Life cycle assessment of a lithium ion battery: comparison between first and second life batteries environmental impacts in microgrid applications

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ABSTRACT – This work aims to evaluate and compare the environmental impacts of 1st and 2nd life lithium ion batteries (LIB). Therefore, a comparative Life Cycle Assessment, including the operation in a microgrid, is performed for a case study, in which the LIBs are used as stationary storage. If only the manufacturing and refurbishment processes are analyzed, the SLB seems to be more benefic to the environmental than the FLB, presenting an GWP of 3.5 kgCO_2eq/(kg of LIB) against 15 kgCO_2eq/(kg of LIB). However, when the complete LCA is performed, the difference between the FLB and SLB's GWP is just 5%. These results show the importance of considering the entire life cycle, from the LIB production to its End of Life treatment.

Keywords – Life cycle assessment, integrated design, second life battery, lithium ion, microgrids, battery storage

1. INTRODUCTION

Given the urgency of providing solutions to the current climate crisis, electrification of transports and use of intermittent renewable sources of energy, e.g. electric vehicles (EV) and photovoltaic (PV) systems, respectively, are becoming more attractive choices to reduce the greenhouse gases emissions. However, the mentioned technologies increase the use of batteries as storage systems. Therefore, the environmental impact of manufacturing, operation and disposal of LIBs needs to be analyzed. Moreover, the systems need to be developed in accordance with eco-design directives.

A well established method to do this is the Life Cycle Assessment (LCA), which is a robust and reliable approach based on ISO 14040 and 14044 [1, 2] standards, that can be used to compare different technological alternatives from an ecological point of view. The LCA evaluates the environmental impacts of a service or a product throughout its lifetime, whose boundaries depend on the assessment objective, e.g. from the extraction of raw materials to the disposal of a product at its end of life (EoL), or only its operation time. The main steps that a LCA study need to follow according to these standards are illustrated in Fig. 1, in which the arrows represent the transitions between steps. As can be seen in the figure, after completing a step it may be necessary to go back to a previous one, e.g. to correct assumptions or add more processes, which makes the LCA an iterative process.

The study of [3] showed that the addition of lithium-manganese oxide (LMO) LIB as stationary storage slightly increases the environmental impacts of a ground-mounted PV system. Therefore, it is possible to use the LIB benefits without decreasing the environmental advantages of a PV system. Whereas [4] analyzes different application scenarios for 2nd life LIB, concluding that its use as stationary storage is only recommended in systems with integrated renewable energy sources.

Moreover, [5] presents the important role of electricity mix to

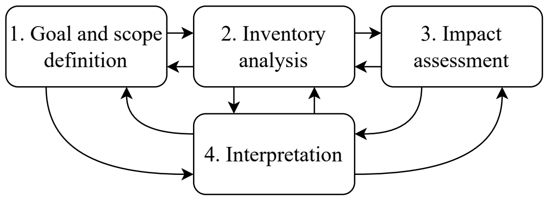

Figure 1. Main steps of the Life Cycle Assessment [1, 2].

the final LCA result. The increase of renewable resources in the local electricity mix could cause a reduction of 9.4% the environmental impacts of SLBs. However, the battery degradation increases the local grid electricity consumption limiting up to 8.1% of the SLB benefits. The results presented by [6] corroborate to the fact that the electricity mix is a crucial factor to have lower environmental impacts. It also revealed that the use of 2nd life LIB (SLB) can improve the environmental performance of microgrids.

This work is focused on the comparison of environmental assessment of brand new versus second life lithium ion batteries (LIB) and their integration in microgrids. The methodology used to perform the LCA is presented at section 2. The microgrid modeling is described in section 3 and the case study description in section 4. Finally, the LCA results are presented in section 4.

2. METHODOLOGY FOR LIFE CYCLE ASSESSMENT OF BATTERY STORAGE INTEGRATED IN MICROGRIDS

The Life Cycle Assessment follows the steps presented in Fig. 1 and is performed on the specialized software SimaPro [7]. The goal is to compare the environmental impacts associated with the use of 1st life LIB (FLB) and SLB as microgrid stationary storage. In order to achieve this objective, the functional unit for our LCA is the demand supply of consumers connected to the microgrid at a specified location during a project lifetime, subject to microgrid modeling considerations presented in section 4. To enable a fair comparison, the SLB is sized in order to have the same initial available capacity. Moreover, the other microgrid components have the same dimensions and technical characteristics for both microgrid configuration, i.e., with FLB or SLB, and their impacts are not computed.

