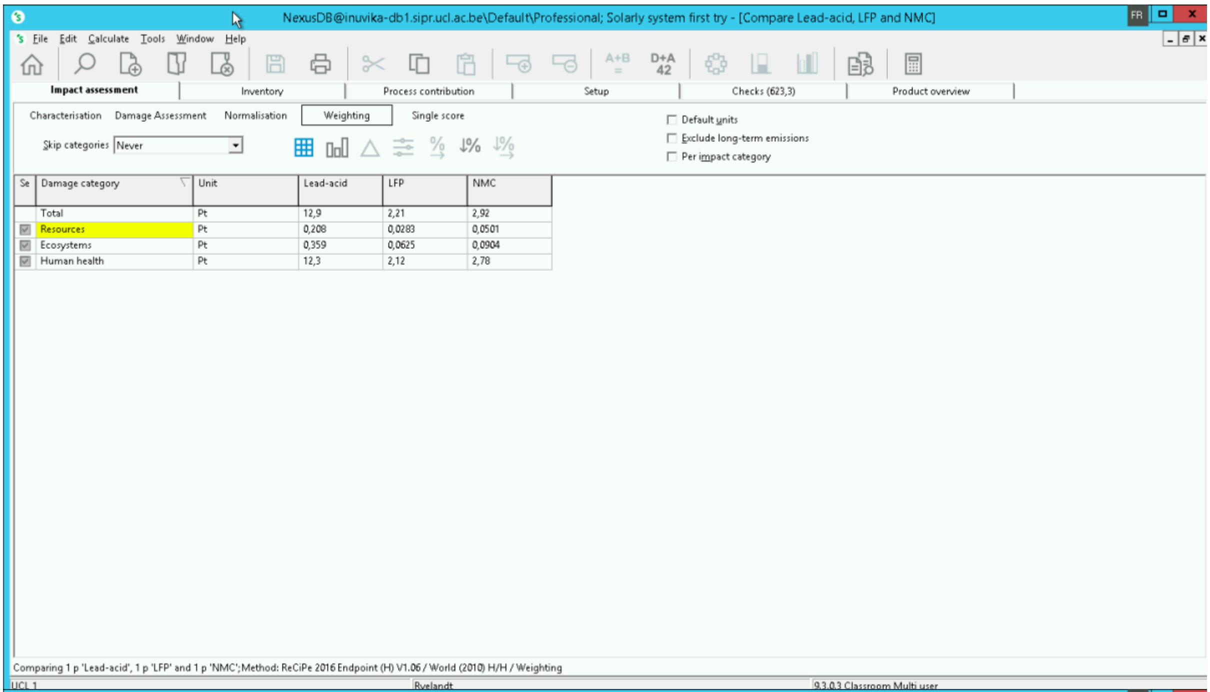
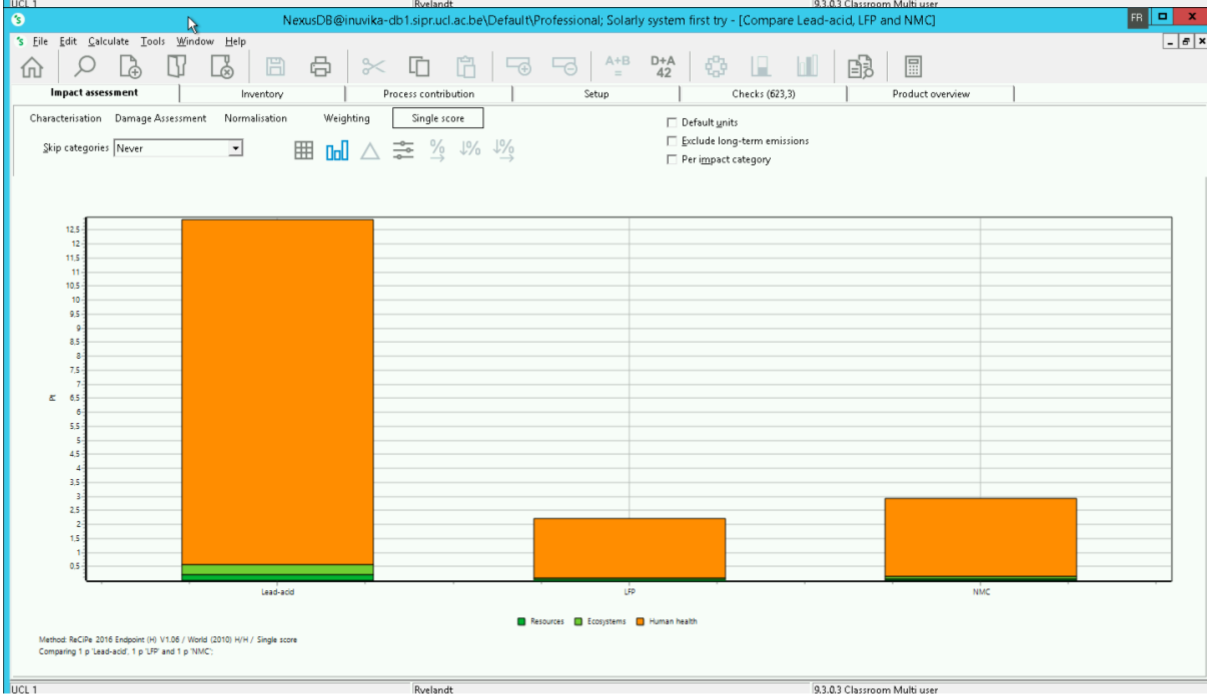
Impact assessment
Inventory
Process contribution
Setup
Checks (623,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories
Never
Default units
Exclude long-term emissions
Per impact category
Resources
Ecosystems
Human health
Lead-acid
LFP
NMC
Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Weighting
Comparing 1 p 'Lead-acid', 1 p 'LFP' and 1 p 'NMC';
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user


