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Battery Second Use: A Framework for Evaluating the Combination of Two Value Chains

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BATTERY SECOND USE: A FRAMEWORK FOR EVALUATING THE COMBINATION OF TWO VALUE CHAINS

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ABSTRACT

A battery second use (B2U) ecosystem is a collection of stakeholders that co-evolve around the value chain of bringing used batteries from an electric vehicle into a secondary system. The maximum potential and limitations of the battery second use ecosystem is determined by the design and architecture of the vehicle battery system. As the automotive original equipment manufacturers (OEMs) are responsible for the vehicle battery pack, they are currently the most critical player in the development of such an ecosystem. The OEM must find value in participating in a battery second use ecosystem and develop a B2U strategy that complements its unique EV strategy, thereby enabling a B2U market.

A B2U strategy is the design and development of a battery system with the intention of having it serve two purposes: (1) the initial use in the vehicle and (2) another mobile or stationary application. An optimal battery second use strategy requires the design and use of the battery to maximize the value of the system over its entire extended life cycle. Within this thesis a framework is developed which allows the evaluation of tradeoffs along the operational second use value chain.

The vehicle OEMs can use the framework to integrate critical process and technical parameters in the development of their battery second use strategy. The structure of the framework can also provide a platform for other stakeholders to present their research within a context that enables collaboration and development of higher levels of knowledge. The collaboration between operational members of the ecosystem and research and governmental institutions will be critical for the development of an economically efficient B2U market.

DEDICATION

This work is the result of the collaboration of a small army of people who must be given due credit. This wonderful group of people has helped me both academically and personally through this process, and to them I will always be grateful.

First, I'd like to thank my committee members who have helped me step by step through this process: Dr. Bodde who's never ending enthusiasm for this topic has helped keep me motivated, and who's persistent questioning was instrumental in creating a more cohesive storyline; Dr. Kurfess for always providing enough pressure to keep me moving forward, and enough guidance to keep me on track; Dr. Taiber for always throwing me a curveball and keeping me on my toes; and Dr. Weber for giving me the chance to live my dreams and standing behind me 100% of the way.

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Finally, I'd like to thank my friends and family, whose love and support I always take advantage of, but appreciate more than anything. Especially to my parents who have enabled me to even attempt something like this. Their unquestioning support and subtle method of parenting have built me up to be the person I am today. I am nothing less than fortunate to have such wonderful people in my life.

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TERMINOLOGY AND ABBREVIATIONS

ANL	Argonne National Laboratory
ARRA	American Recovery and Reinvestment Act
B2U	Battery Second Use
B2L	Battery Second Life, interchangeable with B2U
B2B	Business to Business
B2C	Business to Customer
BESS	Battery Energy Storage System
BEV	Battery Electric Vehicle
BMS	Battery Management System
CARB	California Air and Resource Board
CESS	Community Energy Storage System
DESS	Distributed Energy Storage System
DOD	Depth of Discharge
EOL2	End of Life Secondary Application
EOLv	End of Life Vehicle
EPRI	Electric Power Research Institute
EU	European Union
EV	Electric Vehicle
FERC	Federal Energy Regulatory Commission
GM	General Motors
HEMS	Home Energy Management System
HEV	Hybrid Electric Vehicle
HOV	High Occupancy Vehicle
I	Current
ICE	Internal Combustion Engine
IP	Intellectual Property
LCOE	Levelized Cost of Energy
LFP	Lithium Iron Phosphate, battery chemistry
LIBs	Lithium Ion Batteries, family of battery chemistries
LMO	Lithium Manganese Oxide, battery chemistry
NCA	Lithium Nickel Cobalt Aluminum Oxide, battery chemistry
NiMH	Nickel Metal Hydride, battery chemistry
NMC	Lithium Nickel Manganese Cobalt Oxide, battery chemistry
NREL	National Renewable Energy Laboratory
NVH	Noise Vibration Harshness
OEM	Original (vehicle) Equipment Manufacturer
P/E	Power to Energy Ratio
PHEV	Plug in Hybrid Electric Vehicles

Terminology and Abbreviations (contin.)

SCE	Southern California Edison
SNL	Sandia National Laboratories
SOC	State of Charge
SOH	State of Health
SOF	State of Function
T	Temperature
TMS	Thermal Management System
USABC	United States Advanced Battery Consortium
V	Voltage
VMS	Vehicle Management System
ZEV	Zero Emission Vehicle

1 Introduction To Battery Second Use (B2U) and the Role of the Automotive Original Equipment Manufacturer (OEM)

Energy is a basic need for a functioning society that supports economic activities and everyday life [1] . As the world continues to grow, and if energy is to be supplied in a sustainable manner, the following are necessary [2], [3]:

- reduction of dependence on imported fossil fuels
- increase in distributed energy generation
- de-carbonization of electricity
- enhancements in infrastructure efficiency
- reduction of emissions from the transportation and building sector

In order to promote the development of a more sustainable society, the European Union and other government agencies have set targets to drastically decrease greenhouse gas emissions by 2020 [4], [5]. Two key enablers to help meet these targets are grid energy storage and the development of electric vehicles (EVs) [2], [4], [6–8].

The integration of sustainable, but non-dispatchable, energy sources such as wind and solar, increases the opportunity for storage to help ensure a secure energy supply (Figure 1). Storage also allows for the transition to a more robust, distributed, energy infrastructure, in addition to help defer capital intensive infrastructure upgrades generally associated with large renewable installations [3].

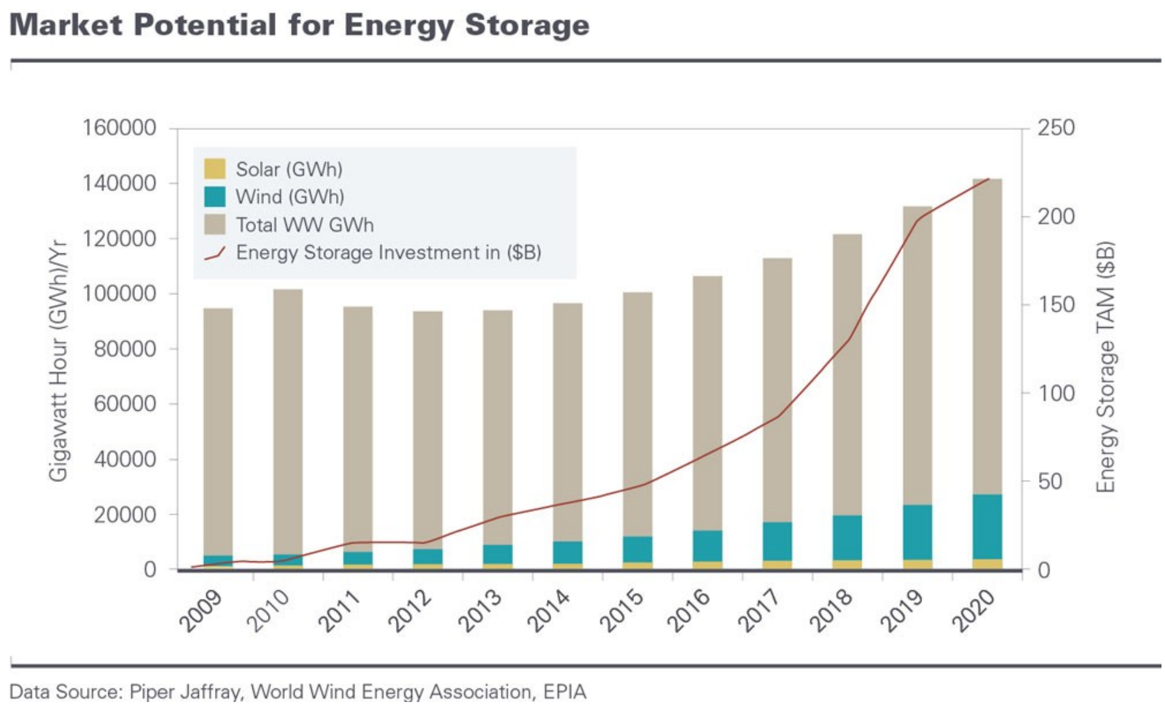


FIGURE 1: MARKET POTENTIAL FOR ENERGY STORAGE WITH INCREASING WIND AND SOLAR INTEGRATION[1] [9]

In the vehicle, energy storage reduces the dependency on petroleum based fuel sources. During operation electric vehicles can significantly reduce the amount of pollutants produced by the transportation sector, depending on local energy mix, and eliminate localized emissions completely. In addition, the higher efficiency of the electric powertrain relative to an internal combustion engine, results in less required energy during the use phase of the vehicle (Figure 2).

[1] Shows investment in all storage technologies, battery energy storage will be a percentage of this total, more information is available in Section 8.2

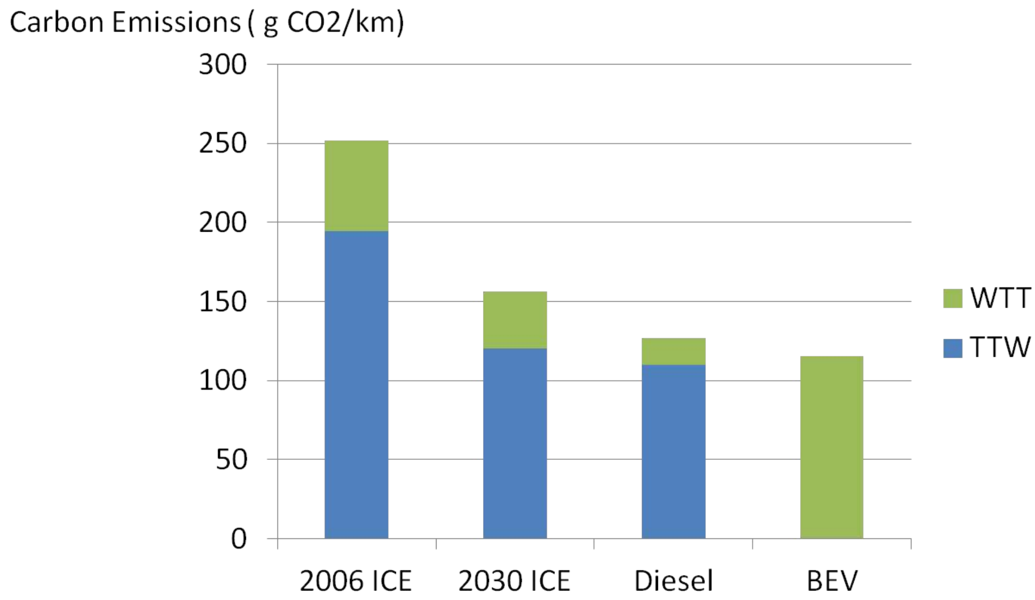


FIGURE 2: LIFECYCLE EMISSIONS FOR VARIOUS VEHICLE TYPES [10], DIVIDED BETWEEN WELL TO TANK (WTT) AND TANK TO WHEEL (TTW) WHERE GRID EMISSIONS ARE BASED ON GRID MIX PROJECTIONS MADE FOR 2030 IN THE EIA ANNUAL ENERGY OUTLOOK.

Stationary energy storage comes in a variety of forms and sizes (see Section 8.1.5). Battery energy storage, although more expensive, offers easier deploy-ability, scalability and better controllability than cheaper bulk energy storage [11]. A promising battery technology for both stationary and EV applications are lithium ion batteries [12]. This relatively new technology has high roundtrip efficiency, high energy density, and good cycling characteristics; but degrades overtime with cycling and calendar age [8], [13].

Over time, the battery in an electric vehicle will no longer be able to provide sufficient range or power performance due to its aging properties. Theoretically, the battery could then be taken out of the vehicle and placed in another less demanding application, where neither energy nor power density is as critical. This application could be either a stationary storage system, or another mobile system such as use in material handling equipment. The vehicle owner could be compensated for the remaining value of the battery,

while the sale of the new secondary system could provide revenue for the vehicle Original Equipment Manufacturer (OEM), third party repurposer, or system integrator. The secondary system could be offered at a lower price or be configured so that it would offer the same price performance value as a new system.

This concept has been traditionally referred to as battery second use (B2U), and was initially motivated by expensive battery systems that drove up the initial purchase price of both EVs and stationary devices. B2U was seen as an opportunity to lower these initial capital costs and enable battery systems to be more price competitive with more traditional technologies. Although this is still true today, recent developments within the vehicle and stationary storage markets have created additional opportunities for B2U. Namely the ability for an OEM to minimize risk and optimize its operational costs related to deployment of new battery technology. In addition, stationary storage system providers ability to offer a turnkey system at a price that can stimulate more widespread adoption. Within this new context battery second use is no longer the use has grown from the concept of using the batteries after 8-10 years in the vehicle in a stationary application, to the optimization of the use of the integrated battery system (cells and BMS) throughout its usable life.

In the short to medium term, a key market enabler for B2U will be the automotive OEM. OEMs currently hold the most competence in terms of battery system lifetime and aging characteristics, which are required for the OEM's warranty analysis. In addition the OEMs are responsible for the design of the battery system in the first life, which will greatly influence the reprocessing and integration costs needed to use the battery in a secondary application.

This section will further discuss the opportunities for B2U through the following

1,1. Discussion of the opportunities for stationary energy storage

1,2. Presentation of the requirements for a battery second use market

1,3. Elaboration on why the OEM is currently a key factor in the development of a B2U market

The final part of this section will present the remaining structure of the thesis, which will explore the needs of an OEM to allow the development of a B2U strategy in order to help enable the formation of a B2U market.

1.1 THE DEVELOPING ENERGY STORAGE MARKET AND DETERMINING POTENTIALS FOR B2U

The electrical grid is a very complex, dynamic, system that relies on the real time management of numerous generators in order to meet demand [1]. Independent of structure of the electrical system, which varies substantially by region, energy storage has a potential role in improving every step with in the electricity value chain (Figure 3). The 'need' for storage is purely a question of economics as the capabilities that storage provides could be accomplished with generating or load shedding equipment, upgrades in the transmission or distribution systems, or interconnections with adjacent electrical systems [3], [14].

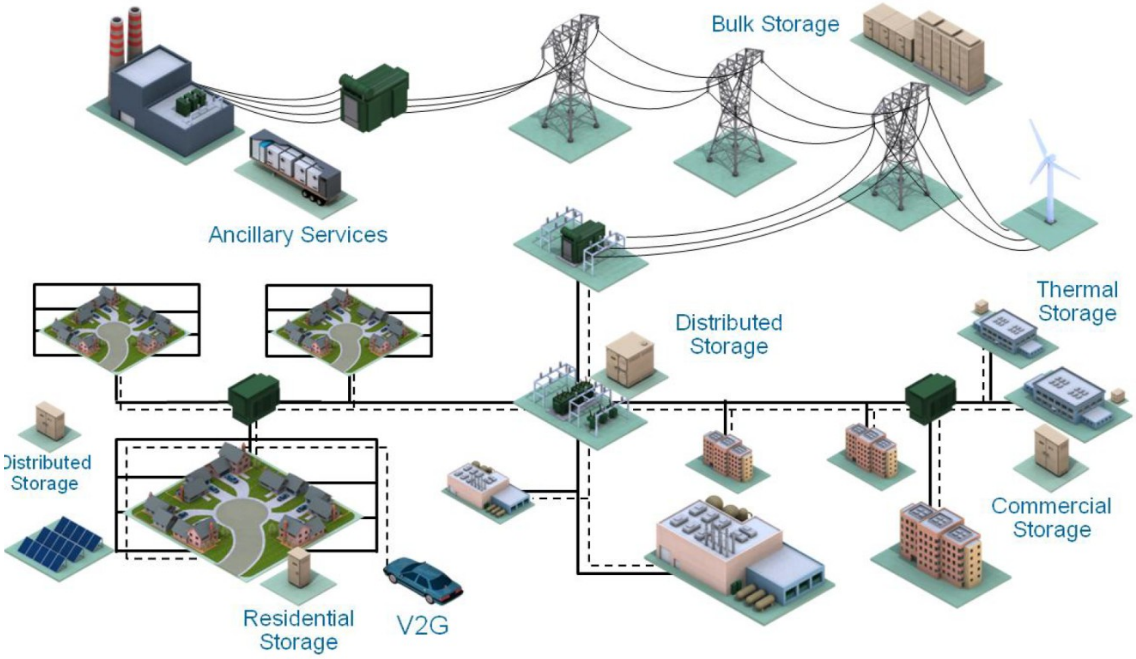


FIGURE 3: POTENTIAL LOCATIONS OF STORAGE FOR THE ELECTRIC GRID [15]

In most industrialized countries, the electricity grid was developed so that large centralized generation units supply energy to high voltage transmission lines that feed lower voltage distribution systems, bringing the energy to the customer. Transmission operators forecast energy demand and schedule generators to dispatch energy into the grid according to the prediction. Discrepancies between actual supply and actual demand are remediated through wholesale or ancillary service markets. The architecture of this traditional system, the technology used, and the players involved determine how the system is operated, regulated, and means by which service providers are compensated [14], [16].

Recently, there have been two major changes that have created significant challenges for the current energy grid; namely (1) the integration of intermittent renewable energy and (2) the increasing participation of the customer in the electrical supply chain.

These two factors have ultimately changed the rules of the energy market by introducing uncertainty in the energy supply, and creating a need for a network to enable the bidirectional flow of energy [17].

Unlike traditional generation sources, renewable energy sources, such as wind and solar, are non-dispatchable and therefore cannot be controlled as they are both intermittent and variable [14]. Therefore, transmission operators must make predictions based on uncertainty on both the demand and supply side of the equation. In addition, wind and solar also have high rates of change, or ramp rates, in their power output. This can drastically effect grid reliability, and if not managed properly lead to the inefficient use of contingency resources [3], [18], [19].

Grid energy storage can help remediate these problems by balancing supply and demand, smoothing the renewable system output, and reducing the need for curtailment due to transmission congestion and reliability. Storage can also help minimize the need to upgrade current transmission assets that can greatly increase the cost of renewable installation projects [9], [14], [18].

The role of customer has also changed drastically in recent years due to access to affordable self-generation technology, and higher control capability through smart metering and smart devices. Therefore, the customer is becoming an active participant in the market and is no longer just the recipient of power [17]. This has led to both significant opportunities and problems for utilities and owners of the distribution network. Opportunities include the ability to incentivize customers to manage their load and the ability to implement automated demand response programs. Both tactics can help improve reliability and decrease the need for expensive infrastructure upgrades.

The problem with distributed generation is uncontrollable injections of large amounts of energy on distribution networks not designed to handle two way energy flows. In addition the increasing penetration of EVs creates additional strains on the distribution network. This leads to problems with grid reliability and power quality, for which the utility is ultimately responsible.

Grid energy storage can help maximize the value of these new consumer capabilities while mitigating their issues. For example, customer sited storage can help increase the self-consumption of energy generated, reducing the amount of energy being injected back into the grid. This system can also level the consumer's load, reducing peak power needs, which then decreases the need for upgrades in distribution infrastructure. On the utility side of the meter, energy storage can help manage power flows and reduce major disturbances to the transmission network.

Currently, the distributed storage market is relatively new and many markets lack the proper mechanisms to capture the true value of electrical storage services, due to the structuring of markets around a traditional energy system architecture. A good example of how the market structure influences the value of storage can in seen in the restructuring of the regulation market, which is discussed in Sidebar 1. In addition, utilities (or other potential service providers) lack the tools to be able to assess and capture the potential values created a distributed energy storage system [20–22]. This is because storage is unique as it is a limited energy resource with a narrow band of dispatchable energy that can provide mutual benefits simultaneously. Determining the optimal load profile depends on market conditions such as tariff structures, market rules, and surrounding infrastructure [16], [21], [23–25]. Software tools are also needed that are capable of integrating these

factors to optimize the use of a storage asset to actually realize the projected value of the system [26].

SIDEBAR 1: CHANGING REGULATION TO MONETIZE TRUE VALUE OF STORAGE.

REGULATION MARKET AND FERC 755: CHANGING MARKET MECHANISMS TO ALIGN WITH VALUE OF STORAGE

Regulation services is energy and power acquired to balance real time discrepancies between energy supply and demand, generally in five minute intervals (Figure 4). Traditionally, regulation services were provided by adjusting the output of selected generators to follow and match grid load. Therefore, a generator participating in the regulation market would supply 50-80% of its capacity to the energy market and reserve the remaining 50-20% for the regulation market. For example, the generator would run at 80% power until being called upon for regulation through an automated supply signal. The generator would use the remaining 20% of its power capacity to follow the supply signal. Payments for the regulation market would be determined by a “pro-rata” basis. Which means regulators would pay to reserve regulation capacity on a per MW basis, since traditional generators are not capacity limited. An energy provider would then be compensated whether or not its asset was used, since it was being paid to provide flexibility in its output.

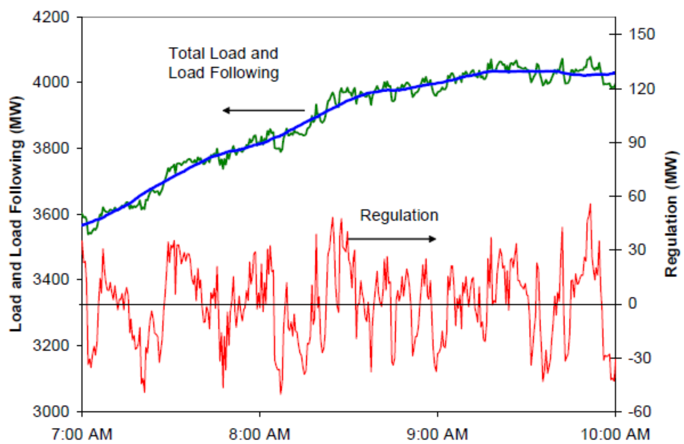


FIGURE 4: EXAMPLE OF FREQUENCY REGULATION LOAD PROFILE, PREDICTED LOAD IN BLUE, ACTUAL LOAD SHOWN IN GREEN, REQUIRED REGULATION ENERGY IN RED [27]

The two main problems with this traditional market are (1) generators generally contain spinning masses with a certain amount of inertia, and (2) generators must contribute to the base load, or energy supply, in order to be able to provide regulation energy. Due to the inertia of the generator there is a limited rate at which it can react to a supply signal (Figure 5). The undershoot or overshoot of the generator’s response to the supply signal would then create the need for more regulation capacity.

Regulation energy from a traditional generation resource cannot come from an asset that isn't already running and supplying to the base load. If regulation is needed at times of low demand and all base load generators are already operating at their lowest outputs; the addition of a regulation resource could create negative wholesale energy prices. This means generators would have to pay for someone to take the extra power off the grid.

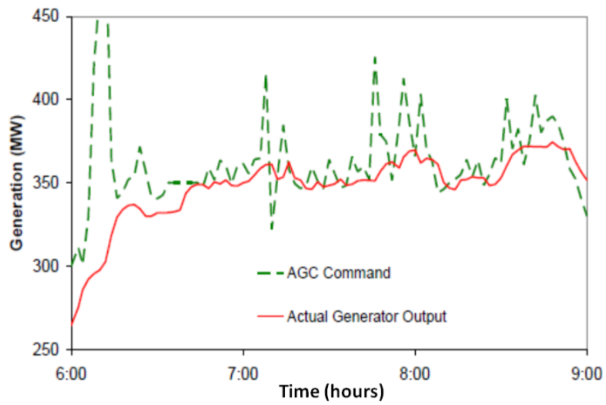


FIGURE 5: EXAMPLE OF COAL FIRE PLANT FOLLOWING FREQUENCY REGULATION CONTROL SIGNAL [27]

Advanced energy storage can provide a better alternative since its fast ramping, and can follow the supply signal better than a traditional generator; can act simultaneously as a load and a generator; and it doesn't add to the base load. As a result, the use of energy storage reduces the amount of regulation energy needed and cannot negatively affect the wholesale energy price. In addition, it allows traditional generators to operate closer to their maximum efficiency point, instead of at a point that allows them to have flexibility to participate in the regulation market. Therefore the regulation services provided by advanced energy storage have a higher system value than regulation provided by the traditional generator.

The structure of the traditional energy supply system, which includes the market rules, tariff structures, dispatch rules, and scheduling software, are all designed around the use of traditional generators to supply regulation energy. Therefore, the system is unable to operate as to maximize the value of energy storage for the system. As a result, energy storage assets were undervalued and insufficiently compensated for their provided service in this market.

This changed in the United States when Federal Energy Regulation Committee issued FERC Order 755 (2011). The new ruling requires system operators to establish a tariff system to ensure frequency regulation services "receive just and reasonable and not unduly discriminatory or preferential rates." As a result, the majority of system operators have set up new market rules which involve prioritized dispatch based on response, and a two part payment based on reserve capacity (MW) and "mileage", or amount of energy provided (MWh). Therefore, fast responding assets such as energy storage are dispatched before traditional generators. Assets are then compensated for being available in addition to the service they actually provide. Since energy storage has a better response rate they are able to follow the supply signal more closely. Therefore for a given supply signal, they are able to supply more regulation energy than a traditional generator. Therefore the "mileage" for an energy storage system is higher than that of a generator, and the compensation received for regulation services higher [21], [27].

In 2013 FERC 784 extended ruling 755 to all ancillary service markets. As a result, more advanced energy storage technologies, such as battery energy storage, have become economically viable solutions in certain markets within the United States [17].

Uncertainties about the quantifiable value of storage, combined with a poorly defined regulatory environment regarding storage, makes it difficult to assess investment decisions related to storage. Without this economic data and more detailed information about operation profiles, the ability to optimally dimension and configure a storage system is also not possible [16].

This creates problems in assessing battery second use since it is difficult to determine product requirements in terms of performance, and assess competitiveness in terms of cost. But waiting until the market solidifies can also result in a missed opportunity for used EV batteries. Therefore, a framework is needed to isolate the problem of battery second use from the overarching uncertainty of the energy storage market. This will allow stakeholders to concentrate on the problems inherent in the use of second use batteries and not the operational problems of energy storage in general.

1.1.1 *Decoupling Market Uncertainty in Order to Understand Technical Requirements and Opportunities for B2U*

In the most general of terms, electricity and electricity services are commodities. That is the properties of the end product, namely the electrons being transferred, are independent of how that energy was produced, transmitted, or consumed. Therefore, the market price for that unit energy will be set dependent on demand and the asset capable of providing this service at the lowest cost. Common metrics used to compare the costs of different assets or technologies that provide a given service is the levelized cost of energy ($/MWh) or levelized cost of capacity ($/kW-yr)

The levelized cost of energy (LCOE) is the revenue from the delivered energy resource needed to cover all life-cycle fixed and variable costs, including a target rate of return for a given asset, which is traditionally limited through a regulatory agency. The levelized cost of capacity is the power equivalent to the LCOE on a yearly basis, and is generally used to compare capacity resources such a natural gas peaker plants or demand response. For a power plant life-cycle fixed and variable costs would include capital system, installation, fuel, operation and maintenance costs [20], [28], [29].

