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Original Research Article

Environmental feasibility of re-use of electric vehicle batteries

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ABSTRACT

The environmental feasibility of re-using electric vehicle (EV) batteries at their automotive end-of-life into stationary applications was analyzed in a parameterized life cycle model. The model assumes that the life of a lithium ion (Li-ion) EV battery is extended to incorporate the re-purposing and re-use in grid storage for a utility application. Compared to using natural gas fuel for peak electrical power generation a 56% reduction in CO_2 emissions is possible when an EV battery is re-purposed to store off-peak clean electricity to serve peak demand. The magnitude of CO_2 mitigation associated with battery re-use is similar to that of switching from using a conventional vehicle to an electric vehicle, meaning that the greenhouse gas (GHG) benefits of vehicle electrification could be doubled by extending the life of EV batteries, and better using off-peak low-cost clean electricity.

Introduction

Technological advances in battery performance combined with the regulatory push for low- and zero-emission vehicles have made widespread electric mobility a growing reality. Commercialization of these systems by major automotive manufacturers is underway, including plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV) [1–3]. A major consideration of electric vehicles (EV) compared to internal combustion engine (ICE) formats is initial material and energy investment and associated environmental aspects of producing large battery packs that represent a significant investment in resources and materials; however, on a cradle-to-grave life cycle basis, this increased environmental loading at the production stage can be offset because of lower environmental impacts associated with EV use phase compared to fossil–fueled ICE vehicles [4,5]. This article considers battery re-use as a further opportunity to gain benefits from the investment made in such batteries.

EV batteries at their automotive end-of-life no longer meet the power requirements for a vehicle, but do retain significant storage capacity that can be used in other applications, like supporting electricity grid operations [6]. Extracting a second use from re-purposed EV batteries may also assist EV owners in recovering some of the initial costs of vehicle purchase.

The technical aspects of battery re-use has been proposed by automakers, governments, and utility companies [6]; however the environmental feasibility of this approach has not been well explored. The environmental and resource investment in the battery can be effectively amortized over a longer lifetime of material use. Environmental benefits can be obtained from re-purposed batteries used to store intermittent low emission renewable energy such as wind and solar used to harmonize supply and demand, or ease electrical grid congestion by providing time of day load electricity leveling in a distributed fashion. In this paper, energy storage is considered to offset peaking power generation from a natural gas plant. CO_2 emissions in all phases of battery life are modeled. The current study does not represent a full life cycle assessment (LCA) study as only CO_2 emissions impact has been considered. This study addresses technical challenges and implications that must be considered in the life cycle of batteries from vehicle applications and their re-purposing include testing and validation of battery degradation, remaining capacity, new powertrain control, and battery management strategies to optimize the entire battery life cycle over multiple purposes. Related LCA studies will be reviewed here because of significance of LCA methodology in the assessment of environmental feasibility of the battery second use and will support such future work.

Objectives of the study

The environmental feasibility and benefits of re-purposing used EV batteries into stationary applications has not yet been

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comprehensively assessed. Given the number of variables around battery life, state-of-health (SOH), and sources of electricity used to charge a battery, it is important to understand under what circumstances it may be environmentally desirable to consider re-packaging EV batteries into stationary uses.

This study addresses these gaps by considering the CO_2 emissions footprint of a number of different battery and vehicle life-cycle scenarios. Specifically this study is a preliminary analysis of the CO_2 emissions that might be offset during the second use of a vehicle battery pack.

Background

Previous studies have examined the technical and economic feasibility of re-purposing used EV batteries [6–9]. Vehicle manufacturers have begun to collaborate with power equipment companies to test the practicality and technical feasibility of re-purposing EV batteries. GM and ABB, and Nissan with Sumitomo/ABB have been testing used Volt and Leaf batteries [10]. As well, research literature indicate technical and economic feasibility [6,7,11,12]. Second use applications are related to Vehicle to grid (V2G) applications, however make use of the vehicle battery pack to store energy for other purposes while the battery is still in the vehicle and still provides for vehicle use. Grid regulation appears to provide the greatest share of added revenue [13–15].

Several factors need to be considered; some correspond to economic parameters, but others, like generation source of grid electricity, do not significantly align with economic assessment. Narula et al. [7] estimated incidental benefits of reduced air emissions by avoiding the operation of natural gas fueled simple cycle combustion turbines during on-peak hours. Williams and Lipman [9] estimated carbon dioxide reductions from the displacement of on-peak electricity with surplus wind energy. Enabling of wind energy and improving capacity factor with EVs as storage has also been studied [15], but not specifically using re-purposed EV batteries. Net greenhouse gas (GHG) benefits of V2G depend on charging and discharging strategies, and on what sources are consumed or displaced. Moreover, average and marginal calculations of the emissions profile of the electric grid should be considered.

