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Final Report

Technical and Economic Feasibility of Applying Used EV Batteries in Stationary Applications

A Study for the DOE Energy Storage Systems Program

Erin Cready, John Lippert, Josh Pihl, Irwin Weinstock, Phillip Symons, and Rudolph G. Jungst

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Abstract

The technical and economic feasibility of applying used electric vehicle (EV) batteries in stationary applications was evaluated in this study. In addition to identifying possible barriers to EV battery reuse, steps needed to prepare the used EV batteries for a second application were also considered. Costs of acquiring, testing, and reconfiguring the used EV batteries were estimated. Eight potential stationary applications were identified and described in terms of power, energy, and duty cycle requirements. Costs for assembly and operation of battery energy storage systems to meet the requirements of these stationary applications were also estimated by extrapolating available data on existing systems. The calculated life cycle cost of a battery energy storage system designed for each application was then compared to the expected economic benefit to determine the economic feasibility. Four of the eight applications were found to be at least possible candidates for economically viable reuse of EV batteries. These were transmission support, light commercial load following, residential load following, and distributed node telecommunications backup power. There were no major technical barriers found, however further study is recommended to better characterize the performance and life of used EV batteries before design and testing of prototype battery systems.

Preface

This study was funded by the U.S. Department of Energy through the Energy Storage Systems Program. The DOE Program Manager is Dr. Imre Gyuk. Sentech, Inc. carried out the work under Contract 20605 with Sandia National Laboratories. The Sandia technical contact is Rudolph G. Jungst, Long-Life Power Sources Department 2525. Sentech, Inc. contributors were Erin Cready, John Lippert, Josh Pihl, and Irwin Weinstock. Phillip Symons of Electrochemical Engineering Consultants, Inc. developed information regarding the potential stationary use applications.

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Abbreviations and Acronyms

Units of measure

A	amperes (amps)
Ah	amp-hours
V	volts
W	watts
kW	kilowatts
MW	megawatts
Wh	watt-hours
KWh	kilowatt-hours
MWh	megawatt-hours
Hz	hertz (cycles/second)
kg	kilogram
ft.	foot
sec	seconds
yr	year

Vehicle and battery terminology

EV	electric vehicle
HEV	hybrid electric vehicle
CEV	city electric vehicle
NEV	neighborhood electric vehicle
ZEV	zero emission vehicle
FLA	flooded lead-acid
VRLA	valve-regulated lead-acid
NiCd	nickel/cadmium
Ni/MH	nickel/metal hydride
Li-ion	lithium-ion
LMPB	lithium metal-polymer
OCV	open-circuit voltage
SOC	state of charge
DOD	depth of discharge
DST	dynamic stress test
AC	alternating current
DC	direct current
OEM	original equipment manufacturer
O&M	operating and maintenance
BOS	balance of system
HVAC	heating, ventilation, and air conditioning
UPS	uninterruptible power system

Organizations

DOE	Department of Energy
SNL	Sandia National Laboratories
ANL	Argonne National Laboratory
USABC	United States Advanced Battery Consortium
CARB	California Air Resources Board
EPRI	Electric Power Research Institute
PG&E	Pacific Gas & Electric
OBC	Ovonic Battery Company
PREPA	Puerto Rico Electric Power Authority

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1. EXECUTIVE SUMMARY

This study evaluated the technical and economic feasibility of applying used electric vehicle (EV) batteries in stationary applications. Such a second use for a "spent" EV battery could possibly give EV owners an opportunity to reclaim a portion of the purchase price of the battery, effectively reducing its cost. This second use scenario could also make lower cost advanced batteries available to the stationary energy storage market and accelerate the establishment of a sustainable market for advanced EV battery technologies.

Overall, the concept of EV battery reuse appears to be a viable one. The study team did not come across any insurmountable technical barriers to the implementation of a second use scheme. In fact, during the course of the study it was learned that there is considerable commercialization of used and reconditioned batteries. There are established markets for used, off-lease forklift batteries, reconditioned automotive starting, lighting, and ignition (SLI) batteries, and reconditioned lithium-ion batteries for laptop computers. Used nickel/metal hydride (Ni/MH) batteries from bench test and/or prototype EVs are being used in a solar program in Mexico. A study by Argonne National Laboratory examined the second use of Ni/MH EV batteries and showed that modules tested to end-of-life on the United States Advanced Battery Consortium (USABC) Dynamic Stress Test (DST) profile could provide performance competitive with new lead-acid batteries in stationary energy storage applications.

While there are no technical "show stoppers," there are some issues that will have to be dealt with before an EV battery second use scheme can be implemented. Several unresolved issues and potential barriers to the implementation of a second use scheme were identified during the development of the hypothetical reuse process. First, non-standardized battery modules and varying patterns of vehicle use could make assembly of matched strings of modules with similar capacities difficult. Second, the mechanism by which the value from the second use makes its way back to the EV buyer needs to be identified. Third, warranty terms and costs will be difficult to determine given the uncertainty in the performance and life of the used EV batteries. Finally, the perceived value of used batteries relative to new batteries in the consumer's mind will have to be addressed to ensure widespread acceptance of used EV batteries.

In addition to identifying potential barriers to EV battery reuse, this study considered the steps necessary to prepare used EV batteries for a second application. EV battery modules will have to be collected from vehicle dealerships or service centers, inspected to ensure physical and electrical integrity, tested to determine performance, and reconfigured into battery packs suitable for stationary applications.

The study also considered stationary applications where used EV batteries could be applied. Eight potential stationary applications for used EV batteries were identified: transmission support, area regulation & spinning reserve, load leveling/energy arbitrage/transmission deferral, renewables firming, power reliability & peak shaving, light commercial load following, distributed node telecommunications backup power, and residential load following. The power, energy, and duty cycles required from batteries for these applications were identified. Two figures of merit were developed to quantify the economic benefits of battery energy storage in each application. The low value was estimated from the expected revenues or savings generated by a battery system operating in the application. The high value was typically extrapolated from what people have paid for similar systems, representing an upper limit to the allowable cost for the system.

An economic analysis was performed to determine the feasibility of utilizing spent EV batteries in the eight potential stationary applications. The costs of acquiring, testing, and reconfiguring used EV batteries were estimated. For a typical 12V, 100 Ah Ni/MH battery module, the cost of testing and repackaging the module into a stationary battery pack came to about $64/kWh. Converting the used EV batteries to stationary applications is a labor-intensive process, with labor costs and overhead representing over half of the conversion costs. If the buy-down for a new EV battery is around $75/kWh based on the manufacturer's rated capacity, the cost of the used battery to the second application comes to about $81/kWh at its reduced second-use rating. Adding this figure to the testing cost gives an estimated selling price for Ni/MH battery packs of $145/kWh. The results for other battery chemistries and module configurations would be similar.

Costs for the assembly and operation of battery energy storage systems to meet the stationary applications were also estimated by extrapolating from data available on existing systems. The projected battery life, cost of the converted battery modules, balance of system costs, and system operating expenses were used to calculate the life cycle costs of a battery energy storage system designed to meet the requirements of each application. These life cycle costs were then compared to the economic benefits derived from the applications to determine the economic feasibility of applying used EV batteries for each application. The exception to this approach was distributed node telecommunications backup power, for which the costs of the used EV batteries alone, rather than a complete energy storage system, were compared directly to batteries currently used in the application.

Based on the results of this analysis, the applications were categorized to indicate their economic feasibility. If the cost of the system was less than the low benefit estimate for the application, then the application was categorized as favorable. If the system cost was higher than the upper benefit estimate, the application was classified as unlikely. If the cost of the system fell between the two economic benefit estimates, the application was categorized as possible. It should be noted that for many of the systems, the battery costs were not the largest component of the life cycle costs. Battery costs over the life of the system ranged from 7% to 65% of the total system costs, and were the primary cost driver for only three of the applications considered in this study.

Four of the eight applications were identified as being possible candidates for economically viable reuse of EV batteries. Transmission support was categorized as being a possible candidate for EV battery reuse, even at relatively high buy-down values. However, the difficulties involved in assembling a system large enough to meet the needs of this application may prove to be a major hurdle to its implementation. Light commercial load following was also identified as a possible application for reuse. Residential load following was the only application identified as a favorable candidate for reuse. Unfortunately, the market for this application is not well defined since it depends on the growth of distributed generation for residential use.

Since the economic analysis for distributed node telecommunications backup power compared the cost of used EV batteries to that of competing battery technologies currently used in this application, the results are highly dependent on the relative lives of the batteries under consideration. Specifically, this application was classified as possible only when the used EV battery could provide a longer lifetime than competing technologies. It is unclear if this is likely to be the case since how long batteries last in this application is primarily determined by calendar life and not cycle life. However, the size of the market for this application taken with the possibility for an economically feasible outlet for used batteries warrants further investigation into distributed node telecom as a candidate for reuse of EV batteries.

The study team recommends that additional testing be performed on used EV batteries pulled from real-world vehicles to better characterize their performance in potential stationary applications. The team further recommends that prototype battery systems based on used EV battery modules be designed and tested for each of the four promising applications identified in the economic analysis.

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2. INTRODUCTION

2.1. Objective of this Study

The high cost of batteries is often considered to be a major factor limiting the sale of electric vehicles (EVs). A considerable number of R&D dollars have been and are being spent by automakers and battery manufacturers around the world to reduce the cost of batteries in order to stimulate the sale of EVs. This study examined another opportunity: the potential for recovering some of the original value of a battery that has served its useful life in an electric or hybrid-electric vehicle, but which is still suitable for another application. The premise is that the battery could be refurbished, resold, and reused for another application, and some of the initial cost recovered through the sale of the battery into this second application.

An EV battery is considered to have reached its *end-of-life* when it can no longer provide 80% of the energy (needed for vehicle range) or 80% of the peak power (needed for acceleration) of a new battery. The *end-of-life* criterion for HEV batteries is a 23% loss in power. A battery that cannot meet these performance criteria, however, may still be capable of satisfying the energy and power requirements of a less demanding application. For example, four alkaline AA cells can provide the power needed to operate a portable CD player for several hours and, when the player no longer spins the disk, the batteries can be removed and put into a clock or a TV/VCR remote where they may provide up to several more months of service. In this case, there was still energy remaining in the batteries when it could no longer spin the CD, but it could not be withdrawn at the relatively high power demanded by the CD spinner. It was, however, available at the lower power needed by the clock or TV/VCR remote.

This technique of finding second uses for "spent" primary batteries may serve as a template for a way to extend the useful life of the advanced secondary batteries being developed for use in electric vehicles. For example, an EV battery that is no longer capable of delivering the power needed to accelerate up a freeway ramp may still provide many useful charge-discharge cycles in a less demanding, lower power application.

Stationary battery applications often do not have the severe weight and volume constraints of the EV application and this can translate into lower energy and power requirements (on a unit weight or volume basis) for batteries. Since used EV batteries are still expected to be capable of storing and delivering substantial energy, it is possible that they might satisfy the requirements of these applications. Finding such a second use for a "spent" EV battery may give the EV owner an opportunity to reclaim a portion of the purchase price of the battery, effectively reducing its cost. This second use scenario would also make lower cost advanced batteries available to the stationary energy storage market and accelerate the establishment of a sustainable market for advanced EV battery technologies.

The objective of this study was to determine the technical and economic feasibility of applying used EV batteries in stationary energy storage applications. The study identified several technical issues that need to be resolved before this reuse concept can become commonplace. The issues studied include:

1. What is the performance and projected remaining useful life of a battery removed from an EV?

2. What are the potential stationary energy storage applications and what are their performance, life, and cost criteria?
3. Are used EV batteries capable of meeting these requirements?
4. What needs to done to a used EV battery to prepare it for use in a stationary application?
5. Can used EV batteries be cost-competitive with other battery options for these stationary applications?

2.2. Definitions

Before continuing with the details of the study, it is necessary to define several terms used throughout this report to refer to the various components that make up a battery to ensure that the reader is clear on what items are being described.

A battery cell is a group of electrodes in a single container exhibiting the fundamental voltage of the battery chemistry. Battery cells are typically 1-4 volts

A battery module is a group of cells mechanically attached to each other and electrically connected in series/parallel arrangements to form the building block of the battery pack. In EVs, battery modules are typically 10-30 volts.

A battery pack consists of a number of battery modules in a single container connected in series/parallel arrangements to achieve the desired voltage and capacity. The battery pack also contains the electronics and thermal management system required to operate the battery. In EVs, the battery pack typically consists of 10-40 battery modules and usually operates in the 100-350 volt range.

The battery or battery system may be a single battery pack (as in EVs), or it may be a number of battery packs electrically connected together to meet the requirements of an application.

2.3. Status of EV Technologies and Markets

For the purposes of this study, electric vehicles sold in the U.S. (including those that have gone out of production), as well as some demonstration and prototype vehicles, were broken into four broad categories. Their descriptions are as follows:

- **EV** – Electric Vehicle: full size passenger automobile with a battery-based electric drive train.
- **CEV** – City Electric Vehicle: small (short wheelbase) passenger automobile with a battery-based electric drive train designed for urban commuting; top speed approximately 60 mph.
- **NEV** – Neighborhood Electric Vehicle: small, low speed (<25 mph) passenger automobile with a battery-based electric drive train designed for short trips.
- **HEV** – Hybrid Electric Vehicle: full size passenger vehicle with an internal combustion engine coupled with an electric motor and battery.

Over the past few years, sales of full-sized EVs in the U.S. amounted to about 4,500 vehicles. Several automakers have demonstration models of CEVs and Ford offers the TH!NK City vehicle for sale in Europe and plans to offer it for sale in the U.S. in the fall of 2002. Several car makers have also demonstrated prototype NEVs, and DaimlerChrysler has sold about 6,200 of its

GEM. In addition, more than 25,000 Honda Insight/Toyota Prius HEVs were sold in the United States through the end of 2001.

Each of these classes of vehicles has different power and energy requirements for the battery. For example, EVs typically have about 30 kWh of energy storage, CEVs and NEVs require about 10 kWh, and HEVs typically have a battery with around 1 kWh of storage.

In addition to considering different types of vehicles, this summary also covers systems based on each of the major battery chemistries used in electric vehicles:

- Ni/MH – Nickel/Metal Hydride
- Li-ion – Lithium-ion
- Ni/Cd – Nickel/Cadmium
- LMPB – Lithium Metal Polymer
- VRLA – Valve Regulated Lead-Acid
- FLA – Flooded Lead-Acid.

Table 1 presents broad descriptions of typical batteries for EVs and HEVs, organized by chemistry and vehicle type; similar data for CEVs and NEVs is shown in Table 2. These tables provide a rough idea of the range of batteries that will be available for potential use in an EV battery second use program. While it is not an exhaustive list, it does contain the specifications of the battery systems installed in most EV's that have been sold in the U.S. (including those that have gone out of production), as well as some demonstration and prototype vehicles. The list does not cover most of the conversion vehicles currently available. The information used here was obtained from the Electric Vehicle Association of the Americas website, the Department of Energy's Office of Transportation Technologies Alternative Fuels Database, vehicle manufacturers, battery manufacturers, and the "Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost and Availability" report submitted by the Year 2000 Battery Technology Advisory Panel to the California Air Resources Board. More detailed tables are available in Appendix B.

2.4. Present Markets for Used Batteries

A literature search related to current markets for used batteries was conducted as part of this study. Originally, the search was to focus solely on EV and HEV batteries, but since few EVs and/or HEVs have been sold to-date, and far fewer have had their batteries reach end of life, the scope of the search was expanded to include the reuse of batteries taken from non-EV/HEV applications. It was assumed that knowledge gained on existing secondary markets for other batteries would be useful to determine the feasibility of establishing a second market for spent EV and HEV batteries.

The results of the literature search demonstrate that there is considerable commercialization of used and reconditioned batteries, including batteries from EVs:

- Amateur radio emergency operators acquire used gel cell lead-acid batteries removed by hospitals from medical instruments on a scheduled basis.
- There is established commerce in used off-lease forklift batteries, reconditioned automotive starting, lighting, and ignition (SLI) batteries, and reconditioned lithium-ion

batteries for laptop computers, as well as batteries with various chemistries for energy storage in small renewable energy systems.

- AC Propulsion, a small-volume electric vehicle manufacturer, is implementing a successful secondary market for spent Optima® deep-cycle spiral-wound recombinant lead-acid batteries.
- Energy Conversion Devices, a manufacturer of both solar photovoltaic modules and nickel/metal hydride (Ni/MH) batteries, is participating in a solar program in Mexico, which incorporates used Ni/MH EV batteries taken from EV bench tests and prototype EVs.

Details of the literature search and on the used battery markets may be found in the Interim Task 1 Report, issued by SENTECH, Inc., included as Appendix A in this report.

Table 1. Battery module characteristics for typical HEV and EV batteries.

Vehicle Type	HEV			EV			
Chemistry	Ni/MH	Li-ion[2]	LMPB[3]	Ni/MH	Li-ion[2]	VRLA	LMPB[3]
Battery Voltage (V)	144 – 274	346		288 - 343	360	312	260
Battery Capacity (Ah)	6.5	3.6		77 - 95	90	60 - 85	119
Battery Capacity (kWh)	0.94 – 1.8	1.2		26 - 32	32	19 - 27	31
Cells/battery	120 – 228	96		240 - 286	96	-	-
Modules/Battery	20 – 38	2		24 - 28	12	26 - 39	13
Module Voltage (V)	7.2	173	50	12 - 13.2	30	8 - 12	20
Module Capacity (Ah)	6.5	3.6	14	77 - 95	90	60 - 85	119
Module Capacity (kWh)	0.047	0.62	0.7	1.0 - 1.1	2.7	0.68 - 0.72	2.38
Module Output Power (kW)[4]	~ 0.9		16	3.2 - 4	12.5	4 - 5	4.9
Motor Output (kW)	10 – 33	17		49 - 102	62	67 - 102	-
Battery Manufacturers	PEVE[1]	Shin Kobe SAFT	Avestor	PEVE Texaco Ovonic	Shin Kobe SAFT	Panasonic East Penn	Avestor
Vehicles	Honda Insight Toyota Prius	Nissan Tino Dodge Durango Dodge ESX3	None	Chevy S-10 Ford Ranger GM EV-1 Honda EV Plus Toyota Rav4 Solectria Force	Nissan Altra	Baker/Ford USPS Ford Ranger Chevy S-10 GM EV-1 Solectria Force	None

Notes:

[1] PEVE – Panasonic EV Energy, a Matsushita company.

[2] The lithium ion characteristics listed here are for Shin Kobe EV and HEV modules. Module level data were not available for SAFT Li-ion batteries since none of the vehicles using SAFT Li-ion batteries are in production yet.

[3] The LMPB characteristics listed here are for prototype modules developed by Avestor, and some of the numbers are extrapolations from cell-level performance. Avestor has not yet mass-produced any LMPB battery packs, and there are no automakers with plans at the current time to use LMPB systems in a production vehicle, although they have been demonstrated in the Ford TH!NK City and the GM Precept.

[4] Module Output Power was estimated using the specific power for the module and an estimated module mass calculated from the total battery pack mass and the number of modules

Table 2. Battery module characteristics for typical CEV and NEV batteries.

Vehicle Type	CEV			NEV
Chemistry	Ni/MH	Li-ion	Ni/Cd	FLA
Battery Voltage (V)	288	120	114	72
Battery Capacity (Ah)	28	90	100	130
Battery Capacity (kWh)	8.1	11	11	9.4
Cells/battery	240	32	-	-
Modules/Battery	24	4	19	6
Module Voltage (V)	12	30	6	12
Module Capacity (Ah)	28	90	100	130
Module Capacity (kWh)	0.34	2.7	0.6	1.6
Module Output Power (kW)	1.1	12.5	1.6	
Motor Output (kW)	19	24	27	5 - 25
Battery Manufacturers	PEVE	Shin Kobe SAFT	SAFT	Trojan
Vehicles	Honda City Pal Toyota ecom	Nissan Hypermini	TH!NK City Solectria Force	Dynasty IT GEM E825 Solectria Flash TH!NK Neighbor

2.5. ANL USABC 2nd Use Study

Between September 1996 and August 1997 Argonne National Laboratory conducted a study for the United States Advanced Battery Consortium (USABC) that examined the second use of Ni/MH EV batteries[1]. Eight Ovonic Battery Company (OBC) Ni/MH modules that had completed more than 500 Dynamic Stress Test (DST) cycles simulating EV lifetime usage were tested to determine their performance in non-EV applications. Test results on the used EV batteries were compared to lead-acid battery test data or warranties supplied on lead-acid batteries by the manufacturer for the specific applications on which they were tested. The approach and results of this work are summarized below.

After completing DST testing, each of the eight modules was characterized according to standard USABC procedures to determine remaining capacity and power capability. Based on these tests, the Ni/MH batteries were derated to either 30 Wh/kg or 45 Wh/kg, representing standard production lead-acid units and advanced technology lead-acid batteries, respectively. The Ni/MH modules were characterized again at their new capacity rating and then placed on life test under one of four test regimes: 1) utility load following; 2) utility frequency regulation and spinning reserve; 3) uninterruptible power sources (UPS) for stand-by power and telecommunications applications; and 4) accelerated life testing.

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[1] N. Pinsky (USABC Program Manager) et al., *Electric Vehicle Battery 2nd Use Study*, Argonne, IL: Argonne National Laboratory, Electrochemical Technology Program, (May 21, 1998), 80 pages plus Appendix.

2.5.1. *Utility load following*

Two modules, one at each rating, were tested for utility load following based a the test profile developed by Pacific Gas & Electric (PG&E) to characterize the PM250, a 250 kW, 167 kWh modular power unit containing 384 lead-acid batteries. The PG&E test applied repeated 3 hour sine shaped discharges with an 86.1 kW peak designed to remove the maximum storage capacity of the battery (167 kWh). Each discharge was followed by a charge to 100% SOC. Every ten discharges, the maximum storage capacity was removed in 1 hour at a 167 kW constant power rate, and the battery was recharged to 100% SOC. This 11 discharge cycle was repeated until the battery string voltage dropped below the defined 0% SOC point before the maximum capacity had been discharged. ANL scaled the power levels for the PG&E tests down to a single Ni/MH module to perform their tests. A plot illustrating the power profile used in testing the PM250 is shown in Figure 1.

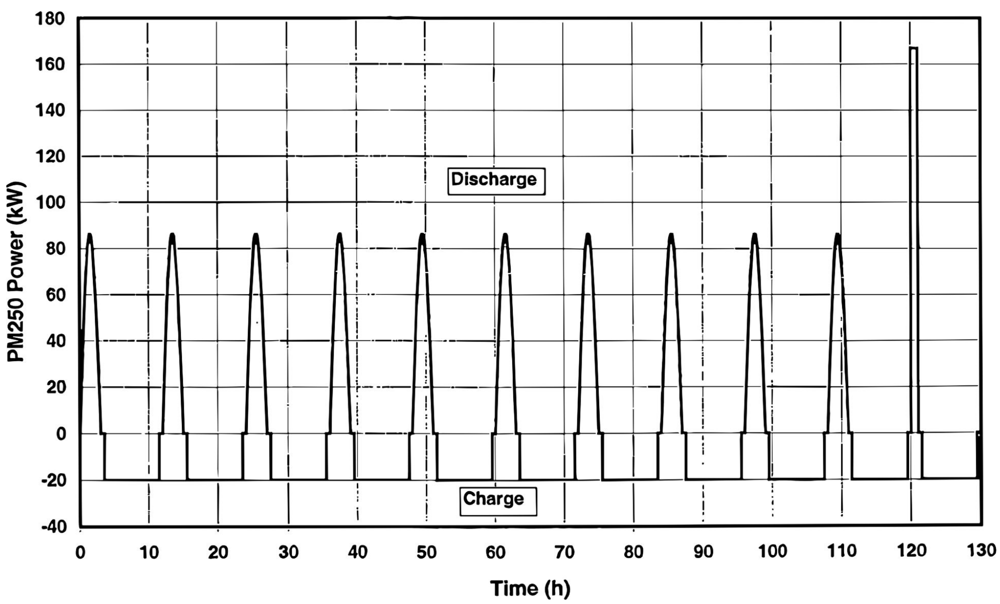

Figure 1. Power profile for the load follow test conducted by PG&E for the PM250 power module

The PM250 system was only able to complete 33 of the sine wave discharges, falling well short of the expected 150 cycles. If other discharges performed by the PM250 battery during testing are included in the total, the battery completed 72 deep discharge cycles before reaching end-of-life. The goal for the Ni/MH modules was to achieve 250 sinewave discharges before reaching the minimum voltage cutoff signifying end-of-life. The 30 Wh/kg derated module completed all 250 planned sinewave discharges and a total of 294 deep discharges before testing was terminated. It still had not reached end-of-life at this point. The 45 Wh/kg module completed 133 sinewave discharges and a total of 162 deep discharge cycles before reaching end-of-life.

2.5.2. *Frequency regulation & spinning reserve*

Two modules were placed on a test profile designed to simulate frequency regulation and spinning reserve operations. This Utility Energy Storage (UES) profile, developed by Sandia National Laboratories (SNL), is based on the actual loads encountered by the Puerto Rico Electric Power Authority (PREPA) battery energy storage facility. Each UES cycle contains three 160 minute long frequency regulation sessions consisting of 32 asymmetrically arranged five minute segments at three different power levels. Each of these sessions is followed by a charge period. At the end of the third charge period, a spinning reserve discharge is performed. This discharge consists of a 15-minute constant power discharge followed by a 15-minute ramp down to zero power. Finally, the battery is recharged to 100% SOC before starting the next UES cycle. As with the PM250 tests, the power levels for this test profile were scaled down to the level of a Ni/MH module. The UES test cycles were performed on one Ni/MH module rated at 30 Wh/kg and one at 45 Wh/kg. The UES test cycle load profiles are illustrated in Figure 2 and Figure 3.

