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| **Dissemination level** | | |
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| **PU** | **Public** | **X** |
| **CO** | **Confidential, only for members of the consortium (including the Commission Service)** | |
| **CI** | **Classified, information as referred to in Commission Decision 2001/844/EC.** | |

[1] **R:** Document, report (excluding the periodic and final reports).
**DEM:** Demonstrator, pilot, prototype, plan designs.
**DEC:** Websites, patents filing, press & media actions, videos, etc.
**OTHER:** Software, technical diagram, etc.

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| **Version** | Date | Changed by | Comments |
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| final | 23/06/2020 | L. Colmenares | Draft accepted by entire consortium. Quality check done. |

Distribution restricted to the E-MAGIC consortium.

## Table of Content

# 1. INTRODUCTION

In 2018, Li-ion batteries (LIBs) installed capacity accounts for more than 86% of the total electrochemical energy storage, and huge LIB demand is expected in the next decades especially for electric or plug-in hybrid electric vehicles. Limited resources combined with this high demand, and a current low rate of recycling have motivated the development of next-generation rechargeable batteries to replace LIBs.

All of this brings the European Union to launch in January 2019 a 4-year project, called E-Magic, and intended to succeed in several breakthroughs in Magnesium-based storage technologies.

The main objectives of this document are to:

- conduct a literature review on rechargeable Magnesium batteries (RMBs) environmental life cycle assessment (LCA) and summarize the results to identify main key drivers.
- elaborate an environmental profile of the future RMB technology.
- provide recommendations to research teams in order to minimize environmental impacts in terms of manufacturing energy, selected materials, battery features (…). These recommendations will be made, as knowledge and technology advance.

First, this document is going to gather the main features of available literature on the matter concerned, and to describe used methodology and system boundaries. Then, results will be analysed to depict environmental key drivers and understand potential discrepancies. Finally, an environmental profile of the expected technologies will be drawn from the literature review, emphasizing specific points on which researchers should pay attention to in order to, as far as possible, lower Mg-based batteries environmental burden.

# 2. LITERATURE REVIEW

## 2.1. Overview of existing studies

A literature review is conducted to identify all available studies published on environmental impact of Mg-batteries. Only one Life Cycle Assessment (LCA) study came out on Google Scholar using the search string "Mg battery LCA" and "Mg battery environment". It has been carried out by Tomasini Montenegro et al. and was released by the Royal Society of Chemistry in 2020.

Therefore, research for other battery types LCA is needed to widen our global knowledge on battery environmental burden and apply it as much as possible to Mg-based batteries. Search string "battery environment", "battery LCA", "Li battery LCA", "Na battery LCA" have been used in a second phase.

Many environmental studies have been drawn up in the last twenty years on batteries related to the increasing presence of batteries in mobile and stationary energy storage applications. Priority to LCA studies is given in this literature review because this standardized methodology facilitates results comparison and drawing conclusions. They have been written by different researcher teams and displayed sometimes divergent results. Recently, a comparison work was conducted by Peters et al. and the IVL Swedish Environmental Research Institute in 2019 to find out the reasons for the wide range of results and gather them into an acceptable narrow range.

Li-metal and Li-S batteries industrial prototypes have been environmentally assessed. Among search results generated, some papers providing an LCA study have been selected and have been examined in detail. For example, publications that are used and quoted in comparison works haven't been taken into account.

***Table 1*** provides information about papers selected from results of the conducted literature review.

| Topics | How many | Who? | When? | Where? |
|---|---|---|---|---|
| Li-S | 2 | 4 ; 5 ; | 2018-2019 | Sweden, US |
| Mg-S | 1 | 1 ; 2 ; 3 ; | 2017-2020 | Germany |
| Na-ion | 1 | 1 ; 2 ; 3 ; | 2016 | Germany |
| Li-ion | 16 | 1 - 16 ; | 2010-2019 | Germany, US, Sweden, Norway, Switzerland, China, France |

| **LEGEND of table 1 :** | | |
|---|---|---|
| 1 | HIU | Helmholtz Institute Ulm (Germany) |
| 2 | ITAS | Institute for Technology Assessment and Systems Analysis (Germany) |
| 3 | KIT | Karlruhe Institue for Technology (Germany) |
| 4 | - | Department of Mechanical Engineering, University of Wisconsin (Milwaukee, WI, the United States) |
| 5 | - | Department of Mechanical and Aerospace Engineering, Case Western Reserve University, (OH, the United States) |
| 6 | IVL | Swedish Environmental Research Institute (Sweden) |
| 7 | EPA | Environmental Protection Agency (the United States |
| 8 | EMPA | Technology and Society Laboratory, Swiss Federal Laboratories for Materials Science and Technology (Switzerland) |
| 9 | NTNU | Norwegian University of Science and Technology (Norway) |
| 10 | - | Beijing Key Laboratory of environmental science and engineering, Beijing Institute of Technology (China) |
| 11 | ANL | Argonne National Laboratory (Unites States) |
| 12 | CNRS UMR | Laboratoire de Réactivité et Chimie des Solides UPJV (Amiens, France) |
| 13 | - | ALISTORE-European Research Institute (Amiens, France) |
| 14 | UPMC | Sorbonne Universités UPMC (Paris, France) |
| 15 | RS2E | Réseau sur le Stockage Electrochimique de l'Energie (France) |
| 16 | - | Collège de France (Paris, France) |

***Table 1** : Main features of examined studies on battery environmental impacts*.

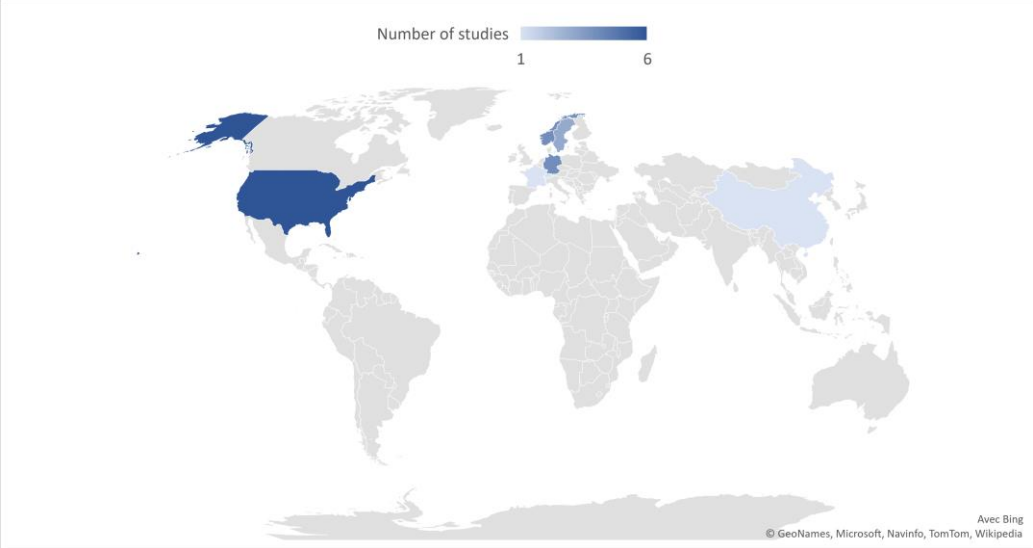



**Figure 1:** *Geographical repartition of the released studies.*

**Table 1** and **Figure 1** show that most of the LCA studies examined in this work are carried out by researcher teams in European countries and in the United States. China has also published some papers, recently more focused on recycling or remanufacturing Li-ion batteries. All the reviewed studies are listed in the bibliography at the end of this report.

## 2.2. Impacts assessment methodology

"LCA" is often used as keyword in the conducted literature review and all the environmental studies on battery that have been taken into account in this work use an LCA approach. This approach is described in the following paragraphs.

### 2.2.1. Life Cycle Analysis approach

It is possible to compare the environmental performance of the battery production by using the "Life Cycle Assessment" (LCA) approach. An LCA is performed by calculating all the energy and material inputs, and the associated emissions and waste outputs, over a whole life cycle, from raw material acquisition to ultimate disposal.

This method has the advantage of incorporating a wide range of environmental issues into an integrated assessment framework.

The LCA approach is based on the International Organization for Standardization (ISO) standard 14040 (2006). The fundamental step, which could lead to significant uncertainties, is the **Life Cycle Inventory** (LCI). It consists of listing all the needed material and quantifying them. Studied product system, system boundaries, functional unit, chosen impact categories and assumptions must be described to address the stated goal.

Some of the impact categories are partially redundant; for example, Abiotic Depletion and Mineral Depletion Potentials (ADP and MDP) use different settings and are usually calculated differently. The most suitable impact categories for battery application are described in 2.2.2 section.

Calculations rely on some proprietary softwares (SimaPro, GaBi, Umberto, …) that can incorporate databases (EcoInvent, GaBi database, ELCD,…) of previous LCAs for inputs such as chemical reagents.

### 2.2.2. Associated environmental impacts

It wonders at this stage what are the impact categories that are as representative as possible of the global environmental impact for batteries.

Peters et al. conducted a literature review in 2016 to identify all available LCA studies on lithium batteries: overall, 36 LCA studies from 2009 to 2016 were evaluated regarding their objective, scope, and considered impact categories. To assess the relevance of the selected impact categories, they choose to normalize the LCA results by dividing the average annual impacts generated in Europe in 1995 (cf. **Figure 2**).

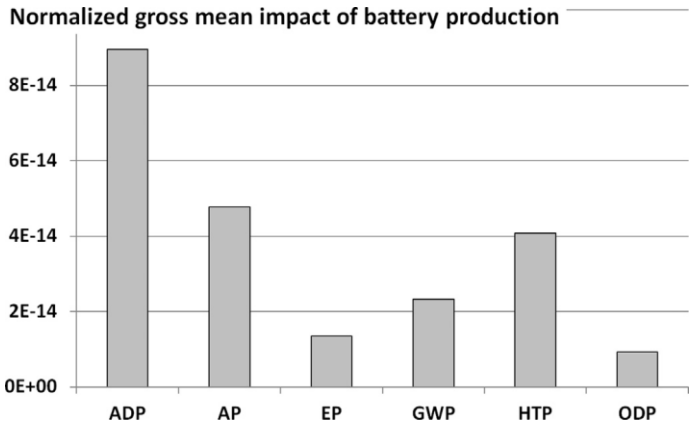



**Figure 2:** *Normalized average environmental impacts of Li-ion batteries (Peters et al., 2016).*

| **Legend :** | |
|---|---|
| ADP: Abiotic Depletion Potential. | AP: Acidification Potential. |
| EP: Eutrophication Potential. | GWP: Global Warming Potential. |
| HTP: Human Toxicity Potential. | ODP: Ozone Depletion Potential. |

Whereas GWP and Cumulative Energy Demand (CED) are by far the most assessed categories in literature, **Figure 2** shows that it would be relevant to also include the following categories for the future battery LCA. Thus, in frame of E-MAGCI project, it will as much as possible (depending on available results) present LCA results for **ADP, AP, HTP,** and **GWP** impacts categories.

### 2.2.3. System boundaries

The environmental assessments can stop part-way through a life cycle: some LCA studies on batteries have a « cradle-to-gate » approach, encompassing raw material production, cathode and anode manufacturing, electrolyte preparation, cell assembly until the factory gate (cf. **Figure 3**). The cradle-to-grave or well-to-wheel approaches are also used in literature, including the use and end-of-life stages.

Nevertheless, the use and end-of-life stages might be dismissed because:

- they may be quite different from one battery type to another (lifetime, electricity mix, energy capacity loss, and end-of-life definition) and,
- they may introduce high uncertainties due to a lack of recycling/reuse industrial data available.