NexusDB@inuvika-db1.sipr.ucl.ac.be\Default\Professional; Solarly system first try - [Compare Lead-acid, LFP and NMC]
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (623,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories Never
Default units
Exclude long-term emissions
Per impact category
Se | Damage category | Unit | Lead-acid | LFP | NMC
Total | Pt | 12,9 | 2,21 | 2,92
Resources | Pt | 0,208 | 0,0283 | 0,0501
Ecosystems | Pt | 0,359 | 0,0625 | 0,0904
Human health | Pt | 12,3 | 2,12 | 2,78
Comparing 1 p 'Lead-acid', 1 p 'LFP' and 1 p 'NMC';Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Weighting
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user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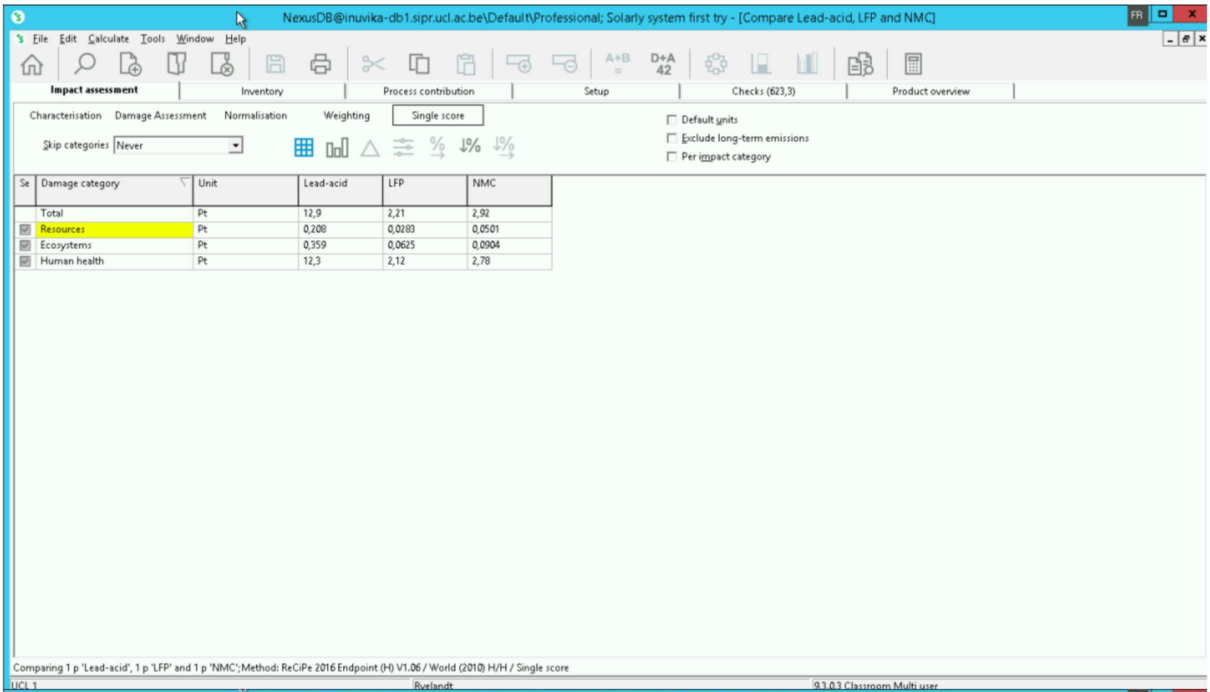
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (623,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories Never
Default units
Exclude long-term emissions
Per impact category
Pt
Lead-acid
LFP
NMC
Resources
Ecosystems
Human health
Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Single score
Comparing 1 p 'Lead-acid', 1 p 'LFP' and 1 p 'NMC';
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user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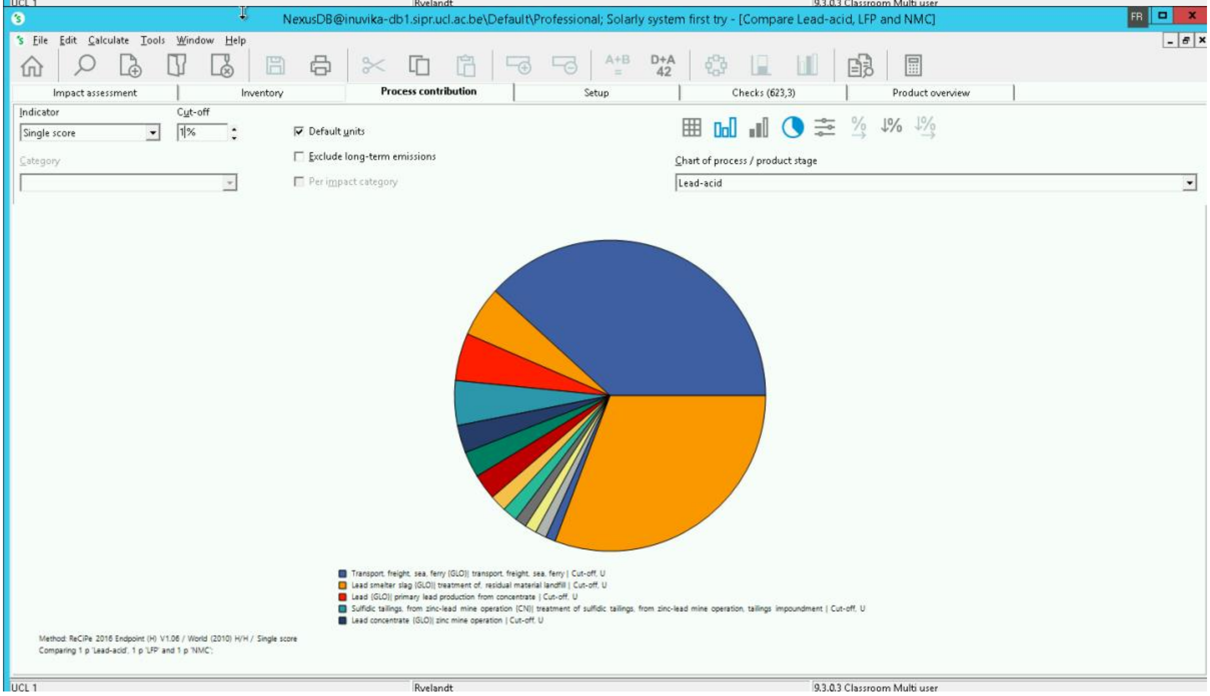
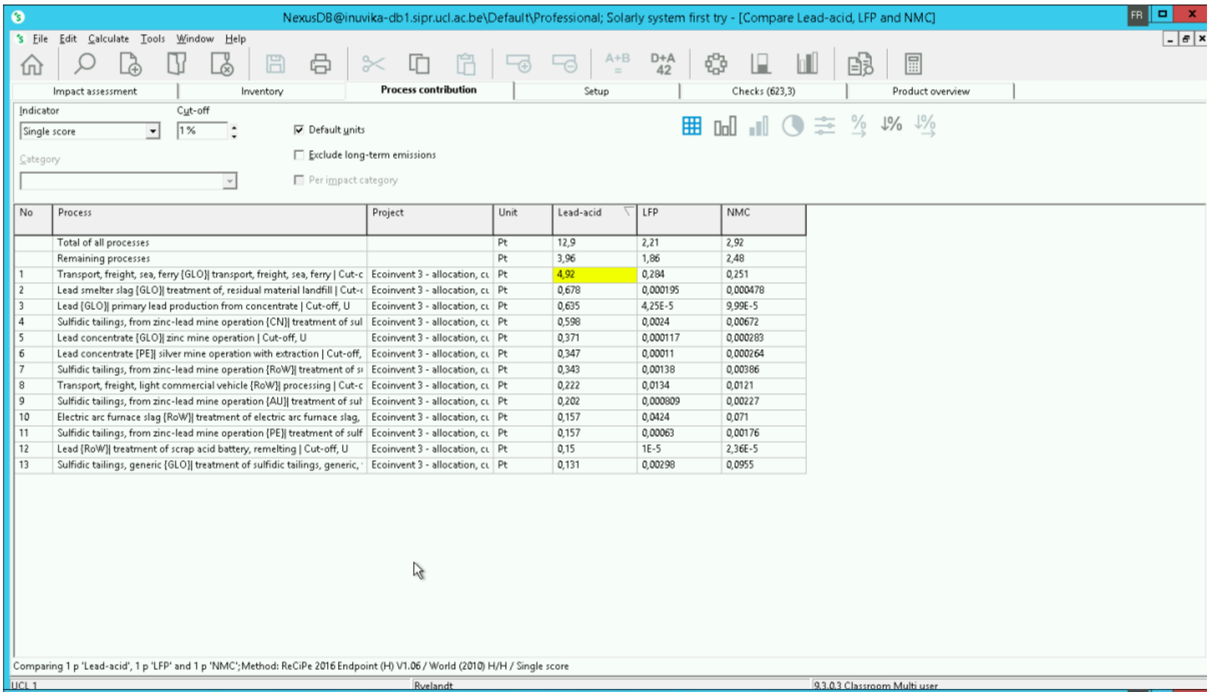
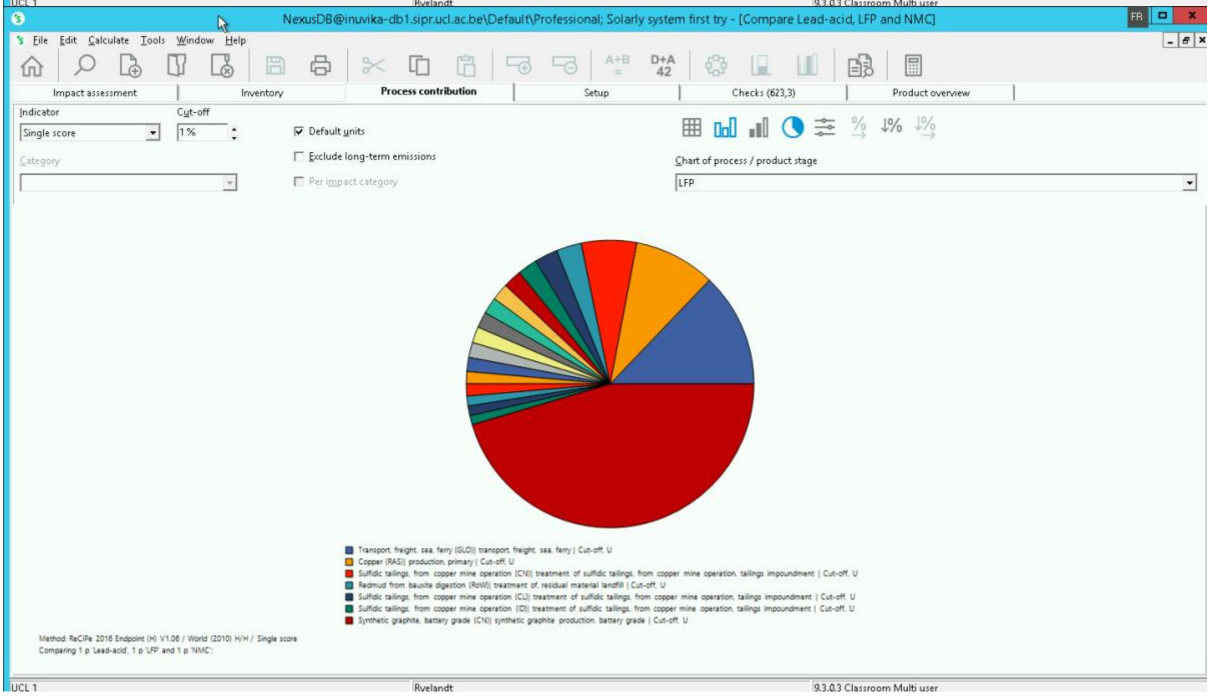
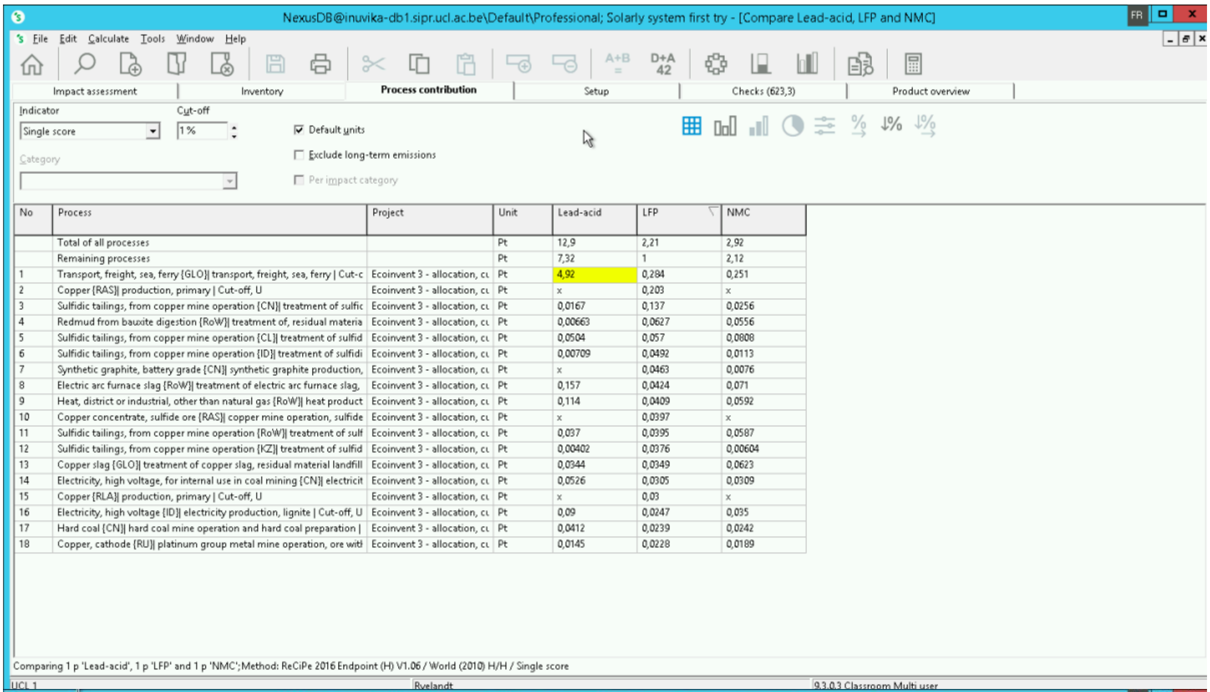
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (623,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories Never
Default units
Exclude long-term emissions
Per impact category
Se | Damage category | Unit | Lead-acid | LFP | NMC
Total | Pt | 12,9 | 2,21 | 2,92
Resources | Pt | 0,208 | 0,0283 | 0,0501
Ecosystems | Pt | 0,359 | 0,0625 | 0,0904
Human health | Pt | 12,3 | 2,12 | 2,78
Comparing 1 p 'Lead-acid', 1 p 'LFP' and 1 p 'NMC'; Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Single score
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user

NexusDB@inuvika-db1.sipr.ucl.ac.be\Default\Professional; Solarly system first try - [Compare Lead-acid, LFP and NMC]
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (623,3)
Product overview
Indicator
Single score
Cut-off
1%
Category
Default units
Exclude long-term emissions
Per impact category
Chart of process / product stage
Lead-acid
Transport, freight, sea, ferry {GLO}| transport, freight, sea, ferry | Cut-off, U
Lead smelter slag {GLO}| treatment of, residual material landfill | Cut-off, U
Lead {GLO}| primary lead production from concentrate | Cut-off, U
Sulfidic tailings, from zinc-lead mine operation {CN}| treatment of sulfidic tailings, from zinc-lead mine operation, tailings impoundment | Cut-off, U
Lead concentrate {GLO}| zinc mine operation | Cut-off, U
Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Single score
Comparing 1 p 'Lead-acid', 1 p 'LFP' and 1 p 'NMC'
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user

