

**BUSINESS MODELS FOR EXTRACTING MORE USEFUL LIFE
FROM LITHIUM ION BATTERY SYSTEMS**

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Executive Summary

Demand for new lithium-ion battery systems is forecast to grow dramatically across the automotive, consumer electronics, and grid storage sectors, from 61GWh in 2015 to 124GWh in 2020. However, current battery disposal practices mean that by 2020, tens of GWhs of still-useful lithium-ion storage capacity could be directed towards landfills. While automotive companies are actively engaged in “second life” concepts for their electric vehicle batteries, it is not apparent that non-automotive batteries have similar markets. These non-automotive batteries have many different chemistries and form factors, and suffer from weak economics in the recycling process. Therefore, finding a “second-life” for non-automotive lithium-ion battery systems is a big challenge, but potentially one with significant economic and environmental benefits.

This project takes an entrepreneurial approach to solving this problem, presenting a business model that aims to profitably (1) convert this low cost “waste” stream from primary users of batteries, (2) diagnose and refurbish systems, and (3) sell these systems to secondary users. Under the context of this business model, the paper explores the economic and technological feasibility of second-life lithium-ion battery systems, and the environmental implications of extending the useful life of existing battery resources.

From an economic standpoint, the research gives a strong, affirmative answer: with the right markets for supply and demand and an efficient remanufacturing process, second-life lithium-ion batteries can offer a significant price advantage over new batteries. Among the many options, the most promising business model involves sourcing lightly-used backup batteries from data centers and targeting stationary storage developers as customers. Under the

assumptions presented in the report, a full production cost of \$134/kWh is estimated, undercutting current new pack prices by almost \$100/kWh.

From a technological standpoint, the research indicates that second-life systems are feasible. This report provides both an overview of the characteristics of used secondary (rechargeable) lithium-ion batteries as well as approaches to cope and compensate for these characteristics in a second-life system. The dominant characteristics are lower peak voltage, lower capacity, higher impedance, and higher self-discharge. The research indicates that these characteristics will have significant impacts on system design and performance, and ultimately the economics of a stationary storage system, but are generally addressable. The key success factors for a second-life system include 1) using batteries of high-quality origin, 2) designing systems for high maintainability and limited downtime, 3) incorporating a robust battery management system (BMS), and 4) effectively sorting “like for like” batteries through state-of-health estimation. Of these factors, the greatest uncertainty lies in state-of-health estimation – both the exact parameters on which used batteries should be matched and what accuracy of estimation is required to achieve that matching.

Lastly, this business model has several significant environmental implications. Extending the useful life of a durable good inherently supports waste diversion and delay of primary extraction of input materials. For a full-scale production facility of 80 MWh, this amounts to an estimated annual diversion of 1155 tonnes of hazardous waste, and 24 tonnes of lithium that need not be mined. While the connection between storage and renewables is also beyond the scope of this report, drawing on California as an example, an 80 MWh battery system supports about 493MW of renewable energy.

Introduction

The recent availability of affordable, energy-dense lithium-ion battery (LIB) systems is poised to change many industries. Demand for new LIB systems is forecast to grow dramatically, from 61GWh in 2015 to 124GWh in 2020 (Chung, 2015; Eaton, 2012) across the automotive, consumer electronics, and grid storage sectors. However, the “useful life” of a battery system is defined by Institute of Electrical and Electronics Engineers (IEEE) as ending when it can hold only 80% of its rated capacity (Eaton, 2012). Where batteries serve mission-critical functions, they are in practice replaced much earlier. Thus, it is conceivable that by 2020, tens of GWhs of remaining lithium-ion storage capacity could be directed towards recycling facilities, or more likely, landfills. While automotive companies are actively engaged in “second life” concepts (ex. home energy storage or uninterruptable power systems) for their electric vehicle batteries, it is not apparent that non-automotive batteries have similarly robust markets. The automotive sector has relatively few product offerings, a well-defined network of dealerships and repair shops, and existing systems for collecting and repurposing materials at end-of-life. However, outside this sector, the batteries have many different chemistries and form factors, and suffer from weak economics in the recycling process.

Finding a “second-life” for non-automotive LIB systems is thus a big challenge, but potentially one with significant economic and environmental benefits. New batteries can be prohibitively expensive, while even lightly used batteries are considered waste. Converting this low cost “waste” stream from primary users of batteries, diagnosing and refurbishing systems, and selling to secondary users would create a potentially lucrative market. Extracting more useful life out of battery systems will be environmentally important for mineral conservation (ex. lithium and conductive metals), as well as energy conservation in the production and recycling processes. Furthermore, if utilities or independent power producers deployed second-life

batteries on the grid, the economic viability of this solution could potentially unlock further levels of intermittent renewable energy penetration across even the lowest cost power markets.

Objective

Hypothesis: Non-automotive lithium-ion batteries are being recycled or landfilled prematurely, often before reaching the end of their “useful life” as defined by IEEE. However, the “useful life” of battery cells may vary by application and customer. This paper explores whether it is possible to extend the useful life of lithium-ion battery systems via refurbishing and guaranteeing performance to eliminate bias against used batteries, and whether a market of secondary customers exists. To that end, this paper will explore specifically whether:

1. A market exists for lower cost battery systems for non-critical applications -- or whether perceptions as to the criticality of battery systems can be altered;
2. A supply of lightly used batteries exists or could be created, and the procurement cost of these batteries is sufficiently low to justify testing and refurbishment;
3. Cell health testing methodologies and systems have matured to the point where the identification of failed -- or soon to fail -- lithium-ion cells can be performed economically and at scale;
4. It is technically and economically possible to package refurbished battery systems, with redundant cells if necessary, in order to meet the performance specifications of potential customers.

Background

From portable electronics to electric cars to backup power systems, lithium-ion batteries are increasingly pervasive in our society. Sales volumes have grown by 21% per year from 2004 to 2014, and are expected to continue at 10% per year through 2020 (Avicenne Energy, 2015).

Owing to the fast deployment of renewable energy and evolving regulatory policy, deployment for grid storage applications is expected to grow even faster, outpacing industry-wide projections four-fold (Greentech Media, 2016).

The lithium-ion battery market faces both a supply-side and a demand-side problem, creating a value gap. On the supply side, batteries are often discarded with much of their useful capacity remaining. This is particularly widespread in backup power applications, such as data centers and telecom infrastructure, where risk-averse operational practices stipulate replacement of large, well-functioning battery systems at 80% or more of their rated capacity. Moreover, due to the classification of batteries as hazardous material, disposal is costly (Argonne National Laboratory, 2011). On the demand side, with the fast deployment of renewable energy, batteries are increasingly needed to provide important services to the power grid, but are too costly. At current costs, the economics are not favorable; hence deployment is assisted by government subsidies or mandatory procurement policies. This creates the value gap: even lightly-used batteries are assumed to have no resale value, but they can still provide very valuable services.

Lithium-ion Battery Recovery from e-waste

The majority of secondary (rechargeable) lithium-ion batteries on the market today are individual cells or small pack assemblies used in portable consumer electronics, where they are valued for their high power density. Due to their energy content and levels of toxicity comparable to other e-waste, lithium-ion batteries cannot be disposed of in standard refuse collection or single-stream recycling collection (American Disposal Services, 2017). As a result, the majority of rechargeable lithium-ion batteries must be collected by specialized e-waste recyclers familiar with the neutralization and proper disposal protocols. Regulations controlling the disposal of small quantities of lithium-ion batteries are not controlled at the federal level, by the EPA, but

instead by individual states or localities (BiPower, 2017). Common sources of batteries include laptops, cameras and video recorders, mobile phones, portable power tools, hoverboards, and IT network equipment. While the volumes sent for e-waste disposal are quite large, the batteries consist of different chemistries, form factors, usage profiles, states of health, and age. Despite the inherent disadvantages in such a varied input stream, there are indications that second-life markets for these batteries exists. One e-waste recycler contacted indicated that they process over 20,000 used 18650¹ cells per day, where they are subjected to tests that reveal the state of health. The “reject rate” for these batteries is fairly low, between 5-15%. This research revealed that a majority of these cells are sold to original equipment manufacturers (OEMs) abroad, re-labeled, and sold under subsidiary labels to consumers in emerging markets. The remaining, rejected cells are either broken down into their constituent components or landfilled. While this represents a second-life market for individual cells, no indication was provided that cells are being diverted to higher-value applications, such as energy storage, or that those cells would be suitable for that purpose.

Second-life Research by Automotive Manufacturers

The growing prevalence of lithium-ion battery packs in hybrid and electric vehicles has led to increasing interest in the second-life uses of these batteries, particularly in stationary energy storage. Vehicle manufacturers are pursuing R&D both in-house as well as through partnerships. The key players in the automotive market are General Motors, BMW, and Nissan. Toyota, while also involved in second-life applications, is primarily focused on the nickel-metal-hydride chemistry in their existing fleet of hybrid vehicles (Transport Evolved, 2015).

¹ 18650 format refers to a certain size of cylindrical, rechargeable battery, with a diameter of approximately 18mm and a height of approximately 65mm.

Using “spent” Chevy Volt batteries, General Motors (GM) has piloted an 80-kWh installation at their Milford, MI site to help balance renewables generation (Transport Evolved, 2015). GM has also teamed up with ABB, a Swiss multinational providing products and services for the power grid, to pilot projects for larger stationary storage (Scientific American, 2010). BMW is pursuing re-use of its i3 batteries both for residential stationary storage (Greentech Media, 2016) as well as partnering with Robert Bosch GmbH, a German multinational providing automotive products and appliances, to integrate large quantities for grid-scale storage. The flagship installation, totaling 2600 packs and a capacity of 2.8MWh, is located in Hamburg and is used for grid stabilization and peak shaving (ElecTrek, 2016). Nissan is also very active in second-life research, announcing projects for both residential-scale storage, in partnership with Eaton (Science Focus, 2016), and grid-scale storage, in partnership with Green Charge Networks and 4R Energy (Transport Evolved, 2015), using retired Leaf batteries.

The substantial R&D resources committed to finding second-life uses of lithium-ion batteries in stationary storage is helping blaze pathways for other market entrants. For example, auto manufacturers and their partners are working with Underwriters Laboratory (a Nationally Recognized Testing Laboratory, or NRTL) to develop safety standards and certifications. Underwriters Laboratory standard UL 1974, which is currently under development, will facilitate the testing requirements for second-life lithium-ion batteries used in stationary storage applications (Underwriters Laboratory, 2017).

Used automotive battery systems have a number of advantages for second-life applications, such as being pre-assembled in large modules and existing within a well-defined network of dealerships, repair facilities, and salvage yards for collection. However, automotive batteries are subject to a number of stressors that may make them less suitable for secondary

applications – including exposure to wide temperature ranges, exposure to vibration and shock, and heavy usage in their primary application.

Methods and Results

Economic Feasibility

Business Model Conceptual Framework

A key goal of this paper is to present research that is *actionable* – that is, research that can easily be used by companies or individuals who want to attempt to address the problem of the value gap. Therefore, the individual sections of results below have been developed to fit within a broader business plan (Figure 1) to ensure that they would actually work in a real-world setting.

Figure 1: General business plan framework for a second-life battery company



The following sections fit within different stages of this business plan, and aim to fit together as part of a cohesive whole.

Demand for Remanufactured Lithium-Ion Batteries

The most critical question in the discussion of second-life batteries is, “*will anyone pay for batteries that aren’t brand-new?*” Without a market for the second-life product, the supply-side and technological evidence presented in the following sections is meaningless. While there are dozens of markets around the world for new lithium-ion batteries (Pillot, 2015), the performance demands of many of these markets are out of reach for most remanufactured cells. In most cases, the two binding performance constraints are **energy density** (measured both in terms of

energy per kilogram and energy per unit volume) and **cost of system downtime** (measured by the cost to the end user in the event that the battery doesn't perform as expected).

