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Cradle-to-Gate Analysis of the Embodied Energy in Lithium Ion Batteries

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Abstract

Battery technology is increasingly seen as an integral element for future energy and transportation systems. Current developments in industry show an increasing number and size of battery producing factories, thus leading to an immense energy demand not only during the production of battery cells but also raw material extraction. Determining the embodied energy of battery cells allows a comparison with alternative energy systems and assessing the overall energy demand that can contribute to define measures for the improvement of its environmental footprint. The present work provides an analysis of the production of battery cells regarding their embodied energy. In order to quantify the embodied energy, a material and energy flow analysis (MEFA) was adapted towards battery production. The methodology focuses on the manufacturing processes and considers indirect and direct energy consumers, different machine states and existing yield losses along the value chain. The approach was applied to the battery manufacturing in the Battery LabFactory Braunschweig (BLB).

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Keywords: Modelling, Energy, Sustainable development

1. Introduction

Batteries are an essential requirement for the economic success of consumer electronics, stationary storage systems and especially electromobility. Due to the lack in tailpipe emissions it is widely considered as key technology to mitigate greenhouse gas emission in the transportation sector. Current batteries rely on lithium ion technology since it offers a combination of high energy density, long cycle stability and the ability to provide deep discharges [1]. Policy regulations and market adaption towards more environmentally sustainable products have led to an eminent increase in worldwide lithium ion battery (LIB) sales from 3.000 MWh in 2000 to over 120.000 MWh in 2017 (currently 57 % market share for automotive batteries) [2]. However, this increase causes new environmental burdens. Batteries consist of a variety of energy-intensive components, e.g. electrodes (cathode and anode), separator, electrolyte and either a hardcase or pouch foil. Cathodes use electrochemically active materials (e.g. LiFePO4 or LiNiCoMnO2) mixed with conductive additives (e.g. carbon black), polymer binders (e.g. polyvinylidene fluoride - PVDF) and a solvent (N-methyl-2-pyrrolidone - NMP). Anodes typically use synthetic or natural graphite in combination with carboxymethyl cellulose (CMC), styrene butadiene rubber (SBR) processed with water as a solvent [3]. Furthermore, the energy-intensive battery manufacturing process and charging during the use phase contribute to the environmental impacts of batteries [4]. Switching to renewable energy sources allows to compensate the additional electricity demand and to reduce greenhouse gas emissions. However, most countries have just started shifting to renewable energies in the last decades, e.g. China, as the current leader in LIB sales, supplied 35% of energy capacity with renewable energy sources in 2016 [5]. Therefore, it will take decades before the global energy demand will be provided through renewable energy sources [6]. Current concerns not only address the environmental consequences but also market competitiveness of battery manufacturers. The energy required along the value chain significantly impacts the overall costs and can be a decisive factor regarding the competitiveness between different battery manufacturers [7].

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As a consequence, reducing the overall energy demand along the value chain contributes to decrease costs and environmental impact of LIB technology. A prerequisite is detailed knowledge of the energy required for LIB along the value chain. Against this background, the present work adapts a material and energy flow analysis (MEFA) towards battery production. The cradle-to-gate approach was applied to the pilot line of the BLB in order to determine the embodied energy for battery production.

2. Background

2.1. Material and energy flow analysis

Material flow analysis (MFA) is a systematic approach allowing to assess flows and stocks of materials within a defined system [8]. MFA applied in the industrial sector investigates the throughput of process chains comprising extraction, chemical transformation, manufacturing, consumption, recycling and disposal of materials [9]. MFA accounts the input/output relations of processes and systems and can be controlled by material balances. Material and energy flow analysis (MEFA) extends material flows with energy flows and stocks in defined terms and uses visualization (e.g. Sankey diagrams) in order to support strategic and priority-oriented design of management measures [9].

2.2. Embodied energy

The embodied energy of a material is defined as the energy required for the transformation process from a raw material to a refined material. The energy comprises typically of energy for harvesting (e.g. mining, crushing, washing) and refining (chemical reduction process, e.g. smelting in metal processing) [10, 11]. Energy that could be recovered from the material is called *embedded* energy [12]. During the manufacturing of multi-material products, the embodied energies of the individual materials are combined. Moreover, additional energy is required for transportation, machines, facilities and personnel [13]. Allwood and Cullen reported that the use of recycled metals can reduce the embodied energy of a product due to lower required energy for recycling. Furthermore, the authors showed that high yield losses immensely affect the overall embodied energy [12].