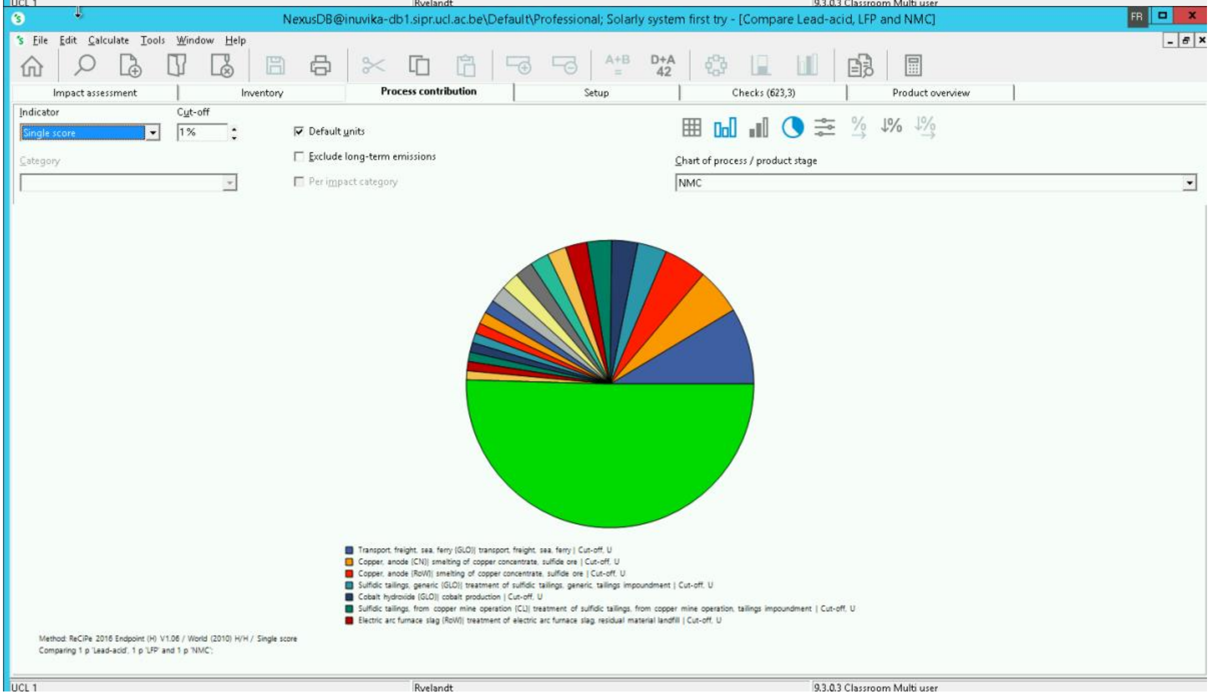


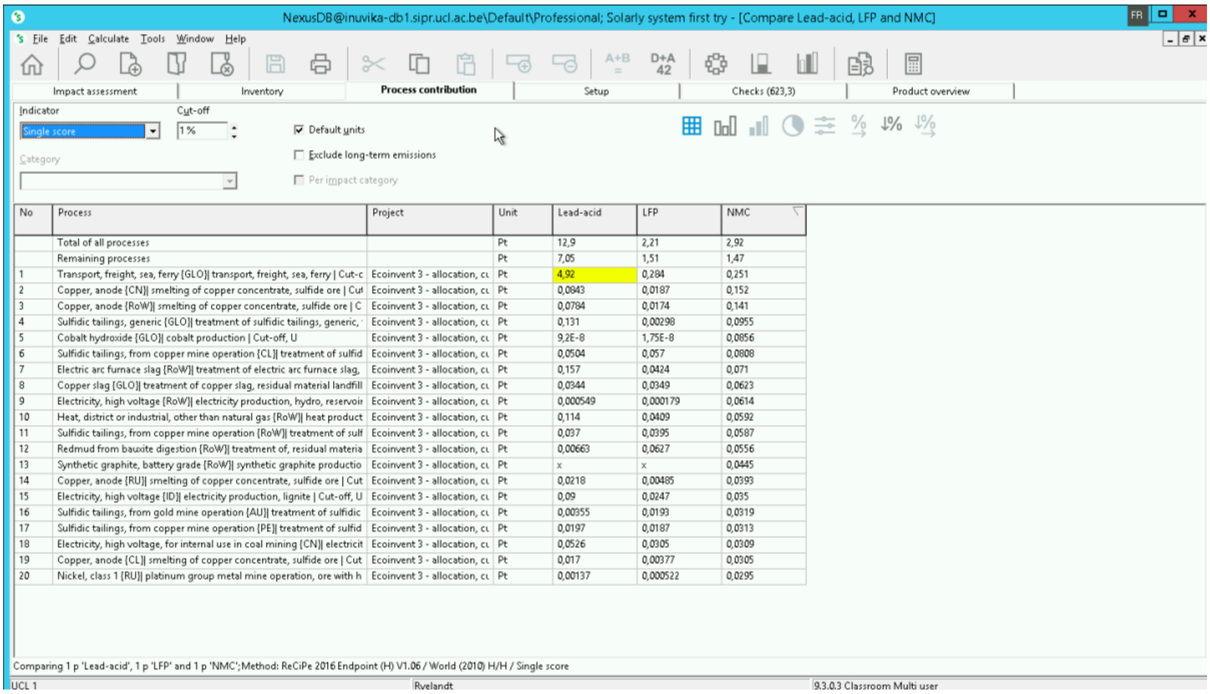
No	Process	Project	Unit	Lead-acid	LFP	NMC
	Total of all processes		Pt	12,9	2,21	2,92
	Remaining processes		Pt	3,96	1,86	2,48
1	Transport, freight, sea, ferry {GLO}| transport, freight, sea, ferry | Cut-c	Ecoinvent 3 - allocation, cu	Pt	4,92	0,284	0,251
2	Lead smelter slag {GLO}| treatment of, residual material landfill | Cut-c	Ecoinvent 3 - allocation, cu	Pt	0,678	0,000195	0,000478
3	Lead {GLO}| primary lead production from concentrate | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	0,635	4,25E-5	9,99E-5
4	Sulfidic tailings, from zinc-lead mine operation {CN}| treatment of sul	Ecoinvent 3 - allocation, cu	Pt	0,598	0,0024	0,00672
5	Lead concentrate {GLO}| zinc mine operation | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	0,371	0,000117	0,000283
6	Lead concentrate {PE}| silver mine operation with extraction | Cut-off,	Ecoinvent 3 - allocation, cu	Pt	0,347	0,00011	0,000264
7	Sulfidic tailings, from zinc-lead mine operation {RoW}| treatment of su	Ecoinvent 3 - allocation, cu	Pt	0,343	0,00138	0,00386
8	Transport, freight, light commercial vehicle {RoW}| processing | Cut-c	Ecoinvent 3 - allocation, cu	Pt	0,222	0,0134	0,0121
9	Sulfidic tailings, from zinc-lead mine operation {AU}| treatment of sul	Ecoinvent 3 - allocation, cu	Pt	0,202	0,000809	0,00227
10	Electric arc furnace slag {RoW}| treatment of electric arc furnace slag,	Ecoinvent 3 - allocation, cu	Pt	0,157	0,0424	0,071
11	Sulfidic tailings, from zinc-lead mine operation {PE}| treatment of sulf	Ecoinvent 3 - allocation, cu	Pt	0,157	0,00063	0,00176
12	Lead {RoW}| treatment of scrap acid battery, remelting | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	0,15	1E-5	2,36E-5
13	Sulfidic tailings, generic {GLO}| treatment of sulfidic tailings, generic,	Ecoinvent 3 - allocation, cu	Pt	0,131	0,00298	0,0955





No	Process	Project	Unit	Lead-acid	LFP	NMC
	Total of all processes		Pt	12,9	2,21	2,92
	Remaining processes		Pt	7,32	1	2,12
1	Transport, freight, sea, ferry {GLO}| transport, freight, sea, ferry | Cut-c	Ecoinvent 3 - allocation, cu	Pt	4,92	0,284	0,251
2	Copper {RAS}| production, primary | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	x	0,203	x
3	Sulfidic tailings, from copper mine operation {CN}| treatment of sulfic	Ecoinvent 3 - allocation, cu	Pt	0,0167	0,137	0,0256
4	Redmud from bauxite digestion {RoW}| treatment of, residual materia	Ecoinvent 3 - allocation, cu	Pt	0,00663	0,0627	0,0556
5	Sulfidic tailings, from copper mine operation {CL}| treatment of sulfid	Ecoinvent 3 - allocation, cu	Pt	0,0504	0,057	0,0808
6	Sulfidic tailings, from copper mine operation {ID}| treatment of sulfidi	Ecoinvent 3 - allocation, cu	Pt	0,00709	0,0492	0,0113
7	Synthetic graphite, battery grade {CN}| synthetic graphite production,	Ecoinvent 3 - allocation, cu	Pt	x	0,0463	0,0076
8	Electric arc furnace slag {RoW}| treatment of electric arc furnace slag,	Ecoinvent 3 - allocation, cu	Pt	0,157	0,0424	0,071
9	Heat, district or industrial, other than natural gas {RoW}| heat product	Ecoinvent 3 - allocation, cu	Pt	0,114	0,0409	0,0592
10	Copper concentrate, sulfide ore {RAS}| copper mine operation, sulfide	Ecoinvent 3 - allocation, cu	Pt	x	0,0397	x
11	Sulfidic tailings, from copper mine operation {RoW}| treatment of sulf	Ecoinvent 3 - allocation, cu	Pt	0,037	0,0395	0,0587
12	Sulfidic tailings, from copper mine operation {KZ}| treatment of sulfid	Ecoinvent 3 - allocation, cu	Pt	0,00402	0,0376	0,00604
13	Copper slag {GLO}| treatment of copper slag, residual material landfill	Ecoinvent 3 - allocation, cu	Pt	0,0344	0,0349	0,0623
14	Electricity, high voltage, for internal use in coal mining {CN}| electricit	Ecoinvent 3 - allocation, cu	Pt	0,0526	0,0305	0,0309
15	Copper {RLA}| production, primary | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	x	0,03	x
16	Electricity, high voltage {ID}| electricity production, lignite | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	0,09	0,0247	0,035
17	Hard coal {CN}| hard coal mine operation and hard coal preparation |	Ecoinvent 3 - allocation, cu	Pt	0,0412	0,0239	0,0242
18	Copper, cathode {RU}| platinum group metal mine operation, ore witl	Ecoinvent 3 - allocation, cu	Pt	0,0145	0,0228	0,0189



