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# Effects of market dynamics on the time-evolving price of second-life electric vehicle batteries

Susan I. Sun*, Andrew J. Chipperfield, Mahdi Kiaee, Richard G.A. Wills

*University of Southampton, SO17 1BJ, UK*

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ABSTRACT

Second-life batteries are defined as those removed from electric vehicles (EVs) when their energy density and power density has degraded below the level required for motive applications but are still performant enough for less demanding stationary applications. They could one day be a plentiful, environmentally benign source of low-cost energy storage. Their price evolution is important to know for designers of and investors in such systems.

A methodology is developed for predicting second-life battery price and sales quantities up to 2050. Although existing data is too scant to draw reliable quantitative conclusions, sensitivity analyses are run to investigate the effects of different EV uptake scenarios, new battery costs, refurbishment costs, recycling net credit, elasticity of supply, and size of demand. No previous work has incorporated all these driving factors in such a transparent way. The second-life price is found to be insensitive to most of these factors, while the quantity sold is sensitive to nearly all of them.

Much work remains to be done in parameterizing the model more accurately. However, this work already elucidates a novel quantitative mode of thinking about what factors influence the long-term price and market size of second-life batteries.

## 1. Introduction

The electric vehicle (EV) industry is growing rapidly, driven by falling battery costs [1] and increasing awareness of the harmful impacts of air pollution [2,3]. Even despite the lagging development of charging infrastructure and the range anxiety of potential customers, current projections of EV uptake indicate that globally, several GWh's of used batteries are likely to be removed from EVs annually by 2030 [4–6]. The challenge this poses to recycling facilities is immense.

However, this challenge also represents an opportunity. Used batteries are removed from the vehicle when their maximum capacity has degraded to 70–80% of the original capacity when new [7,6]. Second-life batteries, as these are called, may still work well in a stationary application which is less restrictive in terms of space and weight than motive applications. Indeed, many demonstration projects and a few commercial ventures exist. Concepts range from off-vehicle storage to buffer EV charging from the grid [8,9], to modelling studies of home batteries that can save on electricity bills by increasing onsite usage of rooftop PV [10,6].

A great benefit of using second-life batteries is that they would displace some of the manufacture of new batteries for stationary applications, with their associated environmental impacts [11]. However, the claim that second-life usage postpones the point at which an EV battery must be recycled, while true for an individual battery pack [7], may not be significant for the EV fleet as a whole, as we show later. The theory is that postponing recycling gives time to increase material recovery rates and profitability in future, whether through innovation or simply as a result of increasing scarcity of cobalt and nickel over time [12,13]. Nonetheless, the environmental benefit of second-life usage, 'reuse before recycle', may in itself be a goal worth pursuing.

The benefits of second-life usage can only be realized once certain drawbacks are addressed: the cost to refurbish a used EV battery (involving testing and voltage-matching the packs [14]); shorter lifetime and decreased efficiency resulting from degradation during the first life [7]; warranty issues and social and regulatory barriers to adoption of second-life batteries [15,13].

It is clear that second-life batteries will be cheaper than their new counterparts. This presents an opportunity to stakeholders in the stationary applications market [16], to cut costs by using second-life batteries rather than new. At the design stage, it is important to know the price range of the batteries. The usage of cheap second-life batteries could significantly affect design decisions, and expected profits.

* Corresponding author.
*E-mail address:* ss3g15@soton.ac.uk (S.I. Sun).

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**Nomenclature**

| | |
|---|---|
| $t$ | time (years), $t = 0$ in year 2010 |
| $E_0$ | original capacity of EV battery (kWh) |
| $E_b$ | capacity when removed from EV (kWh) |
| $P_{eqm}(t)$ | average equilibrium second-life battery price ($/kWh) |
| $Q_{eqm}(t)$ | quantity of second-life batteries sold in year $t$ (kWh) |
| $P_s(Q, t)$ | price-supply curve ($/kWh) |
| $P_d(Q, t)$ | price-demand curve ($/kWh) |
| $g_{EV}(t)$ | annual first-time EV battery sales (kWh) |
| $f_{EV}(t)$ | annual supply of used EV batteries (kWh) |
| $A$ | all-time total first-time EV battery sales (kWh) |
| $p$ | coefficient of innovation ($y^{-1}$) |
| $q$ | coefficient of imitation ($y^{-1}$) |
| $Ra(\tau)$ | Rayleigh-distributed failure probability of EV battery of age $\tau$ years |
| $i$ | generation of EV battery replacement purchase |
| $\mu(i)$ | mean first lifetime of EV battery (years) |
| $r_i(t)$ | EV battery $i$th-generation replacement purchases in year $t$ (kWh) |
| $C_{batt}(t)$ | cost of new stationary battery ($/kWh) |
| $C_{recyc}(t)$ | net credit from recycling an EV battery, i.e. minus any fee charged ($/kWh) |
| $C_{refurb}(t)$ | refurbishment cost to prepare used EV battery for second-life use ($/kWh) |
| $n_e$ | elasticity coefficient, to vary shape of price-supply curve |
| $C_0$ | cost of new stationary battery at $t = 0$ ($/kWh) |
| $C_\infty$ | eventual minimum cost of new stationary battery ($/kWh) |
| $\beta$ | rate of decline of new battery cost (per annum) |
| $P_{d(niche)}(Q, t)$ | niche-market part of price-demand curve ($/kWh) |
| $P_{d(mass)}(Q, t)$ | mass-market part of price-demand curve ($/kWh) |
| $(Q^*(t), P_d^*(t))$ | price-quantity point where niche-market and mass-market segments of price-demand curve meet (kWh, $/kWh) |
| $N_{batt}(t)$ | global maximum annual demand for second-life batteries (kWh) |
| $A_N$ | asymptotic value of $N_{batt}(t)$ (kWh) |

