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Environmental impacts of Lithium Metal Polymer and Lithium-ion stationary batteries

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A B S T R A C T

The installed capacity of stationary batteries is expected to grow rapidly in the coming years. This deployment will have impacts on the environment that must be investigated to guide our policy and technology choices. A large variety of stationary battery technologies exists, however previous studies have failed to assess the environmental implications of several of them. In this study, the environmental performance of Lithium Metal Polymer (LMP) stationary batteries is quantified through the life cycle assessment methodology and compared to Lithium-ion (Li-ion) units. LMP is a promising technology which is advocated as more stable, safe and simple to manufacture than batteries with liquid electrolytes. Models with a storage capacity of 6 MWh and 75 kWh are examined, corresponding respectively to batteries designed for a centralized and a distributed grid configuration. The assessments cover the entire life cycle of the batteries and evaluate their impacts in fifteen different environmental categories.

The results show that the battery manufacturing stage drives the majority of environmental impacts in the different investigated batteries. Li-ion batteries cause significantly more impacts than LMP units in terms of global warming and ozone depletion. The effects on global warming come mainly from the production of components in countries where fossil fuel dominates electricity mixes. The production of polytetrafluoroethylene, used only in Li-ion batteries, is the main contributor to the ozone layer depletion category and also an important source of global warming emissions. Conversely, LMP batteries are responsible for a bigger impact in terms of aquatic eutrophication originating from sulfidic tailings linked to mining activities. An additional finding of this study is that centralized battery system configurations bring smaller environmental impacts than distributed systems with more but smaller storage units.

1. Introduction

Stationary batteries grew from a global power capacity of 800 MW in 2014–1720 MW in 2016 [1–3]. According to different prospective studies [4–6], this deployment is likely to continue and could reach 4000 MW in 2022. This current and forecasted expansion is largely driven by the ability of stationary batteries to bring flexibility to electricity systems with increasing shares of variable renewables [7,8]. Additionally, in comparison to alternative flexibility measures,[1] stationary batteries feature several important attributes. They are highly efficient, they have a fast response time and their modularity makes them scalable to an extensive set of applications and locations [9,10]. In addition to renewable energy output shifting, they can provide different grid services which are increasingly demanded such as frequency response and voltage regulation [10–12]. Finally, they are experiencing a sustained reduction in technology costs and a favorable regulatory framework [11]. The growth of stationary batteries is likely to have environmental implications. It is, therefore, essential to assess carefully the environmental performance of the technologies available to guide our technological and policy choices.

Life Cycle Assessment (LCA) has been used to quantify the environmental performance of batteries in several studies [13,14]. This framework is adopted because of its comprehensiveness: covering all the life cycle stages of the studied products and quantifying their impacts and damages among a wide range of environmental categories [15]. Among the current assessments on batteries, it is possible to

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[1] The following measures are frequently mentioned as a potential solution to increase flexibility: increased demand response, enabling trading close to real time, installation of dispatchable power sources, greater interconnection between markets, combination of complementary renewables, and improved forecasting of variable renewables and energy storage technologies [10,74].

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identify several lines of research and methodological choices that have been favored by the research community. For example, a majority of studies conduct cradle-to-grave assessments, but these assessments only focus on a small set of impact categories: namely climate change and cumulative energy demand [14]. This limited coverage increases the risk of shifting environmental problems from the assessed environmental classes to areas that are not covered (e.g. ozone depletion or toxicity). With regards to the type of applications investigated, an important effort can be noted for the assessment of batteries with mobility purposes, also referred as traction batteries, where the following references [16–30] are relevant examples. In comparison, stationary batteries have been investigated with less dedication. Studies [31,32] focus on the assessment of micro-storage stationary solutions coupled with household solar photovoltaic installation. Study [30] evaluates a plug-in hybrid electric vehicle Lithium-ion (Li-ion) battery of 30 Ah with a second life application as a stationary battery of 20 Ah. A comparative LCA of a different type of stationary batteries is carried out in [33] where the following technologies are investigated: Li-ion, lead-acid, sodium-sulfur, and vanadium-redox-flow. Similarly, study [9] assesses different technologies used for stationary purposes, namely valve-regulated lead-acid, flow-assisted nickel-zinc, and non-flow manganese dioxide-zinc. A comparison of a stationary battery using vanadium and sodium polysulphide electrolytes to pumped hydro storage and compressed air energy units was conducted in [34]. In a recent work, study [35] compares redox flow stationary batteries to technologies with various power-to-X technologies. Despite the intensification of the LCA work in the field, the assessment of solid-state batteries is limited to technologies at an experimental level which are examined in the following studies [36,37]. Moreover, to the best of our knowledge, no research about the environmental impacts of Lithium Metal Polymer (LMP) batteries could be identified in the literature. LMP is a promising solid-state battery technology which is available at a commercial scale for stationary applications. Similarly to other solid-state technologies, it is advocated as less toxic, more environmentally friendly, more stable and simpler to manufacture than other types of batteries [38]. Finally, there are no published studies comparing batteries installed on the grid according to a centralized and a distributed configuration.[2] The increase in the distribution of technologies composing power systems also applies to storage and is considered as an important trend to take into account [39].

In this paper, the environmental impacts of LMP and Li-ion stationary batteries are quantified and compared through the LCA methodology. A set of fifteen impact categories and four damage categories are evaluated. Both chemistries investigated use lithium iron phosphate (LFP) at the positive electrode while at the negative electrode, the Li-ion unit uses graphite and the LMP a metallic lithium. LMP batteries are manufactured by a battery producer located in the province of Quebec, Canada. The Li-ion batteries are considered to be produced in Asia where the majority of the production of this technology is taking place [40,41]. Each technology is then modeled according to a use and subsequent life cycle stages occurring in Quebec or Canada. The models with storage capacity of 6 MWh and 75 kW h are examined corresponding respectively to batteries designed for a centralized and a distributed grid-configuration.

This work closes the gap with regards to the environmental assessment of LMP and solid-state batteries available at a commercial scale. Even though Li-ion units have been extensively studied, their assessment has not been realized according to a use stage in Quebec. Moreover, Li-ion is the most utilized battery technology for grid-scale stationary application and is expected to be an important player in the battery market of Quebec [36,42,43]. This study also highlights the difference in environmental performance between stationary batteries installed in centralized and distributed configurations. Finally, the environmental assessments realized investigate a broader set of impact and damage categories than in the current literature.

This article is organized into the following three sections. First, the LCA approach and the methodological choices made for this study are introduced. Thereafter, the results are presented, discussed and their robustness is tested. Finally, different outlooks are identified, including a conclusion at the end of the paper.

2. Methodology

Life Cycle Assessment (LCA) is a methodology used to assess the environmental impacts of products.[3] The ISO 14040-44 standard defines it as the *compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system*[4] *throughout its life cycle* [44,45]. The term life cycle usually covers the following stages of a product life: the extraction of raw material, the production and processing of materials, the distribution, the use phase, the final disposal at the end of its life, and the transport during and between the different phases [44]. LCAs are comprehensive and reduce the risk of problem-shifting by considering the product entire life cycle and a large set of potential environmental impacts [46,47].

2.1. Goal and scope

The goal of this study is to measure and compare from a life cycle perspective the environmental performance of two stationary LFP battery technologies: Li-ion and LMP. For each technology, models of batteries of 75 kWh and 6 MWh capacities are considered corresponding respectively to models used in a distributed and a centralized battery system configuration. In total, four models of batteries are evaluated. The function of these units is to store electricity from an intermittent electricity production source at one point in time to deliver it at a later time.

2.1.1. Functional unit

The functional unit is defined as *the quantified performance of a product system for use as a reference unit* [44]. It is used to define the studied product according to its function formally and allows comparison of several products according to a functionally equivalent basis [48]. The functional unit used in this study is one megawatt-hour (MWh) of electricity delivery. The environmental performance of a battery can be significantly influenced by its lifetime, its efficiency and its maximum depth of discharge [14]. This functional unit allows capturing the influence of these key parameters on the amount of battery required per output delivered. Furthermore, when considering the production and delivery of electricity, it also enables the study to take account of the efficiency loss of electricity occurring at each charge and discharge cycle.

2.1.2. System boundaries

Fig. 1 shows the boundary of the foreground system analyzed in this study. A cradle-to-grave approach is adopted. The product system includes the extraction of raw materials, the manufacture of the battery and its components, the installation on site, the maintenance and use phase, the production and delivery of the stored electricity, the transport and the end of life treatments.

[2] A distributed configuration consists of small energy storage systems located close to the load and spread across the grid [75]. On the other hand, a centralized battery system is composed of units with bigger capacity and installed on the grid in a smaller number.

[3] Product refers to any goods or service [44].

[4] Product system collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product [44].