To avoid adding more uncertainties than those already identified, in frame of E-MAGIC it has chosen to focus the environmental profile on a **cradle-to-gate perimeter**. Therefore, studied systems comprise the production of all the components (anode, cathode, separator, electrolyte, and casing), their assembly into a cell, and then battery pack manufacture, including the Battery Management System (BMS) and the cooling system.
A few words will be added about the key parameters which substantially impact the use and end-of-life phases in Sections 2 and 3, without getting too much into details.

The mainly used functional unit is defined as **1 kWh of storage capacity** provided by the battery. It seems to be one of the best options to ensure that different battery types can be compare in a cradle-to-gate approach, considering similar performances of use (Matheys et al., 2007). So, we will keep this functional unit in the Mg-battery environmental profile.

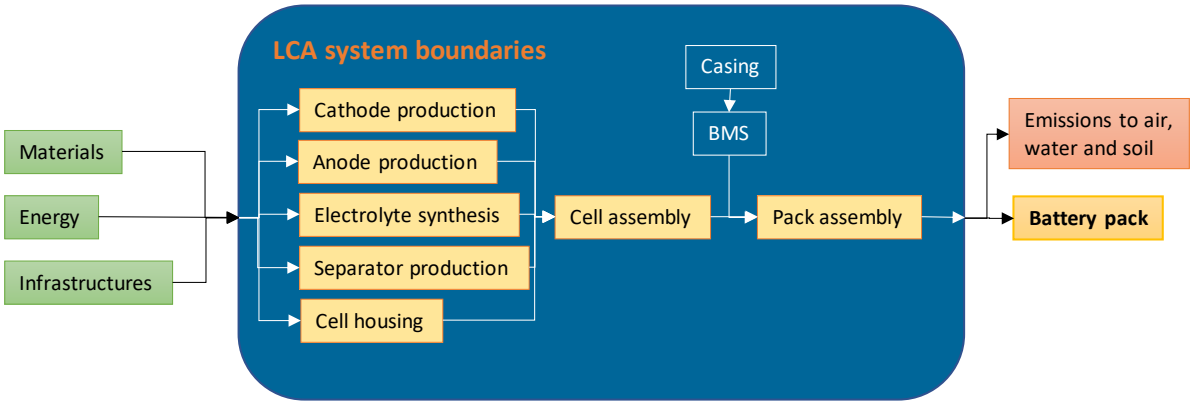



***Figure 3 :*** *System boundaries schematic description in cradle-to-gate approach.*

## 2.3. Studied systems

Paper selected from the literature review as described in Section 2.1 emphasizes two main battery types from an environmental point of view:

- The X-S batteries (X= Mg or Li) with a metallic anode and a mix of Carbon/Sulfur in the cathode.
- The X-ion batteries (X= Li or Na) featured by layered oxides on cathodes whereas the anode is principally made of carbon.

The studied systems of these both battery types will be successively detailed in the following subsections.

### 2.3.1. X-S based batteries

X-S batteries are discussed below.

#### 2.3.1.1. Studied battery description

The main cell components are described in the **Table 2**. It shows that many components are identical between Li-S and Mg-S batteries except for the metallic foil in the anode and nature of the electrolyte.

| | Mg-S<br>*Montenegro et al., 2020* | Li-S<br>*Arvidsson et al., 2018* | Li-S<br>*Deng et al., 2016* |
|---|---|---|---|
| Cell Energy density (kW/kg) | 57 | 200-500 | 300 |
| **HOUSING** | | | |
| *Cell container* | Aluminium composite | - | PP, PE, Aluminium |
| **ANODE** | | | |
| *Active material* | Magnesium foil | Lithium metal foil | Lithium metal foil |
| *Conductive Carbon* | | | |
| *Binder* | | | |
| *Collector foil* | | | Copper |
| **CATHODE** | | | |
| *Active material* | Sulfur | C/S Composite with mesoporous carbon and elemental sulfur | C/S composite made from graphene oxide and sodium thiosulfate |
| *Conductive Carbon* | Black Carbon | | |
| *Binder/Solvent* | SBR/CMC | PVDF/water | PVDF/NMP |
| *Collector foil* | Aluminium foil | | |
| **ELECTROLYTE AND SEPARATOR** | | | |
| *Electrolyte* | $Mg[B(hfip)_4]_2$ | LiTFSI + $LiNO_3$ + DIOX DME | LiTFSI + $LiNO_3$ + DOL DME |
| *Separator* | Polyolefin membrane | | |

**Table 2 :** *Main components and energy densities of assessed X-S batteries.*

A common flow chart of the X-S battery LCA has been drawn in **Figure 4** from the review of Montenegro et al., (2020), Deng et al., (2016) and Arvidsson et al., (2018).

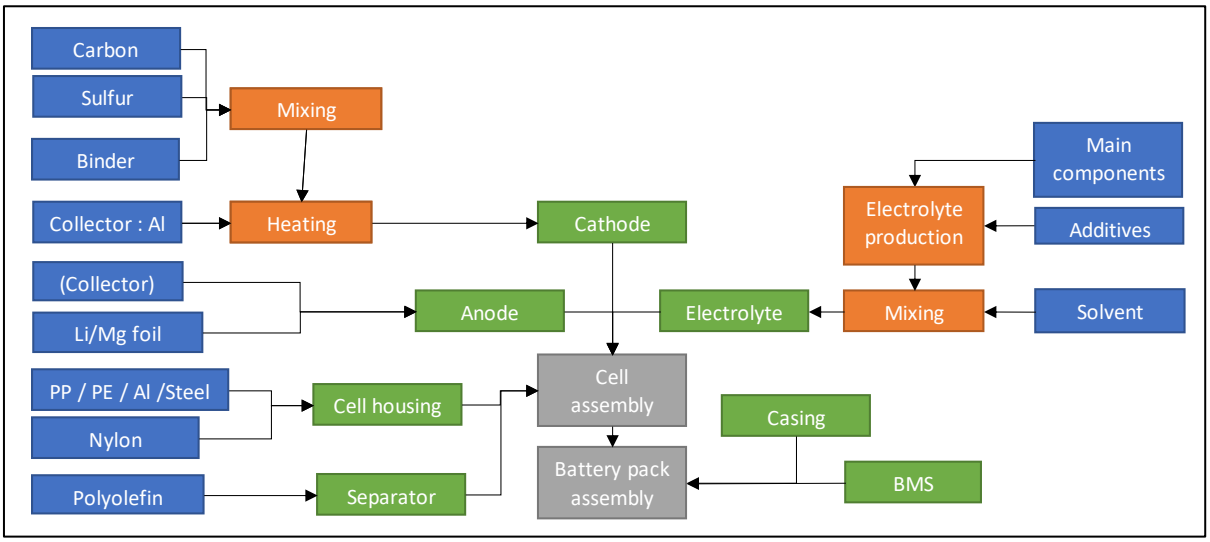



**Figure 4 :** *Simplified flow chart of the X-S batteries.*

### 2.3.1.2. Quality of LCA studies on X-S batteries

The quality of published LCA studies is here examined considering following aspects: maturity of modelled system, data source and assumptions.

None of the assessed Mg-S or Li-S batteries are already marketed. However, the Li-S battery described in the study of Deng et al. (2017) is 'ready to enter commercial production', whereas the environmentally assessed Mg-S cell is a laboratory prototype, which was also tested on a pilot scale. Some features such as cell energy density or material mass breakdown do not seem realistic as admitted by the authors themselves. Consequently, research on Li-S batteries appears to be more advanced compared with that for Mg-S. That is to say, that Mg-S technology is still in an early stage of development (TRL 2-3) and still facing technical issues to overcome.

Moreover, despite the subsequent effort of Montenegro et al. (2020) to use primary data during the LCI stage, some data were missing. They had to dig out data in previous studies on Li-ion batteries (LIBs), assuming equal environmental impacts between both battery technologies at some production stages.

Most of LCI data are sourced from the Ecoinvent database, and previous literature. However, some data are missing in this database: for example, the Mg foil formation process, some steps of the cathode manufacturing, and electrolyte production process are absent. Moreover, numerous hypotheses are made to develop a battery pack from the described laboratory cell prototype. Therefore, LCI data are sourced from other studies, most of the time from studies on LIBs.

### 2.3.2. X-ion batteries

X-ion batteries, especially LIBs, have made significant progress in the last decades. They have been since then the dominating technology used in electric vehicles and for stationary energy systems. Their environmental performance in battery-powered cars is often evaluated, for instance to prove their environmental benefit compared with a gasoline or a diesel engine.

#### 2.3.2.1. Studied batteries description

Environmental impact assessments in literature have mainly been conducted on LIBs. Different types of LIBs can be distinguished by different cathode chemistries:

- Lithium Iron Phosphate (LFP).
- Lithium Cobalt Oxide (LCO).
- Lithium Manganese Spinel Oxide (LMO).
- Composite oxides (Lithium Cobalt Nickel (LCN), Nickel Cobalt Manganese (NCM), Lithium Titanate Oxide (LTO) and Nickel Cobalt Aluminium (NCA)).

One Na-ion battery prototype LCA was published by Peters et al. in 2016. But scarcity of relevant studies on Na-ion batteries implies that the main focus in this chapter will be on LIBs environmental burden.
A description of assessed LIBs in the most noteworthy publications and associated battery pack mass shares are given in ***Figure 5***.

A long list of different components can, therefore, be used for each item of a LIB pack, even for the same cathode chemistry influencing related mass share.

Previous mass shares from **Table 3** have been extracted to illustrate the comparison of main components mass shares in chart (***Figure 5***). Considerable variations can be observed in housing and packing mass shares, whereas mass shares of the main components are grouped in an acceptable value range, if we look at the scale of the cell.

| Item | Parameter | Bauer[20] | M-B[21] | Notter[19] | Zack[18] | Ell[14] |
|---|---|---|---|---|---|---|
| **Cell chemistry** | Type | LTO , NCA | LFP, NCM | LMO | LFP | NCM |
| **Cell container** | Type | pouch | can (18650) | pouch | pouch | pouch |
| | Share of total cell mass | 1.5% | 25.0% | 8.5% | 1.3% | 0.7% |
| | Share of total battery mass | 1.1% | 20.0% | 6.8% | 1.1% | 0.4% |
| | Package material | PP-UP-Al compound | aluminum | PE foil | PP-Al compound | PET-PA-Al compound, incl. tabs |
| **Pack housing** | Share of total battery mass | 20.0% | 17.0% | 14.5% | 9.5% | 32.0% |
| | Dominating material | PP | PET | steel | PP | aluminum |
| **BMS** | Share of total battery mass | 5.0% | 3.0% | 5.6% | 6.0% | 3.7% |
| | Main components | electronics for control unit | copper, chrome steel, integr. circ. | cables, pr. wiring board | transistor, resistor | complex |
| **Cooling system** | Share of total battery mass | -- | -- | -- | -- | 4.10% |
| **Electrolyte** | Share of total battery mass | 13.9% | 12.0% | 13.6% | 16.5% | 9.5% |
| | Solvent | chemicals, organic | chemicals, organic | ethylene carbonate | ethylene glycol dimethyl ether | ethylene carbonate |
| | Salt | $NaBF_4$ | chemicals, inorg. | $LiPF_6$ | LiCl | $LiPF_6$ |
| **Binder** | Share of total battery mass (cathode & anode) | 0.7% | 2.38% (LFP) 2.33% (NCM) | 0.9% | 4.3% (org) 3.6% (aqu) | 1.32% |
| | Type of binder (anode) | TFE 50% * | TFE | Latex | TFE-PE (org) , ABS (aqu) ** | PVF |
| | Type of binder (cathode) | TFE 50% * | TFE | Latex | TFE-PE (org) , ABS (aqu) ** | CMC-PAA |
| | Type of solvent | NMP*** | NMP | Water | NMP(org)*** water (aqu) | NMP |
| **Manufact. Energy** (cell & pack prod.) | Electricity mix | Japan | UCTE | CN / UCTE | n/a | own mix |
| | Electricity (kWh/kg) | 8.25 (NCA) 9.35 (LTO) | 7.5 | 0.19 | 11.70 | 16.80 |
| | Heat (MJ/kg) | 27.73 (NCA) 35.78 (LTO) | 24.9 | 0.05 | 31.68 | 0.00 |
| | Energy demand (MJ/kg) | 57.4 (NCA) 69.5 (LTO) | 51.9 | 0.70 | 73.80 | 60.48 |
| **Package and BMS weight** | Share (weight) of non-active parts | 26.1% | 40.0% | 26.9% | 16.6% | 40.2% |