The data for the Life Cycle Inventory (LCI) are collected from literature and the references are cited in section 4. If no reference is mentioned, then the used data are taken from the ecoinvent 3.7.1 database [8]. The simplified life cycles of both LIBs and their respective boundaries to perform the LCI are presented in Fig. 2.

We consider that the LIBs in its final form is composed of bat-

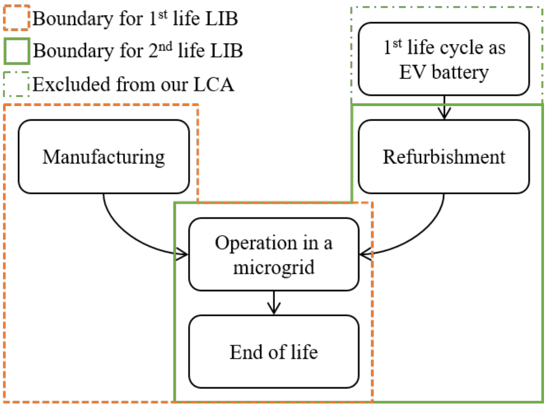

Figure 2. Boundaries of lithium ion batteries (LIBs) life cycle.

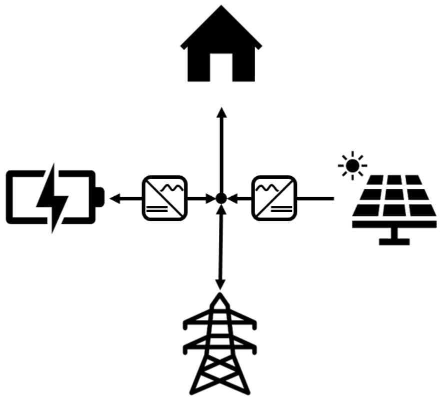

Figure 3. Microgrid architecture.

tery cells, cooling system, battery packaging and Battery Management System (BMS). In terms of mass percentage, the BMS has a small contribution to the LIBs' total mass. Then it is excluded from the LCA.

In the manufacturing process of FLB are included: raw material extraction and transport to produce the LIB components, process energy (electricity and heat) needed to battery manufacturing, and final product transport from the factory to the installation site.

Due to the need of high reliability, the batteries used in EVs are discarded with a high state of health (SoH), e.g. typically 80%. However, they can still attend the technical requirements of a stationary application. Therefore, it is considered that the EVs batteries are refurbished to produce stationary SLBs. In the refurbishment process, only the battery cells are reused in its original form, and the cooling system and battery package are brand new. Consequently, we consider that the cells are environmentally cost-free and the impacts of the refurbishment process are limited to:

- raw material extraction and transport to produce a brand new cooling system and battery packaging;
- process electricity needed in the disassembly of the EV battery, testing of cells SoH, and final product assembly;
- and transportation from a storage unit to the refurbishment plant and then to the final installation site.

The considered microgrid is not self-sufficient, i.e., it does not produce enough power to meet its demand and it needs to draw electricity from the grid. Therefore, the microgrid environmental impacts depend on the electricity mix of its location. The impacts related to the maintenance and the renewable production excess sold to the grid are excluded from the LCA.

The environmental impacts of three LIB end of life (EoL) solutions are analyzed, and they are: pyrometallurgy, hydrometallurgy and direct land field disposal. A pretreatment phase, consisting of disassembly (separation into battery cells, packaging and cooling system), discharge and inactivation of the LIB, is necessary and its impact is considered in the assessment of these different solutions. It is important to note that the recovery of some material during the EoL process is considered as a negative impact, i.e. *avoided burden*, in the LCA.

The global warming potential (GWP) indicator from the IMPACT World+ Midpoint method is considered in the Life Cycle Impact Assessment (LCIA) step. This global indicator is one of the most commonly used and measures the equivalent greenhouse gases emissions during the life cycle in kilogram of carbon dioxide equivalent (kgCO_2eq).

