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# Driving rural energy access: a second-life application for electric-vehicle batteries

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**Abstract**

Building rural energy infrastructure in developing countries remains a significant financial, policy and technological challenge. The growth of the electric vehicle (EV) industry will rapidly expand the resource of partially degraded, 'retired', but still usable batteries in 2016 and beyond. These batteries can become the storage hubs for community-scale grids in the developing world. We model the resource and performance potential and the technological and economic aspects of the utilization of retired EV batteries in rural and decentralized mini- and micro-grids. We develop and explore four economic scenarios across three battery chemistries to examine the impacts on transport and recycling logistics. We find that EVs sold through 2020 will produce 120–549 GWh in retired storage potential by 2028. Outlining two use scenarios for decentralized systems, we discuss the possible impacts on global electrification rates. We find that used EV batteries can provide a cost-effective and lower environmental impact alternative to existing lead-acid storage systems in these applications.

Keywords: electric vehicles, minigrid, battery, second-life, lithium, energy access

## 1. Introduction

The electric vehicle (EV) market share is growing steadily, with current and forecast rapid expansion in Europe, North America, and Asia. In 2012, these three areas accounted for 90% of the deployed EV stock of some 180 000 vehicles, with an annual sales increase from 2011 of 150% (IEA 2013). Furthermore, independent industry analysts, academic researchers, and international groups are projecting significant annual growth in the sales of battery operated EVs (BEVs) over the next decade (IEA 2012, Pike 2012, Al-Alawi and Bradley 2013). Some locations, such as California, with a 2020 target of 1000 000 EVs, highlight the tremendous growth that is possible over the coming years (CA-GIWGZV 2013). This growth has driven examination of extending the battery ownership model to optimize battery use by either providing ancillary services during the vehicle life (i.e. vehicle-to-grid), and/or extending battery life through a second-use phase ('second-life').

Various national laboratory reports (Cready *et al* 2003, Sullivan and Gaines 2010), peer-reviewed articles (Neubauer and Pesaran 2011, Lih *et al* 2012), and consulting firm case studies (Hensley *et al* 2012) have pointed to opportunities for second use applications, and early empirical data from BEV use studies suggest these devices will experience considerable life beyond their expected primary functionality. The majority of these efforts have focused on industrial uses, such as grid firming and load balancing, with the hope of decreasing the upfront ownership costs of these power packs for consumers through a profitable second use application (Peterson *et al* 2010, Neubauer and Pesaran 2011, Lih *et al* 2012). Closer analysis has shown that most of these use cases provide minimal economic returns due to projected decreases in overall battery costs in the future, the cost of repurposing battery packs, and the amount of storage required in large-

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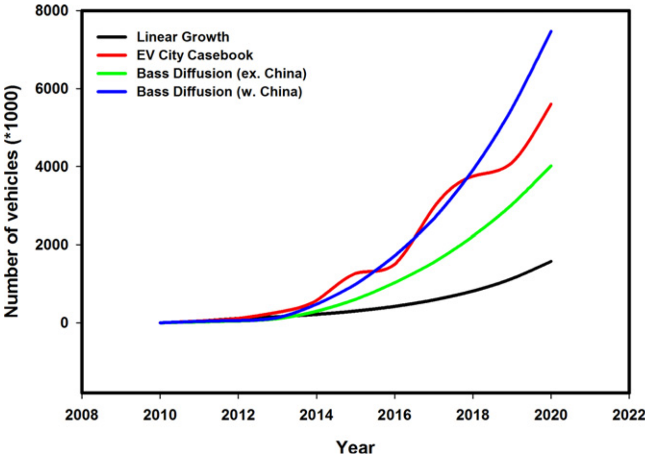

**Figure 1.** Battery powered EV sales forecasts.

scale applications (Peterson *et al* 2010, Neubauer and Pesaran 2011).

The growth in EV deployment today is most evident in developed nations, where goals of decarbonization, improvements in urban air quality, and lower-per-km operating costs drive demand. However, while many nations transition toward electric transportation, globally over 1.2 billion people still lack access to electricity, and approximately an additional one billion have only sporadic or intermittent access. The majority, close to 85%, reside in low-income rural regions with a little probability of grid extension, primarily due to high transmission costs and challenging terrain (SEFA 2013). This issue has been tied directly to a number of socioeconomic development priorities such as education, environmental protection, gender equality, public health, and poverty alleviation (Cabraal *et al* 2005). The Sustainable Energy for All initiative projects that providing universal energy access by 2030 will require an annual investment of approximately $45 billion (SEFA 2012, 2013).