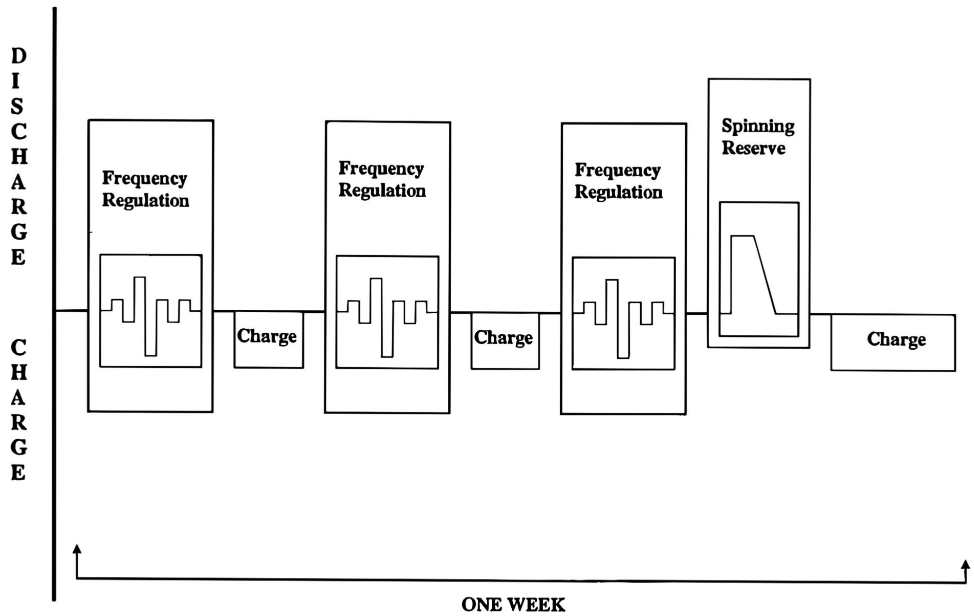

Figure 2. Utility Energy Storage (UES) cycle developed by SNL

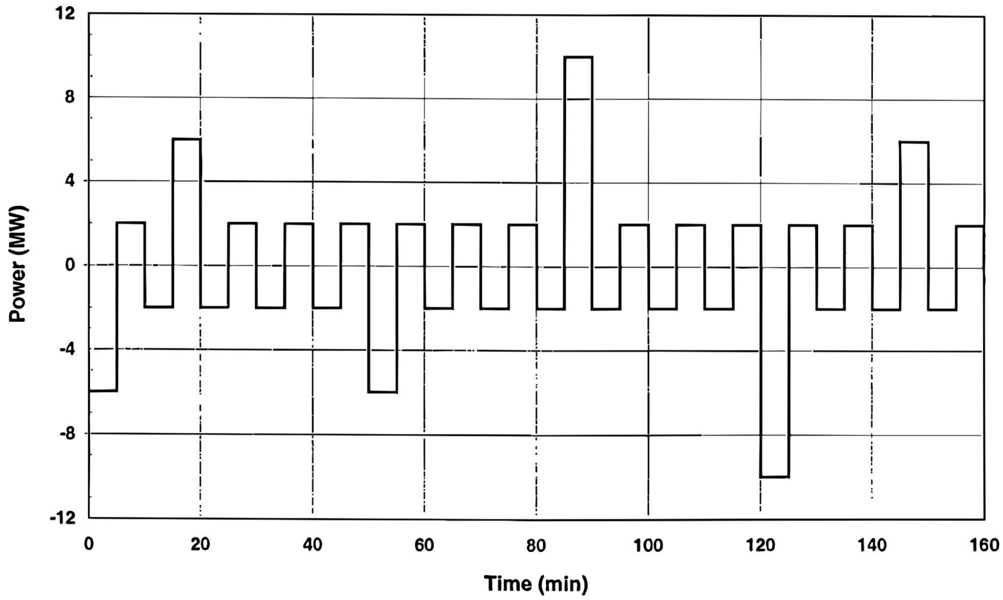

Figure 3. Frequency regulation subcycle of UES test profile

Both OBC modules completed all 16 of the planned UES cycles without reaching the minimum voltage limit. The 45 Wh/kg derated module showed a capacity loss of about 1%, and the capacity loss in the 30 Wh/kg derated module was negligible. This compared favorably with the twelve C&D Technologies lead-acid batteries subjected to similar testing at SNL, which showed 8.5% capacity loss after 13 UES cycles.

2.5.3. Uninterruptible power source and telecommunications applications

Three of the Ni/MH modules, all rated at 45 Wh/kg, were tested under a series of constant current discharge regimes to prove that they could meet or exceed the warranty conditions for an Exide flooded lead-acid battery. Exide's warranty specified certain cycle lives under eight different discharge conditions. Each module was expected to perform at least two of these warranty conditions in succession. The tests and their results are summarized below.

Table 3. Exide UPS warranty conditions and ANL test results

Warranty condition	Module	Discharge rate	Discharge time	Warranted cycles	Cycles completed
1	A	C	1 hr	80	63 (80)
2	A	4C	1.5 min	210	100
3	A	C/8	8 hr	40	25
4	B	4C	4 - 15 min	120	120
5	B	C/4	4 hr	60	54
6	C	4C	30 sec	2700	2700
7	C	2C	30 min	100	67
8	-	4C	45 sec	960	-

The tests on these modules were plagued by uncertain charge procedures, erroneous equipment settings, and unexpected failures. There were a number of changes made to the original test plan, particularly regarding which module would perform what tests and the order of the tests performed, to try to get around these difficulties. Module A reached end of life at cycle 63 of the C rate, 100% discharges, but due to an improper setting the test was allowed to continue to the full 80 cycles at an end of discharge voltage of less than the limit selected for the test. Ignoring this deviation, each of the modules completed one of the Exide warranty conditions before reaching end-of-life.

Of the other five warranty conditions, four were attempted but not met, and the fifth was never attempted. The study authors also note that the warranties for VRLAs, obtained after test protocols had already been developed, warrant somewhat higher cycle lives than those for flooded batteries.

2.5.4. Accelerated calendar life test

One Ni/MH module was placed on a 14 V float charge in an oven at 40°C to accelerate corrosion reactions and possible failure mechanisms. The battery was left at elevated temperature for a total of 144 days, with reference performance tests performed at 96 days and at the end of the test. Over the test period, the C/3 capacity decayed by 13.2% and the peak power degraded by 20% from the start of the test. There was no comparison made between the performance of this module and results from tests of other batteries.

2.5.5. Conclusions

Overall, the test results showed that used OBC Ni/MH EV modules perform at least as well as new lead-acid batteries in stationary energy storage applications. In some instances, the used EV modules appeared capable of performing the same functions as new lead-acid batteries over longer lifetimes. The study demonstrated that reusing Ni/MH EV modules in secondary applications could be technically feasible from a battery performance perspective.

3. A PROCESS FOR RE-APPLYING USED EV BATTERIES IN STATIONARY APPLICATIONS

3.1. Overview

This section discusses the process by which used batteries taken from EVs and/or HEVs might be selected, tested, and refurbished for a second use in a stationary application. The scenario assumes that EV dealers/service centers would dispose of used EV batteries at a refurbishing facility, where the used batteries would be screened, sorted, tested, and finally reconfigured for their second use in stationary applications.

3.2. Acquiring Used EV Batteries

Electric and/or hybrid electric vehicles will most likely be serviced by the same dealerships that sell them. A battery may be removed from an EV for a number of reasons – the vehicle owner complains of inadequate performance, onboard diagnostics indicate that the battery is not performing to specifications, or a predefined mileage or time limit (*e.g.*, 6 years or 60,000 miles) has been reached.

If vehicle is brought to the dealership because it is performing below owner expectations, the service department will probably perform some diagnostic tests to determine whether the fault is caused by a limited number of defective modules or is an overall battery problem. In those cases where there are only a limited number of below-par modules, these may be repaired or replaced and the balance of the battery would be reinstalled in the vehicle.

There are a number of defects that could reduce the performance from a particular module, and the nature of the defect will determine whether a module is repaired or replaced. A module exhibiting high resistance due to corroded or loose module and cell interconnections could probably be repaired and reinstalled. Modules exhibiting leaks, high internal impedance, or an internal short circuit would most likely be replaced. Such modules would probably not be good candidates for reuse.

For an EV battery pack that is approaching or has exceeded its expected life in the vehicle, the dealer service department will probably replace the entire pack. Automobile OEM representatives have indicated that, in such a case, the battery modules would be removed and replaced while the remaining components of the battery pack (interconnects, cooling systems, electronics, and the tray itself) would be reused in the vehicle. The dealerships would thus have a number of used battery modules for disposal – either as scrap or as candidates for installation in a stationary application.

The batteries in HEVs, on the other hand, will be part of an integrated system made up of the electrochemical cells, the thermal management system, and the other components needed to manage the battery in the vehicle environment. When an HEV battery fails prematurely or achieves its expected lifetime in the vehicle, this entire integrated unit will be replaced. It was determined during the course of this analysis that the labor required to disassemble this integrated unit, sort and cull the cells, and reassemble them into modules of reasonable size would make the cost of the used batteries prohibitively expensive. As a consequence, batteries that fail prematurely due to the failure of individual cells or other hardware problems will probably not be viable candidates for second use.

Likewise, HEV batteries that have met their expected lifetime of 15 years will probably not be good candidates for use in a second application. The perceived value of a 15-year-old battery will probably limit the amount of money that people will be willing to pay for it. Based on our estimates, it is unlikely that such batteries would command a high enough price to accommodate the costs of the refurbishing process. Thus, HEV batteries were not included in the detailed economic analysis performed for this report.

3.3. Testing Used EV Batteries

Used EV battery modules, after arrival at a refurbishing facility, will be visually examined to separate out modules with obvious physical damage, leaks, or other signs of abuse. The initial inspection will also include determination of the module's manufacturer specifications and age from labels or bar codes. Voltage and resistance measurements will be performed to identify modules that have failed (due to short circuits or dried-out separators, for example). Physically sound modules that have not surpassed their calendar lives will then be subjected to limited cycle testing to determine their capacity and their power capability, and to make some prediction of their expected life in the second application.

The test regime envisioned is based on the type of characterization tests performed on newly manufactured EV modules, using the USABC Reference Performance Test[2] sequence, and in conversations with EV battery manufacturers. The sequence includes

1. Establish the module capacity via four charge-discharge cycles, charging per the manufacturer's recommended profile and discharging at C/3 (based on manufacturer's original rating) to 100% of capacity.
2. Establish the power capability by recharging, discharging at C/3 to 50% DOD, and determining the sustained (30 sec) power capability at 2/3 of the module's OCV.
3. Sort modules by capacity, power capability, and calendar age for later assembly into packs for use in stationary applications.

The stabilized capacity after the four C/3 cycles may be used to predict the expected life in the second application. Figure 4 shows a hypothetical plot of capacity vs. cycle number data that might be gathered by a manufacturer of EV battery modules as being representative of the expected cycle life of modules discharged at a standard rate, say C/3. By superimposing the capacity data collected on the charge-discharge cycles after EV end-of-life, it is possible to determine where on this standard life curve the used EV modules lie and, therefore, what the expected remaining life is.

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[2] USABC Electric Vehicle Batteries Test Procedures Manual, Revision 2, January 1996.

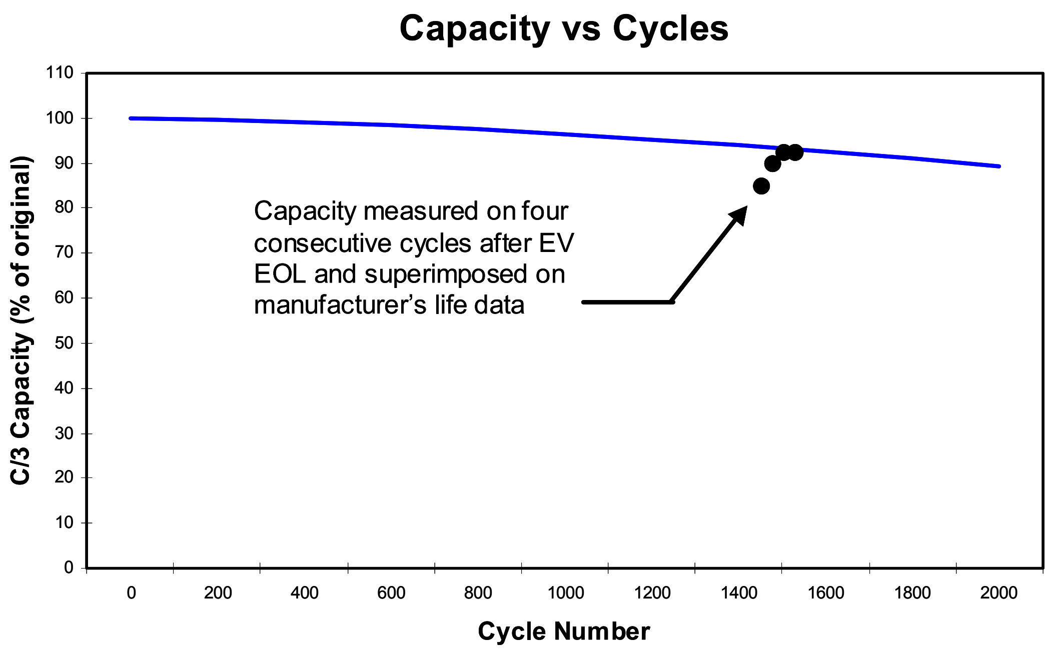

Figure 4. Conceptual illustration of future life prediction

3.4. Reconfiguring Used EV Batteries for Stationary Applications

A canvass of the stationary applications considered in this study shows a wide range in power and energy requirements. Small commercial systems, for example, are likely to be in the 25 kW, 100 kWh range, while utility systems may require up to 100 MW of power and tens of megawatt-hours of storage. Moreover, many of the applications are likely to be unique, requiring a battery configuration unlike any other. The larger systems will be equivalent to more than 100 full EV packs, complicating shipping and handling if fully assembled at the refurbishing facility. On the other hand, assembling thousands of individual battery modules together at the application site could result in high installation costs.

As a consequence, it is likely that the used EV modules will be assembled at the refurbishing facility into battery packs that are small enough for convenient handling, but large enough to reduce installation costs on larger systems. A survey of the applications considered for this study indicates that 25 kWh is a convenient building block to meet the smaller applications (except for small household systems, which could use individual modules). It is possible that used EV battery modules could be assembled into much larger units (for example, skid mounted shipping containers), particularly for the larger applications. However, it is likely that the pack assembly costs on a per module basis would be of similar magnitude for a wide range of pack sizes. The analysis performed here focused on 25 kWh units that could meet the smaller commercial applications as sort of a "placeholder" to estimate pack assembly costs. This size is similar to EV battery packs, allowing for estimation of materials and assembly costs by analogy.

The hypothetical stationary battery pack, or "StatPack," designed for this analysis would contain 21 12V, 100Ah EV modules. These could be arranged into three rows of seven side-by-side modules to create a battery pack with a convenient size. Taking into account space requirements and additional weight for cooling systems and electronics, each StatPack would be roughly 4' wide x 4’ long x 1’ high and weigh around 1000 kg. This size is about the same as a standard shipping pallet, and the weight is small enough to allow handling with forklifts or other commonly used equipment. The modules would probably be connected in series, generating 252 V. Various battery chemistries or module characteristics could lead to slightly different StatPack configurations.

StatPacks would be fabricated from modules that have been fully characterized at the refurbishing facility. The modules in a StatPack would be matched on the basis of cycle tests so that they all have similar capacity and power capability. The StatPacks would contain all the necessary components for thermal and electrical management of the batteries, including fans or coolant channels, module interconnects, sensors, and electronics. After fabrication, the StatPacks would be stored at the refurbishing facility and eventually sold to whomever would assemble and integrate the battery energy storage systems.

3.5. Summary of Refurbishing Process

The complete process for converting used EV batteries to stationary applications is illustrated in Figure 5.

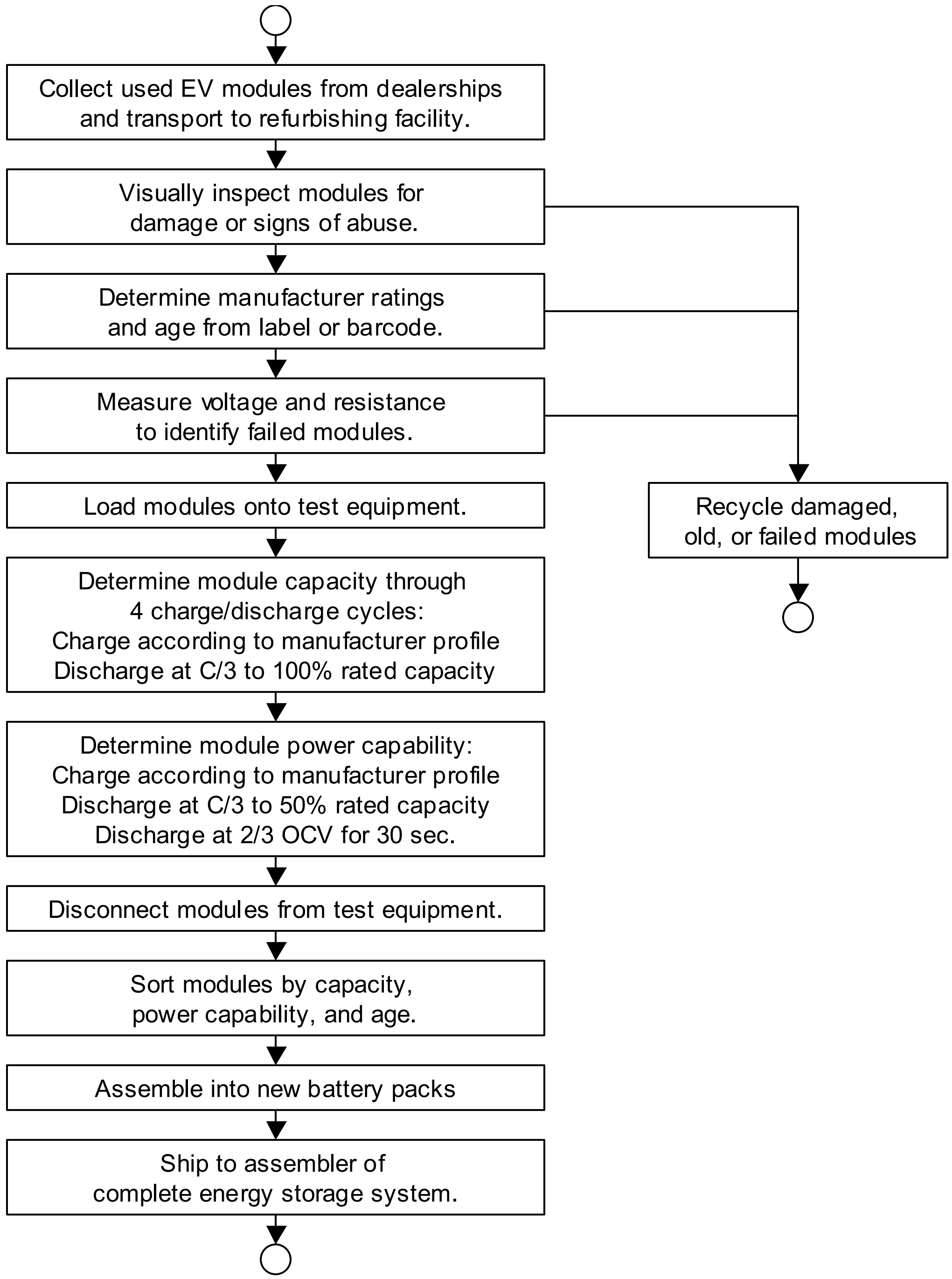

Figure 5. Battery conversion process

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4. APPLICATIONS

A total of eight stationary applications of batteries were analyzed for this study and considered in the economic feasibility analysis. This chapter describes the requirements, benefits, and economic values of each of the applications considered. Most of the application requirements, in particular those listed for the utility scale applications and for power reliability/peak shaving, are based on updates or projections from the "Opportunities Analysis" report developed by Sandia National Laboratories.[3] The requirements for the remaining applications were estimated by the study team.

Two values are listed for the economic benefits of each application. For most of the applications, the lower value is a projection of the typical savings or added revenue derived by the owner of the battery system from its operation. This value is an estimation of what the battery system might be worth to potential users, and hence represents the most somebody might be willing to pay to purchase such a system if they expect to obtain a profit. The second, higher value reflects what people have paid for similar systems currently or formerly in operation. This value gives an idea of the allowable system cost for installation in particularly high value situations or for early adopters of the technology.

Three of the applications are exceptions to these values: light commercial and residential load following and distributed node telecommunications standby power. For the two load following applications, the high and low values were estimated by the study team based on projected benefits derived from operation of such systems. The analysis for distributed node telecom standby power was different from the other applications in that only the batteries were considered, not an entire energy storage system. The high and low benefit values were determined from the price range for lead-acid batteries, the technology currently used to meet the needs of this market.

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[3] P. Butler, *Battery Energy Storage for Utility Applications: Phase I – Opportunities Analysis*, Sandia National Laboratories Report SAND94-2605 (10/1994).

4.1. Transmission support

Application Requirements	
Typical power rating	100 MW
Discharge time	10 sec (up to 5 pulses in sequence during discharge time)
Energy delivery	Up to 100 MWs per pulse
Frequency of use	1/month
Low benefit estimate [4]	$50/kW/yr
High benefit estimate [5]	$150/kW/yr

In this application, the battery system provides pulses of real and reactive power to stabilize transmission lines. The battery must be of sufficient size to support transmission assets, which implies 10s to 100s of megawatts. Since this is a pulse power application, and the pulses are somewhat infrequent, not much storage capacity is required, and the life of the batteries would primarily be determined by calendar life limitations. The first pulse may be discharge or charge, depending on the cause and nature of the particular de-stabilizing event, so the battery must be maintained at an intermediate state-of-charge.

The electricity storage system allows transmission lines in a constricted network to be more heavily loaded during periods of peak demand by customers. This allows utilities to defer investments in transmission assets. The economic benefits listed above are based on estimates of the value of such deferred investments.

4.2. Area regulation & spinning reserve

Application Requirements		
	Area regulation	Spinning reserve
Typical peak power rating	20 MW	20 MW
Average power rating	±10MW	20 MW
Discharge time	Cycled continuously	15 min full power, 15 min ramp down
Energy delivery	±2 MWh	7.5 MWh
Frequency of use	Continuous	1/month
Low benefit estimate [6]	$700/kW	
High benefit estimate [7]	$1500/kW	

These ancillary services are typically provided by generating assets operating at zero or partial loading. A battery system can provide load following (real and possibly reactive power) for area regulation (frequency regulation for an island system) and provide an alternative method for short term, fast response spinning reserve. As in transmission support, the first use for area regulation may be discharge or charge, so the battery must be maintained at a partial state of charge.

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[4] Updated and inflated from Hurwitch et. al., EPRI Energy Storage Workshop materials (1991).

[5] Study team projection.

[6] B. Louks, EPRI Journal 1988, based on Dynastor projections and inflated (1988).

[7] Inflated cost of PREPA BESS, from A. Akhil, S. Swaminathan, and R. Sen, *Cost Analysis of Energy Storage Systems for Electric Utility Applications*, Sandia National Laboratories report SAND97-0443 (1997).

This set of applications requires a fairly strenuous duty cycle. Spinning reserve requires 15 minutes at full power and 15 minutes of ramp down from full power to zero. These events only happen about once a month, but they would require a complete discharge of the battery. Area regulation requires zero net unscheduled power flow between control areas in each 15 minute period. The energy transferred to meet this application is only about 25% of that for spinning reserve, but the battery is cycled continuously.

The benefit of the electricity storage system in both spinning reserve and area regulation derives from reducing or eliminating the fuel and maintenance costs that are normally associated with underutilized generating assets. The benefit derived from area regulation is probably inadequate to justify a battery, but once an electricity storage system has been installed, a battery could be the least cost alternative for this service.

4.3. Load leveling/energy arbitrage/transmission deferral

This is the classic utility application for energy storage: store cheap electricity generated off peak and sell it on-peak when more expensive generators are required. Alternatively, the use of nighttime electricity on-peak can allow deferral of transmission expansions.

Application Requirements	
Average power rating	10 MW/15 MVA
Discharge time	At least 5 hours
Energy delivery	50 MWh
Frequency of use	100-200 days/yr
Low benefit estimate [8]	$50/kW/yr
High benefit estimate [9]	$150/kW/yr

This application requires large storage capacities, with discharges of five hours or more favored by most utilities, particularly for transmission deferral and arbitrage. Each discharge removes most of the capacity of the battery, and discharges would occur every weekday when power use is high, i.e., 100 to 200 days per year.

The benefit of the electricity storage system in this application is the difference between the cost for supplying electricity close to the loads from on-peak generation and transmission assets and the cost for supplying electricity from off-peak assets.

[8] Updated and inflated from Hurwitch et. al., EPRI Energy Storage Workshop materials (1991).

[9] H. Zaininger, *Analysis of the Value of Battery Storage with Wind and Photovoltaic Generation to the Sacramento Municipal Utility District*, Sandia National Laboratories report SAND98-1904 (1998).

4.4. Renewables firming

Application Requirements	
Typical peak power rating	5 MW
Average power rating	1 MW
Discharge time	1-10 hours
Energy delivery	1-10 MWh
Frequency of use	10-20 days/month
Low benefit estimate [10]	$1000/kW
High benefit estimate [10]	$1500/kW

Most renewable energy resources, such as wind and solar energy, are intermittent in nature – they do not provide a reliable, continuous source of power. This limitation prevents system operators from having the same type of control over renewable generating assets that they have over other generating assets. For this reason, prices paid for electricity generated by renewables (unfirm power) are typically lower than what is paid for firm power.