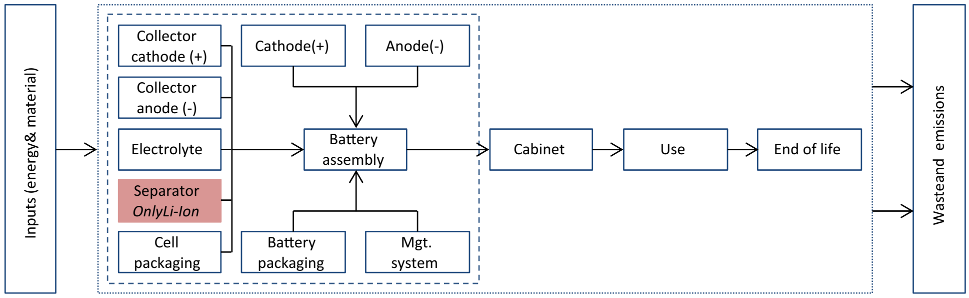


Fig. 1. Li-ion & LMP battery systems boundary (adapted from *Source*: [16]) – 75 kWh (used in distributed system) and 6 MWh (used in centralized system) - the box in red only applies for the Li-ion Battery.

2.2. Life Cycle Inventory

The data used in the Life Cycle Inventory (LCI) come from previous studies and reports as well as industrial partners' information and are documented in this section. Version 3.1 of the ecoinvent database is used as the source of background LCI data [49].

2.2.1. Battery performance parameters

The performance parameters used to create the model are taken from the Batt-DB database (Batt-DB) [50]. Batt-DB is a comprehensive database works regrouping information about different types of rechargeable batteries from industry, literature and scientific reports. The cycle life, the calendric lifetime and the efficiency of the LFP batteries available in the database are presented in Table 1.

The Li-ion and LMP batteries, as well as the distributed and centralized models, are considered to have equivalent performances. The median value of the different parameters for the LFP battery inventoried in Batt-DB is used to model the battery. The values located at the 25th and the 75th percentile from the same database are used in a sensitivity analysis.

2.2.2. Li-ion 75 kW h and 6 MW h

The production of the Li-ion batteries is modeled according to the inventory data available in study [20] which was verified through studies [19,23]. The production is assumed to take place in China. According to industry data, the majority of manufacturers of Li-ion batteries and their components is concentrated in Asia [40,41]. Among them, China is the largest Li-ion battery producer and its battery industry is expected to continue its development [40,51]. LFP is used to produce the positive electrode, while the negative electrode is made of graphite, polymer and solvent. The separator between the two electrodes is made of a porous polymer and the liquid electrolyte is a mixture of organic solvent and a lithium salt. In the original inventory from study [20], the battery packing materials used to assemble cells into modules and then into battery packs is plastic. In this study, batteries are intended to be used in Quebec and a metal packaging is used instead to meet North American security standards. The energy necessary for the assembly of the various components has not been considered because no robust data could be found.

2.2.3. LMP 75 kW h and 6 MW h

The inventory used to model the LMP batteries has been validated by an LMP battery manufacturer but cannot be disclosed for confidentiality reasons. These data were corroborated by the following documents [52–55]. The positive electrode material is also made of LFP, but the negative electrode is composed of lithium metal. The electrolyte consists of a solid polymer containing a lithium salt enabling the ionic conduction. The same metal packing material is used to protect the battery.

Table 1
Performance range of LFP batteries from Batt-DB (*Source*: [50]).

	Cycle lifetime	Calendric lifetime	Efficiency
25th percentile[a]	1986 cycles	10 years	83%
Median[a]	5000 cycles	15 years	96%
75th percentile[a]	5325 cycles	20 years	96.5%

[a] The value for this percentile are based on an 80% depth of discharge (DoD).

2.2.4. Common processes

Data used to model the battery container come from [53,55] for the 75 kW h units and from [56,57] for the 6 MWh units and were adapted to fit the size of the different units. The batteries require little maintenance during the use phase, and the monitoring is performed by remote technologies. The use of one computer to provide monitoring information is considered. The hypothesis of two annual maintenance visits is also assumed. LFP batteries have very low potential recycling values in comparison to units containing high-value metals such as cobalt cathode batteries [58]. Unless legally enforced the recycling of LFP batteries does not occur due to poor or non-existent economic returns [58–60]. In Quebec, there are no recycling rate in place for the batteries investigated [61]. Therefore, given the low expected economic return and as confirmed by industry experts, it is estimated these batteries are not recycled under current conditions. In Canada, there is only one facility based in British Columbia at approximately 4500 km from Quebec that ensures the end-of-life treatment of Li-ion batteries. Regulations about import and export of waste make the use of closer treatment sites in the United States impossible. The batteries are brought by truck to the treatment facility. Steel containers are considered to be 100% recyclable, and the refurbishing processes are left out of the inventory following the cut-off approach. Finally, the production of the electricity stored in the batteries comes from wind power sources as it is the largest intermittent renewable electricity source currently available in Quebec [62].

2.3. Impact assessment method

The impact assessment method IMPACT 2002+ [63] is used in this study. This method offers a combined impact and damage approach [47]. It characterizes close to 1500 different environmental flows into 14 midpoint categories[5] and then into four endpoint categories [64]. Midpoint and endpoints approaches are complementary [65]. On the one hand, midpoints identify potential environmental impacts in a wide range of categories, providing results that are more detailed with a lower uncertainty and considered more robust scientifically [66,67]. On the other hand, the endpoint approach objective is to model these impacts into damages made to areas that are considered important/necessary to be protected such as human health, natural environment, and abiotic environment [68]. Damage modeling involves character-

[5] The version provided by the software used in this study separates human toxicity in two categories: carcinogens and non-carcinogens. This means that results shown here display 15 categories.

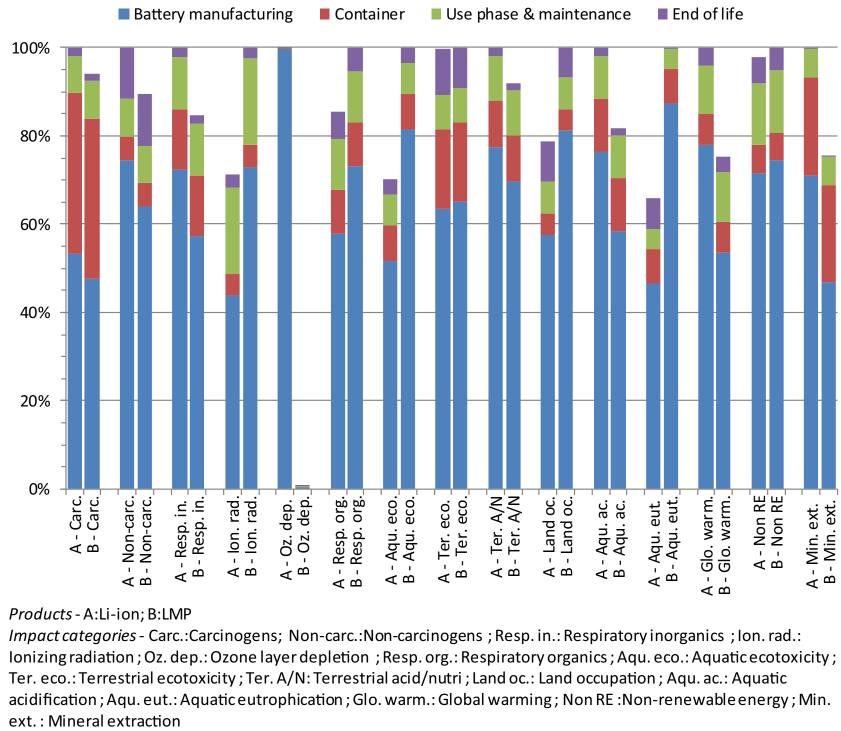


Fig. 2. Contribution and comparison analysis Li-ion and LMP 75 kW h batteries – midpoint results (Impact 2002+).

ization choices based on value choices with no scientific consensus [69]. Nevertheless, results are considered to be easier to understand [66,67] and more tangible due to the relation that is made with areas of protection [69]. IMPACTS 2002+, through its combined impact/damage construction, offers a framework that is consistent with both approaches. Therefore, the results in Section 3 are presented by using both the midpoint and the endpoint approaches.

2.4. Interpretation

In the interpretation section, the results and the conclusion of the study are tested. Two sensitivity analyses and an uncertainty analysis are conducted. These three analyses are further described in the next three subsections. Finally, the results are contrasted with the existing literature based on the review works provided in study [14].

2.4.1. Sensitivity analysis: impact method based approach

This sensitivity analysis aims to evaluate whether the results change when a different impact assessment method is used. For that purpose, analyses are run again with the TRACI 2.1 [70,71]. Even though this method is less detailed than the used method (IMPACT 2002+), it is more adapted geographically to the North-American context which makes it relevant here.

