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Original Research Article

# Energy efficiency of Li-ion battery packs re-used in stationary power applications

Leila Ahmadi [a], Michael Fowler [b,*], Steven B. Young [c], Roydon A. Fraser [a], Ben Gaffney [a], Sean B. Walker [b]

[a] *Department of Mechanical and Mechatronics Engineering, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada*
[b] *Department of Chemical Engineering, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada*
[c] *School of Environment, Enterprise and Development, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, Canada*

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ABSTRACT

The effects of capacity fade, energy efficiency fade, failure rate, and charge/discharge profile are investigated for lithium-ion (Li-ion) batteries based on first use in electric vehicles (EVs) and second-use in energy storage systems (ESS). The research supports the feasibility of re-purposing used Li-ion batteries from EVs for use in ESS. Based on data extrapolation from previous studies with a low number of charge/discharge cycles, it is estimated that the EV battery loses 20% of its capacity during its first use in the vehicle and a further 15% after its second use in the ESS over 10 years. As energy efficiency decreases with increased charge/discharge cycles, a capacity fade model is used to approximate the effect of the relationship between cycles and capacity fade over the life of the battery. The performance of the battery in its second use is represented using a model of degradation modes, assuming a 0.01% cell failure rate and a non-symmetric charge/discharge profile. Finally, an accurate modeling of battery performance is used to examine energy savings and greenhouse gas (GHG) emission reduction benefits from using a Li-ion battery first in an EV and then in an ESS connected to the Ontario electrical grid.

## Introduction

Global adoption of electrified vehicles (EVs) such as pure battery electric vehicles, plug-in hybrid electric vehicles, and hybrid electric vehicles is rising, and the province of Ontario, Canada is targeting a 5% market penetration by 2020 [1–3]. Lithium ion (Li-ion) batteries provide excellent performance in EVs because of their high energy density and advanced gravimetric and volumetric properties [4–6]. Based on manufacturers' warranties that imply the battery has a useful in-vehicle lifespan of approximately 8 years, the battery is assumed to reach the end of its useful automotive life when 20% of its initial capacity is lost. Several studies indicate that batteries with 80% of their original capacity at end-of-life (EOL) within a vehicle can be re-purposed and used in energy storage, peak-shaving and load-following applications, including electric supply, ancillary services, grid systems, and the integration of renewable energy sources [7,8]. Wood et al. (2011) note that the role of battery lifetime is uncertain in quantifying the cost of EVs and that this uncertainty leads to inconsistencies in the results of EV studies. The life cycle costs of EVs are sensitive to the cost of battery replacement and thus depend on the battery's state of charge (SOC) and the ability of the battery management system to minimize battery degradation over time [9]. The second use of the battery adds residual value back to the vehicle by allowing the battery to stay in service longer. In other words, by extending the battery's lifespan, the high initial cost of the battery can be distributed among other users [10]. Further, the automotive and power industries can support each other by charging EV batteries with intermittent renewable energy and excess base load nuclear power. Thus the integration of re-purposed EV batteries into the electrical grid can improve energy storage and provide peak power delivery [11]. Distributed energy storage is seen as critical to the development of a "smart grid." By boosting the flexibility of grid operations through increased energy buffering capacity and new ways to control the flow of energy [12], energy storage systems (ESS) powered by re-purposed EV batteries could be a reliable solution for the challenges posed by intermittent renewable energy sources and congested electrical distribution grids [7].

Technical challenges that are involved in the life cycle of batteries used in both vehicles and ESS include testing and validation of battery degradation and remaining capacity, testing for failed cells within the pack, implementation of new control systems to interface with the battery management system, the safety of the

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[*] Corresponding author. Tel.: +1 519 888 4567x33415.
*E-mail address:* mfowler@uwaterloo.ca (M. Fowler).

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re-purposed pack and battery management strategies to optimize the entire battery life cycle. The authors' experience at the University of Waterloo clearly indicates dismantling of the cells within a vehicle battery pack is neither technically nor economically feasible. Therefore, it is expected that packs will be re-purposed at the pack or module level with at least some of the original battery management system infrastructure in place. Factors for the effective application of re-purposed EV batteries in stationary applications, including state of health (SOH) conditions and potential energy and environmental impacts, have not yet been systematically assessed. Predicting the degradation and SOH of Li-ion batteries after their use in EVs is a central challenge addressed in this paper. In this study, the authors investigate the factors that must be considered to improve the effectiveness application of re-purposed batteries including capacity fade, energy efficiency fade, cell failure rate, and charge/discharge profile. Energy use and greenhouse gas (GHG) emissions over the entire battery lifetime are considered as indicators of the environmental feasibility of battery re-purposing. The analysis is conducted using aggregated data describing Ontario's electrical grid mix, which is about 50% nuclear and 25% renewable power generation – with most of the renewable energy being from hydro.