We find a distinct lack of research exploring potential EV battery applications in the developing world, where there is possibility for significant socio-economic and environmental co-benefits. By building a data set from the current literature and forecasts of lithium battery development, BEV power pack sizing, and BEV sales, we ascertain the size of this reuse pool and describe the potential impacts on rural electrification initiatives in emerging economies. We also explore the technical and economic aspects of the value chain required to deliver EVs to developing country communities, and contrast with the business as usual (BAU) practices of using lead-acid batteries for primary storage. We conclude by exploring future research opportunities and discussing potential areas of concern for project developers, regulators, and researchers.

### *1.1. Micro- and mini-grids*

To address community energy access issues in remote areas where grid extension is not expected or is prohibitively expensive, private enterprises, development organizations, and local governments have turned to distributed, micro- and mini-grid energy supply strategies (Casillas and Kammen 2010, 2011, SEFA 2013). Such applications typically provide households with sufficient electricity for lighting, mobile phone charging, radio use, and, in larger systems, can support communications tools, improved water access, and agricultural processing (Cabraal *et al* 2005). To date, these systems have typically depended on carbon-intensive fossil fuels, such as diesel or gasoline; however, as capital costs decrease, renewable energy generation technologies are becoming a more attractive and sustainable solution (Kishore *et al* 2013). The development of distributed energy micro- and mini-grid projects has been growing steadily in Southeast Asia and Sub-Saharan Africa, and it is expected that close to 70% of all currently unserved populations in these regions will employ such solutions to achieve universal electrification (SEFA 2013).

Community-scale micro- and mini-grids employ locally centralized generation and storage technologies (although with the development of inexpensive, smaller photovoltaic and wind options, interconnected distributed household generation systems are becoming more popular) and a simple distribution network (Kishore *et al* 2013). The scale is typically limited to no more than a few hundred households, because of the associated resistive losses in distribution, high initial capital costs, low initial demand, and limits to total generating capacity (Bhattacharyya 2013).

The United Nations Global Tracking Framework (GTF) report projects that 65% of the off-grid energy required to achieve universal access by 2030 will be supplied by community micro- and mini-grids (SEFA 2013). It is in this application that we envision a potential role for retired EV batteries due to the initial pack sizing (24–75 kWh) and associated upfront capital costs. Used EV batteries could not only power households, but could also be employed in off-grid installations supporting healthcare facilities, telecommunications towers, businesses, and other large-load consumers.

### *1.2. Energy storage for decentralized systems*

Lead-acid battery banks make up the majority of storage employed in decentralized rural electrification today, owing to low upfront capital costs ($100–$500 kWh$^{-1}$ of storage) and a large diversity of commercial products (Chang *et al* 2009, IRENA 2012). However, due to short cycle life (typically 3–5 years) (Huacuz *et al* 1995, Spiers and Rasinkoski 1996, Lemaire-Potteau *et al* 2006) users are required to replace their lead-acid batteries between five and eight times during the total system lifetime (approximately 25 years for solar PV installations). Thus, lead-acid batteries frequently become the primary drivers of overall lifetime system cost (Okou *et al* 2011), while also increasing the environmental and local health impacts resulting from the use, management, and end-of-life of such systems (García-Valverde *et al* 2009, Haefliger *et al* 2009, Shah *et al* 2012). Such high system costs are prohibitive for users in poor remote areas, reducing adoption and technological diffusion rates, and impeding electrification in developing nations (Casillas and Kammen 2011).

To overcome the dual challenges of cost and short-life of conventional lead-acid batteries as the storage hub of rural energy systems we must envision and examine new, inexpensive, and safer options for storage that can easily adapt to the intermittent and low-density nature of renewable generation, while functioning well in the harsh environmental conditions found in much of the developing world. Such batteries should also significantly improve upon today's BAU technology, i.e. lead-acid, both in lifetime costs and environmental impacts.