2.4.2. Sensitivity analysis: key performance parameters

In this section, the key performance parameters are changed using value from the 25th and 75th percentiles of the Batt-DB instead of the median value. The aim is to illustrate the influence of performance parameters on the environmental impacts of batteries.

2.4.3. Uncertainty analysis: Monte-Carlo Simulation

The uncertainty of the results related to inventory data factors is tested with a Monte Carlo analysis. The goal is to draw the uncertainty distribution of our results by recalculating them with a fixed number of 1500 iterations and a confidence interval of 95% according to random variables for each input based on their standard deviation and their probability distribution [72,73]. The Monte Carlo analysis is also used to determine if the difference drawn from comparative analyze is significant. The analysis is run jointly for the compared product systems, and the distribution of the relative difference in the results is constructed [47]. A difference between the impact results of the two products is usually considered to be significant when at least 90% of the run is going in the same direction [72].

3. Results

The first two sections are dedicated to contribution analysis of the four different models of batteries, with Section 3.1. analyzing centralized and distributed Li-ion models and Section 3.2 analyzing centralized and distributed LMP models. A contribution analysis integrating the impacts of the electricity production is realized in Section 3.3. The subsequent two sections are dedicated to comparative analysis. In Section 3.4 the environmental performance of LMP and Li-ion technologies are compared. Section 3.5 presents the result from the comparison of centralized and distributed configurations. Finally, Sections 3.6 and 3.7 respectively perform sensitivity and uncertainty analyses.

The production of the stored electricity and its delivery are left out of the different contribution and comparison analyses except in Section 3.3 and Section 3.6.2. Indeed, all compared batteries store and deliver the same type of electricity. They are also considered to perform similarly regarding efficiency and depth of discharge. Therefore, the electricity stored, lost and delivered will not affect how the units are compared to each other in terms of environmental performance. This choice allows concentrating on the environmental profile of the batteries' life cycles only.

3.1. Contribution analysis Li-ion battery

In this part, the midpoint and endpoint results for the 75 kWh and 6 MWh Li-ion batteries are analyzed. The life cycle stages and processes with a significant contribution to the total impact results are identified and discussed. Additionally, detailed contribution analysis per midpoint and endpoint categories are available in the supporting information.

3.1.1. Midpoint results of the 75 kW h and the 6 MW h

The midpoint results for the Li-ion and LMP 75 kW h batteries are represented in Fig. 2. The contribution of the different life cycle stages to the total score are represented by the stacked elements inside the bars. In this section, only the impacts of Li-ion units are discussed and analyzed.

For the 75 kW h battery, as shown in Fig. 2, the manufacturing stage is the largest contributor across all impact categories with scores ranging from 99% to 53%. Secondly, the battery container production contribution is a maximum of 36% and a minimum of 0.1%. This stage causes the second largest portion of the total impact in nine of the fifteen midpoint categories. Finally, Fig. 2 also shows that the use and maintenance phase impacts range between 27% and 0.1% and is the second largest contributor in four of the categories.

Among the different processes composing the battery manufacturing stage, the ancillary elements are responsible for the majority of the impacts. Their contributions to this stage's impacts range from 77% to 0.1% and are above 50% in thirteen of the impact categories. Ancillary components include the following elements: the battery management system, cells packaging, modules and packs packaging. The battery management system is responsible for shares of the ancillary components' impacts that range from 98% to 36%. Within the battery management system, the integrated circuits are responsible for shares of the impacts ranging from 98% to 28%.

The impacts of the battery container production are caused by the steel required to make the container and the base concrete slab. The steel represents between 99% and 68% of the different impacts, and the base concrete slab contributes between 31% and 0.4%.

The impacts of the use and maintenance phase are caused mainly by the computer use that is required to operate the battery. A more detailed contribution analysis that discusses several impact categories individually is provided in the supporting information at Section SI 1.1.

The midpoint results for the Li-ion and LMP 6 MW h units are available in Fig. 3 and follow the same structure as Fig. 2. In this section, only the results for the Li-ion unit are analyzed.

In the case of the 6 MWh battery (see Fig. 3), the production step is also the largest contributor in all the impact categories with scores ranging from 94% to 81%. The end of life stage causes the second largest portion of the total impact in ten of the impact categories with shares between 13% and 0.1%. The processes related to the battery container cause shares of the impacts ranging from 11% to < 0.01% and are the third highest contributors in ten categories and the second position in five of them.

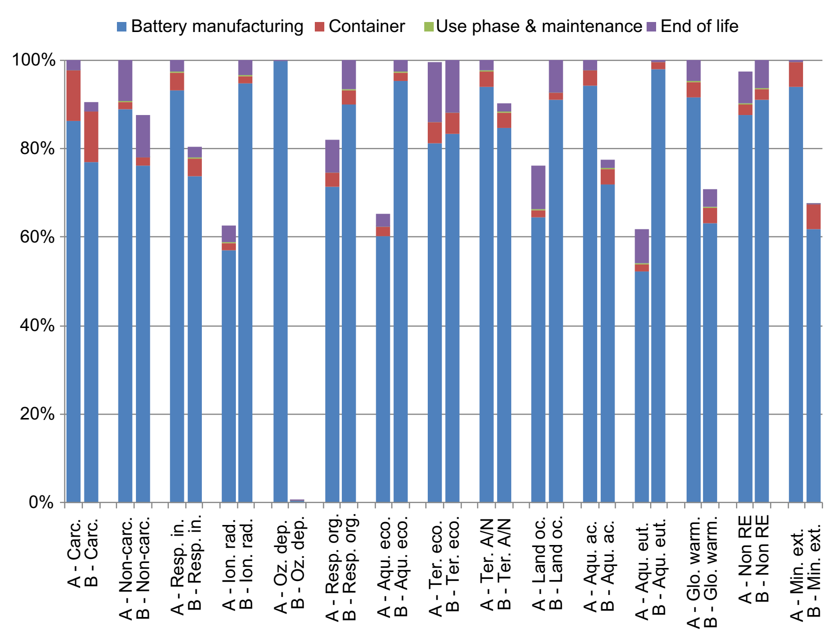
Among the different processes composing the battery manufacturing stage, the ancillary elements are responsible for the majority of the impacts. Their contributions to the impacts of the manufacturing stage range from 76% to 0.1% with shares above 50% in thirteen of the impact categories. The battery management system is responsible for shares of the ancillary components' impacts that range from 89% to 32%. Within the battery management system, the integrated circuits are responsible for shares of the impacts from that stage ranging from 96% to 28%.

The impacts of the end of life stage are caused mainly by the transport of the battery to the treatment plant in British Columbia. The transport is responsible for shares of this stage's impact that range from 97% to 2% and that are above 70% in eleven of the impact categories. Finally, impacts caused by the battery container come from its steel component and concrete slab. The steel causes shares ranging between 98% and 30% of this stage's impacts and the concrete slab production from 70% to 2%. Again, a more detailed contribution analysis that discusses several impact categories individually is provided in the supporting information at Section SI 1.3.

3.1.2. Endpoint results of the 75 kW h and the 6 MW h

The endpoint results of the 75 kW h Li-ion and LMP units are represented in Fig. 4. The contribution of the different life cycle stages to the total score is presented by the stacked elements inside the bars. The results for the Li-ion units are analyzed and discussed in this section.

For the 75 kW h battery (see Fig. 4), the damage scores are dominated by the production stage with a share that ranges from 78% to 65%. The battery container production processes are respon-



Products -A:Li-ion;B:LMP
Impact categories-Carc.:Carcinogens; Non-carc.:Non-carcinogens ; Resp. in.: Respiratory inorganics; Ion. rad.: Ionizing radiation; Oz. dep.: Ozone layer depletion ; Resp. org.: Respiratory organics; Aqu. eco.: Aquatic ecotoxicity ; Ter. eco.: Terrestrial ecotoxicity ;Ter.A/N: Terrestrial acid/nutri ;Landoc.:Land occupation ;Aqu. ac.: Aquatic acidification; Aqu. eut.: Aquatic eutrophication; Glo.warm.: Global warming; Non RE :Non-renewable energy ;Min. ext.: Mineral extraction

Fig. 3. Contribution and comparison analysis Li-ion and LMP 6 MWh batteries – midpoint results (Impact 2002+).