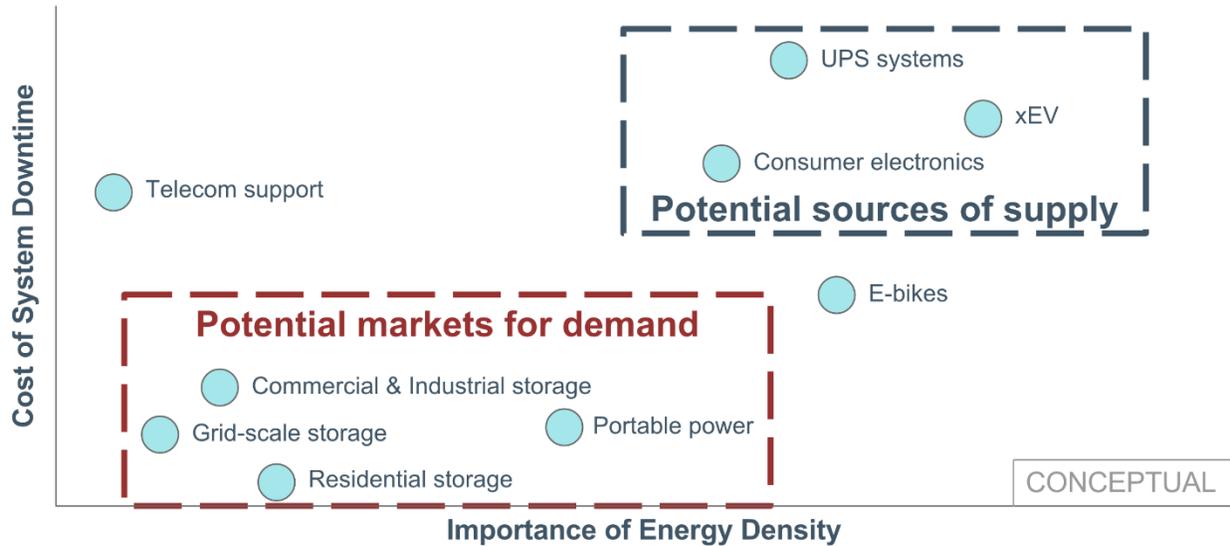
By definition, a second-life battery has lower energy density than a brand-new cell, as some of the battery's ability to hold a charge has been degraded over time, but it still possesses the same physical weight and dimensions. Although there is still plenty of usable charge in the second-life cell, it puts applications like cell phones or other consumer electronics, whose manufacturers are under constant pressure to increase battery life without increasing size, out of consideration.

When it comes to system downtime, second-life batteries are also at an inherent disadvantage due to lack of data. Lithium-ion batteries of various chemistries have been in commercial production since 1991 (Brodde), but because the concept of commercial remanufacturing is a relatively new one, there isn't sufficient data to convince some users that second-life cells won't fail for their mission-critical applications. Even though the second-life batteries were originally manufactured by the same major companies that are trusted sources for new batteries, the added layer of uncertainty stemming from cell age and degradation is enough to disqualify remanufactured cells from consideration in some applications.

The estimates of *cost of system downtime* presented in this paper are simple, conceptual estimates of the cost of system downtime, relative to those from other lithium-ion markets. While a more thorough approach is certainly possible, the complexity of estimating these costs is high and could be the standalone topic for future research, especially when considering the impacts on stationary storage revenue through mechanisms like PJM's frequency regulation performance score (PJM), or the impacts on company reputation through data center downtime.

The following chart helps visualize the various lithium-ion markets in terms of their energy density and cost of system downtime requirements:

Figure 2: Comparison of Lithium-ion markets by downtime cost and required density



A second-life battery business should certainly be conscious of these constraints when choosing a market, but they aren't the only considerations. To get a full picture of any potential markets, evaluation frameworks like SWOT (Taylor, 2017) and Porter's Five Forces (Porter, 2008) should be used. The following analysis represents four of the strongest markets for second-life batteries, and justifies the selection of selling to stationary storage project developers as the strongest option.

Potential Downstream Markets

General: common elements across all options

UNIVERSAL SWOT ANALYSIS - Common elements across all four options	
Strengths	<ul style="list-style-type: none"> Remanufactured cells enjoy a cost advantage over new cells

	<ul style="list-style-type: none"> ● 'Sustainable' branding - anyone using the remanufactured cells can advertise their landfill diversion attributes ● Relatively low <i>cost of system downtime</i> - targeted applications aren't 'mission critical', and while system failure may have costs associated with it, they are generally predictable and not extreme enough to bankrupt the company.
Weaknesses	<ul style="list-style-type: none"> ● Lack of performance data - determining insurance costs or calculating defect rates will be difficult until more data is collected ● Lower energy density than comparable new cells
Opportunities	<ul style="list-style-type: none"> ● Growth in factory output could lead to new economies of scale, further reducing cost ● Every year that a system is in the field, it will generate reliability data to prove the durability of second-life cells
Threats	<ul style="list-style-type: none"> ● Dropping cost of new cells - could undercut the cost of second-life cells, but without the perceived risk ● A few high-profile, early-stage failures or warranty issues could damage the concept of 'second-life' batteries for the entire industry

Self-owned: grid participation

In this scenario, the business would acquire used batteries, remanufacture them into a full, grid-scale system, and then install, own, and operate the system in various deregulated energy markets around the world (e.g. PJM, NYISO, CAISO) that allow participation of independent power producers (IPPs). The installation, ownership, and operation process would closely resemble the activities of IPPs like NRG, NextEra, and AES, and smaller developers like Invenergy and RES Americas.

SWOT ANALYSIS: GRID PARTICIPATION	
Strengths	<ul style="list-style-type: none"> ● Simple downstream approach - no need for a sales force or explicit warranty ● Capture more margin by integrating vertically ● Flexibility - doesn't preclude simply selling packs to developers

Weaknesses	<ul style="list-style-type: none"> ● High barriers to direct grid participation - wholesale trading licenses, collateral requirements, long interconnection times ● Volatility in revenues from market fluctuations ● Deferred revenue - recognize over the course of the system's 10+ year life
Opportunities	<ul style="list-style-type: none"> ● Greater opportunity to develop IP in full storage system ● Greater upside from well-managed market positions
Threats	<ul style="list-style-type: none"> ● Established energy storage developers are poised to expand capacity, potentially saturating storage markets and lowering revenues ● Dropping cost of new batteries could enable developers to build projects at significantly lower cost, pushing second-life systems too far up the cost curve

Niche: portable power

By pursuing a niche market, the business would focus on a much smaller segment of a different market in order to avoid many of the large competitors that threaten it in the grid participation scenario. Examples of potential niche markets include:

- **Portable power:** mid-sized (<50 kWh) battery-powered generators for construction, disaster relief, or similar markets
- **Telecom:** <50 kWh installations to power remote telecom towers
- **Microgrids in developing world:** <100 kWh solar-coupled systems to support village electricity consumption

This section will focus on portable power. With this application, a firm would design the portable power pack, remanufacture the battery cells, and either contract the construction of the pack out to a third party, or build the pack in its own factory. Finally, the firm would be responsible for marketing, selling, and supporting the pack/device in the open market, primarily targeting large construction and equipment rental companies.

SWOT ANALYSIS: PORTABLE POWER

Strengths	<ul style="list-style-type: none"> • Ability to focus on the market niches where second-life batteries can be most competitive • Development of IP could become a strong barrier to new entry
Weaknesses	<ul style="list-style-type: none"> • Potentially limited market size - may not be able to get to a profitable scale while only focusing on portable power • Competition - several companies already looking at addressing this market with second-life batteries • Development of specialized sales force, which may not be able to pivot later on
Opportunities	<ul style="list-style-type: none"> • If successful in this market, the resulting track record of reliability could make the transition to larger, more profitable markets (grid-scale) much easier (increasing bankability)
Threats	<ul style="list-style-type: none"> • Dropping cost of new batteries - could undercut the cost of second-life cells, but without the perceived risk

Remanufacturing as a Service (RaaS)

Under the RaaS scenario, the business would never actually take ownership of the second-life batteries. Instead, the firm would contract with a single supplier/customer who would both provide the used batteries and take delivery of the remanufactured product. Depending on the customer, the final product could take a variety of forms. For example, with data centers, the remanufactured product would likely be a centralized battery backup system to further protect against outages.

SWOT ANALYSIS: RaaS	
Strengths	<ul style="list-style-type: none"> • No ownership of cells - no risk of having to take write-downs on unsold, second-life cells • Dual value proposition to data centers - creating more value for data centers that want the remanufactured cells
Weaknesses	<ul style="list-style-type: none"> • Broader product line required - not all data centers will want/need the same product

	<ul style="list-style-type: none"> • Addressable market is small - unlikely that most data centers will want/need the remanufactured product • Still exposed to warranty issues, scope of liability may be smaller
Opportunities	<ul style="list-style-type: none"> • Service may be expandable to cell sources other than data centers (automotive, etc.)
Threats	<ul style="list-style-type: none"> • If most of the value to data centers comes from the removal of the used cells, then battery recycling facilities will likely be able to provide similar value at a much lower cost

Stationary storage developer sales

With this option, the business would focus on a small section of the value chain for stationary storage: battery pack supply. Instead of an independent product, the packs would need to be assembled with a wide variety of other components supplied by third-party vendors in order to create a functioning system. While the U.S. market for stationary storage is still in its infancy, requiring only 167MWh (\$441 million) in 2015, it is projected to grow to 6GWh (\$2.9 billion) by 2021, and the vast majority of this demand is and will be served by lithium-ion batteries (Greentech Media Research, 2016). Primary customers under this model would be independent system developers and integrators like AES Energy Storage, RES Americas, Younicos, Invenergy, and Stem. These developers have respectively installed capacity of 80MW (Wesoff, 2015), 80MW (various), 80MW (St. John, 2015), 60MW (various), and 38MW (Wesoff, 2016). There are also a number of smaller independent developers that specialize in certain regional or industry-based submarkets. These players are used to procuring components from a variety of vendors and have the engineering expertise to ensure that the components work together. Once these companies have procured the components for a full system and assembled it, they put it into service at either ‘front of the meter’ (FTM) or ‘behind the meter’ (BTM) locations. In FTM applications, systems are connected directly to the electricity grid and provide grid-level services like frequency regulation, transmission and distribution deferral, and resource adequacy. For BTM services, systems are connected to the electrical infrastructure of an electricity-consuming customer, like a warehouse, factory, or house. The electric utility that

serves the customer will often treat the storage system as if it were any other appliance, and simply bill the customer for their net electricity consumption. The advantages of having a storage system include backup power, demand charge reduction, and increased self-consumption of solar power.

SWOT ANALYSIS: STATIONARY STORAGE DEVELOPER SALES	
Strengths	<ul style="list-style-type: none"> ● Fits into value chain for established market - requirements are clear, and customers know what to expect ● Lower cost structure: less engineering/design, fewer components, no market licenses necessary ● Large number of potential customers
Weaknesses	<ul style="list-style-type: none"> ● Warranty and 'bankability' are crucial - customers won't touch the product without strong, enforceable financial support ● Products will have to be designed to operate with third-party components as part of the whole storage system
Opportunities	<ul style="list-style-type: none"> ● Rapid growth expected in stationary storage market ● A single FTM project could absorb the company's entire yearly output
Threats	<ul style="list-style-type: none"> ● Competition from other pack/cell manufacturers will be significant, as the market is already maturing

An additional analysis tool to evaluate the attractiveness of the various markets is Porters Five Forces. The detailed analysis for each market is provided in Appendix 1, and the table below provides a summary of the analyses.

Table 1: Summary of Five Forces Analysis for each downstream market

	Rivalry	Threat of new entry	Supplier power	Buyer power	Substitutes
Self-owned: grid participation	Strong	Moderate	Weak	Weak	Moderate
Niche: portable power	Strong	Strong	Weak	Weak	Strong
Remanufacturing as a Service	Weak	Moderate	Weak	Strong	Strong
Developer sales	Weak	Moderate	Weak	Moderate	Moderate to Strong

Customer Analysis & Recommendation

After completing the analysis, **Stationary storage developer sales** stands out as the strongest option for a second-life battery startup for several main reasons:

First, developer sales have the lightest cost structure and lowest complexity. While all four options require the use of a factory and advanced machinery, the other three options also have an additional design component (either a full storage system or portable power pack) that adds complexity, cost, development time, and risk of failure. Keeping the initial design as simple as possible will improve the chances of making it to market with a strong product.

Second, it has the most attractive market without taking direct market risk. Electricity market structures are changing to allow the inclusion of more storage (FERC, 2016), and selling directly to developers harnesses the pending rapid growth without having participate in the markets directly. Remanufacturing as a service (RaaS) has questionable value to data centers that limits its market size, and the market for stationary storage is growing at 5.5x the rate of the portable

generator market². While developers have strong substitutes for second-life batteries (new cells), the cost advantage of remanufactured cells and lack of other remanufacturing companies result in lower competition.

Finally, lower cost conveys the biggest advantage in developer sales, because of the commodity nature of battery pack sales. In all of the other three markets, product differentiation plays a large role - full system design can greatly increase performance in grid self-ownership, certain features built into a portable power pack can make it more or less attractive to the end user, and the range of options available for RaaS customers can make the difference between choosing RaaS or traditional battery recycling. However, there is relatively little space for differentiation in the direct-to-developer market. As long as battery packs are capable of communicating with the system components, dispatching power as instructed, and meet the basic required properties (lifetime, power/energy density, etc.), competition will occur on a price basis - something the firm's process and batteries are well-equipped to do.

In summary, the central idea behind selecting developer sales is to *keep the target market simple*. Simple means lower startup costs, less development risk, and a much better chance of growing into a successful company.

Supply Sources for Used Lithium-Ion Batteries

Finding the right source of used batteries is crucial to the success of a second-life battery company's business model. Without a steady stream of low-cost, high-quality batteries, it will be impossible to reach the scale and performance thresholds that enable profitable operations.