3. MICROGRID MODELING

The microgrid is intentionally simplified to focus on methodological aspects. It is composed of a smart house, which integrates the system load, a PV system, a LIB, which can be a first or second life one, and the local grid (see Fig. 3). Two inverters interface the PV system and LIB to the microgrid. Both the load curve and PV production are established for a typical year and reproduced for each year of the microgrid lifetime.

The microgrid operation is a rule-based heuristic, in which the dispatch order to supply the load is: photovoltaic, battery and local grid. If the LIB comes to its end of life before the end of project lifetime, it is changed and its initial parameters are restored. The battery degradation depends on its use during the microgrid operation, and the following subsection presents its modeling.

3.1. Battery degradation model

The exchangeable energy degradation model from [9] is considered in this study. The degradation is measured by the battery SoH, which is computed for each simulation step as:

$$\mathrm{SoH}(k+1) = \mathrm{SoH}_{\mathrm{lim1}} + \frac{\mathrm{SoH}_{\mathrm{lim2}} - \mathrm{SoH}_{\mathrm{lim1}}}{E_{\mathrm{exch,MAX}}} \cdot \sum_{i=1}^{k+1} \left| E_{\mathrm{exch}}(i) \right| , \tag{1}$$

where E_{exch} is the exchanged energy during a simulation step, and $E_{\mathrm{exch,MAX}}$ is the maximum exchangeable energy, i.e. the maximum energy that can flow in and out the battery. In Eq. (1), the values of $\mathrm{SoH}_{\mathrm{lim1}}$ and $\mathrm{SoH}_{\mathrm{lim2}}$ depend on the $\mathrm{SoH}(k)$, and are given by

$$\mathrm{SoH}_{\mathrm{lim1}} = \begin{cases} \mathrm{SoH}_{\mathrm{ini}}, & \text{if } \mathrm{SoH}(k) \geq \mathrm{SoH}_{\mathrm{kneepoint}} \\ \mathrm{SoH}_{\mathrm{kneepoint}}, & \text{otherwise} \end{cases} \tag{2}$$

and

$$\mathrm{SoH}_{\mathrm{lim2}} = \begin{cases} \mathrm{SoH}_{\mathrm{kneepoint}}, & \text{if } \mathrm{SoH}(k) \geq \mathrm{SoH}_{\mathrm{kneepoint}} \\ \mathrm{SoH}_{\mathrm{EoL}}, & \text{otherwise} \end{cases} , \tag{3}$$

where $\mathrm{SoH}_{\mathrm{ini}}$ is the initial SoH, $\mathrm{SoH}_{\mathrm{kneepoint}}$ is the value of SoH at which the battery aging accelerates, and $\mathrm{SoH}_{\mathrm{EoL}}$ is the value of SoH at which the battery end of life occurs.

The maximum exchangeable energy $E_{\mathrm{exch,MAX}}$ is function of DoD, which deals with the standard battery cycle in the framework of the application case, E_{ini} is the initial battery capacity and the maximum number of complete cycles $N_{\mathrm{cyc,MAX}}$ is obtained from the cycle to failure curve usually provided in data sheets. It is computed as:

$$E_{\mathrm{exch,MAX}} = \frac{1}{\alpha} \cdot 2 \cdot N_{\mathrm{cyc,MAX}}(\mathrm{DoD}) \cdot \mathrm{DoD} \cdot E_{\mathrm{ini}}, \tag{4}$$

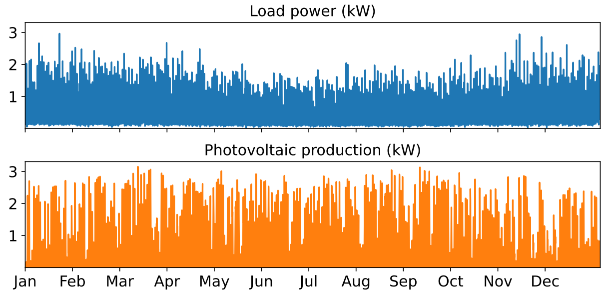

Figure 4. Residential demand and photovoltaic production for a typical year.

Table 1. Data for 1st and 2nd life lithium ion batteries.