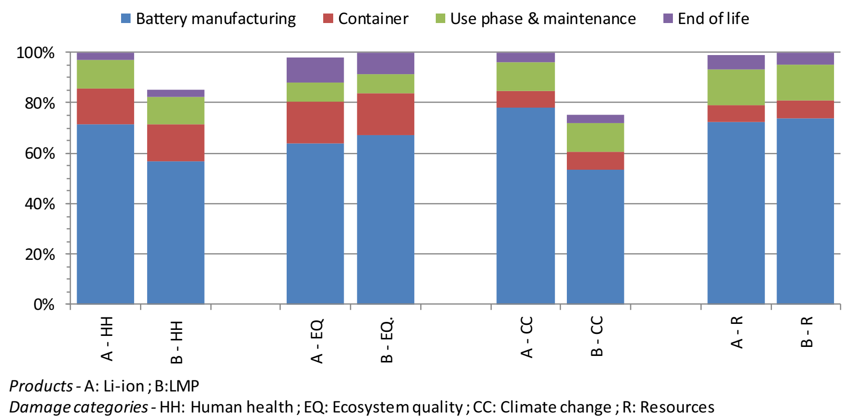


Fig. 4. Contribution and comparison analysis Li-ion and LMP 75 kWh batteries – endpoint results (Impact 2002+).

sible for a share of the damages between 17% and 7%. The use and maintenance phase contributes a share ranging from 14% to 8%. Finally, the end of life phase causes a proportion of the damage varying between 10% and 3%. These contributions and hot spots confirm the results described in the midpoint contribution analysis for 75 kW h unit.

The endpoint results for the Li-ion and LMP 6 MWh units are available in Fig. 5 which follows the same structure as Fig. 4. In this section, only the results for the Li-ion unit are analyzed.

In the case of the 6 MWh battery (see Fig. 5), the damage scores are dominated by the battery production processes. This step is responsible for proportions of the damage scores that range between 92% and 83%. The battery container production processes are responsible for a share of the damages between 4% and 3%. The use and maintenance phase contribute with a share of around 0.2% in all categories. Finally, the end of life phase causes a proportion of the damage varying between 12% and 3%. These results are in line with the results obtained for the contribution analysis of the midpoint score of the centralized unit.

A more detailed contribution analysis that discusses several damage categories individually is provided in the supporting information for the endpoint results of both types of units at the Sections SI 1.2. and SI 1.4.

3.2. Contribution analysis LMP battery

In this part, the midpoint and endpoint results for the 75 kW h and 6 MW h LMP batteries are analyzed. The life cycle stages and processes with a significant contribution to the total impact results are identified and discussed.

3.2.1. Midpoint results of the 75 kW h and the 6 MW h

The midpoint results of the 75 kW h and 6 MWh batteries represented in Figs. 2 and 3 are discussed and analyzed here.

With regards to the 75 kW h battery, as shown in Fig. 2, the manufacturing step is the largest contributor across all impact categories and is responsible for shares of the impacts that vary from 87% to 50%. The battery container production contributes to a share of the impacts that ranges from 39% to 5%. This stage causes the second largest portion of the total impact in eight of the fifteen midpoint categories and is the third contributor in six of them. The use and maintenance phase causes impacts ranging from 19% to 4% and is the third largest contributor in eight of the categories and the second contributor in six of them.

Among the different processes comprising the battery manufacturing stage, the ancillary elements are responsible for the majority of the impacts. Their contributions to this stage's impacts range from 94% to 56%. Ancillary components include the following elements: the battery management system, cells packaging, modules and packs packaging. Among these, the integrated circuits used for the battery management system are responsible for shares of the ancillary components’ impacts that range from 98% to 56%.

The impacts of the battery container production are caused by the steel required to make the container and the base concrete slab. The steel represents between 99% and 68% of the impacts caused by the battery container production, and the base concrete slab contributes between 31% and 1%. Finally, the impacts of the use and maintenance phase are caused mainly by the computer use required to operate the battery. These processes correspond to a share of 96% and 4% of this stage. A more detailed contribution analysis that discusses several impact categories individually is provided in the supporting information at Section SI 2.1.

In the case of the 6 MWh battery, as shown in Fig. 3, the manufacturing stage is the largest contributor in all the different impact categories and is responsible for shares of the impacts that

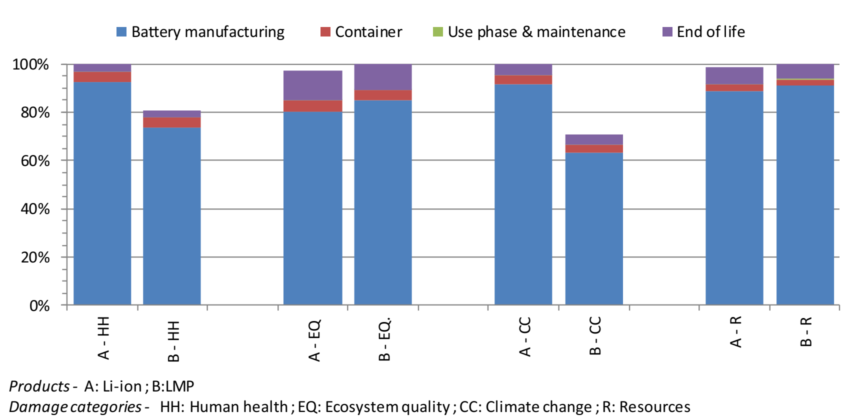


Fig. 5. Contribution and comparison analysis Li-ion and LMP 6 MW h batteries – endpoint results (Impact 2002+).

vary between 98% and 85%. The end of life stage causes the second largest impact in nine of the impact categories with a share of the total impact of between 12% and 0.4%. The processes related to the battery container cause shares ranging from 13% to 2% and are the third contributors in nine categories and second in six of them. Among the different processes composing the battery manufacturing stage, the ancillary elements are responsible for the majority of the impacts. Their contributions to the impacts of this stage range from 94% to 56%. Among the ancillary components, the integrated circuits used for the battery management system are responsible for shares of this stage's impacts that range from 98% to 56%.

The impacts of the end of life stage are caused mainly by the transport of the battery to the treatment plant in British Columbia. The transport is responsible for shares of this stage's impacts that range from 95% to 30% and that are above 70% in eleven of the impact categories. The impacts of the battery container production are caused by the steel required to make the container and the base concrete slab. The steel represents shares of between 98% and 30% of the impacts caused by the battery container production, and the base concrete slab contributes to shares between 70% and 2%. Again, a more detailed contribution analysis that discusses several impact categories individually is provided in the supporting information at section SI 2.3.

3.2.2. Endpoint results of the 75 kW h and the 6 MW h

The endpoint results of the 75 kW h and 6 MW h batteries represented in Figs. 4 and 5 are analyzed and discussed here. The battery production processes dominate the damage scores of the 75 kW h battery (Fig. 4). This step is responsible for portions of the damage scores that range between 74% and 66%. The battery container and the maintenance phase are responsible for a share of the damages between 17% and 7%. The use and maintenance phase contribute with a share ranging from 15% to 8%. Finally, the end of life phase causes a proportion of the damage varying between 8% and 3%. The manufacturing stage dominates the damage scores of the 6 MWh battery (Fig. 5). This step is responsible for portions of the damage scores that range from 91% to 85%. The end of life phase causes a proportion of the damage varying between 11% and 4%. The battery container and the maintenance phase are responsible for a share of the damages between 5% and 2%. Finally, the use and maintenance phase contributes a share of around 0.2% in all categories. A more detailed contribution analysis that discusses several damage categories individually is provided in the supporting information at Section SI 2.2 for the 75 kW h unit and SI 2.4 for 6 MW h unit.

3.3. Contribution analysis considering the battery life cycle and the electricity

The midpoint results for the Li-ion and LMP 75 kW h batteries including the battery life cycle, the production of electricity, its storage and its supply are presented in Fig. 6. The impacts originating from the electricity processes are separated into electricity that is lost and electricity that is delivered. The results for the 6 MWh units are available and presented in a similar graph in Fig. A.2. In addition, the endpoint results for the 75kWh and the 6 MWh units are available in Figs. A.3 and A.4.

The production of the electricity stored in the batteries comes from wind power sources. For the 75 kW h battery, as shown in Fig. 6, the impacts caused by the Li-ion battery in the ozone layer depletion category and by the Li-ion and LMP units in the aquatic eutrophication category are largely dominated by the battery life cycle. In the case of ozone layer depletion, this is explained by the use of PTFE in the Li-ion units. The important aquatic eutrophication is caused by the sulfidic tailing linked to the extraction of different metallic materials. In all the other categories, the share of the battery life cycle to the total impact scores are ranging from 32% to 78%. With regards to the 6 MWh units, the trend is similar with a slight decrease of the importance of the battery life cycle in the total scores (see Section 3.5). In this case, the share of the battery life cycle is ranging from 26% to 72%. Finally, the share of the total impacts caused by the electricity loss comprises between less than 1–3% across all categories and for both the Li-ion and LMP technologies in their centralized and distributed formats.

3.4. Li-ion and LMP comparative analysis

In this section, Li-ion and LMP are compared through the midpoint and endpoint approaches. For the sake of conciseness, the comparison of the batteries with a 75 kW h capacity is the only one discussed here.

3.4.1. Midpoint

The comparison between the midpoint results of the 75 kW h batteries is represented in Fig. 2 and discussed here. The 6 MW h batteries are compared according to their midpoint score in Fig. 3. Additionally, the numerical impact scores for the different individual technology are available in Table A1.