² US Stationary Storage CAGR ('15-'19): 37.4% (Greentech Media, 2016), US Portable Generator CAGR ('14-'19): 6.8% (ResearchMoz, 2015)

By using the factors listed in the Technological Feasibility analysis above, a picture of the ideal used battery emerges:

- a relatively new cell manufactured by a **reputable company**,
- with a **specific chemistry** known for longevity,
- a **standard form factor** to enable scalable disassembly processes,
- possessing a **low number of cycles**,
- which has been kept at a **constant, moderate temperature**, and
- maintained within a **conservative operating charge window**.

In addition to the battery's technical requirements, the **source** of the used batteries must also balance a number of economic considerations, including:

- current and future **scale of used battery output**
- low **costs to collect** all batteries in a central location,
- minimal **shipping distance** to the remanufacturing facility,
- high frequency of **battery replacement**,
- few other economic **disposal options**,
- and a positive, **progressive attitude** towards sustainability and landfill diversion.

These factors were used to rank potential sources of used batteries. The rankings are based on conceptual, qualitative, understanding of how well each source meets the requirements of each factor, relative to the other sources. Each source is given a score between 1 (doesn't meet requirements) and 5 (meets requirements very well). Additionally, each factor is given a weight that reflects how important it is to a business model for second-life battery remanufacturing. Finally, the importance-weighted-average of all the factor scores is summed across each potential source, meaning that the highest-rated source is the best candidate for used battery supply. A complete, factor-by-factor analysis is available in Appendix 2. A high-level summary of the results is reflected in Table 2.

Table 2: Analysis of potential sources of battery supply

Lithium-ion Source	Supplying Entity	
Cell Phones	Device manufacturers	2.60
Cell Phones	Consumers	2.60
Cell Phones	e-waste processors	2.85
Laptops + Tablets	Device manufacturers	2.50
Laptops + Tablets	Consumers	2.45
Laptops + Tablets	e-waste processors	2.75
Automotive	Car company	3.10
Automotive	Consumers	2.70
Power Tools	Device manufacturers	2.15
Backup Power	Data Centers	3.85
Backup Power	UPS Vendors	3.40

This initial analysis points to data centers as a strong potential source of used batteries. The next section will highlight important aspects of data centers that might make them strong candidates for second-life supply.

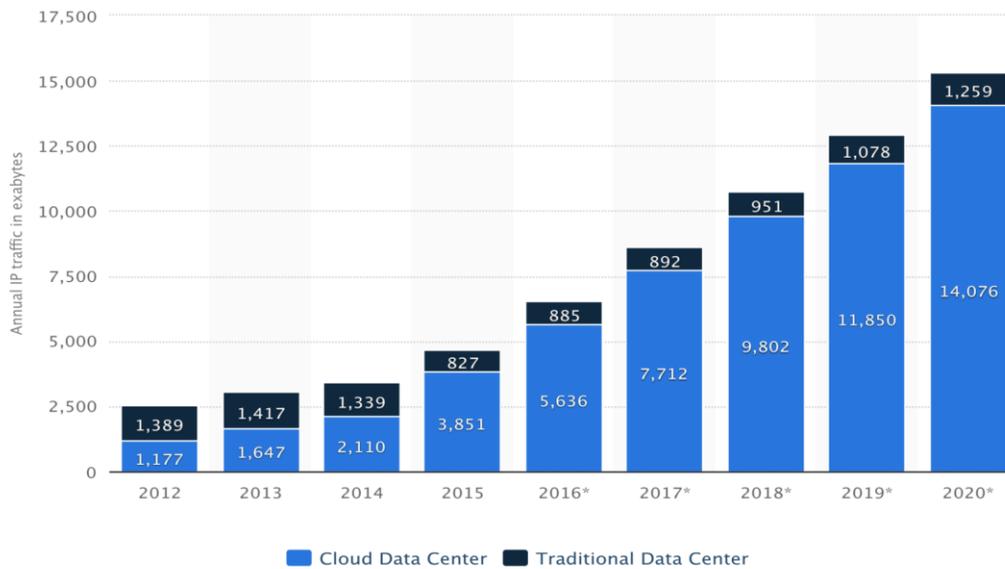
Data Centers

Need for batteries

Data centers have become essential in providing modern technological services. Most people can easily name a wide variety of vital services that rely on data centers, including email, social media, and video streaming. However, many may not realize the extent of our fundamental dependency on the services that data centers provide. Everything from medical records (Sullivan, 2014), to electricity delivery (Turcotte, 2012), to defense information systems (Kundra, 2011) are beginning to transition away from on-site, inefficient, specialized servers, and into cloud-based applications hosted in centralized data centers. By 2020, the global data center IP

traffic (a proxy for the number and size of data centers) is expected to grow to over 15 exabytes³ from 2016's 4.6 exabytes (Figure 2) (Statista, n.d.)

Figure 3: Global Annual IP traffic in exabytes (Statista, n.d.)



In most cases, the argument for such a transition is clear - it is an opportunity for a significant increase in asset utilization and efficiency. According to the Uptime Institute, “30% of servers in [on-site] data centers are consuming power but not doing any useful work” (Brown, 2012). In comparison, centralized data centers allow consolidation and more efficient management of IT assets from a multitude of entities, reducing the cost per unit of work, and enabling companies to reduce their IT expenses. However, even though data centers enable to reduction of IT expenses, it doesn’t mean that customers accept a lower standard of performance. In fact, the average cost of a single minute of unplanned downtime at a centralized data center is estimated to be \$9,000 (Ponemon Institute, 2016). Data center operators realize this, and design their facilities with redundancies that will help them maintain services throughout a wide variety of contingency scenarios.

³ One exabyte = 1 billion gigabytes

One of the most common scenarios is power failure, where the electric grid that feeds the center stops supplying electricity. When this happens, most data centers rely on fossil-fueled backup generation (either diesel or natural-gas powered) with hours of fuel on hand. However, these generators usually take anywhere from a few seconds to a minute to begin producing energy, meaning that a power supply 'bridge' is necessary to maintain server functionality during their startup cycle. The most common device to bridge this gap is a UPS (uninterrupted power supply). Essentially, a UPS is made up of two components: a control system and batteries. When the control system senses a power outage, it quickly (ideally under 5 ms (Loeffler, 2009)) switches the power supply from the grid to its batteries, ensuring that the connected components remain online. This functionality is critical to most data centers. The Uptime Institute, an advisory organization for IT infrastructure, certifies data centers at various 'tiers' of reliability and performance, and even the most basic tier stipulates the inclusion of a UPS system (Stansberry, 2014).

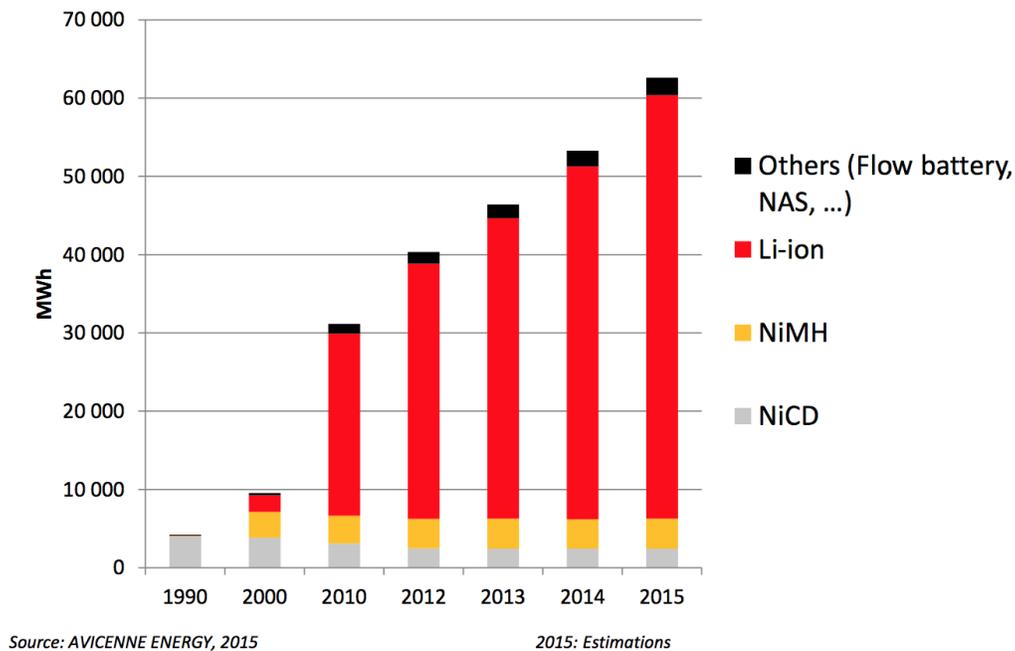
Progression of battery technology in data centers

Historically, data centers have used valve-regulated lead acid (VRLA) batteries in their UPS systems, as lithium-ion batteries were 5-10x more expensive on a capital expenditure basis (Clark, 2016). Although VLRA systems were relatively bulky (energy density of about 100Wh/L (Albright, 2012)), they were cheap (\$120/kWh), required less maintenance than other lead-acid batteries, and were easy to recycle (98% of all lead acid batteries are recycled today (Battery Solutions, 2017)), driving their widespread adoption.

However, the rapid growth of lithium-ion production volumes since the early 2000s (see Figure 4) has fundamentally shifted the marketplace. According to Patrick Donovan, a senior Research Analyst at Schneider Electric (a maker of UPS systems), the capital cost difference has now dropped to 1.5-3x (Clark, 2016). When coupled with the added benefits of lithium-ion batteries -

greater energy density (smaller footprint), longer lifetime, and lower overall operating costs (Albright, 2012), the economics of using lithium-ion batteries in data center UPS systems have begun to look much more favorable, and some major UPS manufacturers have already begun to advertise that lithium-ion's total cost of ownership (TCO) has dropped below that of VRLA (Avelar, 2016).

Figure 4: Growth of worldwide Lithium-ion production, 1990 – 2015 (Avicenne Energy, 2015)



While the adoption of lithium-ion batteries in data center UPS systems is still far from ubiquitous, the shift in economics marks a turning point in the industry - lithium-ion has become the UPS technology of choice, and installed volumes in data centers are likely to spike over the coming years.

Component designs from the Open Compute Project support this assertion. The OCP is a consortium of technology firms (originally founded by Facebook, and whose members include Google, Microsoft, Intel, IBM, and hundreds of others) whose aim is to greatly reduce the cost of data centers by collaborating on the design of standardized, efficient components (Open

Compute Project, 2017). Among these components is a design for a Battery Backup Unit (“BBU V2”), which is essentially an in-rack UPS system that uses popular 18650-format lithium-ion batteries (Open Compute Project, 2015). Although OCP members are free to use their own designs, OCP’s BBU shows that the largest, most important players in the centralized data center space have begun to recognize the value of lithium-ion. Furthermore, the design provides a good starting point for analysis, as its specifications are openly available and it is likely that other designs won’t be materially different in terms of overall battery capacity requirements.

Volume potential

One of the key factors for selecting a source is its **scale of used battery output**. While industry trends discussed in the preceding paragraphs appear to indicate strong potential from data centers, a more rigorous set of calculations should be applied to verify this conclusion. More specifically, the potential output should be expressed in terms of *Megawatt-hours (MWh) of used batteries per year*. This output level will then be compared with the amount of input that is necessary to sustain a business.

The OCP BBU provides a strong starting point for this analysis for several reasons. First, the detailed plans posted on OCP’s website enable accurate calculation of each unit’s power (kW) and energy (kWh) rating. Second, they are the UPS technology used in at least one of Facebook’s major data centers (Gizmodo, 2014). As an industry leader in sustainability, Facebook publishes detailed data surrounding data center energy use, allowing the analysis to connect energy use (a widely-tracked metric in the industry) with UPS capacity needs. Some of the key data points derived from these calculations are listed in the tables below:

Table 3: Calculations of energy storage capacity for a large data center using OCP Standard equipment

Input Values		
	Value	Units
Battery Backup Unit (BBU) V2 Power Output ⁴	3600	watts
BBU V2 Max Voltage ⁴	52	volts (max)
BBU V2 Discharge Duration ⁴	180	seconds
BBU V2 Life (@ 25C) ⁴	6	years
BBU V2 Cycles ⁵	24	cycles/year
BBU V2 Wh	180	Wh

	Value	Units
# of BBU in Power Shelf ⁴	3	BBUs/Shelf
# of Power Shelves in Cabinet ⁴	2	Shelves/Cabinet
# of cabinets per column ⁶	25	Cabinets/column
# of columns per row ⁶	25	columns/row
# of rows per data hall ⁶	2	rows/data hall

Calculated Values ⁷		
kWh per data hall	1,350	kWh
kW per data hall	27,000	kW
MWh per data hall	1.35	MWh
MW per data hall	27	MW
MWh per Data Center (8 halls)	10.8	MWh
MW per Data Center (8 halls)	216	MW

⁴ Open Compute Project Specifications (Sarti, 2015)

⁵ Author calculations – assuming one test and one actual use per month

⁶ Author assumption

⁷ Author calculations

Although this theoretical data center is a relatively large example, it shows that the sheer volume (in MW and MWh) of batteries that go into a single location - enough to power about 8,750 homes for an hour⁸.