Parameter	**FLB**	**SLB**
SoH_{ini}	100%	80%
E_{ini}	10.0 kWh	12.5 kWh
Total weight	53.0 kg	66.3 kg

where the α is the aging accelaration coefficient, i.e., to model the degradation accentuation that occurs after the SoH kneepoint.

The SoH enables the computation of the loss of capacity, where the battery capacity is updated by:

$$E_{\text{tot}}(k+1) = E_{\text{ini}} \cdot \text{SoH}(k+1). \quad (5)$$

In the same way, one can estimate the loss of efficiency with the following equation adapted from [10], where the battery round-trip efficiency is updated by:

$$\eta_{\text{bat}}(k+1) = \eta_{\text{bat},100\%} - \frac{1-(\text{SoH}(k+1))}{12}, \quad (6)$$

where $\eta_{\text{bat},100\%}$ is the efficiency for SoH equals to 100%.

4. CASE STUDY

As mentioned before, the objective is to do a comparative LCA of first and second life LIBs serving as microgrid stationary storage. Therefore, two microgrid configurations are simulated and studied:

1. Residential microgrid with FLB;
2. Residential microgrid with SLB.

The functional unit for our LCA is described as the supply of a house hourly demand located in Toulouse/FR during 30 years, subject to microgrid modeling considerations presented in section 4 and the parameters and data detailed below.

The smart house has an average demand of 0.6 kW and the PV system an installed capacity of 3.5 kW of peak power. Their curves for a typical year are presented in Fig. 4. Each inverter has an efficiency of 98%.

The chosen battery model is the NMC-811, whose cathode active material is composed by 80% nickel, 10% manganese and 10% cobalt. For both configurations, it is considered an energy density of 230 Wh per battery cell kilogram, an efficiency $\eta_{\text{bat},100\%}$ of 98%, and a C-rate of 0.5. Also, the authorized DoD is 80%, with a minimum State of Charge (SoC) equals to 10% and a maximum SoC equals to 90%. Moreover, the $N_{\text{cyc,MAX}}(80\%)$ is 4000 cycles, the SoH kneepoint is set to 80%, the aging acceleration coefficient α is equal to 2, and the LIBs attain their EoL with a SoH equals to 40%. The data that differs for FLB and SLB is presented in Table 1.

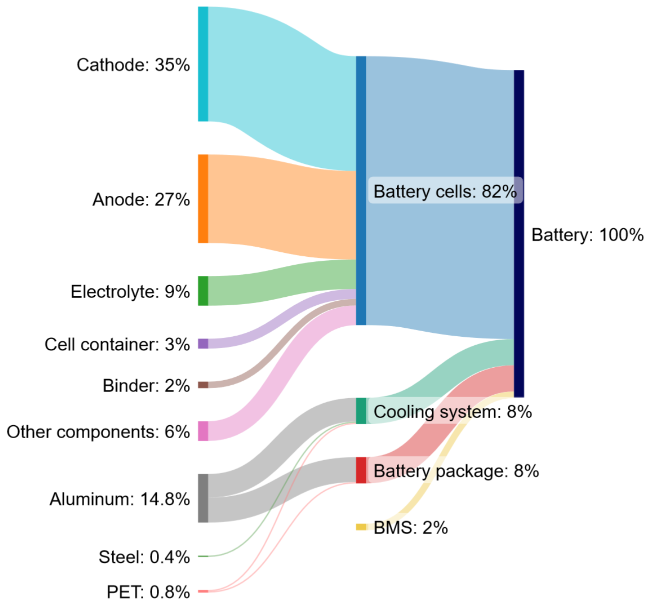

Figure 5. Battery composition in mass percentage.

In order to perform the LCA, information about the battery composition is needed. After analyzing the range of mass percentage of the battery components used in [11], [12] and [13], we chose a composition according to the values already used in the literature. Figure 5 presents the main elements that compose the LIB used in this study and their chosen mass percentage to the final product, which are the same for FLB and SLB. Since the battery cells represent the majority of a LIB, the detailed composition is presented in Tab. 2, in mass percentage of battery cells. Also, the input of materials to produce 1 kg of cathode active material is presented in Tab. 3. To simplify the analysis, we neglected the environmental impacts of the Battery Management System (BMS), which represents only 2% of the final LIB mass.