The largest difference between the two types of batteries is observed in the ozone layer depletion category with a difference of 99%. This difference is due to the presence of PTFE used as a binder in the electrode paste in the case of the Li-ion batteries. LMP batteries do not contain any PTFE. For the other impact categories, the difference is explained as follows:

Aquatic eutrophication: for this category, there is a difference of 34% between the two technologies. LMP is more impactful than Li-ion because it requires a larger part of integrated circuits which, in turn, requires blasting processes to extract the gold responsible for sulfidic tailing. Similarly, there is a larger consumption of lithium iron phosphate for the LMP battery than in the Li-ion battery.

Ionizing radiation: LMP is more impactful for this category due to a more significant consumption of power coming from nuclear sources in the electricity mix used to produce integrated circuits. The difference between the LMP and Li-ion is 29%.

Aquatic Ecotoxicity: for this category, there is a difference of 30% between the two technologies. LMP is more impactful for that category because it requires more integrated circuits and consequently more blasting to extract its gold component.

Land occupation: the difference between the LMP and Li-ion is 21%. LMP is more impactful for that category due to a greater use of integrated circuits which requires gold. Gold extraction involves large mine infrastructure and blasting which causes sulfidic tailing. Similarly, there is a larger use of lithium iron phosphate in the LMP battery than in the Li-ion battery. Lithium iron phosphate uses phosphoric acid which requires land occupation for the construction site and the mineral extraction.

Global warming: for this category, there is a difference of 33% between the two technologies. Li-ion causes a more significant impact because of the aluminum which comes from China and uses coal-generated power, whereas LMP aluminum is sourced in Quebec using mainly hydropower. Production of high voltage electricity from China is the largest contributor for the Li-ion battery. Second, the presence of PTFE in the Li-ion is also impactful. The emission of trifluoromethane and chlorodifluoromethane during the production process of PTFE and its preliminary chlorodifluoromethane are responsible for a significant share of the impact.

Mineral extraction: the difference between the LMP and Li-ion is 24%. Li-ion causes a more significant impact because of the copper concentrate used in the collector. The LMP does not use copper in its anode collector which is composed of aluminum foil instead. There is also a larger amount of copper concentrate used in the battery management system.

3.4.2. Endpoint

The comparison between the endpoint results of the 75 kWh is represented in Fig. 4 and for the 6 MWh batteries in Fig. 5. The

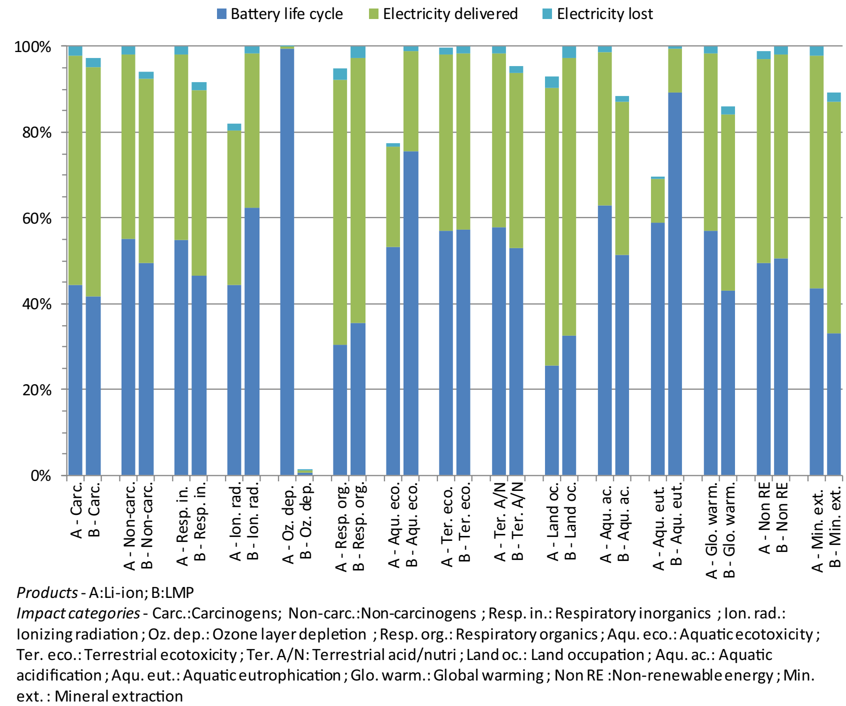


Fig. 6. Contribution and comparison analysis Li-ion and LMP 75 kWh batteries considering battery life cycle and the electricity production– midpoint results (Impact 2002+).

numerical damage results for the four type of batteries are available in Table A.2. For simplicity reasons, only the comparison between the 75 kWh units is discussed here.

The LMP battery causes 14% less damage than the Li-ion battery in the human health category. This is mainly explained by the aluminum which comes from China and using coal generated power, whereas LMP aluminum is sourced in Quebec using hydropower. There is also a larger amount of copper concentrate used in the battery management system for Li-ion. Similarly, in the climate change category, the LMP battery causes 24% less damage. The differences between Li-ion and LMP are not significant in the resources and ecosystem quality categories (see 3.1.2 Endpoint results of the 75 kW h and the 6 MWh). In this case, Li-ion causes damage respectively of 1.1% and 2.23% less than LMP.

3.5. Comparison between centralized and distributed storage

In this section, centralized and distributed system configurations are compared through the midpoint and endpoint approaches. The midpoint results of the Li-ion and LMP batteries in their 75 kW h and 6 MW h format are compared to each other and represented in Fig. 7. The corresponding graph for the endpoint results for the four batteries are presented in Fig. A.1 available in the Appendix A.

As presented in Fig. 7 and Fig. A.1, in most categories centralized storage configurations cause less impact and less damage. The only exception is the distributed LMP system that has less impact than the centralized Li-ion systems regarding ozone layer depletion and global warming/climate change. For all the other cases, the difference between the centralized configuration and its distributed configuration counterpart in the same technology comprises between 11% and 40% for the midpoint categories and between 15% and 27% in the endpoint categories.

The better performance of the centralized systems is prompted by a scaling effect that causes distributed units to have greater environmental impacts per functional unit. Indeed, for a similar output distributed units drive a greater consumption of resources and energy than a centralized system with fewer and bigger storage units. This can be explained by a fixed use of certain processes per unit of storage that occur regardless of the storage capacity. For example, there is a fixed use of several pieces of equipment (e.g. battery management system) that must be installed in every storage unit. These will, therefore, be multiplied in distributed configurations to reach the same storage capacity as in the centralized option. Similarly, the trips that must be realized for maintenance are multiplied from centralized to distributed units to reach a same output. The numerical results of the midpoint and endpoint scores for all individual technologies are available respectively in Tables A.1 and A.2.

3.6. Sensitivity analysis

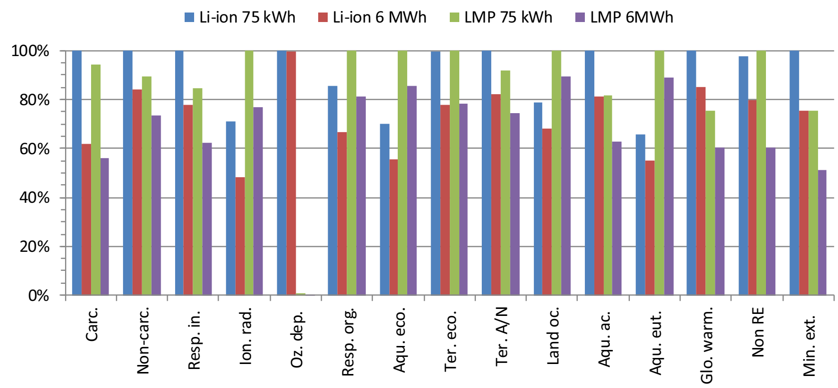
3.6.1. Impact method based approach

In this section, the comparison between Li-ion and LMP 75 kW h is conducted with TRACI, a different impact assessment method, to test if this influences the results. The TRACI impact results for Li-ion and LMP 75 kW h batteries are represented in Fig. 8. The contribution of the different life cycle stages to the total score is presented by the stacked elements inside the bars.

In most of the categories, the conclusion discussed in the Subsections 3.1 and 3.2 remains the same despite the changes of the environmental impact method. For the common impact categories between IMPACT 2002+ and TRACI, the investigation is provided in more details, as follow:

Ozone Depletion: TRACI and IMPACT 2002+ show that LMP is much less impactful than Li-ion with regards to ozone layer depletion. The difference between the two results is superior to 99% with both methods.