In order to evaluate the scale of the entire domestic need for data center UPS batteries, this analysis uses a slightly different approach. Instead of performing a bottom-up evaluation and multiplying the batteries in one data center by the number of data centers present in the US, it calculates a ratio between the MWh of storage in the facility and its annual energy consumption. Using Facebook as an example (because energy consumption data for each center is publicly available (Facebook, 2016)), these ratios were simple to obtain for two major data centers:

Table 4: Calculation of energy storage to energy consumption ratios for Facebook’s data centers, assuming lithium-ion adoption

Input Values		
Energy Use: Facebook NC Data Center	310,000,000	kWh/year
Energy Use: Facebook OR Data Center	284,000,000	kWh/year
# of active data halls: Facebook NC Data Center ⁹	8	data halls
# of active data halls: Facebook OR Data Center ⁹	8	data halls

Calculated Values		
<i>Energy Storage Ratios: Facebook, NC</i>		
ES System Power/Yearly Energy Consumption	0.000874	MW storage/MWh demand
ES System Energy/Yearly Energy Consumption	0.000044	MWh storage/MWh demand

⁸ 10,800 kWh / (10,812 kWh per home per year / 8760 hours per year) = 8,750 homes / hour. (Energy Information Administration, 2016)

⁹ Author’s estimation, based on Google Maps satellite data

<i>Energy Storage Ratios: Facebook OR</i>		
ES System Power/Yearly Energy Consumption	0.000954	MW storage/MWh demand
ES System Energy/Yearly Energy Consumption	0.000048	MWh storage/MWh demand
<i>Energy Storage Ratios: Average</i>		
ES System Power/Yearly Energy Consumption	0.000914	MW storage/MWh demand
ES System Energy/Yearly Energy Consumption	0.000046	MWh storage/MWh demand

Finally, these ratios were applied to a projection of data center energy usage in the US from the Lawrence Berkeley National Lab (Shehabi, 2016) to arrive at a forecast of installed UPS capacity:

Table 5: Projected US Data Center Backup Storage Needs

<i>Calculated based on 70 TWh energy consumption/year</i>		
Total ESS Power Required	63,983	MW
Total ESS Energy Required	3,199	MWh

OCP's BBU plans also list a specified lifetime of 6 years for the batteries (Open Compute Project, 2015). At this rate, the following volume of used lithium-ion UPS batteries would be available each year:

Table 6: Projected yearly retirements of lithium-ion batteries from data centers

ESS Power Retired	10,664	MW/year
ESS Energy Retired	533	MWh/year

Taken together, all of these factors indicate that data centers can be a promising source of supply for second-life batteries. However, just having a strong source of batteries and a

potential market (as discussed in the previous section) doesn't indicate whether a business model based on remanufacturing these cells could be successful.

Price Advantage of Remanufactured Batteries

One fundamental assumption underlies almost every business model based on second-life batteries: *remanufactured cells hold a significant price advantage over new cells*. If this assumption is violated, the business model becomes unsustainable. In the context of this project, this raises two central questions:

1. What is the cost of creating a remanufactured battery with similar characteristics to a new cell?
2. Will the cost of new batteries remain high enough to support a market for second-life batteries?

The first question is answered with an in-depth cost model that calculates the total unit (\$/kWh) costs of remanufactured batteries for a variety of production volumes and other scenarios. This model incorporates data from many sources, but relies heavily on data from Argonne National Lab's 'BatPac' model (Argonne National Laboratory, 2011) for determining capital expenses and material costs.

The second question is answered with market price data and forecasts for new battery cells and packs. With the increased prominence of energy storage over the past few years, price data is available in many forms, including aggregated collections of actual project prices, like those from Bloomberg New Energy Finance and Greentech Media Research, publicly-available quotes from individual storage companies, like Eos or Aquion, non-specific impressions from conversations with developers, and forward-looking projections from research and other analyses. Since a comprehensive analysis of energy storage price trends could be a full project

on its own, this paper will focus on a few widely-accepted studies that provide an overall view of market trends.

Cost Model

The structure of the cost model follows the overall business process, with three main steps from **Figure 1** (Transportation/Procurement, Remanufacturing, and Sales/Distribution) subdivided into eleven individual cost drivers. Each cost driver is constructed with a variety of data points and assumptions that are rolled up into three \$/MWh subtotals - low, middle and high cost estimates. The subtotals from each cost driver are then added together and converted to kWh to arrive at the total \$/kWh cost for the remanufactured battery pack¹⁰. The following pages define each of the individual cost drivers, explain the calculation process, and list some of the key assumptions and sensitivities.

Procurement

- **Packaging Materials** - the crates, pallets, and other protective gear used to ship cells from the source site (data center) to a manufacturing plant. Estimates for this step were created through an engineering cost analysis, based on measurements of cell size, the necessary padding around each cell, and the size of a standard shipping pallet, subject to the pallet's weight limits and deterioration rate. The total cost can be expressed by the following equation:

$$\text{Shipping Material \$ per MWh} = \left(\frac{TC_{pm}}{L_{pm}} \right) * \left(\frac{N_{MWh}}{N_p} \right)$$

Where:

- TC_{pm} is the total cost of one pallet's worth of packing materials

¹⁰ Note: final conversion to kWh made for comparison purposes – most industry quotes given in \$/kWh.

- L_{pm} is the expected lifetime (in trips) of the packing materials
 - N_{MWh} is the number of cells in a MWh
 - N_p is the number of cells that will fit on a pallet
- **Packaging Labor** - the cost for an employee to extract cells from their original housing at the customer site and repackage them for shipping. Estimates were derived by analyzing the design of the OpenCompute battery backup unit, and by estimating the time that it would take an employee to be able to remove the cell and secure it in the outbound packaging.

$$\text{Shipping Labor } \$ \text{ per MWh} = t_c * N_{MWh} * r_p$$

Where:

- t_c is the time (in hours) to disassemble and pack each cell
 - N_{MWh} is the number of cells in a MWh
 - r_p is the labor rate (in dollars per hour) for cell disassembly and packaging
- **Purchasing** - the amount one would have to pay to suppliers for their battery cells. The initial assumption was that during the early stages of the business, suppliers would *pay* to dispose of the batteries, due to their lack of alternative options and the high cost of recycling. After remanufacturing reached scale, suppliers would realize the value of their batteries and demand payment. However, after further research, it appears that this shift has already occurred. Certain e-waste recycling facilities contacted have stated that they are already paying suppliers of used lithium-ion batteries. In some ways, this number is a 'plug', meaning that it is open for negotiation with suppliers, and that negotiating room will flex depending on the rest of the remanufacturing costs and the market price for batteries. In this study, the purchasing cost was assumed to be \$5,000/MWh.

Remanufacturing

- **Pack Materials** - the components that connect, protect, and control the second-life cells.

The estimates for this step were sourced from the BatPac model. With a given set of input assumptions, the model generates a total cost of materials per pack, which is then scaled up to a per-megawatt-hour rate.

$$\text{Pack Material \$ per MWh} = \frac{(C_p + C_b + C_t)}{E_p}$$

Where:

- C_p is the cost (in dollars) of the 'pack materials', which include the enclosure, wiring, etc.
 - C_b is the cost (in dollars) of the battery management unit
 - C_t is the cost (in dollars) of the thermal management equipment
 - E_p is the energy of the pack (in MWh)
- **Capital Equipment** - the testing, assembly, shipping/receiving, and recycling equipment that is needed to carry out a manufacturing process. These were sourced from the BatPac model, which outputs a total cost for equipment, given a yearly production volume. In order to obtain a cost per MWh, the total cost figure was divided by its expected lifetime (six years) and then divided by the yearly output in MWh.

$$\text{Capital Equipment \$ per MWh} = \frac{(EQ_{rs} + EQ_t + EQ_a + EQ_{rc})}{L_{eq} * MWh_y}$$

Where:

- EQ_{rs} is the cost (in dollars) of receiving/shipping equipment
 - EQ_t is the cost (in dollars) of testing equipment
 - EQ_a is the cost (in dollars) of assembly equipment
 - EQ_{rc} is the cost (in dollars) of recycling equipment
 - L_{eq} is the lifetime (in years) of the equipment
 - MWh_y is the yearly production of battery packs (in MWh)
- **Building Space** - the physical space and basic utilities needed to conduct operations.

The BatPac model again provided a basis for the calculations, by estimating the factory

footprint needed for the given level of output, as well as a present-value rate per square meter for the costs of building the factory and all future utility costs. The total upfront investment for plant size was then divided by the estimated lifetime.

$$\text{Building \$ per MWh} = (S_{rs} + S_t + S_a + S_{rc}) * \frac{C_m}{L_b * MWh_y}$$

Where:

- S_{rs} is the floor space (in square meters) needed for receiving/shipping
 - S_t is the floor space (in square meters) needed for testing
 - S_a is the floor space (in square meters) needed for assembly
 - S_{rc} is the floor space (in square meters) needed for recycling
 - L_b is the lifetime (in years) of the building
 - C_m is the present value cost per square meter of keeping the building running (over its lifetime)
 - MWh_y is the yearly production of battery packs (in MWh)
- **Manufacturing Labor** - the employees used to perform all of the essential steps in the remanufacturing process. The BatPac model provided a number of labor hours required for each step in the process, which were totaled and multiplied by an estimated labor rate.

$$\text{Manufacturing Labor \$ per MWh} = (t_{rs} + t_t + t_a + t_{rc}) * \frac{r_m}{MWh_y}$$

Where:

- t_{rs} is the labor hours needed for receiving/shipping
 - t_t is the labor hours needed for testing
 - t_a is the labor hours needed for assembly
 - t_{rc} is the labor hours needed for recycling
 - r_m is the labor cost (in dollars per hour)
 - MWh_y is the yearly production of battery packs (in MWh)
- **Variable Overhead** - the additional expenses that are associated with labor and equipment usage, and that vary with production volume. There are a wide variety of rules of thumb for calculating variable overhead, but the most common simply multiply

the total direct variable costs (like labor, depreciation and materials) by some factor to arrive at the total variable overhead. ANL's BatPac model uses a similar method, setting variable overhead at 20% of depreciation plus 40% of labor costs.

$$\text{Variable Overhead \$ per MWh} = (ML_{MWh} * VO_{ml}) + ((CE_{MWh} + B_{MWh}) * VO_{dep})$$

Where:

- ML_{MWh} is the per MWh cost of manufacturing labor
 - VO_{ml} is the variable overhead rate applied to manufacturing labor
 - CE_{MWh} is the per MWh cost of yearly depreciation on capital equipment
 - B_{MWh} is the per MWh cost of yearly depreciation and utilities for the building
 - VO_{dep} is the variable overhead rate applied to depreciation
- **Fixed Overhead** - the additional expenses that come from running a business, but don't directly vary with production volumes. These include general, sales and administrative (GS&A), as well as research and development (R&D) costs. Ideally, fixed overhead costs would be estimated with a bottom-up approach that utilizes a more specific analysis of headcount and equipment needs. The BatPac model takes a less exact, but more streamlined, approach by multiplying labor, variable overhead, and depreciation expenses by a set factor to arrive at fixed overhead.

$$\text{Fixed Overhead \$ per MWh} = ((CE_{MWh} + B_{MWh}) * FO_{rd}) + ((CE_{MWh} + B_{MWh} + ML_{MWh} + VO_{MWh}) * FO_{gsa})$$

Where:

- CE_{MWh} is the per MWh cost of yearly depreciation on capital equipment
 - B_{MWh} is the per MWh cost of yearly depreciation and utilities for the building
 - FO_{rd} is the fixed overhead rate used to determine R&D expenses
 - ML_{MWh} is the per MWh cost of manufacturing labor
 - VO_{MWh} is the per MWh cost of variable overhead
 - FO_{gsa} is the fixed overhead rate used to determine GS&A expenses
- **Working Capital** - the costs of financing inventory, accounts receivable, and other current assets, minus the funding provided by current liabilities like accounts payable.

Without a full balance sheet, these costs can be difficult to estimate, so the simple method presented by BatPac was utilized. This method simply multiplies the total variable overhead costs by a set percentage (15%), and the resulting product is called working capital.

Distribution

- ***Outbound Shipping*** - the packing materials and other transportation costs of delivering the packs of remanufactured batteries to the end customer. In contrast to the estimation method used for inbound shipping, this step uses a flat dollar per kilogram shipping cost of \$1.13/kg (Foster, 2014), and multiplies the total estimated weight of the outbound battery packs by that number. Outbound shipping costs are only included in the “high” estimate, because customers typically pay for shipping separately.
- ***Warranty*** - the cost of technical support, replacement products, and other damages caused by faulty products. This step was estimated as a percentage of the total cost of all the previously-listed cost drivers.

$$Warranty \$ per MWh = r_w * \sum_{n=1}^{10} C_n$$

Where:

- r_w is the expected warranty rate
- C_n is the per MWh cost of each cost driver element (i.e. C_1 is Packaging Materials, etc)

Total Cost Estimates

After developing the cost calculation framework, three separate estimates – low, middle, and high – were made for each input. The resulting calculations give a range of total cost for remanufactured packs between \$86 and \$260/kWh, with a middle case of \$134/kWh.