2.3. Value chain of LIB

The battery value chain can be divided into four stages (Figure 1). During raw material extraction the materials for the individual components (e.g. cathodes, anodes, separator) have to be extracted (I) and processed (II) further for purity or specific composition [14]. Raw materials reserves are dispersed globally, e.g. main deposits for cathode active materials are located in Australia (lithium), DR Congo (cobalt), South Africa (manganese) and Philippines (nickel) [1] and consequently require energy for transportation. The materials are further processed in battery manufacturing which can be divided into electrode production (III), cell assembly and cell finishing (IV) [3]. During electrode production, active materials, conductive additives and a binder are processed in a dry and a wet mixing step. The produced slurry is coated onto current collector foils (aluminum for cathode and cupper for anode) and subsequently dried before it enters a calendering process. During cell assembly, the electrode coils are cut into single sheets. Then, the sheets are either stacked to an electrode-separator assembly (packaging). During a final drying process, residual water is evaporated from the cell stack and subsequently contacted via ultrasonic welding. The cell stacks are housed in either a hardcase or pouch foil, filled with electrolyte and tempered in an oven. During cell finishing, the cells enter the formation step where they also undergo a quality evaluation for several days [3, 15, 16]. In addition to the process machines, the technical building services (TBS) represent another group of machines involved in battery manufacturing. TBS is responsible for maintaining the factory building and particularly dry room under controlled conditions [13]. Figure 1 exemplarily illustrates the pilot plant scale process chain present at the BLB. Industrial scale production lines may vary slightly (e.g. electrode coils are slitted into smaller rolls, electrodes are winded to electrode-separator assemblies).

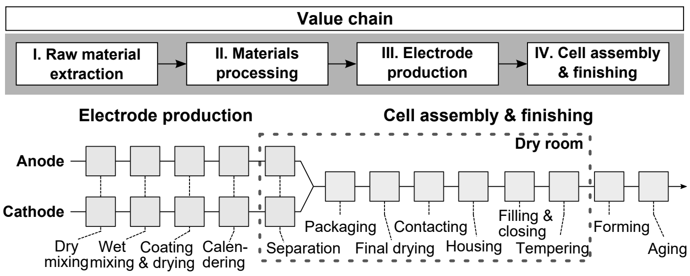

Fig. 1. Value chain of battery production (top) and detailed process chain of electrode production and cell assembly & finishing according to BLB (bottom).

2.4. Existing approaches

In the literature, different approaches exist in order to determine the environmental impact and energy demand of battery systems. However, they oftentimes vary in scale and scope. Life cycle assessment (LCA) is an established method allowing to evaluate the impact of a product. Majeau-Bettez et al. conducted a LCA for different battery systems [17]. The results allow allocating the effect of each battery component regarding different impact categories (e.g. global warming potential). Ellingsen et al. reported cradle-to-gate LCA results for a NMC traction battery highlighting the importance of battery production in terms of environmental impact [4]. The authors showed that over 60% of the global warming potential is caused during the manufacturing of battery cells. Zackrisson et al. analyzed the environmental effects of an organic-based and a water-based solvent during cell manufacturing and found out that the latter is environmentally preferable [18].

LCA allows to compute different environmental impact categories. Energy is a main driver for most impact categories. Knowledge about the embodied energy supports a better process understanding along the value chain. The embodied energy during battery production can directly be related to costs [19]. Several studies focus explicitly on the energy demand during battery manufacturing [19–22]. Energy demands range between 3.3 kWh to 13.3 kWh per cell, respectively 34.3 to 106.2 Wh per Wh of energy storage capacity. The large variability between the values can be explained by the different size and capacity of the battery, production scale, system boundaries and process parameters [23]. The coating/drying process and the TBS have been identified as the main energy consumers during battery manufacturing [18–21]. However, these studies neglect the embodied energy during raw material extraction and material processing and thus present an incomplete representation of the embodied energy of batteries. In summary, while much research has been conducted both on the environmental effects of LIB (cradle-to-gate) and the embodied energy during manufacturing (gate-to-gate), a cradle-to-gate MEFA of battery cells has not been addressed so far. Therefore, an approach is needed differentiating the energy and material consumption between process steps with regard to the energy embodied in the material.