## 2. Methods and assumptions

### 2.1. EV sale projections

A range of academic and industry forecasts show substantial growth in BEV sales over the coming decades (figure 1) with projections ranging from 1.5 to 7.5 million BEVs sold by 2020 (Becker *et al* 2009, IEA 2012, Pike 2012, Al-Alawi and Bradley 2013). We consider three BEV sales scenarios based on market share, growth rate, and the role of emerging markets. In the conservative scenario, we employ the linear growth rate model outlined in the 2012 Pike report, *Electric Vehicle Geographic Forecast,* with adjustments for updated current sales data (Pike 2012). In the mid-range scenario, we utilize the data outlined in the IEA EV City Casebook, which assesses current policies and incentives in major metropolitan regions across the world with actual EV sales data, and projects BEV sales through 2050 (IEA 2012). Finally, for the optimistic scenario, we adopted a Bass Diffusion model, as described by Becker *et al* and reviewed in Al-Alawi *et al* (Becker *et al* 2009, Al-Alawi and Bradley 2013) to project the rate of technological adoption in major EV markets. The Bass model conveniently parameterizes the relationship between current adopters and potential adopters of a new product. For this scenario, we utilize light-vehicle sale projections, in combination with current BEV sales data, to project BEV sales forward through 2020. This diffusion is then applied to major automotive markets: the United States, Japan, Western Europe, and China, which comprised over 90% of BEV sales in 2011 and 2012 (IEA, 2013). Furthermore, we only consider BEV sales through 2020 due to uncertainty around the future of competing EV batteries and emerging alternative vehicle technologies, as well as the role of emerging markets in the consumption of future EVs.

### 2.2. Storage projections

We consider some of the most common lithium anode/cathode arrangements: C/LCO ($LiCoO_2$), C/LFP ($LiFePO_4$), C/NCA ($LiNi_8Co_{15}Al_5O_{20}$), and C/LMO ($LiMn_2O_4$), and calculate future storage stock assuming that individual vehicles average two 25 kWh packs, providing a 200 km range (Lu *et al* 2013). While the batteries employed in these vehicles vary according to the intended range of the vehicle (15 kWh for the smaller models, to 85 kWh for vehicles like the top of the range Tesla Model S) this assumption of storage size is supported by Cready *et al* (2003), Gaines and Nelson (2010), and Neubauer *et al* (2012), and falls well within the mean of ranges outlined in the EV City Casebook (IEA 2012). Total battery lifetime, in terms of calendar and cycling fade, depends on loss of cyclable lithium and interference from byproducts (such as a solid-electrolyte interphase), as well as structural degradation or fracture of active material (Pinson and Bazant 2013). Operable battery lifetime forecasts still rely heavily on limited empirical data, but each of the chemistries considered offers comparable operating temperatures (−20 to 50 °C), and voltages (1.5–4.2 V) (Lu *et al* 2013).

The useful lifetime of lithium batteries is strongly affected by thermal conditions, depth of discharge (DOD), charge voltage, and the number of discharge cycles. While battery packs in BEVs tend to experience a less than optimal (opportunistic) charge cycling and/or thermal conditions during the vehicle use phase, Li-ion batteries will likely retain upwards of 70% of their capacity post BEV end-of-life (Neubauer and Pesaran 2011, Lih *et al* 2012).

We expect 5% of BEV batteries to fail during vehicular use, with the remaining 95% of batteries to serve a total of 12–16 years in both vehicular and second life applications (6–8 years for each) (Cready *et al* 2003). Although currently no large-scale accurate data exist examining BEV battery failure rates, we assume some vehicles will be retired due to accident, electrical failure, in addition to some packs being ineligible for repurposing due to extensive cell faults. Still, the selection of a 5% failure rate could be examined with additional research.

Under these assumptions, we project the quantity of storage available for second-use as batteries transition from vehicle, to second life and finally to end-of-life retirement/recycling. Because aggressive cycle and DOD management is required to maintain the long-term health of these batteries, we assumed the magnitude of storage at 80% DOD in the second-life application, following an initial capacity loss of 30% during vehicular use.