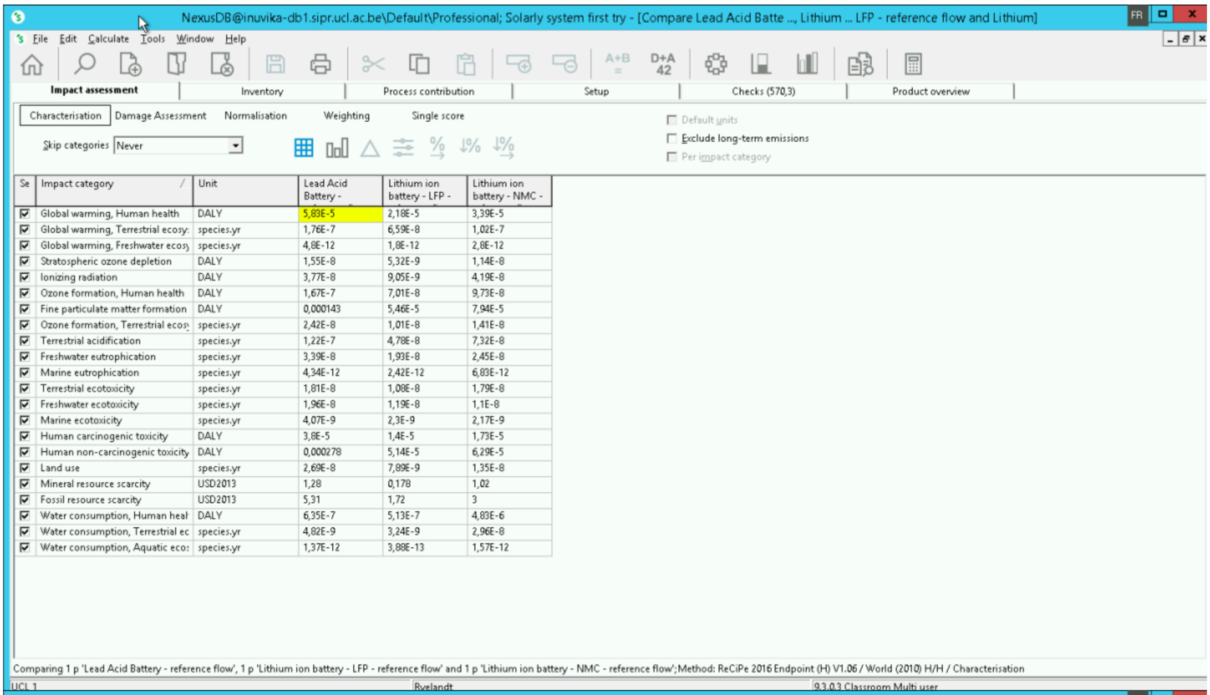


<table>
<tr><th>No</th><th>Process</th><th>Project</th><th>Unit</th><th>Lead-acid</th><th>LFP</th><th>NMC</th></tr>
<tr><td></td><td>Total of all processes</td><td></td><td>Pt</td><td>12,9</td><td>2,21</td><td>2,92</td></tr>
<tr><td></td><td>Remaining processes</td><td></td><td>Pt</td><td>7,05</td><td>1,51</td><td>1,47</td></tr>
<tr><td>1</td><td>Transport, freight, sea, ferry {GLO}| transport, freight, sea, ferry | Cut-c</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>4,92</td><td>0,284</td><td>0,251</td></tr>
<tr><td>2</td><td>Copper, anode {CN}| smelting of copper concentrate, sulfide ore | Cut</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,0843</td><td>0,0187</td><td>0,152</td></tr>
<tr><td>3</td><td>Copper, anode {RoW}| smelting of copper concentrate, sulfide ore | C</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,0784</td><td>0,0174</td><td>0,141</td></tr>
<tr><td>4</td><td>Sulfidic tailings, generic {GLO}| treatment of sulfidic tailings, generic,</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,131</td><td>0,00298</td><td>0,0955</td></tr>
<tr><td>5</td><td>Cobalt hydroxide {GLO}| cobalt production | Cut-off, U</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>9,2E-8</td><td>1,75E-8</td><td>0,0856</td></tr>
<tr><td>6</td><td>Sulfidic tailings, from copper mine operation {CL}| treatment of sulfid</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,0504</td><td>0,057</td><td>0,0808</td></tr>
<tr><td>7</td><td>Electric arc furnace slag {RoW}| treatment of electric arc furnace slag,</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,157</td><td>0,0424</td><td>0,071</td></tr>
<tr><td>8</td><td>Copper slag {GLO}| treatment of copper slag, residual material landfill</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,0344</td><td>0,0349</td><td>0,0623</td></tr>
<tr><td>9</td><td>Electricity, high voltage {RoW}| electricity production, hydro, reservoir</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,000549</td><td>0,000179</td><td>0,0614</td></tr>
<tr><td>10</td><td>Heat, district or industrial, other than natural gas {RoW}| heat product</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,114</td><td>0,0409</td><td>0,0592</td></tr>
<tr><td>11</td><td>Sulfidic tailings, from copper mine operation {RoW}| treatment of sulf</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,037</td><td>0,0395</td><td>0,0587</td></tr>
<tr><td>12</td><td>Redmud from bauxite digestion {RoW}| treatment of, residual materia</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,00663</td><td>0,0627</td><td>0,0556</td></tr>
<tr><td>13</td><td>Synthetic graphite, battery grade {RoW}| synthetic graphite productio</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>x</td><td>x</td><td>0,0445</td></tr>
<tr><td>14</td><td>Copper, anode {RU}| smelting of copper concentrate, sulfide ore | Cut</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,0218</td><td>0,00485</td><td>0,0393</td></tr>
<tr><td>15</td><td>Electricity, high voltage {ID}| electricity production, lignite | Cut-off, U</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,09</td><td>0,0247</td><td>0,035</td></tr>
<tr><td>16</td><td>Sulfidic tailings, from gold mine operation {AU}| treatment of sulfidic</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,00355</td><td>0,0193</td><td>0,0319</td></tr>
<tr><td>17</td><td>Sulfidic tailings, from copper mine operation {PE}| treatment of sulfid</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,0197</td><td>0,0187</td><td>0,0313</td></tr>
<tr><td>18</td><td>Electricity, high voltage, for internal use in coal mining {CN}| electricit</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,0526</td><td>0,0305</td><td>0,0309</td></tr>
<tr><td>19</td><td>Copper, anode {CL}| smelting of copper concentrate, sulfide ore | Cut</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,017</td><td>0,00377</td><td>0,0305</td></tr>
<tr><td>20</td><td>Nickel, class 1 {RU}| platinum group metal mine operation, ore with h</td><td>Ecoinvent 3 - allocation, cu</td><td>Pt</td><td>0,00137</td><td>0,000522</td><td>0,0295</td></tr>
</table>

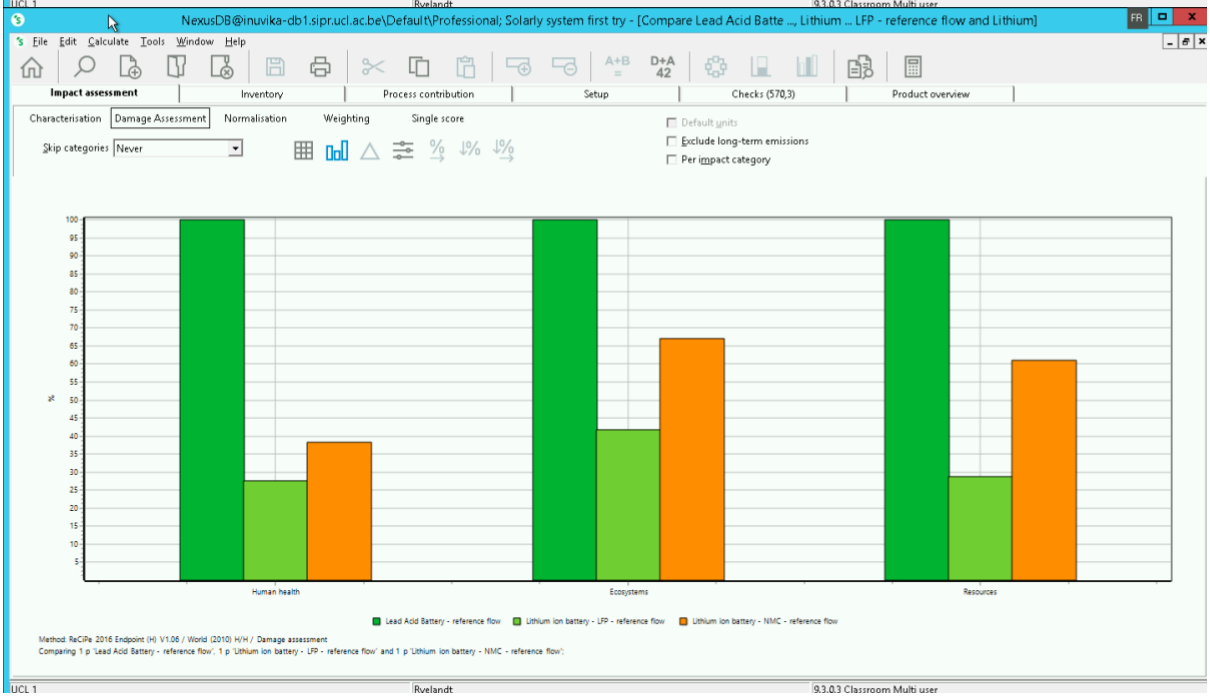
Comparing 1 p 'Lead-acid', 1 p 'LFP' and 1 p 'NMC';Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Single score

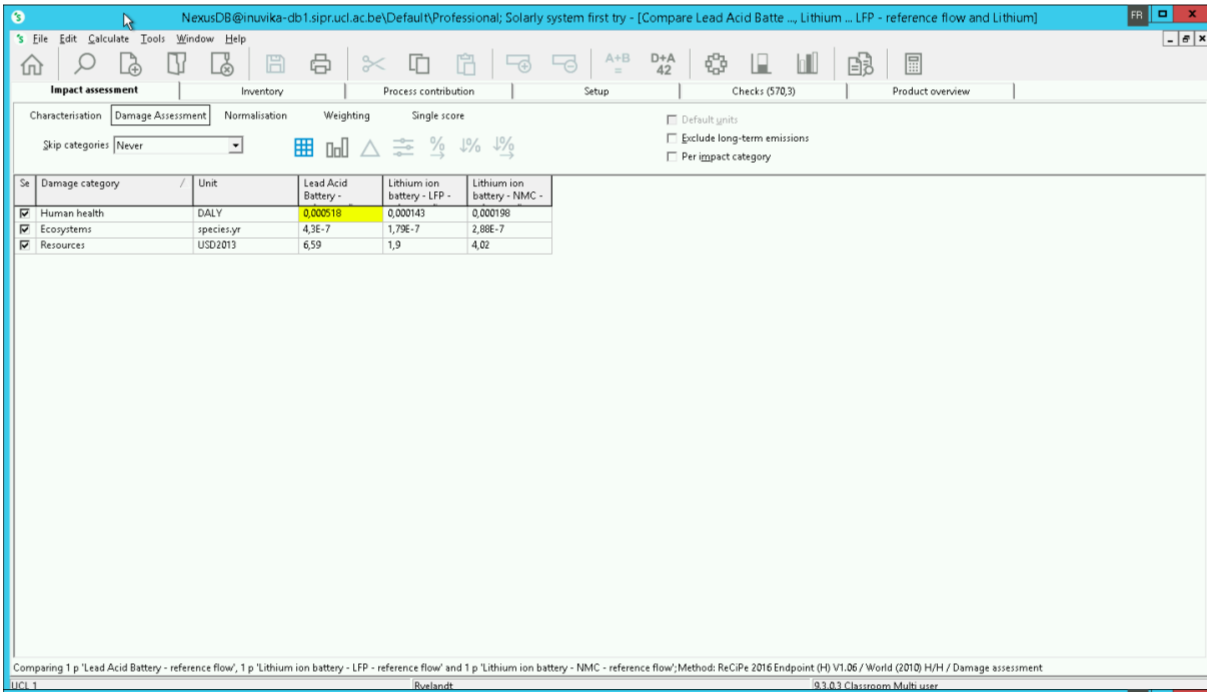
UCL 1 | Ryelandt | 9.3.0.3 Classroom Multi user