For a battery, life cycle costs include capital and installation costs, cost of energy needed to charge and maintain the battery, and operation and maintenance costs including battery exchange, if necessary. The necessity of a battery exchange is dependent on the

degradation rate of the battery, operating conditions of the battery, application requirements, and economics of the system operation.[2]

Figure 6 shows the interdependencies between system parameters that dictate costs and application requirements which will determine the revenue, or monetary value generated by the system. The application is how the battery is used and includes grid applications such as supplying regulation capacity, or end-consumer applications such facility energy management. A full list of applications can be found in Section 8.2.

[2] For example a 1MW/1.4MWh nominal storage system participating in the regulation market has a minimum bid requirement of 1MW for 1 hr and earns \$0.40/kWh or \$350/kW-year. A battery exchange based on application requirements would be required once the usable capacity of the battery drops below 1MWh. A battery exchange based on the economics of the system operation would only be justifiable if it would lead to a LCOE of ≤ \$0.40/kWh.

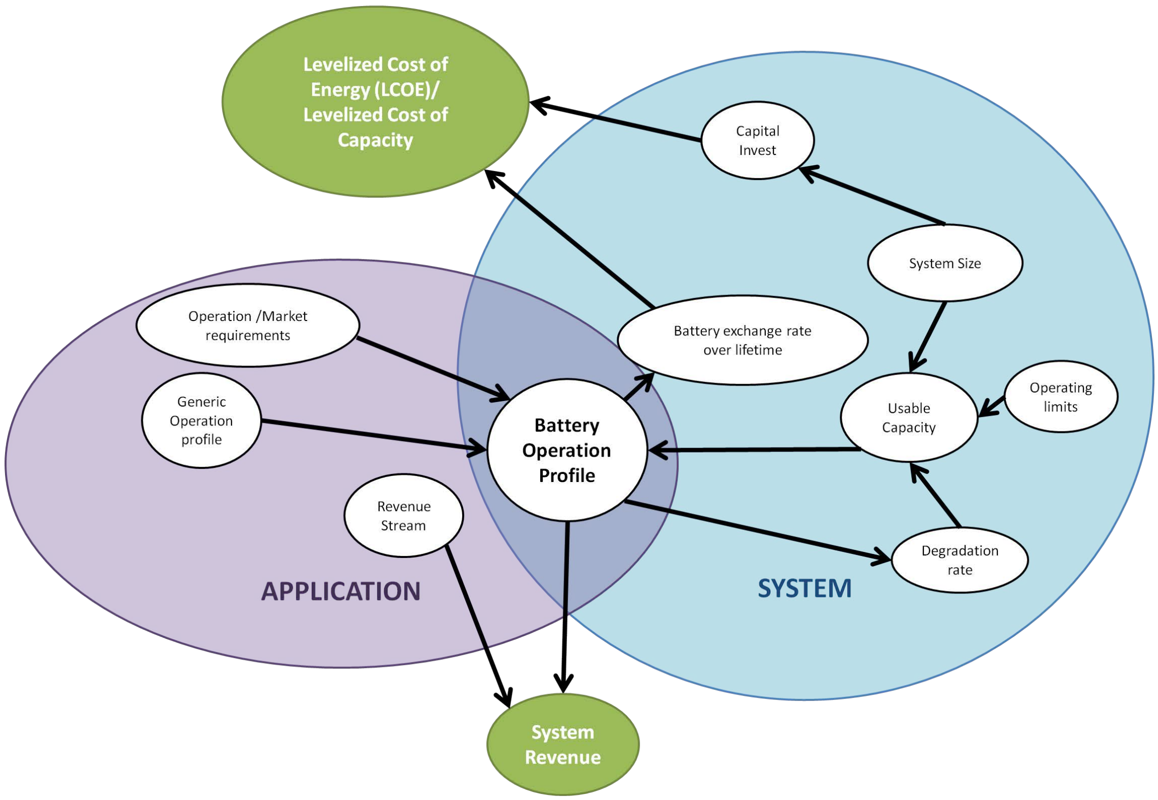


FIGURE 6: SCHEMATIC OF INTERACTION BETWEEN SYSTEM PARAMETERS AND APPLICATION REQUIREMENTS

It can be seen that the battery load profile is the key coupling point between the given application and energy storage system. Therefore if a load profile can be determined, both the levelized cost of energy (LCOE) and levelized cost of capacity from a system can be generated. The competitiveness of the system can then be determined through either a comparison of lifecycle costs for competitive systems, or a net present value calculation based on revenues generated.

Using the service load profile and the LCOE for competing technologies (1) preliminary development goals for a B2U system can be established, (2) the competitiveness of these systems in a stationary market assessed, and (3) a window of

opportunity identified. All three will be necessary to drive the development of a B2U strategy.

1.2 Requirements for the Development of a Battery Second Use Market

A battery second use market is a business ecosystem that enables electric vehicle batteries to be used in a secondary application. According to James F. Moore, a business ecosystem consists of a collection of companies that co-evolve around an innovation; work cooperatively and competitively to support new products, satisfy customer needs, and incorporate the next round of innovation. The development of a business ecosystem begins as a random collection of elements and matures into a more structured community [30].

For a battery second use ecosystem this translates into a collection of stakeholders that co-evolve around the value chain of bringing batteries from the vehicle to a secondary system. This includes the development of markets and infrastructure for reclaiming and reprocessing batteries; development of products capable of integrating used EV batteries; and services capable of selling and maintaining these systems.

The viability of a battery second use ecosystem is dependent on the following:

1. Electric vehicle batteries capable of being mechanically and electrically integrated into a secondary storage system in a safe and cost efficient manner.
2. The infrastructure to support the process of removing the batteries from the vehicle, inspecting the systems for suitability for a second use, integrating the batteries into a new system, bringing that system to market, and supporting the new system during its lifetime.

3. Batteries with performance characteristics that allow used batteries to be economically favorable or competitive to new batteries over a system's lifetime for a given application.

There are four evolutionary stages for a business ecosystem (Table 1). Currently the battery second use ecosystem is in the birth or even pre-birth stage.

Table 1: Evolutionary Stages of a Business Ecosystem [30], Current State of B2U Eco-System Highlighted in Blue

	Cooperative Challenges	Competitive Challenges
BIRTH	Work with customers and suppliers to define the new value proposition around a seed innovation.	Protect your ideas from others who might be working toward defining similar offers. Tie up critical lead customers, key suppliers, and important channels.
EXPANSION	Bring the new offer to a large market by working with suppliers and partners to scale up supply and to achieve maximum market coverage.	Defeat alternative implementations of similar ideas. Ensure that your approach is the market standard in its class through dominating key market segments.
LEADERSHIP	Provide a compelling vision for the future that encourages suppliers and customer to work together to continue improving the complete offer.	Maintain strong bargaining power in relation to other players in the ecosystem, including key customers and valued suppliers.
SELF-RENEWAL (DEATH)	Work with innovators to bring new ideas to existing ecosystem.	Maintain high barriers to entry to prevent innovators from building own alternative ecosystems. Maintain high customer switching costs in order to buy time to incorporate new ideas into your own products and services.

Requirements of this stage include defining the needs of the customer, the value of the product or service, and the best method for delivering it to the market. This requires understanding the demands and requirements for the secondary storage system,

determining the value proposition for used electric vehicle batteries, and developing a value or process chain for delivering the used vehicle batteries to the end use customer.

Although both mobile and stationary secondary applications are feasible, this thesis will focus primarily on the deployment of used EV batteries into a stationary application. Due to the larger discrepancy in system requirements and definition of value of an EV and stationary battery system, the resultant second use ecosystem will have a higher level of complexity. Therefore, if a suitable method can be established for evaluating second use for stationary applications, it can be easily adapted for looking at other mobile applications.

This section discusses the components of the second use value chain, highlighting various interdependencies and challenges along the chain.

1.2.1 Battery Second Use Operational Value Chain

A value chain is the process in which a firm, or in this case a collection of firms, takes base materials and transforms them into a finished product or service [31]. In essence the value chain is the structure of the ecosystem. For battery second use the basis of this value chain is an operational process chain consisting of retrieving the battery system from the vehicle, repurposing it for another application, integrating it into a new battery system, and deploying it into another application (Figure 7).

The value that is extracted from the process chain will be dependent on the strategic management of parameters at each process step, and the most economic integration of stakeholders along the process chain.

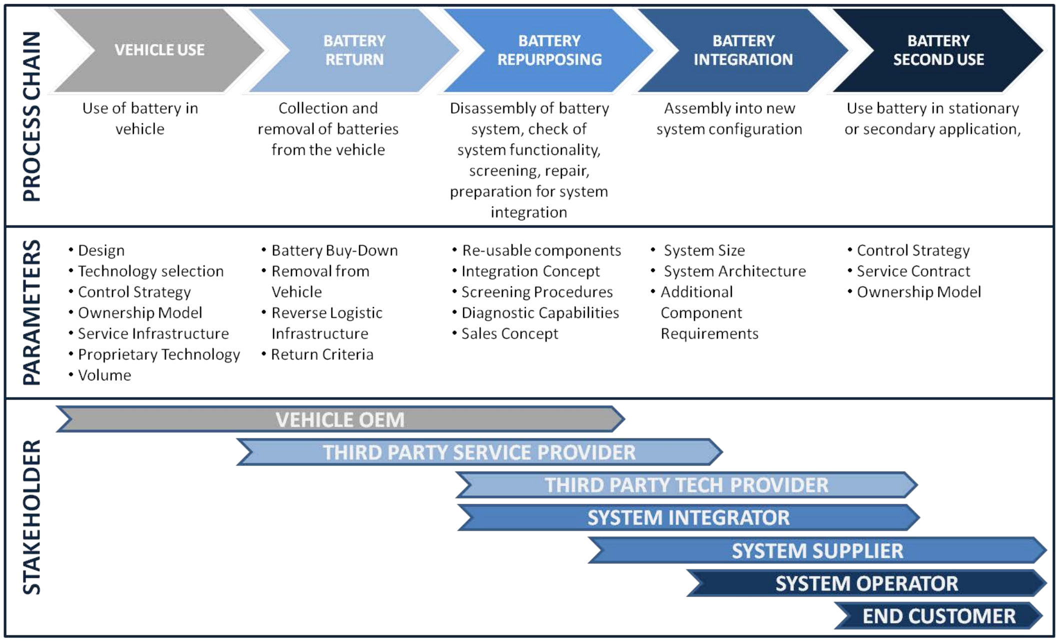


Figure 7: Visualization of Battery Second Use Value Chain

The strategic parameters of each step directly influence either costs, operational requirements, or the performance along the value chain. The performance of the system is then directly linked to the value it generates. These parameters tend to be coupled so that upstream parameters have an influence on downstream parameters. Therefore, upstream parameters have more weight in determining the total value of the system.

The stakeholders along the process chain are all parties that influence the physical form of the battery system, or perform the tasks described in the chain. Each party has a specific bandwidth in which they are able to contribute. For example, the vehicle OEM will probably not be responsible for integrating the batteries into a final stationary product or supplying it to the final customer, since that is generally outside of their core business.

The following sections look at the various steps along the process chain, describes the strategic parameters and their influence on the potential system value.

VEHICLE USE

The vehicle battery is the input into the ecosystem and can be seen as the "base material" that must be transformed into a usable product. The design of the vehicle battery system dictates the processing requirements and cost drivers for creating the final product. In a similar respect, the technical capability of the battery will determine the limits of potential value that can be extracted from the base material. Therefore, the design and performance capability of the battery coming out of the vehicle will determine the requirements and limitations of the value chain.

Operational parameters include the ownership model of the battery and use of proprietary technology. These determine how much control the OEM has over the battery in the vehicle lifetime and how involved they need to be in the development of a secondary system utilizing components of the preliminary vehicle battery systems.

An overview of all strategic parameters for the in vehicle use is presented in Table 2.

TABLE 2: STRATEGIC PARAMETERS FOR IN VEHICLE USE

PARAMETER	DESCRIPTION	INFLUENCE	
Design	The physical, electrical, and control architecture of the vehicle battery system	COST	Determines the limitations of disassembly and repurposing requirements; and options for integration into a new system.
Technology Selection	Chemistry and form factor of the battery cell, in addition to component selection and specifications	COST	The choice of chemistry determines the basis electrical and thermal properties, and aging characteristics; which affects the lifetime performance and control requirements for the system. Component selection affects integration compatibility.
Control Strategy	Electrical and thermal management of the battery pack to ensure battery remains within a safe operating window, while minimizing aging and providing required performance	VALUE	How the battery ages in the vehicle is dependent on the control strategy and cell chemistry. This determines the performance capabilities of the battery at the start of second use. The uniformity with which the battery ages could also influence the integration concept.
Ownership Model	If the batteries owned or leased by the customer	OPER/ COST	Determines the ability to reclaim the batteries throughout their lifetime.
Service Infrastructure	OEM network including dealerships, transportation network, service centers, storage and production facilities	OPER/ COST	Availability of infrastructure that could also be used to support second use value chain and reduce costs required for a second life infrastructure.
Proprietary Technology	Design, engineering, or production attributes of the battery pack that are considered Intellectual Property of the OEM	OPER	OEM might be reluctant to have a 3rd party disassemble the pack or have access to the source code for the control electronics for modifications needed for a secondary use.
Volume	Volume of batteries produced and availability for a secondary application	COST/ VALUE/ OPER	Determines scale of battery second use eco-system and opportunities to realize economies of scale.

*OPER= Operational Influence

BATTERY RETURNS

The first step in repurposing a used EV battery is getting the battery out of the vehicle. The state of health of the battery when it is removed from the vehicle is an important influence factor. This determines the performance characteristics of the pack and therefore the potential value that can be obtained. A battery can be returned, or reclaimed,

for a variety of reasons including a battery exchange or upgrade; return of a lease vehicle; warranty claim; or is returned at the end of the vehicle's operational life. Each return scenario will affect the performance of the battery, volume of available packs, and timeline for battery availability.

Table 3 describes the strategic parameters of this process step; their influence on cost, value and operational parameters of the ecosystem; and the dependencies on upstream parameters.

TABLE 3: STRATEGIC PARAMETERS FOR BATTERY RETURN PROCESS

PARAMETER	DESCRIPTION	INFLUENCE		DEPENDENCY
Buy-down	Monetary or service incentive to buy-back or secure return of the vehicle battery system.	OPER/ COST	Can help ensure volume, and potentially quality, of returning battery systems.	Ownership Model
Removal from Vehicle	Disassembly and removal of battery from the vehicle	OPER/ COST	Availability of additional vehicle components, state of system.	Service Infrastructure, Return Criteria, Design
Reverse Logistic Infrastructure	Transportation requirements, storage facility	OPER/ COST	Where reprocessing steps take place, lead times.	Service Infrastructure
Return Criteria	When the battery comes out of the vehicle.	VALUE	Battery performance characteristics, battery availability, remaining useful life of components.	Technology Selection, Ownership Model

*OPER= Operational Influence

BATTERY REPURPOSING

The repurposing of the battery pack is the disassembly of the pack into its re-usable components; the inspection and testing of these components; and the preparation of "building blocks" or base units for integration into a secondary system. The level of repurposing will depend on the components that can be integrated into the secondary

system. In most cases battery repurposing can happen at either a cell, module or pack level. The cell, module, or pack will then be the base unit used to build the secondary system.

Table 4: Strategic Parameters for Battery Repurposing Process

PARAMETER	DESCRIPTION	INFLUENCE		DEPENDENCY
Re-usable components	Use of other components from the battery pack besides battery cells.	COST	Can reduce need for additional parts that serve same function as vehicle component.	Design, Technology Selection, Return Criteria
Integration Concept	Definition of base unit to be integrated (cell, module, pack)	COST/ OPER	Determines final system design, integration maintenance, and disassembly requirements including procedures, equipment requirements and time.	Design, Technology Selection
Screening Procedures	Determination of which batteries should go to which application, or sent to recycling	COST/ VALUE	Uniformity of batteries in second use and second use system performance. Procedures for screening will influence equipment requirements and lead time.	Return Criteria, Diagnostic Concept
Diagnostic Concept	Determination of state of health of pack through either direct testing or read out from vehicle data	COST	Precision will determine effectiveness of screening; procedures will influence equipment requirements and lead time.	Design, Service Infrastructure
Sales Concept	Sales model for battery base units (e.g. direct sales, supply contract, single strategic partner)	OPER/ VALUE	Stakeholder liability and individual profits. Size and structure of eco-system.	Return Criteria, Reverse logistic Infrastructure

*OPER= Operational Influence

The ability to re-use components will depend on the secondary application requirements and the component's physical, electrical, and communication compatibility with the secondary system. This includes voltage levels, certification requirements, service requirements, and transportability.

SYSTEM INTEGRATION

System integration takes the repurposed base unit and connects them in series and/or parallel to achieve the required electrical properties for a given application. The application size will determine the number of base battery units required, and the system architecture will determine the configuration. Small energy storage systems will most likely require the equivalent of one pack or less of modules/cells; medium systems will require more than one pack worth of modules/cells connected in series or parallel; and large systems will require multiple packs worth of modules/cells connected in series and parallel.

The architecture and configuration of the battery system determines the requirements for the battery management system and therefore the compatibility of vehicle BMS components. The need of additional components will then depend on which components could be re-used from the vehicle system.

TABLE 5: STRATEGIC PARAMETERS FOR SYSTEM INTEGRATION PROCESS

PARAMETER	DESCRIPTION	INFLUENCE		DEPENDENCY
System Size	Number of battery base units needed to meet application requirements	COST/ VALUE	System cost and installation requirements	Return Criteria, Design
System Architecture	Number of base units connected in series and parallel, control architecture, and thermal control	COST/ VALUE	Control strategy for secondary application, service contract in terms of smallest replaceable unit	Integration Concept, Design, Vehicle Control Strategy, Reusable Components
Additional Component Requirements	Balance of system components required such as relays, sensors, TMS, etc.	COST	System cost	Integration Concept, Reusable Components

*OPER= Operational Influence

SECOND USE APPLICATION

The performance of the battery second use system and life time depends on the degraded state of the cells and the control strategy of the secondary application. The control strategy includes being able to electrically and thermally manage cells with various performance characteristics, and determine the appropriate system operating window to ensure safety and system lifetime.

TABLE 6: STRATEGIC PARAMETERS FOR SECOND USE APPLICATION

PARAMETER	DESCRIPTION	INFLUENCE		DEPENDENCY
Control Strategy	Determines operating conditions of battery including usable capacity and power limits	COST/ VALUE	Performance, battery lifetime, number of battery exchanges over system lifetime	Screening Procedures, System Architecture, Technology Selection
Service Concept	Warranty and maintenance conditions	COST/ VALUE	Opportunity to make used batteries competitive with new batteries through additional services	System Architecture, Return Criteria, Technology Selection
Ownership Model	Own, lease, or pay per service	COST/ VALUE	Opportunity to make used batteries competitive with new batteries through additional services	Sales Concept

*OPER= Operational Influence

Since used batteries will not perform as long as new batteries, it might be necessary to develop new service models enabling used batteries to be competitive with new battery systems. These new service models can come in the form of either a service contract or ownership model.

1.3 THE IMPORTANCE OF THE OEM IN THE REALIZATION OF A B2U MARKET

The OEM is currently responsible for the input, or base material into the B2U ecosystem. The market conditions combined with the design and lifetime of the system, will define the bounding potentials for the viability of a battery second use market. Currently, OEMs or Tier 1 suppliers have the most developed understanding of how the batteries will age throughout the vehicle life [32], [33]. This is because lithium battery technology is still relatively new and had previously never been used in an application as demanding as in a vehicle [34]. Therefore, the tools and level of understanding about the battery system needed to develop an EV battery capable of meeting automotive safety and quality standards previously did not exist. These tools are currently being developed through joint collaboration between EV OEMs, battery suppliers, and Tier 1 Suppliers, in order to understand the battery's performance throughout its lifetime. This understanding is critical in the development of a system that can meet the lifecycle requirements of the vehicle; specifically those dictated by the warranty terms of the manufacturer. More information about the vehicle development cycle can be found in Section 8.1.

Since the automotive OEM has the most information about the design and aging of the EV system, it is the best equipped not only to evaluate the potentials of B2U opportunities but also to influence the outcome. Mainly the OEM must know if the current technology is capable of performing long enough to be used in a secondary application; and if it is capable, what are the associated reprocessing and integration costs. If an OEM could understand the tradeoffs between the battery design and potential use cases, it could optimize the use of the battery throughout its lifecycle, and evaluate further business opportunities of a B2U

strategy. This would include decisions about battery ownership models (rent vs. lease), battery design, control architecture, and battery technology selection.

In such early stages of the B2U market it is critical that the OEM is incentivized to explore the potentials of a second use strategy. For OEMs, battery second use would be a potential to enhance the sustainability of their electric vehicles. Battery second use can decrease the electric vehicle's net environmental impact; and can make it more economically viable for OEMs to finance and offer EVs as part of their mobility services portfolio (See Section 8.1.3).

However, battery second use is only a potential to realize these benefits, with its own risks in terms of profitability and liability. Therefore it must be analyzed from a market, technical, and operational level in order to determine if there is a viable business case for a given OEM and what strategic steps are necessary to realize such a business.

1.3.1 The Need for an OEM to Align B2U Strategy with EV Strategy

Each OEM has a unique strategy with regards to the development and deployment of electric vehicles. This strategy dictates the following:

- types of vehicles to be developed
- design of the battery system and type of technology employed in the system
- the volume of vehicles to be produced
- the level of involvement of the OEM in the development of the vehicle battery system
- ownership model of the battery system (lease vs. own)
- service concept for the battery system during vehicle life

Currently each OEM produces a different battery pack, at different volumes, using different technologies. Therefore the requirements for their battery second use eco-systems will be different, and each OEM will need to develop a battery second use strategy that aligns with the strategy used for its electric vehicles.

A battery second use strategy is a collection of decisions made by a stakeholder in the battery second use eco-system that enables the use of EV batteries in a secondary application. With respect to an OEM, a second use strategy could include the following:

- A business case for integrating B2U into the corporate strategy
- Integrating the technical requirements of stationary storage systems into the preliminary development of the vehicle battery system.
- Establishment of operational processes for reclaiming and preparing the batteries for secondary use, and supporting service for the operation of the batteries in the secondary use.
- Development of business relations for the purchase and integration of the used batteries, and sale of final energy storage systems.

A precondition for an OEM to deploy a battery second use strategy is its perception of battery second use as a potential to help its business with a manageable amount of risk. Therefore battery second use must make sense strategically, economically, and operationally for the OEM. Strategic considerations include brand image, re-enforcing corporate sustainability, deepening other current business relations, and supporting or expanding into new business areas [35], [36]. Economically the company must be able to turn a profit, break even, or at the very least be able to mitigate current costs associated with aspects such as transportation or recycling. From an operational standpoint the

company must be able to support the new business area which will require new business-to-business (B2B) and business-to-customer (B2C) service and sales support, logistics systems, processing facilities, and potentially additional development activities. The OEM must assess if these additional responsibilities can be absorbed into the current corporate infrastructure or if a new business unit needs to be created.

The first step in defining and analyzing potential strategies is to understand and define the role the OEM wants to play in the second use eco-system, and how far into the process chain it wants to go. Questions the OEM should answer include:

- Should an OEM sell its batteries as is to a third party repurposer or system integrator?
- Are there technical limitations such as ability to communicate with the BMS? Could this jeopardize the intellectual property in the battery system?
- Are there further opportunities down the value chain that the OEM can do better than anyone else?

In essence, the OEM must have a thorough understanding of how and why competitors and others in the value chain make money, and where its opportunity is to compete [37]. Therefore, it must have a complete overview of the process chain and requirements of that process chain for their specific battery system. This includes trade-offs between process step parameters such as the integration concept and system architecture on costs and end system performance, among others. Within this evaluation process, an OEM would have a particular advantage if it could leverage its toolset from the vehicle development process.

Once a potential has been determined, the next step is to understand the trade-offs along the second use value chain and the upstream vehicle value chain, and identify optimization potentials. Namely, is there an opportunity to extract more value from the battery system through changes in the initial design, and can the requirements of second use be realized alongside the design priorities of the vehicle?

The final step is implementation of the strategy, including building the required partner network and aligning the appropriate internal resources necessary to drive the second life eco-system. The difference between strategy on paper, and a good strategy in real life, is a good strategy creates a path for action and is inherently incomplete without it [37]. Therefore, the development of the battery second use strategy should involve the parties it is going to influence. In essence, strategy cannot be created in a vacuum and will need to gain agreement internally from management and bi-directionally with external partners as the strategy develops. Therefore, communication of numbers, targets, and accurate representation of the current state of knowledge is essential. In the case of battery second use, this can be extremely complex due to the number of trade-offs and influencing factors. This creates a large number of potential scenarios, in addition to the high amount of uncertainty with respect to the technology's performance over time. Therefore clarity and consistency will be key in building support for a second use strategy both internally and externally to the OEM.

1.4 THESIS STRUCTURE

This thesis will present a framework to help an OEM develop and communicate a battery second use strategy. This framework allows for the following:

- Tradeoffs to be assessed throughout the value chain
- The integration of tools and methods used during the vehicle development process
- The representation of inherent variation in the problem
- The ability to communicate uncertainties and accurately represent the current state of knowledge
- Value chain optimization and B2U strategy development

The framework developed can help the OEM identify and quantify the business potentials and tradeoffs related to each strategic factor above; provide information instrumental in the development of new, or furthering current, business relations; identify ideal system type and application for a given EV battery system; in addition to help communicate current barriers and needs to the scientific and regulatory community.

The remainder of the thesis is structured as follows:

Chapter 2: Presents research that has been performed with regards to B2U to date, and discusses the limited ability of current research to enable strategic decision making.

Chapter 3: Discusses the functional and architectural differences between stationary and vehicle battery storage systems, in addition to the differences in the value chains used to produce them.

Chapter 4: Discusses the requirements for a method for assessing the technical and process parameters that can be used for strategic B2U business development. Then a framework is presented that meets these requirements, followed by an example implementation of the framework in a Matlab tool, and example of functionality through a sample analysis using the developed tool.

Chapter 5: Discusses the roles of all stakeholders including OEMs, technology providers, regulators and the research community, their contributions in the past, their roles moving forward, and how the developed framework can support their future work.

Chapter 6: Summarizes new information and contributions of this thesis.

2 Previous Research And Contributions Along the Value Chain

The overarching goal for battery second use (B2U) research is to determine the benefits that B2U brings to stakeholders and society in general. The following questions, derived from the requirements for a viable battery second use ecosystem, must be addressed.

1. What are the requirements for electric vehicle batteries to be integrated into a secondary system in a safe and cost effective manner?
2. What is the infrastructure and associated cost needed to support the process of removing the batteries from the vehicle, inspecting the systems for suitability in a second use, integrating the batteries into a new system, brining that system to market, and supporting the system during its lifetime?
3. What battery performance characteristics are necessary to allow used batteries to be economically favorable, and competitive, to new batteries over a system's lifetime for a given application?