***Table 3:*** *Main components of LIBs (Peters et al., 2017).*

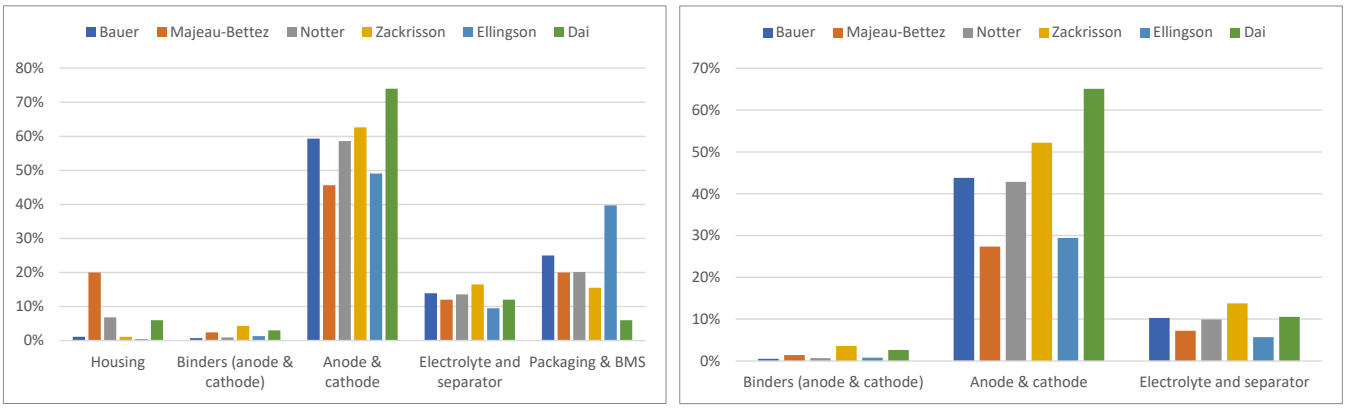



***Figure 5:*** *Battery pack (on the left-hand) and cell mass (on the right-hand) shares comparison according to selected studies (inspired from Peters et al., 2017).*

### 2.3.2.2. Quality of LCA studies on X-ion batteries

Same as X-S batteries, the quality of published LCA studies is here examined considering following aspects: maturity of modelled system, data source and assumptions.

LIBs have been commercialized for three decades. They are in consequence thought to be a mature technology. Primary industrial data are available and can be adopted for LCA calculations. However, LCA maturity must be discussed.

Numerous research teams have carried out LIBs LCA since the 2000s and some studies as the one from Ellingson et al. (2014) are considered as truly comprehensive and representative. However, Peters et al. (2016) and later Ellingson et al. (2017) underlined that the followed methodologies made assumptions and that data sources vary a lot from one LCA to another. Therefore, results show significant discrepancies. That demonstrates a lack of consensus among research community. In this context, Ellingson et al. (2017), who is an important contributor in this domain, propose common assumptions to make possible the comparison across studies.

Regarding data source, only a limited amount of LCI is original, meaning that they rely on their own primary data. That implies that recent LCA studies either reused partially these LCI data, amending them with their own data, or are based completely on the LCI of previous studies. The main used data source is Ecoinvent again.

It would have been tedious and useless to list all made assumptions, due to their high number in each study and even more across studies. However, we intend to list areas where non-disclosure issues or insufficient hindsight compel authors to make a hypothesis:

- During the production phase: battery manufacturing energy demand, energy source, and related methodology.
- During the use phase: electricity mix, charge-discharge efficiency, lifetime energy capacity, and calendric aging which depend on the depth of discharge, charging-rate, and operating and storage temperature, …

# 3. ENVIRONMENTAL IMPACTS OF Mg-BASED BATTERIES IN LITERATURE

## 3.1. Existing X-S batteries LCA results

Mg-S and Li-S LCA studies presented in Section 1. are analysed to extract relevant information.

Unfortunately, different functional units prevent direct result comparison. The impacts of the production phase could however be recalculated per kWh of storage capacity for the considered impact categories, revealing wide disparity in results (cf. **Table 4**). These fluctuations could be explained by different battery energy densities, battery cell development stages, different compositions, different assumptions … For example, the Mg-S cell showed the highest values in all impact categories, which might be related to the considerable energy density of this laboratory prototype. All impact categories are moreover influenced by the unrealistic aluminium cell pouch.

| | | Mg-S *Montenegro et al., 2020* | Li-S *Arvidsson et al., 2018* | Li-S *Deng et al., 2016* |
|---|---|---|---|---|
| **ADP** | *kg Antimony eq/kWh* | 2,5 | - | |
| **AP** | *kg $SO_2$ eq/kWh* | 1,6 | - | 0,6** |
| **HTP** | *kg 1,4DCBeq/kWh* | 325 | - | 41* |
| **GWP** | *kg $CO_2$ eq/kWh* | 323 | 230 | 140* |

**Table 4 :** *X-S cell prototype LCA results for the different impact categories (* : Recalculated from Deng results; ** corresponding to terrestrial acidification potential only and recalculated from Deng results).*

Despite of this variation in result, key contributors could be identified.

### 3.1.1. Identified key contributors

It is noteworthy that the main contributors for GWP are identical whether studied technologies are Li-S or Mg-S batteries:

- **Cell assembly and associated energy** dominate contributing from 40 to 70%, according to the case of studies analysed. The lower value of 40% is related to the unrealistic pouch cell mass share (45% of the total cell mass) of the assessed Mg-S battery: decreasing its weight will reduce its GWP contribution, and cell production impacts will consequently increase proportionally to the weight reduction, moving closer towards the high range of cell production GWP share.

- To a lesser extent, **electrolyte and anode production** are consequent drivers, both around the same contribution value of 10%. Considering the overestimated cell pouch mass for the Mg-S battery, both would be responsible for at most 15% of the total GWP.

Whereas the cathode production has an extremely low GWP in Montenegro and Arvidsson's studies, it appears to have a considerable GWP contribution in Deng's one. It is supposed to be due to the different inputs used to manufacture the Carbon/Sulfur composite, and especially the high-impact graphene oxides compared with black carbon, or highly ordered nanostructured mesoporous carbon.

Cell production, and to a lesser extend electrolyte and anode production have therefore proven to be the key drivers of GWP impact. For the other impact categories, the lack of data is obvious. However, the following points could derive from the literature review:

- HTP and ADP impacts are driven by the presence of metals, as lithium and magnesium foils in the anode, or copper in the BMS (wires and cables). A copper collector can also be found in some cell designs. Electrolyte and especially salt manufacturing can also affect substantially environmental burden for these categories.

- The AP breaks down into energy requirements, metal foils, and electrolyte contributions. The assessed electrolyte AP can become substantial in case of salt manufacturing.

### 3.1.2. Results analysis

Environmental burden of X-S batteries is affected by many parameters and vary by up to 100% across the three available studies.

As emphasized by Arvidsson et al. (2018), variations in LCA results are primarily correlated with energy consumption during battery manufacturing, and to anode composition and associated production process, for set battery electrochemical performance parameters. Then to reduce climate change impact, they advise to work on the following research topics classified from major contributor at the base of the pyramid to minor contributors at the top (cf. **Figure 6**).

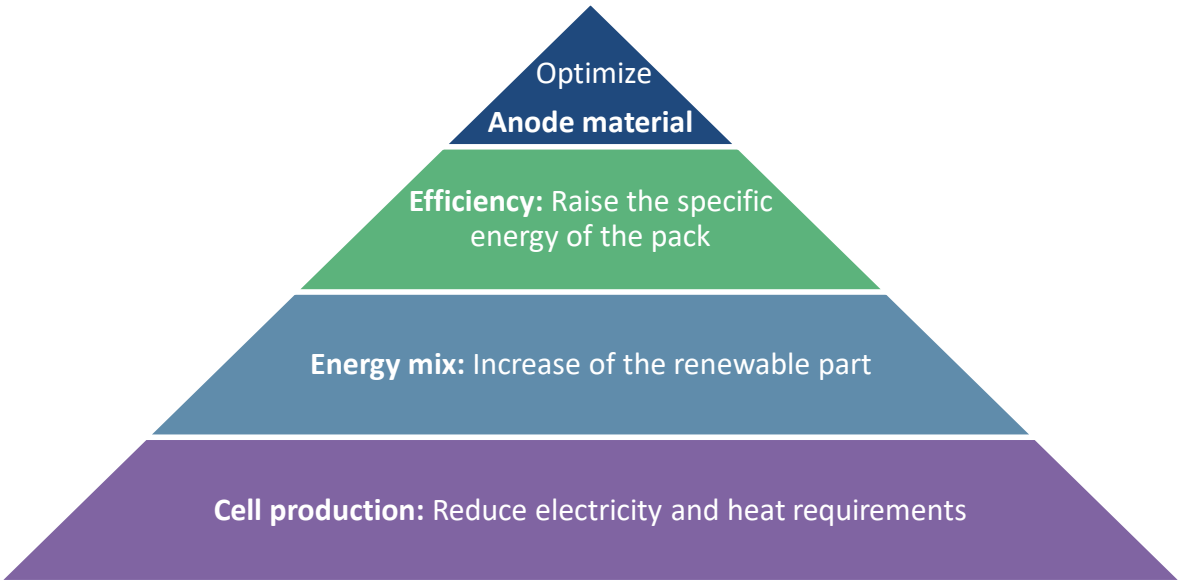



**Figure 6:** *Several ways to improve environmental performance of a Li-S cell (classified from major contributor at the base of the pyramid to minor contributors at the top).*

The stakes are high because they show that impact reduction can reach 90% for GWP.

While the production phase is overall the most impacting phase, it is noteworthy that the use phase can further impact GWP depending on the fossil fuels share in the electricity mix. Only Deng et al. (2019) consider the use phase in its Li-S LCA study, so data must be consolidated.

## 3.2. Review of X-ion batteries LCA results

### 3.2.1. Main key contributors

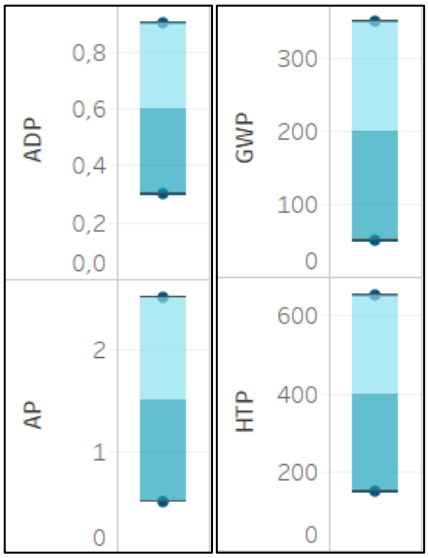
Among the numerous LIB LCA studies, fluctuations in their outcomes are marked, even for a same cathode chemistry. This variability will be explained in the next paragraph (cf. 3.2.2). However, key contributors to environmental impacts are common to all these studies:

- **Manufacturing energy demand** and **cathode paste** for the GWP, and AP categories. Intensive electricity consumption occurred primarily during electrode drying to evaporate solvents, and during cell manufacturing in dry room. Anode substrates and BMS for the HTP category especially because of copper amount.