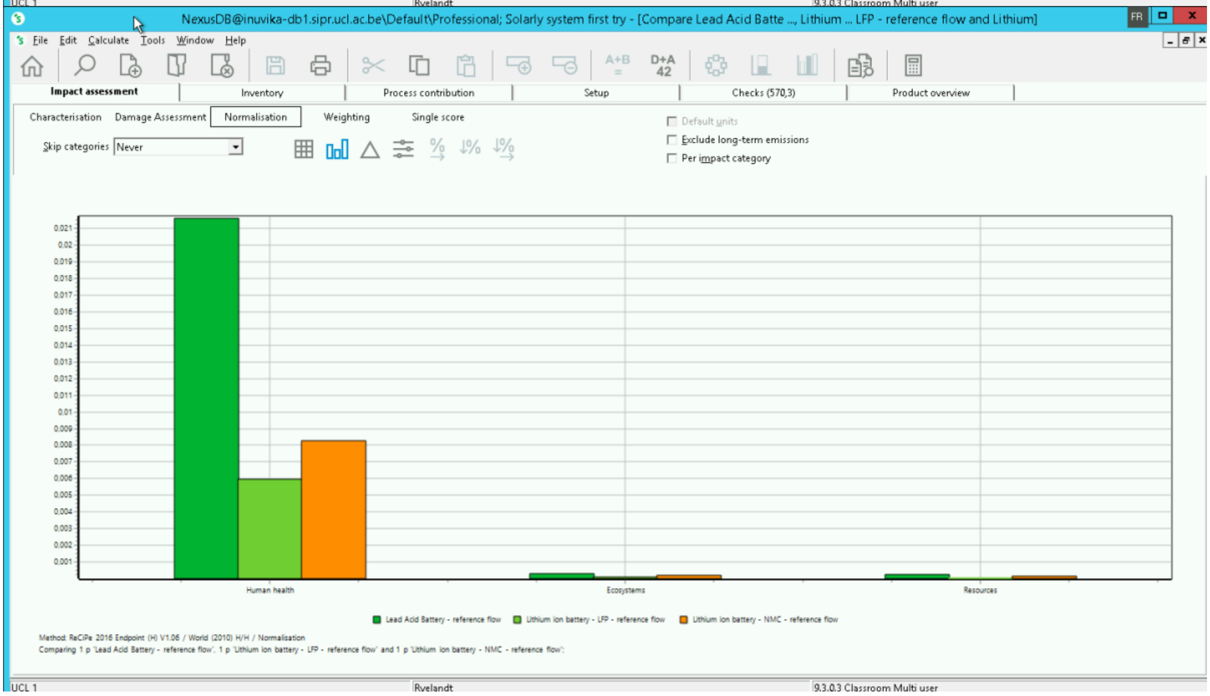
B.1.2 Excluding Transport

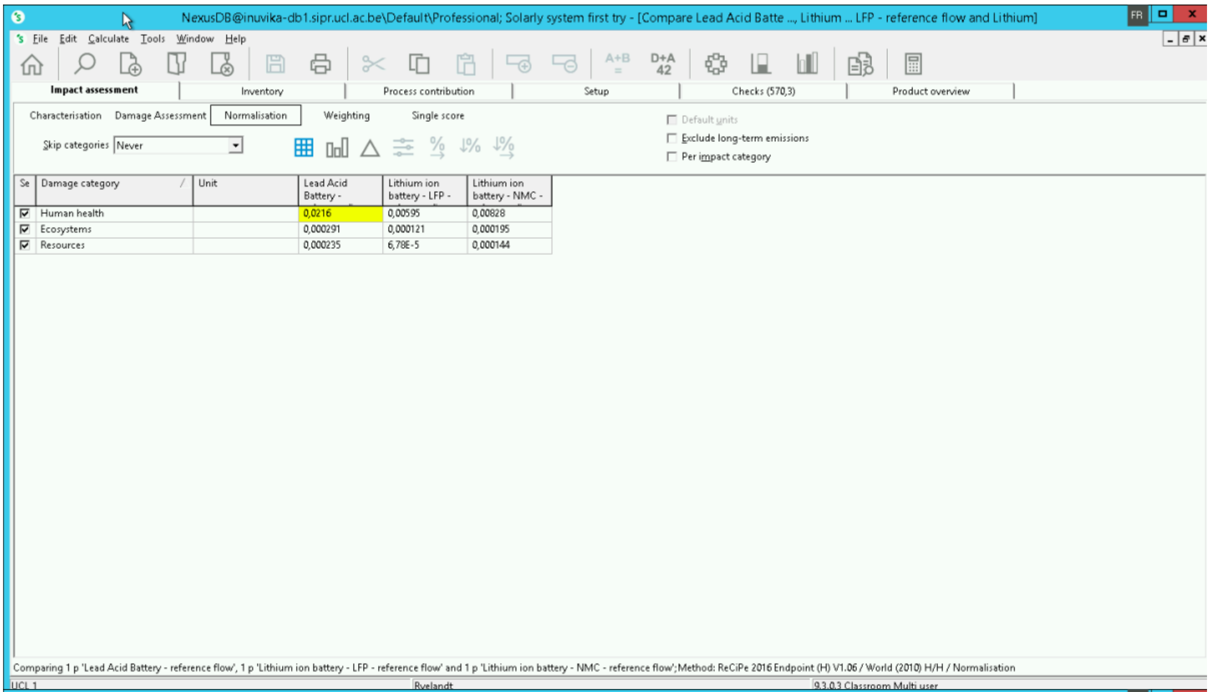


Se	Impact category	Unit	Lead Acid Battery -	Lithium ion battery - LFP -	Lithium ion battery - NMC -
☑	Global warming, Human health	DALY	5,83E-5	2,18E-5	3,39E-5
☑	Global warming, Terrestrial ecosy:	species.yr	1,76E-7	6,59E-8	1,02E-7
☑	Global warming, Freshwater ecosy	species.yr	4,8E-12	1,8E-12	2,8E-12
☑	Stratospheric ozone depletion	DALY	1,55E-8	5,32E-9	1,14E-8
☑	Ionizing radiation	DALY	3,77E-8	9,05E-9	4,19E-8
☑	Ozone formation, Human health	DALY	1,67E-7	7,01E-8	9,73E-8
☑	Fine particulate matter formation	DALY	0,000143	5,46E-5	7,94E-5
☑	Ozone formation, Terrestrial ecosy	species.yr	2,42E-8	1,01E-8	1,41E-8
☑	Terrestrial acidification	species.yr	1,22E-7	4,78E-8	7,32E-8
☑	Freshwater eutrophication	species.yr	3,39E-8	1,93E-8	2,45E-8
☑	Marine eutrophication	species.yr	4,34E-12	2,42E-12	6,83E-12
☑	Terrestrial ecotoxicity	species.yr	1,81E-8	1,08E-8	1,79E-8
☑	Freshwater ecotoxicity	species.yr	1,96E-8	1,19E-8	1,1E-8
☑	Marine ecotoxicity	species.yr	4,07E-9	2,3E-9	2,17E-9
☑	Human carcinogenic toxicity	DALY	3,8E-5	1,4E-5	1,73E-5
☑	Human non-carcinogenic toxicity	DALY	0,000278	5,14E-5	6,29E-5
☑	Land use	species.yr	2,69E-8	7,89E-9	1,35E-8
☑	Mineral resource scarcity	USD2013	1,28	0,178	1,02
☑	Fossil resource scarcity	USD2013	5,31	1,72	3
☑	Water consumption, Human heal	DALY	6,35E-7	5,13E-7	4,83E-6
☑	Water consumption, Terrestrial ec	species.yr	4,82E-9	3,24E-9	2,96E-8
☑	Water consumption, Aquatic eco:	species.yr	1,37E-12	3,88E-13	1,57E-12




NexusDB@inuvika-db1.sipr.ucl.ac.be\Default\Professional; Solarly system first try - [Compare Lead Acid Batte ..., Lithium ... LFP - reference flow and Lithium]
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (570,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories Never
Default units
Exclude long-term emissions
Per impact category
Se | Damage category | Unit | Lead Acid Battery - | Lithium ion battery - LFP - | Lithium ion battery - NMC -
Human health | DALY | 0,000518 | 0,000143 | 0,000198
Ecosystems | species.yr | 4,3E-7 | 1,79E-7 | 2,88E-7
Resources | USD2013 | 6,59 | 1,9 | 4,02
Comparing 1 p 'Lead Acid Battery - reference flow', 1 p 'Lithium ion battery - LFP - reference flow' and 1 p 'Lithium ion battery - NMC - reference flow';Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Damage assessment
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user


NexusDB@inuvika-db1.sipr.ucl.ac.be\Default\Professional; Solarly system first try - [Compare Lead Acid Batte ..., Lithium ... LFP - reference flow and Lithium]
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (570,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories Never
Default units
Exclude long-term emissions
Per impact category
Human health
Ecosystems
Resources
Lead Acid Battery - reference flow
Lithium ion battery - LFP - reference flow
Lithium ion battery - NMC - reference flow
Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Normalisation
Comparing 1 p 'Lead Acid Battery - reference flow', 1 p 'Lithium ion battery - LFP - reference flow' and 1 p 'Lithium ion battery - NMC - reference flow';
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user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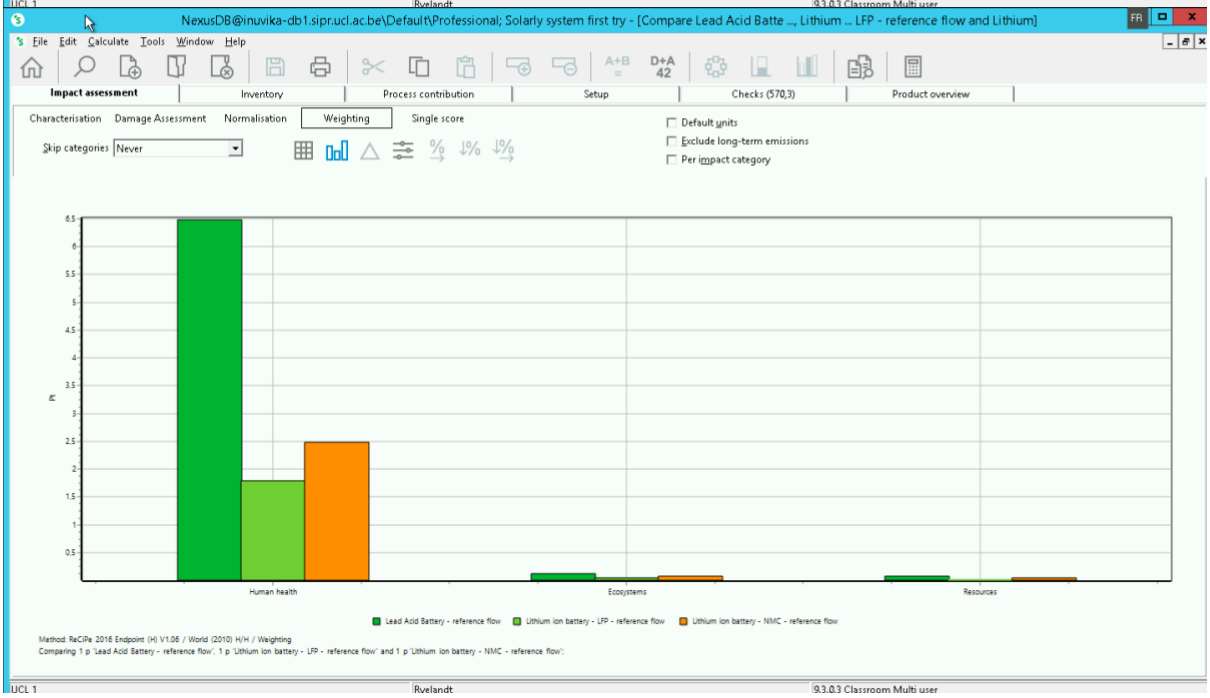
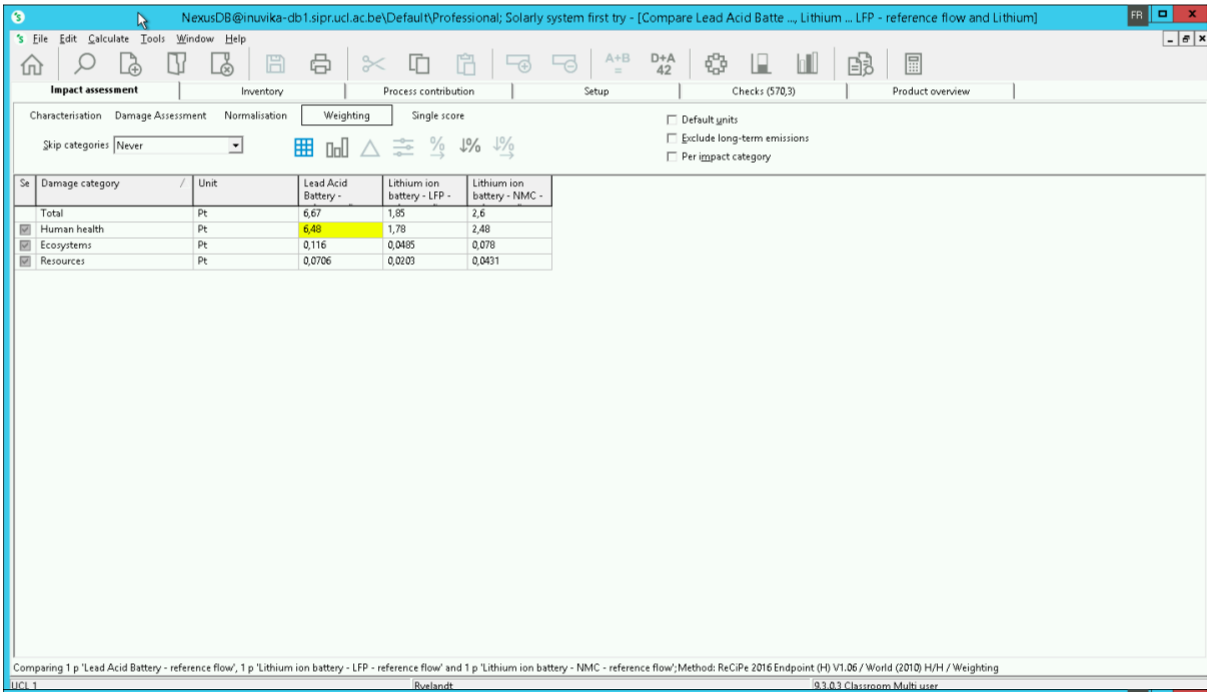
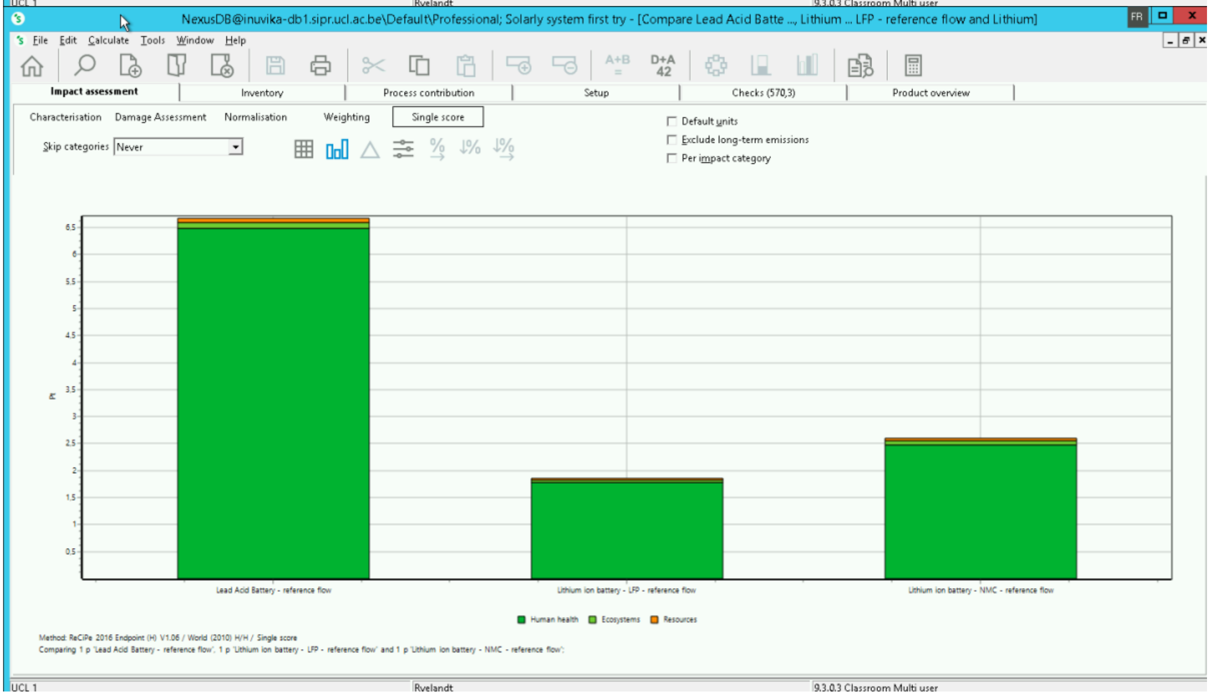
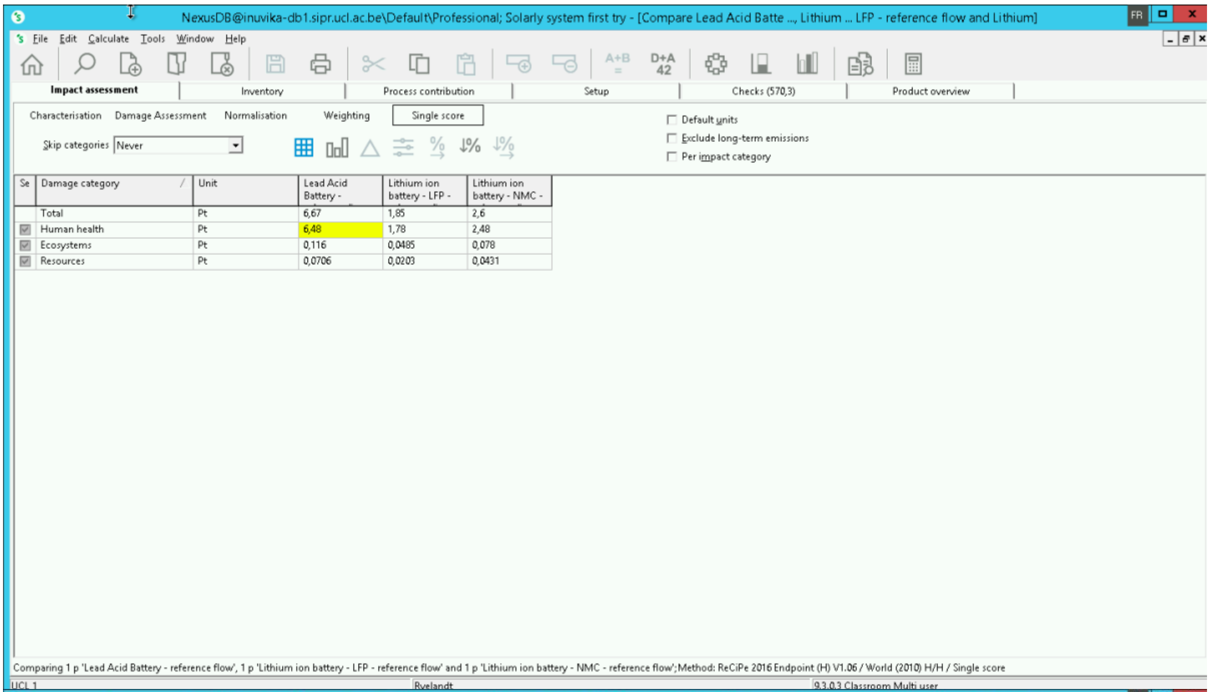
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (570,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories
Never
Default units
Exclude long-term emissions
Per impact category
Se
Damage category
Unit
Lead Acid Battery -
Lithium ion battery - LFP -
Lithium ion battery - NMC -
Human health
0,0216
0,00595
0,00828
Ecosystems
0,000291
0,000121
0,000195
Resources
0,000235
6,78E-5
0,000144
Comparing 1 p 'Lead Acid Battery - reference flow', 1 p 'Lithium ion battery - LFP - reference flow' and 1 p 'Lithium ion battery - NMC - reference flow';Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Normalisation
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user