3. Methodology: Combined material flow and energy analysis

Based on MEFA, a six step methodology was developed to determine the embodied energy for battery production (Figure 2). The approach covers cradle-to-gate and highlights the tracking of material and energy streams. First, the reference flow of the system must be defined in order to allow comparability between different stages and processes along the value chain (*Defining the reference flow*). Subsequently, the individual components of the final product and the necessary value chain can be determined (*Identifying the value chain*). Thereafter, retrograde material flows are generated regarding yield losses along the value chain starting from the requirements of the final product (*Capturing the material flow*). Consequently, the energy flow is captured by power data measurements or life cycle inventory databases (*Capturing the energy flow*). The embodied energy results from the process energies and the energy already embodied in the material (*Determining the embodied energy*). Finally, the results are analyzed allowing to identify main energy consumers (*Analysis*).

3.1. Defining the reference flow

The selection of the reference flow establishes comparability between the different phases and processes along the value chain. The reference flow relates the dimension of each process to the final product, e.g. amount of raw material during extraction per final product unit. When selecting the reference flow, other studies may be taken into account in order to ensure comparability with literature values. Typical reference flow for battery production are defined properties, e.g. energy storage capacity (Wh), cell capacity (Ah) or a single cell. However, a single cell might impede comparability with other studies in case different cell capacities are considered.

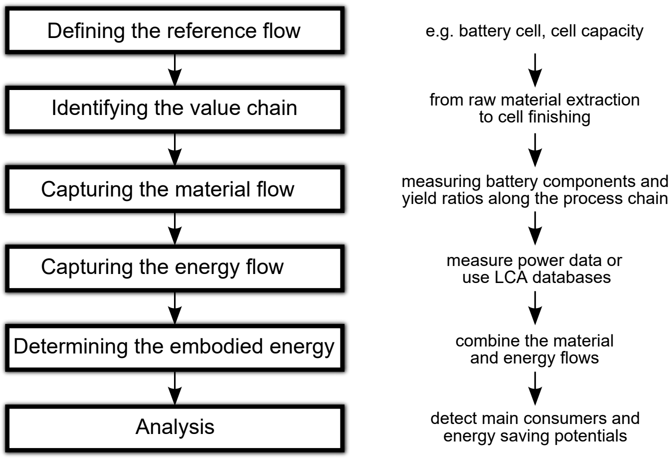

Fig. 2. Six step procedure with examples for battery production, which allows to determine the embodied energy along the value chain.

3.2. Identifying the value chain

Based on the components of the final product, the cradle-to-gate value chain can be identified. Moreover, typical value chain models for batteries can be found in the literature [24]. The manufacturing process of batteries requires raw material extraction, material processing and production [14]. Each phase could be dissected further into sub-processes, consequently increasing the accuracy of the model. However, this approach addresses the production phase and assumes already processed materials as input for the processes during the production. Consequently, the amount of data from life cycle inventory databases can be reduced. Processes may differ depending on the applied technology and thus dynamically affect the overall energy demand. The value chain represents the essential elements for the following material and energy flows. Different battery systems (e.g. all-solid-state LIB) require different materials and also adapted process chains [25].

3.3. Capturing the material flow

After identifying the value chain, the processes must be connected via material flows starting from the final product and moving retrograde (Figure 3). The masses of the individual components of the final product define the quantity of the material flows. Yield losses along the value chain increase the demand of initial material and must be considered. Mass balances help identifying those losses on process level. Furthermore, supplementary material which is used during the production but does not appear in the final product needs to be considered (e.g. organic or water-based solvent which is evaporated during drying).

3.4. Capturing the energy flow

The energy flow along the value chain can be required from life cycle inventory databases or measured directly. The former is typically used in raw material extraction and materials processing while the latter is more appropriate for battery manufacturing. Mobile or stationary measuring devices can be used to collect power data inside a battery factory. Repeated measuring of power data allows to account for dynamic effects during the manufacturing and the influence of changing boundary conditions (e.g. different drying temperatures, production scenarios). Furthermore, the demand for non-productive operational states and technical building services contribute to the overall energy demand. Other energy carriers (e.g. gas, district heating, compressed air) can also contribute significantly and thus should be included in this step.

3.5. Determining the embodied energy

Embodied energy is the combination of thermodynamically stored energy in the material and additionally added energy during processing. Consequently, embodied energy is closely linked with material flows along the value chain. Figure 3 shows exemplary material and energy flows for three processes. Energy flows from material (yellow flows) and from processes (blue flows) are merged in the individual processes. While material (green flows) can be removed (e.g. scrap, evaporating solvent) along the process chain, the overall embodied energy has to increase with the process chain proceeding. Mass balancing on process and system level serves as possible validation method.