- **Anode** and **cathode pastes and substrates** for the ADP category related to their critical metal content (Manganese, Nickel, Cobalt, Lithium…).

### 3.2.2. Results variability and related explanations

Hence, numerous LCA studies have been carried out in the last two decades and produced different results at first sight. Impact ranges for LIB production are given for illustration in **Figure 7**, including different cathode chemistries. The light blue and dark blue colors depict respectively above-average and below-average.




| ADP | AP | HTP | GWP |
|---|---|---|---|
| *kg Antimony eq/kWh* | *kg $SO_2$ eq/kWh* | *kg 1,4DCBeq/kWh* | *kg $CO_2$ eq/kWh* |

**Figure 7:** *Cradle-to-Gate LIBs LCA impact ranges for the selected impact categories and associated units (Peters et al., 2016).*

Even for one specific cathode chemistry, **Figure 8** reveals significant variations of GHG emissions. Fluctuations can reach up to seven times the lowest value.

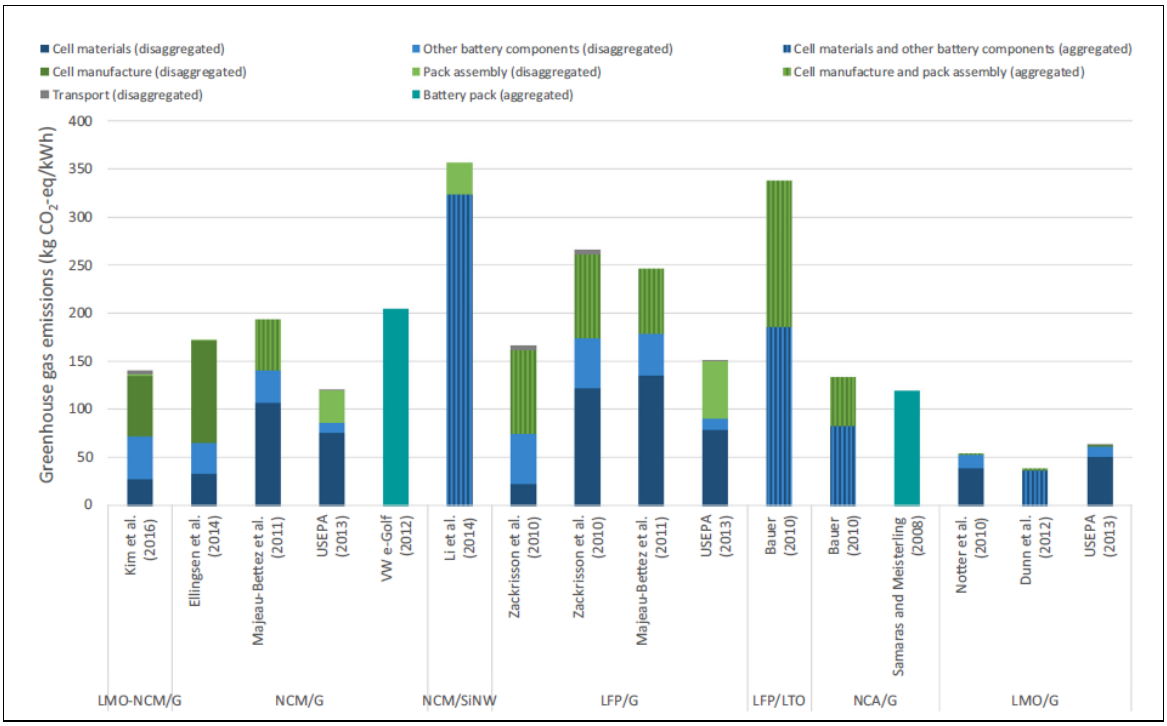



**Figure 8:** *Graphical representation of the LCA results for GWP for different LIB chemistries (Ellingsen et al., 2017).*

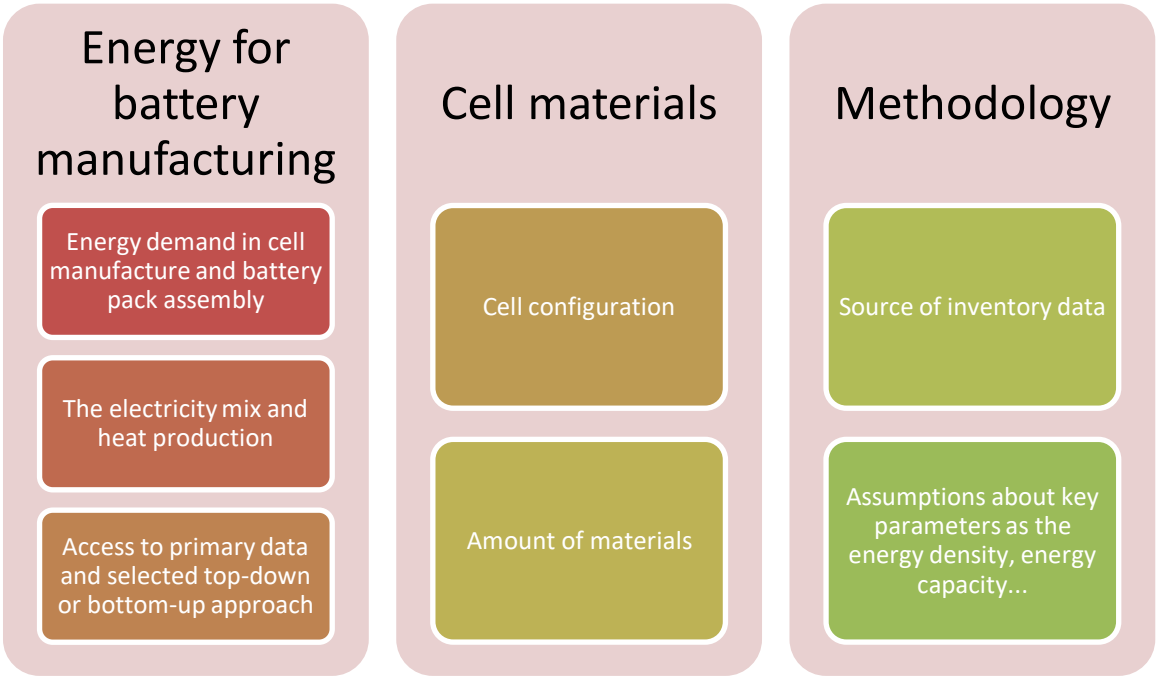



**Figure 9 :** *Major reasons explaining result variability in Li-ion LCA (inspired from Peters et al., 2016 & Ellingsen et al., 2017).*

As discussed earlier, Peters et al. in 2016 and Ellingsen et al. in 2017 have conducted LCA study reviews on LIBs, intending to uncover the reasons for such discrepancies in results. The research teams highlighted relevant assumptions and key parameters to extract average impact values.

Both review studies insisted on the source of inventory data. In fact, a major share of discrepancies between the studies is due to different assumptions like the approach for modelling the energy demand for battery manufacturing and is less attributable to the particular cell chemistry (Peters et al., 2017).

Differences presented in **Figure 8** outcome from the production phase only. A result overview is conducted for the use phase by the same authors. Electricity mix from the grid and assumptions of key parameters like the lifetime storage capacity, or the battery charge-discharge efficiency were found to be behind the use phase variability.

Hence, as identified in the two previous sections, the magnesium battery under development could belong to:

- X-S battery category.
- X-ion battery category.

After identifying the main contributors to the environmental impacts of these two different battery technologies, we are getting back to our primary goal, which is providing the environmental profile of the future RMBs.

# 4. E-MAGIC Mg-BASED BATTERY ENVIRONMENTAL PROFILE

The following section deals with Mg-S and Mg-ion battery features and, it will elaborate successively their respective environmental profiles.

## 4.1. Mg-based and Li-based batteries comparison

### 4.1.1. Main components & related mass shares

Mg-based and Li-S cells are featured by significant electrolyte volume, whereas Li-ion battery weight is dominated by the cathode mass as illustrated in **Figure 10**.

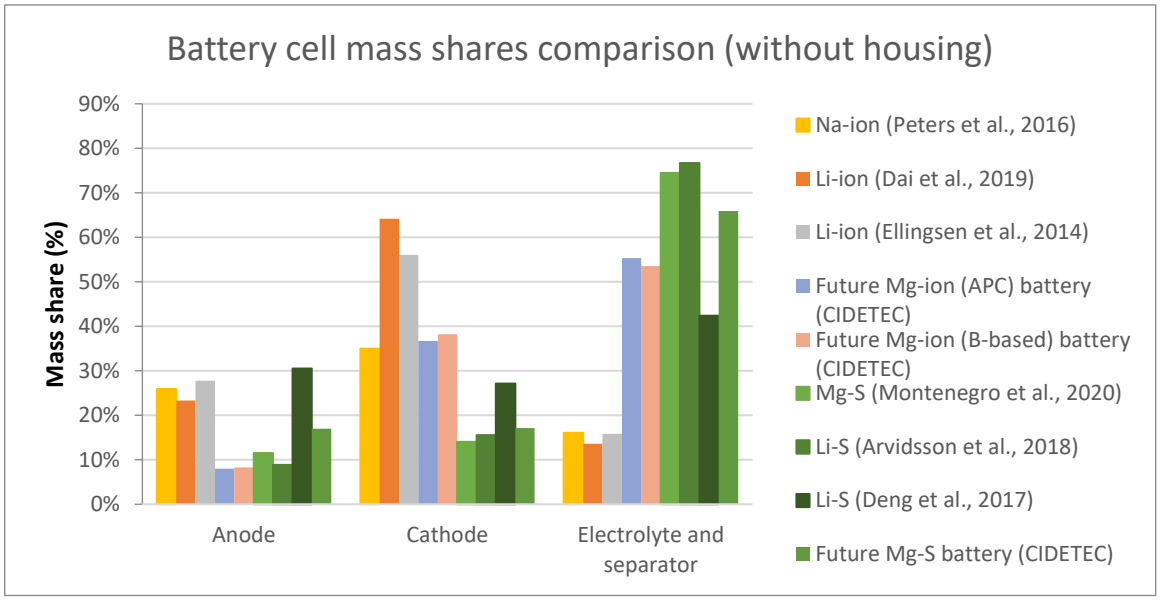



**Figure 10:** *Overview of mass breakdowns of different battery cells (all the sources are referenced in the legend).*

The main focus is now for Mg-based batteries to determine main cell components such as cathode, electrolyte, and anode.

Both compositions of Mg-S and Mg-ion batteries are quite complex to predict at this early stage of research, with several potential material for each component. BMS, cooling system and packaging materials will not be discussed here. They are assumed to be secondary components.

Two remarkable features for RMB technologies are worth noting:

- A **magnesium foil** can be used both as an electrode and a collector, whereas a copper collector is used in the current Li-ion anodes. This entails a slight reduction of the anode weight in comparison with the battery of reference.

- A **high volume of electrolyte**, which accounts for more or less 40% of the total battery mass. Cathode porosity in RMB indeed increases, and separator is bigger to maximize electrolyte volume and consequently extend active material (like Sulfur) dissolution.

