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Energy and climate effects of second-life use of electric vehicle batteries in California through 2050

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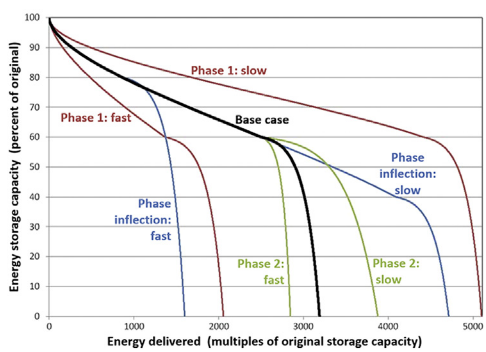
HIGHLIGHTS

- We model potential second-life use of retired PEV batteries for stationary storage.
- Second-life batteries in California may deliver ~15 TWh per year in 2050.
- Enabled renewable electricity generation may displace ~7 Mt CO_2e per year in 2050.
- There is significant uncertainty in PEV adoption and battery degradation scenarios.
- We calculate ESOI and discuss appropriate metrics for large-scale storage systems.

GRAPHICAL ABSTRACT



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ABSTRACT

As the use of plug-in electric vehicles (PEVs) further increases in the coming decades, a growing stream of batteries will reach the end of their service lives. Here we study the potential of those batteries to be used in second-life applications to enable the expansion of intermittent renewable electricity supply in California through the year 2050. We develop and apply a parametric life-cycle system model integrating battery supply, degradation, logistics, and second-life use. We calculate and compare several metrics of second-life system performance, including cumulative electricity delivered, energy balance, greenhouse gas (GHG) balance, and energy stored on invested. We find that second-life use of retired PEV batteries may play a modest, though not insignificant, role in California's future energy system. The electricity delivered by second-life batteries in 2050 under base-case modeling conditions is 15 TWh per year, about 5% of total current and projected electricity use in California. If used instead of natural gas-fired electricity generation, this electricity would reduce GHG emissions by about 7 million metric tons of CO_2e per year in 2050.

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1. Introduction

The usage of plug-in electric vehicles (PEVs) is increasing rapidly, driven by concerns about environmental quality and energy security. PEV sales in the United States (US) increased by a factor of over 5 between 2011 and 2013, from 18,000 to 100,000

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vehicles per year [1]. One report projected that PEVs will comprise 30% of US light-duty vehicle sales by 2030, and 80% by 2050 [2]. The state of California leads PEV sales in the US, accounting for almost one-third of total US PEV sales [3]. As these vehicles age, a growing number of PEV batteries will reach the end of their service lives. If the current California vehicle fleet were fully electrified, it would entail a post-use battery flow of about 900,000 metric tons per year [4]. Recycling is typically considered as the default end-of-life management for PEV batteries. However, these batteries may retain as much as 70–80% of their original storage capacity at the point of retirement. Stationary energy storage applications, where storage capacity and power per unit mass are less critical constraints, offer a potentially attractive option for extending PEV batteries' useful life [5]. Referred to as second-life, using post-consumer PEV batteries as grid-connected stationary energy storage comes with economic, energetic, and environmental tradeoffs. Quantitatively assessing these tradeoffs and the relative scale of second-life batteries' contribution to overall energy storage goals may inform future research and policy decisions.

Previous research has explored various aspects of second-life PEV battery use, with a focus on economic viability. In a pioneering study, Cready et al. [6] considered the techno-economic potential of using retired PEV batteries for a range of second-life applications, identifying 4 promising candidates: transmission support, light commercial load following, residential load following, and distributed node telecommunications backup power. They observed that major uncertainties exist regarding the performance and life span of used PEV batteries. Narula et al. [7] conducted an economic analysis of PEV batteries used for various second-life applications, assuming a fixed (either 5- or 10-year) service life. They found marginal economic benefits for single-use applications, although results improved with multiple simultaneous applications, e.g. area regulation, transmission and distribution upgrade deferral, and energy time shifting. Neubauer & Pesaran [8] assessed the economic impact that second-life batteries use may have on initial PEV costs. They found the upfront cost reductions to be relatively minor, and strongly dependent on the battery degradation profile and specific second-life application. Williams & Lipman [9] analyzed the potential economic impacts of second-life battery use, finding modest but positive economic benefits of second-life battery use. Benefits depended largely on whether multiple services could be obtained from the batteries, and on costs associated with power-conditioning equipment. Neubauer et al. [10] estimated the selling price of re-purposed PEV batteries, and found them to be cost-competitive with established lead-acid battery technology. Ambrose et al. [11] considered the potential for retired PEV batteries to provide electricity storage for rural micro-grids in developing regions, concluding that second-life lithium-ion batteries may be price competitive with new lead-acid batteries and deliver improved performance.

