Transportation Research Part D 47 (2016) 182–194

Contents lists available at ScienceDirect

Transportation Research Part D

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

# Effects of battery chemistry and performance on the life cycle greenhouse gas intensity of electric mobility

Hanjiro Ambrose [a], Alissa Kendall [b,*]

[a] Transportation, Technology and Policy, Institute of Transportation Studies, University of California, Davis, 1605 Tilia St, Davis, CA 95616, USA
[b] Department of Civil and Environmental Engineering, University of California, Davis, One Shields Ave, Ghausi Hall, 3143, CA 95616, USA

ARTICLE INFO

*Article history:*

*Keywords:*
Li-ion battery
EV
LCA
Carbon footprint

ABSTRACT

Lithium traction batteries are a key enabling technology for plug-in electric vehicles (PEVs). Traction battery manufacture contributes to vehicle production emissions, and battery performance can have significant effects on life cycle greenhouse gas (GHG) emissions for PEVs. To assess emissions from PEVs, a life cycle perspective that accounts for vehicle production and operation is needed. However, the contribution of batteries to life cycle emissions hinge on a number of factors that are largely absent from previous analyses, notably the interaction of battery chemistry alternatives and the number of electric vehicle kilometers of travel (e-VKT) delivered by a battery. We compare life cycle GHG emissions from lithium-based traction batteries for vehicles using a probabilistic approach based on 24 hypothetical vehicles modeled on the current US market. We simulate life-cycle emissions for five commercial lithium chemistries. Examining these chemistries leads to estimates of emissions from battery production of 194–494 kg $CO_2$ equivalent ($CO_2e$) per kWh of battery capacity. Combined battery production and fuel cycle emissions intensity for plug-in hybrid electric vehicles is 226–386 g $CO_2e$/e-VKT, and for all-electric vehicles 148–254 g $CO_2e$/e-VKT. This compares to emissions for vehicle operation alone of 140–244 g $CO_2e$/e-VKT for grid-charged electric vehicles. Emissions estimates are highly dependent on the emissions intensity of the operating grid, but other upstream factors including material production emissions, and operating conditions including battery cycle life and climate, also affect life cycle GHG performance. Overall, we find battery production is 5–15% of vehicle operation GHG emissions on an e-VKT basis.



## 1. Introduction

A transition to plug-in electric vehicles (PEVs), including battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), is promoted as a pathway to reduce greenhouse gas (GHG) emissions from transportation, increase national energy security, and improve local air quality. Lithium-ion batteries (LIBs) have become the preferred choice for energy storage in PEVs because they offer superior energy density, charge cycle performance, and decreased environmental burdens compared to other electrochemical options such as NiMH and lead acid (Ambrose et al., 2014). PEVs have been advocated in part because electric powertrain efficiency is significantly greater than conventional internal combustion engines (ICEs), and could lead to deep reductions in operational energy and GHG emissions. As much as 75–95% of life cycle GHG emissions

* Corresponding author.
*E-mail addresses:* hambrose@ucdavis.edu (H. Ambrose), amkendall@ucdavis.edu (A. Kendall).

http://dx.doi.org/10.1016/j.trd.2016.05.009
1361-9209/

from ICE vehicles are attributable to fuel consumption and combustion for operation (Bauer et al., 2015; Castro et al., 2003; Geyer, 2008; Kim et al., 2003). However, increased vehicle production emissions, and decreased operation emissions, means that PEVs may experience a greater proportion of life cycle emissions during production compared to ICEs. In fact, on a percent basis, PEVs may have double the emissions from the production phase, and previous studies have shown that battery manufacture alone can be responsible for 35–41% of those production emissions for a 120–160 km range PEV (~24 kWh battery) (Hawkins et al., 2013).

Despite the potential importance of battery manufacture and replacement, very few life cycle assessment (LCA) based studies of PEVs or PEV traction batteries have considered multiple battery chemistries and differences in battery degradation and service life. Instead, separate bodies of research have developed with different foci: (i) LCA of PEVs and traction batteries; (ii) studies of electricity grids to determine operating emissions for PEVs; and (iii), empirical study, modeling, and performance testing of vehicle traction batteries. Research progress in these three fields has had limited integration, and which, if implemented, could reveal significant sources of uncertainty in emissions estimates for PEVs and important trade-offs for vehicle and climate policies.

