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Research Paper

Effect on battery life of vehicle-to-home electric power provision under Canadian residential electrical demand

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HIGHLIGHTS

- Physics-based model employed to simulate battery pack performance and degradation.
- Baseline pack lifetimes found as function of driving behaviours through simulation.
- High-resolution electricity profiles for Canadian context represent V2H demand.
- V2H effect on pack lifetime found by simulation and compared to base driving cases.
- Pack lifetime was reduced by two years for a daily 8-h V2H event.

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ABSTRACT

Vehicle-to-Home (V2H) is a support activity using electric vehicles where the electric power stored in their batteries is supplied in response to residential electrical demand. It is understood that supplementary battery use such as V2H will reduce the battery service life. Judicious V2H activity can provide energy benefits at acceptable levels of battery life reduction. The present study employs a fundamentals based battery simulation to explore a range of V2H scenarios to assess the net energy benefits, and weigh these against associated battery life reduction attributable to V2H. The frequency (daily, weekly, monthly), duration and time-of-day of the V2H event were test parameters. Long term (i.e. given roughly 16 year battery calendar life) detailed simulations which included a daily driving regime together with V2H activity based on detailed residential electricity use data were used to determine battery lifetimes. Apart from aggressive driving and fast charging which greatly impact electric vehicle (EV) battery life, the largest contributions to battery degradation were for intense participation in V2H services, such as handling the household electrical load for 8 h daily. A 10.6 year battery life with no V2H, was lowered to about 10.2 years with 1 h daily V2H, and to about 8.5 years with 8 h daily V2H. However, lower intensity, and especially lower frequency use of the EV battery can still provide useful V2H services with acceptable battery degradation.

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1. Introduction

Vehicle-to-Home (V2H) describes an energy system where the battery pack from electric vehicle is used to supply the electricity for residential use. As an energy use strategy as concerns utilities, V2H is aimed at alleviating consumption of power in peak periods when demand is highest. V2H could also provide backup power supply for emergencies, or be used as a temporary electricity supply for infrequently used remote buildings.

It is understood that the battery packs in electric vehicles have been designed for power loads associated with driving. Driving demands in general are more severe than residential energy demands, so it is envisioned that vehicle battery packs could find additional use by supplying power to buildings or homes. The present study has been conducted to investigate the effect of real household electrical loads on electric vehicle battery life. There is general interest from the utility side in North America to make use of V2H to assist with grid stability and to minimize infrastruc-

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tural upgrades and expansion, but at present, electrical vehicles on the market here are not equipped with this capability. Of note, is that in Japan, Toyota and Nissan have implemented V2H functionality in electric vehicles [1].

A number of preliminary studies have been made which describe advantages of V2H, such as peak reduction for household electrical demand. Basic models with batteries represented as a simple energy reservoir, without electrochemical functionality were used to show that V2H can improve the uniformity of power demand [2].

A paper on smart grids, considered V2H in a sophisticated residential energy system [3]. A key finding was that an intelligent management system can derive benefits from V2H, and when combined with renewable energy, there will be elevated demands on the electrical storage units, but the extent of this was not quantified. An even more recent effort in this area was published by Putrus et al. [4], where the importance of battery wear associated with V2H was recognized. The modeling approach employed here was overly simplistic and concluded that controlled smart charging of EV batteries did not cause excessive lifetime degradation. An example of a basic economic case for V2H, with simple technical justification, can be seen in [5].

V2H is a very new practice, and the present study is the first to apply physics based modeling to provide some concrete quantitative results to the generally pondered questions of the effect on automotive battery pack life when also using the vehicle for V2H beyond its normal driving use. From the literature it was understood that V2H was a useful concept and could provide a number of practical benefits, and this paper is the first to report through realistic modeling work, on the cost associated with V2H activity expressed as reduced vehicle battery pack life as a function of various usage parameters.

2. Methodology

Two different modeling procedures were required for this project. The first was a simplified fundamentals-based electrochemical model of the operation of a single Li-ion cell. The output of this first model was collected for a range of currents and condensed into a second model, an engineering type empirical model to represent the function of the total electric vehicle Li-ion battery pack. The models are summarized below, full details may be found in [6].