### 2.3. Household energy modeling

To estimate potential impacts on rural energy access, we develop two user scenarios in stationary community grid applications: *basic* and *productive use*. The *basic use* scenario consists of households (interconnected in a community micro- or mini-grid), each consuming an average 321 kWH of electricity per year from a shared PV array (or small wind installation) for basic energy needs (i.e. lighting, cell-phone charging, and access to micro-appliances). This scenario would lie within the range of needs outlined under Tier 2 of projected consumption developed in (GTF) (67–321 kWh per year). The *productive use* scenario envisions families utilizing a larger system for agricultural processing, microenterprise development, and other value increasing services. We estimate such activity to require approximately 2500 kWh/household/year of electricity consumption, which falls within the projected consumption under Tier 5 of the GTF (>2121 kWh per year). Assuming daily cycling over the course of a year, the storage requirement for such systems would be 879 Wh for basic use and 6849 Wh for productive use systems. Assuming an overall PV system life of approximately 25 years, we project an average of four sets of BEV batteries to be utilized over the lifetime of each system.

### *2.4. Financial feasibility*

To approximate financial feasibility, we modeled a hypothetical business ('Second Life') that would be responsible for battery collection, testing, repurposing, shipment to emerging markets, sales to micro-grid developers, recollection of batteries, return shipment to countries where recycling occurs, and delivery of batteries to certified recycling facilities. We believe that such a business model would be the most effective at ensuring quality second-life products and would reduce transaction costs for all parties involved in the retired BEV battery value chain. Second Life would interact with dealerships or mechanics, where vehicle batteries would be returned after effective use in-vehicle, and would also distribute directly to micro-grid installers or distributors of micro-grid components in emerging markets. Although data are limited for some of the value chain links in the emerging market destination, such as the costs of transport from port of entry to the actual point of retail sale, we assumed that the cost of a battery at port could be equivalent to wholesale value, which would directly compare with a lead-acid competitor (in terms of $\$\,\mathrm{kWh}^{-1}$). The price of delivery of batteries from port of destination to the end user will differ greatly (due to variability in distance and terrain); however, due to the greater energy density of lithium batteries, the price of delivery per kWh will be substantially lower than for lead-acid competition.

For the initial battery sale price, post vehicular phase, we employed values derived from previous modeling by Neubauer *et al* and Beer *et al* which found the initial value of used EV batteries would be approximately $10–$100, depending on chemistry and size, prior to repurposing (Beer *et al* 2011, Neubauer *et al* 2012). We expect that these prices would be paid to the EV manufacturers or owners of the battery upon removal from the vehicle.

We expect strong variability in the costs of repurposing (collection/testing/repackaging), with the price per kWh varying from $18 to $140 (Neubauer *et al* 2012). Recycling costs and the value of recovered materials are calculated assuming a mixed waste stream of lithium chemistries. The range of costs associated with recycling lithium batteries is based on two scenarios envisioning a small or large scale facility with appropriately scaled capital costs, variable costs per ton, and annual capacity (Wang *et al* 2014). Transportation and freight costs are based on pack sizing of currently marketed EVs and specific energy projections for used battery packs. The data for this analysis were found through shipping cost estimators available from major shipping companies, as well as peer-reviewed sources (Cready *et al* 2003, Neubauer *et al* 2012, WFR 2013). We examined two scenarios for profit margins and operating costs for Second Life and recycling facilities (10% (low cost/low recovery) and 30% (high cost/high recovery)), although market conditions could significantly affect that portion of the overall cost.

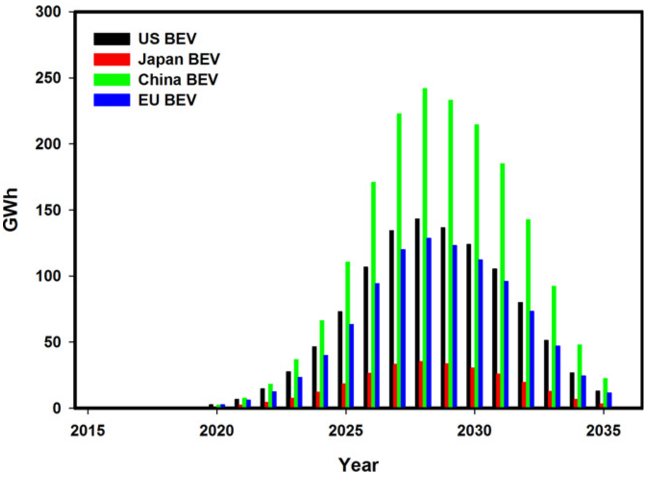

**Figure 2.** Projected storage from retired lithium EV batteries. Calculated at 80% DOD after 30% initial capacity loss in vehicular use phase.