Global warming: both methods reach the conclusion that LMP causes less impact in terms of global warming. The difference between Li-ion and LMP with IMPACT 2002+ is 25% and with TRACI is 38%. This spread is exacerbated by differences in characterization of the emissions involved in the production of PTFE and chlorodifluoromethane which are not present in the LMP batteries. For example, emission of chloridofluoromethane has a characterization factor of 1810 with TRACI and of 540 with IMPACT 2002+. With TRACI, PTFE is allocated an emission of 7.99 kg CO2 eq. and is the main contributor. In the case of IMPACT 2002+, the PTFE production represents an



Impact categories - Carc.:Carcinogens; Non-carc.:Non-carcinogens ; Resp. in.: Respiratory inorganics ; Ion. rad.: Ionizing radiation ; Oz. dep.: Ozone layer depletion ; Resp. org.: Respiratory organics ; Aqu. eco.: Aquatic ecotoxicity ; Ter. eco.: Terrestrial ecotoxicity ; Ter. A/N: Terrestrial acid/nutri ; Land oc.: Land occupation ; Aqu. ac.: Aquatic acidification ; Aqu. eut.: Aquatic eutrophication ; Glo. warm.: Global warming ; Non RE :Non-renewable energy ; Min. ext. : Mineral extraction

Fig. 7. Midpoint comparison distributed and centralized system configurations (Impact 2002+).

emission of 2.44 kg CO2 eq. and is the third largest contributor.

Carcinogens: the results are different in this category. TRACI concludes that LMP causes more impact than Li-ion with a difference of 13% whereas IMPACT 2002+ reaches the opposite conclusion with a difference of 6%. The main difference between the two methods, in this case, concerns the characterization of the process “Slag, unalloyed electric arc furnace steel RoW”. With TRACI, it is responsible for an important share of the impact with 63% of the impacts caused by the Li-ion battery and 59% by the LMP battery. It has no characterization factor with IMPACT 2002+ and is not accounted for in the results. This process occurs more often in the LMP battery lifecycle which explains partly why the LMP unit causes more impacts.

Non-carcinogens: similarly, the results are different. TRACI concludes that LMP causes more impact than Li-ion with a difference of 35% whereas the IMPACT 2002+ result shows the opposite with a difference of 10%. In this case, the process “Sulfidic tailing, off-site {GLO} treatment” caused 91% of the impact for the LMP battery and 87% of the Li-ion battery and once again is not characterized by IMPACT 2002+.

Eutrophication: both methods reach the conclusion that Li-ion causes less impact in terms of eutrophication. The difference between LMP and Li-ion with IMPACT 2002+ is 34% and with TRACI is 34%.

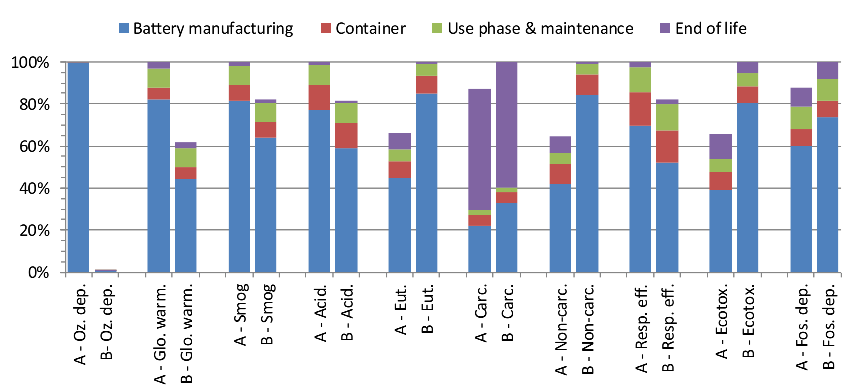
Fossil fuel depletion: LMP is responsible for a greater impact than Li-ion in fossil fuel depletion. The difference of 12% is more significant with TRACI than for IMPACT 2002+ with 2%.

3.6.2. Key performance parameters

The variation in the performance parameters influences the amount of battery required per MW h but also the electricity lost in each cycle. For this reason, the impact from the electricity processes is also taken into account in this sensitivity analysis. The midpoint results for the LMP 75 kW h batteries using the different values from Batt-DB (see Table 1) for the performance parameters and considering the electricity processes are calculated. The midpoint results for the units located at the 75th percentile and compared to the units at the median are presented in Fig. A.5 and the comparison between the 25th percentile and the median is available in Fig. A.6. The difference between the performance parameters from 75th percentile and the median are less important than the difference between the median and the 25th percentile. This results in changes of the impact scores that range from 3% to 5% in the first case and differences comprised between 42% and 63% in the second case. In comparison to the median, the performance parameters from the 75th percentile decrease the amount of batteries needed per MWh by 7%, while batteries at 25th percentile increase this amount by 191%.

3.7. Uncertainty analysis

The simulation is performed for the midpoint comparison between the 75 kW h Li-ion (A) and LMP (B) battery and is presented in Fig. 9. This figure shows, among the 1500 iterations tested, in what proportion the 75 kW h Li-ion and the 75 kW h LMP are superior or inferior to each other



Products - A: Li-ion ; B:LMP
Impact categories - Oz. dep.: Ozone depletion ; Glo. warm.: Global warming ; Smog ; Acid.: Acidification ; Eut.: Eutrophication ; Carc.: Carcinogenics ; Non-carc.: Non carcinogenics ; Resp. eff.: Respiratory effects ; Ecotox.: Ecotoxicity ; Fos. dep.: Fossil fuel depletion

Fig. 8. Contribution and comparison analysis Li-ion and LMP 75 kWh batteries – midpoint results (TRACI).

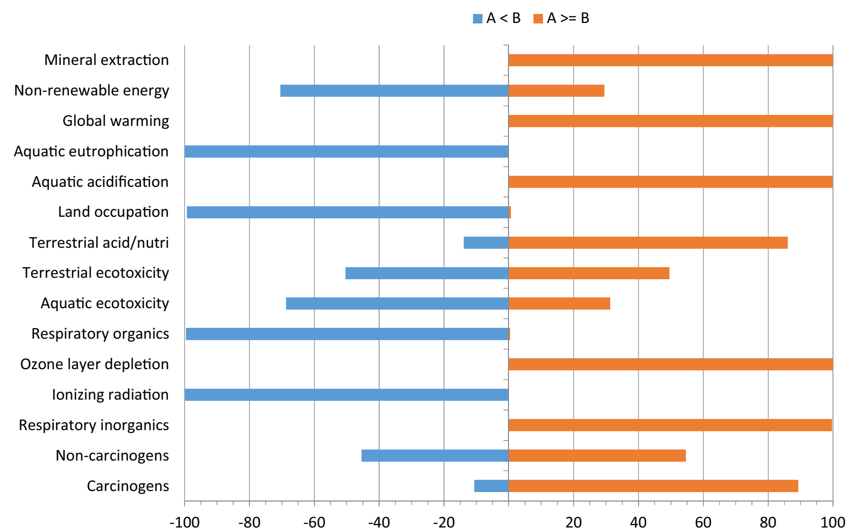


Fig. 9. Monte Carlo simulation comparison analysis Li-ion (A) and LMP (B) 75 kWh batteries – midpoint results.

Table 2
Impact scores for the global warming and non-renewable energy categories per Wh of storage capacity (Impact 2002+).

	Units	LMP 75 kW h	LMP 6 MW h	Li-ion 75 kW h	Li-ion 6 MW h
Global warming	g CO2 eq.	98.46	70.12	130.73	101.8
Cumulative energy demand	Wh	403.4	329.9	394.8	303.1

accross the different midpoint categories. According to the results of the simulation and following the 90% threshold (introduced in Subsection 2.4.3), the simulation confirms that Li-ion batteries cause more impact (A ≥ B) in respiratory inorganics, ozone layer depletion, aquatic acidification, global warming and mineral extraction. Conversely, LMP is more impactful (B ≥ A) for ionizing radiation, respiratory organics, land occupation and aquatic eutrophication. The difference between the Li-ion and LMP technology for the remaining impact categories cannot be considered as significant. It should be noted that Li-ion battery is more impactful in 89.3% of the cases in the carcinogen category.

A simulation is realized for the endpoint categories with the results displayed in a similar manner in Fig. A.7 available in the Appendix A. With regards to the endpoint categories, the simulations shown in Fig. A.7 confirm that the 75 kW h Li-ion battery causes more damage than the LMP (A ≥ B) in terms of human health in 92.5% of cases and in terms of climate change in 100% of the cases. The differences between the two technologies in the ecosystem quality and resources categories are not considered as significant.

3.8. Comparison with the literature

Peters et al. [14] computed the average impact scores for global warming and cumulative energy demand from 36 LCA studies on Li-ion batteries. The average impact scores obtained per 1 Wh of storage capacity are of 110 g CO2eq. for global warming and of 328 W h for cumulative energy demand. To be able to compare the results, these impact scores for the batteries investigated in this study are computed per Wh of storage capacity. The impact scores using this alternative functional unit are displayed in Table 2.