**Table 5** details the possible components to be considered to establish the RMB environmental profile.

| Battery types | Cathode | Electrolyte | Anode |
|---|---|---|---|
| **Mg-ion** | Insertion cathodes composed of a collector, conductive carbon and active material :<br>- oxides containing V, **Mn**, ...<br>- Organic material (polymers based on **polyanthraquinone** or polyimide)<br>- (Fe, Co, Mn)(Fe, Co, Mn)$(CN)_6$<br>- $Mo_6S_8$ or **$VS_4$** material | **- 2 PhMgCl + $AlCl_3$ in THF (all-phenyl complex (APC) electrolytes - for $Mo_6S_8$ cathode)**<br><br>- $Mg(TFSI)_2$ or $Mg(ClO_4)_2$ in ethereal solvent (DME, THF, DOL…)<br><br>- **$Mg[B(hfip)_4]_2$ in ethereal solvents** | **- Sheets of pure Mg metal**<br><br>- Sheets of Mg-based alloys (AZ31) |
| **Mg-S** | Conversion electrodes : **Aluminium collector with C/S coatings** | | |

**Table 5 :** *Possible main components of the future RMB (bold text: most promising components at this stage of research).*

### 4.1.2. Environmental impacts of substances specific to Mg-based batteries

As highlighted by Dolganova et al. (2020), only a few LCA case studies have explored the criticality assessment of the necessary mineral resources for batteries. However, it seems to be worthwhile to deal with resource criticality, because resource demand is predicted to grow substantially as a consequence of electrical vehicle market rapid development. The « worst » extreme demand growth assuming a 100% electric vehicle world is illustrated in **Figure 11** for some resources.

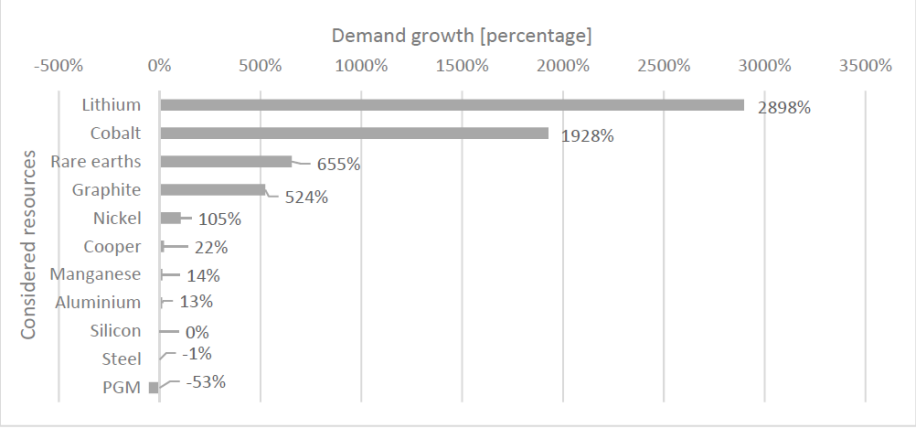



**Figure 11 :** *Predicted increase in resource demand in a 100% electric vehicle world (percentage compared to today's global production) (Dolganova et al.,2020).*

European Commission (EC) established in 2017 a list of critical non-energy raw materials at EU level. The two main high-level components of criticality are retained:

- The Economic Importance (EI) calculated based on the importance of a given material in the EU end-use applications and the performance of its substitutes in these applications.
- The Supply Risk (SR) calculated based on factors that measure the risk of a disruption in the supply of a given material (e.g. supply mix and import reliance, governance performance measured by the World Governance Indicators, trade restrictions and agreements, existence and criticality of substitutes).

Results are presented in **Figure 12**, displaying the supply risk along the y-axis, and the economic importance along the x-axis. Thereby Magnesium and other raw materials like Vanadium or Cobalt that can be found in batteries belong to the EU critical raw materials list, contrary to Lithium.

The EC assessed also in 2017 an end-of-life recycling input rate (EoI-RIR), which refers to the ratio of recycling of old scrap in the EU among the EU supply of raw material.

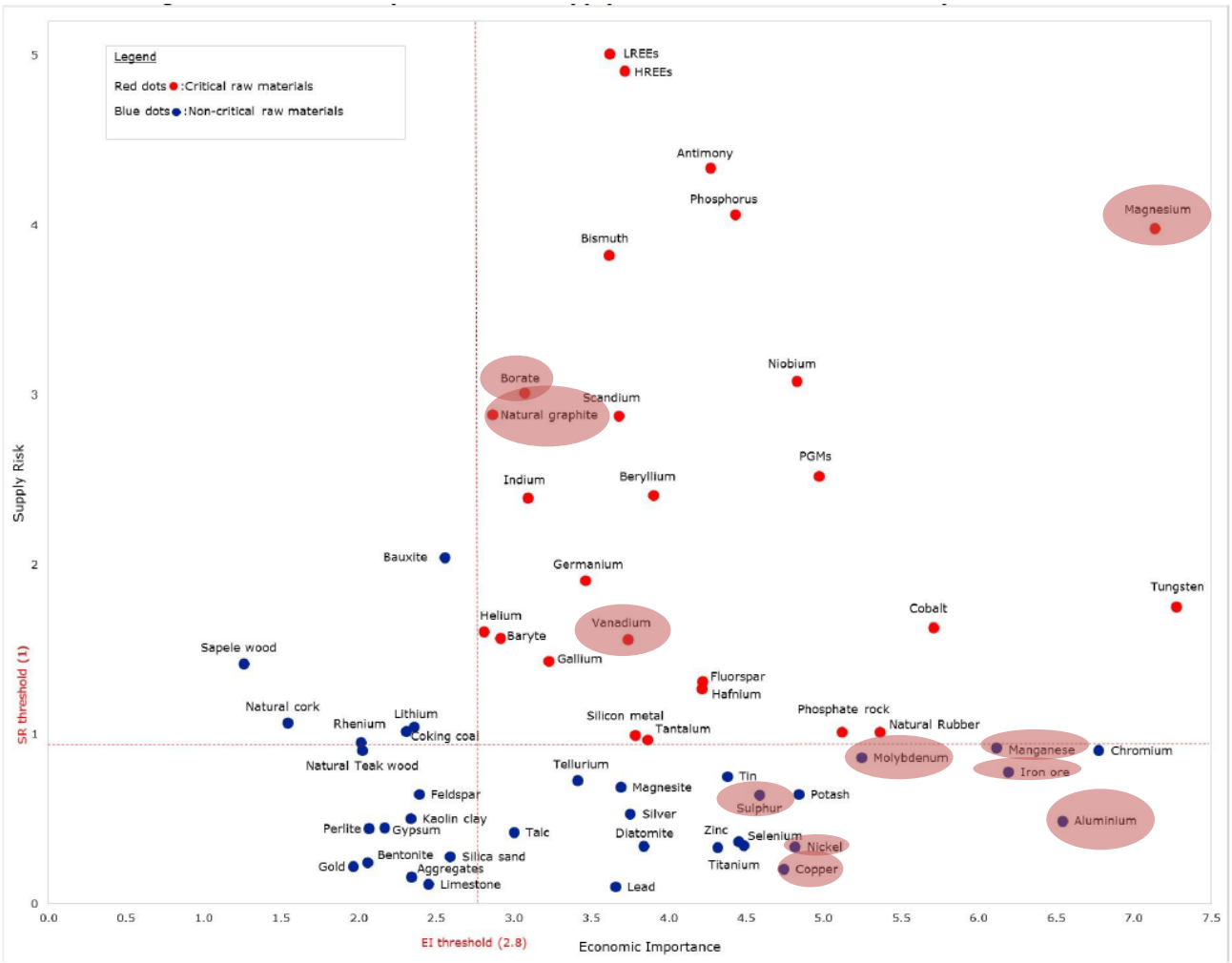



**Figure 12 :** *Economic Importance and Supply Risk results of 2017 European Commission Assessment (mineral resources used in Mg-based batteries are encircled).*

### 4.1.2.1. Magnesium criticality

As shown in **Figure 12**, Magnesium is considered by the EC as a critical raw material. This is mainly due to producers in China who dominate global magnesium metal production of about 1,1 million of tons (USGS, 2020). Several projects are even now under development to increase primary magnesium metal capacity in China and elsewhere (cf. **Figure 13**).

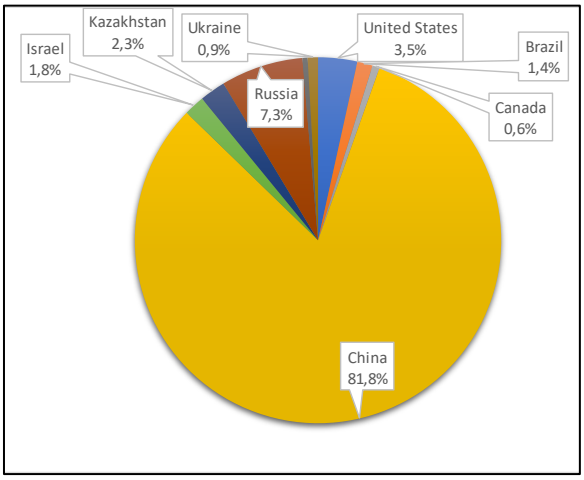



**Figure 13 :** *Main producers of Magnesium worldwide (USGS, 2020).*

All sources consider Magnesium as a very abundant material, to such an extent that magnesium reserves, and resources are not evaluated. It is the ninth most abundant element on earth, and it can be found and extracted from seawater, natural brines, dolomite, serpentine, and other minerals. It is then acknowledged that reserves of magnesium are large enough to meet the worldwide consumption needs for the next centuries.

Moreover, the EoL-RIR for magnesium is assessed at 9% level in the EU (estimate calculated based on EoL-RIR for aluminium), and the worldwide magnesium recycling rate at approximately 20-25%. Magnesium is easily recyclable without experiencing any loss in quality and secondary magnesium is supposed to request between 5 and 10% of primary magnesium energy demand, which is quite low compared with other metals (International Magnesium association).

Finally, Magnesium is considered by the EU as a critical raw material only because of political reasons. There is no issue with the abundance of Mg worldwide.

#### 4.1.2.2. Other materials

**Table 6** lists in a non-exhaustive way raw materials (other than Lithium and Magnesium) currently used in batteries, displaying criticality assessed indicators from EC. Borate, Cobalt, Natural Graphite and Vanadium are considered critical by the EC, so these raw materials should catch the attention of researchers to prevent using them in future batteries as far as possible.

For example, many risks are identified for the cobalt supply. Battery chemistries that do not rely on cobalt, nickel, or copper are considered as advantageous because the reduction of these materials can minimize overall resource criticality (Peters et al., 2016).

| Source | European Commission | | | | | Valero et al., 2018 | | E-Magic |
|---|---|---|---|---|---|---|---|---|
| Material | Stage assessed | Supply risk (critical if >1) | Economic importance (critical if >2,8) | Import reliance (%) | End-of-life recycling input rate (EOL-RIR) | Current Recycling rate | 2050 Recycling rate | Mg-based batteries |
| ***Aluminium*** | Processing | 0,5 | 6,5 | 64 | 12 | | | X |
| ***Bauxite*** | Extraction | 2 | 2,6 | 85 | 0 | | | X |
| ***Borate*** | Extraction | 3 | 3,1 | 100 | 0 | | | X |
| ***Cobalt*** | Extraction | 1,6 | 5,7 | 32 | 0 | 32% | 59% | X |
| ***Copper*** | Extraction | 0,2 | 4,7 | 82 | 55 | | | X |
| ***Magnesite*** | Extraction | 0,7 | 3,7 | 1 | 2 | | | X |
| ***Magnesium*** | Processing | 4 | 7,1 | 100 | 9 | | | X |
| ***Mangenese*** | Extraction | 0,9 | 6,1 | 89 | 12 | 37% | 38% | X |
| ***Molybdenum*** | Extraction | 0,9 | 5,2 | 100 | 30 | 33% | 42% | X |
| ***Natural Graphite*** | Extraction | 2,9 | 2,9 | 99 | 3 | | | X |
| ***Sulfur*** | Processing | 0,6 | 4,6 | 0 | 5 | | | X |
| ***Vanadium*** | Processing | 1,6 | 3,7 | 84 | 44 | | | X |
| ***Iron ore*** | Extraction | 0,8 | 6,2 | 74 | 24 | | | X |

**Table 6:** *Criticality parameters of different materials founded in batteries. In red: materials considered as critical by EC (Study on the review of the list of Critical Raw Materials, European Commission, 2017).*

### 4.1.3. Key parameters influencing LCA results

The key parameters influencing the future Mg-based batteries environmental impacts are assumed to be similar to Li-based battery ones. As studied in previous sections, they are summarized below:

- Manufacturing energy demand, especially energy required to evaporate solvents and reduce moisture inside the cell.
- Amount of metals (Vanadium, Cobalt, Manganese, Molybdenum, Copper, Aluminium …) in the cathode active material, the current collector of cathode and anode, the BMS, and the cooling system.
- To a lesser extent, only for the Mg-S batteries, electrolyte because of its requested large volume.