## 3. Results

In our assessment of BEV sales through 2020, we expect Li-ion technology to retain its current market dominance, and project this resource of BEV batteries to move through full use and reuse phases. Retired batteries will enter the reuse market slowly beginning in 2016, increasing quickly to a peak of 120–548 GWh of storage by 2028 (figure 2). Beginning in 2029, we could expect this storage potential to begin to decline from peak retirements. Even though the more conservative, linear growth scenario suggests BEVs will be less than 2% of global light vehicle sales by 2020, our projection suggests considerable storage potential will be made available.

The role of the Chinese auto market could have significant impacts on the quantity of EVs sold in the coming decade. Industry forecasts suggest that Chinese light-vehicle sales may exceed 30 million units annually by 2020 (Wall 2013), and if similar rates of technological adoption occur in that market, battery retirements from China would be substantial. Applying a diffusion scenario to the Chinese light vehicle market, we find annual Chinese BEV sales could reach 3.5 million vehicles by 2020. This would represent some 240 GWh of retired storage in 2028, 70% more than forecast to be retired in the US that year, with the Chinese BEV market exceeding 40% of the remaining global market by 2020.

Assuming the retired battery resource is directly channeled into use in micro- or mini-grids, the impacts on household electrification could be substantial (figure 3). Considering the most conservative sales projection, and the *basic use* scenario of 879 Wh /household/day, we forecast this storage resource to be adequate to support almost 35 million

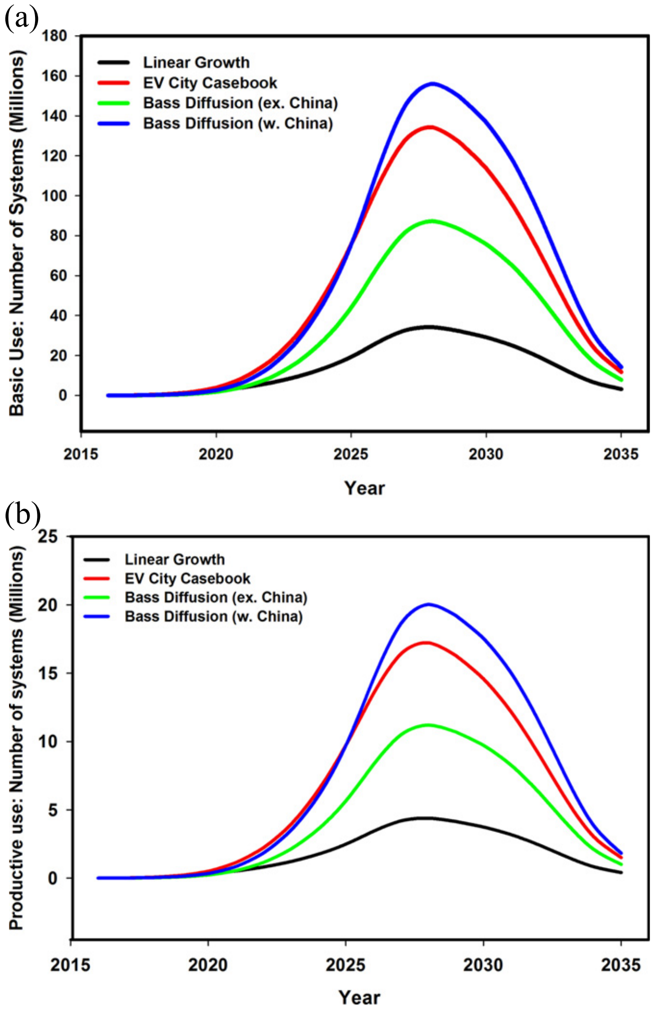

**Figure 3.** Electrification scenarios from second-life EV Batteries. (a) Basic use scenario: 879 Wh of daily storage per system, four batteries per system life. (b) Productive use scenario: 6849 Wh of daily storage per system, four batteries per system life.

systems by 2028. Under the more optimistic IEA projection, the available storage stock is adequate to support basic electrification for 135 million systems, while our global diffusion model suggests storage could support 156 million systems by 2028. If retired BEV batteries are instead employed in *productive use* systems, we expect retirements could provide storage for 340–500 thousand systems by 2020, and over 17–20 million systems by 2028 under the IEA forecast and global diffusion model.