Moreover, we considered that the manufacturing process occurs in the chinese city of Shenzen, so the electricity mix is the chinese during this step. We consider the transport of the FLB is made from the factory to the port of Shenzen/CN by lorry (100 km), the port of Shenzhen/CN to the the port of Marseille/FR by container boat (16230 km), and inside the french territory, the transport is again made by lorry from the port to the installation site (440 km). On the other hand, the refurbishment process occurs in France, using a french electricity mix. It is considered a total of 400 km of lorry transportation, from a storage unit to the refurbishment plant, and then to the final location for the installation.

As mentioned before, during the operation phase we only consider the environmental impacts of the french electricity mix, which the installed capacity in 2022 was the following: 43% of nuclear plants, 18% of hydro-power, 15% of wind power plants, 11% of solar plants, 9% of gas thermoelectrics, and the remaining of other sources. Therefore, the average GWP for this same year is 55 gCO_2eq/kWh [14].

Concerning the EoL processes, we considered an avoided burden of 75%, i.e., the material recovery generates 75% reduction in the environmental impacts of producing a new material. Moreover, it is unrealistic to consider that a material will be 100% recycled. Therefore, the Old Scrap Recovery (OSR) shows the material percentage that is actually recycled, and its value for different materials present at the EoL LIBs processes is introduced in Tab. 4. For the aluminum and steel, the OSR is

Table 2. Battery cells composition in mass percentage.

Component	Material	Percentage
CATHODE	Active cathode material	39.5%
	Carbon black (additive)	1.0%
	Positive current collector (Al)	2.5%
	Subtotal	*43.0%*
ANODE	Graphite	27.0%
	Negative current collector (Cu)	6.0%
	Subtotal	*33.0%*
ELECTROLYTE	Dimethyl carbonate (DMC)	5.0%
	Ethylene carbonate (EC)	5.0%
	LiPF6	1.5%
	Subtotal	*11.5%*
CELL CONTAINER	*Aluminum*	*3.5%*
BINDER	*PVDF*	*2.0%*
OTHER COMPONENTS	Plastic (PET)	1.5%
	Plastic (PP)	1.5%
	Aluminum	3.0%
	Copper	0.7%
	Electronics	0.3%
	Subtotal	*7.0%*

Table 3. Quantity of necessary material input to manufacture 1 kg of LIB active material.

Material	Quantity
Sodium hydroxide (NaOH) (kg)	0.9
Lithium hydroxide (LiOH) (kg)	0.25
Nickel sulfate (NiSO4) (kg)	1.4
Cobalt sulfate (CoSO4) (kg)	0.175
Manganese sulfate (MnSO4) (kg)	0.175
Ammonia (NH3) (kg)	0.045
Process water (l)	20

Table 4. Old Scrap Recovery (OSR) of different materials.

Material	OSR
Aluminum scrap	50%
Copper scrap	90%
Graphite	70%
Steel scrap	40%
Cobalt sulfate ($CoSO_4$)	98%
Manganese sulfate ($MnSO_4$)	98%
Nickel sulfate ($NiSO_4$)	98%

from [15], and for the other materials is from [16].

For the pretreatment phase, we consider 200 km of transport by lorry from the installation site to the EoL facility, 0.5 kWh of electricity to disassembly 1 kg of battery pack. The cooling system and packaging materials are treated during this step, and the battery cells need yet to be processed. The inputs and outputs to treat 1 kg of spent battery cells through pyrometallurgy and hydrometallurgy are from [16]. If the direct landfill disposal is considered, 50 km of additional transport is needed, 1.5 kWh of electricity to process 1 kg of battery cell, and in this case no material is recovered.

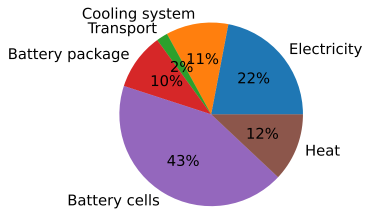

Figure 6. Contribution of processes to the Global Warming Potential of 1st life LIB manufacturing.