An energy storage system can follow the renewable generation (and to a lesser extent the system load) and allow the renewable generator to be counted a firm resource. This application requires a wide range of storage capacities, depending on the nature of the renewable resource and the presence or absence of other generators that fill in the gaps. The duty cycle for this application depends on the nature of the renewable resource, but would probably be similar to that found in the other load following applications, with many shallow DOD cycles superimposed on daily deep discharges. The first event after a period of inactivity may be discharge or charge, depending on the needs of the electric system and the renewable resource.

The benefit of the electricity storage system for renewables is the extra revenue for firm electricity as compared to electricity from a non-firm resource. Additionally, variations in the power from renewables can cause problems with transmission, since wind and solar farms are often placed remote from loads and are often connected through weak lines. The benefit estimates used here are derived from avoided transmission upgrades.

4.5. Power reliability & peak shaving

Application Requirements	
Typical peak power rating	2 MW
Average power rating	1 MW
Discharge time	3-4 hours
Energy delivery	3-4 MWh
Frequency of use	6/yr up to daily
Low benefit estimate [11]	$120/kW/yr
High benefit estimate [11]	$250/kW/yr

An energy storage system can provide electricity during extended outages and reduce the purchase cost for electricity (demand charges, time-of-day prices) by shaving peaks. The second use of EV batteries for Uninterruptible Power Source (UPS) applications alone appears very unlikely, given the low cost of lead-acid batteries for these applications and the fact that they are widely used and have well-defined warranties. Thus, peak shaving must be used together with the power reliability function. In this case, the customer will have to decide

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[10] Based on H. Zaininger, *Analysis of the Value of Battery Storage with Wind and Photovoltaic Generation to the Sacramento Municipal Utility District*, Sandia National Laboratories report SAND98-1904 (1998).

[11] Proprietary source.

on the value of the system for each application and then decide how much capacity to hold back for power reliability.

Battery systems designed to meet this application could be as large as 2 MW in rated power output, but will most likely consist of 100 kW modules. Three to four hours of storage will be required to provide blackout ride-through and significant peak shaving benefits. Blackouts may only occur a few times per year, but peak shaving could be used almost every workday depending on the electricity tariff for the site.

The benefit of the electricity storage system in this application is mostly in the power reliability function, with peak shaving being used to offset the total costs of the system.

4.6. Light commercial load following

Application Requirements	
Typical peak power rating	200 kW
Average power rating	25 kW
Discharge time	3 hours
Energy delivery	75-100 kWh
Frequency of use	Daily
Low benefit estimate [12]	$10/kW/month
High benefit estimate [12]	$20/kW/month

A battery will likely be used in tandem with most distributed generation technologies (including renewables) to allow more efficient and more reliable operation. The battery system would be used for load-following, thereby allowing a generator to run at relatively constant power delivery or a renewable resource to better match the load. This mode of operation would require the battery to be in use (charge or discharge) most of the time, and it would be at a partial state-of-charge for much of the time.

The benefit of the electricity storage system in these applications is in allowing more efficient and more dispatchable local generation. Battery systems would only be practical for these applications if a utility connection were not economically viable, if a battery system owner could arrange to receive a high price for any excess electricity that could be sold back to the utility, or if the battery reduces the cost of the distributed generating system by avoiding the need for an oversized generator to meet peak loads. The benefit estimates shown here were based on avoided utility demand charges.

[12] Study team projections.

4.7. Distributed node telecom backup power

Application Requirements	
Typical peak power rating	5 kW
Average power rating	<5 kW
Discharge time	5-10 hours
Energy delivery	25-50 kWh
Frequency of use	2/yr
Low benefit estimate [13]	$120/kWh
High benefit estimate [13]	$200/kWh

Lead-acid batteries already provide power for distributed nodes (fiber nodes) of the telecomm system during electric utility outages. The replacement of lead-acid batteries for telecom "switches" is deemed very unlikely, but lithium-ion batteries are already being supplied in test quantities for the distributed telecom node application. Very high reliability, i.e., the ability to deliver the stated capacity and power, is a must for this application (in order to minimize costly service calls). Since the batteries are used for backup power, the duty cycle in this application is fairly benign. However, VRLAs used in this application have shown lifetimes as short as one year due to the acceleration of aging processes by the high temperatures frequently encountered in telecom equipment boxes. Advanced battery technologies may show less performance degradation during high temperature float or standby compared to lead acid batteries, resulting in longer battery lifetimes.

The benefit of an alternative to lead-acid batteries in this application is in lower life cycle costs due to longer time between replacements. The benefit estimates listed above are based on the current price for VRLAs.

4.8. Residential load following

Application Requirements	
Typical peak power rating	10 kW
Average power rating	1 kW
Discharge time	3 hours
Energy delivery	3-4 kWh
Frequency of use	Daily
Low benefit estimate [14]	$5/kW/month
High benefit estimate [14]	$10/kW/month

This application is very similar to light commercial load following, just on a smaller scale and operating under different load profiles. Distributed generation technologies for residential use will likely be paired with a battery system to improve their efficiency and reliability.

The benefit of the electricity storage system in these applications is in allowing more efficient and more dispatchable local generation. Battery systems would only be practical for these applications if a utility connection were not economically viable, if a battery system owner can arrange to receive a high price for any excess electricity that can be sold back to the utility, or if the battery reduces the cost of the distributed generating system by avoiding the need for an oversized generator to meet peak loads. The benefit estimates listed above were based on the avoided demand charges calculated for light commercial load following.

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[13] Estimated current cost of batteries for telecommunications.

[14] Study team projections.

5. ECONOMIC FEASIBILITY – ASSUMPTIONS & METHODOLOGY

The first part of this assessment focused on three separate tasks: identifying the steps necessary to prepare used EV batteries for a second application, estimating the requirements and values for a range of potential stationary applications, and projecting the remaining life and performance of a used EV battery module. Once these tasks were completed, an economic analysis that combined the results of all three efforts was performed to determine the economic feasibility of generating a second revenue stream for EV batteries from stationary applications.

A straightforward approach to this analysis was adopted. It began with estimating the cost of each step in the process to convert a module from vehicle to stationary use. This included the design of a hypothetical battery testing and pack assembly facility. The costs from this facility and the other steps in the conversion process were used to generate an estimate of the selling price of a stationary application battery pack comprised of used EV battery modules. The performance projections for the batteries were then used to design a battery system that would meet the requirements for each of the stationary applications. A life cycle cost estimate based on the cost of the stationary battery packs, the number of packs required to build the system, the number of battery replacements over the system life, and the balance of system (BOS) costs was performed for each stationary battery system. This life cycle cost was then compared to the estimated value of the application to identify promising stationary applications. The assumptions used for each of these steps are identified in the following sections.

5.1. Availability and cost of used EV batteries

The goal of the economic analysis was to determine the feasibility of EV battery reuse when electric vehicles are common. For the purposes of this analysis, it was assumed that the only significant sales of electric vehicles in the U.S. in the near-to-mid term will occur in the state of California as a consequence of the California Air Resources Board's (CARB) zero emission vehicle (ZEV) mandate. The impact of the CARB mandate on vehicle sales is fairly difficult to interpret due to partial credits for vehicles such as HEVs and NEVs. The mandate has also become a bit of a moving target in recent years as the regulations have been rewritten and revised. At the time of this writing, the mandate does require a certain level of full-function ZEV (either battery electric or fuel cell vehicle) sales as the mandate comes into force. CARB estimates that by 2006 sales of full function ZEVs will be roughly 10,000 vehicles per year. This study assumes that 10,000 all-battery electric vehicles will be sold each year, and the batteries from these vehicles will be available several years later when the vehicles need battery replacements. At 25–30 battery modules per pack, this corresponds to 250,000-300,000 EV battery modules available for reuse each year.

The value of the used EV batteries for a second application determines the amount of buy-down or rebate that can be applied to the electric vehicle. Conversely, a certain buy-down may be required to ensure commercial viability of EVs. High volume battery production cost estimates for the two leading technology contenders (Ni/MH and Li-ion) range from $225/kWh to $300/kWh. The United States Advanced Battery Consortium (USABC) mid-term commercialization goal for battery cost is $150/kWh. Thus, the cost of the battery to the EV user will have to be reduced by up to $150/kWh to meet the USABC's goals for a marketable electric vehicle. Since there is uncertainty regarding both the projected production costs of EV batteries and the allowable price of the battery in a commercially viable vehicle, this analysis treats buy-down cost as a variable and considers a range of values (from $0/kWh to $150/kWh).

5.2. Collection & transportation

The first cost item in the reuse process is transporting the pallets of used modules from dealerships to a facility for testing, sorting, and reassembly into battery packs suitable for stationary applications. It is likely that the dealerships that sell and service EVs will be spread across the major metropolitan areas of California (Los Angeles, Sacramento, San Diego and the San Francisco Bay Area). These areas are somewhat far apart, so transporting the used battery modules to a centrally located facility could result in significant costs. To avoid these costs, this analysis assumes a total of four facilities will be built, one in each metropolitan area. The cost estimate for each facility includes the price of a medium duty truck equipped to carry batteries and a full time driver to make regular collection stops at local vehicle dealerships

5.3. Testing & repackaging

Assuming EVs are spread evenly across California's high population density areas, each of the four testing and repackaging facilities will have to handle about 62,500 modules each year (the facility was actually designed for an input of 67,200 modules per year to make test equipment design easier). To determine the costs associated with testing, sorting, and repackaging the used EV modules, a hypothetical facility with all the equipment necessary to handle this level of throughput was designed. The facility is assumed to operate for 350 days per year to maximize the use of the capital equipment. This requires an average daily input of 192 modules. A description of the cost components associated with the facility follows.

5.3.1. Capital Costs

Testing Equipment: The first step in designing the facility was to specify the type and cost of testing equipment required to perform the test procedures outlined in Section 3. Most EV modules have a rated capacity of around 100 Ah, so the test stand would have to handle around 33 A during the C/3 discharge. EV battery modules vary in voltage, but most are between 10 and 30 volts. Quotes were obtained from Bitrode Corporation and Maccor, Inc. for a test station that could handle +/-40 A and 40 V. Bitrode designed a system consisting of 16 channels that is expected to cost $43,725.

The cycle tests outlined previously (Section 3.3) require around 40 hours to complete. If time is added for connecting and disconnecting the modules, each module will be on test for approximately 48 hours. The facility must therefore have 318 modules on test at any one time to meet the 192 module input requirement. At 16 channels each, 24 test stations are required. Each day, 12 of these stations will have all their battery modules disconnected and replaced with new modules while the other 12 stations will continue cycling the batteries that were hooked up to them on the previous day.

Since battery test equipment costs scale with rated power, and since only a single pulse will be performed on each module to get an idea of its power capabilities, the test stations were not designed to handle the pulse power characterization. Instead, an estimate was obtained for a separate single channel unit rated at 200 A and 30 V, which would cost about $8,000. One pulse test unit will be required for every two test stations that are switched each day, for a total of six pulse test units. Six computers will also be needed to operate all of the test equipment and collect data. Bitrode estimated the cost of each computer along with its associated peripherals, software, and cables at $7,236.

Materials handling equipment: A conveyor system will move the used EV modules from the loading dock to the test stations and from the test stations to the pack assembly area. Equipment will be required to lift the modules from the conveyor belts and place them into the StatPack containers. The assembled StatPacks will be stored on racks within the facility until they are shipped to the end user. Finally, a forklift will handle unloading of the pallets of modules as well as moving and loading the stationary battery packs. Table 4 contains a listing of all the capital costs for the facility, including the materials handling equipment.

Office and other equipment: The office area of the facility will be equipped with computers, furniture, a photocopier, a printer, a fax machine, and furniture. In addition, the facility will contain a workshop for calibration, diagnosis, and repair of the test equipment. This workshop will be equipped with various tools and devices (such as multimeters, power sources, a soldering iron, *etc.*). These items are included in the capital cost estimate for the facility and are shown in Table 4.

Table 4. Capital costs

Description	#	Unit Cost	Item Cost	Total Cost
Test Equipment				**$1,140,816**
Bitrode Model MCN16-40-40 battery cycler	24	$43,725	$1,049,400	
Bitrode Model RCN1-200-24 pulse test unit	6	$8,000	$48,000	
Computers	6	$7,236	$43,416	
Materials Handling				**$138,462**
Conveyors			$28,871	
Module lifting equipment	8	$1,000	$8,000	
Storage Racks			$5,182	
Nissan PE30YSC forklift	1	$18,595	$18,595	
Medium duty truck	1	$50,000	$50,000	
Office and Other Equipment				**$20,500**
Total Capital Costs				**$1,299,778**

5.3.2. Direct Costs

Materials: The primary material cost for the testing facility comes from the used EV modules. This cost was determined by multiplying the buy-down cost input by the rated energy capacity of the module when it was new to determine the cost per module to the testing facility. Packaging components for the stationary battery pack are the only other significant material cost. Each battery pack will consist of 21 modules arranged in series, giving an overall rated voltage of 252 V and an energy storage capacity of about 25 kWh. Each battery pack will require interconnects, cooling components (such as fans or coolant tubing), electronics, and the package in which the modules are assembled. These components were estimated to cost about $250/battery pack.

Labor: The number of full time employees required to operate the facility was determined from an estimate of the effort required to carry out the testing protocols listed above and generate an output of 192 modules per day. An analysis of the tasks required to disconnect a set of modules from a test station, reconnect a new set of modules, and set up a series of tests indicated that it will take roughly four hours for a technician to completely switch out the modules on a test station. In a single day, a technician could therefore switch out two test stations. This implies the need for six technicians on duty for eight hours a day, seven days a week. The facility would have to employ about eight test technicians.

Eight StatPacks will be produced each day. Assuming roughly one person-day for pack assembly, eight employees will be required to assemble packs eight hours a day, seven days a week, for a total of 12 full time pack assemblers. There will be two supervisors to ensure that one is always on duty during operating hours. The facility will also employ a plant manager, an electrical engineer to maintain the test equipment, a sales and logistics manager who will handle battery shipments and contracts, an office administrator to handle bookkeeping and correspondence, three full time security guards for round-the-clock surveillance, a forklift driver, a truck driver, and a part time janitor. Estimates for the hourly wages for each of these employees were obtained from the Department of Labor's Bureau of Labor Statistics (BLS) website and converted to annual salaries.[15] These salaries were then increased by a factor of 27.4%, the national average for non-wage compensation of civilian workers.[16] The salaries and resulting employment costs are summarized below.

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[15] U.S. Department of Labor Bureau of Labor Statistics, *National Compensation Survey*, http://www.bls.gov/ncs/home.htm#data (12/2001)

[16] U.S. Department of Labor Bureau of Labor Statistics, *Employer Costs for Employee Compensation for March 2001*, http://www.bls.gov/news.release/ecec.toc.htm (6/2001)

Table 5. Employment costs

Description	Number	Annual Salary	Annual Total
Test technicians	8	$41,210	$370,890
Pack assemblers	12	$23,490	$281,880
Forklift driver	1	$26,940	$26,940
Truck driver	1	$26,940	$26,940
Supervisors	2	$46,560	$93,120
Plant manager	1	$85,450	$85,450
Electrical engineer	1	$66,320	$66,320
Sales/logistics rep	1	$58,630	$58,630
Office administrator	1	$28,220	$28,220
Security guards	3	$19,470	$58,410
Janitor	¼	$19,880	$4,970
Total wages			$1,101,770
Non-wage compensation factor			27.4%
Non-wage compensation			$301,895
Total Employment Costs			**$1,403,665**

Rent: After determining the equipment and personnel necessary to run the testing and repackaging facility, a sample floor plan was drawn up to estimate the amount of space required for the operation (see Figure 6. Hypothetical used EV battery testing & packaging facility layout). Based on this floor plan, roughly 10,173 ft^2 of space will be required for the facility. The average rent for R&D/flex facilities from the fourth quarter of 2001 for the four areas where facilities might be built (Los Angeles, Oakland, Sacramento, and San Diego) was $11.27 per square foot per year (triple net), corresponding to annual rent of about $115,000.[17]

[17] Grubb & Ellis, Asking rental rates (R&D-Flex, triple net) for second quarter 2001 from "Industrial Market Trends: A Survey of the Nation's Industrial Markets" (Fall 2001)

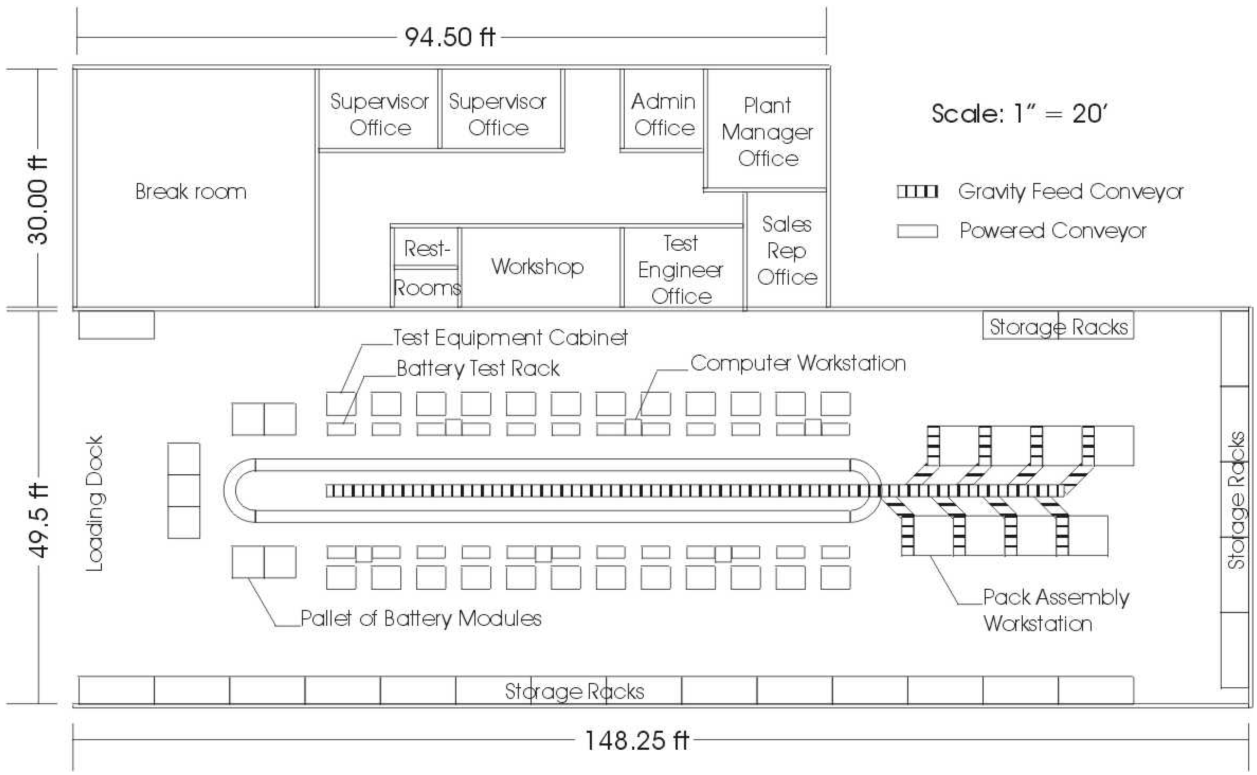

Figure 6. Hypothetical used EV battery testing & packaging facility layout

Electricity: Electricity costs were estimated for battery testing as well as general lighting, heating, and cooling. Testing for each module will require about 9 kWh of electricity for a total of 604,800 kWh of electricity per year. According to data obtained from the DOE Energy Information Administration's website, this electricity would cost $43,300/yr at the average commercial electricity rate of 10.4¢/kWh for the utilities serving the four areas mentioned above.[18] Based on an average annual energy expenditure of $1.58 per square foot of commercial floor space obtained from the Department of Energy's Office of Buildings Technology, HVAC and lighting for the refurbishing facility would cost around $7,200/yr.[19]

Transportation: Assuming the truck for collection of modules from dealerships travels 50,000 miles per year, and maintenance and fuel cost $0.325/mile, the truck would cost $16,250/year to operate.

Other direct costs: This catchall, estimated at 2% of labor costs, includes phones, postage, office supplies, and the other costs of doing business.

5.3.3. Indirect Costs

Insurance, general & administrative costs, and warranty costs are all estimated as a percentage of direct costs: 3%, 16%, and 4%, respectively.

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[18] Department of Energy Energy Information Administration, Form EIA-861, "Annual Electric Utility Report" http://www.eia.doe.gov/cneaf/electricity/esr/esrt15p2.html#cal (4/2002)

[19] Department of Energy Office of Buildings Technology State & Local Programs, BTS Core Databook http://btscoredatabook.eren.doe.gov/tableview.asp?TableID=108&t=pdf (10/2001)

5.3.4. Earnings, taxes, and determination of reconfigured battery selling price

The testing and packaging facility is assumed to have an after-tax internal rate of return (IRR) of 15%. This figure is typical of what many firms require before making an investment in a particular venture. The analysis also assumes that the facility costs will be recovered in five years. While this is somewhat short, potential investors would expect, and perhaps demand, a rapid return from a unique and potentially high-risk venture. In addition, obsolescence may require replacement of some of the testing equipment after five years, particularly if EV battery technologies change significantly. Finally, since testing and packaging the batteries is primarily a labor-intensive effort, this short lifetime has little effect on the overall cost of the stationary battery packs.

The cost of the stationary packs on a per module basis was calculated by determining the revenues necessary to achieve a 15% IRR after state and federal taxes of 8.84% and 34%, respectively. IRR is defined as the discount rate required to make the net present value of a particular venture equal to zero, where the net present value is the sum of all the cash flows over the life of a venture discounted back to the present. Expressed as an equation,

$$NPV = -CC + \sum_{i=0}^{n} \frac{-EXP - TAX + REV}{(1 + IRR)^i} = 0$$

where:

NPV = net present value

CC = capital costs

EXP = expenses

TAX= taxes

REV = revenues

IRR = internal rate of return

i = year

n = lifetime of facility

Taxes are equal to the tax rate times the adjusted gross income for each year:

$$TAX = TR(REV - EXP - DEP)$$

where:

TR = tax rate

DEP = depreciation = CC/n (linear depreciation)

Substituting these values, the expression for NPV becomes:

$$NPV = -CC + \sum_{i=0}^{n} \frac{-EXP - TR(REV - EXP - \frac{CC}{n}) + REV}{(1 + IRR)^i} = 0$$

Solving this expression for the annual revenues yields:

$$REV = \frac{CC + \sum_{i=0}^{n} \frac{EXP + TR(EXP - \frac{CC}{n})}{(1+IRR)^i}}{\sum_{i=0}^{n} \frac{1-TR}{(1+IRR)^i}}$$

Thus, the revenues could be determined from the capital costs, the annual expenses, the tax rate, the internal rate of return, and the projected lifetime of the facility.

The selling price of the converted batteries on a per module basis was calculated by dividing the total annual revenues by the total number of modules that pass through the facility each year:

$$PRICE = \frac{REV}{MODULES}$$

A summary of the costs associated with a refurbishing facility assuming battery modules are obtained at a buy-down of $75/kWh is shown in Table 5. This table also shows the projected selling price of the converted battery packs on a per-module and per-kWh basis.

Table 6. Testing and repackaging costs

Description	Amount	Unit Cost	Total Cost ($/yr)
Direct Costs			
Batteries (buy-down)	60,480 modules	$98.10/module ($75/kWh)	$5,933,088
Pack materials	2,880 packs/yr	$250/pack	$720,000
Labor			$1,403,655
Rent	10,173 $ft.^2$	$11.27/$ft.^2$/yr.	$114,679
Electricity			$79,245
Testing	604,800 kWh	10.4¢/kWh	
HVAC & lighting	10,173 $ft.^2$	$1.58/ $ft.^2$	
Transportation	50,000 miles	$0.365/mile	$18,250
Other direct costs		2% of labor	$22,035
Indirect Costs			
Insurance		3% of Direct Costs	$250,051
G&A		16% of Direct Costs	$1,333,064
Warranty		4% of Direct Costs	$333,401
Capital recovery, earnings, and taxes			$218,403
Required annual revenues			**$10,724,437**
Battery module throughput			**60,480**
Battery pack selling price ($/module)			**$176.43**
Battery pack selling price ($/kWh)			**$147.02**

5.3.5. Cost breakdown

The cost for collecting, testing, and repackaging used EV battery modules into battery packs for stationary applications is broken down into its various components in Figure 7. This figure was generated by taking the cost components listed in Table 6 and dividing them by the total capacity of all the battery packs that would be produced by the refurbishing facility in a year.

The primary cost driver for these battery packs is the purchase price of the used EV batteries, which is determined by the buy-down given to the EV buyer. The battery procurement costs account for over half of the stationary battery pack costs. Testing and conversion of the used EV batteries is primarily a labor intensive process, with employment and overhead costs each accounting for around 12-13% of the total battery pack costs. The other major cost component is the materials for repackaging the used EV modules into a battery pack, which makes up about 7% of the total pack cost.