We find the costs of transporting retired batteries from a national port to an emerging market, and back to a recycling hub, to vary only marginally across different destinations and representing only 2% of the total costs of the battery to an end micro grid installer under both high (\$11.26 $\mathrm{kWh}^{-1}$) and low (\$1.70 $\mathrm{kWh}^{-1}$) freight estimates.

We envision a waste stream of mixed lithium chemistries, and estimate the costs of recycling to range from \$17 to \$75 $\mathrm{kWh}^{-1}$. This does not include the value of raw materials recovered from batteries. Using current prices for raw materials, theoretical and published rates for mechanical and hydrometallurgical recovery, and the percent compositions of those materials in each chemistry found in Wang *et al* (2014) and Gaines and Nelson (2010), we estimate the value of extracted raw materials to be somewhere in the range of \$20 and \$36 $\mathrm{kWh}^{-1}$.

Considering the range of profit/operating cost margins of SecondLife and of lithium recycling facilities, we estimate the sale price of retired Li-ion batteries to emerging market community grid developers to fall between \$46–\$321 $\mathrm{kWh}^{-1}$.

## 4. Discussion

One of the main criticisms of lead-acid deep-cycle batteries is their short lifetime (3–5 years), which does not adequately match the 25–30 years of average lifetime for PV or wind systems. As battery life frequently depends on active maintenance of electrolyte levels (with the exception of sealed or gel lead-acid batteries), the useful life of lead-acid batteries can be even further shortened to as little as 1–2 years. This is especially true in communities with low technical capacity or inadequate access to tools and materials (i.e. distilled water for electrolyte balancing) (Huacuz *et al* 1995, Lemaire-Poteau *et al* 2006). Conversely, second-life Li-ion EV batteries are expected to have lifetimes of approximately 6–8 years and do not require active maintenance of electrolyte levels (Neubauer and Pesaran 2011, Lih *et al* 2012).

The dominant failure mechanism for Li-ion batteries in vehicular applications is impedance increase, rendering the stored energy inaccessible for the short-time constant-discharge required by vehicles (Cready *et al* 2003). Recent data suggest thermal conditions could have dramatic effects on the useful life of these batteries in vehicle; vehicles considered for an NREL study in areas with higher-than-average battery pack temperatures (Phoenix, AZ), experienced annual percentage increases in resistance at approximately twice the rate of vehicles studied in Minneapolis, MN across different driving styles, where average pack temperatures were 20–30 °C lower (Smith *et al* 2010, Pesaran *et al* 2013). However, employed in environments with lower voltage requirements (such as rural micro-grids) these batteries could still experience 5–10 years of continued functionality in reuse scenarios (Peterson *et al* 2010, Lih *et al* 2012).

Temperature sensitivity for batteries varies among chemistries, but lead-acid batteries are much more sensitive to higher temperatures associated with emerging market environments (especially in Sub-Saharan Africa and Southeast Asia). Significant cycling degradation occurs in lead-acid batteries above 25 °C, whereas lithium-ion cells can withstand temperatures as high as 40 °C prior to reduction in cycling capabilities (Divya and Østergaard 2009, Lu *et al* 2013, Pesaran *et al* 2013).

Considering that wholesale, deep-cycle lead-acid batteries cost between \$100–\$500 $\mathrm{kWh}^{-1}$ at port of entry (IRENA 2012), second-life EV batteries could be price competitive with some of the least expensive lead-acid storage technologies. With the price of new Li-ion batteries likely to fall from \$1000 $\mathrm{kWh}^{-1}$ to \$200 $\mathrm{kWh}^{-1}$ as demand

and manufacturing scale grow, we might expect the price of repurposed batteries to fall towards the low end of price estimates by 2020 (Hensley *et al* 2012, Neubauer *et al* 2012). Furthermore, if we consider an average lifetime of 6–7 years for second-life EV batteries, we may expect savings 32–50% over the lifetime of the system, when compared to a set of lead acid batteries with a 3–5 year lifespan.