Battery second use research is plagued with uncertainty and the burden of continuously changing environmental conditions. As a result, researchers are forced to establish boundary conditions and adopt creative methods that allow them to account for the necessary contributing factors and answer their research questions despite these uncertainties.

This section will provide an overview of previous research that has worked to answer the questions above and is structured as follows:

2.1. Discusses the history of battery second use research to date, and evaluates the effects of the changing environmental conditions on research focus.

2.2. Presents an overview of the current landscape of parameters that have been defined and quantified by literature to date.

2.3. Analyses the methods used in current research and discusses the resulting polarization between economic and technical studies.

2.4. Presents the requirements for moving forward, including the need for methods that allow the integration of more technical and economic parameters, in order to make the data actionable.

2.1 History of Battery Second Use Research and The Effects of a Changing Market Context

Initial investigations into the further use of electric vehicle batteries in a secondary system were motivated by the need to decrease the capital cost of electric vehicles. It was presumed that by making an EV price competitive with traditionally powered vehicles, a sustainable market for electric vehicles could be created. Given the battery was responsible for approximately 2/3 of the vehicle price[3] [38]; it was the natural starting point for driving cost reductions. In order to make EVs competitive, the price of the battery would need to be reduced by approximately 50%[4] [39].This could be accomplished either through dramatic technology improvements, or by decoupling the battery from the vehicle and analyzing different value opportunities such as battery second use.

[3] In 2008
[4] In 2011

The first study for battery second use was conducted by Argon National Laboratories (ANL) by Pinsky et al. for the United States Advanced Battery Consortium (USABC) in the late 1990s. The study was based on nickel metal hydride (NiMH) batteries as they were the most promising EV battery technology at the time. The goal of the study was to assess if used, de-rated, EV batteries could provide the same performance as lead-acid batteries[5] in stationary applications. The study compared the performance of used NiMH cells and new lead-acid cells when cycled through application specific load profiles. In every case the used batteries performed at least as well if not better than the new lead-acid batteries [40].

After Pinsky et al. concluded that used EV batteries were competitive in terms of performance, Sandia National Laboratories (SNL) conducted a study to determine if used batteries could be priced competitively in the stationary market. The study, documented in a report by Cready et al. assumed a used EV battery could be sold at a price that would make EVs price competitive with traditional vehicles; not based on a market price. In other words if battery prices need to be $150/kWh to compete with traditionally powered vehicles, but the actual price of the battery is $300/kWh then the battery would be sold for $150/kWh after vehicle use. The price to refurbish the battery would be added to the $150/kWh, to get the price a stationary storage system integrator would pay for the battery. The cost to the system integrator was then compared to high and low thresholds for system costs for eight stationary applications [41].

The majority of subsequent studies have either built upon or refined the work done by Cready et al. [42–44]. Narula et al. used the reprocessing cost estimates from Cready et

[5] the most promising stationary battery technology at the time

al., and integration cost estimates and system benefit data from Corey and Eyer [45], to determine the potential benefit/cost ratios for energy storage systems using used EV batteries [43]. Neubauer et al. used the same data to compare the potential market volume for suitable stationary applications and the volume of returned EV batteries [44]. This analysis was then later expanded on to determine the payback period of systems using secondary batteries [42]. In another related study Williams et al. used the same ground data from Corey and Eyer, and Cready et al. to analyze the sensitivity of initial EV battery lease payments to various second use cost assumptions [46].

The studies mentioned above found that, in the near term, a substantial decrease in initial vehicle cost is not possible due to the projected decrease of new battery prices and current battery lifetimes. They also indicated there is a potential for B2U in the future. This is particularly true if stationary systems are capable of capitalizing upon multiple value streams through providing a combination of services. A conclusion that has been reached with respects to storage systems in general [16], [23].

2.2 Landscape of Battery Second Use Studies to Date

To date studies have accomplished the following for battery second use:

- identify and discuss the potentials and barriers for B2U
- define and partially quantify, or estimate the relevant parameters
- use this information to evaluate the technical and economic viability of B2U from a societal perspective

This section will consolidate the main findings from these studies and present them using the structure of the value chain, followed by general conclusions from each study.

Due to the range of approaches to answering the three questions related to battery second use, the studies to date can be divided into five groups summarized in Table 7. The table also shows which question from the beginning of this section each group of studies addresses.

TABLE 7: CATEGORIZATION OF RESEARCH STUDIES

Category	Qs Addressed	Study Examples
1. Research looking to quantify the benefits of battery second use.	2	Cready et al. [41], Narula et al. [43], Neubauer et al.[42], Williams et al. [46], Cicconi[47]
2. Qualitative overviews of parameters effecting battery second use.	2,3	Wolfs [48], Price [49]
3. Trade off analyses and optimal use scenarios.	2	Viswanathan [50] , Lih [51], Hein [52], Neubauer [44]
4. Research for systems with used secondary batteries.	1,2,3	Mukherjee [53], Tong [54], Keeli [55], Onar [56]
5. Technical and operational research about battery systems and electric vehicles.	2	Subramoniam [36], Barre[57], Kim [58], Qian [59]

Category 1 studies seek to determine either the economic impacts of battery second use, focusing primarily on the feasibility of reducing the initial purchase price of the vehicle; or the environmental impacts through reduction in new material requirements. These studies require a detailed breakdown of costs or environmental factors required for each process step to determine the overall economic or environmental potential. Due to the complexity and interdependencies of parameters along the value chain, these studies tend to take point estimate assumptions and a limited number of fixed scenarios in order to make their analyses manageable.

Category 2 studies are similar to Category 1 in scope but don't integrate the information of each process step for an overall quantitative analysis. Since these studies

aren't limited by the requirement to quantify every parameter, they tend to take a wider view for potentials related to battery second use.

Category 3 studies look at various use scenarios for the battery system over its lifetime. Studies include optimal use of the battery over its lifetime, or the optimal use within the context of a single process step. These studies require similar information as Category 1 studies, but use dynamic models, instead of point estimates, in order to do their optimizations. They are generally also narrower in scope, focusing on only a sub-section of the value chain.

Category 4 studies look at operational and technical aspects of stationary storage systems that integrate used EV batteries. These studies look at a range of problems from system sizing, system architecture, and control strategies. Although most of these studies claim to focus on systems with used batteries their analyses are generally also applicable to new batteries.

Category 5 studies provide contextual information for analyzing battery second use. These studies are generally not specific for battery second use, but provide insight into the technical requirements and potential opportunities. Therefore they can be viewed as complementary to battery second use specific research. The technical research covers a broad range of topics including battery aging, system configurations and architectures, and battery management system requirements. Operational research includes topics such as remanufacturing, corporate strategy, and operations management. The papers selected to be included in this literature review are not exhaustive but are representative of current research and knowledge of parameters that will influence battery second use.

A short description of all studies incorporated in this literature review can be found in Section 9.

2.2.1 *Contributions Related to the Vehicle Use Phase*

Critical factors effecting battery second use from the vehicle use stage as discussed in literature include the size, number of available systems, and how the battery ages during vehicle use [41–43], [46].

The size of the battery is critical in linking the number of batteries available to the capacity available for the energy storage market and establishing a sense of scale. For Category 1 studies the supply of used EV batteries could then be compared to stationary storage demand and a market price for second use batteries determined. Therefore battery sizes were clearly defined as 16kWh for PHEVs and 25kWh for HEVs, based on vehicles currently available in the market [42], [43], [46].

All studies model battery systems as black boxes with a given capacity. Little consideration is given to the design, electrical and thermal properties, or the architecture of the battery packs. All of these parameters will affect the real aging characteristics during the operation of the vehicle [60], [61]. In reality, each OEM is using a different chemistry, with a different control strategy and battery pack design. In addition, there is little experience with battery pack aging under real life conditions. Therefore, battery packs from each manufacturer will have different aging characteristics and the real life aging characteristics of the system is highly uncertain [52].

According the Category 5 studies, the state of health of the battery is determined by the chemistry of the cells, manner in which the vehicle is driven, how the battery is

electrically and thermally managed, ambient temperature, and how long the battery remains in the vehicle [60], [62], [63]. Therefore, there will be a certain amount of variation in State of Health (SOH) between vehicle battery systems, in addition to variation between modules with in a pack due to non-uniform thermal loads. From both Category 1 and 3 studies, Neubauer et al. were the only ones to consider the variation in electrical and thermal load profile on the battery aging characteristics [42].

2.2.2 Contributions Related to The Vehicle Battery Return Phase

The buy down price of the used batteries, reverse logistic process, and return criteria, are the key factors for determining the returning batteries SOH and cost required for getting the battery out of the vehicle. Another key factor is the decision to go into second use, which is dependent on the highest value secondary application, or recycling value. The majority of B2U studies to date only investigate the re-use of batteries in a stationary application. Other opportunities such as down grading to a mobile application with lower power requirements are mentioned, but not discussed in detail [46].

There is a general consensus between studies that the buy down price of the battery will be dependent on the price of new batteries or on the end customer's willingness to pay [14], [32], [33], [46] ,[51]. In some studies researchers choose to include an additional used product factor since they believe customers will be unwilling to pay the same per kWh price for a used battery [42], [46] . Most studies assume that the new battery price can be modeled by an "immature market" price function that tapers off after 2020 on a price per kWh basis as shown in Figure 8 [46].

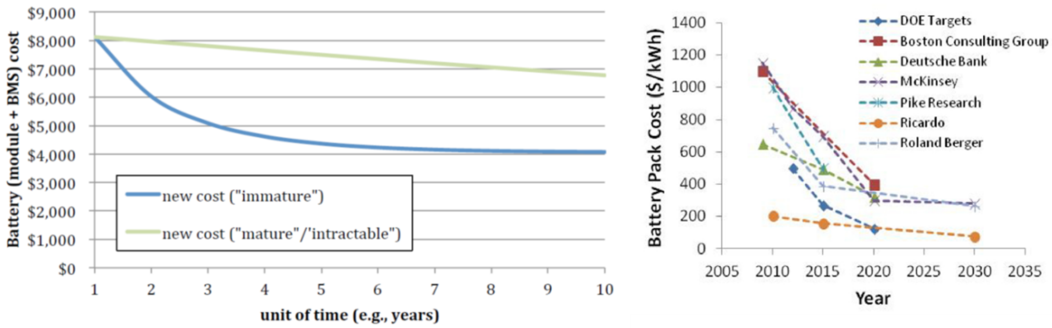


Figure 8 : Illustrative Cost Projection Models for Battery Systems from [46] (left)[6] , Collected Cost Projections from [42] (Right).

In Cready et al. it is assumed that the returning batteries are due to systems being outside their warranty requirements. In this scenario, the EV customer would take the vehicle to the dealership where the dealer would remove and replace the modules. The dealer would pay the customer for the modules, and the modules would be collected by the repurposer who would take the modules to the repurposing facility.[7] Since Cready et al.'s analysis was limited to the state of California; they assumed that there would be one repurposing facility per major metropolitan area.[8] They also assumed that 10,000 battery systems would be available per year in all of California. At that volume, it was determined that one truck per facility would be sufficient to pick up approximately eight packs per day. The costs associated with these assumptions were then used in [41–43], [46]. Williams et al. et al. made one update in that they assumed an additional $500/pack is necessary for removing the pack from the vehicle [46].

[6] Assumes 16kWh pack from Chevy Volt

[7] This case is highly unlikely since the majority of OEMs require the dealerships to return warranty claim parts to the OEM for evaluation and validation that the part failed to meet its warranty requirements.

[8] Sacramento, San Francisco, Los Angeles, and San Diego

The United States Advanced Battery Consortium (USABC) defines PHEV/EV battery performance targets for the end-of-life vehicle criteria (EOLv) to be 20% degradation in either power or energy capacity after 10 years or 1,000 cycles at 80% DOD [64]. This 80% is also common in the majority of warranty agreements available on the market at the time [65], [66] . Therefore the majority of the Category 1 and 2 analyses begin with the assumption that the battery coming out of the vehicle has 80% of its original capacity after 8-10 years within the vehicle [40], [41], [43], [48]. For second use power fade is assumed to be not as critical since it is assumed the majority of second use applications will generally have lower power requirements resulting in a power to energy ratio (P/E) of 2-4:1 [44], [52] versus a P/E of 3:1 for EV applications and 5-10:1 for PHEVs [67].

Although the 80% is seen as a logical starting point, it is in essence an arbitrary value and the actual EOLv will be either dependent on the customer or battery ownership model [42], [62].Therefore, some studies have used a more conservative 70% point estimate, which still assumes that the battery will be returned due to insufficient performance in the vehicle application. Motivations for other return scenarios involve maximizing the value of the battery over its lifetime. This could include taking the battery out of the vehicle early, due to favorable market conditions or a higher demand for secondary use cases [42], [50].

Such scenarios are explored mainly in Category 3 studies, where the life of the battery in the vehicle must be varied, therefore linear models for aging as a function of number of years in the vehicle are established [50], [52], [68]. These models are based on either experimental lab data; linear degradation based on the warranty offers, or is determined from amp-hour throughput models and assumptions about battery use in the

vehicle. Both Beers and Hein utilized this method to establish point estimates about the EOLv, while Viswathan took advantage of the flexibility of the method to look at optimal use strategies between first and second applications [50], [52], [68].

The most advanced method of determining the when the battery should be removed from the vehicle and the corresponding SOH, was developed by Neubauer et al. As explained in their second paper, the authors optimize the battery use over the vehicle lifetime in order to minimize the vehicle's total cost of ownership. This is done using a vehicle simulation modeling the powertrain and a statistically significant sample of vehicle drive patterns. It was found that it was never financially justified to replace the battery during automotive use given their assumptions about new battery prices. Therefore the battery would be used for the full 15 year vehicle life and would have an additional 5 years for secondary use. Although their method established a statistical distribution for the degradation of the battery during vehicle use, the authors chose to use a point estimate of 60% SOH for the remainder of their analysis [42].

In reality, vehicle batteries could be returned for other reasons including a battery technology upgrade, lease vehicle refurbishment, or end of total vehicle life. In each case the batteries return through different logistics networks and might include other parts from the vehicle besides the modules. Additional components could include the thermal management system, system housing, control electronics, and power converters. The potential to use these components can help add to the value proposition of battery second use. But such alternative return scenarios have not been investigated to date.

According to Category 5 studies, the choice of a firm to develop a remanufacturing, or in this case second use, business is generally positively influenced by the presence of pre-

existing buyback and lease programs. In addition, the availability of cores (in this case, batteries) will also influence the ability to create a stable business [36]. These aspects, although critical to understanding the motivations of an OEM to develop a B2U strategy, are currently not addressed in B2U specific research.

2.2.3 *Contributions Related to the Repurposing Phase*

Repurposing includes collecting, testing, inspecting, disassembling, sorting, and reassembling the battery pack or modules as needed. Costs associated with refurbishment depend on the facility, labor, variable material, and capital equipment costs. The size of the facility and most cost efficient processes will depend on the required production volume and reprocessing level.

Category 1 studies use, or extrapolate upon, the reprocessing costs calculated by Cready et al. These costs assume that vehicle battery modules are repurposed at a volume of about 318 modules per day. Each NiMH module has a capacity of 2.1kWh and module voltage of 12 V. Each module is tested for 40 hours in order to establish its capacity and power rate capabilities, sorted according to state of health and then assembled into a standardized battery unit consisting of 21 modules connected in series. The final product or 'StatPack' has a nominal 25kWh capacity and a voltage of 235V. Each StatPack includes all equipment required for the thermal and electrical management of the cells including fans or coolant channels, module interconnects, sensors, and electronics. The cost breakdown of this system can be seen in Figure 9. The final product would then be sold to a system integrator.

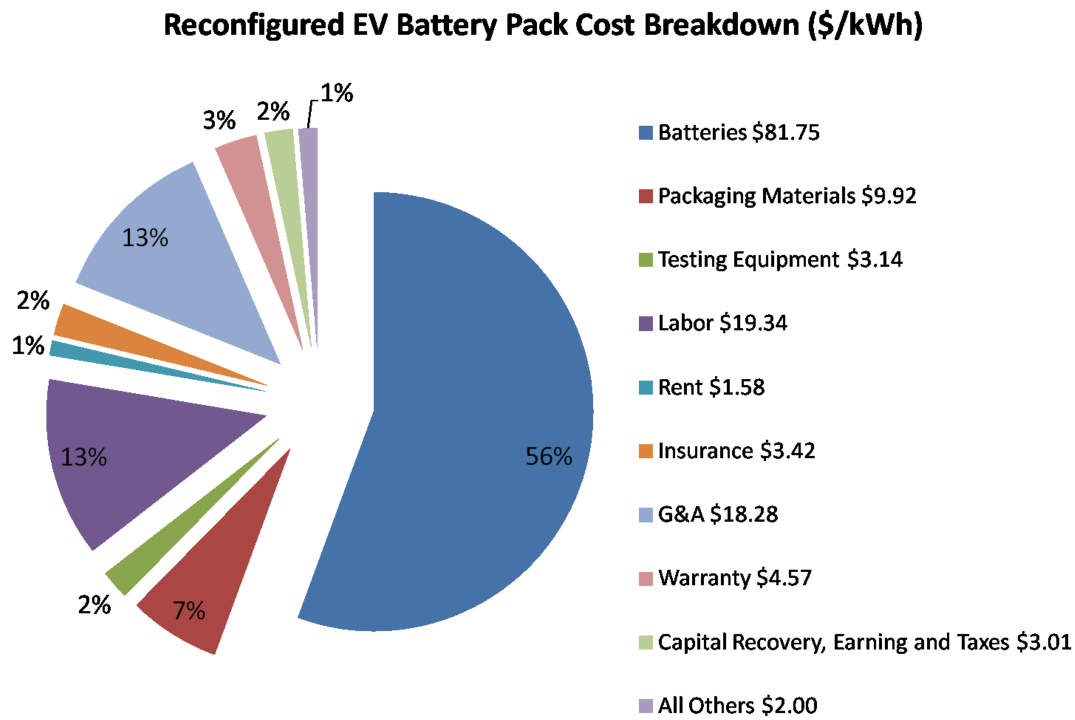


FIGURE 9: REPURPOSING COST BREAKDOWN FROM CREADY ET AL.[41][9]

Although this analysis was established with NiMH batteries, the same general procedures can be directly applied to lithium ion cells. The resulting refurbishment cost is $65/kWh which includes an internal 15% rate of return for and a facility lifetime of 10 years. Narula extrapolated upon these numbers to determine costs associated with a facility capable of refurbishing 142,300 full packs per year. In their study Narula et al. assumed that the same equipment and facility requirements as Cready et al. This is not correct since Cready assumed reprocessing on a module level with a volume of 2,880 packs per year. Therefore Narula established a much lower repurposing cost of $2.66/kWh.

[9] Earnings assume an after tax internal rate of return of 15%, and a return of facility costs in 5 years

Neubauer et al. also extrapolated upon Cready's data, but assumed the same annual throughput on a per kWh basis. As part of their study, Neubauer et al. also included an analysis on the effects of module size and cell failure rate. In order to incorporate this into their study, they had to normalize the facility costs and equipment costs to be able to scale with their module properties. In other words, Cready specified test equipment to test 318 x 2.1kWh modules per day at 1C which cost $1,049,400 in 2002. Updating that number to account for inflation in 2011 the equipment cost is approximately $2000/kW. Through their analysis, Neubauer found that at a cell failure rate of < 0.1% there is a very little change in repurposing costs for modules greater than 8kWh. Therefore a point value of $32/kWh was taken for repurposing costs. If modules are less than 8kWh, repurposing costs are higher (Figure 10).

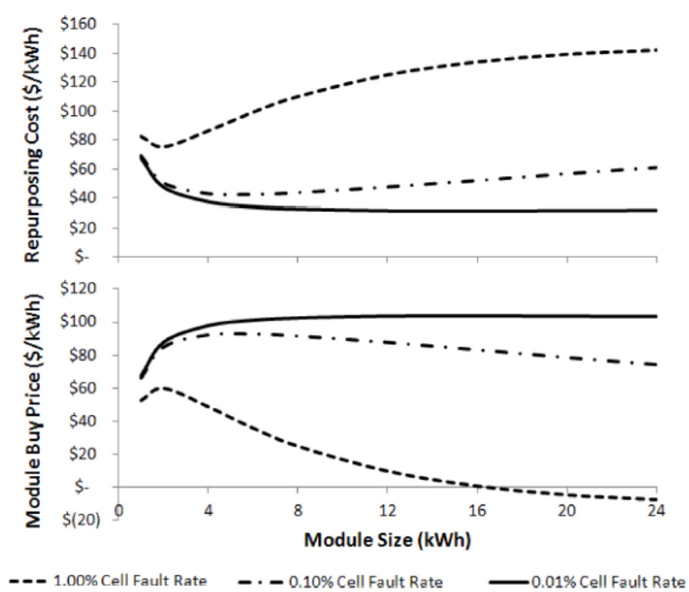


FIGURE 10: REPURPOSING COST AND REQUIRED MODULE BUY PRICE AS A FUNCTION OF MODULE SIZE AND CELL FAULT RATE FOR A REPURPOSED BATTERY SELLING PRICE OF $132/KWH NEUBAUER ET AL [42]

Williams et al. et al. described four potential repurposing scenarios (Table 8), but only quantified the one matching the process described by Cready et al. For their costs they used the $/kWh breakdown defined by Cready, updated the costs from 2002 to 2010 values to get approximately $64/kWh, added $500/pack for removal from the vehicle. Then based on their usable capacity (Table 9), they found the repurposing cost for a PHEV, Chevy Volt, and Nissan Leaf. Unlike Neubauer et al., Williams et al. et al. did not update the equipment cost requirements even though they assumed reprocessing on a pack level.

TABLE 8: DIFFERENT REPROCESSING SCENARIOS DEFINED BY WILLIAMS ET AL. [46]

Scenario	Description
Scenario 0: Minimal Repurposing	1. Receive used batteries at repurposing facility 2. Visually examine battery modules for physical damage, leaks, and signs of abuse 3. Examine data from battery/module management system (BMS health meter or "cloud based" data storage, if any) 4. Use pack as is
Scenario 1: Low Repurposing Cost (Base Case)	Same Steps 1-3 of Scenario 0 4. Conduct initial voltage and resistance measurements to identify failing or failed modules 5. Remove failed modules for possible refurbishment, cell reconditioning (see Strategy 3), or recycling 6. Replace removed modules with suitable ones sorted by capacity, power capability limits, and calendar age 7. Repackage modules for use in HESA[10] unit with existing balance of battery systems 8. Conduct additional testing of apparently "good" HESA battery system to verify condition
Scenario 2: Moderate Repurposing Cost (some customization for 2nd Use application)	Same Steps 1-6 of Scenario 1 7. sort modules by capacity, power capability, and calendar age 8. conduct additional testing of apparently "good" modules to verify condition 9. repackage modules into appropriately sized packs for second use application, with adaptation of existing or inclusion of newly-designed balance-of-plant systems (potentially including modified thermal management)
Scenario 3: Full Repurposing Costs	In addition to all steps in Scenario 2, dismantle battery modules into component cells, conduct individual testing, potentially "recondition" bad cells, then reassemble modules

[10] Home Energy Storage Appliance

TABLE 9: CAPACITY ASSUMPTIONS FROM WILLIAMS ET AL. [46]

Battery System	Rated Capacity in Vehicle	Usable Capacity in Vehicle	Capacity Second Use (80%)
PHEV (Prius)	5.2kWh	3.9kWh	4.2kWh
Chevy Volt	16kWh	10.4kWh	12.8kWh
Nissan Leaf	24kWh	20.4kWh	19.2kWh

Other qualitative insights about the repurposing process discussed in literature include:

- The repurposing process will have a limited environmental impact [47].
- Sensitivity to battery transportation costs will be dependent on hazard classification [43], [46]. Current classification is Hazmat 9 [69].This can lead to transportation costs of $3.85/lb which is about$1,500 per Volt battery pack ($120/kWh) [43].
- The need for standardized testing procedures for re-qualifying, or certifying battery systems, and the need for repurposed EV systems to meet stationary system standards and requirements [46].
- Additional value of having battery history available [46] to prescreen or determine system state of health. In the future this could also eliminate the need for battery testing, which is time consuming and requires capital equipment investments.
- Ability to increase the value of a repurposed system by re-using additional vehicle components such as sensors, power electronics, and safety devices [46].

According to Category 5 research, motivators for a firm to establish an integrated remanufacturing process will be driven by profit potential, and remanufacturing operations will only be undertaken with a sound monetary foundation. By leveraging the current organizational structure, the repurposing process could benefit from the use of pre-

established logistic networks and products designed for remanufacturing [36]. Barriers could include an OEMs desire to protect proprietary information, and availability of usable cores (or in this case, batteries) to guarantee a steady supply to second life battery consumers [36]. To date, none of these factors have been explicitly addressed in second use research.

2.2.4 Contributions Related to the System Integration Phase

Integration consists of process and cost components that are common to all energy storage appliances independent of if they use new or used batteries. System integration involves connecting a given number of repurposed second life battery systems in series and parallel to obtain the proper application requirements in terms of capacity and power. The batteries are then connected to the power control system, which is then mechanically and electrically integrated into the system housing along with monitoring and control systems, safety systems, and system level thermal and climate control systems. Costs incurred in this process step will determine the capital cost of the system.

Category 1 studies generally used a per kW or per kWh normalization in order to scale battery costs into complete system costs to be able to calculate the expected NPV of the system. Some integration costs, such as the power control system, scale with power (price/kW); while others, such as balance of system, scale with energy content (price/kWh). Therefore the overall system costs will depend on the system size and specified power to energy ratio (P/E). Both the system size and P/E are dependent on the chosen application. Cready et al. used values for system requirements that were determined from a study by Sandia National Labs in 1994 [70]; and system costs were estimated from pilot projects

using primarily lead acid batteries and documented in [71] from 1998. These values were either used directly or extrapolated upon by Neubauer et al., Narula et al., and Williams et al.. A large discrepancy between studies lies in the use of the second life capacity or beginning of life capacity to determine the overall integration costs Figure 11.