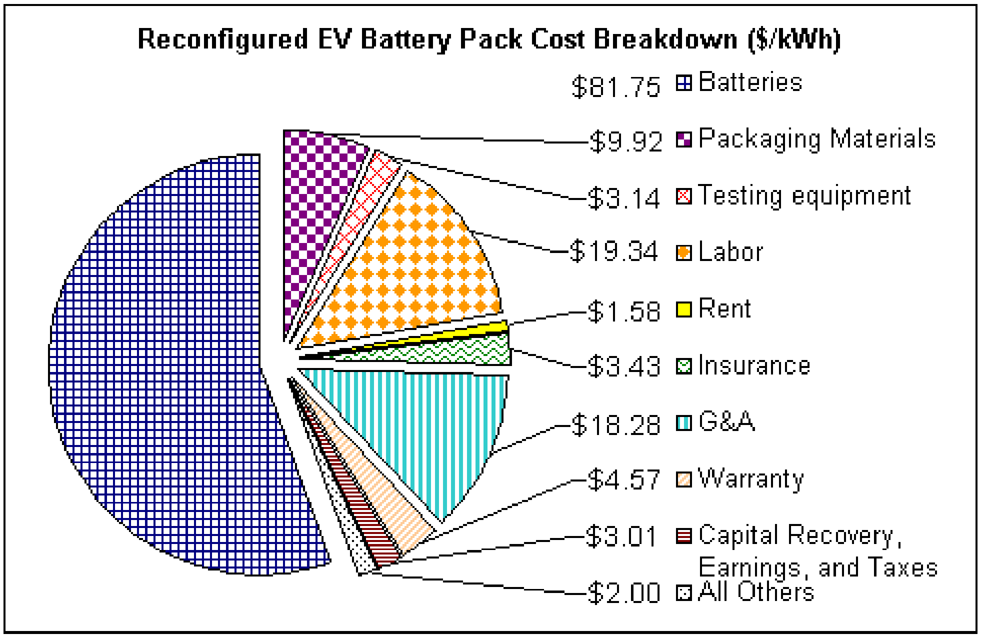

Figure 7. Cost breakdown for reconfigured EV batteries

5.4. Energy storage system life cycle costs

The price of the batteries represents only a single (and often small) component of the cost of a complete energy storage system. There are a number of other costs that are incurred during assembly, installation, and operation of such systems that need to be considered to determine life cycle costs. Racks and wiring are required for connecting the battery modules and holding them in place. Nearly all energy storage systems include a power conditioning system (PCS) to ensure that the output of energy storage device matches the requirements of the application (for example, 240V, 60Hz AC power). Sensors must be installed to monitor the performance and condition of the battery. Also, both regular and unscheduled maintenance will be required over the life of the system. Furthermore, the batteries themselves will most likely need replacement over the expected life of the energy storage system.

This section describes the methodology for estimating these and other costs. It also explains how all of the costs were brought together to determine the life cycle costs of an energy storage system designed to meet each of the applications described in Section 4.

5.4.1. Application requirements & system characteristics

The first step was to design an energy storage system for each application that could meet that application's power and energy requirements. The number of battery modules required to meet the needs of each application was calculated based on the modules' projected power and energy capabilities.

5.4.2. Duty cycle and projected life

To determine the replacement costs of the battery, the battery life had to be estimated. Since both the amount of time that the battery will remain in the vehicle and the number of discharge cycles it will see before being removed are uncertain and will vary from one vehicle to the next, the life of the battery in the stationary application is difficult to estimate. For this analysis, battery life in the second application was treated as a variable. To generate the plots shown in Section 6, battery life was arbitrarily varied from 1 to 9 years. In addition to these cost vs. life curves, a best guess value was established for the life of the battery in each application by comparing the projected cycle life and the expected calendar life.

Cycle lives were determined by dividing the annual energy throughput required by the application duty cycle by the expected throughput remaining in the battery after use in an EV (based on cycle lives projected by battery manufacturers, where available). For a somewhat simplified example, if an EV battery module had a projected life of 1500 cycles, and it were removed from the vehicle after 1000 cycles, it would be expected to have 500 cycles remaining in the second application. If this same module had a capacity of about 1 kWh, it should have an energy throughput of around 500 kWh remaining for the second application. If the duty cycle for the application required 100 kWh of energy throughput each year, the battery module would be expected to last about 5 years in that application.

The calendar life in the stationary application was estimated to be 5 years. If the battery is designed for a 10-year life, and it is removed from the vehicle after around five years, that would leave around five years remaining for the second application. Please note that this is a somewhat arbitrary guess since it is unclear how long the battery may actually last in the vehicle. There is also some uncertainty on the impact of the vehicle environment (particularly temperature extremes) on battery calendar life. Furthermore, the life in the second application may be considerably longer since the environment for stationary applications is typically much more benign than that found in vehicles.

For the best guess estimates, the life of the battery was set as the lesser of the cycle and calendar lives.

5.4.3. Battery costs

The cost of a single set of batteries was calculated by multiplying the number of modules required to meet the application by the selling price of the refurbished module (see Section 5.3). The number of battery replacements was then determined by dividing the system design life (typically 20 years) by the expected life of the battery. The present value of all the battery purchases over the system life was calculated by discounting the costs of all the replacements back to present day dollars and adding them to the initial purchase cost.

5.4.4. Balance of system costs

Typically, the procurement costs of all the non-battery equipment that goes into an energy storage system, as well as the cost of assembling and starting up the system, are lumped together as balance of system (BOS) costs. These include (but are not limited to) the facilities for housing the batteries, equipment to connect the battery modules together and monitor their performance, equipment to connect the battery to the local electricity supply, electronics to control the operation of the battery system and condition its output appropriately, and transportation for all the components to the application site. For this analysis, the BOS costs were broken down into three categories: accessories, facilities, and transportation; PCS, interface equipment, and controls; and installation and startup.

For each of the applications, an existing analogous system was chosen as a starting point for estimating BOS costs. For example, GNB has installed a backup power/peak shaving system at its lead smelting facility in Vernon, California, to allow orderly plant shutdown during blackouts and avoid demand charges by providing peak power. The costs of this system have been detailed in several reports.[20] This system was used as the template for several applications, including power reliability/peak shaving. The cost components for this battery system were separated into the groups listed above. The cost of each group was then divided by an appropriate size metric to generate a scaled cost. For example, the battery accessories & facilities costs were divided by the storage capacity of the Vernon system to generate a $/kWh unit value for those components, while the PCS, interface equipment, and controls costs were divided by the rated power output to give a $/kW figure. See Table 7 for all of the unit BOS costs for each of the applications.

These unit costs were then multiplied by the appropriate system parameters for each of the stationary applications to give a scaled estimate of the various BOS costs. The resulting projected costs are summarized in Table 8. Note that distributed node telecom has no BOS because this study looked only at the batteries for this application, not the entire system. There are no similar systems available for residential load following, so the costs for these systems were estimated by the study team based on expected PCS and maintenance costs.

5.4.5. Operating and maintenance costs

Operating and maintenance (O&M) costs must also be considered if an accurate life cycle cost is to be determined. These items include routine and unscheduled maintenance, repair or replacement of failed or damaged battery modules or packs, periodic monitoring to ensure nominal system operation, and the cost of the electricity used in operating the system (powering sensors, controls, cooling devices, etc.) as well as that consumed by the system due to losses during normal operation.

Annual O&M cost estimates were determined in much the same way BOS costs were estimated. The O&M costs for an analogous system were divided by the power rating of that system to give a $/kWyr value (see Table 7). These unit values were then multiplied by the rated power of the hypothetical system designed to meet the stationary application to give a scaled O&M cost estimate. The results of this calculation are summarized in Table 8.

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[20] A. Akhil, S. Swaminathan, and R. Sen, *Cost Analysis of Energy Storage Systems for Electric Utility Applications*, Sandia National Laboratories report SAND97-0443 (1997) and S. Swaminathan, N. Miller, and R. Sen, *Battery Energy Storage Systems Life Cycle Costs Case Studies*, Sandia National Laboratories report SAND98-1905 (1998).

Table 7. BOS and O&M costs for analogous battery systems

Application	Similar system[21]	Accessories, facilities, shipping	PCS, interface equipment, controls	Installation and startup	O&M
Units		$/kWh	$/kW	$/kWh	$/kWyr
Transmission Support	PREPA	$525	$442	$360	$38
Area Regulation & Spinning Reserve	PREPA	$525	$442	$360	$18
Load Leveling /Arbitrage/ Trans. Deferral	Chino	$117	$336	$52	$29
Renewables Firming	Vernon	$482	$319	$90	$58
Power Reliability & Peak Shaving	Vernon	$482	$319	$90	$58
Light Commercial Load Following	Vernon	$482	$319	$90	$58
Distributed-Node Telecomm Standby	Batteries only	N/A	N/A	N/A	N/A
Residential Load Following	N/A	Included	$100	Included	$102/yr

One of the costs associated with installing and operating a battery system is proper disposal or recycling of the batteries when they reach the end of their useful life. At present, the battery manufacturer is responsible for the battery from cradle to grave, and the cost of handling the batteries at end of life is included in the price of the new EV battery. It is assumed here that recycling/disposal costs will continue to be paid by the primary user of the battery (the EV owner). The money set aside for recycling/disposal will somehow be passed along with the battery through its various applications until it reaches end of life, or the responsibility for proper disposal will remain with the battery manufacturer. Either way, the fees will not have to be directly borne by the user of the battery in the second application. Therefore, disposal/recycling fees were not included in the system costs for this analysis.

Salvage value for the balance of system equipment was also not included in this analysis. If the energy storage systems last for as long as planned here (20 years for most applications), most of the balance of system components will have lived out their useful lives. Some components may be obsolete, and others may not be sufficiently portable to warrant use in another system or for another application. Therefore, it was assumed that there would be very little salvage value left in the system when it reaches end of life, and whatever is remaining is expected to offset any decommissioning expenses.

5.4.6. Total system costs

The total capital cost for installing the system was calculated by adding together the battery costs and the BOS costs. The total capital cost was then amortized over the life of the system to give an annualized capital cost. This annualized capital cost was added to the annual O&M costs to determine the annualized cost of installing and operating the system, which this study refers to as the life cycle cost. This value was then divided by the size of the system to give a per unit figure of merit in $/kW/yr or $/kWh/yr. Table 8 summarizes the results of all of these calculations for a

[21] Costs for analogous systems inflated from A. Akhil, S. Swaminathan, and R. Sen, *Cost Analysis of Energy Storage Systems for Electric Utility Applications*, Sandia National Laboratories report SAND97-0443 (1997) and S. Swaminathan, N. Miller, and R. Sen, *Battery Energy Storage Systems Life Cycle Costs Case Studies*, Sandia National Laboratories report SAND98-1905 (1998).

Table 8. Life cycle cost components for stationary energy storage systems based on used EV batteries

	Units	Trans. Support	Area Reg. & Spinning Reserve	Load Leveling	Renewables Firming	Power Reliability & Peak	Lt. Comm. Load Following	Dist. Node Telecom	Res. Load Following
Application Requirements & System Characteristics									
Peak power required	KW	100,000	20,000	15,000	5,000	2,000	200	5	10
Required capacity	KWh	140	40,000	50,000	10,000	8,000	100	50	4
Modules required	mod	16,667	33,334	41,667	8,334	6,667	84	42	5
Peak power available	KW	100,002	80,002	100,001	20,002	16,001	202	101	12
Capacity available	kWh	20,000	40,001	50,000	10,001	8,000	101	50	6
Duty Cycle & Projected Life									
Typical energy delivery	kWh	140	2000 / 7500	100,000	10,000	4,000	100	50	4
Frequency of use	Uses/yr	12	17520 / 12	200	240	256	365	2	365
Annual energy throughput	kWh	1,680	35,130,000	20,000,000	2,400,000	1,024,000	36,500	100	1,460
Throughput per module	KWh/mod	0.10	1,054	480	288	154	435	2	292
Projected battery life	Yr	5.00	1.09	2.40	4.00	5.00	2.65	5.00	3.94
Projected system life	Yr	20	20	20	20	10	10	20	20
Battery Costs									
Cost of one set of batteries	$	$2,900,000	$5,880,000	$7,400,000	$1,470,000	$1,180,000	$14,800	$7,400	$880
Battery purchases		4	19	9	6	2	4	4	6
Present value of battery purchases	$	$8,000,000	$62,800,000	$38,700,000	$5,220,000	$2,050,000	$46,900	$20,100	$3,150
Balance of System Costs									
Similar system		PREPA	PREPA	Chino	Vernon	Vernon	Vernon	batt. only	N/A
Accessories, facilities, transportation	$	$10,500,000	$21,000,000	$5,840,000	$4,820,000	$3,850,000	$48,600	N/A	Included
PCS, interface equipment, controls	$	$44,200,000	$8,840,000	$5,040,000	$1,590,000	$638,000	$63,800	N/A	$1,000
Installation & startup	$	$7,210,000	$14,400,000	$2,610,000	$902,000	$721,000	$9,090	N/A	Included
Total BOS first cost	$	$61,900,000	$44,300,000	$13,500,000	$7,310,000	$5,210,000	$121,000	N/A	$1,000
Operations & Maintenance Costs									
Total O&M costs	$/yr	$3,830,000	$367,000	$434,000	$290,000	$116,000	$11,600	N/A	$102
Total System Costs									
Capital costs	$	$69,900,000	$107,000,000	$52,200,000	$12,500,000	$7,260,000	$168,000	$20,100	$4,150
Annualized capital costs	$/yr	$6,550,000	$10,000,000	$4,890,000	$1,170,000	$1,030,000	$23,900	$1,880	$389
Total annual expenses	$/yr	$10,400,000	$10,400,000	$5,330,000	$1,460,000	$1,150,000	$35,500	$1,880	$491
System unit annual cost	$/kW/yr	$104	$520	$355	$293	$573	$177	$38	$49

used EV battery with a $75/kWh buy-down, roughly 1000 cycles remaining in its useful life, and an expected calendar life of 5 years.

5.5. Feasibility categories

After all of the calculations were completed, the system life cycle cost was compared to the application values listed in Section 4 to determine the feasibility of using the reconfigured EV batteries in each application. For the purposes of this report, three categories of feasibility were developed. If the system life cycle cost is more than the high value estimate, the application is deemed "unlikely" for that battery. If the life cycle cost is less than the high value but more than the low value, the application is described as "possible" for the battery. Finally, if the life cycle cost is less than the low value estimate, the application/battery combination is termed "favorable." The results of the calculations and the feasibility assessments are summarized in the following section.

6. ECONOMIC FEASIBILITY – RESULTS OF ANALYSIS

6.1. Nickel/Metal Hydride

Ni/MH batteries are the most mature advanced battery chemistry used in electric vehicle applications in the U.S. As such, obtaining data on life and performance was relatively easy compared to other battery chemistries considered. Based on conversations with battery manufacturers, it was assumed that a used Ni/MH EV module could provide a cycle life roughly equal to that of the vehicle application at a slightly de-rated capacity. Further, we assumed that the used EV battery would have a calendar life of 5 years in the second application. The battery replacement schedule was determined using the lesser of the predicted cycle and calendar lives.

Half of the applications considered in the study involve systems that would be installed by a utility to provide benefits or services to the grid as a whole. The results of the analysis for these four utility applications are summarized in Table 9. The lifetimes shown represent the best estimate of how long the battery would last in the application. The term in parentheses after the life estimate indicates whether the life in the application was limited by duty cycle or calendar life.

Table 9. Analysis of used Ni/MH EV batteries in utility applications

Application	Life (yr)	Buy-down ($/kWh)	System life cycle cost ($/kW/yr)	Low value ($/kW/yr)	High value ($/kW/yr)	Analysis
Transmission stabilization	5 (calendar)			$50	$150	
		$0	$116			Possible
		$50	$119			Possible
		$100	$121			Possible
		$150	$125			Possible
Area regulation &	1.1 (cycle)			$35	$75	
spinning reserve		$0	$319			Unlikely
		$50	$453			Unlikely
		$100	$587			Unlikely
		$150	$721			Unlikely
Load leveling	4.8 (cycle)			$50	$150	
		$0	$158			Unlikely
		$50	$222			Unlikely
		$100	$286			Unlikely
		$150	$350			Unlikely
Renewables firming	4.0 (cycle)			$50	$75	
		$0	$226			Unlikely
		$50	$270			Unlikely
		$100	$315			Unlikely
		$150	$356			Unlikely

6.1.1. Transmission support

Of these four applications, only transmission support appears to be a possible candidate for a second use of EV battery modules. For the entire range of buy-down values, the life cycle system cost is between the two value estimates, categorizing the application as "possible" for used Ni/MH EV modules. This is graphically represented in Figure 8, which shows the variation in life cycle cost with both battery life and buy-down.

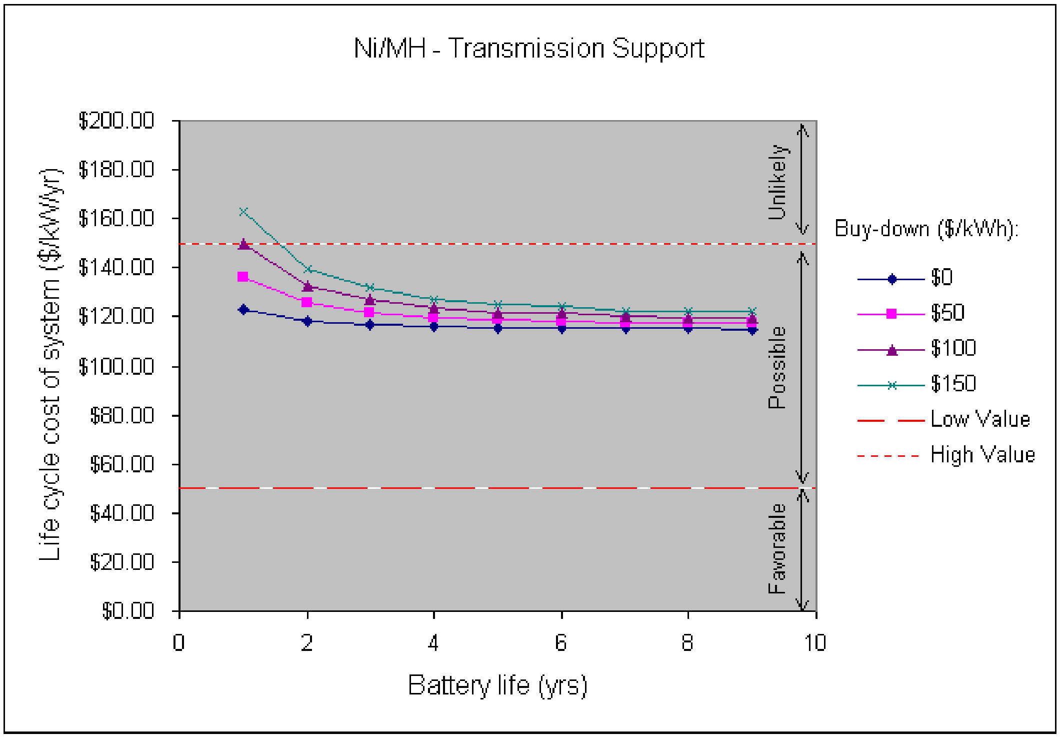

Figure 8. Life cycle cost as a function of battery life and buy-down for transmission support

Note that since this application requires only pulse discharges, the total energy that passes through the battery is quite small. Thus, there is no predicted cycle life for this application. The life of the battery will be limited by calendar aging processes.

The horizontal dashed lines on the graph in Figure 8 indicate the estimated values of the application and serve as boundaries between the three viability categories. As expected, the life cycle cost increases with increasing buy-down and decreasing life, but only to a small degree. This relative insensitivity to battery costs is due to the nature of the application, which requires short duration, high power pulses. These requirements result in the balance of system components being the major cost driver for the battery system, as illustrated in Figure 9. The PCS, interface, monitors and controls account for 40% of the total life cycle costs, O&M costs account for an estimated 37%, and battery accessories make up about 9%. The battery and its replacements account for only 7% of the total life cycle costs.

Due to this insensitivity to battery costs, transmission support can tolerate buy-downs as high as $150/kWh at battery calendar lifetimes as short as two years. The only point where the cost curves look unfavorable is at high buy-downs and a one-year life. Since the battery is expected to be calendar life limited in this application, it is unlikely that the life would be this short.

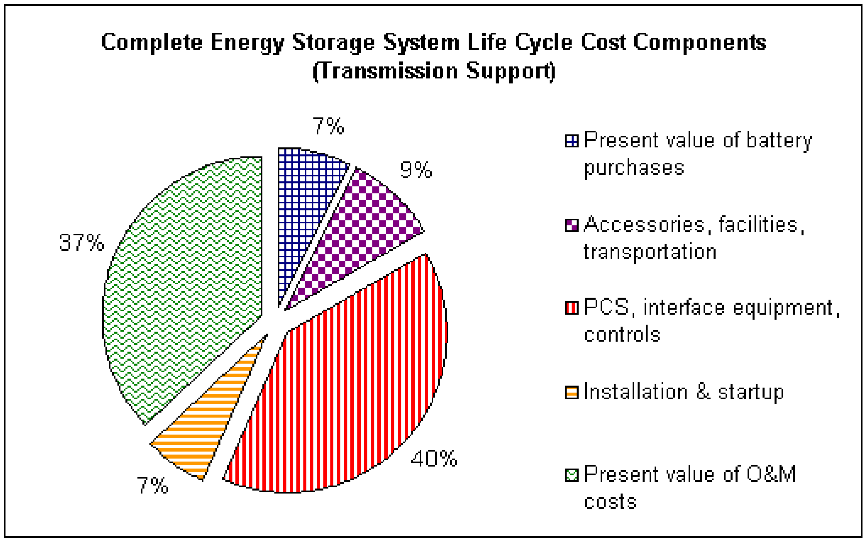

Figure 9. Primary cost drivers for transmission support

6.1.2. Area regulation & spinning reserve

The life cycle cost curves for area regulation & spinning reserve are shown in Figure 10, below.

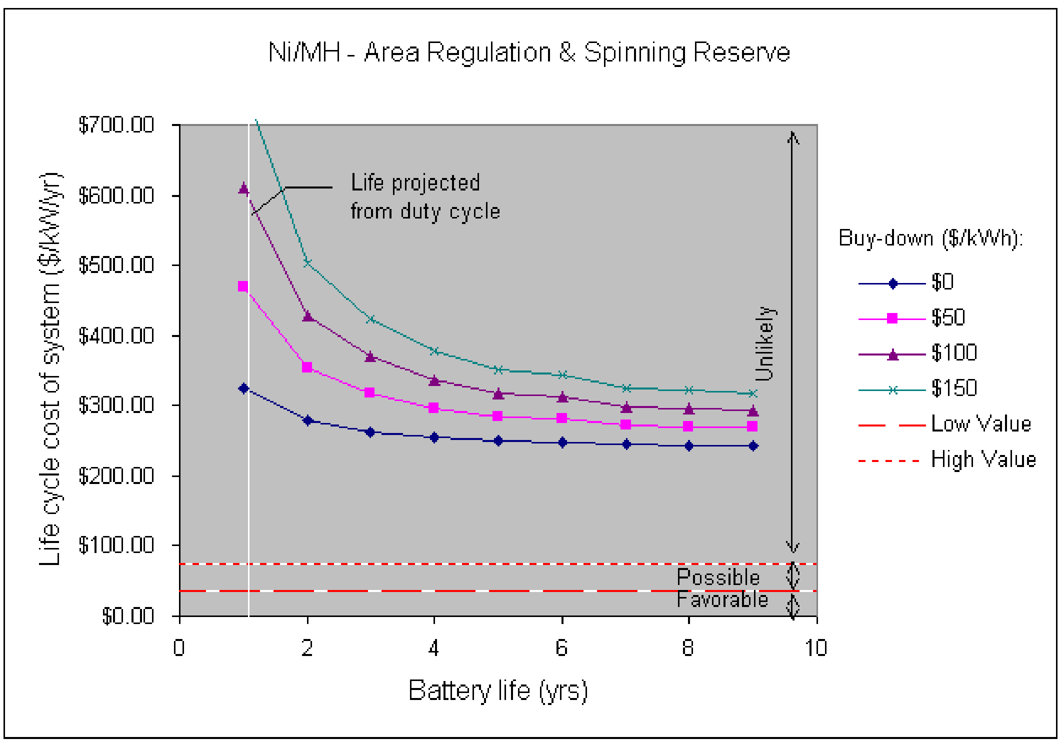

Figure 10. Life cycle cost for Ni/MH in area regulation and spinning reserve

The vertical white line on this plot indicates the projected battery life based on the expected energy throughput remaining in the battery and the duty cycle for the application. Area regulation is a fairly strenuous application, requiring continuous cycling of the battery, and the effect on life is apparent in this plot. However, even at high lifetimes, and even if the batteries could be obtained for free, this application would not be viable. This is due to both the relatively low value of the estimated economic benefits derived from this application and the high cost of installing and operating the system.

As Figure 11 illustrates, battery costs dominate the life cycle costs for a system designed to provide area regulation & spinning reserve. There are therefore two potential pathways to reduced costs: lower conversion costs or significantly improved battery performance. It is unlikely that a quantum leap in battery life (representing a doubling of the projected cycle life, for example) is just around the corner, so the most likely path to cost reduction is in reduced battery testing and reconfiguring costs. While it is possible that these costs could be somewhat lower than what was estimated for this study, it is unlikely that the cost reductions necessary to make this application viable are achievable.

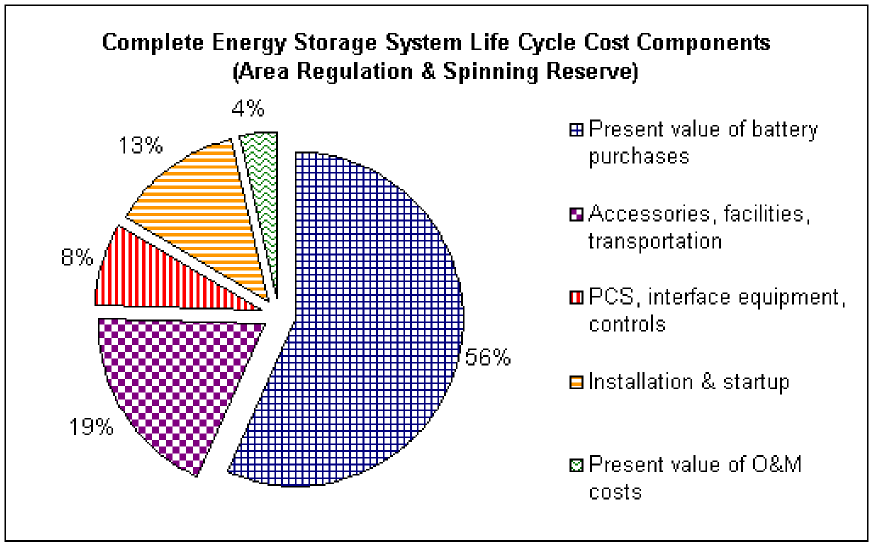

Figure 11. Primary cost drivers for area regulation & spinning reserve

6.1.3. Load leveling/energy arbitrage/transmission deferral

Load leveling/energy arbitrage/transmission deferral looks somewhat better than area regulation & spinning reserve, but it is still classified as unlikely. The life cycle cost curves are shown in Figure 12.

