Transportation Research Part D 55 (2017) 82–90

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions

Linda Ager-Wick Ellingsen *, Christine Roxanne Hung, Anders Hammer Strømman

Norwegian University of Science and Technology, Program for Industrial Ecology and Department of Energy and Process Engineering, Sem Sælandsvei 7, NO-7491 Trondheim, Norway

ARTICLE INFO

Article history:
Available online 27 June 2017

Keywords:
Life cycle assessment
Life cycle inventory analysis
Lithium-ion traction battery
Electric vehicle
Greenhouse gas emissions

ABSTRACT

The various studies that consider the life cycle environmental impacts of lithium-ion traction batteries report widely different results. This article evaluates the inventory data and results to identify the key assumptions and differences in the studies. To aid the identification, we compile the reported life cycle greenhouse gas emissions of batteries. The studies find production-related emissions in the range of 38–356 kg CO_2-eq/kW h. One of the main sources of the large variations stems from differing assumptions regarding direct energy demand associated with cell manufacture and pack assembly. Further differences are due to assumptions regarding the amount of cell materials and other battery components. The indirect emissions associated with the use phase depend on the conversion losses in the battery, the energy required to transport the weight of the battery, and the carbon intensity of the electricity. Of the reviewed studies assessing the use phase, all estimate energy use associated with conversion losses while only one considers the mass-induced energy requirement. Although there are several industrial end-of-life treatment alternatives for lithium-ion batteries, very few studies consider this life cycle stage. Studies using the "recycled content" approach report emissions in the range of 3.6–27 kg CO_2-eq/kW h battery, while studies using the "end-of-life" approach report emission reductions in the range of 16–32 kg CO_2-eq/kW h battery. The uncertainty associated with the end-of-life results is high as the data availability on industrial process is limited. Based on our findings, we discuss how the life emissions of lithium-ion traction batteries may be reduced.

1. Introduction

Transport-related greenhouse gas (GHG) emissions have more than doubled since 1970, and have increased at a faster rate than any other energy end-use sector. The transport sector consumed over half of global primary oil and was responsible

Abbreviations: BEV, battery electric vehicle; EOL, end-of-life; GHG, greenhouse gas; LCA, life cycle assessment; LCO, lithium cobalt oxide; LFP, lithium iron phosphate; LMO, lithium manganese oxide; LTO, lithium titanium oxide; NCA, lithium nickelcobalt-aluminum oxide; NCM, lithium nickelcobalt-manganese oxide; PHEV, plug-in hybrid electric vehicle; SiNW, silicon nanowire.

* Corresponding author.
E-mail address: linda.a.ellingsen@ntnu.no (L.A.-W. Ellingsen).

http://dx.doi.org/10.1016/j.trd.2017.06.028
1361-9209/

for nearly one-fourth of global energy-related CO_2 emissions in 2010 (Sims et al., 2014). Light duty vehicles were responsible for around half of the total transport energy use. From the current number of around one billion vehicles (Sousanis, 2011), the total light duty vehicle ownership is expected to double in the next few decades (IEA, 2009). These patterns forecast a dramatic increase in gasoline and diesel demands, and have implications for climate change, urban air quality, and energy security. The projected increase in GHG emissions makes it particularly difficult for the transport sector to reduce its emissions and oil dependency, and this has led to policies that mandate more stringent fuel economy standards and encourage alternative drivetrain configurations and fuels (Wallington et al., 2016). Electric vehicles have emerged as strong candidates among the available transport alternatives (Hawkins et al., 2012a). Compared to conventional vehicles, electric vehicles can offer advantages in terms of powertrain efficiency, maintenance, and reduced tailpipe emissions.