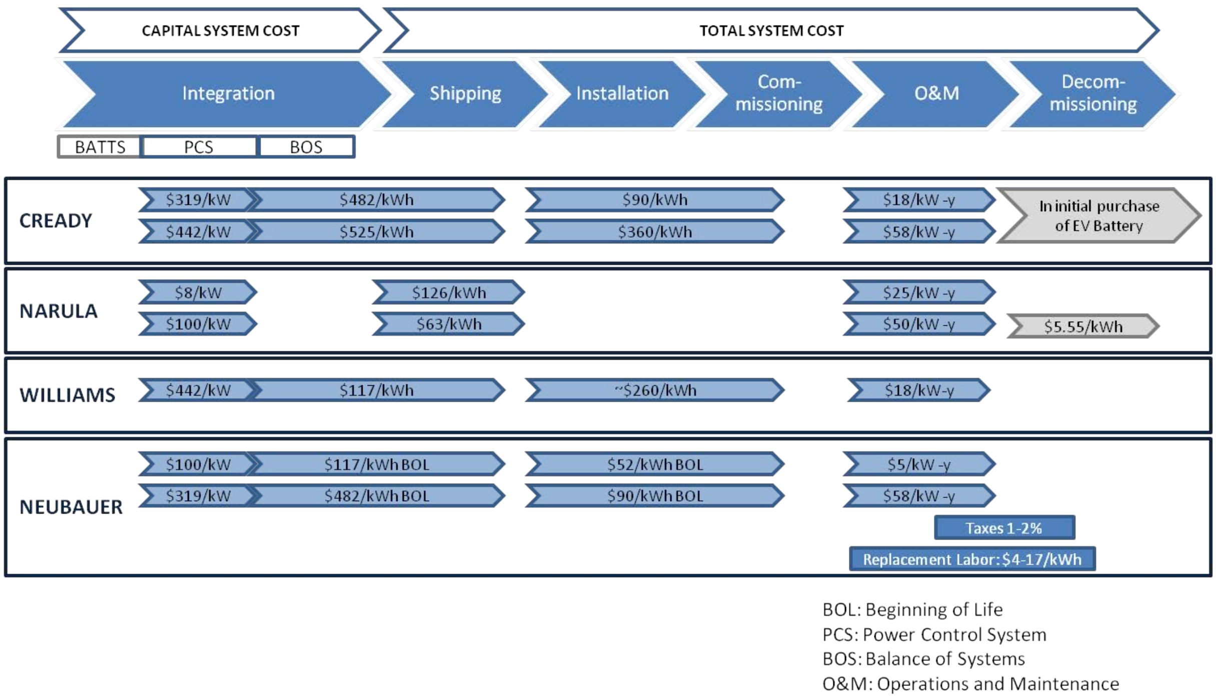


Figure 11: Overview of Integration Costs Assumptions for Category 1 Studies

To date, the majority of Category 1 studies assume stationary systems will be designed around EV battery packs or modules[41–43], [46]. They assume there will be a standardized battery module or pack where standardization includes module or pack size, communication protocols, control architecture, and monitoring. The standardized pack must also meet all regulation, certification, installation, maintenance, and safety requirements for various stationary applications. According to Kim et al. a combined hardware-software architecture is also essential for the efficient management of a large

scale battery system [58]. To date the majority of second use studies only consider hardware integration.

Category 4 studies look at different system architectures that could potentially improve the performance of a battery system with used batteries with different aging characteristics (Figure 12). These studies propose integrating individual battery packs or modules with dedicated power control elements which are then coupled to a large grid-tied AC/DC inverter. The power control elements can take the form of a DC/DC converter [48], [53], or H-bridge within specialized inverter topology [72]. This type of architecture will enable the maximum performance of individual battery packs, higher efficiency at high power, and better system reliability [48], [53], [72]. It is assumed that this type of architecture would be preferential for used battery systems but the studies do not discuss the impact on system performance or cost.

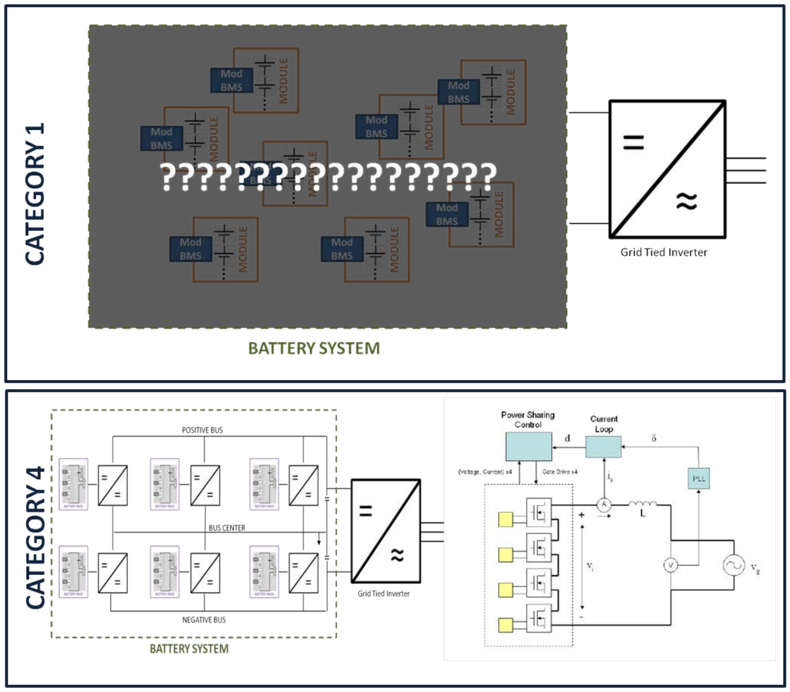


FIGURE 12: DIFFERENCE IN ARCHITECTURE ASSUMPTIONS FOR CATEGORY 1 AND 4 STUDIES [48], [53], [72]

This raises the question of whether systems using used batteries should have a dedicated system architecture, or if they should use the same architecture as systems using new batteries. This question has yet to be suitably addressed in literature.

2.2.5 *Contributions Related to the Second Use Phase*

Second use application(s) and how the system is controlled in order to meet the application requirements, will determine the maximum obtainable value of process chain.

Category 1 studies use identified applications to estimate system requirements needed for calculating system costs, estimate revenues, and evaluate if positive NPV is possible. The majority of studies concentrate on initial capital system costs [43], [44], [50], others take a step further to look at lifecycle costs including aging and battery replacements [41], [42], [45]. The requirements for battery replacements are based on the application load profile and control strategy [41]. But due to the lack of information about the system architecture, exact application requirements, and electrical properties of the batteries, load profiles are estimated as a given number of full cycles per year. This combined with simplified assumptions about the aging characteristics of the battery system allows these studies to estimate the number of battery exchanges required over the system lifetime.

According to Category 5 studies, a detailed evaluation of battery aging would require modeling the electrical and thermal loads of the battery as a function of time. Parameters effecting aging include C-Rate, depth of discharge, cycle number, and operating temperature [57], [63]. It's assumed that second life is less strenuous than the in vehicle application. The number of cycles is considered by [41], and the DOD by[44], [50]; but the operating temperature and effects of constant operation on temperature profile are not considered. The ambient temperature and changing thermal properties of the cell will be critical to the aging of the battery in a secondary application [46].

Initial studies, performed in 2000, assumed that there would be a market for used batteries if they could be price competitive with battery systems currently available on the market [73]. At this time there was little discussion about the value of energy storage for grid services, so applications were limited to those currently being served by commercially available systems. These included telecommunications, utility substation/power station back-up (black start), and UPS applications. It was assumed that there would be a one to one replacement of the, generally employed, lead acid batteries with either NiMH or Li-ion technologies. Although the study was generally qualitative in nature, it was found that the estimated lifecycle costs of the new technology were too high to compete with the low price of lead acid based systems. In addition, the customers of these markets were by nature very risk-adverse and satisfied with the performance of the current technology making the impedance for market entry relatively high.

In 2002 Cready et al. [41] took a wider view and looked at a range of eight potential storage applications. The potential benefits of each application were determined as a range between the potential revenues of the application as a lower bound, and the price of a competing system on the upper bound. Of the eight applications, four were identified as being economically viable for battery second use: transmission support, light commercial load following, residential load following and distributed node communication.[11]

Narula at al. found that for all combinations of assumptions[12] three applications would have a lifetime benefit to cost ratio greater than one. But it must be noted that the

[11] Details about specific applications can be found in Section 8.2

[12] low benefit/low system cost, low benefit/high system cost, high benefit/low system cost, high benefit/high system cost

three applications identified[13] have a relatively limited market size compared to the availability of used batteries, and therefore are expected to saturate quickly.

Neubauer et al. performed a similar study and concluded that the same three applications identified by Narula et al. would be the most appropriate for used EV batteries. Neubauer was also able to confirm Narula et al.'s speculation about the saturation of the market. In addition, they showed that the marginal present value of revenue generated per pack would fall below the present value of system costs in 2023 and the market for all three applications would saturate by 2025.

Hein and Williams et al. came to similar conclusions about the saturation of the regulation market. This is consistent with indications from [21] and [27] that show although the requirements for regulation is expected to grow with increased renewable penetration, the use of fast ramping assets such as battery energy storage can reduce the need for regulation assets. Therefore, the regulation market can be seen as a shrinking target, as the increase of regulation assets on the grid will reduce the price of regulation energy, and the increase of fast ramping regulation assets will decrease the amount needed in the market [21].

Currently regulation energy is one of the few high value, monetizable applications, which is why it receives the majority of attention in the storage industry. This is expected to change with new regulations and the maturation of the energy storage market [17]. Therefore it is expected that new profitable applications will appear overtime, indicating that a B2U strategy must be able to adapt with these changing market opportunities.

[13] transmission and distribution upgrade deferral, area regulation, and electric service quality

Narula et al. also investigated the potential of combined applications. It was identified that applications combined with other low utilization applications, requiring service only a few hours a year, had a potential to increase benefit/cost ratios. Community Energy Storage (CES) was an application of particular interest since it could provide time of use rate management services to end users as well as voltage support, service reliability, other ancillary services, and potentially transmission and upgrade deferral benefits to the utility. Currently, barriers to the implementation of such a system include monitoring and control requirements and the market mechanisms required to capture the true value of the system [26], [43]. Onar took the results of Narula et al. and investigated potential control strategies for integrating multiple CES devices providing services to multiple households [56] and the grid, but did not quantify the benefits of such combined of applications. It should be noted that the results of this study is applicable to both new and used battery systems.

Quantification of a potential mixed use scenario was performed by [68], who used the open source Distributed Energy Resources Customer Adoption Model (DER-CAMS) to determine the optimal use of a battery system between a commercial energy management system and the regulation market. Using specific load profiles from a commercial building in Northern California and day-ahead regulation market prices from 2008, they determined an optimal size for the battery system and an annual cost reduction of $40,955 in the energy bill of the facility, including the annualized costs of the battery system. These results are highly dependent on the assumptions for system integration and aging, which are in general much lower than other studies to date.

A key to the optimal control of a battery system, is the most efficient utilization of the battery which includes management priorities between application requirements and battery aging [74]. The effectiveness with which the battery system meets the application requirements will be dependent on the control strategy's ability to accurately determine the battery's capability and state as a function of time [75]. Keeli developed a rule based control algorithm for a system using secondary battery, where the nominal characteristics of the battery are unknown by the control system. The method proposed can be used to properly size a system for peak shaving, and determine rules for the charging and discharging of the battery [55]. Although the concept is interesting it was not shown how battery aging will affect the performance of the algorithm, which is necessary to maximize the efficiency of usage thereby minimizing the payback time of the system [74].

The difference in performance between old and new batteries will be lower overall capacity, an increase in internal resistance, the rate of degradation and the difference between cell properties within a module or pack [57]. Tong et al. looked at integrating used batteries with different properties into a single system for an off-grid EV charging systems with an integrated PV system. Within their lab demonstration system they attached cells with different capacities in parallel into a battery block before attaching batteries into series to minimize the amount of inaccessible capacity [54]. Although an innovative method of integrating battery cells with different capacities, a comparison with the performances of a new system was not performed. Therefore, an evaluation of the methods effectiveness is not possible. The study would also benefit from investigating the limits to the mismatch of battery capacities and internal resistance, in addition to the relationship to the control strategy.

Potential operational barriers identified for battery second use are summarized in Table 10. These include both soft factors such as the customer's perception of used batteries, and technical factors such as matching battery characteristics.

TABLE 10: POTENTIAL OPERATIONAL BARRIERS FOR B2U

Barrier	Source
Warranty requirements and uncertainty involved with aging properties	[41], [44], [52]
The risk adverse nature of utilities	[40]
The perceived value of used batteries	[41], [42]
The ability to match batteries with similar characteristics in a string	[41]
How battery value will reach EV customer	[41]
Non standard battery modules	[41]
Use of different technologies	[52]

2.3 METHODS AND LIMITATIONS OF STUDIES TO DATE

Within Section 2.2 research papers contributing to the current state of knowledge about B2U were split into five categories. Due to the focus of the individual studies, and amount of information available, each study presents a different emphasis on the various steps in the process chain as shown in Figure 13.

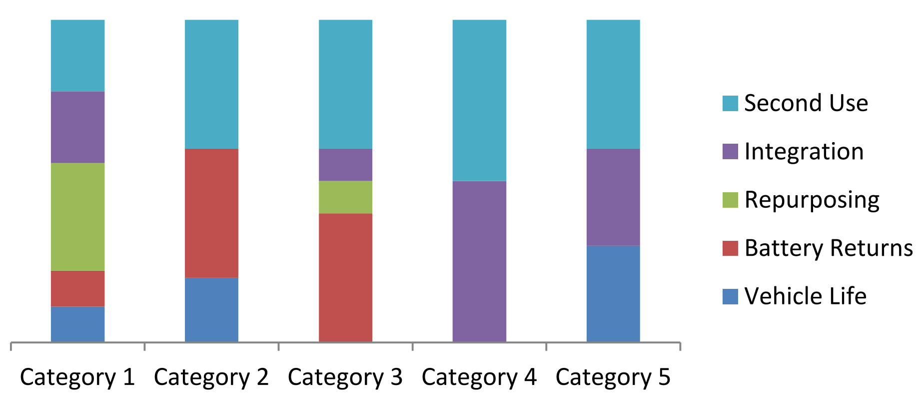


FIGURE 13: QUALITATIVE REPRESENTATION OF EMPHASIS ON PROCESS STEPS BY STUDY CATEGORY

Each category makes a critical contribution to the overall state of knowledge, but each has its own strengths, weaknesses, and ability to influence the development of a B2U market.

Category 1 studies are the most comprehensive with respect to capturing the scope of the entire value chain. Due to the breadth and complexity of technological and economic parameters involved, these studies must adapt methods that allow them to integrate the information available. This generally involves extrapolating and adapting the limited amount of available information; specifically regarding system architectures, battery ownership models, and market structures. As a result, they must use simplified models which can only represent a small amount of the interdependencies along the value chain. In addition, the combination of methods used to extrapolate the data with the methods used for the individual studies, creates inconsistencies between the studies and a lack of cohesiveness in the overall results.

Category 2 and 3 studies complement Category 1 studies in their ability to address dimensions that cannot be cleanly integrated into the Category 1 studies. Category 2 studies are able to address more soft factors and market dynamics, but tend to lack continuity and ability to draw overarching conclusions. These studies are generally a random identification of facts, contributing factors and opportunities, which cannot be easily integrated into a single coherent picture.

Category 3 studies show the interdependencies and trade-offs between parameters that must be held constant within Category 1 evaluation. But due to the large number of parameters, interdependencies, and availability of information; these studies must limit their choice of variables and scope. Therefore these studies tend to leave out critical pieces

of the value chain, or have difficulties in defining their contribution within the context of the entire value chain.

Category 4 studies investigate technical parameters relating to the deployment of the used battery in a secondary system. These studies generally hold critical insights into the technical parameters relating to the operation and design of a used battery system; but don't address the impact of these factors on the potential competitiveness of second use systems against new battery systems.

Category 5 studies are those that don't directly apply to battery second use, but contain critical technical, operational, and economic insight. It is therefore essential to be able to integrate the developing methods and knowledge presented in these papers into Category 1 type analyses.

In general, the incompatibility between each category of studies creates barriers in terms of building higher levels of knowledge and understanding about the ecosystem. Namely, there is a need for Category 4 and 5 knowledge and models to be integrated into Category 1 type analyses, and the ability Category 3 analyses to define their place within the context of the entire value chain.

2.4 Conclusions About the Current State of Research for B2U

Studies to date have worked to define the landscape for battery second use including process step requirements, market parameters, and technical factors. These studies have determined that the future of battery second use is promising but uncertain.

Due to the complexity of the problem and the lack of technical information about system design, the majority of studies must make assumptions or generalizations that limit

their ability to explore the entire potentials for battery second use. The methods employed are generally driven by the type and form of available information, instead of the underlying technical and process attributes of battery second use. This creates a disparity between (1) individual research studies; and (2) the problem being analyzed in research and the reality of opportunities present (Figure 14).

	VEHICLE USE	BATTERY RETURN	BATTERY REPURPOSING	BATTERY INTEGRATION	BATTERY SECOND USE
CURRENT ASSUMPTIONS	• Model system as black box • Standardized modules	• Batteries return at end of warrantied lifetime • All batteries will have same SOH	• Analyze single repurposing process	• System Integrated as black box component	• Value based on revenues generated • Only consider initial purchase price of the system
REALITY	• Range of designs and vehicle architectures available on market	• Multiple return scenarios possible • Battery SOH will not be the same between packs	Opportunities for optimizing: • Re-usable components • Integration Concept • Screening Procedures • Diagnostic Capabilities • Sales Concept	• Range of architectures that can be used that will influence cost and performance of the system	• Competitiveness will depend on lifecycle cost of system versus a system with new batteries
NEEDS	• Ability to analyze various battery designs to evaluate optimal parameters for battery second use	• Ability to analyze multiple return scenarios and find optimal conditions to maximize value of system over its lifetime	• Ability to analyze multiple repurposing scenarios and repurposing levels and evaluate the effects on process chain costs	• Ability to analyze multiple system architectures and system requirements and effects on system cost and performance	• Ability to evaluate lifetime system performance and costs

FIGURE 14: GAPS BETWEEN CURRENT RESEARCH AND OPERATIONAL REALITY

The disparity between research studies creates inconsistencies in the current state of knowledge, discontinuities that prevent the results from being actionable, and prevents the creation of higher states of knowledge. The methods needed to fill the gap between B2U research and the current state of knowledge is available in the Category 4 and 5 type research.

Moving forward, a method will be needed to be able to:

1. Incorporate the methods from Category 4 and 5 research into the methods and analysis of Category 1 studies.
2. Structure the problem to allow the creation of higher level knowledge, the ability to act on generated incites, and enables stakeholder strategy development.
3. View the battery as an integrated system, and not just a collection of battery cells.

The method should be based on attributes of the problem, and not the availability of information to allow for consistency between individual research contributions. The development of this method will also require the better representation of the interests and views of the OEM and system integrator, whose interests are currently poorly represented in literature. Therefore the technical and process requirements for B2U, in addition to the needs and motivators of both stationary and vehicle system developers should be evaluated. This will help identify the current state of the market and potential future directions and the requirements for evaluating the most appropriate path forwards.

These technical and process parameters will be explored in more detail in Section 3. This is followed by the proposal of a framework, in Section 4, that seeks to meet these defined needs for a methodology to address the three questions posed at the beginning of this Section.

3 TECHNICAL REQUIREMENTS FOR BATTERY SECOND USE AND THE INTEGRATION FOR THE VALUE CHAINS FOR VEHICLE AND STATIONARY SYSTEMS

As discussed in Section 1 the goal of merging the vehicle and stationary battery value chains is to maximize the value of the vehicle battery over the course of its useful life. This requires transferring the functionality of storing power and energy from the original vehicle application to a secondary one, integrating the highest value system at the lowest possible cost, and maximizing the value already inherent in the vehicle system. Therefore analysis should consider potentials past the cell level, and explore the system level functionality that can be transferred between the two applications. The efficiency, with which the functionality of these two systems can be integrated, depends on the functional requirements and the ability to overlap the system architecture of the primary and secondary applications.

Section 2 discussed how research to date shows battery second use has a potential benefit, but contains a large level of uncertainty due to changing market dynamics, and absence of technological and process details. The lack of technical and process details is due to the use of methods that capitalize on the type of data available, rather than the structure of the problem, and the absence of the interests of the vehicle OEM and system integrators. Therefore, there is a lack of information on how vehicle and stationary storage systems are developed, sold, and managed throughout their lifetime. These details are necessary if opportunities for merging the two value chains are to be properly analyzed.

Therefore this Section presents the following:

3.1. A technical decomposition of vehicle and stationary systems to identify potential mechanical, electrical, and communication interfaces and opportunities for the integration of a vehicle battery system into a stationary system.

3.2. Overview of system components and architectures for stationary and vehicle systems to identify further requirements or potential limitations for the integration of vehicle systems into a stationary device.

3.3. Analysis of the vehicle and stationary system value chain to identify influencing factors, key motivators, opportunities and business requirements that will drive the development of a second use market.

3.4. Evaluation of combined technical, operational, and strategic factors on the potentials and limitations in the development of battery second use ecosystem.

3.1 Differences and Overlap of Functional Requirements for Stationary and Vehicle Battery Systems

The following looks at the functional attributes of stationary and vehicle battery systems. This will allow the identification of potential attributes that can either help, or hinder the development of a product capable of using second-hand EV batteries.

The vehicle battery pack is an integral part of the electrified vehicle system. Vehicles are extremely complex systems that must meet an ever increasing number of consumer and regulatory requirements [76], [77]. Therefore, the battery system must support vehicle level functions, such as safety, in addition to its primary function of storing energy used to propel the vehicle. A non-comprehensive list of vehicle requirements is depicted in Figure 15.

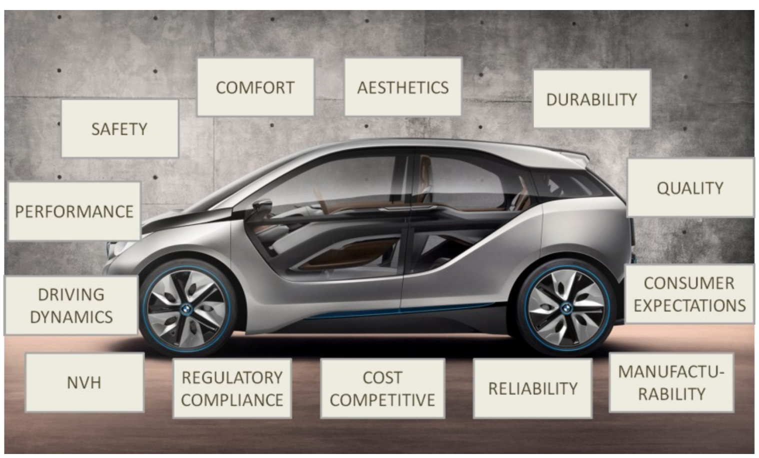


Figure 15: List of Vehicle Requirements, non-comprehensive [78]

Functional requirements of a stationary storage system will vary with system size, installation location, and end customer. Examples of the size and range of storage products can be seen in Figure 16. Small and medium sized systems for installation within a home or commercial building will need to have a relatively long life time, low maintenance

requirements, dimensioned to fit through standard doorways, be a single unit and have a certain level of aesthetics. While medium to large scale systems owned by a utility will generally be placed outdoors and therefore require weatherproof housings, accessibility for easy service, and potentially a self contained HVAC system. Examples about the various system sizes can be found in the Section 8.1.5.

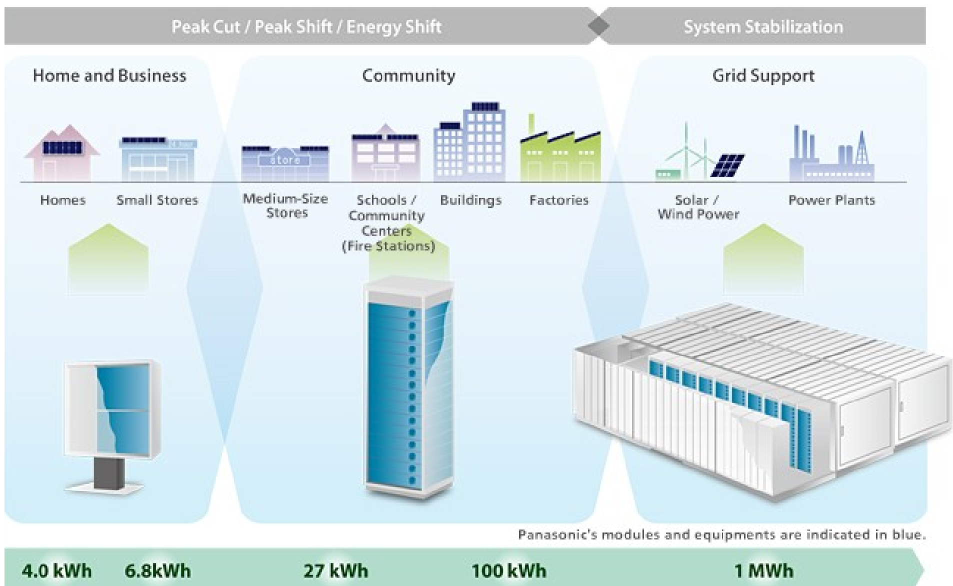


FIGURE 16: STATIONARY STORAGE SYSTEM SIZES [79]

This section will discuss and compare the functional requirements described in Table 11 for both vehicle and stationary battery storage systems.

TABLE 11: FUNCTIONAL CATEGORIES ANALYZED FOR VEHICLE AND STATIONARY BATTERY STORAGE SYSTEMS

Category	Description
Packaging	Enclosure, outer system dimensions, environmental protection, physical integration of components
Thermal Management	Heating or cooling of battery system to maintain optimal operating conditions
Mechanical	Structural requirements to maintain mechanical system integrity
Lifetime	Use characteristics including cycle life, up time, and calendar life
Electrical	Power and Energy requirements, current ad voltage loads
Control	Requirements for maintaining safe operating range, and ensuring power and energy capability needed for the application
Safety	Internal protection of the system from external anomalies, and protection of people and interfacing systems

3.1.1 PACKAGING REQUIREMENTS

Packaging refers to the enclosure, protection, physical interface and dimensions of the battery system. This includes overall system packaging in addition to the packaging of sub-components, such as modules and the thermal management system.

Packaging and the physical integration of components into the vehicle presents one of the largest restrictions for the vehicle battery system. The art of packaging includes optimizing the placement of vehicle components for weight distribution, performance, manufacturability, serviceability, safety, and user interface. There are two main options for packaging the battery system into the vehicle. Either (1) the battery can be integrated into an existing vehicle architecture, or (2) be packaged as a single integrated system. These two strategies are generally referred to as “conversion” and “purpose built” vehicles, respectively. Examples of both strategies can be seen in current production vehicles; such as the Chevy Volt, which is a conversion; and the purpose built BMW i3 (See Section 8.1.4).

Other vehicle packaging considerations involve maintaining a clean environment around the battery cells. Any debris or moisture could degrade the electrical contact

between cells, or create soft shorts within the system. In addition, proper distance must be maintained between high voltage and grounded components (*i.e.* air and creep distances) to prevent arcing during electrical anomalies.

Packaging requirements for a stationary system are more flexible since the volume restrictions are more lenient and environmental conditions more controllable. Packaging for stationary systems is driven predominantly by installation, maintenance, and transportation requirements. Depending on system size, overall system footprint might also need to be considered [15].