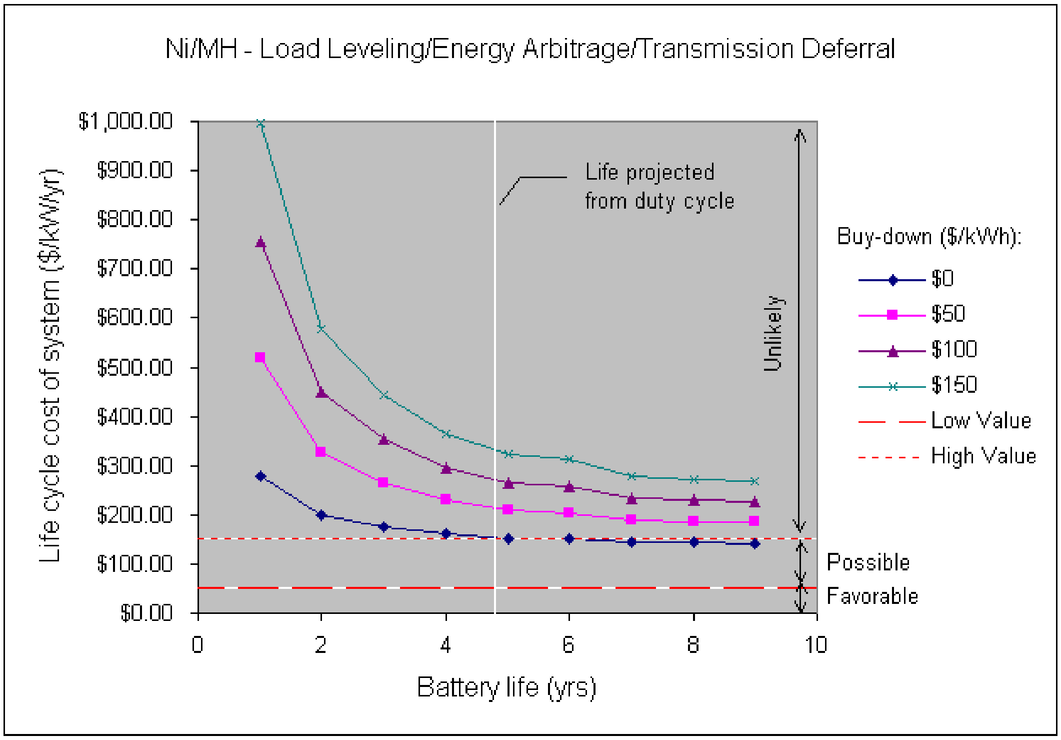

Figure 12. Life cycle cost curves for load leveling/energy arbitrage/transmission deferral

This application appears to be just on the border of possible when the used EV batteries are obtained for free. However, any reasonable buy-down that could lower the purchase price of EVs puts the life cycle cost well above the expected economic benefit from the application. This is one of the higher value applications, but it also has one of the highest life cycle costs of the systems studied here. The vast majority of this cost (68%) comes from the batteries themselves, as shown in Figure 13. Much as with area regulation & spinning reserve, the only way to significantly reduce the life cycle costs of these systems would be reduced testing & reconfiguring costs.

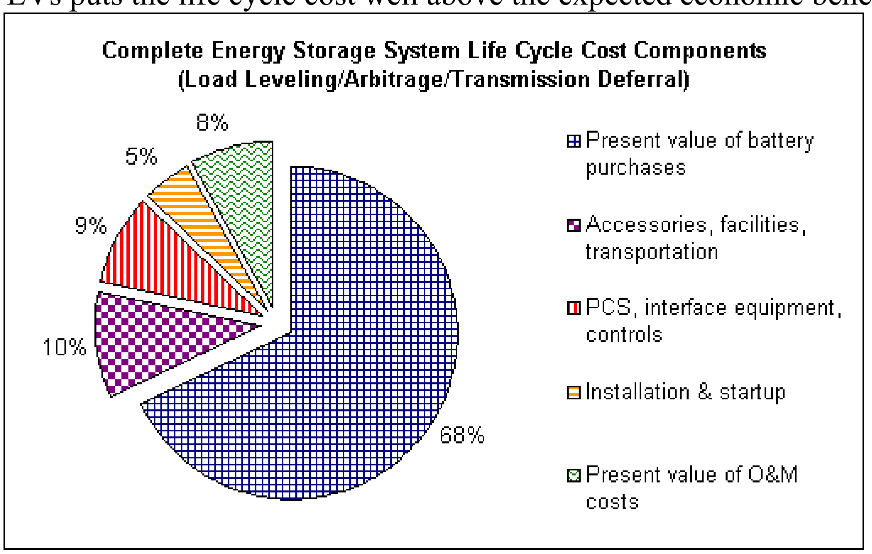

Figure 13. Primary cost drivers for load leveling/energy arbitrage/transmission deferral

6.1.4. Renewables firming

The fourth utility scale application, renewables firming, is similar to area regulation and spinning reserve in that it is estimated to have a fairly low economic benefit, but high system life cycle costs. The life cycle costs as a function of life and buy-down are shown below in Figure 14.

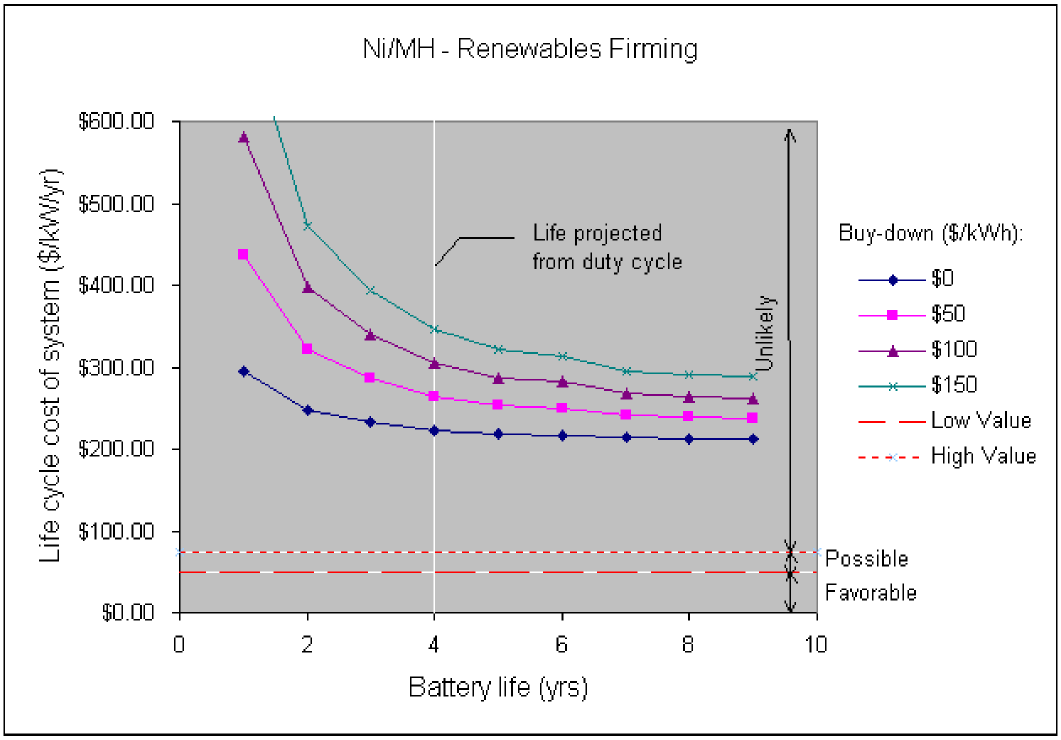

Figure 14. Life cycle cost curves for renewables firming

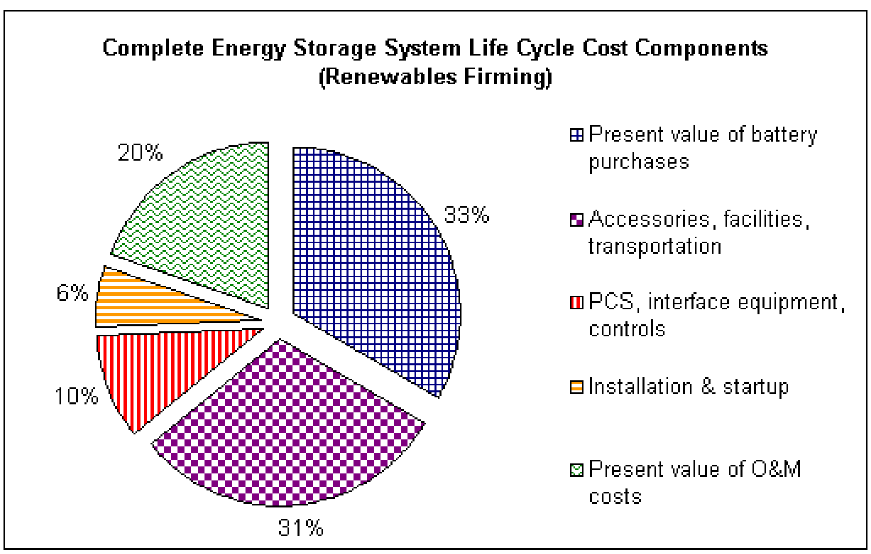

Figure 15. Primary cost drivers for renewables firming

The life cycle costs for a system designed to meet this application are split fairly evenly between the various cost components. As Figure 15 illustrates, the life cycle costs derive mostly from the batteries, the battery accessories and facilities, and O&M costs. It is doubtful that sufficient cost reductions in all of these areas to make this application possible could be achieved.

The remaining applications considered in this study would most likely be installed on the customer side of the meter to provide benefits to a particular customer or facility. The results for these commercial and residential applications with Ni/MH batteries are shown in Table 10.

Table 10. Analysis of used Ni/MH EV batteries in commercial & residential applications

Application	Life (yr)	Buy-down ($/kWh)	System life cycle cost ($/kW/yr)	Low value ($/kW/yr)	High value ($/kW/yr)	Synopsis
Power reliability & peak shaving	5 (calendar)			$120	$250	
		$0	$473			Unlikely
		$50	$540			Unlikely
		$100	$606			Unlikely
		$150	$672			Unlikely
Light commercial load following	2.6 (cycle)			$120	$240	
		$0	$155			Possible
		$50	$169			Possible
		$100	$184			Possible
		$150	$200			Possible
Distributed node telecom	5 (calendar)			$32	$53	
		$0	$12			Favorable
		$50	$29			Favorable
		$100	$46			Possible
		$150	$63			Unlikely
Residential load following	3.9 (cycle)			$60	$120	
		$0	$29			Favorable
		$50	$42			Favorable
		$100	$56			Favorable
		$150	$69			Possible

6.1.5. Power reliability & peak shaving

The life cycle cost curves for power reliability & peak shaving are shown below in Figure 16. This application is expected to generate a fairly high economic benefit, but the system designed to meet the application requirements is fairly expensive, putting it well into the unlikely range even with free batteries that last a long time.

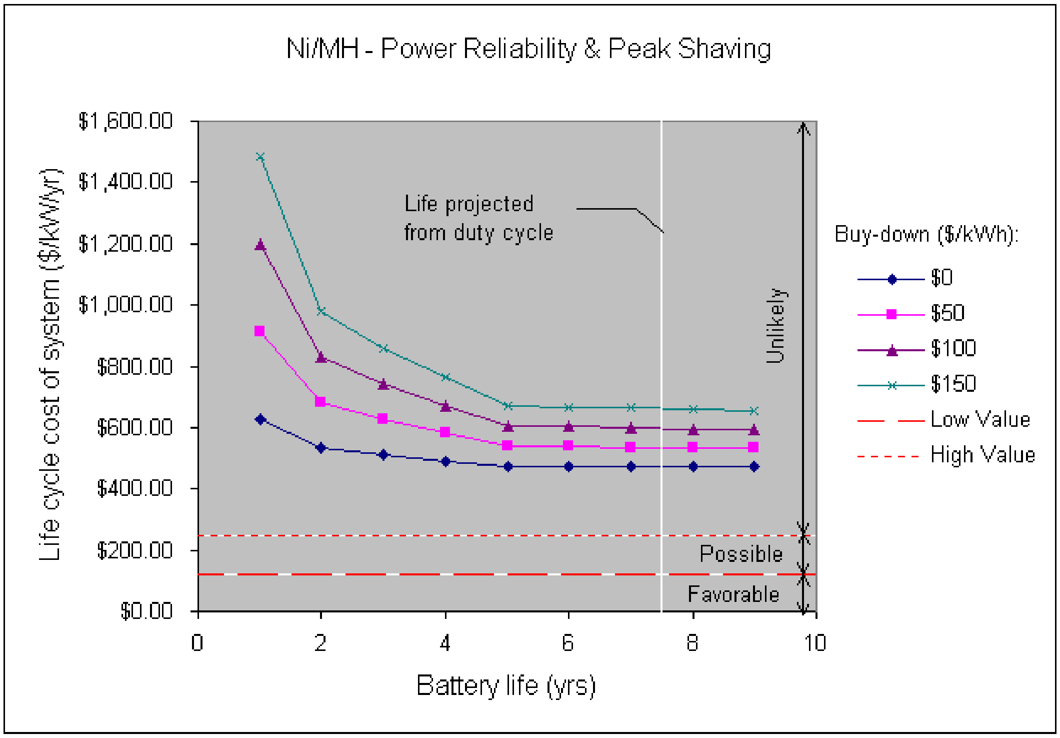

Figure 16. Life cycle cost curves for power reliability and peak shaving

Power reliability and peak shaving is primarily an energy intensive application, and this is illustrated by the cost breakdown shown in Figure 17. Nearly half of the cost of the system for comes from battery accessories and facilities, while about a quarter of the cost comes from the batteries themselves. It is possible that facilities costs for many potential installations could be reduced through creative siting of the battery system, but this reduction would probably not be enough to make this application viable in and of itself. It is unlikely that the costs for racking, interconnects, and other accessories could be significantly reduced.

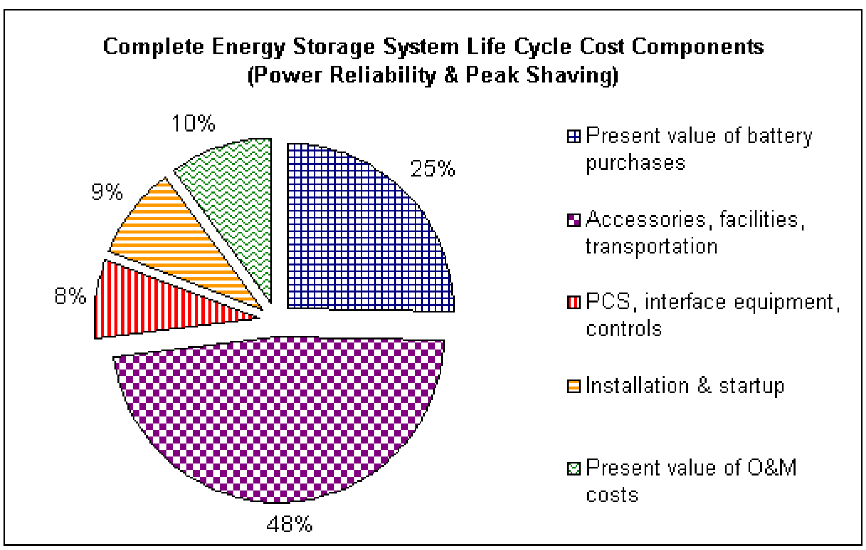

Figure 17. Primary cost drivers for power reliability and peak shaving

6.1.6. Light commercial load following

In contrast, the other two commercial applications look much more promising. Light commercial load following is categorized as "possible" for nearly the entire range of buy-downs and battery lifetimes considered here. The life cycle cost curves are shown in Figure 18 below.

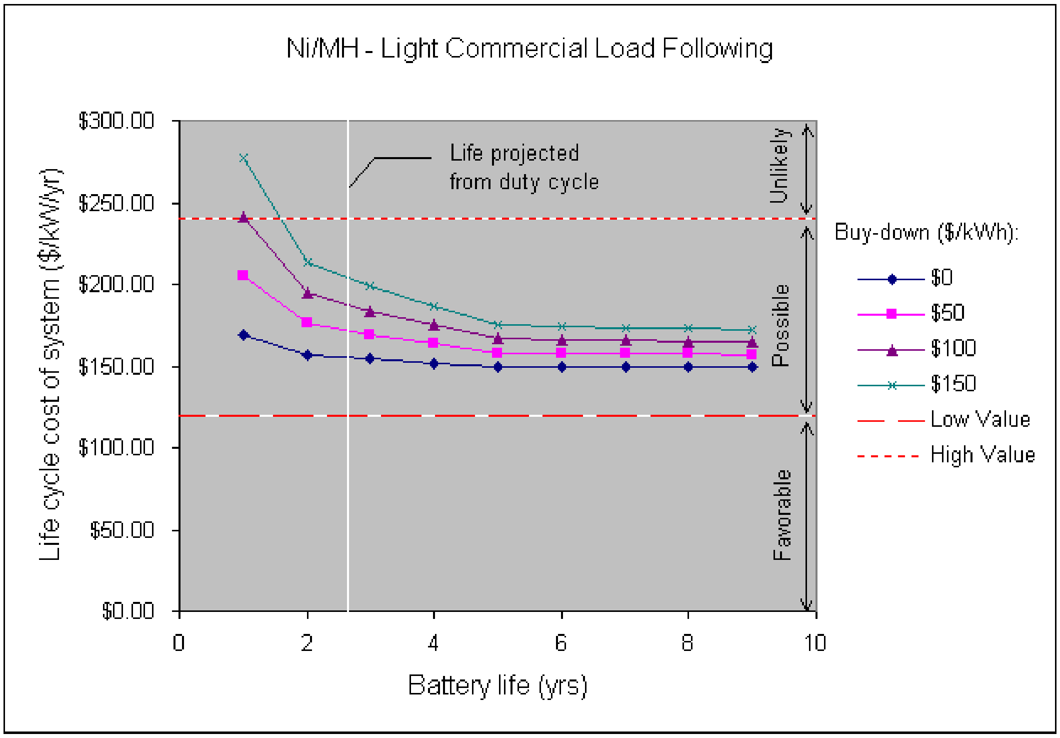

Figure 18. Life cycle curves for Ni/MH in light commercial applications

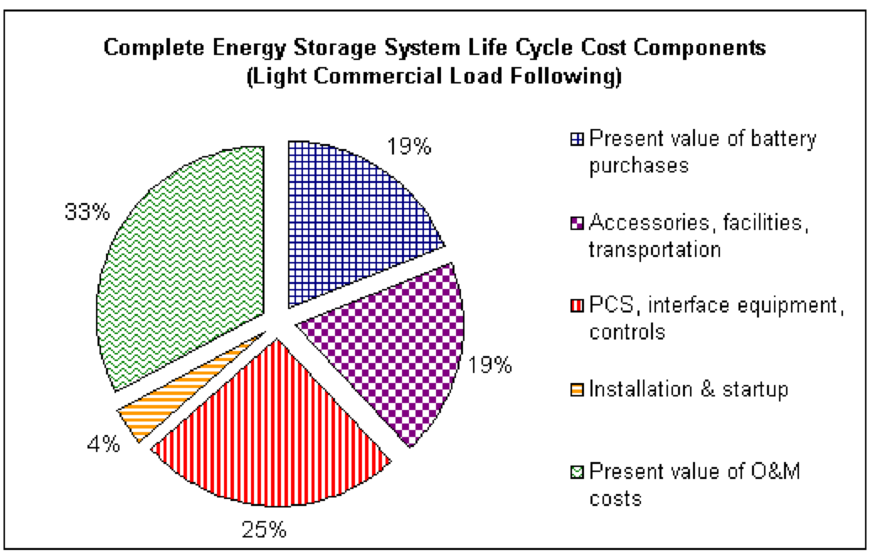

Figure 19. Primary cost drivers for light comm. load following

Load following is a fairly strenuous application, requiring nearly continuous low depth of discharge cycles superimposed on daily deep discharges. At higher buy-downs, battery life becomes increasingly important. Based on the projections made here, light commercial load following could support moderate buy-downs even at the somewhat short lifetimes expected given the application duty cycle. However, shorter than predicted battery lives combined with high buy-downs could push this application into the unlikely range.

6.1.7. Distributed node telecommunications standby power

The other commercial application that may show promise for the second use of EV batteries is distributed node telecommunications standby power. This application is a bit of a special case in this study in that the economic analysis considered only the batteries rather than a fully integrated energy storage system. This was done because it is likely that the used EV batteries will be used as a direct replacement for the VRLAs currently used for this application and will probably utilize existing electronics, wiring, containers, and other components.

Another difference between distributed node telecom standby power and the other applications considered in this study lies in how the economic benefit of the batteries was derived. For this application, the high and low estimates for the economic benefit derived from the used EV batteries were based on the cost range for VRLAs. Since the economic analysis for this study was conducted on a life cycle cost basis, the expected life of the VRLAs was needed to calculate the economic benefit of the batteries over the system life.

Unfortunately, definitively determining the life of VRLAs in distributed node telecom applications is impossible. Since they are being used for backup power, the batteries are not cycled frequently. Calendar life is typically the limiting factor that leads to battery replacement in this application. Variations between sites (temperature extremes, exposure to the elements, and other factors) and different batteries lead to a range of lifetimes.

To account for these variations, two cases were run in the analysis performed for this study in an attempt to bound expected battery lifetimes. The first case assumed a VRLA life of two years, and the second considered a five year life. These two cases lead to very different results, as shown below in Figure 20 and Figure 21.

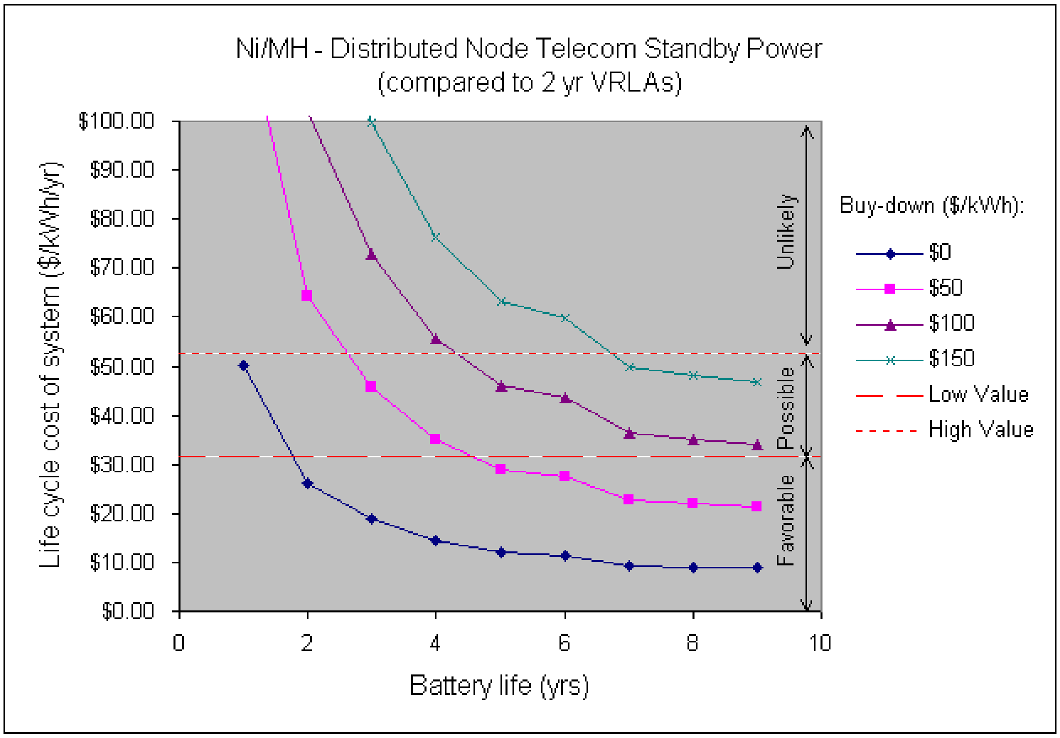

Figure 20. Life cycle cost curves for distributed node telecom standby power compared to VRLA batteries lasting two years

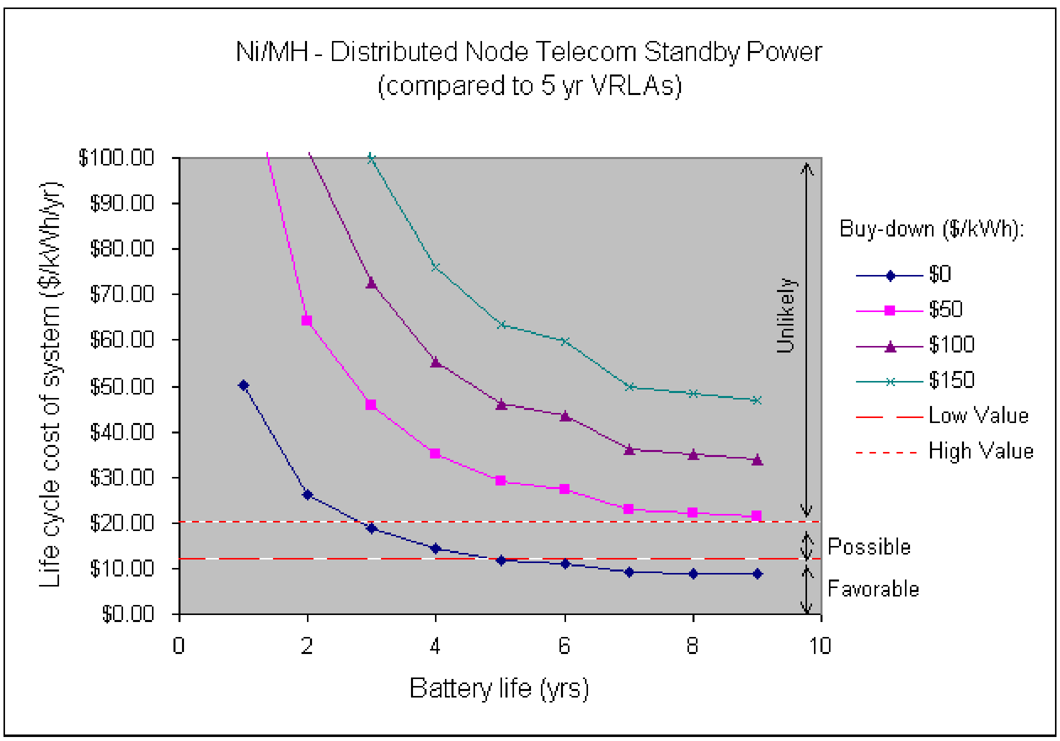

Figure 21. Life cycle cost curves for distributed node telecom standby power compared to VRLA batteries lasting five years

When compared to VRLAs that last five years, used Ni/MH EV batteries do not appear to be a good candidate for this application. The feasibility is only categorized as possible at low buy-down values and fairly long (four years or more) lifetimes. However, if the competing VRLAs last only two years, then under certain conditions the economic feasibility is classified as possible or even favorable. Since only the batteries are considered in the analysis for this application, there is a strong dependence on both buy-down cost and battery life. In general, if the used EV battery lasts significantly longer than the VRLAs (at least 50% longer), the application can support modest buy-downs. As the lifetime of the EV battery increases, the feasibility of the application improves and higher level buy-downs can be achieved.