All batteries undergo calendar aging: a gradual decomposition of the electrolyte over the life of the battery due to basic material degradation [13]. Importantly, a drop in useable capacity will represent larger SOC changes in charge-sustaining operation for a given drive cycle (i.e. a battery pack will have larger changes in SOC to travel the same distance).When determining how the capacity of the battery fades, the capacity has a direct correlation to the charge-depleting range of the vehicle [14]. Several studies have examined the capacity fade effect for different kinds of Li-ion batteries in ideal laboratory settings. However, most have not examined the high numbers of charge/discharge cycles that occur during use in an EV or any subsequent use [15–17].

### *Objective of the study*

The objective of the present research is to fill a gap in knowledge regarding SOH of EV Li-ion batteries to effectively re-purpose them in ESS. This contributes to a better understanding of how Li-ion batteries can perform as ESSs in their second use. Specifically, this is done by examining the effect of Li-ion battery degradation based on two parameters "capacity fade" and "energy efficiency fade," during first use in an EV and second use in a stationary application. Energy efficiency fade is a relatively new concept that is elaborated, given the importance of energy efficiency for an ESS composed of second use batteries. Energy efficiency fade has not been a significant concern in automotive applications but is critical in the second use as it directly impacts the economic viability of energy load shifting arbitrage [18]. Energy efficiency and energy efficiency fade is of less concern in the vehicle use phase of the battery pack lifecycle as the cost of electrical energy to refuel a vehicle is so much less than the cost of the equivalent gasoline to refuel for an equivalent distance travelled. The rate of capacity fade of a Li-ion battery is estimated during the battery's use in a vehicle followed by use in stationary application. In order to improve upon the authors' previous analysis of $CO_2$ emissions for Li-ion batteries and vehicle life cycle scenarios [19], energy and GHG emissions are used as indicators to evaluate the environmental benefits of Li-ion battery re-purposing over the whole battery lifetime. A model of GHG intensity versus battery lifetime has been developed based on the projected 2030 Ontario electrical grid mix. Moreover, in order to consider energy issues, an estimate of the energy used by the Li-ion battery over its two-phase life has been developed. The research findings are valuable to broader applications of extending the useful life of EV Li-ion batteries in high value applications.

## Theoretical background

In previous researches it is suggested that re-purposed EV batteries can be used for energy storage applications [8,10]. In the preceding study by Ahmadi et al. (2014), utilizing a re-purposed Li-ion battery in ESS applications, such as peak shifting, was found to reduce $CO_2$ emissions by 56%. Building on the previous work, this study is focused on the effect of charge/discharge cycling on capacity fade and energy efficiency fade over the extended life of the battery.

The long-term reliability of Li-ion batteries is an important characteristic of the technology. In a typical configuration graphite is used as the anode because it provides high energy density and stability over a large number of charge cycles [20]. $LiFePO_4$ is used as the cathode due to its environmental affability, low cost, material availability, and cycling stability [20–22]. Due to these properties and its potential use in vehicle applications, $LiFePO_4$ is the cathode chemistry analyzed in this study. Moreover, a combination of the graphite anode and the $LiFePO_4$ cathode has been determined to be reliable cell chemistries for ESS applications because of its outstanding cycling stability, energy density, and cost [20,23,24].

Several studies show that capacity fade is a common occurrence in EV batteries that is brought about by aging and charge/discharge cycling [4,15,23,25–27]. Capacity fade is a gradual loss in energy capacity for a given current and is generally measured against Amp-hours (Ah). 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 [14]. Moreover, surface layers on the anode and cathode play a barrier role in reactions with the electrolyte. This, in turn, causes an increase in cell impedance and a reduction in the charge/discharge cycling efficiency of the battery [28]. These two effect lead to energy efficiency fade, which measures the ability of the fraction of energy that is stored in the battery compared to that delivered to the battery during charging. In an EV, capacity and power fade have significant implications. A reduction in the useable capacity results in larger SOC swings in charge-sustaining operation for a given drive cycle and a shorter driving range. Power fade reduces the maximum discharge and charge power of the battery, resulting in less power available during acceleration and a reduced ability to recapture power during regenerative braking [14,29].

There are several different types of efficiencies defined for batteries [30] and all decrease over the lifetime of the battery. Energy efficiency is sometimes referred to as "electrical efficiency" and is defined as the ratio of electrical energy that can be removed from the battery to the electrical energy supplied:

$$\eta_{\text{electrical}} = \int (VI)_{\text{dis}}\,\mathrm{dt} \Big/ \int (VI)_{\text{chg}}\,\mathrm{dt}$$

Where, $I_{\text{dis}}$ and $I_{\text{chg}}$ refer to the discharge and charge current respectively and $V$ refers to the cell voltage which is the same during discharge and charge.

This efficiency is not a significant concern to vehicle manufacturers but it has important implications in the second use stationary applications of the battery. In practice, the actual energy efficiency observed will vary according the usable SOC window, charge and discharge rates, as well as operating temperature. Note that this is different than "columbic efficiency", which is defined as the ratio of the discharged capacity to the Ah needed in order to bring the battery to the discharge initial SOC, expressed as follows:

$$\eta_{\text{columbic}} = \int I_{\text{dis}}\,\mathrm{dt} \Big/ \int I_{\text{chg}}\,\mathrm{dt}$$