3.1.2 Thermal Management Requirements

The thermal management system (TMS) is needed to mitigate temperature dependent aging effects; by maintaining an operation temperature between 15°C and 40°C and minimizing temperature gradients within the battery system. The type of thermal management system required is highly dependent on thermal properties of the cell, battery system design, operating requirements, and the ambient temperature [60], [80].

The challenge for the TMS in the vehicle is being able to maintain the proper operating temperature of the battery pack given a wide range of ambient conditions. The TMS must be able to keep the temperature of the battery within the operating window independent of if the vehicle is parked the desert in Arizona in the middle of summer, or through the Rocky Mountains in the middle of winter [81].

Thermal management for stationary systems is less critical since the ambient conditions are more regulated, load conditions less severe, and the system packing density lower. Therefore systems typically rely on natural convection or forced air convection from

a system level thermal management system that is also responsible for the inverter, other power electronics, and switching devices.

3.1.3 Mechanical Properties

Mechanical properties of the battery system depend on the physical environment in which the system is to operate. The system must be able to handle the associated loads and vibrations within that environment and also meet requirements related to installation, maintenance and removal. For vehicular battery systems, the more demanding requirements will come from the in-vehicle operation, while stationary requirements will be dominated by transport and installation requirements.

As a part of the vehicle system, the battery is subjected to a harsh dynamic environment in addition to being an integral part of the safety, structural, and NVH (Noise Vibration and Harshness) characteristics of the vehicle. Therefore the system must have a robust mechanical design and often consist of additional structural elements in order to meet these requirements.

Mechanical requirements for stationary systems are significantly less demanding since stationary systems operate in a much less dynamic environment. The most significant requirement is the mass of the system, or system components. This will define equipment, process, and accessibility requirements for installation and maintenance. Other considerations include the potential for a module to be dropped during transportation, installation, or maintenance [15].

3.1.4 *Lifetime Requirements*

Lifetime requirements refer to the duration and frequency in which the system is used, examples of which can be seen in Table 12. These requirements will dictate how the batteries degrade or age over time, the technical specification of components, and maintenance procedures.

A typical commuter vehicle is driven about 30 miles per day [82] during a total of 3 hours per day [83]. Therefore a typical load profile for an electric vehicle involves a dynamic discharge followed by a controlled charging period every 2-3 days [82]. The exact load profile of the battery will depend on the mass of the vehicle, selection of vehicle components, and control strategy for the battery.

In order to save energy the vehicle electronics are only active when the vehicle is on or charging. Therefore the specification of the system electronics assumes the system will only be on for a limited time per day. Currently batteries must meet car manufacturers' battery system warranty which is typically 8-10 years or 60,000-100,000 miles [65], [84].

Table 12: Example Applications and Lifetime Requirements for Battery Energy Storage Systems

APPLICATION	DURATION	FREQUENCY	Lifetime
Vehicle:			8-10 Years
Driving	10-50 min (3hrs/day)	1/day	
Charging	2-6hours	2-3/week	
Frequency Regulation	15 min	>8,000/year	15 years
Home Energy Management	2-4hours	150-400/year	10-15 years

The cycling characteristics and uptime of a stationary storage system will depend on the application or combination of applications the system is to perform. Some applications require the continuous operation of the system; others will require operation for a few

hours on a daily or weekly basis. In the case of continual operation, components must allow for a continuous run time. Some applications, such as frequency regulation or voltage support, require short bursts of power for short amounts of time. Other applications such as peak shaving require long steady discharges. Examples of different types of stationary application load profiles can be seen in Figure 17. Currently system manufacturers are typically offering system warranties of 10-20 years [85].

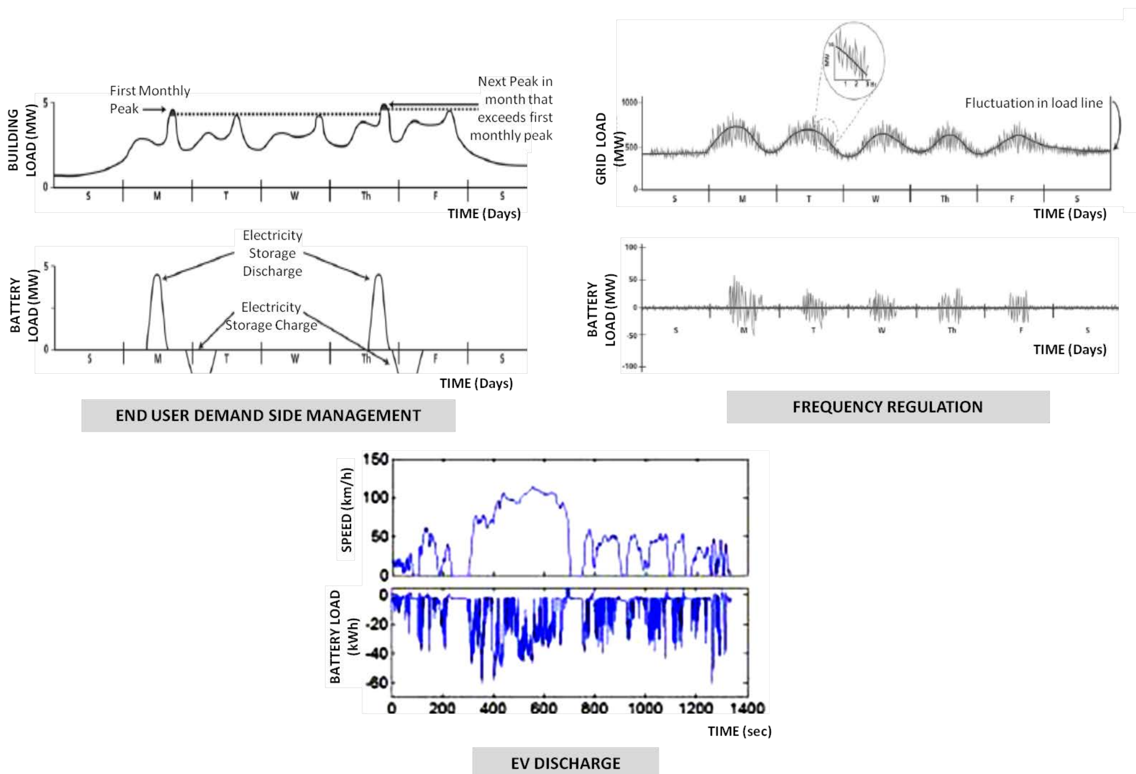


FIGURE 17: EXAMPLE STATIONARY APPLICATION LOAD PROFILES [20], [62]

3.1.5 *Electrical Requirements*

The electrical parameters refer to the power and energy, and operating voltage range of the battery system. The voltage level and amount of current running through the system will determine the specification for components such as fuses and relays, in addition to requirements for isolation , safety and certification [86].

Electrical requirements in the vehicle are dependent on user requirements for range, acceleration, charging and regenerative breaking. EV systems are generally designed to allow for a maximum of 6C pulse and 2C continuous discharge [57],[87] . Traditional charging protocols use a constant current-constant voltage strategy at a maximum of 1C in order to ensure maximum SOC after charging. Generally vehicle battery systems have a nominal system voltage of 340-400V. Modules can range from 8V-50V depending on design [66], [78].

Electrical requirements for a stationary system are dependent on the system size and application. Examples of typical voltage levels for stationary systems are shown in Table 13 and common power and energy ratios shown in Table 14.

Table 13: System Voltages For Various System Sizes, (s) designates most common voltage range

SYSTEM SIZE	DC Voltage
Small (1-10kW)	12-60V
Medium (10-100+ kW)	300-400V (s) 800-900V
Large (100s-1MW+)	300-400V 800-900V (s) 1200V+

TABLE 14: POWER TO ENERGY RATIOS FOR VARIOUS APPLICATIONS

APPLICATION	P/E
Vehicle	2 [33]
Frequency Regulation /Renewable Integration	1-4 [18], [88]
End User Behind the Meter	0.1-0.5 [18]

3.1.6 CONTROL REQUIREMENTS

The battery is controlled and monitored through a Battery Management System (BMS). A BMS is responsible for ensuring the battery cells are within their safe operating range while being able to meet the application power requirements. The BMS is responsible for controlling cell or module balancing, the thermal management system, calculating the system's SOC, fault detection, prognostics, determining system capabilities based on current state, and communication with the rest of the system as shown in Figure 18.

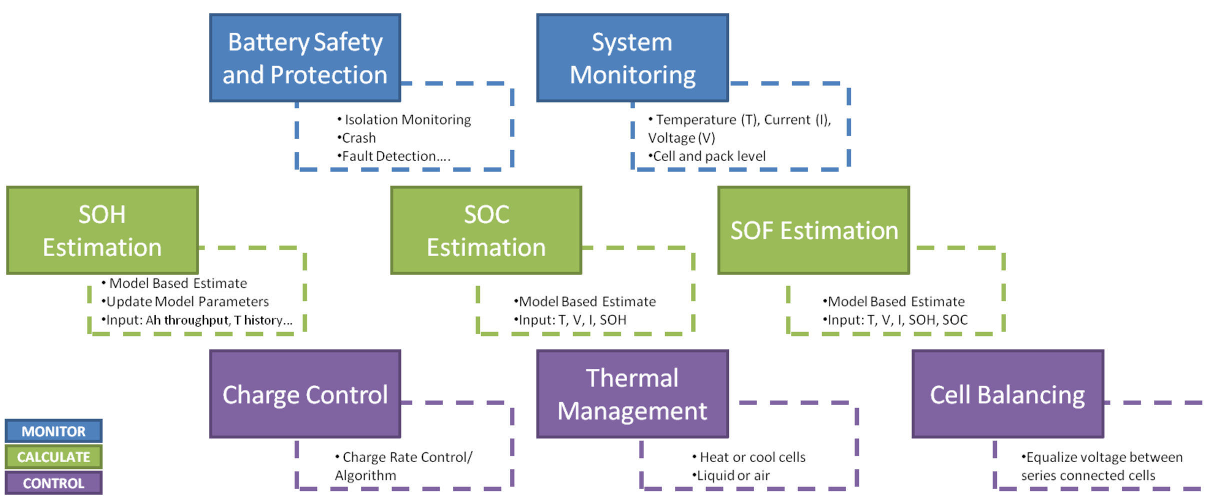


FIGURE 18: OVERVIEW OF MAIN FUNCTIONS OF A BMS [59], [89], [90].

The complexity of the BMS is not due to the functionality that the system has to perform but on the inadequacy of the information with which it is supplied. This is due to the accessibility of monitoring the electro-chemical reactions in the cell using cost effective

sensor technology. The BMS relies on temperature, current, and voltage sensors in combination with complex model based algorithms and look up tables to infer the current state of the battery system [91–93]. An example of a BMS architecture can be seen in Figure 19. When designing a BMS the best modeling technique is dependent on the chemistry of the cell and design of the battery system. Therefore a BMS is generally developed specifically for a battery pack or system [94].

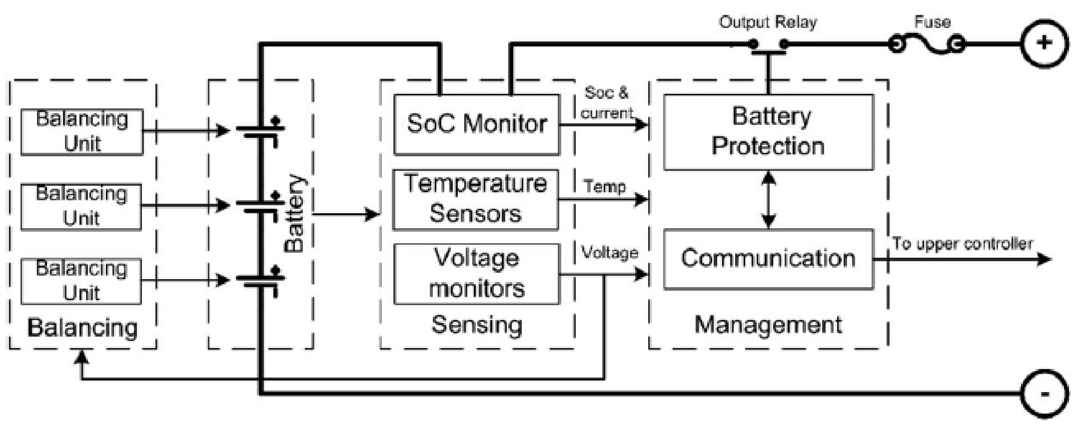


FIGURE 19: EXAMPLE SCHEMATIC OF A BATTERY MANAGEMENT SYSTEM [95]

The main challenge for stationary systems is the ability to funnel large amounts of data[14] to the master BMS [96]. The main challenge in the vehicle is the ability to implement efficient BMS control algorithms with the limited processing power in the vehicle [90].

In both applications system reliability is a key criterion for the control system. For vehicle systems the robustness of the control strategy requires multiple levels of redundancy due to the safety requirements of the system [97], [98]. Stationary systems

[14] Minimum of 38,000 data points for a 500kW system [96]

reliability standards requires the isolation of communication between the high volume of BMS data points and time critical signals from the PCS [96].

The control strategy employed will be dependent on the system design, application and usage profile. For example, in a vehicle charging is generally a controlled process, which also allows time for cell balancing and the re-calibration of sensors. For applications such as frequency regulation, the system is constantly under dynamic loading, therefore charging is a dynamic process and cell balancing must be planned through a scheduled electrical maintenance routine or active balancing during operation.

3.1.7 Safety Requirements

Safety requirements include protecting the system internally from external disturbances, preventing damage to any system that might interface to the system, and most importantly protecting the people who come into contact with the system throughout its lifetime. Therefore safety must be considered during the production of the system until its final disassembly and disposal.

Safety is one of the most important requirements of the battery system for electrical vehicles [81], [99]. Therefore battery systems are generally equipped with multiple redundant safety features including cell level safety devices; special circuitry to prevent over charge and discharge; temperature monitoring; crash sensors; and special safety disconnect systems that will electrically isolate the battery automatically if an anomaly is detected (*e.g.* high current, crash, electronic fault), or manually if service on the vehicle is required [100].

Currently, the majority of safety information for batteries in stationary systems is on the integrated system level. In stationary applications, the systems should be able to protect themselves from internal and utility grid disturbances. Therefore, the battery system should be able to protect itself; in addition to communicating problems to the main system, to contain the battery problem or protect the battery from anomalies on the system level [15].

For both stationary and vehicle systems it is important to have proper labeling of high voltage components, and limit access to the system to those trained to work with high voltage. This requires proper lock out equipment that isolates the system, making it safe to work on. Vehicle systems might also be designed such that special tools are needed to access the pack to prevent non-certified parties from tampering with the system. For stationary systems the batteries are generally located in the equivalent to an electrical closet, where only certified personnel have access. Home energy systems should be designed as a protected system similar to a traditional home appliance such as a microwave or refrigerator.

The largest difference between the safety of a stationary and vehicle system is in their fault detection and problem mitigation. For stationary systems the default safety mode is to disconnect the system. In the vehicle, a complete disconnect of the system could leave the occupants in a potentially life threatening situation if the vehicle is stranded in the middle of a busy highway. Therefore the default mode in the vehicle will be to decrease power output, or revert to a "limp mode", that allows the driver time to safely move off the road. This functionality is generally programmed into the BMS control logic. This is just one example of an adaptation that would need to be made if the BMS for the vehicle were to be re-used.

3.2 System Architectures for Stationary and Vehicle Systems

To a certain extent, the construction of a stationary and automotive battery system (*i.e.* base component requirements) are fundamentally the same. In each application cells are connected in series and parallel in order to obtain the proper capacity and power necessary for the application. Generally cells are grouped into modules which allow for easier assembly and maintenance. The modules are then assembled into a housing which also contains a Battery Management System (BMS), Thermal Management System (TMS), sensors, passive safety devices, and additional high voltage and communication components that interface to the rest of the system [89]. Figure 20 shows an example of the basic construction of a vehicle and stationary energy storage system.

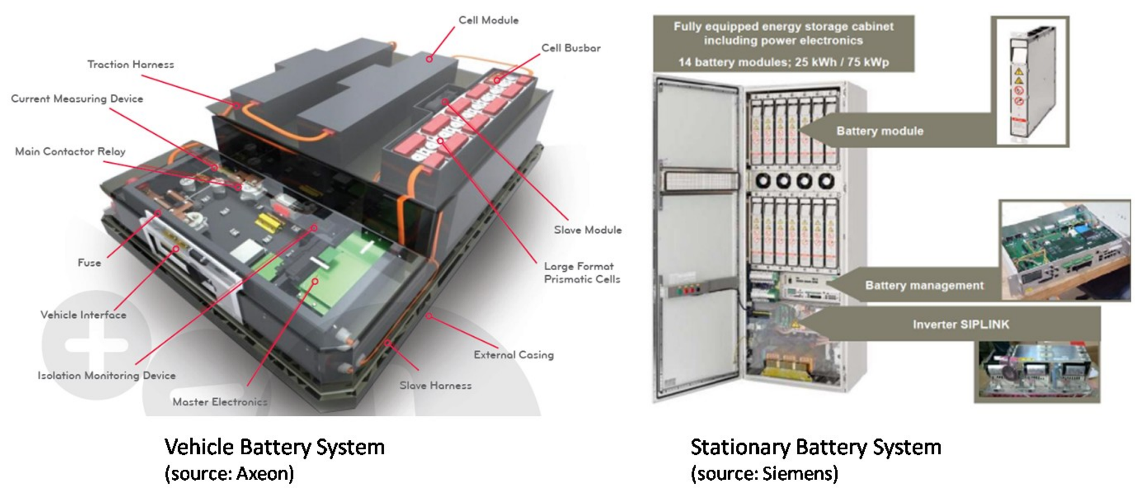


Figure 20: Example Vehicle and Stationary Storage system Architecture and Components [89], [101]

Although the basic components of stationary and vehicle applications are theoretically the same, the overall system architecture and design will dictate the potentials and limitations for a battery second use strategy.

3.2.1 Physical System Architectures

PHYSICAL ARCHITECTURE FOR VEHICLE SYSTEMS

Currently there is a variety of batteries with different physical architectures available on the market; examples of which can be seen in Figure 21. For passenger vehicles the battery pack voltage are generally between 300-400V, and be capable of accepting currents of up to 300Amps [57]. Lithium ion batteries on the market today have a nominal voltage of 3-4V per cell, which requires that approximately 96-99 cells be connected in series to create a 300-400V battery pack. Current capability will depend on the capacity of the cell[15], which can range from 3Ah for small consumer cells to 60Ah for large prismatic cells.

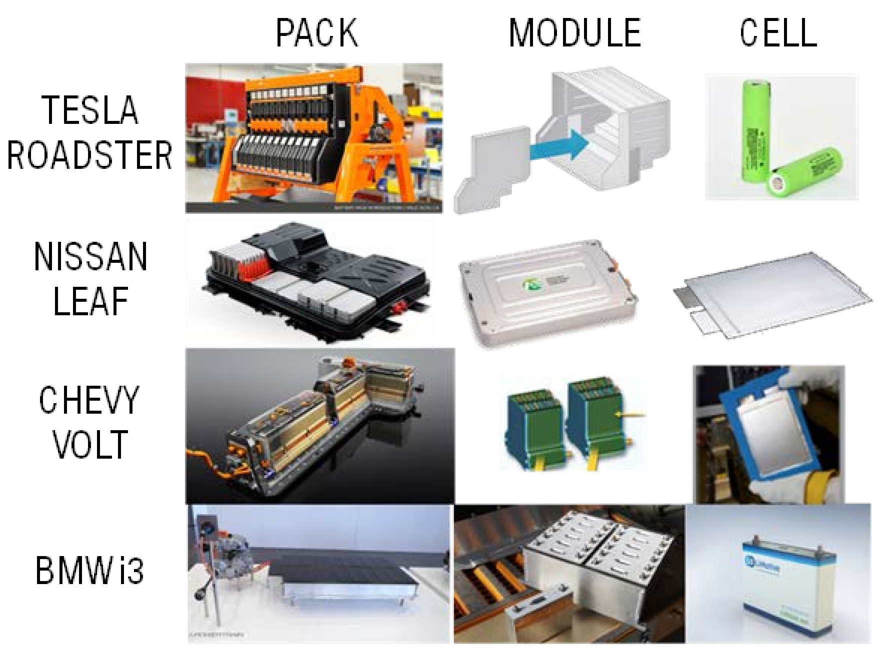


Figure 21: Example pack, Module, and Cell breakdown of Battery Systems (from top to bottom) Tesla Roadster, Nissan Leaf, Chevy Volt, and BMW i3 [65], [66], [78], [102]

[15] Or parallel connected cells

Smaller capacity cells must be connected in parallel before they are stacked in series in order to meet the necessary voltage level and power requirements. Connecting the cells in parallel before formulating the battery string reduces the number of individual voltage measurements, since batteries connected in parallel maintain the same voltage during (dis)charging [103].

Battery cells are grouped into modules in order to meet assembly, maintenance, and durability requirements. The size and configuration of the modules will depend on the packaging concept and types of cells used. Most OEMs try and use standardized modules, but due to packaging constraints this is not always possible. Modules will generally contain voltage and temperature sensors, control electronics for data communication and potentially integrated elements from the thermal management system. In order to meet mechanical requirements, modules might be permanently assembled through either welding of components or use of an epoxy.

Modules are then mechanically and electrically configured into a battery pack, which includes additional components such as relays, crash sensors, isolation sensors, battery pack housing, components for the thermal management system and communication, electrical, and mechanical interfaces to the vehicle.

To better understand the differences in vehicle battery systems architectures currently available on the market, descriptions of example commercial vehicle systems are provided in the Section 8.1.3.

PHYSICAL ARCHITECTURE FOR STATIONARY SYSTEMS

The stationary 'battery system', is a component within an integrated energy storage system. The battery system consists of the battery cells, wiring, battery specific housings or racks, safety devices such as fuses and relays, all components needed for the BMS including sensors, control electronics, and actuators; and a dedicated thermal management system if needed. The battery system is then combined with a power control system, site controller, HVAC system and integrated into a common housing to become and integrated storage system Figure 22.

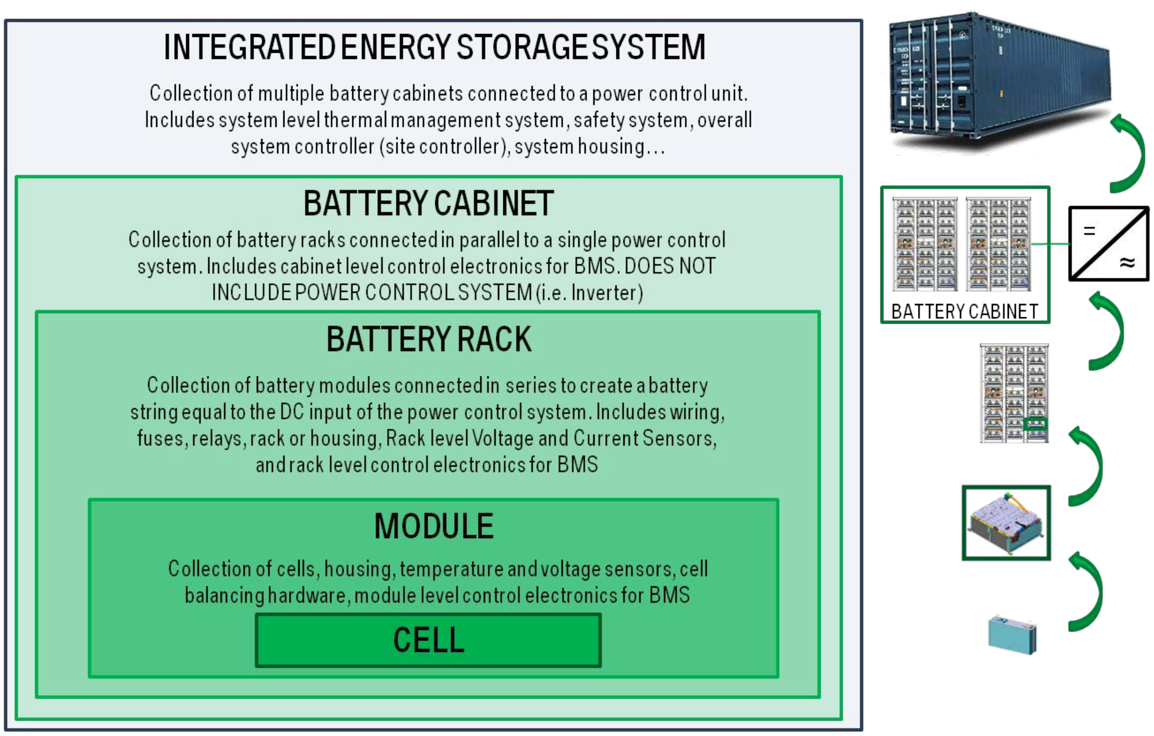


FIGURE 22: STATIONARY SYSTEM ARCHITECTURE (BATTERY SYSTEM LEVELS DESIGNATED IN GREEN)

There are four main physical and electrical layers for the battery system. On the lowest level are the individual battery cells, which for stationary systems tend to be higher

capacity prismatic cells (100Ah+), but some systems will also use large numbers of 18650 and smaller format cells.

The cells are then integrated with temperature and voltage sensors into modules. The size of the modules are generally limited by maintenance requirements in terms of electrical and occupational safety, which is a voltage limit of 60V and 50lbs [104], [105]. Modules are then integrated into strings, with a voltage range that is compatible with the power electronics. Each rack is equipped with its own safety fuse, current and voltage sensors, and DC disconnect. Racks are then connected in parallel to form a battery cabinet, and the cabinet connected to a single power inverter.

For small systems, one battery rack could be used per cabinet, therefore the cabinet/rack level for integration are combined. For medium sized systems, there will probably be only one cabinet per system containing multiple racks. For larger systems, multiple cabinets will be used and coupled together on the AC side of the power electronics. In the large system, the 'battery system' refers to all the cabinets without the power conversion system.

How the batteries are connected in series and parallel will determine the operating performance over the system lifetime. Specifically the capacity of a battery string is limited by the weakest cell in that string. When charging or discharging, once that cell reaches its maximum/minimum voltage the entire string must stop charging. For strings connected in parallel, the distribution of current between each string will be dependent on the relative capacity of the strings, and strings with a higher capacity discharge faster that those with a lower capacity.

The constraints due to the battery configuration, will dictate the tradeoff between the control complexity and need for uniformity between cells. If all the batteries are similar then the control system can be relatively simple. If the batteries are all different, which will probably be the case in battery second use, the control system must account for the difference in component capacity and internal resistance when computing the system states (*e.g.* SOC, SOH, SOF). The optimal design will depend on the cost of the system control system and the anticipated lifetime performance of the system.

3.2.2 Control System Architecture

The control architecture defines how the BMS is implemented. This includes the level at which functionality of the BMS is implemented and communication requirements between system layers. The control architecture will depend on the physical system architecture and performance requirements of the application.