6.1.8. Residential load following

The residential load following application appears promising. In fact, this is one of only two applications studied that generates a life cycle cost less than the low value estimate, classifying it as "favorable" (see Figure 22).

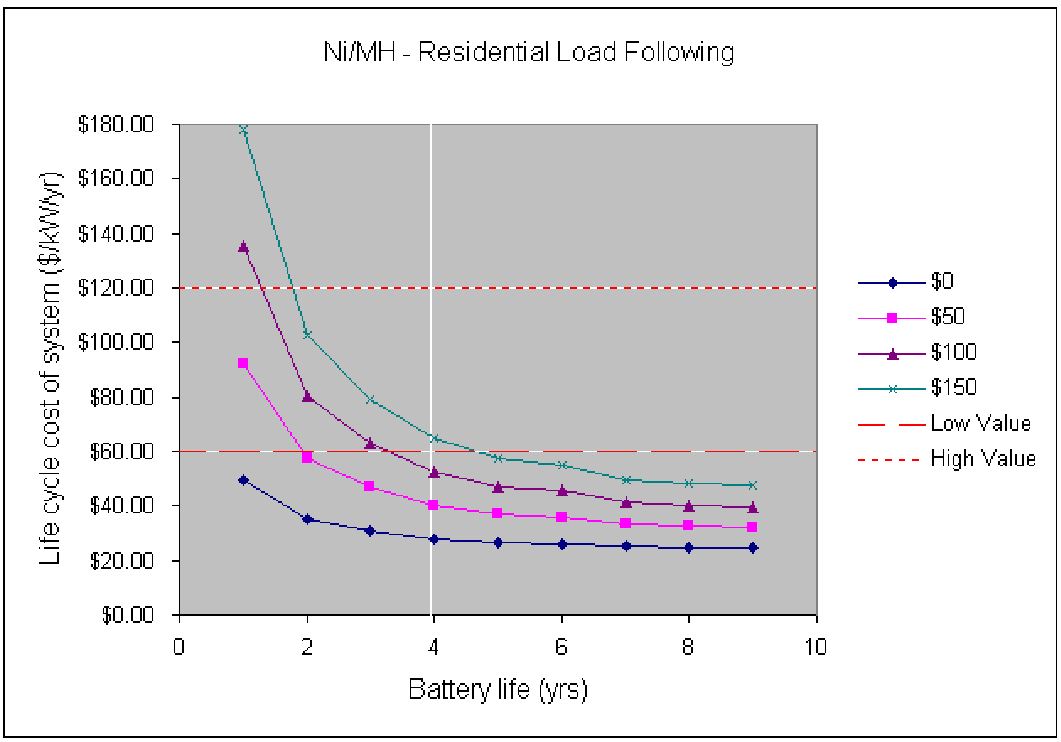

Figure 22. Life cycle cost of Ni/MH in residential application

The favorable economic predictions for this application are due in part to the low balance of system costs, illustrated in Figure 23. Since a residential load following battery will most likely be teamed with a distributed generator (such as a photovoltaic array or fuel cell), most of the necessary power electronics will already be in place. The only additional equipment required is a charge controller and possibly some switchgear. Furthermore, maintenance on these types of systems is expected to be very low.

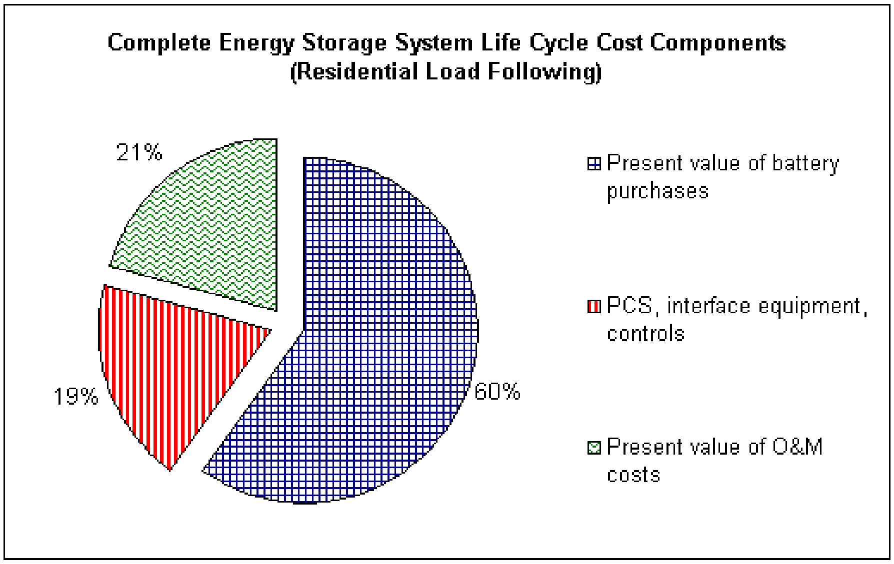

Figure 23. Primary cost drivers for residential load following

Due to these low BOS costs, the system cost for this application is very sensitive to the cost of the battery. At the projected life of four years, this application can accept buy-downs of up to $150/kWh and still be in the favorable range. However, as battery life decreases, the viability of the application drops off rapidly, particularly for high buy-downs. Still, this application probably represents the best opportunity for the second use of EV batteries. The biggest drawback to this application is that only a handful of modules are required to meet the application requirements, so a large number of customers would be required to provide a large enough market to handle the hundreds of thousands of EV battery modules that may reach the market.

There are also some questions regarding the maturity of the residential distributed generation market, and the widespread market penetration necessary to ensure a home for each used battery may not occur for a number of years.

6.2. Other chemistries

A number of battery chemistries have been considered in the past or are currently under development for electric vehicle use. Before the rise of nickel/metal hydride, most full function EVs were made with either lead-acid or nickel/cadmium batteries. Lead-acid batteries are still some of the least expensive and most widely used secondary batteries, and that will not likely change any time soon. In recent years, there has been a trend toward using advanced batteries in full-function EVs, although nearly all of the low-speed NEVs on the market utilize lead-acid batteries. Even so, it is unlikely that lead-acid batteries will find application in a second use scheme since very little benefit will be derived from using refurbished lead-acid EV batteries rather than new lead-acid batteries. In fact, new lead-acid batteries are low enough in cost that a refurbished EV battery could end up being more expensive after testing and repackaging than its new counterpart. Furthermore, limited life is one of the drawbacks of new lead-acid batteries, and this problem will only be compounded by exposing a battery to the environment found inside an EV for an extended period of time before it is placed in the stationary application.

Nickel/cadmium found extensive use in EVs in Europe, and has been mentioned as a candidate EV battery by at least one U.S. automaker. Even so, there is currently a big push by environmentalists in both Europe and the U.S. to ban the use of cadmium due to concerns regarding the final fate of the heavy metal after disposal. The European Union has already made moves to phase out the use of cadmium, and similar efforts are being pursued in the U.S. Thus, it is unlikely that Ni/Cd batteries will see much use in EVs in the future.

There are several other battery technologies under consideration for use in EVs. Lithium-ion (Li-ion) batteries in particular are receiving a great deal of interest due to their potentially high specific energy and specific power. To date, they have not yet proven capable of meeting the cycle/calendar life demands of electric vehicle applications. Lithium-polymer batteries are also under development for EVs, but these are further still from achieving cycle life performance goals. Since these batteries are still developmental in nature, the study team was unable to obtain much data from which to project the performance and life of these batteries in second applications.

Much of the analysis described in the previous sections of this report is independent of battery chemistry. In fact, all of the transportation, testing, and balance of system costs should be independent of the type of battery. Packaging cost is probably the only item that may change significantly from one technology to another. Li-ion modules, in particular, require electronics at the module and, possibly, even the cell level to prevent overcharge and cell reversal, both of which can lead to thermal runaway and possible catastrophic disassembly. Incorporation of these electronics into the stationary battery pack may add to the packaging costs. It is unclear at this point what types of electronics will be installed on Li-ion EV modules and how those will be integrated with the battery pack and the vehicle as a whole. It is possible that some of the electronics could be re-used in the stationary battery pack, which could reduce or eliminate the aforementioned increase in packaging costs. Regardless, packaging materials represent a fairly small part of the overall cost of the stationary battery pack, so it is unlikely that these changes will significantly affect the results of the analysis.

The only other inputs to the analysis that may change with battery chemistry are the battery capacity and the projected cycle and/or calendar life. Most EV modules currently under development have about the same rated capacity at the start of their lives, so the only major differences in performance over the 2^{nd} life will be due to capacity fade and remaining calendar life. The two sets of life cycle cost curves in the next two figures are based on “generic” 12-V 100-Ah EV modules. The modules are assumed to go through a vehicle life that is equivalent to 1000 DST cycles. The first module (Figure 24) is assumed to have a 10% fade in capacity over both lifetimes, leaving it at 90 Ah at the end of the stationary application. The second module (Figure 25) is assumed to fade 30% to 70 Ah under the same conditions. The four vertical white lines indicate cycle lives relative to the life in the vehicle. For example, the 0.25 line represents a module that operates for only 25% of the vehicle life, or about 250 cycles. Similarly, the 2.0 line identifies a module that operates for twice the vehicle life, or 2000 cycles.

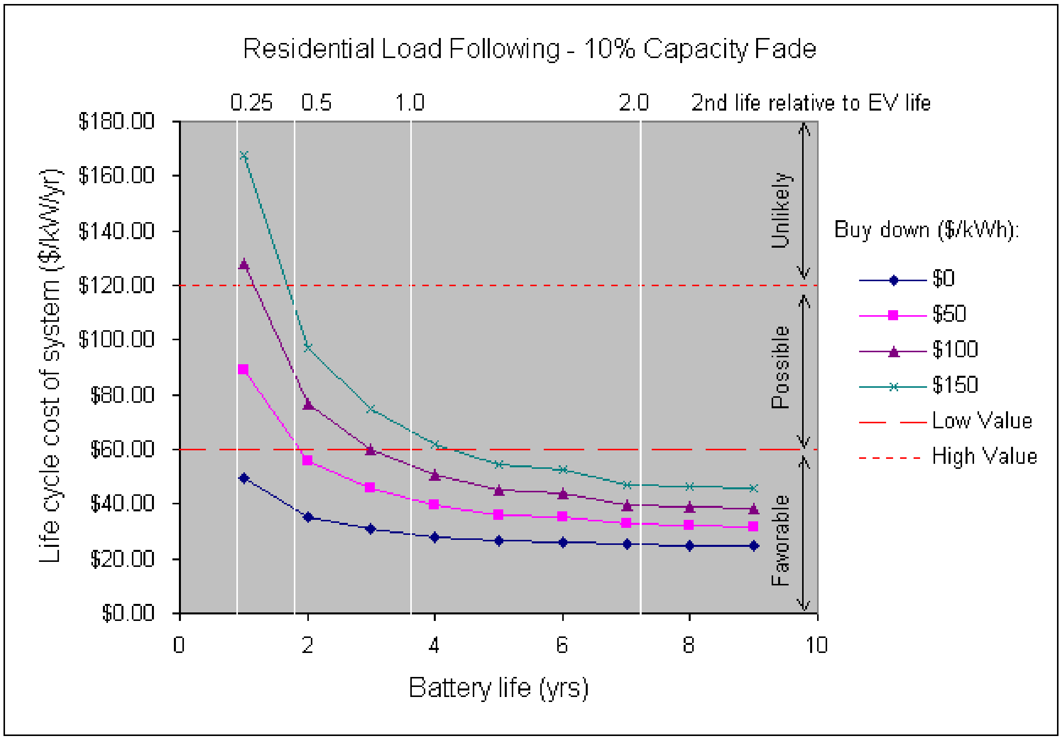

Figure 24. Life cycle cost curves for a generic 100Ah 12V EV battery that experiences a 10% capacity fade over its entire life

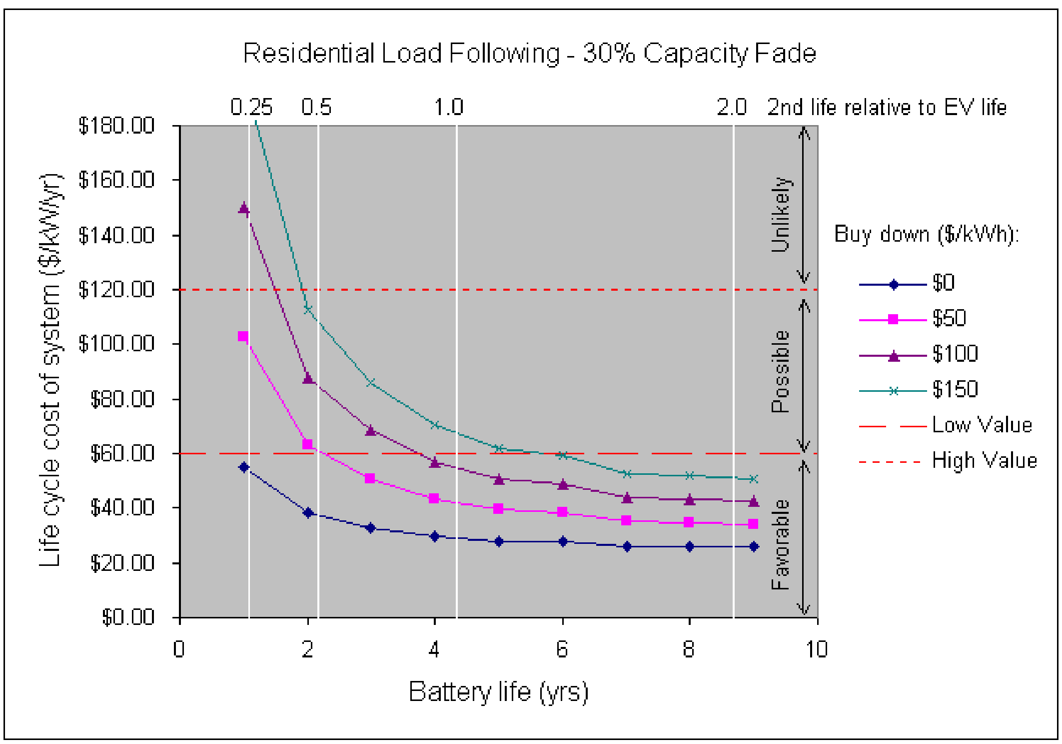

Figure 25. Life cycle cost curves for a generic 100Ah 12V EV battery that experiences a 30% capacity fade over its entire life

Comparing these two plots reveals very little difference between the economic feasibility of the two modules. In fact, the additional 20% change in capacity fade had only a marginal impact on the life cycle cost of the battery system. It also slightly shifted the projected lifetime in years for the various cycle life projections. It would appear that the analysis performed above for Ni/MH should hold for any battery chemistry that can provide a similar cycle life in the second application. Furthermore, the economic feasibility of the various applications is only affected when the life of the used EV module is very short (a year or less).

Unfortunately, the study team was unable to obtain cycle life projections for the more developmental battery technologies. Should such data be obtainable in the future, plotting the projected life on the figures developed for this report should give a good first order estimate of the economic feasibility of a second use for the battery module in question.

7. ISSUES AND BARRIERS

In the process of determining the technical and economic feasibility of using EV batteries in second applications, the study team identified several issues that may prove to be hurdles to battery reuse if they are not addressed. Some of these issues are technical in nature, while others are more economic or market oriented.

7.1. Technical

- *Lack of available battery life & performance data for modules coming out of EVs.* It is difficult to determine whether or not using EV batteries in second applications will work without more test data on the performance of modules after they are removed from vehicles. Life projections in the second application are compounded by the variability that can be expected in vehicle duty cycles, which will affect the cycle life, as well as climate extremes, which could impact calendar life. Definitive data on the spread of EV module capacities and power capabilities, as well as cycle life tests in second applications, will be required before second use of EV batteries can be considered feasible.
- *Difficulty in obtaining modules with similar capacities for matched strings.* The modules in a battery string need to have similar capacities in order to ensure maximized utilization of battery capacity and prevent possible damage to individual modules. This is particularly true for deep discharge applications, although it is less important for pulse power or low depth of discharge cycling. If the variability of the EV application described above results in a wide range of capacities in used EV modules, it may be difficult to obtain sufficient modules to assemble a matched string, particularly for larger applications.
- *Non-standardized battery modules.* Both of the aforementioned issues are compounded by the potentially large number of battery suppliers involved in the market. If every automaker uses a different module configuration, locating matched modules for assembly into packs, and matched packs for assembly into larger systems could prove difficult.
- *Integration of power electronics for Li-ion modules.* Li-ion cells are susceptible to thermal runaway and catastrophic failure during overcharge or cell reversal. Li-ion battery packs will likely have special electronics to prevent these conditions from occurring. These electronics will at least reside at the module level and may even be present at the cell level. When the used EV battery modules are reconfigured into stationary battery packs, these cell and module level electronics will either have to be integrated into the pack level electronics or replaced with similar components that can be interconnected with the rest of the battery management system. Since it is currently unclear exactly what a Li-ion EV battery module will look like, the implications of integrating these electronics on both the economic and technical feasibility of a battery reuse process were not determined in this study.

7.2. Market

- *Unclear chain of custody for an EV battery reuse process.* If the second use is to have any impact on the commercial viability of electric vehicles, the buy-down from the second use must find its way back to the vehicle purchaser. While this could take the form of a rebate at the time of battery trade-in, it is unlikely that most people would be willing to pay more upfront for the car based on the assumption that they will get their money back at a later date. The most effective approach would be to give the vehicle purchaser the discount up front. This could be accomplished in several ways.

1. The automaker could purchase the battery from a supplier at full price and not charge the vehicle owner for the entire cost of the battery based on the assumption that they will recoup the loss when they sell the battery into the second application.
2. Alternatively, the battery manufacturer could maintain custody of the battery for the entire vehicle life, and essentially lease it to the EV owner. When it is removed from the vehicle, the battery could then be reconfigured by the battery manufacturer and sold to a stationary application. However, one of the battery manufacturers consulted during this study expressed displeasure with the idea of leasing the battery or dealing with used EV battery modules.
3. The reconfiguring could also be performed by a third party who would then sell it to the stationary application user or a system integrator.

The point of all this is that there are a number of ways a battery reuse process could be carried out. While this does not necessarily create a barrier to the concept, a chain of custody will have to be established that results in reduced cost for the EV buyer and is acceptable to all parties involved. Chain of custody may also be important for determining warranties – who will warrant what to whom.

- *Warranty terms and costs.* Given the uncertainty in the used battery performance and life together with the lack of experience with some of the systems considered here, it will be difficult to establish warranties and budget for them appropriately. However, warranties will be absolutely essential to the success of any second use process. Simply put: no warranties, no sales.
- *Perceived value.* The utility industry places a premium on reliability and is notoriously skeptical of new technologies and unproven approaches. It is unlikely that utilities will readily buy into the concept of used batteries. Other potential customers may be more open-minded, but the perceived value of used goods may play an important role in the success of EV battery reuse.
- *EV production uncertainty.* Given the flexible nature of the mandates that currently appear to be driving EV production, the potential for other vehicle technologies (primarily fuel cells), and the whims of the consuming public, the future of battery electric vehicles is far from certain. As long as there is not a guaranteed stream of EV batteries, it will be difficult to convince anybody to invest in the facilities necessary to process EV batteries for a second use.

8. CONCLUSIONS

Overall, the concept of EV battery reuse appears to be a viable one. The study team did not come across any insurmountable technical barriers to the implementation of a second use scheme. In fact, during the course of the study it was learned that there is already considerable commercialization of used and reconditioned batteries. Furthermore, a study by Argonne National Laboratory examined the second use of Ni/MH EV batteries and showed that modules tested to end-of-life on the United States Advanced Battery Consortium (USABC) Dynamic Stress Test (DST) profile could provide performance competitive with new lead-acid batteries in stationary energy storage applications.

While there are no technical "show stoppers," there are some issues that will have to be dealt with before an EV battery second use scheme can be implemented. First, non-standardized battery modules and varying patterns of vehicle use could make assembly of matched strings of modules with similar capacities difficult. Second, the mechanism by which the value from the second use makes its way back to the EV buyer needs to be identified. Third, warranty terms and costs will be difficult to determine given the uncertainty in the performance and life of the used EV batteries. This is an important issue since warranties will be absolutely essential in achieving market acceptance of the batteries. Finally, the perceived value of used batteries relative to new batteries in the consumer's mind will have to be addressed to ensure widespread acceptance of used EV batteries.

Used EV batteries will most likely be available as individual modules rather than entire EV battery packs. These modules will have to be collected from vehicle dealerships or service centers, inspected to ensure physical and electrical integrity, tested to determine performance, and reconfigured into battery packs suitable for stationary applications.

The testing and reconfiguration process considered here is relatively simple, but essential for the success of the EV battery reuse concept. Testing is required to establish the capacity and power capabilities of the used EV modules. This information will be needed in designing the stationary battery system. It will also aid in predicting a module's remaining life, which will be necessary in establishing warranties. The labor and equipment required for EV battery testing and reconfiguration will represent a significant portion (roughly half) of the final selling price of the used EV modules into the second application.

In spite of the costs involved in the refurbishing process, EV battery reuse looks like it could be an economically viable concept. The economic analysis conducted for this study looked at the feasibility of applying used EV batteries in eight different stationary applications. Of these eight, the feasibility of applying used EV batteries in four of the applications (transmission support, light commercial load following, distributed node telecommunications backup power, and residential load following) was classified as either favorable or possible.

It should be noted that, for many of the applications considered, the battery was not the primary cost driver in the life cycle costs. Often the most expensive component of the system was the power conversion electronics or operating and maintenance costs. The cost of the battery alone is insufficient to determine the economic feasibility of a stationary energy storage system.

Surprisingly, the four applications classified as economically feasible do not have a lot in common. In fact, they include both the largest and the smallest of the battery sizes considered here. They also do not show any similarity in how much of the system cost is represented by the battery. It is difficult to draw any generalizations on application requirements, system sizes, or battery characteristics from the results shown here. It would appear that used EV battery/stationary application combinations have to be considered on a case-by-case basis.

Finally, there are sufficient uncertainties in the values used in this analysis (particularly in the performance of the batteries and the economic benefits derived from the applications) to warrant testing and demonstration of the concepts presented here. Potential testing and demonstration programs are detailed in the following section.

9. RECOMMENDATIONS

Based on the analyses performed for this study, using EV batteries in a second stationary application appears to be a viable concept. However, there are sufficient uncertainties and limitations in the scope of the present study to warrant additional work in this area. The largest unknown in any hypothetical second use process is the performance and life remaining in the battery when it is removed from the vehicle. While conversations with battery manufacturers indicate that some of this testing has been performed, at present there is no publicly available data regarding used EV battery characteristics. Any future programs seeking to further the reuse concept should include significant testing of modules taken from vehicles to characterize their performance and evaluate their capabilities under various stationary application duty cycles.

Implementation of second uses of EV batteries will also require proof of concept and early deployment programs to show potential investors that the idea is a valid one and to identify implementation difficulties. The analysis performed for this study indicates that future demonstrations should focus on four applications: transmission support, light commercial load following, residential load following, and distributed node telecommunications backup power. A description of possible programs and a cost estimate for each follows.

9.1. Used EV battery module testing

Due to the uncertainties in used EV battery performance, any demonstration program must be preceded by, or run concurrently with, a focused testing program designed to characterize the used modules and quantify their capabilities and lifetimes under stationary application load profiles. The testing should include a fairly large number of used modules to provide a statistically significant sample that could identify differences between chemistries, vehicle use patterns, and climate extremes.