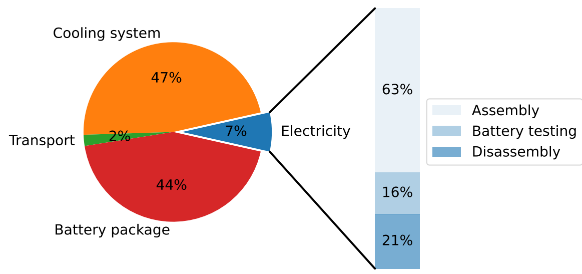

Figure 7. Contribution of processes to the Global Warming Potential of 2nd life LIB refurbishment.

5. LIFE CYCLE ASSESSMENT RESULTS

This section presents the results obtained for the case study. First, the manufacturing 1st life LIB and refurbishment of 2nd life LIB GWPs are presented in unitary terms (per kilogram of battery produced or refurbished). Then, the results for the treatments of 1 kg of spent battery at its EoL are presented. Finally, the operation results obtained for the microgrid simulation during the 30 years of project and the LCA of the 1st and 2nd life LIBs integrated on the microgrid.

5.1. *Environmental impacts of manufacturing a 1st life LIB and refurbishment of a 2nd life LIB*

The LCA of manufacturing and refurbishment stage results in a GWP of 15 and 3.5 kgCO_2eq/(kg of LIB), respectively. Figure 6 presents the contribution of different components and processes to the FLB manufacturing values. As expected, the battery cells are responsible for almost half of the FLB manufacturing GWP, as they are the component with the major share in the battery composition and have high use of minerals. The process energy (electricity and heat), which contributes with 33%, is directly caused by the Chinese energy mix (high share of coal source). The cooling system and battery package contribute almost equally to the GWP, due to their similar compositions. Despite the long distance involved in importing, the transport only represents 2% of the GWP.

As mentioned before, the battery cells are impact free for the SLB, since the majority of GWP is due to the manufacturing of new components (battery packaging and cooling system), as can be seen in Fig. 7. Therefore, the precision of these components' data needs to be ensured. This could be done by collecting the composition and manufacturing information directly with the manufactures for the specific models that are used in the SLBs. The contribution of electricity is smaller for SLB than FLB, mainly because of the french mix. Another reason is the lower consumption in the disassembly, testing and assembly (total of 2.38 kWh/kg of LIB), than the manufacturing of a brand new battery (4.67 kWh/kg of LIB). The transport represented again only a small piece of the total GWP.

Table 5. Global Warming Potential (GWP) in gCO_2eq/kg of battery for different LIBs' End of Life treatments.

End of Life treatment	**GWP (gCO_2eq/kg of battery)**
Pretreatment	-797
Pyrometallurgy	267
Hydrometallurgy	-648
Direct land field disposal	320

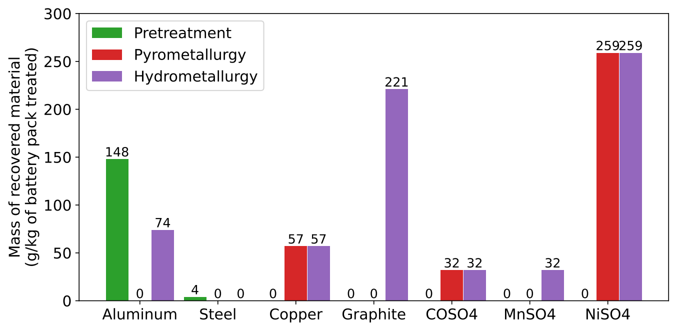

Figure 8. Mass of recovered materials for different LIBs' End of Life treatments (without applying the Old Scrap Recovery (OSR) factor).

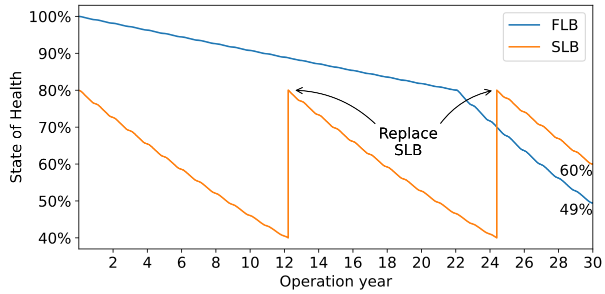

Figure 9. State of Health evolution during 30 years for 1st and 2nd life LIBs.