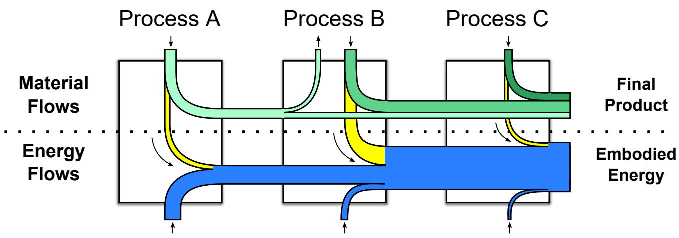

Fig. 3. Sankey diagram of material (green) and energy (process energy - blue, energy from material - yellow) flows along processes.

3.6. Analysis

After establishing material and energy flows of the examined system, the results can be used to generate knowledge about the value chain. Sankey diagrams present an effective approach, which allows visualizing material and energy flows along multiple processes. Hence, main energy contributors (material or processes) and their proportion to the overall energy demand can easily be identified.

4. Case study

The developed methodology was applied to LIB allowing to identify the overall embodied energy along the value chain (cradle-to-gate). The case study determines the impact of the electrode production, cell assembly and cell finishing on the overall embodied energy demand. Electric energy as the only energy carrier was considered during battery production.

4.1. Application of the procedure

First, the reference flow was determined to be the energy storage capacity of a 33.3 Wh LIB. The battery cell weights 273.6 g and uses NMC 622 and graphite as the cathode, respectively anode active materials. An extensive list of all battery components can be found in the supplementary material of [22]. The value chain was separated into raw material extraction and processing and battery manufacturing. The BLB process chain was used for battery production. The process chain is illustrated in Figure 1. Dry and wet mixing was combined to a single process step. Cells are assembled under dry room conditions. The BLB is a research infrastructure and thus differs from industry scale battery factories regarding throughput, capacity utilization and energy demand. The material flow was established retrograde starting from the final product. A medium yield ratio percentage was assumed in order to consider a more realistic scenario. The individual yield ratios and the retrograde approach can be found in [19]. The final battery cell consists of anode and cathode coating material (added during mixing – solvent evaporates during drying), aluminum and copper foil as current collectors (added during coating/drying), a separator (added during packaging), a pouch foil (added during housing) and electrolyte (added during electrolyte filling/closing). The material flows in combination with the process energy were used to determine the embodied energy during the battery production. Considering yield ratios during the individual process steps allows to identify the actual material demand for the production of battery cells. Based on these material flows, the energy demand due to raw material extraction, material processing and transportation were obtained from the life cycle inventory database Ecoinvent 3.4. Primary energy data of the BLB was used for process and TBS energies. The results of Ecoinvent and BLB were combined in an energy Sankey (Figure 4). Energy from materials, process machines and TBS were distinguished in order to identify major energy consumers along the process chain.

4.2. Discussion

The embodied energy of a battery cell is composed of the energy necessary for materials, process machines and TBS (Table 1). The energy for the materials require 391.0 Wh/Wh (34%) and is mainly due to the demand of active materials (295.8 Wh/Wh). Particularly, the NMC exhibits an energy-intensive processing due to mining and further processing. Furthermore, the current collector (aluminum and copper foil) contribute 79.0 Wh/Wh. The process energy

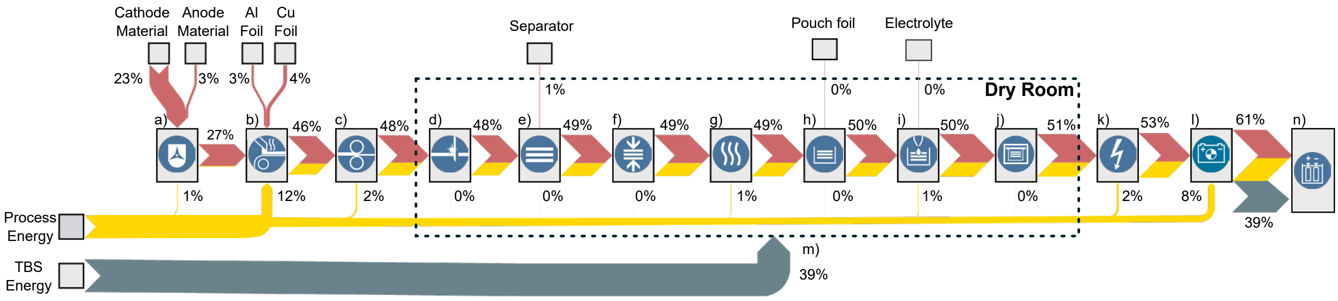

Fig. 4. Sankey diagram of the battery production showing energy demand for materials (red), process machines (yellow) and TBS (blue). Processes match with Table 1.