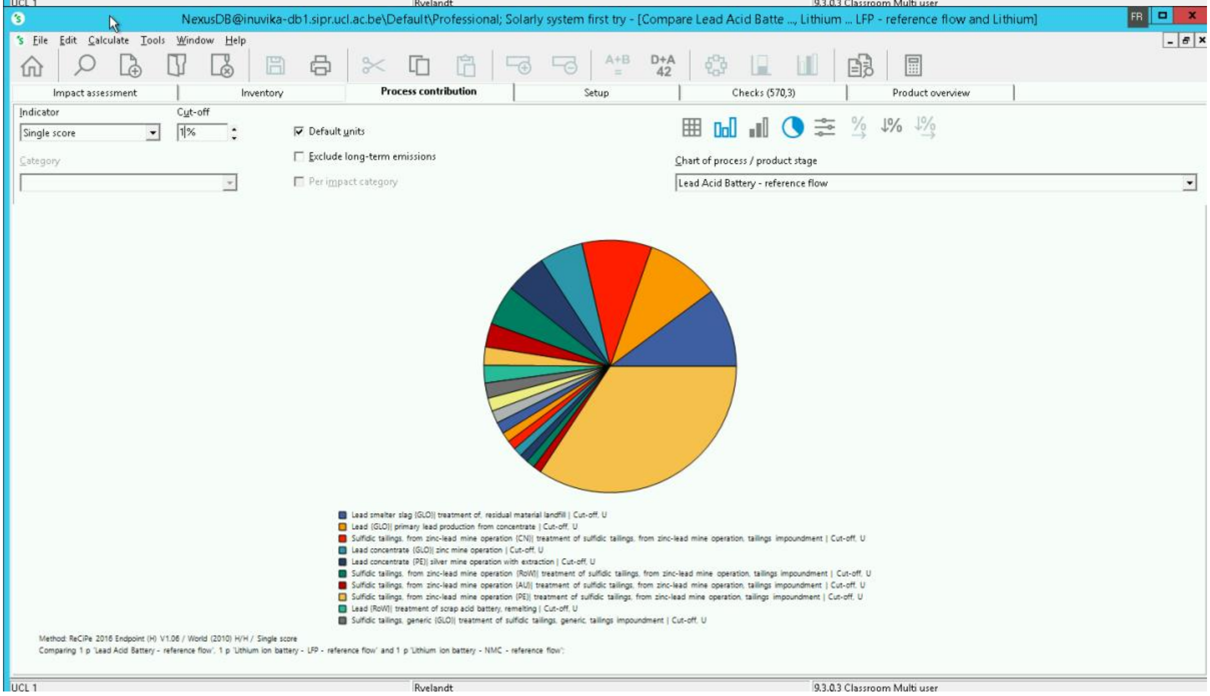

NexusDB@inuvika-db1.sipr.ucl.ac.be\Default\Professional; Solarly system first try - [Compare Lead Acid Batte ..., Lithium ... LFP - reference flow and Lithium]
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (570,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories
Never
Default units
Exclude long-term emissions
Per impact category
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
Human health
Ecosystems
Resources
Lead Acid Battery - reference flow
Lithium ion battery - LFP - reference flow
Lithium ion battery - NMC - reference flow
Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Weighting
Comparing 1 p 'Lead Acid Battery - reference flow', 1 p 'Lithium ion battery - LFP - reference flow' and 1 p 'Lithium ion battery - NMC - reference flow';
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user

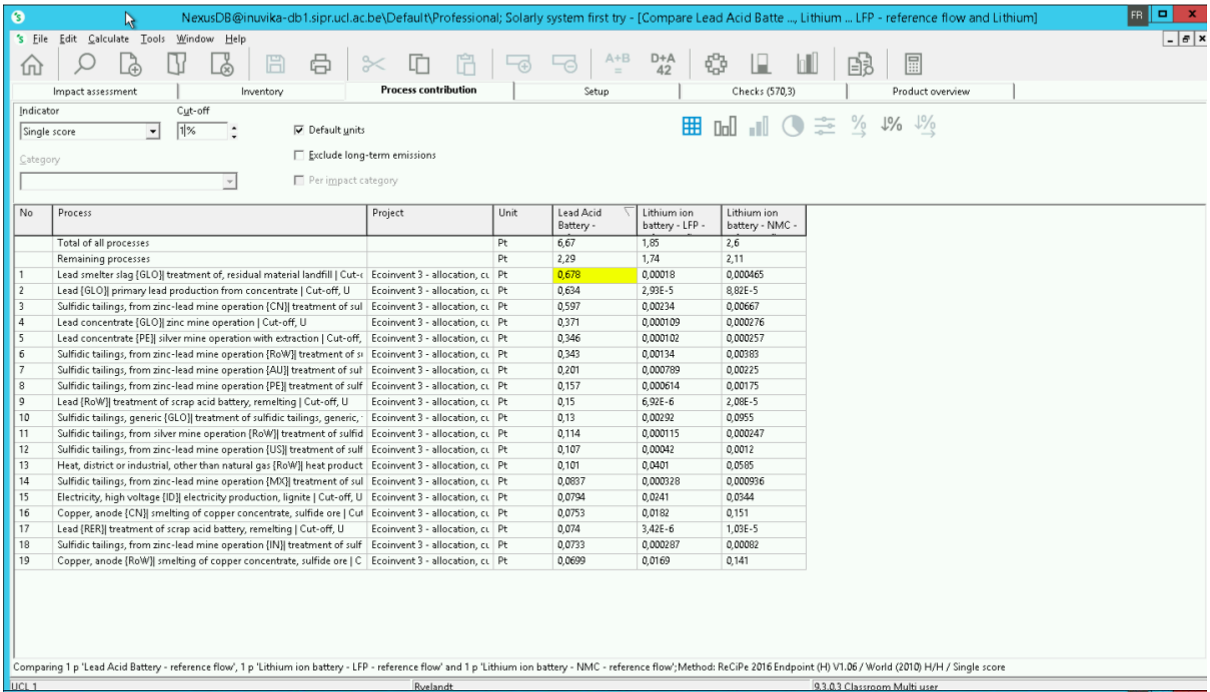


Se	Damage category	Unit	Lead Acid Battery -	Lithium ion battery - LFP -	Lithium ion battery - NMC -
	Total	Pt	6,67	1,85	2,6
	Human health	Pt	6,48	1,78	2,48
	Ecosystems	Pt	0,116	0,0485	0,078
	Resources	Pt	0,0706	0,0203	0,0431