Life cycle assessment

To assess environmental performance of EVs and their battery systems, previous studies have employed the method of LCA, which provides a comprehensive view of impact categories across all stages of the life cycle of a product system from "cradle to grave" [16,17]. Assessment involves the steps of scoping, inventorying quantifying flows of resources and environmental releases, assessing potential impacts, and then interpreting and evaluating the robustness of results [17]. LCA is data intensive and typically is performed with a mix of data sources of variable data quality. Several software packages are available, and a number of national and international databases are widely employed in LCA studies. When comparing across similar vehicles with different powertrains this task is further complicated and has been the subject of considerable deliberation for LCA of electric vehicles (see for example, [18]).

LCA of electric vehicles

Prior studies on the life cycle of EVs indicate that three areas in the vehicle life-cycle are dominant with respect to potential environmental impacts. First is battery manufacturing, including mining and production of metals like cobalt and lithium, which contribute to several impact categories [4,19,20] including in particular to local air quality [19,21,22]. Manufacturing contributes as much as half of the GHGs over the life of an EV; and electronics associated with battery systems may contribute up to half of the acidification impact category [21]. Secondly, the other major area of impact is the EV use phase. Potential impacts are driven by both the quantity of energy used in a vehicle and by the mix of energy sources used to generate electricity supplied by the electric power grid [4,19,23]. Helms et al. [24] showed that the acidification impact category is significant for EVs powered with electricity generated from fossil fuels like coal. Hawkins et al. [4] assessed a variety of environmental impact categories for conventional and electric vehicles assuming a 150,000 km vehicle lifetime and based on a European electricity mix. Their results suggest a downturn in GHG emissions by 20–24% for EVs in comparison to gasoline ICE vehicles. They suggest that the vehicle lifetime has a great effect on the GHG emissions per distance for EVs, as the emissions intensity production is amortized. The environmental performance of EVs is critically dependent on the combination of the vehicle and electricity production impacts as well as key factors such as energy use. LCA studies on EV storage batteries similarly show that the use phase dominates many of the life cycle impacts [20,25]. Thirdly, recycling of materials at the end-of-life of the EV, especially the battery, is important in the environmental profile [26], although this is often not considered [4]. The material and resource impacts made in initial production can be partially recovered by accounting for a credit for materials that are recycled.

Battery degradation

Battery degradation is a significant factor for EV batteries. Knowledge of battery degradation is considered in designing durable stationary electrical systems [22]. All batteries experience calendar aging, a gradual decomposition of the electrolyte for a given temperature [27] over the life of the battery simply to basic material degradation. However, the cycling of batteries accelerates their degradation especially if the thermal cycling is not closely controlled. Battery degradation impacts two main distinct performance metrics–capacity fade and power fade. Capacity fade represents a gradual loss in energy capacity for a given current and it is generally measured in Amp-hours. Capacity fade is predominately caused by the formation of a solid electrolyte interface (SEI) passivation layer at the anode-electrolyte interface due to its consumption of lithium ions [28]. Power fade, measured in watts, is a gradual increase in internal impedance that decreases available power. The SEI also contributes to power fade since the passivation layer at the cathode-electrolyte interface increases resistance to ion transport. Loss of electrode active material can also be caused by fracturing or cracking due to excessive mechanical stresses. As cracks develop, electrical isolation and blocking of insertion sites becomes more extensive and leads to power and capacity fade, consequently [29,30]. Moreover, surface layers on anode and cathode play a barrier role in reactions with electrolyte and cause a growth in cell impedance and reduction in cycling efficiency of the battery [31].

For electric vehicle configurations, both capacity and power fade each have two major implications. For capacity fade, the first is that a reduction in useable capacity represents larger state-of-charge swings in charge-sustaining operation for a given drive cycle. Secondly for capacity fade, the battery capacity has a direct correlation to charge-depleting range of the vehicle. Considering power fade, the first implication is that the minimum and maximum high voltage but limits will be achieved at lower battery discharge and charge currents respectively. The maximum discharge and charge power of the battery is reduced, resulting in less power available during accelerations and less ability to recapture power during regenerative braking. Since the drive cycle and vehicle