The results in Table 2 show that the results from this study are reasonably in line with previous findings on the environmental impacts of batteries. The 6 MWh LMP is significantly lower than average regarding the impact on global warming. This can be explained by an important part of their supply chains using hydroelectricity from Quebec and the absence of PTFE. Conversely, decentralized LMP scores higher regarding cumulative energy demand. Petroleum used in the transport processes linked mainly to the cathode and electrolyte production is the most important contributor to this category.

4. Conclusion and outlook

This study assesses the environmental profile of Li-ion and LMP stationary batteries in the context of Quebec through the LCA methodology. The environmental hotspots are identified for the different units, and the differences between them regarding environmental performances are highlighted. The environmental assessment of LMP units is based on a robust inventory validated by a battery producer. The adaptation of the inventory of the Li-ion unit to a use phase in Quebec provides new insights and enables to make consistent comparisons. The decentralization trend occurring in power systems is taken into account by assessing units installed in centralized and distributed configurations. Moreover, this LCA succeeds in offering a comprehensive assessment by exploring a broad range of environmental impacts and damages and by covering the entire life cycle of the products under scrutiny. This work provides a quantitative reference to support technology choice of stationary batteries from an environmental perspective.

The results show that the battery manufacturing stage drives the majority of environmental impacts in the four batteries investigated. More specifically, the stage of the supply chain driving the consumption of electricity in countries relying heavily on coal power and the extraction and production of various metallic components such as gold, copper, steel and aluminum are causing important environmental impacts. Li-ion batteries cause more impacts regarding ozone layer depletion and global warming impacts than LMP units. With regards to global warming, Li-ion batteries cause a more significant impact due to the larger part of their supply chains located in China and relying on electricity from coal-fired plants. The production of PTFE used only in Li-ion batteries is the main contributor to the ozone layer depletion category and an important source of global warming emissions as well. Conversely, LMP batteries are responsible for a more important aquatic eutrophication impact. The main contributor to this category is the sulfidic tailing processes that are linked to gold used in the integrated circuits. Finally, an important outcome of this study is that centralized battery system configurations bring smaller environmental impacts than distributed systems with more but smaller storage units.

Despite the comprehensiveness provided by the LCA methodology, there are elements that are not captured by the assessment. Further analysis should be carried out to include the indirect changes that the introduction of batteries prompts in power systems and which are not accounted for in the assessment. For example, the storage of the surplus power from intermittent sources and its use during peak hours can substitute conventional peak power sources which are likely to bring environmental effects worth examining. To include this type of substitution and other market-driven effects, a consequential LCA must be performed. The inclusion of these elements would bring a more representative and accurate quantification of the battery environmental profiles and would increase the relevance of such an assessment in terms of decision and policy making. Finally, the economic or social implications of using and producing the batteries are not addressed in this study. This could be achieved by performing a Multi-Criteria Decision Analysis which could integrate the result from the present assessments.

Appendix A

See Figs. A.1–A.7 and Tables A.1 and A.2.

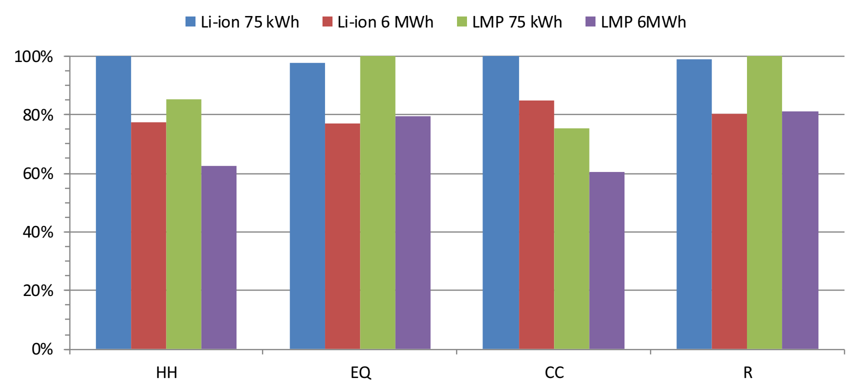
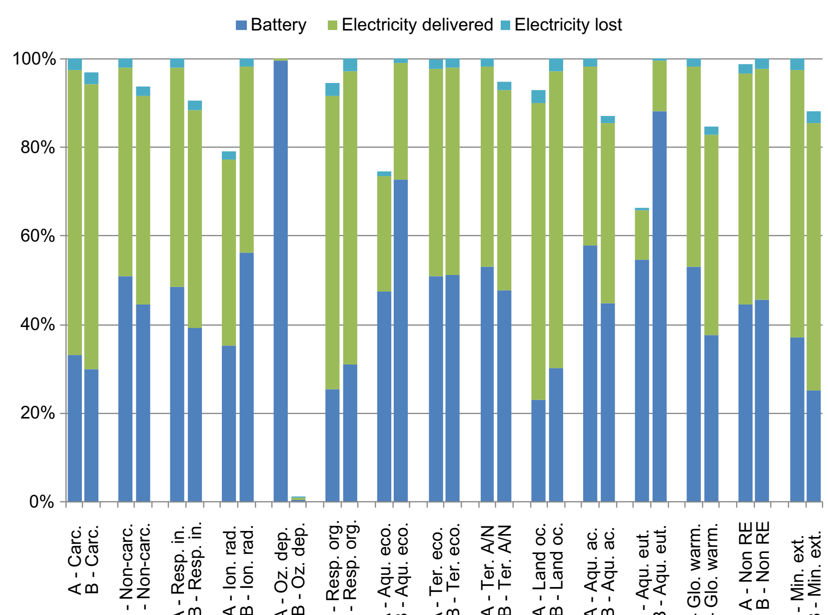


Fig. A1. Endpoint comparison distributed and centralized system configurations (IMPACT 2002+).



Products -A:Li-ion;B:LMP
Impact categories-Carc.:Carcinogens; Non-carc.:Non-carcinogens ; Resp. in.: Respiratory inorganics; Ion. rad.: Ionizing radiation; Oz. dep.: Ozone layer depletion ; Resp. org.: Respiratory organics; Aqu. eco.: Aquatic ecotoxicity ; Ter. eco.: Terrestrial ecotoxicity ;Ter.A/N: Terrestrial acid/nutri ;Landoc.:Land occupation ;Aqu. ac.: Aquatic acidification; Aqu. eut.: Aquatic eutrophication; Glo.warm.: Global warming; Non RE :Non-renewable energy ;Min. ext.: Mineral extraction

Fig. A.2. Contribution and comparison analysis Li-ion and LMP 6 MWh batteries considering battery life cycle and the electricity production– midpoint results (IMPACT 2002+).

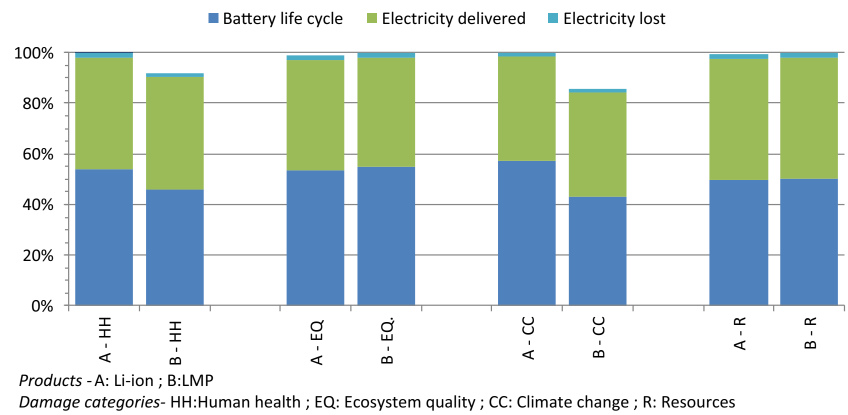


Fig. A.3. Contribution and comparison analysis Li-ion and LMP 75 kWh batteries considering battery life cycle and the electricity production– endpoint results (IMPACT 2002+).

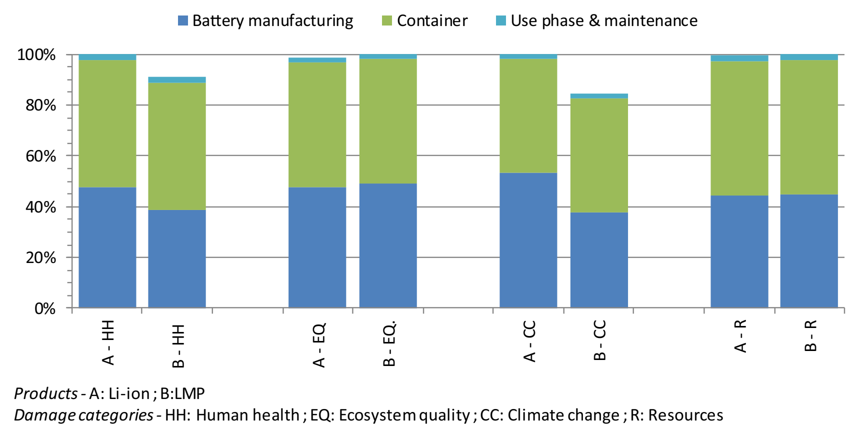


Fig. A.4. Contribution and comparison analysis Li-ion and LMP 6MWh batteries considering battery life cycle and the electricity production– endpoint results (IMPACT 2002+).