CONTROL ARCHITECTURE FOR VEHICLE SYSTEMS

The control architecture for a vehicle system consists of two or three nestled layers which mimic the architecture of the system (Figure 23). The lower cell and module layers are responsible for the monitoring functions, while the higher level pack layer is responsible for the communication and control functions. The functionality of cell level balancing and voltage monitoring is incorporated on the module level.

CELL	MODULE	PACK	VEHICLE
BATTERY SAFETY AND PROTECTION			
• Internal fuse •Shutdown separator		• Isolation monitoring •Crash sensor •Fault Detection •Fuse/ Over current protection •HV Contactors •Reduce Power	•Crash detection •Isolate battery from vehicle
SYSTEM MONITORING			
	• T_mod measure • V_cell measure	• V_pack measure • I_pack measure	
		SOH EST.	
		• Model based estimate •Update model parameters •Input: Ah throughput, T history…	
		SOC EST.	
•Lowest cell V		•Model based estimate •Input: T, V, I, SOH	•Determine range
		SOF EST.	
		•Model based estimate •Input: T, V, I, SOH, SOC	•Service light
		CONTROL CHARGE	
		• Charge Rate Control/ Algorithm	
THERMAL MANAGEMENT			
	•Contact to cells	•Thermal control (on/off)	•Heating element •Radiator •Pump
CELL BALANCING			
	•Balancing Hardware	•Balancing control/command/algorithm	

MONITOR CALCULATE CONTROL

Figure 23: Location of Possible BMS Functionality within Vehicle Architecture [90]

Communication between layers is determined by the pack architecture and reliability requirements. Reliability will depend on the communication protocol used. For automotive applications this is usually a galvanically isolated CAN BUS network or fiber optic systems [66]. The main factor in selecting a communication network within the vehicle battery system is isolation from electromagnetic noise from the high voltage components, and cost. In general the control architecture will be different between battery systems and is often proprietary knowledge of the OEM.

CONTROL ARCHITECTURE FOR A STATIONARY SYSTEM

For stationary systems, the layers of the control architecture will match the physical architecture of the system. The presence of another system layer makes the stationary system slightly more complicated than the vehicle system in terms of how system parameters are calculated. But it also allows for more flexibility in where information is processed and how it is communicated. The overall architecture for a specific system will be dependent on cost and the portfolio strategy of the system supplier in terms of modularity and scalability (See Section 3.3.2).

Due to the early stages of the stationary battery storage market details about stationary system architectures are not widely published. Therefore, a brief description of functionality of each system level will be discussed based on the information that is available [20], [74], [104], [106], [107].

An example of how the control architecture might be deployed is shown in Figure 24. For systems using a large format cell, it is common to have a cell level BMS for voltage and temperature measurements, and cell balancing. In instances where very large cells are used, the cell level combines with the module level. Otherwise the functionality of the module level BMS is almost synonymous with that in the vehicle.

The rack level BMS is then responsible for acquiring all of the data from the lower levels in addition to measuring the rack voltage and current, and managing fault detection in the rack. At this level, the rack level BMS can either communicate that data directly to the higher level system controller, communicate only the key variables, or calculate the state of the rack (*e.g.* SOC, SOF, and SOH) to be communicated to the next level controller. The rack

level BMS might also have the ability to disconnect the battery string for safety reasons, balance the cells within the rack, or activate a local thermal management system.

CELL	MODULE	RACK	CABINET	SYSTEM
BATTERY SAFETY AND PROTECTION				
• Internal fuse •Shutdown separator		• Isolation monitoring •Fault Detection •Fuse/ Over current protection	•Disconnect from Inverter •Isolation monitoring •Fault Detection •Fuse/ Over current protection	•Reduce Power •Shut off Inverter •Isolation monitoring
SYSTEM MONITORING				
•T_cell measure • V_cell measure		• V_rack measure • I_rack measure	• V_cab measure • I_cab measure	
		SOH EST.		
		• Model based estimate •Update model parameters •Input: Ah throughput, T history…		
		SOC EST.		
•Lowest cell V		•Model based estimate •Input: T, V, I, SOH		•Determine available energy/storage
		SOF EST.		
		•Model based estimate •Input: T, V, I, SOH, SOC		•Limit power
			CONTROL CHARGE	
			Charge Rate Control/ Algorithm	
THERMAL MANAGEMENT				
		•Thermal control (on/off)		•System HVAC
CELL BALANCING				
Balancing Hardware			•Balancing control/command •Balancing algorithm	

MONITOR CALCULATE CONTROL

FIGURE 24: LOCATION OF POSSIBLE BMS FUNCTIONALITY WITHIN A STATIONARY SYSTEM ARCHITECTURE

The functionality of the cabinet level BMS is to take all the lower level system information and determine the SOH, SOF, and SOC of the system and communicate it to the main system controller. The means of accomplishing this task will be dependent on the functionality of the rack level BMS.

3.3 THE VALUE CHAIN BRINGING STATIONARY AND VEHICLE SYSTEM TO THE MARKET

Understanding how and why vehicle and stationary systems are developed, sold, and managed throughout their lifetime is necessary in order to identify the operational opportunities and barriers of combining the two value chains. The concept of the Value Chain was conceived by Michael Porter in 1985 (Figure 25) as a means of breaking down the everyday business of a firm into strategically relevant activities. These activities could then be analyzed in terms of improvement potentials, market differentiation, and development of a competitive advantage. The value chain of a given firm is then an element of a larger value system that includes suppliers, distributors and the customer.

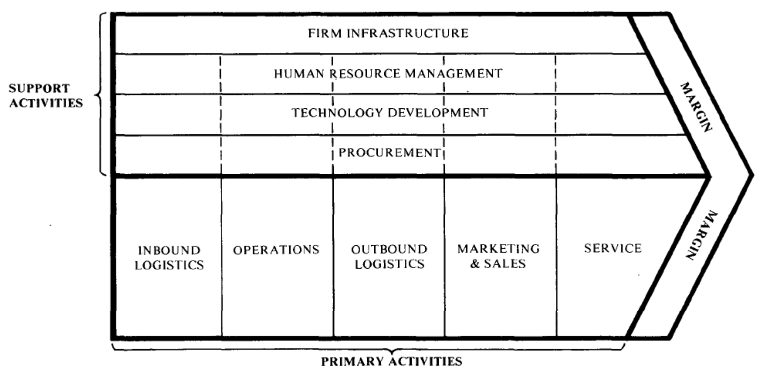


Figure 2–2. The Generic Value Chain

FIGURE 25: PORTER'S ORIGINAL VALUE CHAIN

Porter's original value chain has become a seminal part of business strategy and business management education. Its original conception has been built upon, re-evaluated, and evolved to better capture the ever changing needs of the modern corporation. An example of a reconceived Value Chain was presented by Presutti and Mawhinney in 2009, which they called the Contemporary Value Chain in order to differentiate it from Porter's

Original Value Chain. The Contemporary Value Chain (Figure 26) will be used as a framework to evaluate the activities within the vehicle and stationary market that might affect battery second use.

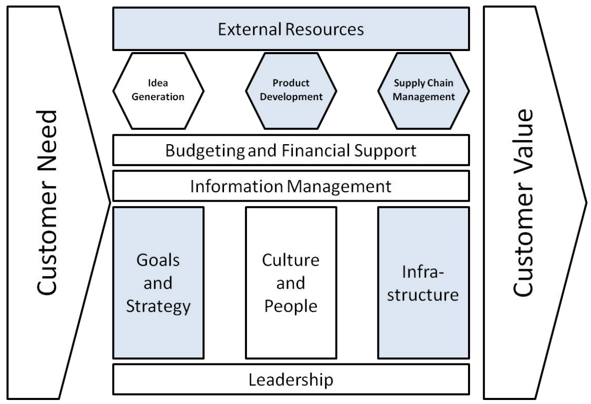


FIGURE 26: CONTEMPORARY VALUE CHAIN WITH FOCAL POINTS HIGHLIGHTED IN BLUE [108]

For this purpose it is not necessary to evaluate the entire chain. Instead only certain elements (highlighted in blue in Figure 26) will be used to better understand potential motivators and barriers to the development of a second use ecosystem. Details about each element are shown in Table 15.

TABLE 15: DESCRIPTION OF CONTEMPORARY VALUE CHAIN COMPONENTS CONSIDERED FOR ANALYSIS

Value Chain Component	Description
Goal and Strategy	Strategic Partnerships, Volume, Product Portfolio, Market Presence, Level of Standardization
Product Development	Integration Strategy, Scalability, Platform Concepts
Supply Chain Management	Single Supplier vs. Multi-source, Sales Concept
External Resources	Involvement of supplier, In House Development vs. Outsourcing, co-Development vs. Standardized Interface
Infrastructure	Manufacturing Facilities, Distribution Network, Service Network, Supply Network, Reverse Logistics, Global Network

3.3.1 The Vehicle Value Chain and the OEM's Electrification Strategy

The vehicle value chain for each automotive manufacturer is as unique as the vehicles they produce. The means by which Ferrari designs, develops, produces, sells, and services their vehicles is completely different than GM. The value propositions of the products are different and therefore the processes employed, methodologies, and infrastructure are optimized to bring the product to market and maximize its unique value proposition.

Just as each OEM has its own strategy for bringing conventional vehicles to market, they will also have their own strategy for developing, deploying, selling, and servicing electrified vehicles. The terms under which an OEM will release an EV will depend heavily on how the OEM views the role of electric vehicles in their company, and their strategy of integrating the new technology into their corporate value chain. The combination of product role and integration into the corporate value chain will be referred to as an OEM's Electrification Strategy.

THE GOAL OF INTEGRATING ELECTRIFIED VEHICLES INTO THE PRODUCT PORTFOLIO

The OEM must evaluate and define the value of adding electrified vehicles to their product portfolio. Reasons for building electric vehicles could include meeting fleet emission standards such as the CARB (California Air Resource Board) portfolio standards or CO_2 standards [109]; creating, or altering, the image of the OEM to be more sustainable, or innovative [110]; and capitalizing on new market opportunities. A breakdown of electrification strategies of various OEMs can be seen in Figure 27.

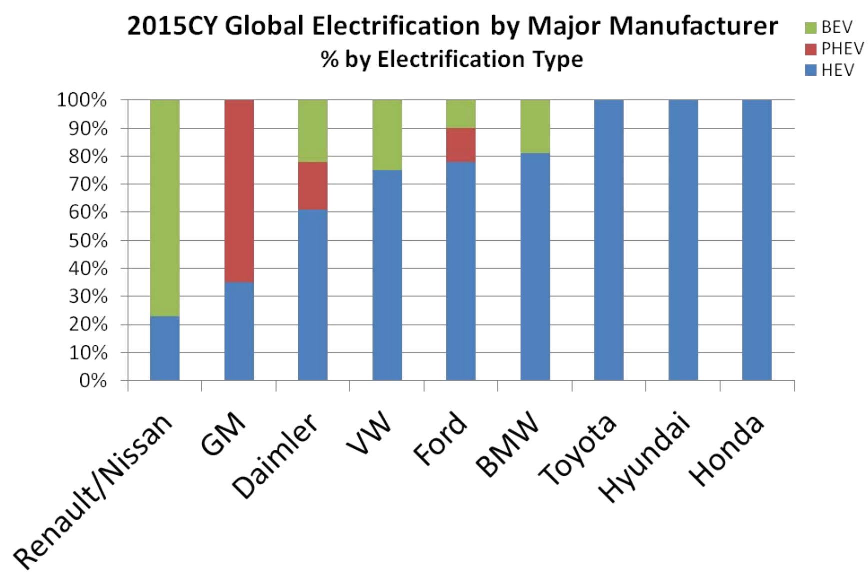


Figure 27: Breakdown of Electrification Strategies by Manufacturer [111]

The goal established by the OEM will then dictate the volume, deployment schedule, and product portfolio the company will bring to each of its global markets. This goal will also influence the interest and motivation factors for an OEM to develop a B2U Strategy.

DECISIONS FOR DEVELOPING AN ELECTRIC VEHICLE

The main choice in developing an EV is the use of either a common or dedicated platform. A common vehicle platform involves sharing of similar system elements, development processes, and production facilities. System elements can include the vehicle chassis, powertrain, and/or electronic system architecture. The use of a common platform architecture can greatly decrease development and production costs for the OEM [112].

A common platform can be either a platform shared with other electric vehicles or one shared with conventionally powered vehicles. The Chevy Volt for example shares a common platform with the traditionally powered Chevy Cruze. Currently there are no

widely used EV platforms but there is speculation that the platform used in the Tesla Model S will be extended to the Model X and other future generation vehicles [113].

The use of a common platform shared with a traditional powertrain vehicle will determine the packaging restraints for electric vehicle components; and will often result in a distributed battery system. The wide adoption of this strategy might create resistance to standardization as it would further limit packaging options.

THE OEM'S USE OF EXTERNAL RESOURCES

Due to the ever increasing number of regulations, customer expectations, and new innovations, the development of a vehicle is steadily becoming more complex. At the same time, OEMs are forced to have shorter development cycles in order to stay competitive [114]. To keep up with these demands, an increasing amount of research, development, and engineering is being pushed back onto suppliers and engineering service providers [115]. Therefore suppliers are no longer just suppliers of material, and are becoming an integral part of the development process. This relationship, if managed effectively can significantly decrease the amount of cost and time necessary to bring a product to market [108]. Never the less, each OEM has parts of their business in which they regard as a core competence that is critical in ensuring the value of their product. These elements are critical to the strategic advantage of the OEM and therefore they prefer to keep these competencies in house.

For new technologies being integrated into the vehicle, such as an electric drivetrain, the OEM must decide early on what to outsource and what to develop in house. The OEM will use one of the following three strategies shown in Table 16.

TABLE 16: OEM BATTERY SYSTEM DEVELOPMENT STRATEGIES

Strategy	Description	OEM example
In House Development	This involves buying the battery cells and developing the power electronics, thermal management, communications, and physical architecture in-house. By developing all components in house these firms develop a strong core competency in battery system development, but at a price of high development costs and a longer time to market.	Tesla and BMW
Purchase battery systems as a "black box" component.	Through this type of agreement, the OEM has little involvement in the development of the battery system past the specification of requirements for the vehicle application. This type of agreement allows a shorter time to market and decreases the amount of development time and cost. But at the expense of minimal learning about the new technology.	Toyota for the RAV4e and Mercedes Benz purchase battery systems from Tesla Motors
Joint Venture Development	Use strategic partnerships to co-develop their battery systems with cell supplies. These agreements leverage the competencies of both partners allowing for a shorter time to market, and lower development costs. This comes at the expense of the OEM being dependent on a single cell provider and prevents the OEM from applying their typical purchasing negotiation techniques and price pressure.	GM/ LG Chem's subsidiary Compact Power Inc, and Nissan/ NEC

The amount of interest in a B2U strategy, and an OEM's ability to steer this strategy will depend on the amount of involvement the OEM has in the development of the vehicle battery system.

INFRASTRUCTURE OF AN OEM

The infrastructure of an OEM includes all assets that allow the OEM to produce, distribute, sell, service, and (in some cases) re-collect and dispose of the vehicles they produce. This includes transportation and logistics networks, production facilities,

dealerships, and the service network. Key infrastructure elements that will affect a battery second use strategy include the vehicle's service concept and the transportation network.

Due to the technical complexity and electrical danger associated with high voltage components the service concept for electric vehicles can be different than that of traditional vehicles. Many OEMs will only allow dealerships to sell EVs after the dealership invests in equipment and facility upgrades needed to support the vehicles, in addition to specialized high voltage training for the service technicians. But even a certified dealer will be limited in the types of service they are allowed to do on the pack. And in many cases dealerships will be limited to diagnosis capabilities and actual repair will be performed at a specialized facility or at the factory [69].

THE VEHICLE SUPPLY CHAIN MANAGEMENT

A key strategic element to an OEM is its supply chain, and the role of the OEM within that supply chain. Automotive supply chains are extremely complex, global operations, whose structure will depend on the distribution and volume of the product [116].

The goal of supply chain management is to reduce risk and cost, maintain quality and maximize customer value; while simultaneously being able to get the right product, to the right place, at the right time. Strategic supply chain decisions and their impacts on a second life strategy are summarized in Table 17 [117].

TABLE 17: STRATEGIC SUPPLY CHAIN DECISIONS AND IMPACTS ON SECOND USE STRATEGY

Strategic Supply Chain Decisions	Implications for Second Use
The number, location, capacity, and type of manufacturing plants and warehouses to use	Potential infrastructure support for battery second use repurposing.
Set of suppliers	Diversification of the supply base can reduce risk for the production of the vehicle, but could potentially create another level of complexity for battery second life.
Selection of transportation channels	Potential infrastructure support for battery second use repurposing.
Amount of products and materials to ship between suppliers, plants, warehouses, and end customers	Help support spare-part requirements for second life business.
Amount of products and materials to inventory	Help support spare-part requirements for second life business.

Due to the oligopolistic nature of the automotive industry, there is a large imbalance of power between suppliers and the OEM. Therefore it is relatively easy for OEMs to transfer responsibilities of cost reduction and product development back onto suppliers. This includes forcing suppliers to comply with performance guidelines or be subjected to replacement [118]. This dynamic, coupled with high volume production allows OEMs to obtain an optimal per piece price for their components.

3.3.2 *Stationary Storage Value Chain And Market Structure*

The stationary storage market is relatively new and underdeveloped, with a mix of market players whose roles are not consistent across product offerings. The basic components of this market can be seen in Figure 28 and are described in Table 18.

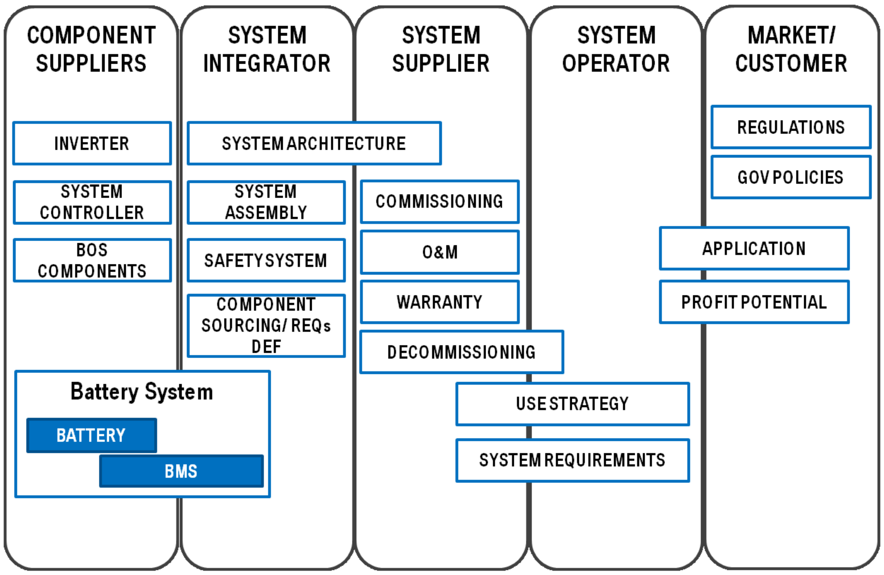


Figure 28: Structure of Value Chain for Stationary Battery System

The purpose of this section is to identify the potential customer for the used EV battery systems, influential factors to their value chain, and opportunities for used batteries. Currently the stationary storage market is in its evolutionary birth phase (Section 1.2, Table 1), with no clear market structure as a result of the absence of stakeholders in certain roles. Therefore stakeholders tend to take up neighboring roles in order to bring their product to market. Because of this lack of concrete market structure, all roles can be considered a potential customer for used batteries.

TABLE 18: ROLES OF STATIONARY SYSTEM STAKEHOLDERS

Role	Description
Component Suppliers	Firms producing inverters, system controllers, and balance of system components. Firms providing battery systems (cells+ BMS) will be competitors to the used battery systems, and might even include the vehicle cell or system provider. These battery companies could still be a potential customer if they choose to expand their business to include battery refurbishment.
System Integrators	Firms responsible for engineering the system and determining the system's architecture for a given application, including system size, component requirements, and external interface. This entity is also responsible for the sourcing and assembly of components into a final system. These firms could either be direct customers of the secondary battery systems, or be responsible for developing systems compatible with used electric vehicle batteries. In the later case these firms would be responsible for establishing a standardized interface to the battery system.
System Supplier	Responsible for the sale, distribution, commissioning, and warranty of the device developed and produced by the system integrator. Depending on market structure the final product sale could include of the batteries, not include the batteries, or include the batteries as a part of a service contract. Selling the system including the batteries will probably require a service or warranty agreement. In the case where batteries are not included, the system operator will need to source the batteries themselves. The final variant would establish a supply contract with the system operator to upgrade the batteries at predefined intervals based on time, use, or performance throughout the system lifetime.
System Operator	The role of the system operator is to decide when and how the system is used, in which market it is to participate in, and which functions it is to provide. The system operator will purchase the system from the System Supplier. The system operator might own multiple systems, of various sizes and configurations, from different system suppliers but can choose to source the batteries from a single component supplier.
Market/ End Customer	The entity paying for the services of the energy storage system and ideally also profiting from the benefits of that service.

Any given firm in the stationary storage market can play a combination of the roles above (Figure 29). For example the System Operator might also be the End Market Customer, which is the case for home energy systems, or industrial management systems in

complex plant environments. The End Customer might also be the System Operator and Integrator. Coming from the production side, it is also common for Component Suppliers to act as the System Integrator and System Supplier.

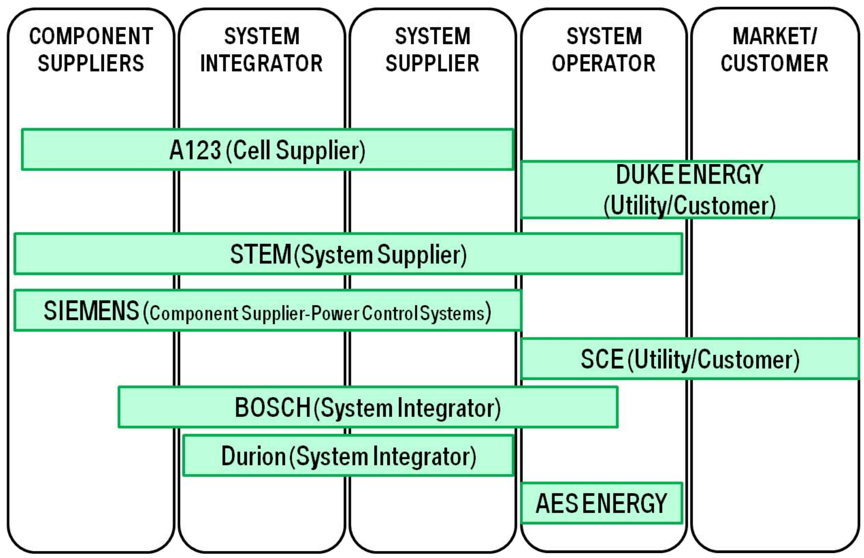


FIGURE 29: EXAMPLES OF CURRENT OVERLAPPING ROLES IN STATIONARY STORAGE MARKET[16]

Currently there are three main technologies integrated into an energy storage system; the storage medium (or batteries), the power electronics, and the overall system control and interface. In today's market the System Integrator, or company offering the final product, can be either a firm specializing in one of these three technologies, firms specializing in integrated systems that use battery storage, or a pure system integrator. The competence of the firm will define the value chain for that given product.

STRATEGY AND GOAL FOR BRINGING A STATIONARY SYSTEM TO MARKET

To identify the motivation or potential barriers to their adoption of used batteries, the strategy and goal of a system supplier needs to be understood. Looking at the three

[16] SCE= Southern California Edison

types of companies currently bringing storage solutions to the market (Table 19), it can be seen that each type of firm will have different priorities, which will dictate the requirements and willingness to adopt used batteries.

Table 19: Types of Stationary System Suppliers

	Goal	Implications for Second Use	Example
Integrated System Developers	Increase value of overall system	Value of battery system comes from entire integrated system's output.	Solar World, STEM, Voltwerk
Component Supplier	Support Sales of Product Offering	System requirements must match component supplier's product.	Princeton Power Solutions, Siemens, ABB, Bosch
System Integrator	Fill need in market for integrated storage solutions	Will look for optimal solution for system and components.	Younicos, Durion
End Customer	In house development of system to meet custom need	Opportunity for niche market	Nissan and 4R Energy

For firms that develop systems that use storage, such as a solar system provider, the final system value comes from the value of the integrated system. Storage is just a component of the entire system; therefore the value proposition of storage will be dependent on its incremental cost to the system. These companies will be willing to use secondary batteries if the incremental cost and added value provided by the used batteries is better than systems with new batteries.

For component suppliers (*e.g.* companies offering power control systems), that chose to develop battery systems, the system will be designed around the main product offering. Therefore the system architecture and requirements will probably be dictated by the properties of that component, and optimized around that component. Interest in second

life batteries will depend on the compatibility of the vehicle battery system with these requirements, and the price relative to new batteries.

A system integrator, in general, is technology and architecture neutral. The value of the system is dependent on the integrators ability to integrate system components in the most effective and efficient method possible. Therefore the system integrator's design is more flexible than the component supplier. Interest in second use batteries will depend on overall system cost relative to a system using new batteries.

An end customer might develop their own system in order to meet a specific need. In this case the end customer might be a large industrial firm or enterprise, or even a utility, which needs a customized solution. The interest in second use batteries will depend on overall system cost in addition to lifecycle operational costs across the enterprise.

STATIONARY SYSTEM PRODUCT DEVELOPMENT

Within the development process, two decisions need to be made:

1. Should the product be scalable?
2. What technology should the system use?

The ability to create a scalable product will allow the system provider to address a number of market requirements with a single base product. The ability to be storage technology neutral will allow the product to be adaptable as the technology in the system evolves and prevents dependence on a single supply relationship.

Scalability can come from the battery supplier, or system integrator. The idea of scalability is similar to the platform concept in a vehicle in which it is intended to save costs and optimize development time. The scalability of the system will determine the system

architecture and component selection. The choice of creating a scalable system will depend on expected sales volume and expected market penetration.

The ability to be technology neutral is also desirable for system providers since there is currently uncertainty in which storage medium will be most desirable, and the stability of the supply chain. Decisions regarding technology neutrality will determine how the supply chain, and the physical and control interfaces of the energy storage system, are structured. The ability to decouple the storage system from the rest of the system will be highly dependent on the establishment of a standardized interface between the two. Ideally this would be an industry standard that benefits both component suppliers and system integrators (Section 5).

EXTERNAL RESOURCES FOR STATIONARY STORAGE SYSTEM DEVELOPMENT

The use of external resources will depend on the current core competencies of the firm and the corporate infrastructure. With respect to battery second use, the main influencing factor is if the system supplier develops their battery in-house, or purchases it as a system component.