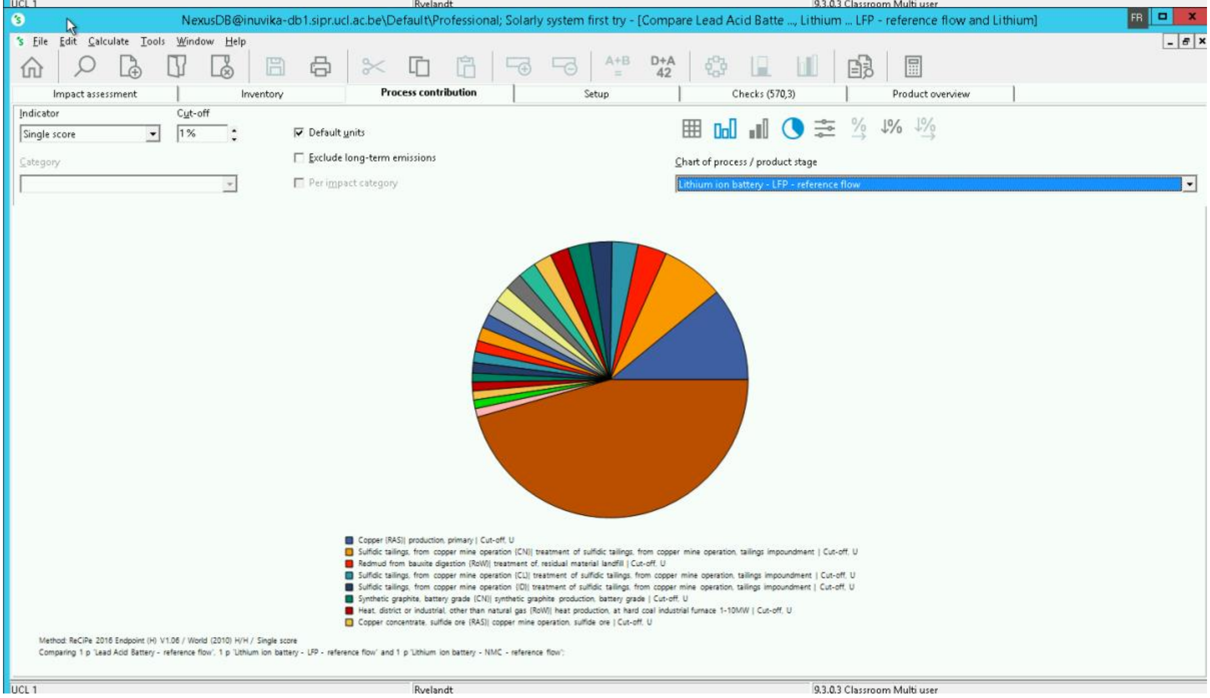


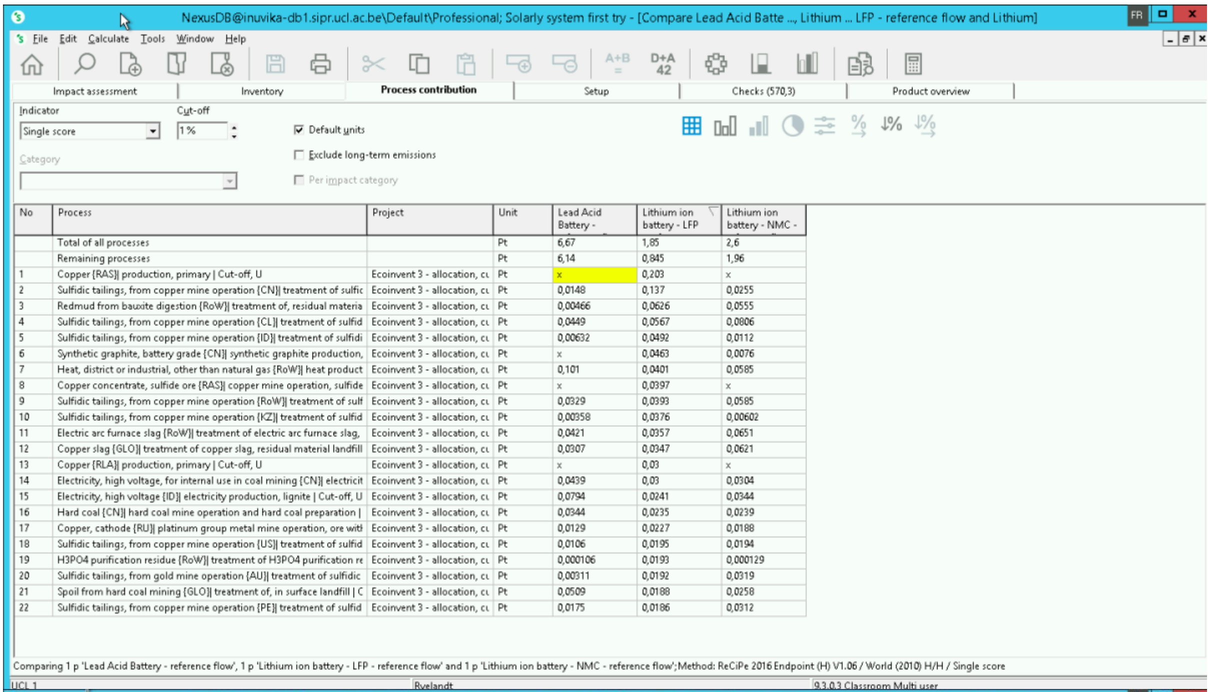

NexusDB@inuvika-db1.sipr.ucl.ac.be\Default\Professional; Solarly system first try - [Compare Lead Acid Batte ..., Lithium ... LFP - reference flow and Lithium]
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (570,3)
Product overview
Characterisation
Damage Assessment
Normalisation
Weighting
Single score
Skip categories Never
Default units
Exclude long-term emissions
Per impact category
Se | Damage category | Unit | Lead Acid Battery - | Lithium ion battery - LFP - | Lithium ion battery - NMC -
Total | Pt | 6,67 | 1,85 | 2,6
Human health | Pt | 6,48 | 1,78 | 2,48
Ecosystems | Pt | 0,116 | 0,0485 | 0,078
Resources | Pt | 0,0706 | 0,0203 | 0,0431
Comparing 1 p 'Lead Acid Battery - reference flow', 1 p 'Lithium ion battery - LFP - reference flow' and 1 p 'Lithium ion battery - NMC - reference flow';Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Single score
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user


NexusDB@inuvika-db1.sipr.ucl.ac.be\Default\Professional; Solarly system first try - [Compare Lead Acid Batte ..., Lithium ... LFP - reference flow and Lithium]
File Edit Calculate Tools Window Help
Impact assessment
Inventory
Process contribution
Setup
Checks (570,3)
Product overview
Indicator
Single score
Cut-off
1%
Default units
Exclude long-term emissions
Per impact category
Category
Chart of process / product stage
Lead Acid Battery - reference flow
Lead smelter slag {GLO}| treatment of, residual material landfill | Cut-off, U
Lead {GLO}| primary lead production from concentrate | Cut-off, U
Sulfidic tailings, from zinc-lead mine operation {CN}| treatment of sulfidic tailings, from zinc-lead mine operation, tailings impoundment | Cut-off, U
Lead concentrate {GLO}| zinc mine operation | Cut-off, U
Lead concentrate {PE}| silver mine operation with extraction | Cut-off, U
Sulfidic tailings, from zinc-lead mine operation {RoW}| treatment of sulfidic tailings, from zinc-lead mine operation, tailings impoundment | Cut-off, U
Sulfidic tailings, from zinc-lead mine operation {AU}| treatment of sulfidic tailings, from zinc-lead mine operation, tailings impoundment | Cut-off, U
Sulfidic tailings, from zinc-lead mine operation {PE}| treatment of sulfidic tailings, from zinc-lead mine operation, tailings impoundment | Cut-off, U
Lead {RoW}| treatment of scrap acid battery, remelting | Cut-off, U
Sulfidic tailings, generic {GLO}| treatment of sulfidic tailings, generic, tailings impoundment | Cut-off, U
Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Single score
Comparing 1 p 'Lead Acid Battery - reference flow', 1 p 'Lithium ion battery - LFP - reference flow' and 1 p 'Lithium ion battery - NMC - reference flow';
UCL 1
Ryelandt
9.3.0.3 Classroom Multi user



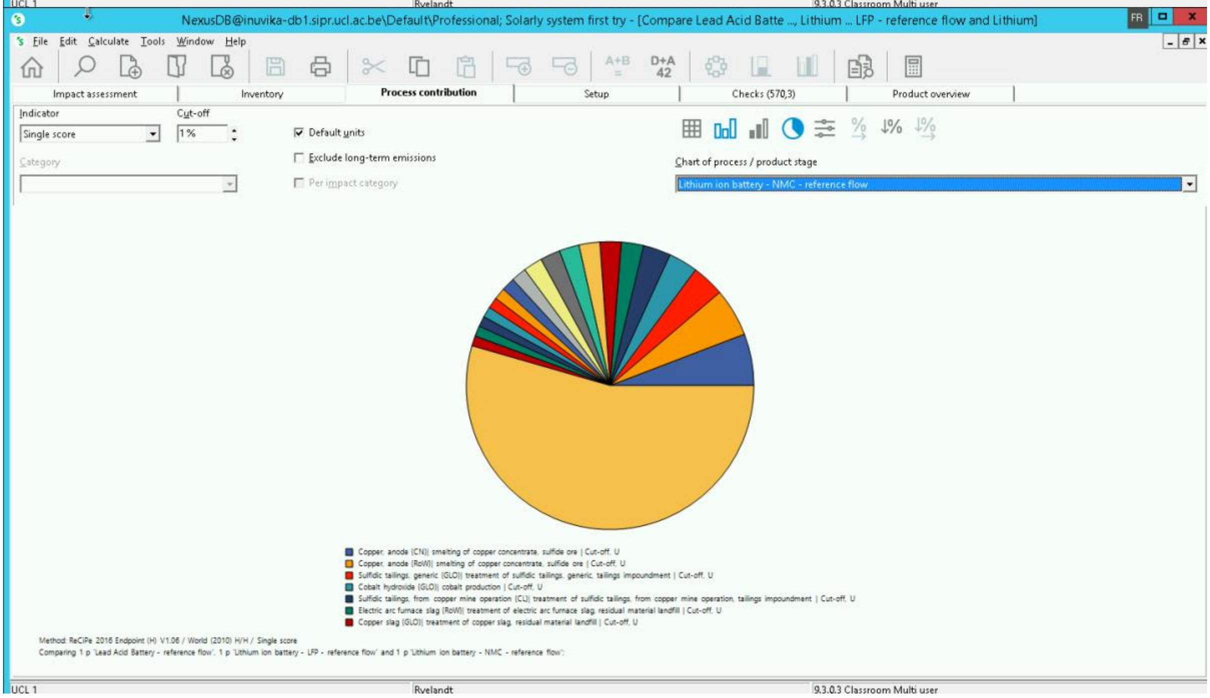
No	Process	Project	Unit	Lead Acid Battery -	Lithium ion battery - LFP -	Lithium ion battery - NMC -
	Total of all processes		Pt	6,67	1,85	2,6
	Remaining processes		Pt	2,29	1,74	2,11
1	Lead smelter slag {GLO}| treatment of, residual material landfill | Cut-(	Ecoinvent 3 - allocation, cu	Pt	0,678	0,00018	0,000465
2	Lead {GLO}| primary lead production from concentrate | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	0,634	2,93E-5	8,82E-5
3	Sulfidic tailings, from zinc-lead mine operation {CN}| treatment of sul	Ecoinvent 3 - allocation, cu	Pt	0,597	0,00234	0,00667
4	Lead concentrate {GLO}| zinc mine operation | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	0,371	0,000109	0,000276
5	Lead concentrate {PE}| silver mine operation with extraction | Cut-off,	Ecoinvent 3 - allocation, cu	Pt	0,346	0,000102	0,000257
6	Sulfidic tailings, from zinc-lead mine operation {RoW}| treatment of s	Ecoinvent 3 - allocation, cu	Pt	0,343	0,00134	0,00383
7	Sulfidic tailings, from zinc-lead mine operation {AU}| treatment of sul	Ecoinvent 3 - allocation, cu	Pt	0,201	0,000789	0,00225
8	Sulfidic tailings, from zinc-lead mine operation {PE}| treatment of sulf	Ecoinvent 3 - allocation, cu	Pt	0,157	0,000614	0,00175
9	Lead {RoW}| treatment of scrap acid battery, remelting | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	0,15	6,92E-6	2,08E-5
10	Sulfidic tailings, generic {GLO}| treatment of sulfidic tailings, generic,	Ecoinvent 3 - allocation, cu	Pt	0,13	0,00292	0,0955
11	Sulfidic tailings, from silver mine operation {RoW}| treatment of sulfid	Ecoinvent 3 - allocation, cu	Pt	0,114	0,000115	0,000247
12	Sulfidic tailings, from zinc-lead mine operation {US}| treatment of sulf	Ecoinvent 3 - allocation, cu	Pt	0,107	0,00042	0,0012
13	Heat, district or industrial, other than natural gas {RoW}| heat product	Ecoinvent 3 - allocation, cu	Pt	0,101	0,0401	0,0585
14	Sulfidic tailings, from zinc-lead mine operation {MX}| treatment of sul	Ecoinvent 3 - allocation, cu	Pt	0,0837	0,000328	0,000936
15	Electricity, high voltage {ID}| electricity production, lignite | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	0,0794	0,0241	0,0344
16	Copper, anode {CN}| smelting of copper concentrate, sulfide ore | Cut	Ecoinvent 3 - allocation, cu	Pt	0,0753	0,0182	0,151
17	Lead {RER}| treatment of scrap acid battery, remelting | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	0,074	3,42E-6	1,03E-5
18	Sulfidic tailings, from zinc-lead mine operation {IN}| treatment of sulf	Ecoinvent 3 - allocation, cu	Pt	0,0733	0,000287	0,00082
19	Copper, anode {RoW}| smelting of copper concentrate, sulfide ore | C	Ecoinvent 3 - allocation, cu	Pt	0,0699	0,0169	0,141