Table 7: Range of modeled costs for remanufacturing

All-in Pack Costs	Low	Middle	High
Total cost per kWh	\$86	\$134	\$260

Market Price Forecasts

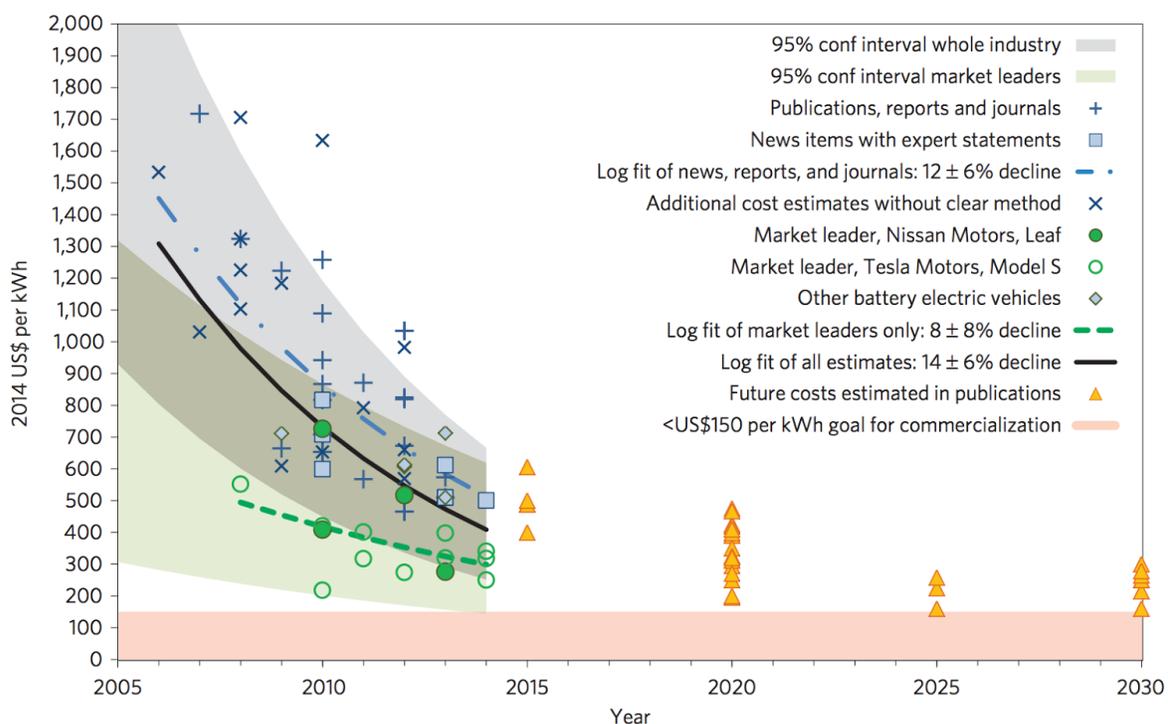
As noted earlier, there are a plethora of resources that attempt to forecast the downward trend of lithium-ion battery prices. This abundance of resources can actually make the situation less clear, especially when trying to compare across studies. Differences between ‘system’, ‘pack’, and ‘cell’ costs, and ‘power’ and ‘energy’ applications can cause incorrect comparisons and misleading conclusions. Therefore, care must be taken when compiling data from a variety of sources.

To reduce these risks, this paper will focus on the results from two oft-cited sources: Nykvist and Nilsson’s “Rapidly falling costs of battery packs for electric vehicles” (Nykvist, 2015) and Bloomberg New Energy Finance’s continually-updated lithium-ion battery pack price index (Randall, 2016). Both studies highlight the most relevant point of comparison: the future costs of battery packs¹¹.

¹¹ Authors define battery packs as groups of cells organized into modules, controlled by a battery management system and contained within a physical package or casing. They do not include inverters, switchgear, and external thermal management systems.

In their paper, published in the “Nature Climate Change” journal in March of 2015, Nykvist and Nilsson analyze over 80 individual data points on the price of lithium-ion battery packs from 2007-14. From these data, they calculate a ‘learning curve’ that describes how battery prices have been dropping with relation to time, and use this relationship to offer insights into the future trajectory of pack prices. They conclude that the market-leading (i.e. cheapest) firms will have pack costs around \$230/kWh by 2017-18. See **Figure 5** for a graph showing their data points and learning curves.

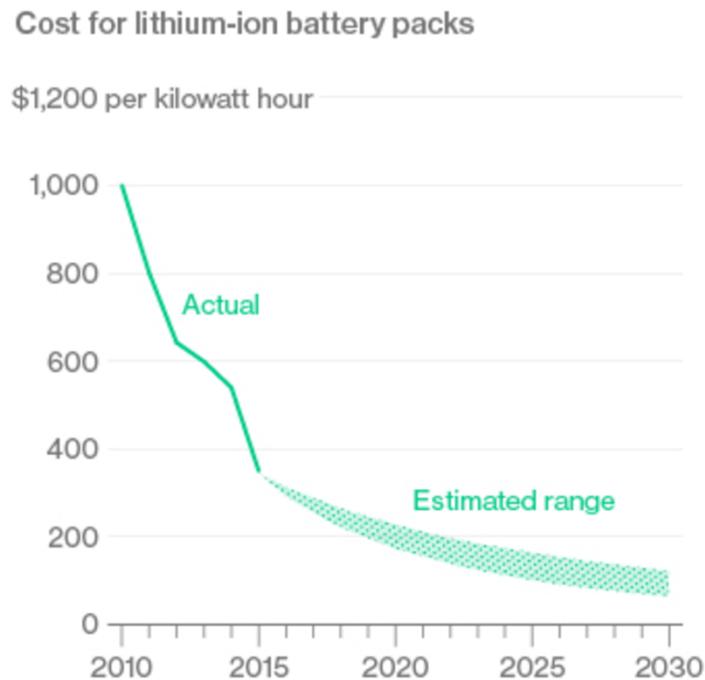
Figure 5: Nykvist and Nilsson’s declining cost curve for lithium-ion battery packs, with projections through 2030



For the past half of a decade, Bloomberg New Energy Finance (BNEF) has been collecting data on the cost of lithium-ion battery packs directly from suppliers. Although they don’t publish the raw data, they do convey their results through their ‘Lithium Ion Battery Price Index’ that shows up in many of their articles (Randall, 2016) and presentations (Liebreich, 2016). In much the same way as the Nykvist study, these graphs show rapidly declining cost from 2010-2015,

followed by a more gradual 'learning curve' that extends beyond 2025. Also like Nykvist's paper, BNEF shows a target value of about \$225/kWh in 2017. This is followed by a slower decline to about \$175/kWh by 2022 (as seen in **Figure 6**).

Figure 6: BNEF's lithium-ion cost curve, with projections through 2030



This cost discrepancy between new (\$175-230/kWh) and remanufactured (~\$134/kWh at scale) battery packs highlights the opportunity in the business model. These numbers certainly don't guarantee the success of the business model, as there are already examples of battery pack costs dropping faster than anticipated and breaking the \$200/kWh barrier, and there are any number of issues that could go wrong with scaling up the remanufacturing operation. However, the same forces that are working to lower the cost of new packs can also be harnessed to move the cost of remanufactured cells closer to their lower bound of \$86/kWh. This mechanism will likely keep a significant gap between the prices for remanufactured and new batteries, indicating that this opportunity will be present for the foreseeable future.

Technological Feasibility

While a battery is represented on electrical schematics as a simple voltage source, the reality is that a battery cell is based on complex and dynamic electrochemical reactions. Integrating hundreds or thousands of battery cells to work in concert, producing a reliable output, and operating over many cycles and years is an enormous challenge – even when working with new batteries. Even new batteries of the same chemistry, manufacturer, production line, and vintage, will have inherent differences that must be taken into consideration when designing a module. These differences will be exacerbated by both time and usage conditions of the batteries in their primary application. Therefore, the technical feasibility of creating a second-life product that meets the performance needs of customers is a serious consideration.

Mechanisms of Battery Degradation

Differences among Batteries & Determinants of Ageing

In evaluating the technological feasibility of remanufacturing used batteries into modules, it is important to understand a number of basic factors and ageing determinants that cause differences between cells:

Chemistry – while grouped together as a class, lithium-ion chemistries are very different.

Chemistry of a lithium-ion cell impacts key specifications and operating characteristics, and there are many (possibly insurmountable) challenges to assembling batteries of different chemistries in a module together – notably the nominal voltage and charge/discharge profiles.

The nominal voltage can vary from 2.4V for Lithium Titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$) up to 3.8V for Lithium Manganese Oxide (LiMn_2O_4) (Battery University, 2016). In series configuration, voltage differences create impractical or potentially dangerous charge/discharge conditions. In parallel configuration, undesirable electrical potentials are created between the cells, rather than across

the load. Differences in charge/discharge profiles also complicate integration. Voltages and currents from a cell are not constant, they vary over the course of a single cycle depending on the chemistry (Battery University, 2016). These differences are significant, and can create potentially damaging strain. Due to the dynamic nature of the electrochemical reactions, these differences are also difficult or impractical to control with BMS. Therefore, battery modules focused on safety and longevity need to consist of a single chemistry (Battery University, 2016).

Capacity – the capacity of a battery indicates the nominal energy that can be stored within a cell in Amp-hours (Ah). The nominal capacity does not necessarily indicate the actual capacity, which could be larger or smaller. Typical chemistries in an 18650 form factor have a nominal capacity of 1.5-3.0Ah per cell. Calendar age, cycle age, rate of discharge, and permissible operating parameters all ultimately impact a cell's capacity. Deviations in cell capacity, even within new cells of a single chemistry from a single manufacturer, exist and are accommodated by a battery management system (BMS) (Weicker, 2014).

Calendar Age – calendar age of a battery is the time elapsed since manufacturing. Lithium-ion battery calendar life expectancy varies by chemistry, and can range from a few years up to 20 years. Lithium Titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$) and Lithium Iron Phosphate (LiFePO_4) are examples of chemistries with long shelf lives (Weicker, 2014).

Cycle Age – the cycle age of a battery is a measure of the number of charges/discharges since manufacturing. Lithium-ion battery cycle life expectancy ranges from hundreds to thousands, also depending on chemistry. Lithium Titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$) chemistries are expected to have the highest cycle life, in the range of 3,000-7,000 (Battery University, 2016). Cycle life is closely linked to the operating window of those cycles, as batteries that experience larger relative charges and discharges will degrade at a faster rate (Weicker, 2014).

Temperature – the temperature at which lithium-ion batteries are charged, discharged, and stored impacts both cycle life, calendar life, and battery performance. While lithium-ion batteries have a wide range of operating temperatures, charging at temperatures below freezing or charging/discharging at elevated temperatures leads to degradation of the cells - reducing capacity and increasing impedance (Weicker, 2014).

Holding Charge – unlike other battery technologies (ex. lead-acid), lithium-ion batteries do not benefit from a full charge. A full charge creates high voltage potential. Even within the parameters of the battery specifications, this leads to additional stress on the battery. By limiting or eliminating “saturation” charge on the cells, the lifetime of a cell can be extended, although at the expense of energy capacity available. As a guideline, every 70mV reduction in charge voltage lowers capacity by 10% (Battery University, 2017). Batteries sourced from applications with low holding charges can be expected to last longer in a second-life application.

Internal Cell Defects – all battery cells, regardless of manufacturer, contain internal cell defects. These can include impurities in electrodes, inconsistencies in manufacturing thicknesses, separator integrity (ex. pinholes), non-uniform coatings, and other anomalies. The impact on performance may be negligible at first, but over time have greater impact on cell performance and safety. Therefore, quality of initial manufacturing, stability of electrolytes and separators, and resilience against defects are important variables in useful life of a battery cell (Weicker, 2014).

Depth of Discharge – Depth of Discharge (DoD) is a measure of the energy delivered by a battery cell relative to the total energy available from a fully charged cell. A complete discharge of a fully charged battery would have a DoD of 100%. All lithium-ion chemistries last longer under conditions with smaller DoD, and changes in DoD can impact cycle life by an order of magnitude. Unlike other battery technologies (NiCad), lithium-ion does not have a memory

effect that benefits from periodic full discharges. Lithium-ion batteries that experience deep discharges must be re-charged quickly to prevent further damage to the integrity of the electrodes (Battery University, 2017).

Operating Window – the range in which a battery is charged and discharged relative to its energy capacity specifications, upper bounded by the “Holding Charge” and lower bounded by the “Depth of Discharge” as described above.

Self-Discharge – although lithium-ion batteries are relatively stable, stored charge within a battery is lost over time. This self-discharge occurs in relation to the battery chemistry, the storage temperature, the holding charge, and the age of the cell. Even new batteries will self-discharge, and the self-discharge rate will vary from cell to cell (Weicker, 2014).