To go further, as demonstrated by Arvidsson et al. (2018), the source of used electricity (renewable energy share), and battery energy density can also significantly reduce the environmental burden.

## 4.2. Environmental profile of Mg-based batteries

### 4.2.1. Assumptions and results

Three profiles will be generated from the literature review. They correspond to three RMB prototypes which run at least at a very basic level:

- One **Mg-S battery**.
- One **Mg-ion battery with APC as electrolyte**.
- One **Mg-ion battery with $Mg[B(hfip)_4]_2$ as electrolyte**.

Mg-S and Mg-ion batteries will be compared respectively to the Li-S battery from Deng et al. (2017) and the Li-ion battery from Ellingsen et al. (2014), which will be therefore named "batteries of reference" in the following sections. Indeed, Mg-S and Li-S batteries are supposed to be relatively similar in terms of composition, and the same parallel is drawn between Mg-ion and Li-ion batteries. The assumed composition for the three future batteries and their mass breakdowns are given in **Table 7** and **Table 9**. RMB mass breakdowns come from a preliminary CIDETEC's work (WP5), whereas RMB features correspond to E-Magic project objectives. They are summed up in **Table 7** to **Table 10**.

The methodology followed to build the environmental profiles of the RMBs consists of a rough estimation of what would imply the main deviations in terms of material used and mass share (cf. **Figure 14**) of each component for each impact category. AP for acidification issues, ADP for resource scarcity, HTP for human toxicity issues and GWP for greenhouse gas emissions would be considered. For the selected impact categories, this evaluation is performed from LCA detailed results, which allows each material to be compared against another. The rule of 3 is then applied to take into account the expected increase in energy density (cf. **Table 8** and **Table 10**).

If no information about the future material of the assessed batteries is available, a neutral hypothesis is taken, meaning that the environmental burdens are deemed similar.

In the same way, housing, BMS, cooling system, and packaging material are supposed to be strictly identical to the LIB of Ellingsen et al. (2014).

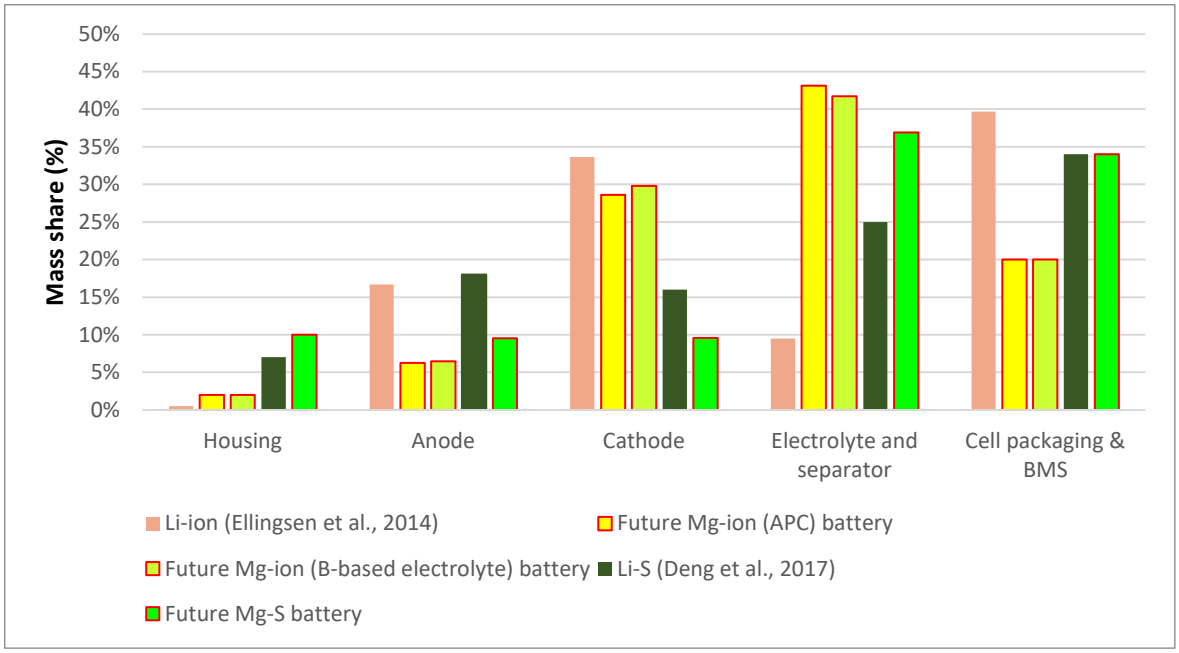



**Figure 14:** *Future RMB mass breakdown and comparison to existing battery breakdown (All the sources are referenced in the legend).*

**Future Mg-ion batteries**

We assume that:

- **Mg-ion cell composition** resembles the Li-ion cell one closely. One remarkable difference consists of the magnesium metal anode, replacing a graphite host used to intercalate lithium ions and the copper current collector. Cathode will display the same major components, including a supposed slightly lower amount of heavy metals in the active material. Due to the lack of sufficient data, the environmental impact of the APC is evaluated as equivalent of the $LiPF_6$ electrolyte, whereas the borate-based electrolyte is supposed to be lower. Cell housing and packaging would not show any major difference of composition as no environmental information is available (cf. **Table 7**).

- Concerning the **Mg-ion battery mass breakdown**, anode mass share should be a few percent lower owing to the magnesium metal anode, and electrolyte one much higher.

- Whereas no information is available about **Mg-ion battery manufacturing energy**, it is proposed to use LIB production energy consumption.

| | MATERIALS & MASS SHARES | | |
|---|---|---|---|
| | Future Mg-ion battery 1 (APC) | Future Mg-ion battery 2 (Borate-based electrolyte) | LIB (Ellingsen et al., 2014) |
| **Housing** | **2%** | **2%** | **1%** |
| *Cell sealing* | Aluminium composite | | Aluminium composite |
| **Anode** | **6%** | **6%** | **17%** |
| *Active material* | Mg metal foil | | Synthetic graphite |
| *Conductive Carbon* | | | |
| *Binder* | | | |
| *Collector foil* | | | Copper foil |
| **Cathode** | **29%** | **30%** | **34%** |
| *Active material* | $Mo_6S_8$ | | NMC 111 |
| *Conductive Carbon* | Black carbon | | Black carbon |
| *Binder* | PVdF | | PVdF |
| *Collector foil* | Nickel foil | Aluminium foil | Aluminium foil |
| **Electrolyte and separator** | **43%** | **42%** | **10%** |
| *Electrolyte* | APC in THF | $Mg[B(hfip)_4]_2$ in DME | LiPF6 |
| *Separator* | Glass fiber | Polyolefin (CELGARD) | Polyolefin separator |
| **Cell packaging, cooling system & BMS** | **20%** | **20%** | **40%** |
| *Cell packaging* | PP, PE, Al composite, steel | | PP, PE, Al composite, steel |

**Table 7 :** *Proposed composition of the future Mg-ion batteries compared to Li-ion chosen reference.*

| | | Mg-ion | Li-ion |
|---|---|---|---|
| **Specific energy** | *Wh/kg* | 250 | 174 |

**Table 8 :** *Proposed features of the future Mg-ion battery compared to Li-ion chosen reference.*

According to the Mg-ion battery description given above and the targeted high energy density, the following environmental profile has been drawn (cf. **Figure 15** and **Figure 16**).

For each indicator, the first bar on the left indicates the environmental performance of the chosen reference. Then floating bars in red (when reduction) or in blue (when increase) indicates the evolution of this performance according to the change in composition or feature indicated in **table 7** and **table 8**. Evolutions are regrouped in main components mass and nature changes (anode, cathode, electrolyte and packaging) to finish with specific energy change. The last bar cumulates all evolutions in a final relative estimation of the environmental performance on chosen indicator of future design compared to reference one.

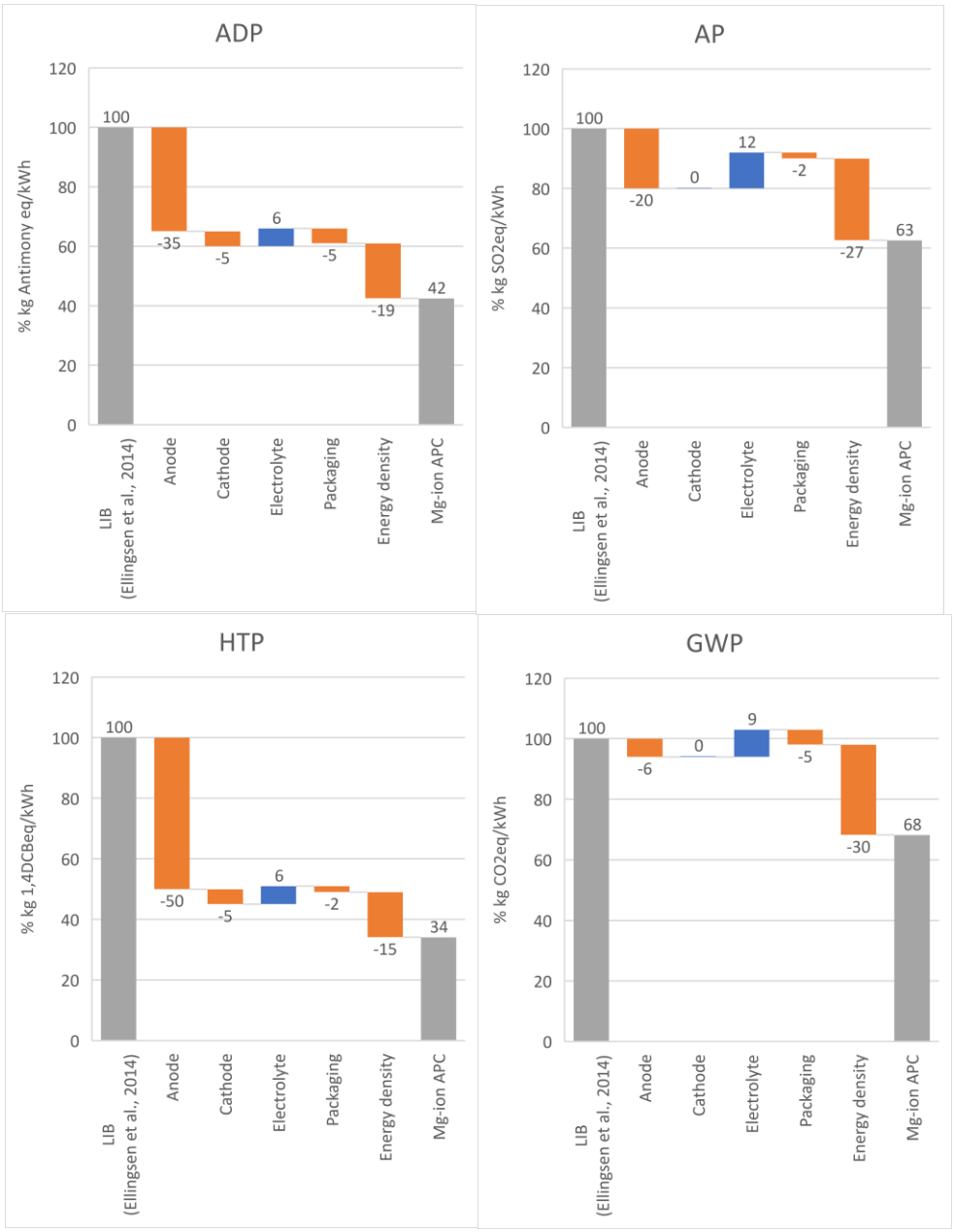



**Figure 15**: *Estimated environmental profile of the future Mg-ion (APC) battery compared with the Li-ion battery from Ellingsen et al. (2014).*