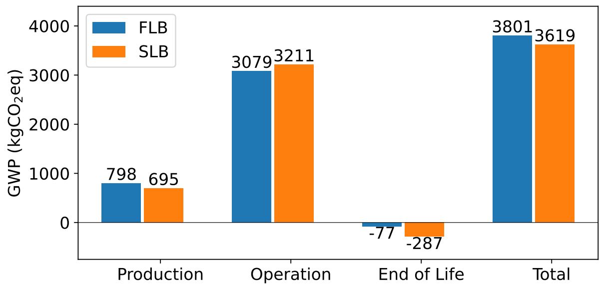

Figure 10. Microgrid Global Warming Potential with 1st life and 2nd life LIBs.

5.2. *Environmental impacts of end of life processes*

The GWP of the pretreatment and the three EoL LIBs treatments are presented in Tab. 5. Although the pretreatment presents the simplest processes, it is the one which avoids more emissions. This is due to the high quantity of aluminum recovered from the battery package and cooling system (as can be seen in Fig. 8) and low energy requirement to disassembly the materials from the LIBs. As expected, the direct land field disposal does not have a negative impact, as none material is recovered. Even though the pyrometallurgy and hydrometallurgy treatments recover a similar quantity of material (Fig. 8), the hydrometallurgy is the only one that has a negative impact. That is because the pyrometallurgy requires more electricity during its processes. Therefore, only the pretreatment plus hydrometallurgy were considered in the following results analysis.

5.3. *Environmental impacts of microgrid operation*

It is possible to compute the total amount of electricity bought from grid and the necessary number of battery replacements by simulating the microgrid operation over 30 years. Figure 9 shows the evolution of the battery degradation, measured by the SoH, for the cases with microgrid with integrated FLB and SLB. It can be seen that the installed FLB does not need to be replaced during the studied project lifespan. Also, it arrives at 30 years with a SoH of 49%, which means that if the considered project lifetime was a bit longer, a replacement would be necessary. As for the SLB, two replacements are needed, the first near 12 years and the second near 24 years of microgrid's operation. However, its remaining life is higher than for the FLB.

Moreover, the system with FLB consumes 55987 kWh from the grid during the project lifetime. Because of the greatest degradation slope after 80% of SoH, which reduces the battery capacity following Eq. (5), the system with SLB needs to buy more electricity from grid, resulting in a total consumption of 58388 kWh. In both systems, the photovoltaic production supplies 39% of the house load. The difference is just 1% for the grid power supply (36% for FLB and 37% for SLB) and battery supply (25% for FLB and 24% for SLB), that can be caused by the models uncertainties.

The GWP for different phases of the microgrid life cycle during the project lifetime is presented in Fig. 10. Even with the two SLB replacements, the production GWP is 13% lower for the three SLBs. The operation phase presents the largest contribution to the total GWP with a relative difference of 4% between both LIB types. However, analyzing the absolute value, the operation phase withdraw the benefits from the SLB refurbishment. Therefore, the microgrid with SLB obtained a total GWP only 5% lower than the one with the FLB mainly because the use of more and bigger SLBs, that caused a higher *avoided burden* at the EoL.

6. CONCLUSIONS

The results of the Life Cycle Assessment are directly related with the assumptions made. If we consider only the fabrication processes, the SLB seems to be more environmentally friendly as the unitary GWP indicator is almost 5 times lower than the FLB one (15 and 3.5 $kgCO_2eq/(kg$ of LIB$)$). However, the high participation of the operation phase to the total microgrid GWP demonstrates the importance of performing a LCA that includes the microgrid simulation with more realistic components models. The complete Life Cycle Assessment shows that the SLB has a slightly lower total GWP than a brand-new one, that can be caused by the data uncertainties. Despite the relative low difference in the results obtained for the microgrid case study, the use of second life LIBs can be justified by the resource scarcity and circular economy concept. Future works should be carried out to assess the environmental impacts related to other indicators and the economic feasibility of the SLB used as stationary storage. The sensitivity analysis of the results regarding different hypothesis and input data also needs to be investigated.

7. ACKNOWLEDGMENTS

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