Abuse – lithium-ion batteries can intentionally or unintentionally be subject to abuse, and that abuse can significantly impact expected lifetime, performance, and safety of a cell. Abuse conditions include overcharge, overdischarge, overcurrent, temperature extremes, mechanical impact, and others (Weicker, 2014). While BMS are generally designed to pre-empt electrical abuse, and in many cases provide data on historical abuse, other causes may be more challenging to track and evaluate.

Impact on Battery Cell Performance

While all of these factors need to be considered, generally speaking they cause similar impacts.

Used batteries will show certain macro characteristics: *lower peak voltage, lower capacity, higher impedance, higher self-discharge, and shorter time to failure* than they did at time of original manufacturing.

Lower peak voltage impacts operation when the voltage of a series string falls below the “cutoff” voltage of the application, and when stronger batteries in parallel try to charge the weaker ones.

Lower capacity impacts operation by creating cells that drain first, and charge first. Once drained, other cells must carry disproportionate load and can cause total voltage issues. Once charged, the weak cell may be overcharged in process of achieving full charge in the overall string. The loss of capacity is also referred to as capacity fade. This capacity fade leads to a lower state of health, which is defined mathematically as the percentage of remaining capacity over nominal capacity.

Higher impedance impacts operation by reducing net current available for load, wasting energy in the form of heat generation (which can further accelerate ageing of the cell and others in proximity).

Higher Self-discharge impacts operation by loss of energy over time, representing lost revenue and potentially creating imbalances in charge levels. Self-discharge will vary by cell and occurs in relation to the battery chemistry, the holding charge, the storage temperature, and cell age.

Shorter time to failure impacts operation by adding burden to remaining cells, which uncontrolled could lead to a cascading failure event, and labor/materials to identify and replace failing modules.

Despite these hurdles, and the myriad of factors that contribute to them, it is possible to design modules that can accommodate the inherent weaknesses of used battery cells, and extract more useful life before disposal.

Design and Manufacture of used Battery Modules

Success Criteria

In light of the many ways in which lithium-ion battery cells can differ in both initial manufacturing, and then experience a wide array of use conditions in their primary application, a successful second-life battery pack will need certain characteristics to be successful:

1) Use batteries of high-quality origins

Many of the complications arising from used batteries are simply an exacerbation of instabilities or defects present within the cells at time of production. Therefore, batteries that last the longest in second-life applications will be of stable chemistries from top-tier manufacturers that maintain the tightest production tolerances. Data on usage profile from the primary application should also be available (from existing BMS) or readily estimable.

2) A “super” battery management systems (BMS)

Battery management systems (BMS) for large lithium-ion packs are already commercialized, and those packs have many capabilities to cope with differences among battery cells. In a second-life application, a BMS will need even greater tolerance for a variety of inputs. This will allow second-life module to generating a consistent output, maximize charge and discharge capabilities, and enforce safety parameters. Key functionalities will include the ability to balance/equalize energy within a module and ability to work around cells that become inoperable.

3) High maintainability with limited downtime

Like all large battery systems, maintenance will inevitably be required on a second-life product, and it is likely that those maintenance needs will be greater than those of an assembly with new batteries. Therefore, it is critical to have worked maintainability into every aspect of the module’s design, and to incorporate capabilities such as “hot swappable” components that can be removed and repaired without requiring system downtime.

4) Effective sorting of “like-for-like” batteries, and elimination of outliers

A well-functioning second-life battery pack will not simply take used batteries and repackage them along a single parameter. Closely matching battery cells along multiple parameters is as important as having a high-quality supply source. Cells need to be matched according to their ability to hold charge, expected remaining years and cycles, charge/discharge profiles, impedance, and other key factors. Segmenting the input supply to create homogeneous groupings, and discarding outliers (even good ones), will yield better packs while minimizing waste.

Of these four key success factors, the most valuable for a second-life battery company to develop would be tools for estimation of battery health. This will be explored further in the section below.

Tools for Estimation of Battery Health

This section explores whether methodologies have matured to the point where “healthy” cells can be identified from “unhealthy” cells, and whether this can be performed economically and at scale. Academic research attempts to estimate the percent capacity remaining of a cell, and estimate where it lies on the degradation curve. Approaches vary in complexity, time, cost, and accuracy, and there are typically trade-offs between these objectives. Sorting cells into two classes – healthy and unhealthy – thus requires some judgment and will depend on many supply-specific factors, such as cell consistency, as well as the desired lifetime of the second-life system. Therefore, the focus will be characterizing the remaining capacity as a proxy for cell health. Judgment on how to use that information in the recombining and packaging of cells will be used in the remanufacturing stage.

While state of health testing and modeling should be agnostic of the first-life application of the cells, most methodologies have been developed in the context of repurposing batteries used in electric vehicles. Furthermore, methodologies tend to focus around cells whose remaining capacity tends to be around 60-80% of nominal capacity. While the average remaining capacity of the cells from backup power applications is neither known, nor controllable, it is expected that these cells would have a higher remaining capacity, and thus it is unclear that the accuracy of these models extends for higher capacity cells. There is little evidence, though, to suggest that this would be a problem. Furthermore, all research focuses on testing the health of single cells at a time. If hundreds of thousands of cells need to be tested, this could be costly and time consuming. No research has pointed to the classification of multiple cells concurrently for remaining capacity, but if such research were performed, this could potentially improve the scale at which this operation could be done.

State of Health Estimation Methodologies

Several state of health estimation methodologies described below could be used for this aforementioned purpose. The choice of which approach to use would be a business decision, since it involves tradeoffs between development and testing cost, testing time, test intrusiveness (wear on battery during testing), number of batteries sacrificed, and estimate accuracy. Methodologies are presented in order of increasing complexity, which generally corresponds to increased accuracy.

DC Resistance – A simple linear model based on DC resistance is proposed in (Zhang, 2011).

The formula is as follows:

$$State\ of\ Health = \frac{R_{EOL} - R}{R_{EOL} - R_{new}} \times 100\%$$

where R_{EOL} is the end of life resistance of the battery, R_{new} is the beginning of life resistance of the battery, and R is the measured resistance of the cell in question. This method is said to be

relatively inaccurate and sensitive to disturbances (Zou, 2015), but provides for a basic first-order approximation of state of health, is fast to measure, and may prove more helpful for certain chemistries and vintages than others.

Single Charge Cycle – Charging the cell to full capacity and then discharging it gives a good proxy of a cell's state of health. This can be measured by a process known as Coulomb counting, in which an ammeter is connected to the cell and integrates the current measurements over a discharge cycle, revealing the amount of charge stored in the cell. Depending on the cell chemistry and vintage, accuracy is typically within 5-10% of actual capacity (Zou, 2015). This method is somewhat imprecise because of noisy current measurements and small fluctuations in capacity between adjacent cycles that make estimating the “actual capacity” require multiple cycle measurements.

Electroacoustic Response – Recent promising research suggests that electroacoustic responses, both reflected and transmitted, can be used to infer state of charge, state of health, and other electrochemical-based parameters of batteries. This was published in a paper by Princeton scientists (Hsieh, 2015), who have since worked to commercialize their research in a company called Feasible with the Cyclotron Road program (Cyclotron Road, 2017). Feasible has a patent filed and is still an emerging technology, thus, little can be said about its effectiveness. It is quite promising, but would involve a different business model – likely in the form of a partnership with the company itself.

Multiple Charge Cycles with Machine Learning Feedback Loops

Machine learning feedback models use adaptive algorithms, regressions, and other mathematical techniques to estimate cell capacity using operating data as an input. Although mathematically these methods are not as simple as the previous methods, owing to the

inconsistency of supply, these methods are more suitable for obtaining highly accurate estimates of cell capacity. Two of these methods are Extended Kalman Filtering and Vector Machines.

Extended Kalman Filtering – In (Plett, 2004) and (Lee, 2008), an extended Kalman filter is proposed for measuring the decaying capacity of a battery over time by modeling an equivalent RC circuit and measuring the discharge current and voltage over time. Kalman filters use Bayesian inference to estimate a set of unknown variables that contain Gaussian noise with reasonable accuracy. In this case, this noise comes in the form of the voltage and current measurements, which make it difficult to otherwise obtain a precise estimate of cell capacity, as mentioned earlier. Once the initial profile is built, by cycling the cell several times to estimate model parameters, convergence to within 5% was found within 60 seconds. The main drawback of this method is that the initial modeling of the RC circuit may vary from cell to cell, and the model is sensitive to these parameters (Zou, 2015). This method would work well if there is a high degree of consistency between cells, so that one universal model can be applied. Otherwise a model will need to be built for various groupings of similar cells, and there would need to be a mechanism by which to quickly group cells before testing.

Vector Machines – Vector machines are binary linear classifiers, which attempt to create groups from example data sets with gaps as wide as possible. Vector machines are similar to linear regression, which bifurcate data into effectively into two groups, one set of data above the regression line, and the other set of data below the regression line, where the line drawn minimizes the sum of squared residuals, however, vector machines work on a hyperdimensional space. In this case, the “groups” are ranges of

capacity, and the vector machine attempts to classify a cell based on its discharge voltage profile into a capacity range.

They take as their inputs the voltage discharge profiles as well as impedance measurements. From this data set, a sample entropy measurement is computed, which essentially measures how chaotic a data set is. The use of vector machines requires large data sets to learn to identify groups. In (Widodo, 2011), 30 batteries cycled 30 times are used to calibrate the model. However, once trained, they could predict capacity to within 1%.

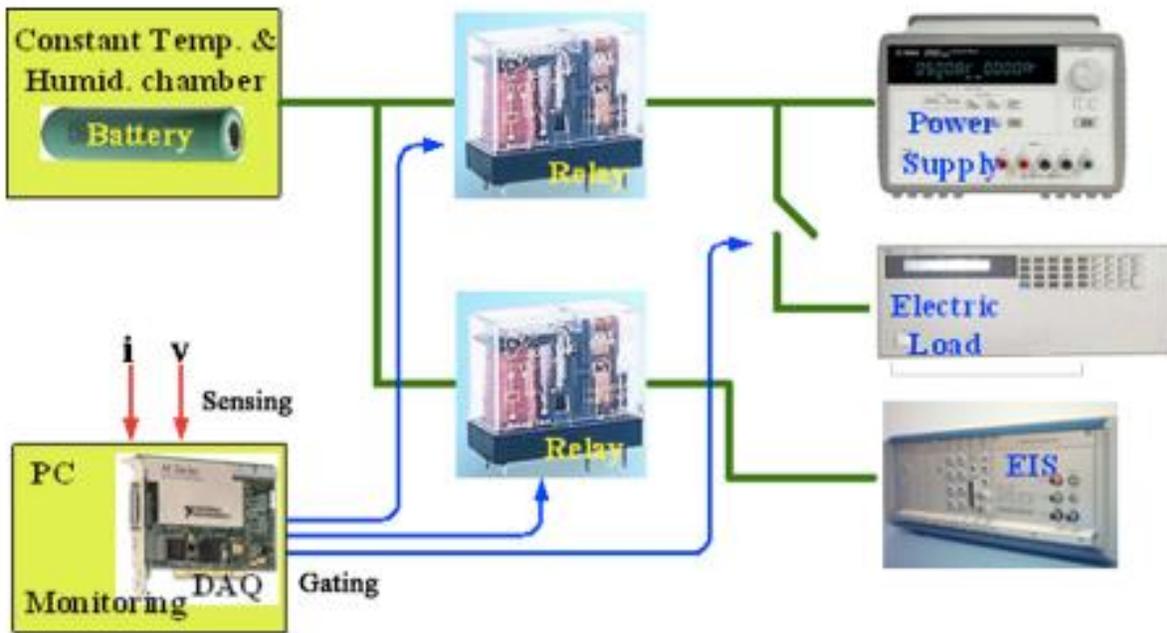
Economics and Scalability

All of these methods could be applied at scale. Moreover, the selection of testing methodology likely plays only a small role in the overall cost of testing. The degree of accuracy, speed, consistency of supply, and requirements of output product all play more significant roles in the selection of a testing methodology. However, a few conclusions can be made:

1. Using a DC resistance model is likely too inaccurate for meaningful sorting and remanufacturing of battery packs.
2. Electroacoustic response is likely too immature at this point, and the intellectual property would need to be licensed or acquired at added cost to the process.
3. A single discharge cycle may be sufficient if cell consistency is high across all cells and cells have been “broken in”. For certain incoming shipments, this may be the case, but for others it may not.
4. The application of machine learning with multiple charge cycles requires very similar equipment, although some approaches require an electrochemical impedance spectroscopy (EIS) unit, which is quite expensive. Setups generally would require a DAQ (Data Acquisition Unit), DC power supply, relays, electric load, electrochemical impedance spectroscopy (EIS) unit. On the software side, a PC could perform the

computation, and would need to be capable of running a technical computing platform, such as MATLAB. Such a setup is depicted in **Figure 7**.