Neubauer and Pesaran [17] have attempted to predict the evolution of second-life battery costs by assuming the cost of the battery as new is reduced according to its degraded state of health, reduced again by a 'second-hand discount factor', and with the refurbishment cost subtracted. The second-hand discount factor is arbitrary: they analyzed scenarios 50% and 75%. Even after accounting for state of health and refurbishment cost, there is no reason to believe that the second-life price would vary proportionally to the new battery price.

Foster et al. [18] have conducted cost-benefit analyses comparing EV battery refurbishment and recycling. They found that for research and development costs of $50/kWh, refurbishment is profitable if the second-life price exceeds $114/kWh, the difference being mainly transportation costs. Similarly, Casals et al. [14] calculated refurbishment costs under various scenarios to find the minimum viable second-life price. Neither examine whether a second-life market can exist at these prices, or indeed support prices above their calculated minima.

An alternative for potential second-life users is to design the system under a range of different battery cost scenarios, and pick an option passively in response to the market [10,19]. This may be adequate for a one-off investment, but not if batteries must be replaced over the system lifetime (wind turbines and solar panels may last over 25 years, compared to 15 years or less, even for new batteries).

Here we present a methodology to rationalize the estimation of time-evolving second-life battery price. Principles of microeconomics are used to account for changing supply of and demand for second-life batteries, factoring in the cost of or income available from immediate recycling (without second-life usage), and both niche and mass-market stationary applications. Where Neubauer and Pesaran [17] assume a fixed second-life market and find it would rapidly be saturated by used EV batteries, our methodology attempts to model a more realistic situation, where a larger supply of second-life batteries would reduce the price and thus expand the market for them.

The model setup is explained in Section 2. The model is developed further and parameterized in Section 3. Results are presented in Section 4, followed by discussion in Section 5. The conclusions are in Section 6.

## 2. Model setup

The modelled system and its constituent parts are defined here, with a brief overview of the calculation methodology. This is followed by the assumptions used, with some justification of their validity.

### 2.1. System definition

#### 2.1.1. System boundary

In this work, calculations are done on a global basis. Since battery recycling is a global business, with used batteries being transported to plants in only a few countries, and recycled materials being exported worldwide [14], it stands to reason that battery refurbishment (as the process of preparing a used EV battery for the second-life market will be referred to) would be similarly global.

#### 2.1.2. Sellers

The sellers of second-life batteries would include EV owners but predominantly EV manufacturers, given the trend for battery leasing, where the EV owner does not own the battery outright but pays a monthly fee to rent it from the manufacturer [9,20]. The results presented in this work are independent of who the sellers are. The competing alternative to selling onto the second-life market is to send the battery to recycling straight away.

#### 2.1.3. Buyers

The buyers of second-life batteries are suppliers of batteries for stationary applications. The competing alternative to buying second-life is to buy new stationary batteries. The supplier may further re-package, market, distribute and install the batteries (new or second-life), with a markup to the end customer. It should be noted that companies specializing in battery refurbishment may be created in future [21]. These companies would act as middlemen between sellers and buyers. This complication is avoided here by attributing the refurbishment costs solely to sellers (as if the refurbishment companies are subsidiaries of the EV manufacturers, for example).

#### 2.1.4. Calculation methodology

The higher the price of second-life batteries, the greater the incentive to sell. The lower the price, the greater the incentive to buy. These tendencies are quantified respectively in the price-supply and price-demand curves, which change from year to year in response to the changing supply of used EV batteries, developments in battery recycling, etc. Quasi-static equilibrium is assumed, whereby the price-quantity equilibrium is converged upon each year. Equilibrium is the crossing point of the price-supply and price-demand curves: an above-equilibrium price would be lowered by sellers competing to attract more buyers, and a below-equilibrium price would be bid upwards by competing buyers [22]. Price-quantity equilibria are found for every year from 2017 to 2050, giving the time evolution of second-life price