INFRASTRUCTURE FOR SALES AND SERVICES OF STATIONARY STORAGE SYSTEMS

The corporate infrastructure of a company will determine which market the company will pursue and what role they plan to take in the development of the product. Factors affecting battery second use include global market penetration, sales and service infrastructure.

Due to the large number of state and municipal level regulations, the number of markets to which a system supplier can sell their system is generally limited. Therefore it

will be important to have system integrators that offer systems in the same markets where electric vehicles are sold.

Sales and service infrastructure requirements will depend on the end customer and nature of final product offering. The sale and service of residential storage systems will have different requirements compared to a large industrial or utility system. Due to the aged state of the batteries, it might be necessary to offer an enhanced service model, therefore having the service infrastructure available to support this will be critical. If the system integrator does not have this capability it could be a decisive factor for not supporting a second life business.

SUPPLY CHAIN FOR STATIONARY STORAGE SYSTEMS

Due to the developing market phase there is currently no stable market structure. Currently system and component suppliers are trying to establish their place in the market while simultaneously minimizing risk [119]. Therefore the majority of system providers try to maintain flexibility that allows them to adjust quickly and minimize the amount of capital investment required. As a result they have very inefficient supply chains which, when coupled with low production volumes, cannot realize the same economies of scale as the automotive sector.

3.4 Combining the Two Value Chains: Opportunities and Barriers

The ability to reduce costs and leverage value already designed into the vehicle system will depend on the overlap in system architectures and component interoperability. Due to similarities in functional requirements, opportunities exist for re-using components of the battery system, such as the cells, pre-packaged modules, control electronics, control logic from the battery management system, and potentially even the thermal management system.

Operational opportunities that can increase the overall efficiency of the value chain depend on the operational structures of both the stationary and vehicle value chain. Opportunities include leveraging pre-existing infrastructure and corporate resources, the use of which will be dependent on the identification of value in a B2U strategy by the individual stakeholders along the value chain.

3.4.1 Technology Opportunities and Barriers

Potential barriers in the ability to integrate the systems are the electrical compatibility of components, the ability and design of the components to meet the requirements of two systems with minimal additional cost, and the impact of the aging characteristics of the cell.

AFFECTS OF MODULE DESIGN

The configuration of the battery pack or modules will affect control, electrical, thermal and mechanical integration into the secondary system. Limiting factors include the weight, volume, packing density and configuration of the vehicle modules. These factors are determined by the higher mechanical, packaging and safety requirements of the vehicle. The

number and arrangement of cells will limit the ability to arrange the battery pack or modules to meet the stationary system's electrical requirements. While the placement of BMS functionality within the system, will affect interoperability of the control system.

ABILITY TO MEET LIFETIME REQUIREMENTS

A main concern is the ability of the used batteries to fulfill their initial lifetime requirements, plus the added lifetime requirements of the stationary system. This applies to battery cells and other components that could be potentially used in a secondary application, such as sensors, contactors, and control electrics. The usability of these components will depend on their designed lifetime in terms of cycle life, hours of operation, and calendar life; in addition to their electrical properties including voltage levels and expected current loads [86]. In general EVs tend to have a lower overall up time and highly dynamic loading conditions, with system voltages between 300-400V and current levels around 1-2C. While stationary systems have a higher up time and less dynamic loading conditions, and can run at system voltages of up to 1200V and 4C charge and discharge rates. Generally vehicle components are cost optimized to meet their vehicle lifetime target and specifications. Designing these components to meet two application requirements could potentially impact system cost and ultimately the capital cost of the vehicle system.

EFFECTS OF BATTERY AGING

With respect to the aging of the battery cells, each battery will age differently overtime due to slight differences in their micro-structures, chemical composition, exposure to stress factors such as heat, and numerous other variations [57]. Overtime, the differences in electrical and thermal properties will only continue to diverge. For a system using multiple sets of aged batteries from different packs, these differences could be even more

significant. Therefore an effective balancing and electrical maintenance strategy becomes even more critical to use the maximum capacity of the battery system. This would involve adapting the stationary system's battery management system for aged cells and to either be compatible with the hardware from the vehicle or retrofit the vehicle systems with new hardware.

THERMAL MANAGEMENT

Another opportunity lies in the thermal management system. Due to the less controlled ambient conditions, higher packaging density and more demanding load profile the vehicle TMS has higher requirements than a TMS for a stationary system. There are therefore three options for the TMS of a stationary system with used EV batteries:

1. Use the system level TMS of the stationary system, which might be sufficient dependent on the packing density of the battery.
2. Install a new TMS dedicated to the battery system.
3. Use the TMS from the vehicle, which will depend on the overall packaging design, and might require the introduction of new systems, such as a water loop, pumps, etc.

Each option has a tradeoff in terms of cost, complexity, and performance. The design of the thermal management system should also consider the increase heat generation due to the higher internal resistance of the aged cells.

3.4.2 Non-Technical Factors and Resulting Market Requirements

A pre-condition to enable the merger of the two value chains, is that the stakeholders along the value chain must see a net benefit for themselves. For an OEM this means evaluating how battery second use can help their bottom line and how they can offer

a valuable product on the market that will be attractive relative to new batteries. Therefore the OEM must identify the end customer of their battery system and identify requirements for their end value proposition.

Advantages for the OEM include the economies of scale, the oligopolistic nature of the automotive supply chain, and global distribution network. OEMs therefore have access to components at very competitive pricings, and a pre-existing network that can be utilized to support battery second use.

An incentive for system integrators to develop systems with used batteries is the potential to offer a product onto the market at a lower price point than systems with new batteries. But due to the uncertainty in demand, the market for stationary system is in the development stages, and has not reached a stable or efficient operating point.

Currently there is a low volume of systems on the market, a lack of standards and industry norms, and no standard value chain structure. Therefore any conclusions about the future of what this market will look like, or how battery second use will integrate into this structure is purely speculative. That being said, given the functional and architectural analysis performed in this section, it is speculated that the integration of used batteries into a secondary system will take one of the following three forms in Table 20.

The level of standardization could range from the standardization of the communication interface, system voltage intervals, or module dimensions to testing and system rating methods. A further discussion on the potential levels of standardization and the implications for the development of a B2U market can be found in Section 5.2. This section will discuss the nature of standardization with respect to establishing a system

boundary or interface. The nature of this interface will determine if used batteries could be fully integrated into a generic battery stationary storage market or should be isolated in a separated sub-market specifically for used batteries.

TABLE 20: POTENTIAL INTEGRATION OPTIONS FOR BATTERY SECOND USE

	Description	Opportunities	Barriers
Industrial Standardized Interface	Industrial standardized interface between battery system and power controls for both used and new battery systems	• Plug and play battery systems • Economies of scale through scalable and modular systems • Open market for battery system purchasing • Reduction of one time engineering costs.	• Technology capable of meeting requirements of two applications Agreement between system integrators and battery suppliers on: • proper communication protocols • control requirements • safety and reliability standards
Second Life Specific Standardized Interface	Industrial standardized interface between battery system and power controls optimized for characteristics of aged batteries	• Open battery second use market • Market efficiency through economies of scale • Reduction of one time engineering costs	• Alignment of vehicle system architectures and control strategies with second life requirements • OEM Intellectual property • Price competitiveness with new systems
Second Life Customized Interface	Secondary systems designed around a specific pack design	• Optimal solution for individual battery systems • Minimal impact of vehicle design	• Involvement of OEM in system development • Price competitiveness of low volume systems

Of the three forms, the industrial standardized interface will be the most economically efficient since it would allow used and new batteries to compete openly on a price per unit performance basic. In this case batteries will be considered a commodity, and would be subjected to the low margin characteristics of a commodity market. This could also be less than ideal for second use batteries if the standardized interface is developed to

maximize the value of new batteries and doesn't allow for the unique operating conditions required for used batteries.

The second life specific standardized interface would be the most efficient for establishing a second use sub-market as it would have the same characteristics as the industrial standard, but allows for architectures that are better suited for used batteries. Such architectures would be able to efficiently manage multiple aged battery systems with various characteristics in a single system.

The final possibility, the second life customized interface, will probably be the most prevalent in the near term. In this option each stationary system is customized around a specific vehicle battery system, which then dictates the design of the stationary system. This option allows for the most flexibility in terms of integration concept, but will require the joint development of systems between a system integrator and vehicle OEM.

In the long term the most appropriate integration interface will be dependent on the cost impacts along the entire value chain. These costs will then determine the ultimate price of the system. This, in combination with the system performance, will determine the competitiveness of the used battery system to a new battery system.

In the short term the identification of the most appropriate interface must start with the OEM as they know the most about the technology and design. These evaluations can then influence the OEM's decisions within the next few design cycles and will either enable or prevent the creation of a viable second use market.

4 Battery Second Use (B2U) Analysis for Strategic Business Development: Making Technical and Cost Data Actionable

Research to date suggests a potential positive net benefit for battery second use (B2U), but lacks the refinement and continuity needed to support the realization of an electric vehicle OEM's B2U business strategy. In the short term, the involvement of electric vehicle OEMs will be critical in enabling a battery second use market, due to their control over the initial input into the system. In the long term the development of an OEM business strategy will be critical in maximizing the output of the battery second use ecosystem.

As discussed in Section 2, due to their use of high level approximations, research to date lacks the granularity necessary to analyze tradeoffs between decisions along the value chain, and limits the ability to show sensitivities to process and technology parameters. Therefore using the current methods, the amount of uncertainty and risk involved with developing a battery second use business strategy cannot be adequately assessed.

Since the advanced energy storage market is still in a development stage, development targets are difficult to fix and system requirements are difficult to define. On the technology side, open questions about the aging characteristics of industrial, or automotive grade, lithium ion batteries makes it difficult to determine if they will be suitable for a secondary application. But the storage market is starting to reach a commercial status and electric vehicles are starting to come to the mass market. If an OEM is to develop a second life business strategy, it will need to understand, despite these uncertainties, where the opportunities lie and the technological, economic, and operational constraints, discussed in the previous section, for bringing used electric vehicle batteries to a secondary market.

This section will discuss a framework developed to aid an OEM in the analyses necessary for developing a B2U business strategy and is structured as follows (Figure 30):

4.1. Describes the requirements for analyses to optimize the battery use across the value chain, including the relevant technical and process parameters, and interdependencies that must be considered.

4.2. Proposes a framework for a Battery Second Use analysis tool that is able to meet the defined requirements.

4.3. Describes the functionality of a MATLAB tool that uses the framework.

4.4. Demonstrates the tool's ability to meet the defined requirements and how it can be used to evaluate opportunities, assess technological and economic constraints, and evaluate operational factors related to a B2U strategy.

4.5. Reviews the contributions of the framework and its role in the development of a B2U strategy for an OEM.

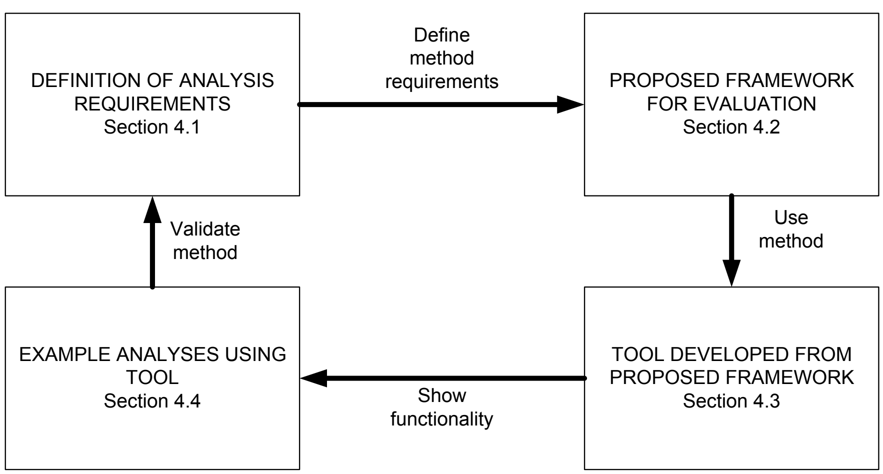


FIGURE 30: STRUCTURE OF CHAPTER 4

4.1 Requirements for Technology and Process Analysis to Enable the Development of a B2U Business Strategy.

Due to changing dynamics in both technology and market, the evaluation of the technology and process requirements for a sustainable business strategy consists of a series of iterative analyses. These analyses must work to evaluate the value chain presented in Section 1.2.1 in order to identify opportunities, communicate uncertainties, and capture the variance inherent in the problem.

The goal of these analyses is to do the following:

- Identify a window of opportunity, and associated uncertainty of that window, allowing for the definition of development targets
- Assess the ability of current technologies to meet those targets and identification of process requirements.
- The ability to capture variance inherent in the problem and enable the development of a robust product and processes.
- Allow for volume planning and battery fleet management by capturing temporal and spatial dimensions including the effects of market and technology developments, and battery availability.
- Value chain optimization

The nature of these analyses will change as more information is collected and the parameters of individual process steps, as defined in Section1.2.1, are better understood. Preliminary analyses consist of rough estimations and a few discrete scenarios in order to identify the potential opportunities. These analyses should answer questions such as: What

types of costs are associated with bringing batteries into a secondary application? What order of magnitude should be expected? And what are the relevant performance metrics?

Parameters of these analyses will carry a certain amount of uncertainty, which should be adequately represented and the effects of which quantified. Results of this level of analysis will determine the boundary conditions and identify focus areas for proceeding studies and data collection.

Successive analyses require the incorporation of more details in order to better understand the contributing factors and potential trade-offs along the value chain. From a process side, this includes the definition of process requirements; including definition of process steps and associated costs. At this level of analysis, variations related to the state of health and aging characteristics of the batteries must be adequately represented. A sustainable battery second use process must mitigate the financial and performance impacts of these variations.

Based on the system requirements presented in Section 3, product details that should be accounted for in the analysis are shown in Figure 31. The system architecture will be dependent on the system size, and will define the possible integration concepts. Together the system architecture and integration concept will determine the component costs and repurposing requirements. Lifetime performance and cost will be dependent on both the integration concept and control strategy.

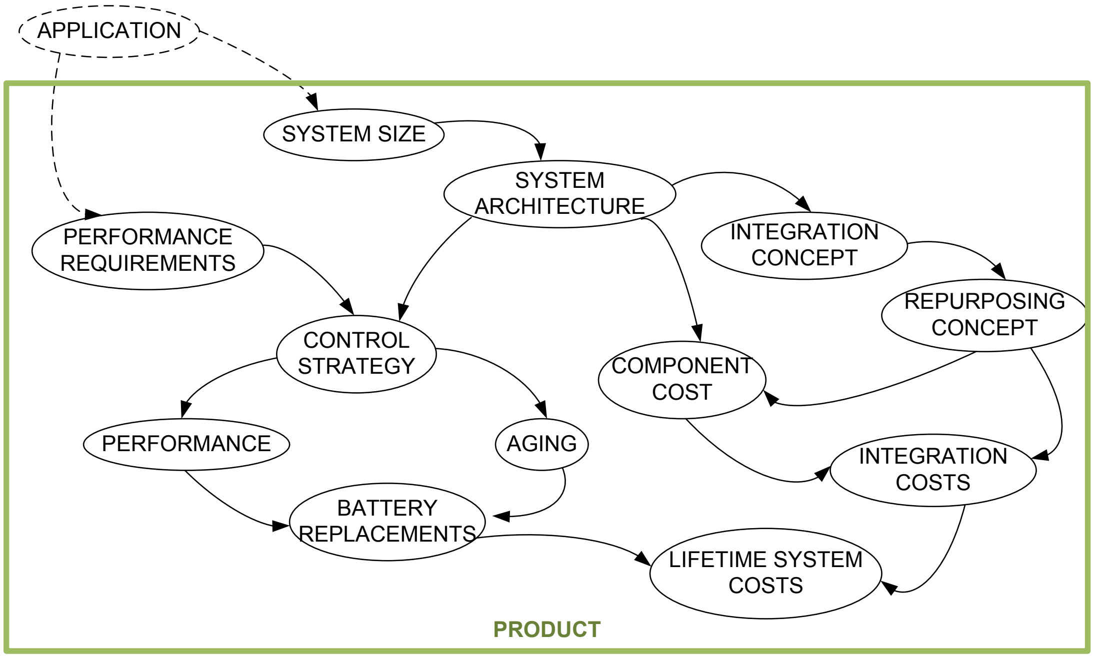


Figure 31: Influence Diagram for Properties of a Battery Energy Storage System

Lifetime costs include the initial purchase price of the battery system and cost of necessary battery replacements over the system lifetime.

Depending on the development phase of the business strategy, adequate details needed to fully characterize both product and process might not be available. Therefore analyses must be able to transition between various levels of detail in order to leverage the available data while not losing scope of the entire problem space. An example of information available to the OEM and how it can be used is discussed in Sidebar 2. Although the availability of information to the OEM puts them in a key strategic advantage, they must also be able to put their information in the context of the larger picture.

In order to do this, individual components of the problem should be modeled in such a way that their level of detail can be changed independently of the other constituent parts.

SIDEBAR 2: EXAMPLE OF STRATEGIC OPPORTUNITY FOR AN OEM

LEVERAGING TOOLS FROM VEHICLE DEVELOPMENT PROCESS

An OEM possesses information about the design and potential performance of the battery over time, due to the development requirements of the vehicle, but will probably lack information about integration costs, and repurposing requirements. Therefore the OEM can perform a detailed simulation of the battery for a given application in order to determine ideal operating conditions, battery size, and thermal management requirements, but will need to use coarse approximations to quantify and analyze if a more robust thermal management system is justifiable from a lifetime cost perspective.

For example a trade off assessment can be performed by integrating the electro-thermal model of the battery system, used primarily to validate warranty requirements into the value chain analysis. The model can be used to assess the amount of heat being generated, and rate of battery degradation for a given secondary use load profile. The cost of a suitable thermal management system can be determined through either

1. An abstracted model such as price per performance metric (*i.e.* cost/rate of heat extraction)
2. A specification and design of different thermal management systems (i.e. natural convection, forced convection, liquid cooled)

The relationship between the cost of the thermal management system, load profile, and battery aging must then be simplified into a meta-model (i.e. look up table) that can then be used in a trade off analysis along the entire value chain.

Other opportunities to leverage tools from the vehicle development process include

1. Warranty assessment methods to determine the SOH of the battery coming out of the vehicle for different return scenarios (See Section 8.1.2).
2. Production planning and service concept data to estimate repurposing costs.
3. Battery aging and thermal models, generally used for warranty assessment and BMS development, for assessment of aging in a second use application.

Components lacking sufficient detail, such as repurposing or transportation costs should use approximations with an associated amount of uncertainty in order evaluate the responsiveness of the system to the unknown. In early analyses, it will be difficult to differentiate the effects of variation and uncertainty since the magnitude of both will be

roughly equivalent. But as more information is obtained, the amount of uncertainty associated with various parameters will be reduced, and the effects of the variances inherent in the problem can then be better understood.

From the detailed analysis key, contributing factors can be identified and used to prioritize research and development goals. In addition, detailed models can be used to parameterize meta-models to analyze further scenarios, higher level trade-off and sensitivity analyses, and incorporation of spatial and temporal factors. Spatial and temporal factors include the availability of batteries for second use, the falling cost of new batteries, and improvements in cell and battery technology.

Given the requirements above, a methodology for evaluating battery second use must allow for the following:

- Continuity between various levels of evaluation.
- Integration of new knowledge as it becomes available.
- Capture the variance and uncertainty inherent in the problem.

Such characteristics dictate that the methods should utilize a modular structure, to allow the individual analysis and integration of the constituent parts of the problem; use statistical representations instead of point values, to properly represent variances and uncertainties; and leverage knowledge from the vehicle development process when possible.

4.2 Framework for Analysis to Guide Business Strategy and Prioritize Research and Development Needs

This section presents a framework which enables the analyses needed to incorporate technical and process parameters into the development of a B2U business strategy. This allows for the incorporation of data as it becomes available, comparison between analyses, and quantification of the effects of variability and uncertainty. The framework allows for the use of methods from the vehicle development process, and is structured so that knowledge generated during vehicle development can be leveraged by the OEM.

4.2.1 *Using the Value Chain to Establish Structure of Framework*

The value chain supplies natural break points for technical and process evaluation. The following steps in the value chain are the key components needed to analyze a B2U strategy. Examples of strategic considerations are provided as sidebars and the strategic parameters for each process step can be found in Section 1.2.1. Each key component is represented by its own sub-Model (Figure 32).

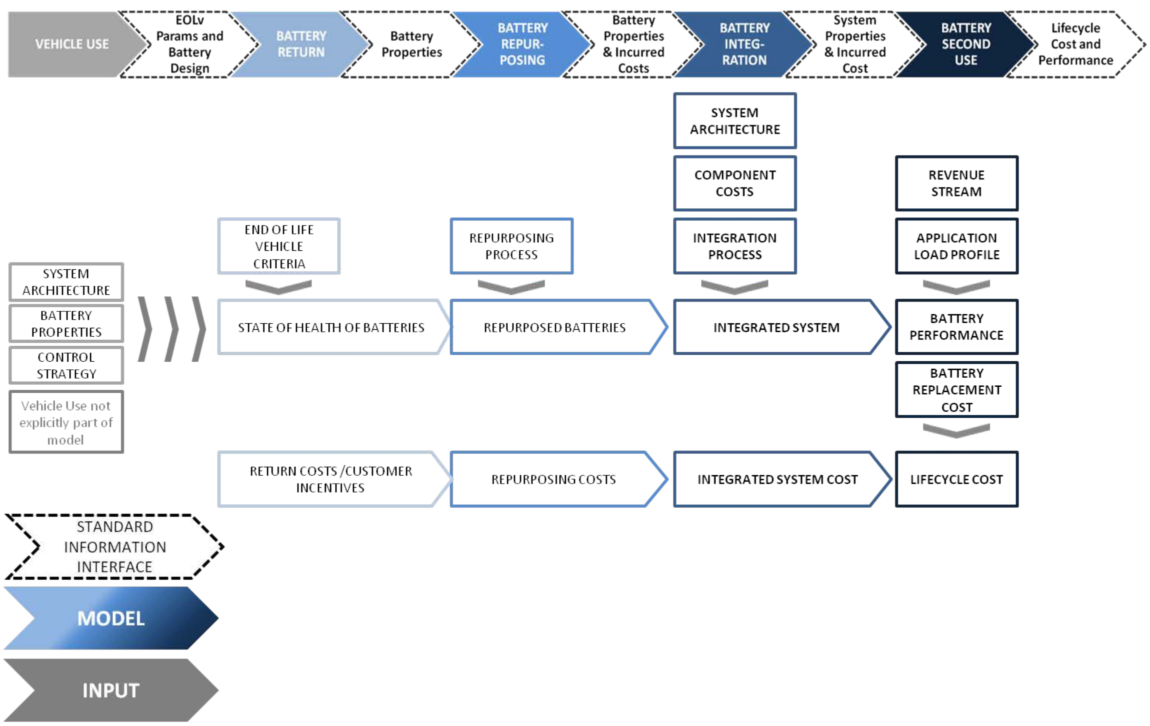


Figure 32: Visualization of Battery Second Life Analysis Framework

BATTERY RETURN MODEL

TABLE 21: BATTERY RETURN MODEL DATA REQUIREMENTS

	Inputs	Outputs
BASIC MODEL REQUIREMENTS	battery architecture (# modules/pack, #cells/module);	remaining capacity per pack and per module cost of removing battery system
DETAILED MODEL REQUIREMENTS	criteria for removal from vehicle (EOLv criteria); nominal battery characteristics	full SOH of battery: remaining capacity, internal resistance
	battery return volumes for various EOLv criteria	volume of batteries available for second use
	spatial distribution of battery return	volume and location of batteries available for second use

In developing a B2U strategy the OEM will need to assess the effects of different return concepts and ownership models, system designs and control strategies on the value chain. The battery return model determines the state of batteries coming out of a vehicle dependent on the end-of-life vehicle criteria, as shown in Table 21.

The properties of the battery includes design parameters, state of health (SOH), and in more advanced modeling cases temporal and spatial availability of used batteries. It is also necessary to establish the architecture of the battery, particularly the number of modules per pack, and the number of cells per module. This will be critical for determining repurposing and integration requirements, limitations, and costs. Other battery information includes the nominal capacity and voltage characteristics (SOC v VOC properties) of a new battery system. This information in conjunction with the battery SOH will determine the performance of the system in a second use application.

It is expected that all batteries returning will not be of the same state of health, so detailed modeling scenarios will represent the SOH of batteries as a probability distribution. The characteristics of this distribution could depend on a combination of factors including return concept, number of years in the vehicle, and/or location in which the vehicle operates. The SOH of the battery pack, or module, will determine its suitability and remaining useful life for a given secondary application.

An end-of-life vehicle (EOLv) criterion determines when the battery comes out of the vehicle and the requirements for the reverse logistics infrastructure. EOLv can be either a performance based parameter (*e.g.* 80% capacity), an operational based parameter (*e.g.* 5 years in vehicle), or a distribution of parameters representing various return concepts. Return concepts can include the removed battery from a battery upgrade, warranty claim, or vehicle returning at the end of its useful life. Returns through an upgrade or warranty claim will probably occur through the dealership, while returns at the end of vehicle life will come through the recycling network. This will affect the return logistic costs and availability of other vehicle components for repurposing for a secondary application.

An example of operational strategies that an OEM can evaluate within this process step is presented in Sidebar 3

SIDEBAR 3: STRATEGIC OPPORTUNITY FOR AN OEM IN VEHICLE USE PHASE

BATTERY FLEET MANAGEMENT AND OPTIONS FOR LIFECYCLE MANAGEMENT

An OEM's battery fleet is considered to be all of the batteries produced by the manufacturer. This fleet can be divided into steerable and non-steerable batteries. Steerable batteries belong to vehicles that the OEM has control or ownership over. This includes lease, car-sharing or internal use vehicles. The return and life cycle management of these batteries can be dictated by the OEM. Therefore the OEM can decide when to remove the batteries from the vehicle, which can secure a minimum volume for second use supply.

Non-steerable batteries are sold to the end customer. The OEM has no control over these batteries and can only influence their returns through incentive offers and marketing. The return of these batteries is unpredictable and will be ultimately up to the decision of the customer. Therefore it is difficult to guarantee a steady supply of used batteries from the non-steerable fleet.

Increasing the percentage of batteries in the steerable fleet can help optimize the use of the entire battery fleet through battery second use and further service capabilities. A theoretical example could be as follows, the lifecycle optimal time to put a battery into a second use application is at 80% degradation. A customer owns a battery that has degraded to 80% after 5 years. The OEM can offer the customer the option to exchange their battery for a minimal price to a battery coming out of a lease vehicle that is only degraded to 95%. Therefore the lease vehicle battery would be repurposed into the end customer vehicle, maximizing its value for the in vehicle applications, and the customer's battery would be used for a secondary application.