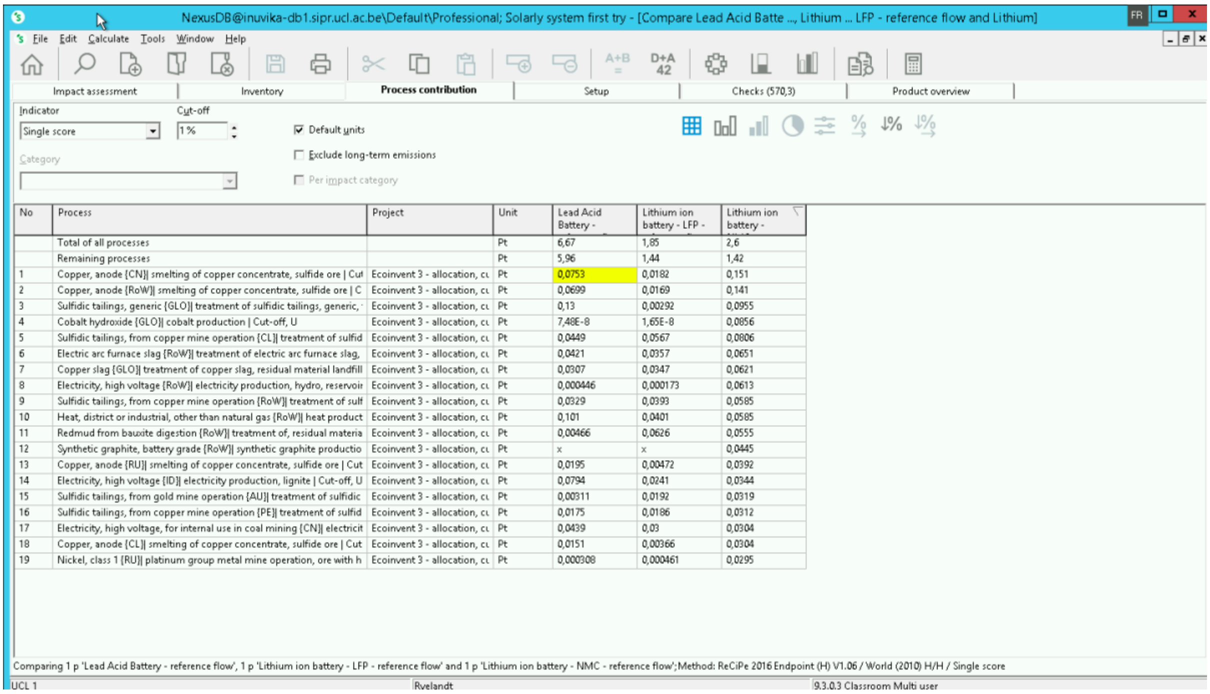




No	Process	Project	Unit	Lead Acid Battery -	Lithium ion battery - LFP	Lithium ion battery - NMC -
	Total of all processes		Pt	6,67	1,85	2,6
	Remaining processes		Pt	6,14	0,845	1,96
1	Copper {RAS}| production, primary | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	x	0,203	x
2	Sulfidic tailings, from copper mine operation {CN}| treatment of sulfic	Ecoinvent 3 - allocation, cu	Pt	0,0148	0,137	0,0255
3	Redmud from bauxite digestion {RoW}| treatment of, residual materia	Ecoinvent 3 - allocation, cu	Pt	0,00466	0,0626	0,0555
4	Sulfidic tailings, from copper mine operation {CL}| treatment of sulfid	Ecoinvent 3 - allocation, cu	Pt	0,0449	0,0567	0,0806
5	Sulfidic tailings, from copper mine operation {ID}| treatment of sulfidi	Ecoinvent 3 - allocation, cu	Pt	0,00632	0,0492	0,0112
6	Synthetic graphite, battery grade {CN}| synthetic graphite production,	Ecoinvent 3 - allocation, cu	Pt	x	0,0463	0,0076
7	Heat, district or industrial, other than natural gas {RoW}| heat product	Ecoinvent 3 - allocation, cu	Pt	0,101	0,0401	0,0585
8	Copper concentrate, sulfide ore {RAS}| copper mine operation, sulfide	Ecoinvent 3 - allocation, cu	Pt	x	0,0397	x
9	Sulfidic tailings, from copper mine operation {RoW}| treatment of sulf	Ecoinvent 3 - allocation, cu	Pt	0,0329	0,0393	0,0585
10	Sulfidic tailings, from copper mine operation {KZ}| treatment of sulfid	Ecoinvent 3 - allocation, cu	Pt	0,00358	0,0376	0,00602
11	Electric arc furnace slag {RoW}| treatment of electric arc furnace slag,	Ecoinvent 3 - allocation, cu	Pt	0,0421	0,0357	0,0651
12	Copper slag {GLO}| treatment of copper slag, residual material landfill	Ecoinvent 3 - allocation, cu	Pt	0,0307	0,0347	0,0621
13	Copper {RLA}| production, primary | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	x	0,03	x
14	Electricity, high voltage, for internal use in coal mining {CN}| electricit	Ecoinvent 3 - allocation, cu	Pt	0,0439	0,03	0,0304
15	Electricity, high voltage {ID}| electricity production, lignite | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	0,0794	0,0241	0,0344
16	Hard coal {CN}| hard coal mine operation and hard coal preparation |	Ecoinvent 3 - allocation, cu	Pt	0,0344	0,0235	0,0239
17	Copper, cathode {RU}| platinum group metal mine operation, ore with	Ecoinvent 3 - allocation, cu	Pt	0,0129	0,0227	0,0188
18	Sulfidic tailings, from copper mine operation {US}| treatment of sulfid	Ecoinvent 3 - allocation, cu	Pt	0,0106	0,0195	0,0194
19	H3PO4 purification residue {RoW}| treatment of H3PO4 purification re	Ecoinvent 3 - allocation, cu	Pt	0,000106	0,0193	0,000129
20	Sulfidic tailings, from gold mine operation {AU}| treatment of sulfidic	Ecoinvent 3 - allocation, cu	Pt	0,00311	0,0192	0,0319
21	Spoil from hard coal mining {GLO}| treatment of, in surface landfill | C	Ecoinvent 3 - allocation, cu	Pt	0,0509	0,0188	0,0258
22	Sulfidic tailings, from copper mine operation {PE}| treatment of sulfid	Ecoinvent 3 - allocation, cu	Pt	0,0175	0,0186	0,0312

Comparing 1 p 'Lead Acid Battery - reference flow', 1 p 'Lithium ion battery - LFP - reference flow' and 1 p 'Lithium ion battery - NMC - reference flow';Method: ReCiPe 2016 Endpoint (H) V1.06 / World (2010) H/H / Single score





No	Process	Project	Unit	Lead Acid Battery -	Lithium ion battery - LFP -	Lithium ion battery -
	Total of all processes		Pt	6,67	1,85	2,6
	Remaining processes		Pt	5,96	1,44	1,42
1	Copper, anode {CN}| smelting of copper concentrate, sulfide ore | Cut	Ecoinvent 3 - allocation, cu	Pt	0,0753	0,0182	0,151
2	Copper, anode {RoW}| smelting of copper concentrate, sulfide ore | C	Ecoinvent 3 - allocation, cu	Pt	0,0699	0,0169	0,141
3	Sulfidic tailings, generic {GLO}| treatment of sulfidic tailings, generic,	Ecoinvent 3 - allocation, cu	Pt	0,13	0,00292	0,0955
4	Cobalt hydroxide {GLO}| cobalt production | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	7,48E-8	1,65E-8	0,0856
5	Sulfidic tailings, from copper mine operation {CL}| treatment of sulfid	Ecoinvent 3 - allocation, cu	Pt	0,0449	0,0567	0,0806
6	Electric arc furnace slag {RoW}| treatment of electric arc furnace slag,	Ecoinvent 3 - allocation, cu	Pt	0,0421	0,0357	0,0651
7	Copper slag {GLO}| treatment of copper slag, residual material landfill	Ecoinvent 3 - allocation, cu	Pt	0,0307	0,0347	0,0621
8	Electricity, high voltage {RoW}| electricity production, hydro, reservoir	Ecoinvent 3 - allocation, cu	Pt	0,000446	0,000173	0,0613
9	Sulfidic tailings, from copper mine operation {RoW}| treatment of sulf	Ecoinvent 3 - allocation, cu	Pt	0,0329	0,0393	0,0585
10	Heat, district or industrial, other than natural gas {RoW}| heat product	Ecoinvent 3 - allocation, cu	Pt	0,101	0,0401	0,0585
11	Redmud from bauxite digestion {RoW}| treatment of, residual materia	Ecoinvent 3 - allocation, cu	Pt	0,00466	0,0626	0,0555
12	Synthetic graphite, battery grade {RoW}| synthetic graphite productio	Ecoinvent 3 - allocation, cu	Pt	x	x	0,0445
13	Copper, anode {RU}| smelting of copper concentrate, sulfide ore | Cut	Ecoinvent 3 - allocation, cu	Pt	0,0195	0,00472	0,0392
14	Electricity, high voltage {ID}| electricity production, lignite | Cut-off, U	Ecoinvent 3 - allocation, cu	Pt	0,0794	0,0241	0,0344
15	Sulfidic tailings, from gold mine operation {AU}| treatment of sulfidic	Ecoinvent 3 - allocation, cu	Pt	0,00311	0,0192	0,0319
16	Sulfidic tailings, from copper mine operation {PE}| treatment of sulfid	Ecoinvent 3 - allocation, cu	Pt	0,0175	0,0186	0,0312
17	Electricity, high voltage, for internal use in coal mining {CN}| electricit	Ecoinvent 3 - allocation, cu	Pt	0,0439	0,03	0,0304
18	Copper, anode {CL}| smelting of copper concentrate, sulfide ore | Cut	Ecoinvent 3 - allocation, cu	Pt	0,0151	0,00366	0,0304
19	Nickel, class 1 {RU}| platinum group metal mine operation, ore with h	Ecoinvent 3 - allocation, cu	Pt	0,000308	0,000461	0,0295

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