demand in the BLB is 313.9 Wh/Wh (27%). Here, the coating and drying process contribute 142.3 Wh/Wh which is caused by high drying temperatures of up to 120°C. Finally, TBS represents the largest energy share with 448.7 Wh/Wh (39%). The reason for this can be found in the pilot line scale character of the BLB. The dry room occupies a large in area in order to provide enough space for different technologies in the research factory. Overall, the energy values within this case study are in the same order of magnitude as current literature values with the exception of the characteristic high TBS energy demand. [19–21] report energy values between 34.31 Wh/Wh – 106.24 Wh/Wh. The energy demand of the materials strongly depend on the selected materials, production processes and cell design (e.g. size, housing, number compartments).

Table 1. Material, process and embodied energies per energy storage capacity during battery manufacturing. All values in Wh/Wh.

	Material Energy	**Process Energy**	**Embodied Energy**
a) Mixing	295.8	11.3	307.1
b) Coating/drying	79.0	142.3	528.4
c) Calendering		22.1	550.5
d) Separation		0.1	550.6
e) Packaging	9.6	1.3	561.5
f) Contacting		0.1	561.6
g) Final drying		6.4	568.0
h) Housing	3.8	0.6	572.4
i) Electrolyte filling & closing	2.8	9.2	584.4
j) Tempering		0.6	585.0
k) Formation		27.6	612.6
l) Aging		92.3	704.9
m) TBS		448.7	1153.6
n) Total	391.0	762.6	1153.6

4.3. Analysis

Figure 4 visualizes the results of the case study in a Sankey diagram. The energy demand by materials, process machines and TBS are displayed with different colors (red, yellow, blue). It can be seen that most of the energy from materials and process machines (75%) enter the process chain during the first two processes (mixing and coating/drying). Consequently, waste further down the process chain contains the high initial environmental embodied energy but evidently also high material costs and thus needs to be avoided due to economical and also ecological reasons. The results also suggest that post-production recycling in the BLB is ecologically feasible if the energy demand of the recycling process is below 1153.6 Wh/Wh assuming that the same quality of the initial material can be achieved (may differ between materials). TBS clearly impacts overall embodied energy demand but literature values for industry scale (31.2 Wh/Wh [21]) suggest a lower share of the overall embodied energy demand. Correspondingly, all three energy quantities (materials, processes, TBS) contribute relevantly to the overall embodied energy. Based on the results of this case study, three promising potentials for reducing the embodied energy can be identified. First, a different composition of the cathode active material with lower embodied energy would decrease the overall demand. Furthermore, the energy demand for the drying process needs to be reduced. Using water-based instead of organic-based solvents requires lower drying temperatures and consequently less energy during the electrode production. Thus, the retention time in the dry room must be reduced further consequently allowing an increase of the throughput. Finally, emerging battery systems, like all-solid-state batteries, do not require time-consuming electrolyte filling, tempering and cell finishing [25]. Results show that those processes contribute 11% to the embodied energy. Consequently, new battery systems can further decrease the embodied energy of batteries.

5. Conclusion and Outlook

The presented work provides an MEFA which captures the essential material flows and the correlated energy demands in battery production. The presented six step procedure allows to determine the embodied energy of batteries and includes different energy flows (e.g. from the raw materials and processing, battery manufacturing). Energy values for raw material extraction and materials processing were based on Ecoinvent data. Primary energy data from BLB were used to quantify the effect of process machines and TBS. The approach can be used to identify main energy consumers and determine the effect of process efficiency measures and yield losses on the overall energy demand. The results show that all energy carriers relevantly contribute to the overall embodied energy. Raw material extraction and materials processing represents 34% (391.0 Wh/Wh). Process machines and TBS contribute 27% (313.9 Wh/Wh) and 39% (448.7 Wh/Wh), respectively. 75% of the energy from the materials and process machines enter the process chain during the first two processes. Consequently, waste further down the process chain entails a large material and energy burden. Three potential reduction measures were derived based on the results of the case study. The presented approach can be applied to different products. Future work will consider further energy carriers during production (gas, long district heating and compressed air).

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