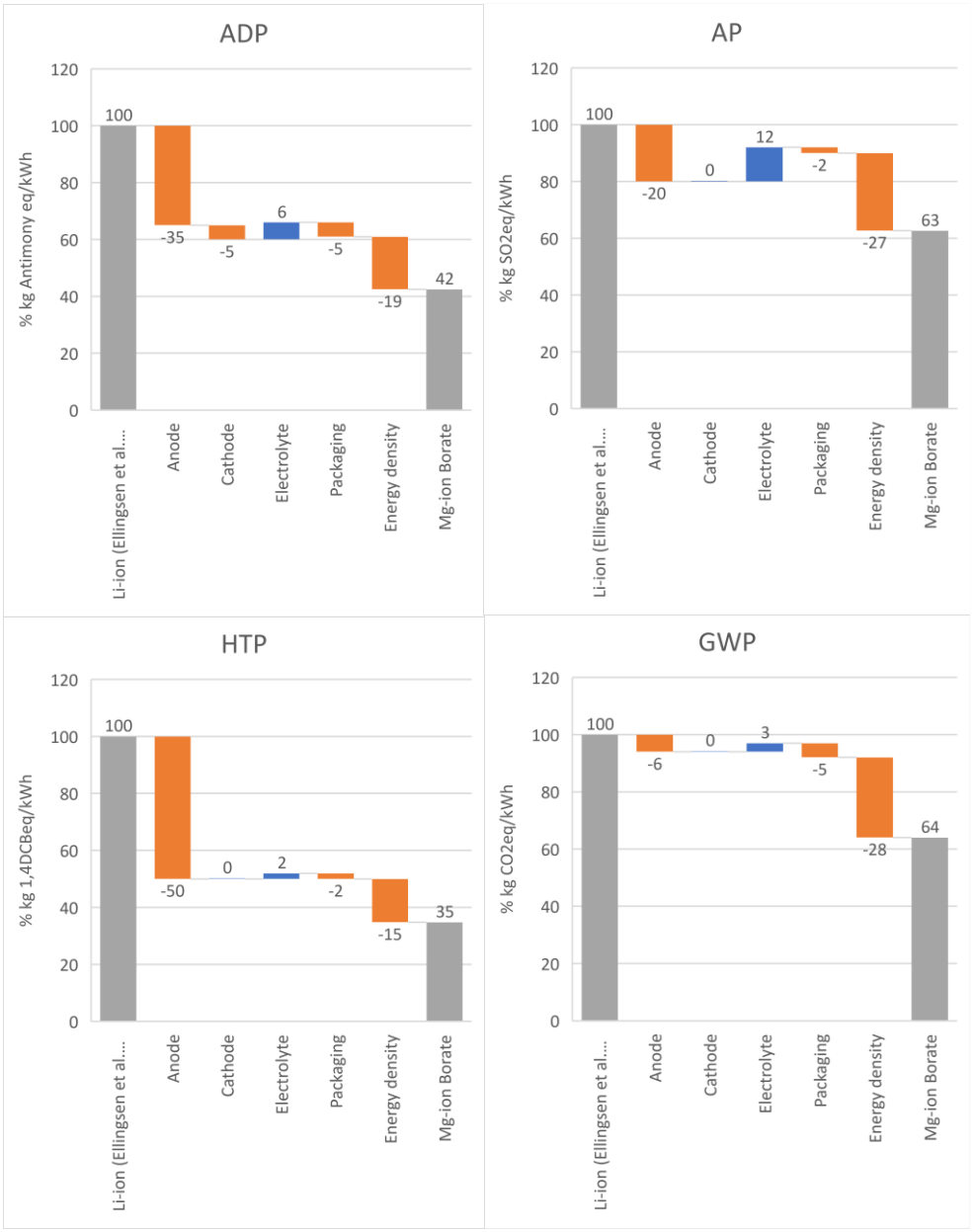



**Figure 16:** *Estimated environmental profile of the future Mg-ion (Borate-based electrolyte) battery compared with the Li-ion battery from Ellingsen et al. (2014).*

The both Mg-ion (APC and borate-based electrolytes) batteries could therefore have an environmental burden reduced by 25% to 75% according to the impact category concerned, compared with the Li-ion battery from Ellingsen et al. (2014). This can be predominantly explained by:

- The high energy density targeted in the project.
- The low impact of the Mg metal anode mainly due to its low density. Magnesium is also supposed to have slightly reduced adverse impacts than Carbone with the copper foil.

GWP impact declines less than other impact categories, especially because of the low contribution of cathode and anode in the LCAs of reference.

One major difference lies in the nature of the electrolyte. As we consider the APC electrolyte impact identical to the electrolyte of reference, GWP impact of the $Mg[B(hfip)_4]_2$ (borate-based) electrolyte is lower because its production would require less energy due to its low hygroscopy (Montenegro et al. (2020)).

Moreover, impact variations observed for the two cathodes and battery packaging are essentially related to their mass share deviations.

As a reminder, Ellingsen et al. (2014) took the hypothesis of a mix of primary and secondary sources of aluminium and copper, leading to an optimistic environmental burden evaluated. Same hypothesis has been made for the future Mg-ion batteries.

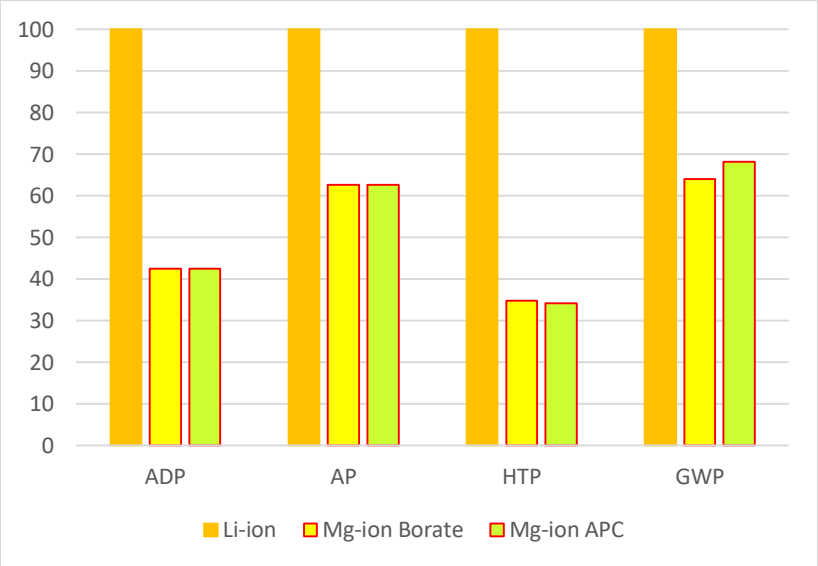



**Figure 17**: *Comparison of the environmental profiles of the two future Mg-ion batteries for ADP, AP, HTP and GWP impacts.*

Finally, the comparison of the two future RMB environmental profiles shows that:

- ADP, AP and HTP impacts are very similar. There is no difference.
- GWP impact is lower because the $Mg[B(hfip)_4]_2$ (borate-based) electrolyte is less energy-consuming.

Such small difference is not sufficient to conclude on the advantage of one design on another for Mg-ion cells due to high uncertainties linked to environmental profile approach. The complete LCA planned for E-Magic will better help on distinguishing design options among Mg-ion technology.

**Future Mg-S battery**

In the same way, we assumed that:

- The Mg-S battery composition closely resembles the Li-S battery one. One remarkable difference consists of the magnesium metal anode, replacing a Li foil coated on a copper current collector. Cathode will be quite similar except that its coatings will assemble native sulfur and black carbon instead of sodium thiosulfate and graphene oxides. The $Mg[B(hfip)_4]_2$ electrolyte replaces the $LiPF_6$ one. Cell housing and packaging would not show any major difference.

- The Mg-S battery mass share is supposed to be quite similar to a Li-S one (cf. **Figure 14**), except that, once again, the percentage weight of electrolyte would be a bit higher whereas the cathode weight would be proportionally lower.

- Because released LCA on Li-S or Mg-S batteries used LIB manufacturing energy in their calculations, it is proposed to use the same strategy for Mg-S environmental profile building.

| | Materials and mass shares | |
|---|---|---|
| | Mg-S battery | Li-S battery (Deng et al., 2017) |
| **Housing** | **10%** | **7%** |
| *Cell sealings* | Aluminium composite | multi layered polymer pouch |
| **Anode** | **10%** | **13%** |
| *Active material* | Mg foil | Lithium metal foil with a protective layer (TEOS) |
| *Conductive Carbon* | | |
| *Binder* | | |
| *Collector foil* | | Copper foil |
| **Cathode** | **10%** | **20%** |
| *Active material* | Sulfur | Sodium thiosulfate + HCl |
| *Conductive Carbon* | Black Carbon | Graphene oxide |
| *Binder* | PVDF | |
| *Collector foil* | Aluminium foil | |
| **Electrolyte and separator** | **37%** | **25%** |
| *Electrolyte* | Mg[B(hfip)4]2 in DME | LiTFSI + LiNO3 + DOL DME |
| *Separator* | Polyolefin (CELGARD) membrane<br>Polyolefin membrane (PP, PE, PP) | |
| **Cell packaging, cooling system & BMS** | **34%** | **35%** |
| *Cell packaging* | PP, PE, Al composite, steel | |

**Table 9 :** *Proposed composition of the future Mg-S battery.*

As shown in **Table 10**, the energy density of the future Mg-S battery is quite high, and consistent with the objectives of the E-Magic project. This high energy density convinced us not to use the study of Montenegro et al. (2020) as a reference for the Mg-S battery environmental profile. Indeed, this study consider a battery prototype which the energy density reaches only 45,6 Wh/kg with a heavy cell pouch. It has however been taken into accounts to assess the environmental burden of some specific components like the magnesium foil and the $Mg[B(hfip)_4]_2$ salt production.

| | | Mg-S | Li-S |
|---|---|---|---|
| **Specific energy** | *Wh/kg* | 450 | 220 |

**Table 10 :** *Proposed features of the future Mg-S battery.*

According to the Mg-ion battery description given above, the following environmental profile has been drawn (cf. **Figure 18**).