If we assume that Li-ion batteries will retain 70% of their initial gravimetric energy density for second-life applications, or a specific energy of 70–100 Wh $kg^{-1}$ at retirement, they would be almost double the effective energy density of even high quality, sealed-gel lead acid batteries (Tarascon and Armand 2001). Li-ion batteries will also have close to triple the volumetric energy density of lead-acid storage: 175–280 Wh $L^{-1}$ (with 70% degradation), versus 50–100 Wh $L^{-1}$ for lead (Tarascon and Armand 2001). This implies that in the case of international container shipment, where volume is typically the constraint for electronic goods, one would need three times fewer containers to ship the same goods an equivalent distance, both by ocean freight and by truck (WFR 2013). Energy density also has significant implications on transport in-country, i.e. from the port of entry to the final micro-grid installation site. Batteries typically have to be shipped by road (versus rail or river transport), and in many remote rural cases, will reach their final destinations via animal or human means. This implies that the ease and cost of transport of lighter, more compact batteries could be a significant deciding factor in implementation.

Li-ion cells have been shown to have significantly lower environmental and energy impacts associated with assembly and production as compared to lead acid. Depending on the battery pack size (based on range), Li-ion batteries can have as little as 50% of the total environmental impact assuming similar use conditions (Matheys and Timmermans 2006). Furthermore, changes in the manufacturing process and other technological improvements have continued to decrease the impacts from Li-ion cells (Zackrisson *et al* 2010). Finally, lithium chemistries can have significantly lower environmental impact than lead-acid or nickel-metal hydride across a wide range of other indicators, including water toxicity and eutrophication, ozone depletion potential, ecotoxicity, and particulate matter formation (Majeau-Bettez *et al* 2011).

### *4.1. Concerns and further research*

One uncertainty in this analysis is the future technological dominance of lithium in EV applications. While some researchers (SVB 2013) have expressed confidence in the dominance of lithium chemistries for EVs for decades to come, recent history suggests that the path of innovation may lead elsewhere. However, we can expect Li-ion chemistries to remain the primary choice for EV manufacturers for the next decade, a timeline that is clearly reflected in our model. While it would be unwise to stipulate dominancy any further into the future, if Li-ion chemistries remain a popular option for EV uses for greater than a decade, we can expect an even larger resource potential for second-life storage applications.

Another concern is that second-life batteries could be employed in competing end-use applications in industrialized markets, such as wholesale storage in commercial and industrial applications, transmission support, EV applications after refurbishment, and residential level distributed energy storage. Cready *et al*, in their analysis of the potential applications of EV batteries suggest that second-life batteries could be sold into these applications for around \$145 $kWh^{-1}$ (after repurposing), a value that closely parallels the low end of our projections. However, the challenges of preparing used EV batteries for applications in industrialized countries can be more significant than if employed in remote minigrids. Of those identified, the most significant in our regard are the matching of batteries into large strings for bulk storage applications and the perception of value from end-consumers relative to new batteries (Cready *et al* 2003). Still, it is possible that the profits in these sectors could outweigh the costs and create sufficient demand. Neubauer and Pesaran (2011) found that certain services could yield nearly \$1700 $kWh^{-1}$, which would provide a compelling sink for retired EV batteries. However, in their estimates, the authors found that EV batteries would saturate the 10-year market needs in profitable sectors (Transmission and Distribution, Area Regulation, and Electric Service Power Quality) after the retirement of only 830 000 EVs, which constitutes less than half of our modest sales projections and approximately 10% of the optimistic. Another potential end use which has not been explored in literature, direct repurposing in EVs would be challenged by the decrease in volumetric energy density and resistance related performance degradation, and we believe would not represent a significant cost savings over replacement with new equipment.

Recycling of lithium batteries is a complex process that requires extensive infrastructure and industrial facilities (Xu *et al* 2008, Wanger 2011), which could impact the end-of-life components of our proposed lifecycle. The majority of resource projections for components of Li-ion batteries do not demonstrate potential scarcity in upcoming decades (Gruber *et al* 2011), and overall ROI for Li-ion EV battery recycling is projected to be relatively low (Gaines and Nelson 2010), unless processes are improved (Lain 2001).