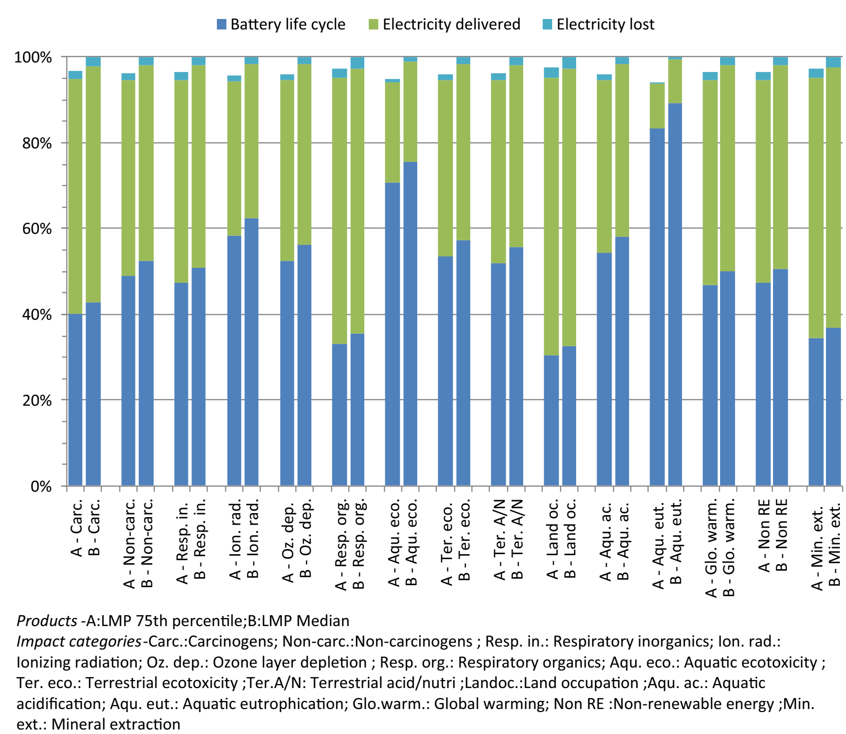


Fig. A.5. Sensitivity analysis key performance parameters - Comparison LMP 75 kWh batteries according to the value located at the Median and 75th percentile of Batt-DB – midpoint results (IMPACT 2002+).

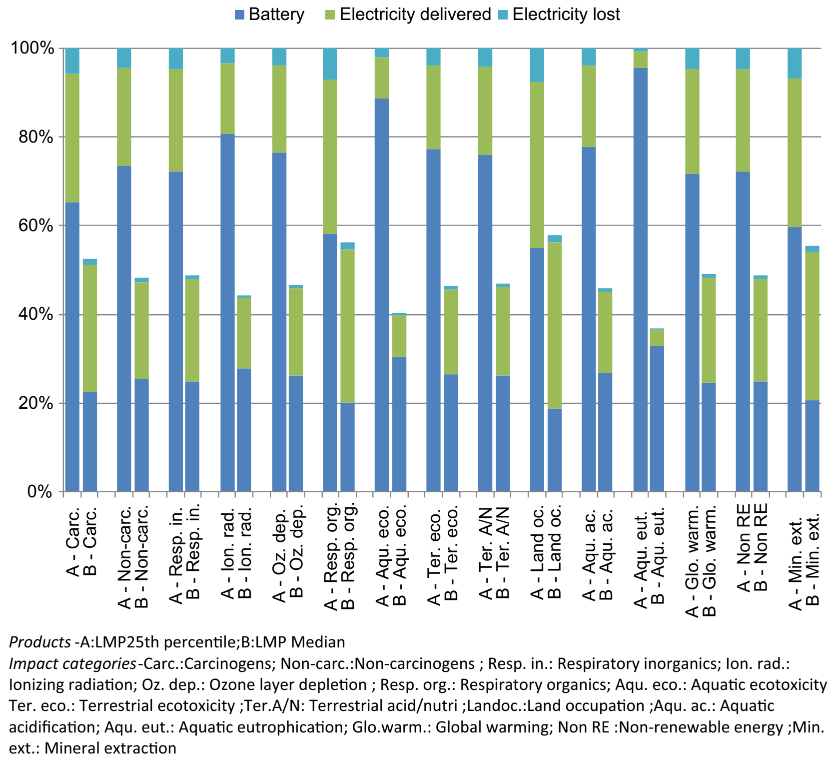


Fig. A.6. Sensitivity analysis key performance parameters - Comparison LMP 75 kWh batteries according to the value located at the Median and 25th percentile of Batt-DB – midpoint results (IMPACT 2002+).

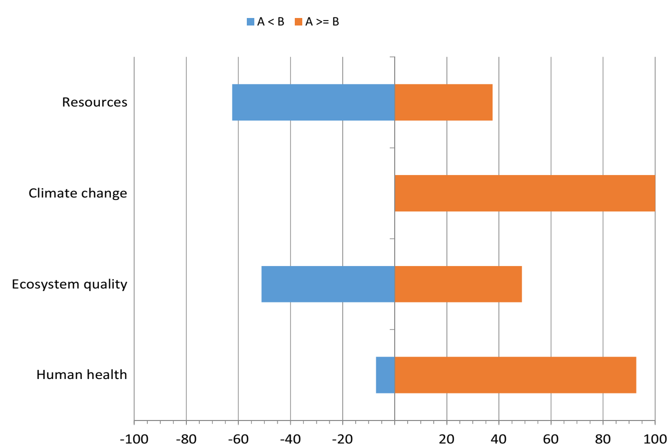


Fig. A.7. Monte Carlo simulation comparison analysis Li-ion and LMP 75 kW h batteries – endpoint results.

Table A.1
Impact scores for all individual technologies (IMPACT 2002+).

Impact category	Unit	Li-ion 75 kW h	LMP 75 kW h	Li-ion 6 MW h	LMP 6 MW h
Carcinogens	kg C2H3Cl eq	1.30E+00	1.22E+00	8.02E−01	7.27E−01
Non-carcinogens	kg C2H3Cl eq	1.43E+00	1.28E+00	1.20E+00	1.05E+00
Respiratory inorganics	kg PM2.5 eq	5.09E−02	4.32E−02	3.96E−02	3.19E−02
Ionizing radiation	Bq C−14 eq	2.86E+02	4.02E+02	1.94E+02	3.10E+02
Ozone layer depletion	kg CFC−11 eq	4.06E−04	2.49E−06	4.05E−04	2.07E−06
Respiratory organics	kg C2H4 eq	9.65E−03	1.13E−02	7.52E−03	9.17E−03
Aquatic ecotoxicity	kg TEG water	6.73E+03	9.59E+03	5.33E+03	8.19E+03
Terrestrial ecotoxicity	kg TEG soil	1.58E+03	1.58E+03	1.23E+03	1.24E+03
Terrestrial acid/nutri	kg SO2 eq	7.59E−01	6.98E−01	6.24E−01	5.64E−01
Land occupation	m2org.arable	6.91E−01	8.78E−01	5.97E−01	7.84E−01
Aquatic acidification	kg SO2 eq	2.78E−01	2.27E−01	2.25E−01	1.75E−01
Aquatic eutrophication	kg PO4 P-lim	8.53E−02	1.29E−01	7.14E−02	1.15E−01
Global warming	kg CO2 eq	3.40E+01	2.56E+01	2.89E+01	2.05E+01
Non-renewable energy	MJ primary	3.70E+02	3.78E+02	3.01E+02	3.09E+02
Mineral extraction	MJ surplus	1.57E+01	1.18E+01	1.18E+01	8.02E+00

Table A.2
Damage scores for all individual technologies (IMPACT 2002+).

Damage category	Unit	Li-ion 75 kW h	Li-ion 6 MW h	LMP 75 kW h	LMP 6MW h
Human health	DALY	4.38E−05	3.38E−05	3.73E−05	2.74E−05
Ecosystem quality	PDF*m2*yr	1.43E+01	1.13E+01	1.47E+01	1.16E+01
Climate change	kg CO2 eq	3.40E+01	2.89E+01	2.56E+01	2.05E+01
Resources	MJ primary	3.86E+02	3.13E+02	3.90E+02	3.17E+02

Appendix B. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rser.2017.04.057.

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