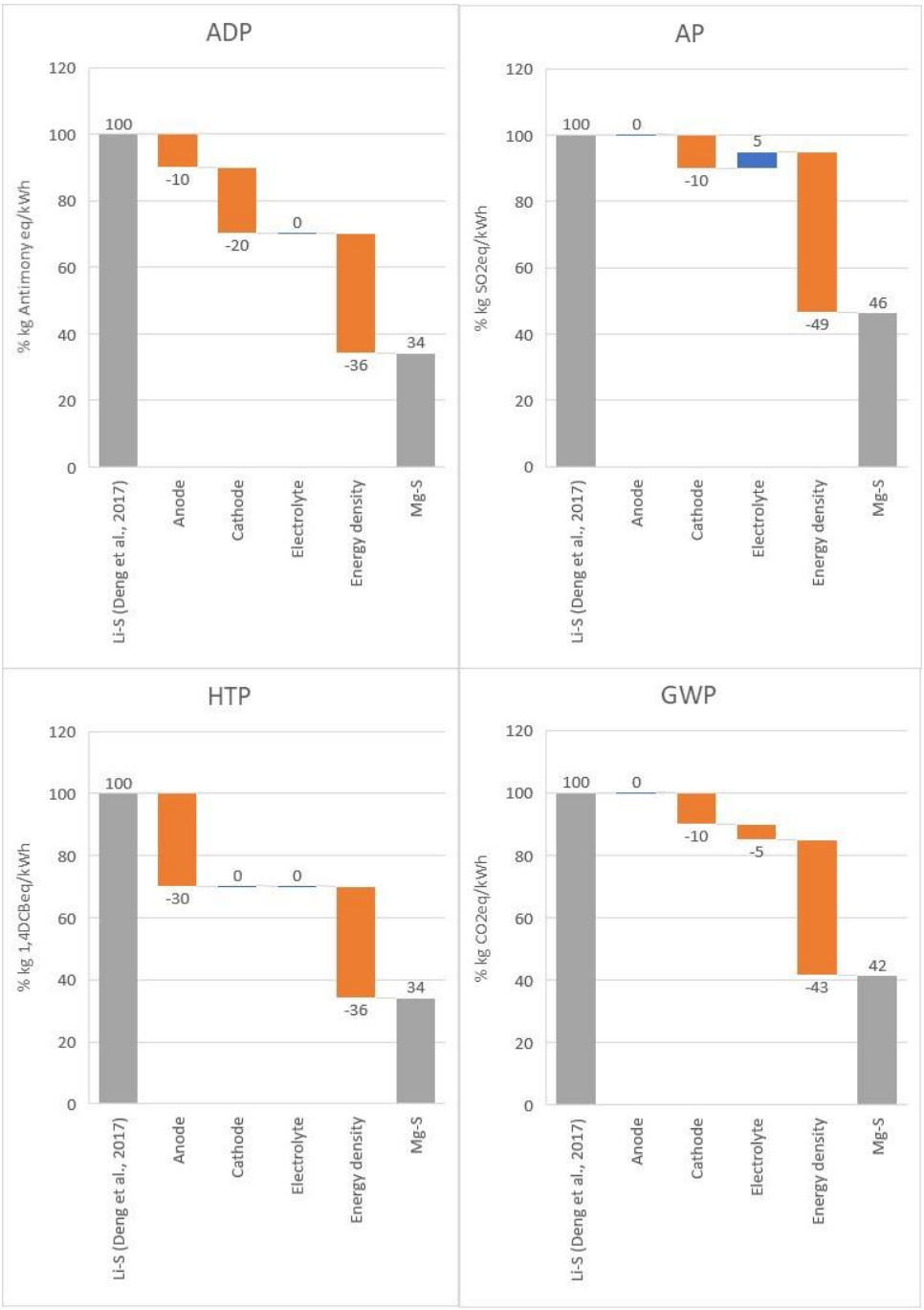



**Figure 18 :** *Assessed environmental profile of the future Mg-S battery compared to Li-S reference battery.*

The Mg-S battery could also have an impact reduced in half or more compared with the Li-S battery from Deng et al. (2017). This can be predominantly explained by:

- The high energy density targeted in the project.
- The low impact of the Mg metal anode.

It has to be noticed that the lower impact of the $Mg[B(hfip)_4]_2$ electrolyte is offset by its higher volume.

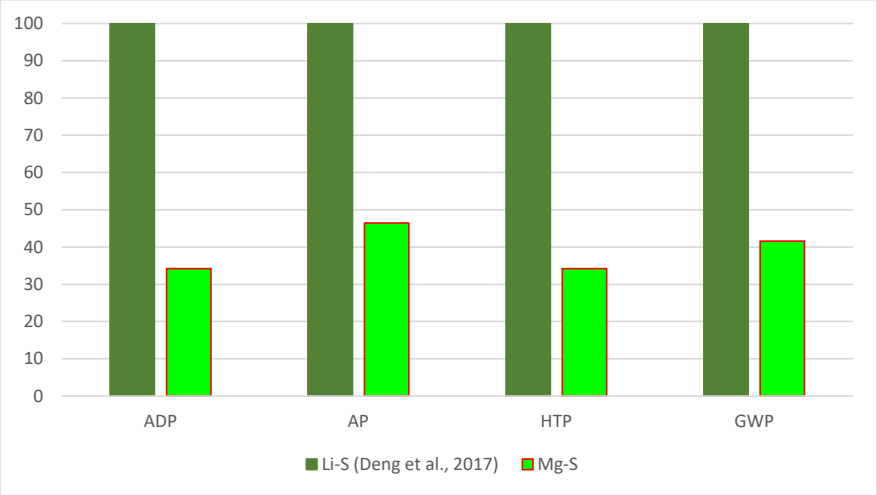



**Figure 19:** *Environmental profile of the future Mg-S battery compared to Li-S reference battery. The environmental burden of this future Mg-S battery is supposed to fall from 55 to 65% compared to the selected reference.*

### 4.2.2. Eco-design recommendations relative to key contributors

Recommendations are proposed below to reduce the contributions of the main key drivers identified in 4.1.3.

#### 4.2.2.1. Energy consumption

Lowest environmental impacts are related to a high share of renewable energy sources like preferably hydroelectric power, in opposition to fossil fuels. Moreover, even if it is still relatively unknown, high values of toxicity impacts could be obtained because of lignite waste management. As a reminder, the European electricity mix relies more heavily on lignite that the Chinese electricity mix, which is more hard-coal oriented.

Optimizing process efficiency is another way to reduce manufacturing energy. It is also easy to understand that if commercial facilities operate close to maximum production capacity, energy consumption would be consequently minimized, and lower than at pilot or laboratory scales.

Energy consumption depends on the materials and processes chosen to make up the future RMB. Type of mine, metal concentration in the ore, process type, process efficiency are essential factors than can make vary primary energy demand.

In the same way, a water-based solution precipitation method has been developed recently for the graphene-sulfur composite production with a high yield rate. This eliminates the use of toxic solvents and is regarded as a

low-cost and environmental-friendly process, with promising potential for future industrial-scale productions (Deng et al., 2017).

#### 4.2.2.2. Avoid heavy and critical metals

Among all the heavy metals and other metals that can be part of Mg-based batteries, it is necessary to check if they belong to the EU critical raw materials list. To go further, it is interesting to collect recycling rates, as shown in **Table 6**, and to use preferentially metals that are or will be reused or recycled.

Heavy metals also share a common feature: their toxicity for humans and the larger living world. Toxicity variability has not been explored in detail in this report.

#### 4.2.2.3. Energy density

Increasing battery energy density is also an essential key to reduce the environmental impact of Mg-based batteries. Promoting light and high specific capacity materials enables to optimize battery efficiency. Mg-based batteries are promising, by offering higher energy density than LIBs. They consequently are expected to outperform the environmental qualities of commercial current batteries.

### 4.2.3. Other eco-design recommendations

Among the low-contributors, the literature review praises some components instead of the most-used ones because of their lower impact on environment. They are listed in **Table 11**.

A good example is using plastic instead of aluminium for cell pouches. Despite lower environmental impacts whatever the impact category, simple PVC or PE pouches might show inferior resistance or durability than aluminium composite material and eventually require a higher mass share for assuring the same function. In Montenegro et al. (2020) study, no information is available to know if the cell pouch mass share is a technical requirement or just a lack of optimization. That's why commercial LIBs cell pouches are made of aluminium composites.

Otherwise, water-based binder like SBR/CMC has the advantage that no organic (and toxic) solvent is needed (Peters et al., 2016).

Lastly, as outlined by Arvidson et al. (2018), it seems to be more environmentally friendly to add sodium thiosulfate rather than native sulfur to form the Carbon/Sulfur composite in the anode. Arvidson and its co-writers add that carbon sources have different environmental burdens, even if differences stay quite low (a few percent). Then black carbon or nanostructured carbon should be opted for.

| | ...Recommended | Compared to... |
|---|---|---|
| **Sulfur sources (active material in cathode)** | Sodium thiosulfate | Native Sulfur |
| **Cell housing and packaging** | PE & PP (if identical durability has been proven) | Aluminium composite or steel |
| **Electrolyte** | Mix of organic and inorganic LiCl | $LiPF_6$ ou $NaBF_4$ |
| **Binder & solvent** | Water_based CMC/SBR<br>Latex<br>Organic binder | PVdF in NMP solvent, TFE |
| **Carbon** | Black carbon<br>Nanostructured carbon | Graphene oxides, CMK-3 |

***Legend:***
*TFE: Tetrafluoroethylene*
*SBR: Styrene-Butadiene-Rubber*
*CMC: Carboxyl-Methyl-Cellulose (water-based binder)*
*PVdF: Polyvinylidene fluoride (organic binder)*
*NMP: n-Methyl-Pyrrolidone*

**Table 11 :** *Some eco-design recommendations for different battery technologies.*

## 4.3. Potential improvements and missing points of the profile

### 4.3.1. Lack of environmental data on some components or processes

As discussed earlier, LCA study results show major discrepancies that can be explained by a lack of available data. First, as underlined by Peters et al. (2016), little information is provided in the literature concerning the ADP and AP impact categories which are still estimated as far from trivial (cf. **Figure 2**).

Moreover, if we only focus on environmental key drivers, the following points could introduce uncertainties:

- Missing energy consumption about some manufacturing steps, like for example magnesium metal foil formation. LCA results would be enhanced if energy demand is standardized in terms of energy sources, considered energy (primary or secondary) … For example, an United-States electricity mix could be set and, taking in account in all LCA studies to facilitate LCA comparison.

- Numerous compounds and their formation process are still missing in the Ecoinvent database or in other reference databases. Research struggle to assess the environmental burden of each processing steps involved in producing those materials as for example the $Mg[B(hfip)_4]_2$ electrolyte.

### 4.3.2. Approximate results to use carefully

Approximations were made because of early stage of R&D of the subject of the topic. Main directions of RMB research have still a low technology readiness level. Some new components are still in a testing phase or do not exist yet to make the future battery functional. That implies that this report merely sums up the released literature and presents the future possible components known at this stage of development.

A particular caution has to be taken for the use of dressed environmental profile because of inherent approximation of the methodology itself. For example, in the absence of quantified impact of one of the

components, it has been supposed that it has the same environmental impact as the component of reference. Therefore, if there are significant variations in environment footprint between the both components, it might imply substantial changes in the final result.

Moreover, it has to be noticed that high energy density has the major leverage effect on the battery environmental load, so the drawn environmental profiles depend on project objective achievements in terms of energy density.

An LCA must be completed during E-Magic project as soon as a functional RMB is born, taking into account all the selected components to assess more accurately the environmental performance of the future battery.

# 5. CONCLUSION

To conclude, the undertaken literature review has brought out only one study related to the environmental performance of RMB. This study assessed the environmental burden of an Mg-S battery, which is still a laboratory prototype, and authors admit that their outcome "*should be considered purely on an indicative level*". Therefore, it has been decided to enlarge upon Li-ion and Li-S battery environmental impacts to collect as much data as possible. Life cycle assessment (LCA) studies were opted for as base data for our approach because this methodology is standardized and enables easy comparisons between the obtained results.

X-S and X-ion (X as Mg, Na or Li) environmental impacts vary by up to 100% across the three available studies for the considered impact categories. These LCA results show thus significant discrepancies which can be explained by a lack of available data, whether about the environmental impacts of main components or related energy demand to manufacture the battery. However, the main contributors to the environmental burden can be identified: first, the manufacturing energy, and then, all the components that are made of heavy or critical metals like the anode, the cathode, the BMS …

Elaborating an environmental profile from this literature review was a complicated task especially because of the demonstrated uncertainties and the low technology readiness level (TRL) of proposed RMB. Three environmental profiles are however proposed: an Mg-S and two Mg-ion batteries. These RMBs show a preliminary significant lower environmental burden from at least 50%, mainly due to the low weight of the magnesium anode and the high energy density objectives of E-Magic project.

An LCA must be completed as soon as a functional RMB is developed (Task 6.3 of E-MAGIC project), taking into account all the selected components and real energy density obtained to assess more accurately the environmental performance of the future battery.

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