Rates of recycling of lead acid batteries vary around the world; however, even with comparatively high rates of recycling (>50%) in countries such as Pakistan (Shah *et al* 2012), most recycling is carried out in small scale backyard recovery operations, which result in high levels of human exposure to dangerous chemicals and heavy metals, and high levels of risk for vulnerable segments of the population. This problem is not unique to Pakistan (van Beukering and Bouman 2001, Haefliger *et al* 2009), and is likely to grow in size if the use of lead batteries increases due to their greater adoption for community electrification.

There are a few excellent examples of successful large-scale recycling programs tied to energy access initiatives in emerging regions, which could be used as models to develop and expand second-life Li-ion recycling. The experience in Bangladesh has been particularly successful. To date, more than 2000 000 solar home systems have been installed in

Bangladesh, all of which employ a lead-acid battery (IDCL 2012). The current recycling program in Bangladesh includes: collection of the used batteries and transportation to recycling plants where the lead, and in particular the lead-oxide components, are recycled to pure lead for subsequent re-use as a raw material. This effort, focused on traditional lead-acid batteries, provides a number of key lessons about private sector engagement, as well as approaches to meeting or exceeding standards for the percentage of batteries returned. A global program focused on Li-ion batteries could be based on many of the award winning principles of this effort.

Furthermore, improvements in lithium recycling could increase material recovery rates and boost the economic value of recycling these devices (Castillo *et al* 2012), although chemistries with higher concentrations of cobalt or lithium (such as LCO or LMO batteries), will be more valuable to recyclers, and possibly cheaper to recycle (Wang *et al* 2014). If the battery waste stream was entirely composed of cobalt oxide chemistries, the value of recovered materials (~$37 kWh$^{-1}$) could exceed the costs of recycling at a higher volume facility ($10–$46 kWh$^{-1}$). Conversely, iron phosphate has a very low concentration of lithium (~1%), and a lower overall recovery value; a waste stream composed predominately of LFP batteries would likely be less attractive to recyclers.

The transport of EV batteries, from the location of vehicular use to rural mini-grids in developing countries and then to recycling, will have variable environmental and economic impacts on this scenario, and further research is required to precisely quantify this contribution. Although many current lead-acid batteries are shipped from the US and China to developing countries, it is possible the costs of transporting retired EV batteries to some areas may not be competitive with locally produced alternatives. However the impact of transport will differ significantly on a case-by-case basis, and there is no empirical case data available that precisely quantifies this aspect of the value chain.

An additional concern currently raised about lithium batteries is the issue of thermal management and failure. Thermal management systems are important to prevent breakdown in a lithium battery, as above 120 °C lithium cathodes begin to react with electrolytes (Wang *et al* 2012). In community grid applications, precise charge control, combined with sheltered, unexposed storage locations, could significantly reduce the risk of accelerated degradation from thermal variation. Furthermore, such charge control, if properly administered, would have the aggregated benefit of extending battery life through DOD regulation. There are other means of further reducing the risk of thermal failure, such as local technician capacity building, user education, and the use of improved system monitoring and control equipment.

The costs and difficulties of repurposing and refurbishing Li-ion batteries for developing region applications could vary significantly, due to diverse second-life system designs and the range of battery configurations currently employed by the automotive manufacturing industry. However, we expect these costs to be lower than repurposing for large-scale grid applications due to a lesser need for voltage matching across large groupings of interconnected power packs (Neubauer *et al* 2012). Furthermore, we believe that efforts among manufacturers to agree upon common system components to encourage economies of scale could lower these hurdles in the future.

The second life of EV batteries could have significant impacts on electrification in the developing world, supporting a shift to renewables and providing energy access to some of those least likely to obtain it. These impacts could also occur rapidly, especially if viable pathways of distribution and deployment can be developed. Second life applications of EV batteries also greatly decrease their life-cycle emissions, by allowing the full usefulness of the cell to be exhausted before it is recycled or disposed. Policy incentives, along with responsible management and improved local capacity, would be critical for supporting this application, and would also serve to encourage end-use recycling. Pilot projects of second-life storage applications in developing countries should be undertaken, and could provide important data on actual field lifetime of such systems, as well as insight into best practices for their management.

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