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The environmental impact of Li-Ion batteries and the role of key parameters – A review

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A B S T R A C T

The increasing presence of Li-Ion batteries (LIB) in mobile and stationary energy storage applications has triggered a growing interest in the environmental impacts associated with their production. Numerous studies on the potential environmental impacts of LIB production and LIB-based electric mobility are available, but these are very heterogeneous and the results are therefore difficult to compare. Furthermore, the source of inventory data, which is key to the outcome of any study, is often difficult to trace back. This paper provides a review of LCA studies on Li-Ion batteries, with a focus on the battery production process. All available original studies that explicitly assess LIB production are summarized, the sources of inventory data are traced back and the main assumptions are extracted in order to provide a quick overview of the technical key parameters used in each study. These key parameters are then compared with actual battery data from industry and research institutions. Based on the results from the reviewed studies, average values for the environmental impacts of LIB production are calculated and the relevance of different assumptions for the outcomes of the different studies is pointed out. On average, producing 1 Wh of storage capacity is associated with a cumulative energy demand of 328 Wh and causes greenhouse gas (GHG) emissions of 110 gCO_2eq. Although the majority of existing studies focus on GHG emissions or energy demand, it can be shown that impacts in other categories such as toxicity might be even more important. Taking into account the importance of key parameters for the environmental performance of Li-Ion batteries, research efforts should not only focus on energy density but also on maximizing cycle life and charge-discharge efficiency.

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1. Introduction

The electrification of the transport sector and the buffering of fluctuating electricity generation in the grid are considered to be key elements for a future low-carbon economy based mainly on renewable energies [1,2]. Lithium-Ion batteries (LIBs) have made significant progress in the last decade and are now a mature and reliable technology with still significant improvement potential [3–5]. For mobile applications, they are already the dominating technology and their share in stationary energy systems is steadily increasing [6]. Several different types of LIB chemistries are widely established and broadly available, each with its own advantages and drawbacks [7]. Their increasing presence in daily life has also focused the attention on potential environmental concerns related to their production and disposal [8]. This issue has been repeatedly addressed by researchers, and numerous studies on the potential environmental impacts of LIB production and LIB based electric mobility are available [9–11]. For the quantification of the potential environmental benefits, these studies apply life cycle assessment (LCA). This is a standardized methodology for quantifying environmental impacts of products or processes, taking into account the whole life cycle [12–14]. The vast majority of existing studies focuses only on one or two types of batteries and all apply their own impact assessment methodology. Furthermore, studies often rely on the inventory data of previous publications, differ significantly in scope and system boundaries, and use fundamentally different assumptions for certain key parameters like battery cycle life or efficiency. Thus, the LCA results differ significantly due to these high uncertainties, and it is difficult to get a clear picture of the environmental performance of each LIB chemistry. Several reviews have been published in this regard but these are either comparably old [15] or focus primarily on electric mobility [9–11], rather than on battery production. In fact, there is currently no recent review about life cycle assessments of LIB. This paper reviews existing studies on the environmental impact of Li-Ion battery production. It provides a detailed overview of all relevant studies in the field and the key parameters of the LIBs assessed by them. By comparing the results and the assumptions made in the different studies, key drivers of uncertainty and thus of discrepancies among existing studies can be identified, providing recommendations for future LCA studies on LIB.

2. Review methodology

An extensive literature review is conducted in order to identify all available studies published on the environmental impacts of LIB production. The literature search is done in Science Direct, Scopus and Google Scholar using the search strings 'LCA battery, "assessment battery production", "assessment Li-Ion battery", "analysis battery production", and "battery impact environment". All publications on life cycle assessment of batteries or battery production from 2000 to 2016 are considered. Those studies on e-mobility and stationary battery storage systems are also taken into account whenever the battery production phase is included and assessed as a separate process step. Furthermore, studies on new LIB technologies like all-solid-state cells are also taken into consideration and listed in the corresponding tables, since they show the potentials of future developments in LIB technology. Nevertheless, they are excluded when it comes to calculating average values from the reviewed studies, since they are still in a very early development phase and their technical properties are too different for being directly compared with conventional LIB. Studies focusing only on cathode materials or laboratory cells are generally excluded in order to maintain a sound basis for comparison. For all studies, the key assumptions and the obtained results are extracted and recalculated for 1 Wh of energy storage capacity. This allows for comparing studies that use different functional units and for calculating the mean value from all corresponding results as generic average. Whenever value ranges are given in the studies, the average value is used for calculations. Furthermore, the key sources of original Life Cycle Inventory (LCI) data are traced back thoroughly for each study to identify possible interdependencies and common data sources, thus providing valuable information for future works. For all reviewed studies, the key parameters used for modelling the battery production process but also for characterizing the battery performance are extracted and contrasted, and their relevance for the life cycle environmental impact is determined.

Finally, the key assumptions regarding battery performance parameters are compared to the current state of the art in battery technology in order to assess their robustness. For this purpose, a specific technology database for electrochemical storage systems is used (Batt-DB) [16,17]. It is based on a permanent review of battery specifications available from manufacturers and research articles, providing an all-embracing picture of the current state of the technology. The Batt-DB currently contains 563 datasets from 49 scientific publications and 39 industry data sources (battery manufacturers) from 1999 to 2016. This allows for a statistical technology assessment. The sources included in the Batt-DB mainly consist of peer-reviewed articles from renowned scientific databases (Scopus, Science Direct and IEEEXplore) as well as reports from research institutes (e.g., Sandia Laboratories, Fraunhofer etc.). Manufacturer data is mainly obtained from publicly available technical data sheets and web pages. The database search is limited to include only lithium-based chemistries and publications not older than 2009; the same applies to the existing LCA studies, where the vast majority and, above all, the most relevant publications were released after 2009. This limitation provides a still sufficient amount of up-to-date datasets from scientific publications [18–60] and industry data sources [61–83].

Since the review focuses primarily on the impact of battery production, recycling of batteries is not considered, although this might have a considerable influence on the results. Especially the impacts associated with mining and resource extraction for the battery active materials can be reduced by recycling, since the