2.1. Model description: Li-ion battery model

Based on measured charge and discharge data, and a set of material parameters, the fundamental electrochemical single particle model (SPM) [6,7] was used to produce a number of charge and discharge curves at currents ranging from very small currents to very large currents that are beyond practical ranges for experimental tests.

Charge and discharge curves from the SPM then formed the basis of an empirical representation of the Li-ion battery in an equivalent resistance type (Gao) model [8]. The Gao model is then used in vehicle use scenarios to track the operational state of the Li-ion battery. In this project, a constant battery temperature of 30 °C was assumed.

In the Gao model, the voltage during discharging is given by:

$$V(\mathrm{t},\mathrm{DOD},I(t)) = \mathrm{OCV}(\mathrm{DOD}) - I(t)R_{\mathrm{int}}(\mathrm{DOD}) \tag{1}$$

where $I(t)$ is the current and R_{int} is the internal resistance. This equation describes that under load, there is a shift of the voltage as a function of depth-of-discharge (DOD), equal to the internal resistance multiplied by the current.

At a given DOD, an imposed power load P, where $P = IV$, determines a required current $I(t)$ based on the cell voltage. Applying this current over a time step will cause a small voltage drop, and correspondingly advances the DOD via:

$$\Delta\mathrm{DOD} = \frac{-I(t)\Delta t}{\alpha\beta\cdot\mathrm{cap}_{\mathrm{ref}}} \tag{2}$$

In this case, $\mathrm{cap}_{\mathrm{ref}}$ is the battery capacity and α and β are Gao model parameters [8].

2.2. Operating envelope

Conventional cycling methods involve discharging and charging at a fixed current between fixed upper and lower voltage limits. However, both the state of charge and the depth of discharge are properties related to cell capacity rather than voltage. Using fixed voltage limit cycling will result in variable SOC and DOD values for the cycle history of each cell and operating conditions such as temperature and current. To compare partial cycling methods without these biases, fixed percent capacity ranges can be applied to bound charge and discharge stages. For example, to conduct a 5% charge/discharge cycle, 2.20 A h cells would be charged until the relative capacity increased 0.11 A h and then discharged the same amount.

Charging and discharging a battery at constant current based on capacity limits instead of voltage limits poses the question of how to define the limits for continuous cycling. Internal resistance in the cell will shift the potential during operation away from the open circuit potential of the cell in proportion to the applied current. For operation that adheres to the cell manufacturer's recommendations as well as real world performance dictates specified by battery management systems, the voltage was required to stay between 3.0 V and 4.2 V. Working within these limits, initial characterization tests were made on the selected 2200 mA h Lithium-ion cells. Ten cycles of 5% ΔDOD cycles were performed at various currents and SOC centres to probe the safe operating envelope, shown in Fig. 1. The temperature was held to 30 °C ± 0.1 °C for these tests. The operating envelope of Fig. 1 was determined with in-house exploratory data which measured voltage steps that arise from the cell internal resistance when a current is suddenly applied. Under charging conditions, the internal resistance causes a step change increase in potential, while the opposite occurs with discharge.

The experimental setup consisted of 18,650 cells placed inside a temperature controlled chamber and connected to independent channels on an Arbin BT2000 series battery test system. Each channel was both a potentiostat and galvanostat which provided both

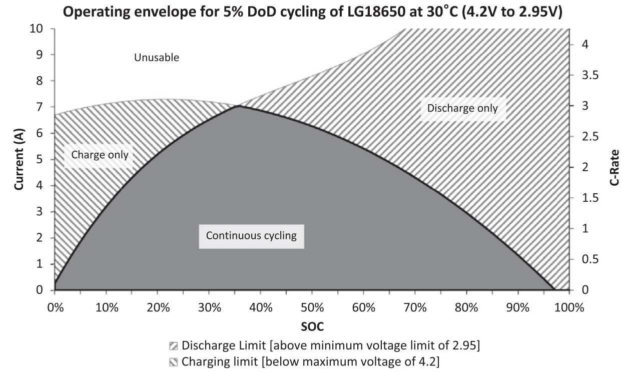

Fig. 1. Operating envelope for 5% range DOD cycling of 2200 mA h Li-NMC 18,650 cells at 30 °C.

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