9.2. Transmission support

Transmission Support	
Number of systems	1
Length of demonstration	3 months
EV battery modules	600
Equivalent EV battery packs	24
System storage capacity	650 kWh
System rated power	3.2 MW

While transmission support proved to be the most economically viable utility scale application in the analysis for this study, it will also be one of the most difficult to demonstrate. Based on the assumptions used here, a 100 MW transmission support system would require over 17,000 used EV modules, which would require the batteries from nearly 700 vehicles. In fact, no automaker has sold more than 1,000 full function EVs with the same battery. Thus, it is unlikely that more than 10,000 or so of the same battery module would be available for demonstration programs in the near term.

However, a bench-scale test of used EV modules under a simulated transmission support load profile would be insufficient to prove the validity of the concept. One of the biggest challenges in deploying used batteries for this application is showing that large numbers of modules can be strung together, and large numbers of strings can be interconnected in a reliable fashion to generate high voltages and meet the high current demands for the application. Thus, any demonstration for this application should involve a battery system with a voltage over a thousand volts, comprised of several strings containing hundreds of modules each.

A reduced scale system would be unable to meet the needs of a real world transmission support application. Furthermore, it is unlikely that any utility would be willing to potentially jeopardize the integrity of a transmission asset to demonstrate an unproven concept utilizing used components. Therefore, any demonstration of this concept will likely rely on testing in a laboratory setting with sophisticated simulation equipment. There are a number of facilities located in the U.S. and Europe that perform testing and validation of transmission equipment. It is likely that any of these could handle the types of tests required to put a battery system for transmission support through its paces.

The study team recommends a program including the design, assembly, and testing of a reduced scale battery system for transmission support. The system should be comprised of roughly 600 battery modules, divided into three strings of 200 modules each. Such a design would generate 2400V, store about 650 kWh, and be capable of a pulse power output of around 3.2 MW. The battery should be integrated with the necessary electronics, monitors, and controls and installed at a transmission equipment test facility for several months of testing under simulated transmission support conditions.

The first step in this program should involve identifying partners and locations for both obtaining used EV batteries and performing the testing. It is likely that the modules from these batteries could be obtained free of charge from automakers or battery manufacturers through some sort of cost sharing partnership. After it is clear that sufficient EV battery modules are available, system design and component procurement can proceed. As with all of the demonstration programs, the used EV battery modules should be characterized before they are assembled into the energy storage system. Assembly and integration of the system will probably occur onsite at the testing facility. Several months of testing will be required to characterize the capabilities of the battery system and identify potential problems with actual installations. Since transmission support is primarily a pulse power application, the life of the batteries will be limited by calendar life issues, not cycle life limitations. Therefore, parallel accelerated calendar life testing may be of interest. Once testing is completed, the results of the program should be analyzed and reported.

A summary of these steps and the costs associated with them is shown below.

Activity	**Cost**
1. Identify partners and site for testing	$50,000
2. Obtain used EV modules of the same type	Cost share
3. Design system	$200,000
4. Obtain the balance of system components	
PCS, interface equipment, controls and monitors	$2,870,000
Interconnects, racking, cooling	$175,000
5. Perform baseline performance tests to characterize the modules	$600,000
7. Assemble and install system	$100,000
8. Perform system testing	$85,000
9. Analyze success of system; identify barriers to implementation and quantify value	$50,000
TOTAL	**$4,130,000**

9.3. Light commercial load following

Light Commercial Load Following	
Number of systems	5
Length of demonstrations	2 years
EV battery modules/system	100
Equivalent EV battery packs	4
System storage capacity	110 kWh
System rated power	200 kW

In a light commercial load following application, the battery system is utilized to allow a distributed generator to operate at or near constant loading. This is typically a more efficient mode of operation for the generator, and it can significantly reduce the size (and cost) of the distributed generator since it does not have to meet the entire peak load. When operating in a grid-connected mode, a battery can be used to avoid demand charges.

The demonstration program for this application should include several installations to test the use of the battery with an array of different distributed generation technologies, such as microturbines, fuel cells, and fossil-fueled gensets. The study team recommends a total of five installations, the demonstration at each site lasting for two years. Each system will utilize roughly 100 used EV battery modules, contain about 100 kWh of storage capacity, and generate around 200 kW of peak power. Exact values for these system parameters will depend on the needs of the site where the system is installed.

The first step in mounting this demonstration program will be to identify sites and partners for installing the battery systems. Facilities operating under rate structures with high on-peak electricity charges or high demand charges should be the focus of this effort. This application offers an interesting opportunity for leveraging R&D funds with other DOE programs seeking to demonstrate distributed generation (DG) in a light commercial setting. Sites already selected for DG projects could be retrofitted with refurbished EV batteries. Alternatively, a system could be designed from the ground up in partnership with a DG demonstration program.

Once sites and partners have been selected, the energy battery systems will need to be designed. It is likely that each site will require a different system, depending upon the DG technology in use and the application load profile. After the designs are completed, the system components will have to be procured. It is likely that the EV battery modules could be obtained through some sort of cost-sharing arrangement with an EV battery manufacturer or automaker. Furthermore, the distributed generator could be purchased by another DOE program. Depending on the distributed generator technology, it may be possible to integrate the battery system with the electronics built into the generator to minimize the cost of the power electronics. The costs of the facility to house the energy storage system (which could be as simple as a space in the basement of the building or a trailer parked outside) would probably be provided as a cost share by the owner/operator of the property where the system is installed.

Once the EV batteries have been characterized, the system can be assembled. While the batteries could be connected together and placed in some sort of shipping container elsewhere, integration of the generator into the system will probably have to occur onsite. After the site has been prepared, system installation, startup, and shakedown can proceed. This will probably take a couple of weeks of labor from an engineer and a technician.

During operation, system performance can be monitored autonomously, but occasional visits for data collection and analysis will be required over the two year operating period. Regular and unscheduled maintenance visits will also be necessary to keep the system operating in an optimum manner. The study team figures that a one day visit to each site once a week by an engineer familiar with the system would be sufficient to monitor system operation and handle maintenance issues. At the end of the two years, a report analyzing the success of all five systems and identifying pitfalls and unsuspected problems should be generated.

The estimated costs for all of these steps are summarized below.

Activity	Cost/system	Total cost
1. Identify partners and site for demonstration	----	$50,000
2. Design system	$50,000	$250,000
3. Obtain used EV modules of the same type	cost share	
4. Obtain the balance of system components		
Generator	cost share	
PCS, interface equipment, controls and monitors	$130,000	$650,000
Interconnects, racking, cooling	$21,000	$105,000
Facility	cost share	
5. Perform baseline performance tests to characterize the modules	$100,000	$500,000
6. Assemble system	$100,000	$500,000
7. Prepare site, install and test system	$14,000	$70,000
8. Monitor and maintain system	$120,000	$600,000
9. Analyze success of system; identify problems and quantify value	----	$50,000
TOTAL	$485,000	**$2,775,000**

9.4. Residential load following

Residential Load Following	
Number of systems	10
Length of demonstrations	2 years
EV battery modules/system	5
Equivalent EV battery packs	0.2
System storage capacity	5 kWh
System rated power	10 kW

This application is much like light commercial load following, only on a smaller scale. In addition to the microturbines, fuel cells, and fossil-fuel gensets mentioned above, residential load following could also involve renewable generators such as PV or possibly even a small wind turbine. We would recommend at least four types of systems for demonstration:

1. grid-connected household with a roof-top PV array and net metering
2. off-grid household with PV
3. off-grid household with a propane genset (and possibly wind or PV)
4. off-grid household with a fuel cell

In all, a total of ten systems would be desirable. Each system would consist of 5 or so EV battery modules, with a total capacity of about 5 kWh and a rated power of around 10 kW. At this size, ten systems would be feasible. Two year tests would be desirable to show the operation of the system over varying seasons and prove its long term durability.

As with all the demonstrations suggested here, the first step will be to identify partners and locations for potential installations. Much as with light commercial load following, opportunities for synergies with other government and commercial programs exist for this application. Several fuel cell companies are in the process of testing and demonstrating prototype fuel cell systems for residential power generation, and they may be willing to utilize used EV battery modules in their systems. The Department of Defense is ramping up a residential fuel cell demonstration program at bases across the country. And Texaco Ovonic Battery Co. is already installing used EV battery modules with PV arrays in remote Mexican villages. Leveraging funds and facilities with these programs could significantly reduce the costs of installing a demonstration system.

Unlike the other demonstration programs described here, the battery systems designed for each of the residential sites would probably be quite similar. To reduce costs, the study team recommends that a single battery system be designed for integration into a number of residential distributed generation systems. This system could be assembled into a box or two at a central facility and shipped to the application site for integration into the generating system. Some residential generators may already have power electronics capable of handling the battery system, although others will require additional components. It is possible that cost of the electronics, controls, and monitors will have to be borne by the demonstration program, but the distributed generator and any facility costs will likely be covered through cost-sharing partnerships with other DOE programs or with the end user of the system. The used EV batteries will probably also be obtained free of charge through a cost share from a battery or vehicle manufacturer.

After the system design is complete and the components are obtained, the batteries can be tested and assembled into a self contained system at some central facility. It is assumed here that assembly of the battery systems and initial shakedown will take about a week for an engineer and a technician. After this initial checkout, the system will be ready for transport to the application site. Another week of labor will be required to integrate the battery system with the generator and test the entire power system.

Monitoring, maintenance, and repair will be required once the system is up and running. Most of the monitoring for these systems could be done offsite, and an allowance for telemetry was included in the cost estimate for monitors and controls given below. Each site should only take a half day or so of an engineer's time to analyze the performance of the system once a week. An additional visit to the site once every two months should cover any regular maintenance or unscheduled maintenance for each site. All of these functions should be continued for the entire two years of the demonstration. When the two years are completed, a report summarizing the performance of all the systems and analyzing their economic benefits should be produced.

All of these steps and their approximate costs are summarized below.

Activity	**Cost/system**	**Total cost**
1. Identify partners and site for demonstration	----	$50,000
2. Design system	----	$50,000
3. Obtain used EV modules of the same type	cost share	
4. Obtain the balance of system components		
Generator	cost share	
PCS, interface equipment, controls and monitors, interconnects, racking	$20,000	$200,000
Facility	cost share	
5. Perform baseline performance tests to characterize the modules	$5,000	$50,000
6. Assemble system	$5,000	$50,000
7. Prepare site, install and test system	$7,000	$70,000
8. Monitor and maintain system	$48,000	$480,000
9. Analyze success of system; identify problems and quantify value	----	$50,000
TOTAL	$83,000	**$1,000,000**

9.5. Distributed node telecomm

Distributed Node Telecom Backup Power	
Number of systems	
Phase I	1
Phase II	9
Length of demonstrations	
Phase I	1 year
Phase II	2 years
EV battery modules/system	48
Equivalent EV battery packs	2
System storage capacity	52 kWh
System rated power	5 kW

Unlike the other three applications mentioned in this section, distributed node telecommunications backup power has a well-established market currently being met by batteries. This application offers a potential early entry market for used EV batteries. It also presents the opportunity to work alongside with the potential end users of the battery system to accurately specify the application requirements, design a system that meets their needs, and test it in real-world situations alongside competing technologies. However, distributed node telecomm standby power requires an extremely reliable battery system. Before telecommunications companies are willing to accept used EV batteries as a replacement for the new VRLAs they current use in this application, they will have to be convinced of the reliability and durability of these batteries.

The study team recommends a two phase demonstration program designed to show that used EV batteries can meet the needs of this application in a reliable fashion. Furthermore, this program should be run in such a way as to minimize both the risk and the cost to the telecommunications company that is involved.

The first phase of the demonstration program will consist of prototype design, assembly, and testing. Since it is unlikely that telecommunications companies will be willing to install an unproven system in the field, this prototype will be put under extensive testing at a telecom company test facility for about a year. During this testing period, the prototype system will be operated under a wide range of conditions to monitor its performance and ensure it will function as designed under all the conditions it would be expected to encounter in actual installations. If Phase I is successful, the program will proceed with Phase II, in which 9 battery systems will be placed in the field for two years and carefully monitored.

As with all of the programs recommended here, the first step will be to identify partners and sites for the demonstration. The telecommunications company will be a particularly key player, and will need to be identified early in the process to ensure involvement in all facets of the program.

Once the players have been identified, the engineering team can work closely with the telecommunications company to design a system that meets their needs. This will be followed by procurement of the various components for one system. As with the other programs, the EV batteries could be obtained free of charge through a cost sharing agreement with either a battery manufacturer or automaker. It is assumed that most of the rest of the system components will be provided as a cost share from the telecommunications company since the system will have to be integrated into their equipment. There is an allowance for monitors and telemetry included in the budget estimate for this program since these systems will likely be heavily instrumented to monitor their behavior.

Once the first set of battery modules has been benchmarked, it will be ready for integration into the prototype. It is assumed here that assembly will take approximately two weeks of labor from an engineer and a technician, and shakedown will take another two weeks. Once the system has been checked out, it will be ready for testing by whatever protocols the telecommunications representatives recommend. This is expected to take about one day per week of time from an engineer working onsite at the test facility to monitor the system performance, set up tests, move the system around if necessary, and perform maintenance or repairs.

After Phase I has been successfully completed, the prototype system design can be evaluated to identify necessary improvements. The materials for the nine Phase II systems can be obtained from the same sources used for the prototype system. After battery benchmarking, the second set of systems can be assembled and tested, which is predicted to take a total of two weeks for each system. Installation in the field should take a day or so. Monitoring will most likely be performed at a central facility via telemetry installed in the battery system and should only require a couple of days a week to analyze the data from all the systems. One maintenance or repair visit is scheduled each month to meet the needs of all the systems.

Finally, once the second phase of the project reaches completion, a report analyzing the performance and economics of the used EV batteries in this application should be generated. The steps involved in both Phases and their estimated costs are summarized below.

Activity	**Cost/system**	**Total cost**
1. Identify partners and site for demonstration	----	$50,000
2. Design system	----	$50,000
3. Obtain used EV modules of the same type	cost share	
4. Obtain the balance of system components		
PCS, interface equipment, controls and monitors	$1,000	$10,000
Interconnects, racking, cooling	cost share from telecom	
Facility		
5. Perform baseline performance tests to characterize the modules	$48,000	$480,000
6. Assemble & test prototype	----	$61,000
7. Assemble remaining systems	$9,900	$99,000
8. Prepare site, install and test systems	$2,100	$21,000
9. Monitor and maintain systems	----	$182,000
10. Analyze success of systems; identify problems and quantify value	----	$50,000
TOTAL	$37,000	**$1,218,000**

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APPENDIX A:
INTERIM REPORT ON BATTERY REUSE INFORMATION SEARCH

Introduction

The current high cost of batteries is a major barrier hindering the more widespread adoption of electric vehicles (EVs) and hybrid-electric vehicles (HEVs). Most efforts addressing this obstacle consist of research and development aimed at reducing the cost of producing EV and HEV batteries. With support from Sandia National Laboratories, this study is examining another often overlooked opportunity: the potential for recovering some of the original value from a battery that has served its useful life in an electric or hybrid-electric vehicle, but which is still suitable for another application. The premise is that the battery could be refurbished, resold, and reused for another application, and some of the initial cost recovered through the sale of the battery in a secondary market. The objective of this study is to determine the technical and economic feasibility of reusing spent EV and HEV batteries, and to identify potential stationary applications.

Methodology

A literature search was conducted as part of this study. Originally, it was to focus solely on EV and HEV batteries. The scope of the search was expanded, however, to also include the reuse of batteries taken from non-EV/HEV applications during their first lifetime. Very few electric vehicles (EVs) and hybrid-electric vehicles (HEVs) have been commercialized to date, and far fewer have had their batteries reach end of life. Consequently, few EV and HEV batteries have been removed from vehicles and sold or used in a secondary market. It was assumed that knowledge gained on existing secondary markets for other batteries would be useful to determine the feasibility of establishing a secondary market for spent EV and HEV batteries.

The literature search involved making personal contacts by phone and/or e-mail, and conducting literature and Internet searches. Contacts were made with organizations and companies dealing with electric and hybrid-electric vehicles, or which install battery renewable energy systems, to determine if they knew of any secondary battery markets. Searches on the Internet as well as through non-peer-reviewed publications were conducted on the secondary use of batteries. In addition, publicly available online databases (such as SciFinder© and INSPEC©) were used to search peer-reviewed publications for information on EV/HEV battery reuse as well as issues surrounding cycle life and performance degradation in EV and HEV batteries.

Summary of results

The study findings demonstrate that there is considerable commercialization of used and reconditioned batteries, including batteries from EVs:

- Amateur radio emergency operators acquire used gel cell lead-acid batteries from hospitals.
- There is established commerce in used off-lease forklift batteries, reconditioned automotive starting, lighting, and ignition (SLI) batteries, and reconditioned lithium-ion batteries for laptop computers, as well as batteries with various chemistries for energy storage in small renewable energy systems.
- AC Propulsion, a small-volume electric vehicle manufacturer, is implementing a successful secondary market for spent Optima® deep-cycle spiral-wound recombinant lead-acid batteries.
- Energy Conversion Devices, a manufacturer of both solar photovoltaic modules and nickel/metal hydride (Ni/MH) batteries, is participating in a solar program in Mexico, which incorporates used Ni/MH EV batteries taken from EV bench tests and prototype EVs.
- Argonne National Laboratory conducted a study in 1996-1997 for the United States Advanced Battery Consortium (USABC), examining the second use of Ni/MH EV batteries. The study demonstrated that there is merit in considering the reuse of EV batteries for other applications.

Second Use of Electric and Hybrid-Electric Vehicle Batteries

A small secondary market for various battery chemistries exists for a range of applications. The most extensive secondary market is for lead-acid batteries, several types of which are being reused in a number of applications.

Comprehensive Automotive Reclamation Services (CARS) of Maryland, a Baltimore company that disassembles used and damaged cars and light trucks, added reclaiming and reselling lead-acid batteries after purchasing a Pulsetech digital battery analyzer to determine which batteries had bad cells and which could be reused. CARS of Maryland shifted from recycling all the batteries, earning about $1.50 each, to reselling reconditioned batteries for about $25 each. "In just one month, CARS of Maryland has recovered about 500 batteries using the Pulse Recovery System™. The company can now resell these batteries to new markets such as cab and other fleet customers." [1]

International Business Club, a Canadian company, acts as a broker for business opportunities, including reconditioning automotive lead-acid batteries. [2] Its website provides information on services the company provides to set up a battery reconditioning business. Few technical details on how to recondition batteries or on their Batteries Tech 2000 reconditioning system are provided other than the statement that Batteries Tech 2000 can recondition 10 batteries simultaneously in a period of 20 hours. They have reconditioned and sold more than 25,000 batteries over the past three years. All batteries were sold with 6- to 12-month warranties, and less than 5% of the reconditioned batteries were returned. Defective batteries were replaced with reconditioned batteries. Battery recyclers were one source where they received their batteries to recondition. Their customers have included used automobile dealers, new and used auto parts dealers, fleet owners, retailers of trucks and heavy equipment, and to a lesser extent golf courses.

Hospitals regularly replace sealed lead-acid (SLA) batteries (gel cells) used to power medical diagnostic instruments, alarm systems, and uninterruptible power sources (UPS) on a fixed schedule before they are worn out. These batteries often can be obtained for free to power emergency communications activity. An Amateur Radio Emergency Service (ARES) member gives advice to other members on how to inspect, recharge, and test donated gel cells. [3]

> Inspection: Check out open circuit voltage to expedite distribution by sorting out batteries, which may be load tested immediately. Any 12-volt batteries having an open circuit voltage (Voc) of 12.8 V or greater are ready for load testing. Those with Voc of less than 12.8 V are charged by connecting in parallel across a regulated 13.8-V power supply. Any that are not accepting charge after 4 hours are discarded. Total charging should not exceed 140% of capacity.
>
> Testing: Batteries which accept charge to Voc greater than or equal to 12.8 V must still be load tested after recharging. An easy quick check is to apply a load in amperes which approximates battery capacity in amp-hours, for 10 seconds, monitoring voltage drop. In a "good" battery the voltage drops, but quickly stabilizes after a few seconds, does not continue to fall and recovers within a few seconds after the load is removed. The author has gotten reliable service from 12-V batteries that don't drop below 11.7 V at "C" load for 10 seconds.
>
> If time is available, and there is only a small number of batteries, a better test is to approximate a continuous work load for at least a full minute. The author tests 12-V batteries up to 2 Ah with an 8-W fluorescent light at 0.6-A load. Larger ones up to 10 Ah can use a 12-V, 50-W incandescent lamp at 4-A load. For larger batteries, connect the test battery to the intended transmitter and the transmitter to a nonradiating dummy load, monitoring voltage drop for a minute of full-power key-down. Accept for reissue batteries which do not exhibit more than 0.5-V voltage drop at normal working load and duty cycle. From the author's personal experience, one in ten donated batteries is rejected and recycled. When subjecting a battery to a current load which exceeds C/5, or 1/5, of its amp-hour capacity, expect a 25-30% reduction in its delivered capacity. At lower temperatures available capacity is further reduced. Lead-acid batteries typically lose 50% of their capacity at 32° F!

A ham radio operator and member of the Electric Vehicle Association of Washington, DC confirmed that ham radio operators often use used 12-volt gel cell batteries. [4]

Deep-cycle lead-acid batteries are commonly found in secondary markets. A member of the Electric Vehicle Association of Washington, DC, who is starting to design his own three-wheel EV, said that a store, Battery Warehouse on Gude Drive in Alexandria, Virginia, sells used batteries, such as forklift batteries. [4]

SURPLUS TRADERS, a major buyer and importer of manufacturers' excess inventories, maintains a business-to-business website aimed at redistributing these materials to manufacturers, exporters and large quantity users. [5] On 9/18/01 there was the following posting: "FORK LIFT BATTERIES WANTED: We have buyers for off-lease and surplus forklift batteries in usable condition and forklift battery chargers in any condition."

AC Propulsion, developer of the "tzero" high-performance electric sports car about to enter small-volume production reported that it has implemented a very successful secondary market for spent Optima® yellow top batteries. The used EV batteries are "sold for SLI (starting, lighting, and ignition) application at $25 each—about 25% of the original cost—with a two-year warranty." [6] pp 9-10.

One typical application for used EV and HEV batteries is a small renewable energy system. According to Richard Perez [7] of *Home Power* magazine, a publication devoted to helping individuals set up and operate small renewable energy systems, dozens of articles on used batteries have appeared in the do-it-yourself renewable energy magazine over the years.

One homeowner, for example, recently reported on his successful use of used C&D lead-acid batteries in his stand-alone solar-electric photovoltaic (PV) home system. [8] He had acquired these batteries as surplus from telephone company backup service in 1983 when they were five years old. After having been told frequently that his batteries must be about to crash or were somehow unfit to rely on, he decided to conduct a drawdown and load test run. The homeowner contacted the battery manufacturer in Pennsylvania and identified his battery bank as consisting of C&D KCT-720 cells rated at 720 Ah at the 8-hour rate, or 882 Ah at the 20-hour rate. In April 1999, he disconnected the PV array and turned on many of the household loads to discharge the battery to a 20 percent state of charge, which he achieved after 4 days. He then turned on all the lights in the house, and loaded the inverter with the freezer and the deep-well pump to test whether the voltage would hold up to keep the Trace SW4024 inverter on for all essential services. He then added a 1-kW hotplate to the load. The voltage held at 21.4 volts under a 104-amp load on the severely discharged batteries. The test was successful, with the inverter operating without failure. He then shut down all the loads, reconnected the PV system, and began charging the battery at a 10-amp rate. After four variably sunny days, the battery was fully charged. The doomsayers who said the homeowner's system was about to crash were proven wrong, since he indicated that the batteries performed normally during the two years since the test.

Oasis Montana Inc. Alternative Energy Supply and Design maintains a website that sells surplus and used renewable energy components, including used batteries. [9] On 9/18/01 there was a posting for "16 Marathon 12V 125Ah Batteries. Approx. 12 years old." The origin of the batteries was not given except to indicate that they are located in Saskatchewan, Canada.

Paul Hess at the Energy Efficiency and Renewable Energy Clearinghouse, the U.S. Department of Energy's clearinghouse for information on energy efficiency and renewable energy, indicated that he had met someone who was at Solar Energy International in Carbondale, CO about 10 years ago who reconditioned batteries and resold them for renewable energy systems. [10]

Solar Energy International (SEI), which installs small renewable energy systems and conducts training courses on teaching others how to do installation, reported that the battery distributor formerly located in Colorado closed his marginal operation several years ago. [11]

Peter Lowenthal, of the Solar Energy Industries Association, the trade association of U.S. solar energy companies, reported that many of the batteries in small renewable energy systems in developing countries are lead-acid, either automotive starting, lighting, and ignition (SLI) or deep-cycle lead-acid. Often they are poorly maintained or abused, are discharged extensively, and are not adequately charged before the next usage. [12]

In addition to deep-cycle lead-acid batteries, commercial and concept electric vehicles employ nickel/metal hydride and lithium batteries. In Europe, nickel/cadmium batteries are commonly used as well. Hugh Marrow of the International Cadmium Association reported by phone that used nickel/cadmium batteries develop high impedance, but can be used for low drain applications for as long as 10 more years after no longer being of use in EVs. [13]

Jade Mountain, a company specializing in the retail of renewable energy products and systems, several years ago had reconditioned batteries for sale: nickel/cadmium, nickel/iron, and Ni/MH batteries. [14] They stopped selling them because of low demand and difficulty in obtaining supply. "Problem was that we couldn't afford to stock expensive, slow-selling products such as this, and the supply wasn't too reliable, so when orders finally came in, we'd typically find that there were no batteries to be had," they reported by e-mail.