Figure 7: Sample schematic for data capturing multiple charge and discharge cycles (Lee S. , 2008)



A sample budget is below:

Item	Low price	High price
DAQ	\$150	\$5,000
Relay	\$1	\$10
DC Power Supply	\$300	\$3,000
Electric load	\$200	\$1,000
EIS unit	\$15,000	\$31,000
PC with Matlab	\$1,000	\$3,000

In total, the necessary equipment should cost about \$20,000-40,000.

Conclusion

Based on this research, lithium-ion battery cells can be tested economically and at scale.

Exactly which methodology is used will depend on many unknowns, such as the variability of timing, volume, vintage, and chemistry of supply. Furthermore, there may be varying efficacy of different methodologies depending on supply sources. With simple DC resistance being a proxy for remaining capacity, and electroacoustic response being still a nascent technology, it is likely that developing a statistical model, perhaps with the application of machine learning, and using inputs such as impedance, resistance, and charge/discharge voltage would be the most viable option at this point. Exactly which of these techniques is most appropriate depends on a number of business factors. Given that most models were calibrated with batteries dissimilar to lightly used, 3-6 year-old lithium-ion 18650 cells, a pilot is needed to verify the accuracy of the methodologies.

Disassembly of Existing Modules

The practicality of disassembling modules into cells will vary from one primary application to another, depending on the means and methods of original assembly. It is most favorable to test battery cells individually to determine state of health, but separating the cells electrically may require separating the cells physically. To maintain the integrity of each cell and reduce safety concerns in the remanufacturing process, the cells will need to be physically separated without damaging the outer casing/housing, the terminals, or safety venting features.

For ease of manufacturing the original product, some large battery modules feature cells that are resistance-welded to the assembly, yielding better physical and electrical connections (Lee S. S., 2010). Especially where prismatic pouch cells with foil-like casings are used, it may be impossible to separate individual cells physically without damaging the casing. As a result, it may be necessary to test those cells at the module level, or eliminate them from the supply

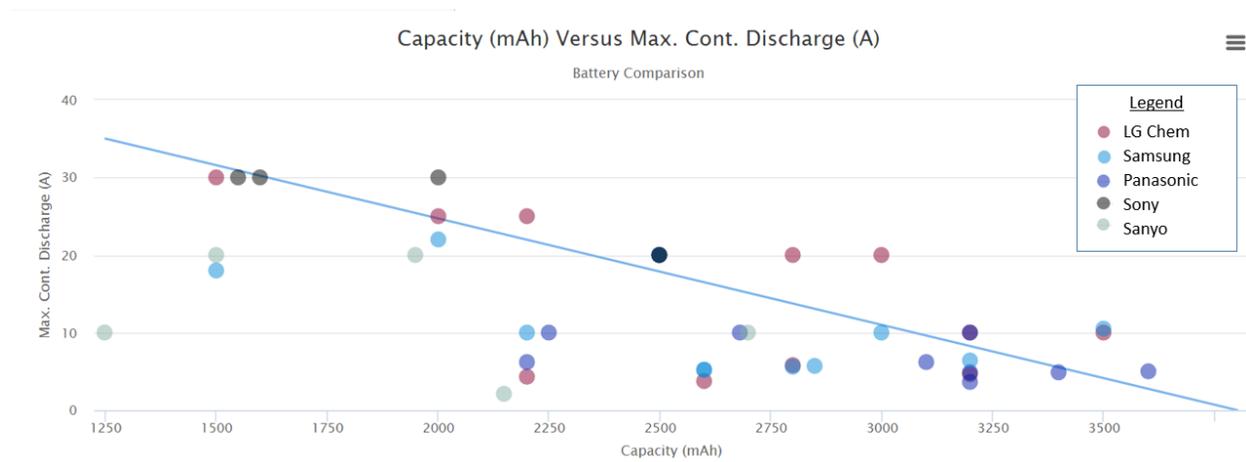
source. These disassembly issues are not expected for modules assembled from 18650 cylindrical cells.

Power vs. Energy Applications

Uninterruptible Power Supply (UPS) batteries in data centers are purpose-built to quickly support heavy electronic loads for a short duration, allowing for backup generation resources to turn on and smoothly ramp up loading. In general, these systems are designed to provide high power (kW or MW), but only for 90 to 180 seconds (Open Compute Project, 2015).

Different lithium-ion chemistries and product offerings from different manufacturers clearly indicate a tradeoff between ability to deliver high power and ability to store high energy. **Figure 8** below plots a number of offerings in the 18650 form factor, color coded by manufacturer, where it can be seen that higher capacity generally means lower cell discharge rates (Amps) (Best18650Battery, 2017).

Figure 8: Comparison of discharge rates (amps) to cell capacity (mAh)



Batteries sourced from data centers, at least for the foreseeable future, are likely to be “high drain” batteries (located in the upper left quadrant of the chart). For example, the Open Rack v2

Battery Backup specification cites 18650 cells rated for minimum storage of 1500mAh (about half the best-available) but a current capacity of up to 30A (Open Compute Project, 2015). This represents a “20C” discharge capability ($30A / 1.5 \text{ A-h} = 20C$). Due to these extreme capabilities, using such batteries in a second-life power application (ex. grid frequency stabilization) is very possible, even under reduced working parameters.

High-drain batteries could also be used for energy applications in their second life, but will have a lower energy density than systems purpose-built for long-term energy storage. This means that second-life energy systems may require at least 2x the footprint of today’s currently available systems, and possibly a greater factor versus future systems. However, a key determinant of battery health is increased impedance – increasing heat generation and reducing net current available for loads. Due to the low-impedance nature of high-drain batteries, it may be expected that after ageing, impedance will remain within acceptable limits longer than a high-energy battery.

Environmental Impacts

There are three main environmental benefits associated with the creation of a secondary market for lithium-ion batteries:

1. **Waste Diversion** – Lithium-ion batteries sent to a secondary application have their lives extended and diverted from a hazardous waste stream. A full-scale production facility of 80MWh / year will require 288,889 cells (author calculations above), each with a weight of 50g (Panasonic, 2017), amounting to 1155 tonnes of batteries diverted from waste streams per year.
2. **Lithium Conservation** – Recent interest in lithium-ion as the chemistry of choice for electric vehicle batteries has yielded significant research in the environmental impacts of

lithium production (Stamp, Lang, & Wager, 2012). Avoiding the mining of lithium saves machinery emissions, land use impacts, and other significant pollutants. A typical 3.46Ah 18650 has about 1.04g of lithium in it¹², meaning that about 24 tonnes of lithium per year need not be mined by the operation of the aforementioned 80MWh / year production facility.

3. **Enabling Renewables** – The link between renewable energy integration on the power grid and its reliance on battery storage is beyond the scope of this report. California’s 2020 concurrent storage and renewables targets are a reasonable starting point from which to make a rough estimate of the impact that new storage capacity can have in supporting renewable energy. California’s 2020 renewable portfolio standard (RPS) calls for 33% of its electric energy to be sourced from renewables (California Public Utilities Commission, 2017), and to have 1.3GW of storage deployed by the same date (California Energy Commission, 2017). In 2016, California’s renewables contributed 27% of the electric energy consumed in the state, producing 69TWh of electricity, with a generation capacity of 26.1GW. Scaling this linearly to achieve the 33% RPS, California will require 32.1GW of renewable generation capacity. The storage procurement mandate does not specify the capacity of the storage installed, but typical lithium-ion storage installations, like the 80MWh facility in the Southern California Edison territory, have a 4-hour capacity (Aoyagi-Stom, 2017). Thus, the relationship between renewable capacity and storage capacity is as follows:

$$\frac{\text{Renewable capacity (GW)}}{\text{Storage capacity (GWh)}} = \frac{32.1\text{GW}}{1.3\text{GW} \times 4\text{h}} \sim 6.16$$

Taking 6.16 and multiplying it by the full-scale production facility output of 80MWh suggests that 493MW of renewable energy could be supported in a California setting.

¹² Determined by multiplying the battery capacity in Amp-hours by ratio of (0.3 g Lithium / Amp-hour) (FedEx, 2017)

While this makes several assumptions about the relationship between renewables and grid-scale storage, this serves as a first-order approximation as to the amount of renewable energy that such a facility could support.

Regulatory Considerations

The key regulatory areas that impact this business model are shipping, factory hazards, certifications, and recycling/disposal of lithium-ion batteries.

Shipping

This business model involves the shipping and handling of secondary (rechargeable) lithium-ion batteries. The batteries are considered a “Dangerous Good” and listed as a “Class 9 - Miscellaneous Hazardous Material” by the United Nations, and transportation is regulated in the US by the Department of Transportation’s (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) (Energy Assurance, 2017). As with many hazardous materials, the restrictions surrounding lithium-ion batteries are intended to enhance packaging and harmonize hazard communication. While there are looser regulations surrounding batteries “shipped for disposal or recycling,” it is assumed that at a minimum a remanufacturer must adhere to the stricter shipping standards on the output side of the process. To be conservative, it is assumed that the more stringent standards will also apply to the input battery supply.

Concerns with Shipping

Lithium-ion batteries are susceptible to damage in transportation including short circuiting, puncture, incineration, crushing, immersion, and exposure to elevated temperatures that could leak otherwise sealed electrolyte material, lead to explosion or fire, or off-gas potentially harmful substances (CO, CO₂) in enclosed spaces (Saft, 2005). Many lithium-ion batteries must carry a minimal holding charge to prevent breakdown of the cell chemistry (Weicker, 2014), and thus these issues cannot be resolved by simply discharging all remaining energy.

Air Transport

Transport policies for lithium-ion batteries vary by common carrier (UPS, FedEx, DHL, and others). Some carriers only allow shipment by pre-approved customers, others require that the batteries be packaged with supporting equipment (UN3481) or without supporting equipment (UN3480). Separate warehousing of batteries is often required by the carrier. UPS and others also prohibit air shipment of batteries collected for recycling or repair of defects, which could be problematic (UPS, 2017). In general, the regulatory hurdles related to air shipment of bulk batteries are extensive and likely prohibitively expensive.

Ground Transportation

The transportation of secondary lithium-ion batteries (in bulk) via ground transportation including roadways and railways is regulated by the Hazardous Materials Transportation Act (HMTA), which specifies the responsibilities of a shipper, as outlined by the US DOT (US Department of Transportation, 2017):

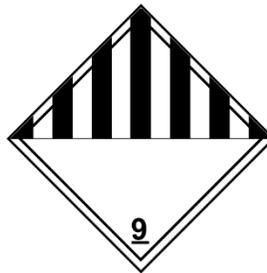
- 1) **Classification of hazardous material** – the shipper is responsible for understanding the difference between hazardous and non-hazardous materials, including materials that are treated as non-hazardous per the Resource Conservation and Recovery Act (RCRA). Misrepresenting a non-hazardous material as a hazardous material can have severe consequences.
- 2) **Proper shipping name** – the shipper is required to correctly identify hazardous materials by the recognized name (ex. “Lithium Ion Batteries Packed with Equipment”).
- 3) **Class/Division** – the shipper is required to understand the different types of hazardous waste and correctly classify the materials.
- 4) **Identification Number** – shipment is labeled and documented under the applicable material code (ex. UN3481)

- 5) **Hazard Warning Label** – packager must apply hazard warning labels (HAZMATEAM, 2016) to be visible on outermost container and visible from all directions (examples below):



- 6) **Packaging** – packager must provide adequate inner packaging and outer packaging. Inner packaging primarily prevent short-circuit between individual cells and separates battery terminals from any metal objects with a non-conductive material (ex. plastic). Outer packaging must be strong enough to withstand drop tests, but does not necessarily need to be waterproof.
- 7) **Employee Training** – anyone involved in the packaging or shipping of batteries, or direct managers of those employees, must complete a series of training every three years (more info below).
- 8) **Shipping Papers** – a manifest of all hazardous materials and quantities with the shipment, which must be signed by trained personnel.
- 9) **Testing** – shipment must contain only batteries that have met the standards of the UN's Manual of Tests and Criteria 38.3
- 10) **Emergency Response & Telephone Number** – all shipments must include the contact information for a responsible party, available 24hrs in case of emergency.
- 11) **Certification** – shipping company must be registered annually with the DOT (more info below) regardless of size of business or shipments.

- 12) **Compatibility** – shipper must verify compatibility of hazardous materials with other items included in the shipment.
- 13) **Blocking and Bracing** – shipment must be packed in to vehicle to avoid physical damage from transportation.
- 14) **Placarding** – ground vehicles transporting hazardous materials must display placards that indicate nature of contents (ex. placard for Class 9 hazardous below).



- 15) **Incident Reporting** – shipper is responsible for recording reportable incidents with the DOT.

Companies involved in the shipping of lithium-ion batteries must be registered with the US DOT by completing form F 5800.2 annually and paying a registration fee. Registration year is period from July 1 to June 30. Small business fee is \$275 and not-small business fee is \$2600 per year (US Department of Transportation: Pipeline and Hazardous Materials Safety Administration, 2016-2017), “small business” for battery storage company is <1250 employees per NAICS code 336911 (US Small Business Administration, 2016). Employees involved in the shipping of lithium-ion batteries must complete training and certification under CFR 49 172.700-704 (Government Publishing Office).