Fewer studies have considered the environmental or energetic implications of second-life battery use. Ahmadi et al. [12] estimated the potential CO_2 emissions reduction of using repurposed vehicle batteries to store off-peak electricity in Canada, thus avoiding natural gas-fired peak generation. Faria et al. [13] conducted an environmental assessment of second-life PEV battery use for peak shaving and load shifting, based on grid characteristics of several European countries. Both studies found that greenhouse gas (GHG) emissions reduction from second-life use depends strongly on the carbon-intensity of the electricity sources involved, but neither explored the sensitivity of the results to highly uncertain system parameters including battery degradation and capacity thresholds of first- and second-life use.

PEV adoption and the availability of retired batteries will grow alongside an evolving energy supply system, including increasing amounts of renewable electricity sources. The intermittency of these sources, such as solar and wind, requires energy storage for maximum performance. In this study, we explore the extent to which second-life use of retired PEV batteries can provide this electricity storage role. We seek to address several research questions in this analysis. First, we determine which factors most significantly affect the net-energy balance of second-life battery usage. Second, we quantify the potential contribution of second-life batteries to California's energy storage needs through 2050. Last, we quantify the net life-cycle GHG benefits from using second-life batteries to support intermittent renewable electricity sources.

2. Methods

2.1. Modeling framework

We develop and apply a parametric life cycle model to describe the interrelated energy and material flows of the PEV battery system. The model is driven by scenarios of future adoption of PEVs in California, and the resulting stream of retired PEV batteries. We focus on the potential for second-life usage of the retired batteries and its net impact on energy use and greenhouse gas (GHG) emissions, while assuming other life-cycle phases (battery manufacture, first life, and final recycling) remain unchanged. The system boundaries of this study include all direct impacts of second-life use such as battery transport, thermal management, and charging. The boundaries also encompass components of the broader energy system, including the displacement of fossil energy production by enabling diurnal energy shifting of intermittent renewable electricity production. The analytical framework is shown schematically in Fig. 1. We assume that future electricity output from renewable sources will exceed demand during peak generation times, and electricity storage allows the use of this electricity later in the diurnal cycle during peak demand times.

Based on modeled material and energy flows through the year 2050, we calculate and compare several metrics of second-life system performance. These include the electricity delivered, the energy balance, the GHG balance, and the energy stored on invested. The electricity delivered is simply the summation of the electrical energy discharged from the second-life batteries, in units of TWh. This can be expressed on an annual basis, or cumulative over the study period (2015–2050).

The energy balance is a summation of major energy flows throughout the system, and is defined by Equation (1):

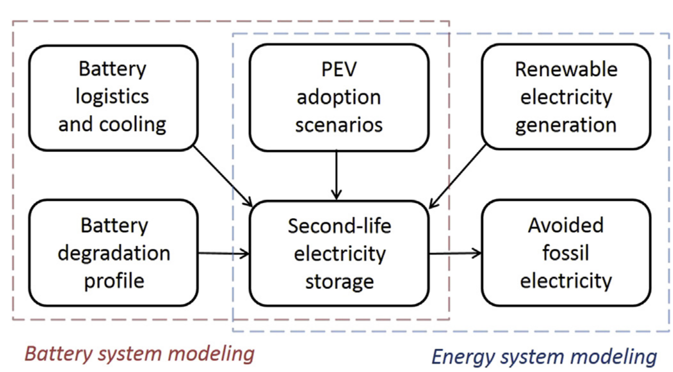

Fig. 1. Schematic diagram of analytical framework integrating battery system modeling with broader energy system modeling. Electricity storage in second-life PEV batteries enables dispatchable output of intermittent renewable electricity, thus avoiding fossil electricity generation. Scenario modeling of PEV adoption and battery degradation defines the scale of the operation.