This study builds on these bodies of previous research by offering a novel integration of automotive battery cycle-life modeling and life cycle GHG assessment, with the specific goal of assessing how differences between lithium chemistries will affect GHG emissions performance. We apply a probabilistic modeling approach, Monte Carlo simulation, to capture the inherent variability and uncertainty in predictive modeling of a PEV traction battery life cycle. This provides a new framework for comparison of emissions across life cycle stages and technological designs. In addition to considering five possible LIB chemistries, the assessment captures spatial and temporal heterogeneity in electricity grid emissions, variability in battery-to-wheels efficiency including ambient climate impacts, causes and effects of battery aging and health, and uncertainty in lifetime e-VKT delivered by a battery.

## 2. Materials and methods

### 2.1. Lithium ion traction batteries

In short-range configurations, traction battery manufacture is likely a small share of overall PEV production emissions due to the small size of the batteries involved (<6 kWh). Early estimates for plug-in hybrid vehicles suggested that potential production emissions for a 10–15 mile all-electric PHEV to be 2–5% of the vehicle's life cycle emissions (Samaras and Meisterling, 2008). In the United States, ranges of PEVs, both pure electric and hybrid, have increased significantly over the last five years as more electric vehicle models have been introduced (see SI: Fig. A and Table A for historical data) (U.S. Department of Energy, 2015). A favorable policy landscape for vehicles considered "zero emissions" at federal and state levels (Mock and Yang, 2014), in addition to rapidly falling battery prices (Nykvist and Nilsson, 2015), are helping to increase deployment of long-range PEVs. For long-range PEVs, such as an all-electric vehicle with 25 kWh of on-board storage, battery production likely contributes 12–15% of overall life cycle emissions (Bauer et al., 2015; Hawkins et al., 2013).

A variety of lithium cathode and anode materials are being used in, or considered for, mass market vehicles. These chemistries have significantly different expectations for cycle life, from 1000 to over 5000 cycles in vehicle service, as well as different nominal and maximum voltages (2.4 V/2.8 V to 3.8 V/4.2 V) (Burke and Miller, 2009). These differences affect the choice of battery management systems, cooling systems, and other components (Nelson et al., 2011), and may affect cost. Heterogeneity in material composition of the battery also has implications for both the supply of raw materials and the economic value of recovered and recycled materials (Wang et al., 2014).

Samaras and Meisterling (2008) was among the earliest studies to examine the life cycle GHG emissions from a PEV, comparing ICE, hybrid electric, and three PHEV applications (30, 60, and 90 km electric range distances) (Samaras and Meisterling, 2008). The study assumed a lithium nickel–cobalt–manganese (NMC) battery chemistry, and modeled the battery's production-related impacts and performance characteristics using the results of an often-cited study (Rydh and Sandén, 2005). Rydh and Sandén examined the NMC battery as one of a number of energy storage options for photovoltaic systems (not vehicle applications). At the time of Samaras and Meisterling's research there were no commercially produced PHEV vehicles, so their study was necessarily conjectural. They found relatively small contributions from the battery to the life cycle impacts of the vehicle.

Notter et al. (2010) was among the earliest and most transparent studies that explicitly examined the contribution of LIB production to the life cycle emissions of a BEV (Notter et al., 2010). They model a lithium manganese-oxide (LMO) battery, developing their own life cycle inventory, and estimate significantly lower production-related impacts compared to those from Rydh and Sandén, and as a consequence those of Samaras and Meisterling. They find the LIB contributes 15% of life cycle impacts, based on the Ecoindicator 99 approach (Hawkins et al., 2012).

Majeau-Bettez et al. (2011) performed an LCA of three PEV battery chemistries, nickel metal-hydride (NiMH), lithium nickel–cobalt–manganese (NMC), and lithium iron-phosphate (LFP), and assume that the LFP battery has twice the cycle life, 6000, compared the NCM and NiMH batteries. Like Samaras and Meisterling, they develop the life cycle inventory and battery performance characteristics for the LIB based on the work of Rydh and Sandén. The authors show larger battery manufacturing impacts compared to the earlier studies of Notter et al. and Samaras and Meisterling.