Preparation and Packaging Considerations

Safely transporting hundreds of thousands of battery cells cost effectively will require effective deconstruction, specialized packaging, and automated sorting equipment. Most existing battery systems will need to be de-constructed to extract the battery cells – whether it is easier to do this at a supplier site or at a separate factory is unclear. Breakdown to the cell level may be

complicated by original fabrication methods of the encasement and cells themselves – cells may be difficult to access and potentially resistance welded to other components within the assembly. These challenges are easier to handle off-site, but shipping cells in their original encasements will entail much higher shipping costs and waste burden on the factory side. If cells can be extracted on site, they will then need to be physically protected and electrically insulated on their way to the factory. Shipping of certain cell form factors, such as 18650 cylindrical batteries, can be accomplished in palletizable “cartons” that insulate the battery terminals. Other form factors (prismatic or pouch cells) do not share the same physical size standard and terminal lead locations, and may require customized solutions. Lastly, with the high volumes of batteries involved, automated processes for sorting, orienting, and packaging cells will dramatically improve labor costs. Here as well, the 18650 form factor will be superior because its consistent physical dimensions will facilitate the use of automated equipment.

Factory Hazards

Factory safety is an important consideration in dealing with batteries containing a variety of chemicals, potentially volatile electrolytes, and stored energy. The proposed business model does involve the disassembly and reassembly of secondary lithium-ion battery packs. It does not, however, involve the disassembly or reassembly of individual battery cells. Therefore, while precautionary measures are necessary in handling materials, electrolytes and other hazardous materials will remain sealed. Furthermore, only non-destructive testing will be used to assess cell health and performance. Maintaining the battery cells in a safe, temperature-controlled, and ventilated environment will still be required. Should a breakage of a cell or spillage of contents occur, simple measures such as wearing proper gloves and eye protection will be sufficient to protect workers involved in cleanup.

Product Certifications

The Occupational Safety and Health Administrations (OSHA) requires that a battery assembly module, due to its nature as an electrical system, achieve certification by a National Recognized Testing Laboratory (NRTL) (US Department of Labor, 2017). This certification provides benefits to both the manufacturer and a prospective customer. By purchasing a certified product, the customer receives safety, insurability, and a product that meets jurisdictional code requirements. By selling a certified product, the manufacturer can reveal latent defects in materials or design, and limit their liability in the event of an accident. The most common NRTL in the United States is Underwriters Laboratory (UL). A list of UL's key standards for battery systems are outlined below:

UL 1642: Lithium Batteries – Covers the use of lithium-ion batteries as power sources in products, and are intended to reduce the risk of fire, explosion, or injury

UL 1973: Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications – Covers the use of electric energy storage systems (EESS) to handle abuse conditions

UL 9540: Energy Storage Systems and Equipment – Covers requirements for installation

UL 1974 (Under Development): Covers use of second-life electric vehicle (EV) batteries for use as energy storage systems in residences, commercial facilities, or microgrids (Underwriters Laboratory, 2017).

Approaching UL or another NRTL for certification will likely require the assistance of a specialized consultant familiar with the process, entail the provision of multiple test samples, require substantial time, and cost of roughly \$8,000 per marked product, plus annual listing fees (References for Business, 2017). Once products are approved, there will be substantial constraints on material or design changes unless re-tested. These risks will be mitigated by

focusing on a select number of profitable configurations, and extensive in-house testing and vetting of product performance prior to seeking certifications.

While other certifications and certification agencies exist, like the Institute of Electrical and Electronics Engineers (IEEE) and the International Electrotechnical Commission (IEC), the requirements of an NRTL like Underwriters Laboratory are considered most pertinent to the US market and most challenging to attain.

Disposal and Recycling

Due to the high toxicity of lead, states have enacted strict regulations on the recycling of lead acid batteries, with over 99% of battery lead recovered (Battery Council, 2017). These have included provisions such as mandatory “take back” requirements for manufacturers and deposit incentives that encourage users to return end-of-life batteries back to collection centers.

However, lithium-ion batteries do not contain heavy metals and contain mostly copper, cobalt, nickel, and iron. Once discharged, lithium-ion batteries can generally be disposed of in municipal landfills. A movement towards resource conservation led to an update of the EU’s 2006/66/EC directive in 2006, requiring up to 45% recollection rates (Wikipedia, 2017).

Regulations related to disposal and recycling could benefit or damage this business model. If higher collection rates are mandated, large users will be under more pressure to seek economical means to meet the mandates. On the negative side, if “take back” provisions are instated, it will be more difficult for a new player to insert itself into the material flows. Also, if recycling is subsidized or incentivized, it could reduce the competitive advantage of remanufacturing.

Conclusion

Economic

One of this paper's central questions is, "does it make economic sense to build a business around remanufacturing used li-ion batteries?" Over the preceding sections, the research gives a strong, affirmative answer: with the right markets for supply and demand and an efficient remanufacturing process, second-life li-ion batteries can offer a significant price advantage over new batteries. There are several key components to this conclusion:

1. Directly targeting stationary storage developers is the most promising sales

strategy - Utility-scale stationary storage is the best match for the performance characteristics of second-life batteries (lower energy density), and offers a way to mitigate negative market perceptions around reliability (through performance guarantees). The market is also an attractive one, with rapid near-term growth projections and high price sensitivity.

2. Data centers offer the most attractive source of used li-ion battery supply - Data

centers offer lightly used, high-quality battery cells that are replaced on frequent, consistent cycles - all of which are highly desirable qualities for a second-life business model. Additionally, the nascent state and projected rapid growth of the li-ion UPS market for data centers allows new businesses to gain a foothold and scale with supply.

3. Full production cost estimates put second-life packs at about \$134/kWh,

undercutting current new pack prices by almost \$100/kWh - By reducing primary cell material inputs to virtually nothing, remanufactured batteries save a large percent of costs relative to new. Although it may take a startup some time to reach an efficient

manufacturing scale, it is likely that many production cost efficiencies employed by new pack manufacturers can also be used in remanufactured packs, helping maintain the second-life cost advantage in the long term.

Technological

The technological analysis presented provides both an overview of the characteristics of used secondary (rechargeable) lithium-ion batteries as well as approaches to cope and compensate for these characteristics in a second-life system. The dominant characteristics are lower peak voltage, lower capacity, higher impedance, and higher self-discharge. The research indicates that these characteristics will have significant impacts on system design and performance, and ultimately the economics of a stationary storage system, but are generally addressable. The key success factors for a second-life system include 1) using batteries of high-quality origin, 2) designing systems for high maintainability and limited downtime, 3) incorporating a robust battery management system (BMS), and 4) effectively sorting “like for like” batteries through state-of-health estimation. Of these factors, the greatest uncertainty lies in state-of-health estimation – both the exact parameters on which used batteries should be matched and what accuracy of estimation is required to achieve that matching. Overall, research indicates that the technical know-how exists or is under development, specifically in the automotive industry. However, automotive batteries are generally subject to greater wear and tear, further exacerbating the key characteristics of used batteries. This leads to the conclusion that the proposed second-life model, using predominantly lightly-used batteries from backup storage applications (UPS) is technologically feasible.

Environmental

A lifecycle extension analysis of lithium-ion backup batteries is beyond the scope of this report, however, any business model that extends the useful life of a durable good inherently supports

waste diversion and delay of primary extraction of input materials. For a full-scale production facility of 80 MWh, this amounts to an estimated annual diversion of 1155 tonnes of hazardous waste, and 24 tonnes of lithium that need not be mined. While the connection between storage and renewables is also beyond the scope of this report, drawing on California as an example, an 80 MWh battery system supports about 493MW of renewable energy.

Appendix

APPENDIX 1: Five Forces Analysis of various offtake markets

Self-owned			
Force	Rating	Pros	Cons
Rivalry	Strong	+ Information on competitors and marketplace conditions widely available in competitive markets	- Certain markets (like PJM's frequency regulation market) have become fully saturated with high levels of energy storage, greatly reducing earning opportunities for other storage systems.
Threat of new entry	Moderate	+ High capital requirements create natural barriers to new entry	- firm also needs to meet capital requirements . Large reserves and high initial expenses are required to achieve certification for participation in energy markets.
Supplier power	Weak		- Market operators (PJM, NYISO, etc) that control access to the grid for electricity assets may not have official regulations dealing with energy storage, effectively preventing access to the market.
Buyer power	Weak	+ In competitive energy markets, power is fairly evenly distributed across a wide number of participants, including utilities, energy traders, and IPPs. + Increased penetration of renewable generation sources like wind and solar generally creates greater need for the services that energy storage can provide.	

Substitutes	Moderate	+ Energy storage has a distinct operating characteristics (response time, ramp rate, etc) that give it an advantage over most other grid assets	- Other grid assets (demand response, natural gas turbines) can provide similar services to energy storage
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Niche: Portable Power			
Force	Rating	Pros	Cons
Rivalry	Strong	+ firm could hold a unique (or sparsely-populated) position as a supplier of portable <i>batteries</i>	- A major, incumbent, mature solution already exists for the same need (portable generators). These companies are established and likely to compete to retain market share.
Threat of new entry	Strong		- Other companies (Freewire) are testing the waters for this market - Much lower barriers to entry - designing a new backup product doesn't take massive amounts of capital or complex IP
Supplier power	Weak	+ There are many potential suppliers for input components	
Buyer power	Weak	+ There are many potential buyers for completed systems - rental agencies, construction firms, individuals, etc.	
Substitutes	Strong	+ Portable batteries offer advantages that generators don't: quiet, no emissions, don't require gas to refuel.	- Most users of portable power solutions don't care too much about the advantages of batteries. They just want power.

Remanufacturing as a Service			
Force	Rating	Pros	Cons
Rivalry	Weak	+ This is a brand-new business model. Although there are individual players to address data centers' specific needs (battery disposal, backup power), there isn't one company that does both.	
Threat of new entry	Moderate		- Aside from capital investment in a remanufacturing facility, there aren't obvious barriers to entry
Supplier power	Weak	+ The only suppliers for this business model are for equipment and labor, both of which have robust, competitive markets	
Buyer power	Strong		- The data center market is relatively concentrated, which may lead to pressure on margins in the long term '- Most operating data centers don't have much need for additional backup power, creating the need to target customers who are both retiring batteries <i>and</i> building or upgrading facilities.
Substitutes	Strong		- Pre-existing diesel backup - Battery recycling companies

Developer Sales			
Force	Rating	Pros	Cons
Rivalry	Weak	+ This is a brand-new business model. Although there are individual players to address data centers' specific needs (battery disposal, backup power), there isn't one company that does both.	
Threat of new entry	Moderate	+ Exclusive deals with major data center companies could prevent other competitors from being able to reach the necessary scale for profitability	- IP doesn't play a huge role in the business, meaning there aren't as many barriers to entry
Supplier power	Weak	+ The only suppliers for this business model are for equipment and labor, both of which have robust, competitive markets	
Buyer power	Moderate	+ The developer market is fairly diverse, without a clear dominant player	- The data center market is relatively concentrated, which may lead to pressure on margins in the long term
Substitutes	Moderate to Strong	+ Currently, the price point of new batteries is still significantly above the projected all-in price of remanufactured cells	- New batteries. Price projections show that brand-new cells will continue their relatively rapid decline, putting pressure on the manufacturing process to consistently increase its efficiency

APPENDIX 2: Analysis of various sources of used lithium-ion batteries

Li-ion Source	Supplying Entity	Criteria Weight										TOTAL 100%		
		Cell Manufacturer 5%	Chemistry 15%	Form Factor 10%	Standardization 10%	Low Cycles 20%	Constant Temperature 10%	Operating Charge Window 5%	Scale of output 5%	Collection Cost 10%	Shipping distance 5%		Replacement frequency 5%	Disposal alternatives 5%
Cell Phones	Device manufacturers	4	4	2	1	3	2	5	2	3	4	2	2	2.60
Cell Phones	Consumers	4	4	2	1	3	2	5	1	3	4	3	3	2.60
Cell Phones	e-waste processors	4	4	2	1	3	2	5	4	3	4	3	2	2.85
Laptops + Tablets	Device manufacturers	4	4	2	1	3	2	5	2	3	2	2	2	2.50
Laptops + Tablets	Consumers	4	4	2	1	3	2	5	1	3	2	2	3	2.45
Laptops + Tablets	e-waste processors	4	4	2	1	3	2	5	4	3	2	3	2	2.75
Automotive	Car company	5	4	3	2	3	2	4	4	3	2	2	4	3.10
Automotive	Consumers	5	4	3	2	3	2	4	1	3	2	1	3	2.70
Power Tools	Device manufacturers	3	3	2	1	2	2	3	2	3	2	3	2	2.15
Backup Power	Data Centers	4	3	4	5	5	3	3	4	3	3	3	3	3.85
Backup Power	UPS Vendors	4	3	3	4	4	3	3	4	3	3	2	3	3.40

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