Both the editor of EV World®, a website specializing in electric and hybrid electric vehicles, and the President of the Electric Vehicle Association of Washington, DC, indicated that Energy Conversion Devices was exploring a secondary use for their used Ni/MH batteries. [15] [16] Energy Conversion Devices, a manufacturer of both solar photovoltaic modules and nickel/metal hydride (Ni/MH) batteries, reported by telephone that they are participating in a solar program in Mexico which incorporates Ni/MH EV batteries that have completed lab testing or useful life in prototype EVs. [17]

Dell Computer, a computer retailer, sells refurbished lithium-ion batteries for laptop computers on its website: <http://www.dell.com/us/en/gen/default.htm>. [18] A search conducted on September 26, 2001 on "Reconditioned batteries" at their Home and Home Office use site, <http://accessories.us.dell.com/sna/index.asp?customer_id=19>, produced seven hits on refurbished lithium-ion batteries for sale.

In order to get an idea of how these refurbished batteries differ in price and warranty from new batteries, the prices for these refurbished lithium-ion batteries were compared to prices for new, comparable lithium-ion batteries listed for the same Dell laptop computers. In some cases, the watt-hour listing on the Dell refurbished batteries differed slightly from the amp-hour and voltage ratings listed by the other two retailers.

Table 1. Price Comparison for New vs. Refurbished Computer Batteries

Dell Laptop Computer Model	Dell Computer[1] (refurbished)	Batteries Direct[2] (new)	Raymond Sarrio[3] (new)
Inspiron 3000 (~40Wh)	$89.95		$189.00
Inspiron 3500 (~45 Wh)	$119.00	$189.00	
Inspiron 5000 (~52 Wh)	$84.95	$129.00	
Latitude CS (~50 Wh)	$109.00	$189.00	
Latitude LM (~42 Wh)	$129.00	$194.00	$179.00

Notes to Table 1:

[1]Dell provides free 3-5 Day Ground shipping. No warranty information is provided on the refurbished batteries, or explanations of how they "refurbish" the batteries.

[2]Batteries Direct (<http://batteriesdirect.com>) provides free Standard Delivery (4-7 days) and charges $3.95 for 2-3 Days Priority Delivery. Laptop computer batteries are covered by a PRORATED one-year warranty from the date of purchase.

[3]The Raymond Sarrio Company (<www.sarrio.com>) provides a 30-day "no questions asked return policy" and a 1-year warranty against defects on all batteries sold. They also provide free UPS 3-Day Select shipping anywhere in the continental United States.

Of major interest is a study conducted by Argonne National Laboratory between September 1996 and August 1997 for the United States Advanced Battery Consortium (USABC) that examined the second use of Ni/MH EV batteries. [19] Tests were conducted on eight Ovonic Battery Company (OBC) Ni/MH batteries that had completed more than 500 Dynamic Stress Test life cycles, simulating EV lifetime usage. Modules were tested to determine their performance relative to that of lead-acid modules in five non-EV applications: 1) utility load following; 2) utility frequency regulation and spinning reserve; 3) commercial and industrial off-road vehicles; 4) uninterruptible power sources (UPS) for stand-by power; and 5) accelerated life testing. Test results on the reused EV batteries were compared to lead-acid battery test data or warranties supplied on lead-acid batteries by the manufacturer for the specific applications on which they were tested.

The OBC batteries were initially tested for performance, their module-rated capacities were reduced, and they were selected for specific application tests. The specific energy range to be examined in the study was determined by reviewing previous EPRI lead-acid battery test data. Standard production lead-acid units had a specific energy of approximately 30 Wh/kg (Hawker and Optima® batteries), and advanced technology lead-acid units were approximately 45 Wh/kg, which was the best measured for the Electrosource Horizon® battery. Two of the OBC Ni/MH modules were derated to 30 Wh/kg, and the remaining six were derated to 45 Wh/kg.

1) The utility load follow tests were based on tests used by Pacific Gas and Electric Company (PG&E) to characterize the PM250 Power Management System. The OBC modules were put through repeated 3 hour sine-wave discharges to 80% depth of discharge followed by charges to 100% SOC. They were also subjected to periodic (every 10 cycles) 1-hour constant power discharges at the 1-hour rate. One each of the standard and advanced technology derated modules were put through 250 load follow cycles. The standard technology derated module completed all 250 load follow cycles and a total of 294 deep discharge cycles; the advanced technology derated module only

completed 133 load follow cycles before failing on a constant power discharge. However, this still accounted for a total of 162 deep discharge cycles to end of life (EOL), which was far better than the 72 cycles performed by the Delco-Remy lead-acid modules tested by PG&E.

2) Two more OBC modules (one each of the advanced technology and standard technology derated modules) were tested under the Sandia National Laboratories (SNL) Utility Energy Storage (UES) test cycle. Developed to model the expected duty cycle of the 20-MW Battery Energy Storage system installed by the Puerto Rico Electric Power Authority (PREPA), the UES cycle contained three 50-hour-long frequency regulation sessions separated by intermediate charges. These sessions were followed by a spinning reserve discharge (15-minute constant power discharge followed by a 15-minute ramp down) and a final charge to 100% SOC. The test plan called for reference performance tests to be conducted every four UES cycles to establish a performance baseline. Both OBC modules completed all 16 of the planned UES cycles. The advanced technology derated module showed a capacity loss of about 1%, and the capacity loss in the standard derated module was negligible. This compared favorably with the lead-acid batteries subjected to similar testing at SNL, which showed 8.5% capacity loss after 13 UES cycles.

3) After the stationary application tests were conducted on the four utility modules, the modules were placed on off-road vehicle life test using the Battery Council International (BCI) cycle life test procedure for deep-cycle batteries (e.g., marine, golf, RV). The BCI procedure defines a constant-current (CI) cycle life test with 2-h rate discharges to 100% DOD discharge cutoff voltage (11 V) until the battery capacity declines to less than 50% of its 2-h rating. Three of the four Ni/MH modules were still performing BCI cycles when testing was halted due to dwindling funds. No comparison was made with the performance of lead-acid batteries for this application.

4) Three modules were tested for UPS application. Test conditions for the UPS test were based on the Exide lead-acid battery (flooded cell type) warranty. Exide indicates a warranted number of cycles for eight discharge conditions (combinations of eight discharge rates and eight discharge times). Three OBC modules (derated to 45 Wh/Kg) underwent tests in an attempt to satisfy all eight Exide warranted conditions. Each of the three modules successfully completed at least one of the Exide warranted conditions, but they fell well short of the eight warranted conditions that were planned. The report authors felt that the tests were performed under accelerated conditions with uncertain charge procedures, and the modules could have performed better under different circumstances. However, they also acknowledged that the warranted conditions tested were for flooded cells, and advanced technology lead-acid batteries are warranted for significantly higher numbers of cycles.

5) One battery underwent float-charge life testing at an elevated temperature ($40^{o}C$) to accelerate possible corrosion reactions and failure. Reference cycles were conducted at ambient temperature (approximately $23^{o}C$) periodically during this life test to determine the effect of the elevated temperature on battery deep-discharge capacity, resistance, and power. The peak power of the module was declining at a rate of 0.11 W/kg per day at 40°C, which is close to the decline of 0.087 W/kg per day seen in a new OBC module

subjected to similar tests. This led the authors to conclude that the impact of temperature on performance degradation in the OBC modules is similar throughout their cycle lives.

Overall, the test results showed that used OBC Ni/MH EV modules perform at least as well as, if not better than, new lead-acid batteries in stationary energy storage applications. In fact, the derated EV modules appeared capable of performing the same functions as lead-acid batteries over longer lifetimes. The study demonstrates that reusing Ni/MH EV modules in secondary applications could be technically feasible from a battery performance perspective.

Peer-reviewed journal search

Searches performed utilizing online databases turned up no peer-reviewed articles on battery reuse. There were a number of articles on cell or electrode-level cycle life for both nickel metal hydride and lithium-based chemistries, but very few of these dealt with entire battery packs or even mass-produced cells. Most of the published information on cycle life and performance degradation for entire batteries identified during this search dealt with lead acid systems. The most informative of these papers is listed below:

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Crow, J. et al. “Summary of Electrical Test Results for Valve-Regulated Lead-Acid (VRLA) Batteries.” *Journal of Power Sources* 95 (2001): 241-247.

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Peters, K. “Review of Factors That Affect the Deep Cycling Performance of Valve-Regulated Lead/Acid Batteries.” *Journal of Power Sources* 59 (1996): 9-13.

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Conclusion

Entrepreneurial individuals and companies have set up secondary markets for a variety of types of batteries. These batteries, once used in one type of operation, have been taken and applied to a new application where they have been given a new, second life. Spent nickel/metal hydride batteries, at least those used in electric vehicles, appear to have sufficient capacity and life to be used for a number of stationary applications. Additional tests will need to confirm this, as well as determine if this is true for HEV batteries, and for batteries with other chemistries, especially lithium-ion batteries. Setting up a successful secondary market for spent EV and HEV batteries will also require favorable economics.

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[7] E-mail communication with Richard Perez of *Home Power* magazine. The additional articles he mentioned were not purchased because they did not appear to deal with EV/HEV batteries, nor with advanced, non-lead-acid batteries.

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[12] Personal communication with Peter Lowenthal, Solar Energy Industries Association.

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[14] E-mail communication with Jade Mountain. Jade Mountain can be reached on the Internet at <http://www.jademountain.com/> and via e-mail at <info@jademountain.com>.

[15] E-mail communication with Bill Moore, editor of the EV World® website: <www.evworld.com>.

[16] Personal communication with David Goldstein, President, Electric Vehicle Association of Washington, DC, who stated that he had heard that ECD had a proposal to use 50% capacity Ni/MH batteries in UPS units.

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APPENDIX B:
EV BATTERIES AVAILABLE ON THE U.S. MARKET

This appendix contains a summary of the battery systems found in electric vehicles sold or demonstrated in the U.S. The purpose of this summary is to provide a rough idea of the range of batteries available for potential use in an EV battery secondary use program. As such, it is not an exhaustive list. It does, however, contain the specifications of the battery systems installed in most EV's that have been sold in the U.S. (including those that have gone out of production), as well as some demonstration and prototype vehicles. It does not contain most of the conversion vehicles currently available. The information used here was obtained from the Electric Vehicle Association of the Americas website, the Department of Energy's Office of Transportation Technologies Alternative Fuels Database, vehicle manufacturers, battery manufacturers, and the "Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost and Availability" report submitted by the Year 2000 Battery Technology Advisory Panel to the California Air Resources Board.

For the purposes of this study, electric vehicles were broken into four broad categories to allow for comparisons and simplification of the data. Their descriptions follow:

EV – Electric Vehicle: full size passenger automobile with a battery-based electric drive train.

HEV – Hybrid Electric Vehicle: full size passenger vehicle with an internal combustion engine coupled with an electric motor and battery.

CEV – City Electric Vehicle: small (short wheelbase) passenger automobile with a battery-based electric drive train designed for urban commuting; top speed approximately 60 mph.

NEV – Neighborhood Electric Vehicle: small, low speed (< 25 mph) passenger automobile with a battery-based electric drive train designed for short trips.

Each of these classes of vehicles has different power and energy requirements for the battery. For example, EV's typically have about 30 kWh of energy storage, CEV's and NEV's require about 10 kWh, and HEV's typically have a battery with around 1 kWh of storage.

In addition to considering different types of vehicles, this summary also covers systems based on each of the major battery chemistries used in electric vehicles:

Ni/MH – Nickel/Metal Hydride

Li-ion – Lithium-ion

NiCd – Nickel/Cadmium

LMPB – Lithium Metal-Polymer

VRLA – Valve-Regulated Lead-Acid

FLA – Flooded Lead-Acid.

Tables 1 and 2 below contain broad descriptions of typical batteries organized by chemistry and vehicle type. The remaining tables contain more detailed specifications for the battery systems found in most electric vehicles available on the U.S. market today, as well as a number of prototype and demonstration vehicles expected to reach production in the next few years.

Table 1. Battery Module Characteristics for typical HEV and EV batteries.

Vehicle Type	HEV			EV			
Chemistry	Ni/MH	Li-ion[2]	LMPB[3]	Ni/MH	Li-ion[2]	VRLA	LMPB[3]
Battery Voltage (V)	144 – 274	346		288 - 343	360	312	260
Battery Capacity (Ah)	6.5	3.6		77 - 95	90	60 - 85	119
Battery Capacity (kWh)	0.94 – 1.8	1.2		26 - 32	32	19 - 27	31
Cells/battery	120 – 228	96		240 - 286	96	-	-
Modules/Battery	20 – 38	2		24 - 28	12	26 - 39	13
Module Voltage (V)	7.2	173	50	12 - 13.2	30	8 - 12	20
Module Capacity (Ah)	6.5	3.6	14	77 - 95	90	60 - 85	119
Module Capacity (kWh)	0.047	0.62	0.7	1.0 - 1.1	2.7	0.68 - 0.72	2.38
Module Output Power (kW)[4]	~ 0.9		16	3.2 - 4	12.5	4 - 5	4.9
Motor Output (kW)	10 – 33	17		49 - 102	62	67 - 102	-
Battery Manufacturers	PEVE[1]	Shin Kobe SAFT	Avestor	PEVE Texaco Ovonic	Shin Kobe SAFT	Panasonic East Penn	Avestor
Vehicles	Honda Insight Toyota Prius	Nissan Tino Dodge Durango Dodge ESX3	None	Chevy S-10 Ford Ranger GM EV-1 Honda EV Plus Toyota Rav4 Solectria Force	Nissan Altra	Baker/Ford USPS Ford Ranger Chevy S-10 GM EV-1 Solectria Force	None

Notes:

[1]PEVE – Panasonic EV Energy, a Matsushita company.
[2]The lithium-ion characteristics listed here are for Shin Kobe EV and HEV modules. Module level data were not available for SAFT Li-ion batteries since none of the vehicles using SAFT Li-ion batteries are in production yet.
[3]The LMPB characteristics listed here are for prototype modules developed by Avestor, and some of the numbers are extrapolations from cell-level performance. Avestor has not yet mass-produced any LMPB battery packs, and there are no automakers with plans at the current time to use LMPB systems in a production vehicle, although they have been demonstrated in the Ford TH!NK City and the GM Precept.
[4]Module Output Power was estimated using the specific power for the module and an estimated module mass calculated from the total battery pack mass and the number of modules.

Table 2. Battery Module Characteristics for typical CEV and NEV batteries.

Vehicle Type	CEV			NEV
Chemistry	Ni/MH	Li-ion	NiCd	FLA
Battery Voltage (V)	288	120	114	72
Battery Capacity (Ah)	28	90	100	130
Battery Capacity (kWh)	8.1	11	11	9.4
Cells/battery	240	32	-	-
Modules/Battery	24	4	19	6
Module Voltage (V)	12	30	6	12
Module Capacity (Ah)	28	90	100	130
Module Capacity (kWh)	0.34	2.7	0.6	1.6
Module Output Power (kW)	1.1	12.5	1.6	
Motor Output (kW)	19	24	27	5 - 25
Battery Manufacturers	PEVE	Shin Kobe SAFT	SAFT	Trojan
Vehicles	Honda City Pal Toyota ecom	Nissan Hypermini	TH!NK City Solectria Force	Dynasty IT GEM E825 Solectria Flash TH!NK Neighbor

For additional details on the individual vehicles, see Tables 3-8.

Table 3. HEV's by Manufacturer – Honda, Nissan, Toyota, DaimlerChrysler

Manufacturer Model	Honda Insight	Nissan Tino	Toyota Prius	DaimlerChrysler ESX3	DaimlerChrysler Durango
Chemistry	Ni/MH	Li-ion	Ni/MH	Li-ion	Li-ion
Battery Manufacturer	PEVE	Shin Kobe	PEVE	SAFT	SAFT
Battery Model	HEV	Mn type HEV	HEV	Hi Power	Hi Power
Battery Voltage (V)	144	345.6	273.6	165	259.2
Battery Capacity (Ah)	6.5	3.6	6.5	8	16
Battery Capacity (kWh)	0.936	1.24416	1.7784	1.32	4.1472
Modules/Battery	20	2	38		
Module Voltage (V)	7.2	172.8	7.2		
Module Capacity (Ah)	6.5	3.6	6.5		
Module Capacity (kWh)	0.0468	0.62208	0.0468		
Module Output Power (kW)	~0.9		~0.9		
Cells/Module	6	48	6		
Connection	series	series	series		
Cell Voltage (V)	1.2	3.6	1.2	3.6	3.6
Cell Capacity (Ah)	6.5	3.6	6.5	8	16
Cells/battery	120	96	228		72
Cell Design	cylindrical D cell	cylindrical	prismatic, plastic	cylindrical	cylindrical
Motor Output (kW)	10	17	33		
Sales Figures:					
1996					
1997					
1998					
1999 (1st qtr)					
1999 (2nd qtr)					
1999 (3rd qtr)					
1999 (4th qtr)	17				
2000 (1st qtr)	397				
2000 (2nd qtr)	1149				
2000 (3rd qtr)	1290		2610		
2000 (4th qtr)	952		2952		
2001 (1st qtr)	597		2490		
2001 (1^{st} – 4^{th} qtr)	3901		12116		
Total	7706		17678		
Availability	Retail	Japan Only	Retail	Prototype	Prototype

Table 4. EV's by Manufacturer – DaimlerChrysler, Ford

Manufacturer	DaimlerChrysler	Baker/Ford	Ford	
Model	EPIC Minivan	ECRV Postal Delivery Veh.	Ranger EV[1]	
Chemistry	Ni/MH	VRLA	VRLA	Ni/MH
Battery Manufacturer	SAFT	East Penn	East Penn	PEVE
Battery Model	NH 12.4 (old)	UX 168	UX 168	EV 95
Battery Voltage (V)	336	312	312	300
Battery Capacity (Ah)	95	85	85	95
Battery Capacity (kWh)	31.92	26.52	26.52	28.5
Modules/Battery	28	39	39	25
Module Voltage (V)	12	8	8	12
Module Capacity (Ah)	95	85	85	95
Module Capacity (kWh)	1.14	0.68	0.68	1.14
Module Power Output (kW)	3.2	4	4	3.8
Cells/Module	-	-	-	10
Connection	-	-	-	series
Cell Voltage (V)	-	-	-	1.2
Cell Capacity (Ah)	-	-	-	95
Cells/battery	-	-	-	250
Cell Design	monoblock	monoblock	monoblock	prismatic, plastic
Motor Output (kW)	75	67	67	67
Sales Figures:				
1996				
1997	17		27	
1998	0		310	
1999 (1st qtr)	10		28	
1999 (2nd qtr)	41		119	
1999 (3rd qtr)	23		179	
1999 (4th qtr)	55		207	
2000 (1st qtr)	51		46	
2000 (2nd qtr)	9		130	
2000 (3rd qtr)	0		73	
2000 (4th qtr)	0		140	
2001 (1st qtr)	0	500	2	
Total	206	500	1261	
Availability	Out of Production	500 CA & DC USPS[2]	Fleet and Retail	

Notes:

1 The Ford Ranger EV was initially offered with VRLA batteries only. In recent model years, customers could select Ni/MH batteries as an option. The sales figures are for both options together.

2 500 ECRV Postal Delivery Vehicles were ordered by the US Postal Service and will be deployed in California and the District of Columbia. The USPS has the option of purchasing 5000 more of the vehicles after evaluation.

Table 5. EV's by Manufacturer - GM

Manufacturer Model	GM EV1[1]		Chevy S-10 Electric[1]	
Chemistry	VRLA	Ni/MH	VRLA	Ni/MH
Battery Manufacturer	Panasonic	Texaco Ovonic	Panasonic	Texaco Ovonic
Battery Model	EV 1260		EV 1260	
Battery Voltage (V)	312	343	312	343
Battery Capacity (Ah)	60	77	60	77
Battery Capacity (kWh)	18.72	26.4264	18.72	26.4264
Modules/Battery	26	26	26	26
Module Voltage (V)	12	13.2	12	13.2
Module Capacity (Ah)	60	77	60	77
Module Capacity (kWh)	0.72	1.0164	0.72	1.0164
Module Output Power (kW)	5	4	5	4
Cells/Module	-	11	-	11
Connection	-	series	-	series
Cell Voltage (V)	-	1.2	-	1.2
Cell Capacity (Ah)	-	77	-	77
Cells/battery	-	286	-	286
Cell Design	monoblock	prismatic, metal	monoblock	prismatic, metal
Motor Output (kW)	102	102	85	85
Sales Figures:				
1996	39			
1997	264		278	
1998	258		99	
1999 (1st qtr)	93		45	
1999 (2nd qtr)	0		11	
1999 (3rd qtr)	0		57	
1999 (4th qtr)	45		10	
2000 (1st qtr)	89			
2000 (2nd qtr)	65			
2000 (3rd qtr)				
2000 (4th qtr)				
2001 (1st qtr)				
Total	853		500	
Availability	Out of Production		Out of Production	

Notes:

[1] The GM EV-1 and Chevy S-10 Electric were both initially offered with VRLA batteries only. In recent model years, customers could select Ni/MH batteries as an option. The sales figures are for both options together.

Table 6. EV's by Manufacturer – Honda, Nissan, Toyota, Solectria

Manufacturer Model	Honda EV Plus	Nissan Altra EV	Toyota RAV4	Solectria Force
Chemistry	Ni/MH	Li-ion	Ni/MH	VRLA, NiCd, or Ni/MH
Battery Manufacturer	PEVE	Shin Kobe	PEVE	
Battery Model	EV 95	Mn type EV	MHB-100	
Battery Voltage (V)	288	360	288	156
Battery Capacity (Ah)	95	90	95	
Battery Capacity (kWh)	27.36	32.4	27.36	
Modules/Battery	24	12	24	13
Module Voltage (V)	12	30	12	12
Module Capacity (Ah)	95	90	95	
Module Capacity (kWh)	1.14	2.7	1.14	
Module Output Power (kW)	3.8	12.5	3.8	
Cells/module	10	8	10	
Connection	series	series	series	
Cell Voltage (V)	1.2	3.75	1.2	
Cell Capacity (Ah)	95	90	95	
Cells/battery	240	96	240	
Cell Design	prismatic, plastic	cylindrical	prismatic, plastic	
Motor Output (kW)	49	62	50	42
<u>Sales Figures:</u>				
1996				
1997	105		69	
1998	133	30	359	
1999 (1st qtr)	29	26	79	
1999 (2nd qtr)	21	4	78	
1999 (3rd qtr)	7	0	51	
1999 (4th qtr)	5	0	47	
2000 (1st qtr)	0	11	1	
2000 (2nd qtr)	0	4	18	
2000 (3rd qtr)	0	5	77	
2000 (4th qtr)	0	30	10	
2001 (1st qtr)	0	1	27	
2001 (2nd qtr)	0	19	26	
2001 (3rd qtr)	0	0	77	
2001 (4th qtr)	0	0	26	
Total	300	130	945	
Availability	Out Of Production	Fleet in CA	Fleet	Retail

Table 7. CEV's by Manufacturer – Honda, Nissan, Toyota, Ford TH!NK

Manufacturer Model	Honda City Pal	Nissan Hypermini	Toyota e-com (62 mph)	Ford TH!NK City (56 mph)
Chemistry	Ni/MH	Li-ion	Ni/MH	NiCd
Battery Manufacturer	Panasonic	Shin Kobe	Panasonic	SAFT
Battery Model	EV 28	Mn type EV	EV 28	STM 5-100 MRE
Battery Voltage (V)	288	120	288	114
Battery Capacity (Ah)	28	90	28	100
Battery Capacity (kWh)	8.064	10.8	8.064	11.4
Modules/Battery	24	4	24	19
Module Voltage (V)	12	30	12	6
Module Capacity (Ah)	28	90	28	100
Module Capacity (kWh)	0.336	2.7	0.336	0.6
Module Output Power (kW)	1.1	12.5	1.1	1.6
Cells/Module	10	4	10	-
Connection	series	series	series	-
Cell Voltage (V)	1.2	3.75	1.2	-
Cell Capacity (Ah)	28	90	28	-
Cells/battery	240	16	240	-
Cell Design	prismatic, plastic	cylindrical	prismatic, plastic	monoblock
Motor Output (kW)		24	19	27
Sales Figures:				
1996				
1997				
1998				
1999 (1st qtr)				
1999 (2nd qtr)				
1999 (3rd qtr)				
1999 (4th qtr)				
2000 (1st qtr)				
2000 (2nd qtr)				
2000 (3rd qtr)				
2000 (4th qtr)				
2001 (1st qtr)				
Total				
Availability	Demo	Demo	Demo	Demo (retail in EU)

Table 8. NEV's by Manufacturer – Dynasty, GEM, Solectria, Ford TH!NK

Manufacturer Model	Dynasty IT NEV	GEM (DaimlerChrysler) E825	Solectria Flash	Ford TH!NK Neighbor
Chemistry	FLA	FLA	FLA	FLA?
Battery Manufacturer	Trojan	Trojan		
Battery Model	30 XHS			
Battery Voltage (V)	72	72	144	72
Battery Capacity (Ah)	130			
Battery Capacity (kWh)	9.4			
Modules/Battery	6	6	12	6
Module Voltage (V)	12	12	12	12
Module Capacity (Ah)	130			
Module Capacity (kWh)	1.6			
Cells/Module	-	-	-	-
Connection	-	-	-	-
Cell Voltage (V)	-	-	-	-
Cell Capacity (Ah)	-	-	-	-
Cells/battery	-	-	-	-
Cell Design	-	-	-	-
Motor Output (kW)	25	2.5	34	5
Sales Figures:				
1996				
1997				
1998				
1999 (1st qtr)				
1999 (2nd qtr)				
1999 (3rd qtr)				
1999 (4th qtr)				
2000 (1st qtr)				
2000 (2nd qtr)				
2000 (3rd qtr)				
2000 (4th qtr)				
2001 (1st qtr)		6261		
Total		6261		
Availability	Retail	Retail	Retail	Retail (Fall 2001)

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