Understanding the system-wide trade-offs of replacing conventional vehicles by electric vehicles requires a life cycle perspective. Environmental trade-offs that arise from the change in powertrain configuration are best analyzed using life cycle assessment (LCA) (Nealer and Hendrickson, 2015). As lithium-ion battery cells offer an unmatchable combination of high energy and power density, it makes them the battery of choice for electric vehicles (Nitta et al., 2015). Several studies have assessed the production impact of lithium-ion traction batteries (LIBs) as part of a battery electric vehicle (BEV), a plug-in hybrid electric vehicle (PHEV), or as its own product. Studies have mainly assessed LIBs with a graphitic anode in combination with a cathode of either lithium nickel-cobalt-manganese oxide (NCM), lithium iron phosphate (LFP), lithium nickel-cobalt-aluminum oxide (NCA), lithium manganese oxide (LMO), or a blended LMO-NCM cathode material. In addition, studies have also assessed a lithium titanium oxide (LTO) anode in combination with an LFP cathode and a silicon nanowire (SiNW) anode in combination with an NCM cathode. In contrast to production, the use phase and end-of-life (EOL) treatment of the battery are only evaluated in a few studies. Although several LCA studies have assessed LIBs, these assessments find significantly different results. Thus, there is much uncertainty associated with the data and results, making it difficult to provide direction for reducing environmental impacts of LIBs. Moving forward, it is important to understand why the studies obtain such widely different results. The main objective of this article is to identify the key assumptions and differences between the various LCA studies on LIBs. This will also allow us to identify potential issues that should be considered in future studies on LIBs and point out where further work is needed.

In this article, we considered LCAs of LIBs from various literature sources. Studies assessing only the LIB as well as those examining BEVs and PHEVs studies were evaluated. Unfortunately, few of the BEV and PHEV studies provide a transparent inventory or a detailed contribution analysis of the LIB. Furthermore, many of these studies base their battery inventory on previously published studies and therefore do not contribute new data. Although there are fewer studies that assess only the LIB, these studies more often include inventory data and a detailed contribution analysis. We mainly considered studies published in peer-reviewed journals, but we also included three grey literature cradle-to-gate studies. The first of these is the Volkswagen assessment of the battery used in the electric Golf (Volkswagen, 2012). Volkswagen has a long tradition of performing LCAs of their various vehicle models, and their reports are certified according to the ISO 14040 and 14044 standards. The other two studies were performed by the Paul Scherrer Institut (Bauer, 2010) and the United States Environmental Protection Agency (USEPA, 2013), two institutes that have extensive experience with LCA. To more easily pinpoint differences between the reviewed studies, we collected the reported cradle-to-gate results. Although most of the studies considered several different types of emissions, we limited our presentation to GHG emissions as global warming potential is the most consistently reported environmental impact category in the reviewed literature. Because the studies report GHG emissions based on different functional units, we recalculated the emissions for a common functional unit of 1 kW h of battery capacity. Even though there are much fewer studies that assess the use phase and EOL, which simplifies the search, we recalculate the reported GHG emissions for these life cycle stages where possible.

This article is divided into four sections, including this introductory section. In Section 2, we examine the underlying assumptions and key parameters to uncover the causes of discrepancies in reported results. In Section 3 we discuss our findings, distil the information from the LCA literature, and use this to suggest measures that can succeed in reducing life cycle GHG emissions of LIBs. Finally, Section 4 summarizes the most important findings, discusses knowledge gaps, and provides directions from the literature.

2. Life cycle inventory data and reported results

In the text below, we present the results and examine the life cycle inventories from the various studies. We start by reporting the compiled GHG emissions associated with production. Using the emissions as a starting point, we seek to identify and discuss key assumptions and differences among the various studies. Then, we examine the use phase and EOL treatment.

2.1. Production

The different studies vary in how they report the breakdown of the GHG emissions due to production. Where possible, we disaggregated emissions associated with cell materials (dark blue), other battery components (pale blue), cell manufacture (dark green), battery pack assembly (pale green), and transport (grey). For studies where fewer details are provided, we reported aggregated emissions associated with production of cell materials and battery components combined (blue,