REPURPOSING MODEL

TABLE 22: REPURPOSING MODEL DATA REQUIREMENTS

	Inputs	Outputs
BASIC MODEL REQUIREMENTS	battery architecture, repurposing level (cell, module, pack)	cost per module or pack for repurposing
DETAILED MODEL REQUIREMENTS	repurposing steps and requirements, additional component requirements	cost breakdown of reprocessing requirements (capital costs, fixed costs, variable costs, labor, etc)
	warranty information on component failure rate; screening requirements	battery repurposing costs based on total SOH of battery system
	volume based repurposing requirements (out-sourced, manual, automated)	comparison of different process options dependent on volume availability

The repurposing model includes the costs and processes needed to get the battery out of the vehicle and ready for integration into a new system. This includes disassembly, recycling of non-usable components or packs, and repair of necessary components. The level of repurposing can also be dependent on sorting criteria and/or integration concept (Table 22).

In more advanced modeling scenarios temporal and spatial volume factors for a repurposing network can also be modeled; such as the volume of batteries in a certain region available as a function of time, and modeling of costs associated with a level of reprocessing sophistication. An example of how these factors could affect an OEM's B2U strategy is presented in Sidebar 4.

Sidebar 4: Strategic Opportunity for an OEM in Vehicle Return Phase

BATTERY DISTRIBUTION, VOLUME, AND REPURPOSING STRATEGY

Strategically an OEM must decide what role they want to play in the battery second use eco-system. A key decision is if they want to repurpose the batteries themselves or allow a third party to do the repurposing. Key factors within this decision include protection of proprietary information, cost, market production volume, and ability to leverage other enterprise assets such as logistic networks.

The volume of vehicles the OEM has in a given market will determine the required logistics network. Therefore B2U strategy might need to be optimized per region. A region with low volume of available batteries will not justify the establishment of a dedicated reprocessing facility. The per piece reprocessing costs will be higher and realization of economies of scale is not possible. In this case the use of a third party reprocesser might be more economically efficient then reprocessing the batteries in house.

In contrast, regions with large densities of available batteries might have dedicated repurposing facilities where volumes are able to realize economies of scale. Another option would be to collect batteries and ship them to a centralized repurposing center, in which case the associated transportation costs must be accounted for. As a result the distribution of reprocessing costs will be dependent on volume availability and location.

INTEGRATION MODEL

Table 23: Integration Model Data Requirements

	Inputs	Outputs
BASIC MODEL REQUIREMENTS	system size: number of packs/modules per system, usable capacity of batteries	cost per battery system, rated capacity of system
DETAILED MODEL REQUIREMENTS	system architecture and component costs	breakdown of system costs
	sorting requirements for specific system application and system size	volume distribution of packs/modules; cost per system for fleet of batteries
	full integrated system component requirements	capital system cost

The integration model captures the costs and processes needed to integrate the repurposed vehicle battery systems into a new battery system including housing, thermal management system, wiring, and control electronics (BMS). These parameters are dependent on integration concept and final system architecture, an example of which can be seen in Sidebar 5.

SIDEBAR 5: EXAMPLE OF TECHNICAL PARAMETERS FOR SYSTEM INTEGRATIONS

SYSTEM ARCHITECTURE AND INTEGRATION CONCEPT

For an integration concept using the battery modules from the vehicle for a community energy storage system (CES) will require different components than a concept using entire EV battery packs for a large system providing regulation energy. The system architecture of the systems will also be different. The CES might use a single lower voltage inverter with a DC bus voltage of 300-600V with a single battery pack worth of modules connected in series to form a string, and multiple strings then connected in parallel to the single inverter. The system providing regulation energy on the other hand might use higher voltage inverters with a DC bus voltage of 800-900V, two battery packs connected in series to a single inverter, and then multiple smaller inverters are coupled on the AC bus in order to meet the required system capacity.

Each architecture will have different component requirements and challenges with respect to control. The lower voltage systems are more compatible with the ratings of the components in the vehicle system. But lower voltage means higher currents and lower efficiency; which might be irrelevant if the limiting factor of the system efficiency could be the battery system. Due to these losses, the design of systems for high value applications such as regulation energy generally uses higher voltage inverters. The higher voltage systems require the battery system to use certified components compatible with the higher voltage level. Integrating these requirements into the vehicle system could potentially increase over all system cost, and retrofitting the pack with new components for a secondary application could be prohibitively expensive.

It is also necessary to determine the new rated capacity of the system which will be dependent on the capacity of the integrated modules or packs and system architecture. For systems connected in series, the usable capacity of the string will be determined by the

weakest cell or module in the string. While the cumulative capacity of battery strings connected in parallel is the sum of the individual string capacities. If packs of modules with a wide range of characteristics are used together in one system, the usable capacity of the system will depend on the relative difference between the packs/modules and the load profile. In this case a dynamic simulation is needed to characterize the usable capacity.

The system architecture will also dictate the type of service concept and associated cost. Therefore this model determines not only the system capital cost and but also the cost of replacement battery systems.

More detailed models can include the entire integrated storage system costs which include the power conditioning system, system controller, system housing, and wiring.

SECOND LIFE BATTERY MODEL

TABLE 24: BATTERY SECOND LIFE MODEL DATA REQUIREMENTS

	Inputs	Outputs
BASIC MODEL REQUIREMENTS	system lifetime, battery aging rate, number of cycles, allowable DOD	number of battery replacements, lifecycle system cost, usable capacity of system
DETAILED MODEL REQUIREMENTS	battery performance model, load profile, control parameters, system properties	battery performance over lifetime, lifecycle system costs
	system architecture and properties, control parameters, thermal management system characteristics	battery performance over lifetime, lifecycle system costs
	revenue stream, installation and maintenance costs, lifetime system costs	system payback period, NPV of system

The second life model determines the lifecycle costs of the system particularly with respect to battery replacement requirements due to battery aging. Basic model requirements include information on the number of expected cycles per year for a given application, overall system lifetime, allowable DOD and battery aging rate (or number of remaining battery cycles). The overall usable capacity of the system is dependent on the control strategy or allowable DOD, which may be limited in order to mitigate aging (see Sidebar 6).

A more detailed model would include the use of more sophisticated representations of the battery system. Higher level models include battery performance models parameterized by system properties (*i.e.* battery capacity, SOC vs. VOC, internal resistance) and control limits (*i.e.* Vmax, Vmin). More detailed technical models could include the electrical and thermal simulation of the entire system including the PCS and control algorithms. Financial models can include the modeling of revenue streams which can be used with simulation of the system performance to determine actual revenue generation of the system.

SIDEBAR 6: OPPORTUNITIES AND TRADE-OFFS IN SIZING A USED BATTERY SYSTEM

SYSTEM SIZE AND SERVICE STRATEGY: DEVELOPING OPERATIONAL STRATEGIES TO COMPENSATE FOR AGED CHARACTERISTICS OF BATTERY SYSTEMS

Due to the relationship between cell loading, system size, control strategy, and battery aging; a trade-off can be made between installed system size, operating window, and number of battery exchanges. Either the system can be designed to minimize capital cost or to minimize the number of battery exchanges needed during the system lifetime (Figure 33). In the first case, the operating window is limited only by the safe operating range of the battery system, and the batteries are used without regard to aging. Once the batteries have degraded and can no longer provide the specified function, they are replaced. In this case the energy storage system might be owned by the end customer, and the batteries provided through a service contract.

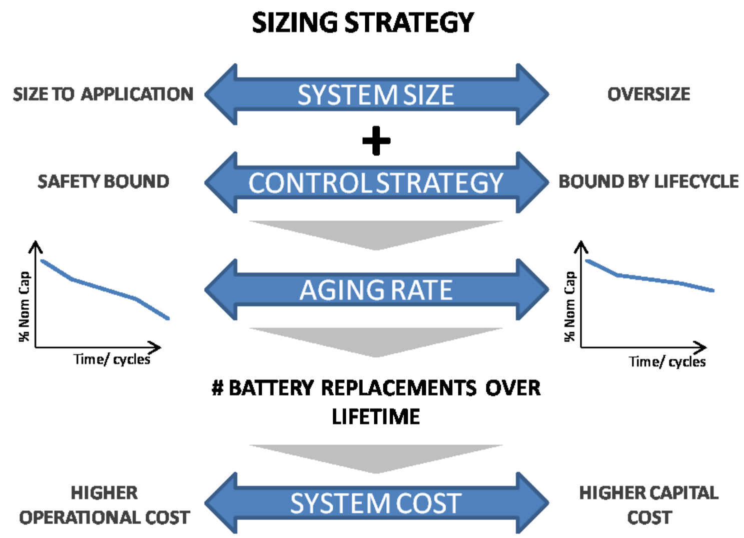


FIGURE 33: TRADEOFF AND RELATIONSHIP BETWEEN SYSTEM SIZE, CONTROL STRATEGY, AGING RATE AND LIFECYCLE COSTS

Systems designed to maximize the battery life would probably be oversized so that the operating window could be reduced without sacrificing performance. The amount of oversize will depend on the load profile, lifetime requirements, and aged properties of the cells. There is also a practical limit to which the system can be oversized and still be acceptable to the customer. In this case the customer might own both the energy storage system and batteries and performance would be guaranteed through a warranty agreement

The choice of strategy will be dependent on the application and customer. For example a large system, owned by an energy provider for frequency regulation would probably be a good applicant for the high performance strategy. Frequency regulation is a high value application that can be relatively strenuous on a battery pack. Even if the batteries were new they would have to be exchanged at regular intervals. Therefore the service contract strategy for used batteries might be attractive. On the other end of the spectrum a battery used for a home energy system to manage the energy use of a household will probably be accepting of a slightly larger energy storage system, but not tolerant of having to exchange the batteries at regular intervals

It should be noted that although this work focuses primarily on stationary applications, the methodology applied here is also applicable for non-stationary applications such as commercial vehicles, material handling equipment, marine, etc.

4.2.2 *Ability to Refine Detail in Order to Meet Analysis Needs*

The use of a modular structure allows for the refinement of constituent parts as data becomes available. Information is shared between process models using standardized data structures containing information about battery (or system) properties and incurred costs. In order to capture the effects of variance and uncertainty, a statistically significant number of batteries are represented. The data exchange between two models is always the same, independent of the modeling level. The use of standardized interface and statistical representations ensures continuity and easy comparison between analyses and modeling levels. An example of various levels for the Battery Return and Battery Second Use models can be seen in Figure 34.

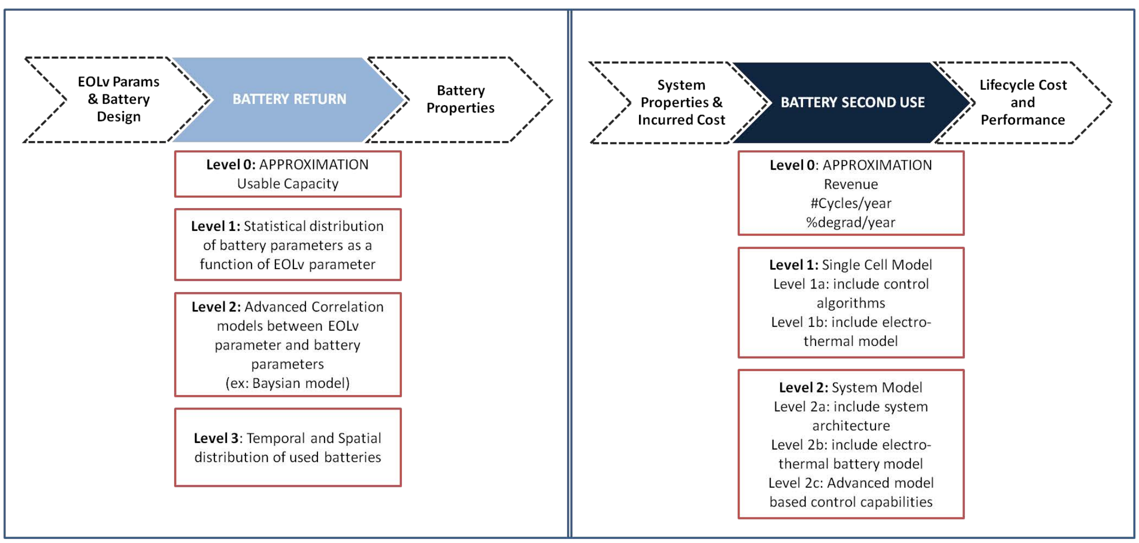


Figure 34: Example of Modeling Levels for the Battery Return and Battery Second Use Models

4.3 EXAMPLE OF TOOL BASED ON THE PRESENTED B2U ANALYSIS FRAMEWORK

The following is a description of the modeling assumptions for a tool developed based on the framework described in Section 4.2.

In Figure 35 components within each main function in the framework (Figure 32) are replaced with sub-function blocks to create a visualization of data flow and general information exchange between main functions. This section provides a high level overview of the functionality of the tool and modeling assumptions.

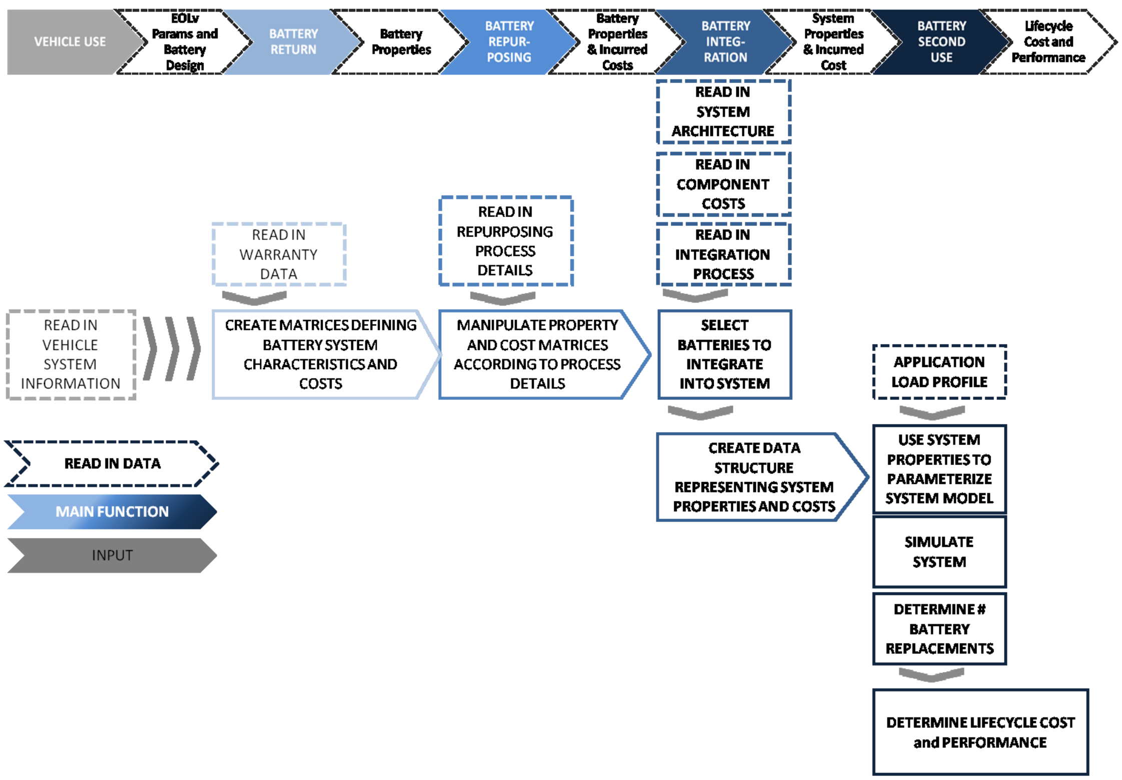


FIGURE 35: VISUALIZATION OF BASE TOOL STRUCTURE

Each main function is self contained which allows for various levels of analysis within that function, in addition to running numerous scenarios within the function and along the value chain.

4.3.1 *BATTERY RETURNS MAIN FUNCTION*

The **Battery Return** main function reads in the system details including battery configuration, and battery cell properties. This information is used together with warranty prediction information to determine the properties of the modeled battery systems.

The battery configuration is described by the number of cells connected in series and parallel to form a module, and the number of series/parallel modules creating a pack. Cell properties include the nominal capacity and internal resistance of a new cell, the characteristic SOC vs. VOC curve, and 1C full cycle aging rate.

The warranty prediction data is a series of probability distribution functions whose parameters change as a function of time. There are four sets of distributions; two of the distributions describe the capacity and resistance development of the entire pack as a function of time. The other two distributions describe the distribution of capacity and internal resistance of individual modules within the battery pack as a function of the degradation of the entire pack. This data can be generated using a warranty analysis tool similar to the one described in Section 8.1.2.

Using a given end-of-life criteria, which is specified as the number of years the pack operates in the vehicle, the tool randomly samples each of the distributions in order to populate matrices representing the properties of individual battery packs. One matrix represents one battery pack, and each row represents one module. This process is repeated until a large number of matrices (10,000+) have been generated.

4.3.2 Repurposing Main Function

The **Repurposing** main function takes the data structure produced from the **Battery Return** main function and determines the associated cost for repurposing each battery system. The repurposing costs can be specified using two methods. Either reprocessing can be described as a series of process steps, with associated labor and costs per step. Or it can be described in terms of entities needed to accomplish the reprocessing (*i.e.* number of employees, equipment, facility requirements). The overall reprocessing requirements can be designated by either or both methods.

Process based refurbishment can be specified with the parameters in Table 25.

TABLE 25: PARAMETERS FOR PROCESS STEP BASED REFURBISHMENT

Process Information	Description
Level at which reprocessing occurs	Designate Cell/Module/Pack level process, this allows process steps to be shared between repurposing scenarios and pack designs, as repurposing costs will scale with vehicle pack design or reprocessing scenario.
Process Type	PROCESS: Normal process such as cleaning, testing, inspection, etc. Does not alter the properties of the battery. DISPOSAL: Disposes of any packs or modules (depending on process level) that are outside of the defined limits. SORT: Sorts packs or modules according to sorting criteria.
Time required for the process step	Information is generally available through service concept development and planning. And is a standard metric needed for production resource planning.
Frequency in which the process step occurs	100% correlates to a process done on every pack or module, and anything less than 100% correlates with a repair type process which may not be performed on all packs or modules. This parameter can come from warranty data when appropriate.
Number of hours requiring specialist(or higher qualified labor) and standard labor	Due to the high voltage many process steps required higher trained professions. Breaking out the hours needed between standard and specialized labor is needed for headcount planning and process optimization.
Description of additional parts required and part cost	Additional or replacement parts needed.
Associated fixed cost, including equipment and tools	Fixed or capital equipment costs can be specified here or in entity based repurposing.
Recycling cost of disposed parts	Disposal of unusable battery modules or components.

The information shown in Table 25 is commonly available when defining assembly processes for the production of the battery pack, service concept and procedures during the vehicle lifetime, or decommissioning procedures when recycling the vehicle. Which means it would be readily available to an OEM in order to evaluate repurposing costs.

Entity-based refurbishment calculates the required costs based on an itemized list of required entities, denoted as 'Subsystems'. The six predefined subsystems are defined in Table 26.

TABLE 26: REPURPOSING COST CATEGORIES FOR ENTITY BASED REPURPOSING

	SUBSYSTEM	COMPONENTS
1	Capital Costs of Test and Dismantling Equipment	battery testers, computers, hand tools, etc.
2	Capital Cost of Material Handling Equipment	forklifts, conveyors, robots, etc.
3	Capital Cost of Office Equipment and Other	computers for administrative use, desks, tables, chairs, etc.
4	Labor	direct labor, management, and administration
5	Direct Costs	consumables such as electricity, raw material, parts
6	Indirect Costs	facility costs, insurance, taxes

Costs are specified for a given system level. The accumulated costs per pack for facility level entities are calculated using an assumed annual production volume/battery pack throughput, internal rate of return, and facility lifetime.

4.3.3 *INTEGRATION MAIN FUNCTION*

The **Integration** main function reads in information about the system architecture then, using functions similar to those used in the **Repurposing** main function, calculates the process and entity based integration costs.

The system architecture is defined by the number of cells, modules, racks, and power cabinets connected together in series and parallel to form the battery system. For information on the technical details of each system level see Section 3.2.1.

TABLE 27: EXAMPLE SYSTEM LEVEL BREAKDOWN OF SYSTEM ARCHITECTURE FOR A LARGE SYSTEM, WHERE 'S' AND 'P' DESIGNATES THE NUMBER OF SERIES AND PARALLEL CONNECTIONS PER SYSTEM LEVEL, RESPECTIVELY.

SYSTEM LEVEL	*System*	0	**S**	**P**	
	Power Cabinet	1	1	20	Cabinet/System
	Rack	2	1	3	Racks/Cabinet
	Module	3	16	1	Modules/Rack
	Cell	4	12	1	Cells/Module
		5	10000		

The program uses the information about the system architecture and randomly selects the proper number of battery packs or modules and arranges them into a data structure representative of the system architecture (Table 27).

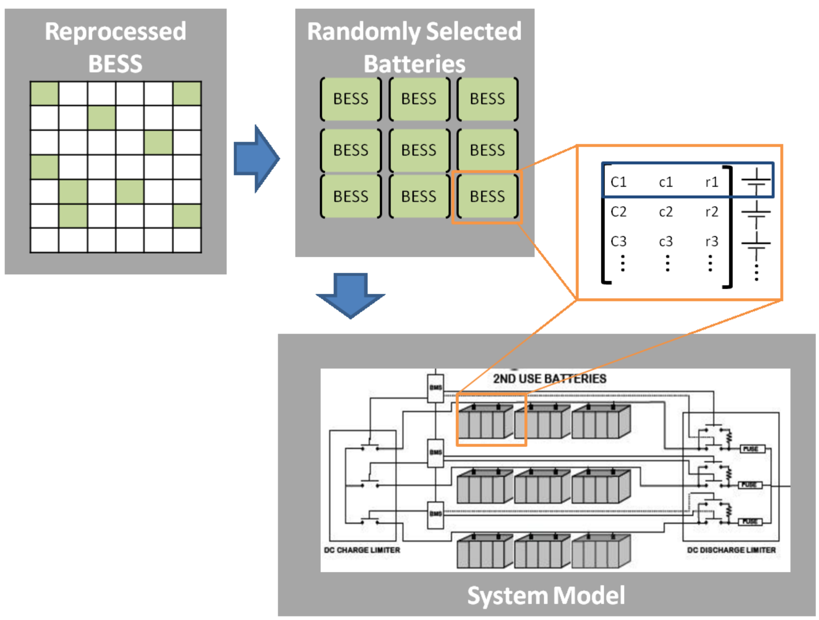


FIGURE 36: VISUALIZATION OF "SELECT" SUB-FUNCTION

The function for calculating process based integration costs is similar to the process based Refurbishment functions.

Similar to the "entity based" refurbishment, entity based integration calculates the required costs based on an itemized list of required entities, denoted as "Subsystems". There are eight predefined subsystems defined in Table 28.

TABLE 28: PREDEFINED SUBSYSTEMS FOR ENTITY BASED INTEGRATION

	SUBSYSTEM	COMPONENTS
1	Battery	Battery cells/modules/packs, battery management system, battery thermal management, racking, HV DC wiring, LV communication and sensor wiring, relays, fuses, etc
2	Power Control System	Inverter, system controller, etc.
3	Balance Of Systems	Wiring, fire suppression, safety and monitoring equipment, grounding and shielding components
4	Thermal Management System	Fans, sensors, pumps, HVAC, air filters etc.
5	Connectors and Interface	Switches, relays, external system communication, HV disconnects
6	Labor	Specialized, non-specialized, direct and indirect
7	Research and Development	Certification, software programming, hardware development, etc.
8	Misc	Signage, environmental testing, taxes, warranty, indirect costs

The costs from the process-based integration are combined and added as an additional component to the Battery subsystem. The breakdown of costs for the battery system and the parameters for replacement systems are also determined. Replacement systems have the same battery properties as the original system and costs associated with the exchangeable components of the integrated battery subsystem.

4.3.4 *SECOND USE MAIN FUNCTION*

The **Second Use** main function performs the following:

1. Calculates the properties of the battery system based on a specified depth of discharge and parameters of the battery system from the **Integration** main function.

2. Determines the number of battery exchanges needed over the lifetime of the secondary system.
3. Calculates system lifecycle costs, potential profits, and performance metrics of the system.

Depending on the level of information available the three steps above, can be performed using one of two methods. For preliminary analysis in which only high level information about the application and battery aging characteristics are known, a 'Basic' method can be employed. If more information about the secondary application is known such as the load profile, or power demand as a function of time; and the aging characteristics of the battery are better understood and quantifiable (*i.e.* a weighted Ah throughput model is available) then a more 'Advanced' method can be used. The difference between the two methods is defined as follows and differences in data requirements can be seen in Table 29.

TABLE 29: DATA REQUIREMENTS FOR SECOND USE MODEL

Requirement	Basic Model	Advanced Model
Battery Properties	Remaining number of full cycles in battery, Capacity	SOC vs. VOC characteristics, aging characteristics, Capacity and internal resistance
Application Characteristics	Number of annual full cycles for the given application	Load profile defined as power requirements as a function of time
System Model	Account for bulk efficiency losses	Model operating efficiencies of individual components
Cost of Replacement Battery System	Price/system	Model price per component with varying failure rates
Lifetime of complete energy storage system	years	years
Market price of new battery system	Price/kWh	Price/kWh

Since the capacity of batteries connected in series are limited by the capacity of the weakest cell, and the capacity of cells connected in parallel is equal to the sum of the capacities of the individual cells (i) , the usable capacity of the battery is determined as follows

1. Calculate capacity of systems connected in series as

$$Cap_{series,x} = \min\left(Cap_{i,x}\right) \quad \textbf{Eq. 1}$$

2. The capacity of systems connected in parallel is calculated as

$$Cap_{p,x} = \sum_{i=1}^{p} Cap_{i,x} \quad \textbf{Eq. 2}$$

Calculation steps one and two are first conducted on the rack level (*x=r*), then repeated on the cabinet level (*x=c*).

Based on the remaining number of full cycles, the annual full cycle requirement of the application, and lifetime of the system the number of replacement battery systems is determined as follows.

$$\#_{Replace} = ceil(\ cyc_{yr} * \frac{Sys\_life}{remainlife_{cyc}}) \quad \textbf{Eq. 3}$$

Lifetime cost of the system can be determined as follows

$$COST_{LIFE} = COST_{BATT} + COST_{SYS} + COST_{REPLACE} * \ [\#_{replace}] \quad \textbf{Eq. 4}$$

$$COST_{kWh_{LIFE}} = \frac{COST_{LIFE}}{[\%nom\ Cap]\ [CAP_{nomsys}]} \quad \textbf{Eq. 5}$$

The potential profit is then calculated as

$$PROFIT = PRICE_{kWh} - COST_{kWh_{LIFE}} \qquad \text{Eq. 6}$$

In the 'Advanced' method the application load profile is the expected power requirements of the system as a function of time. And this profile should be representative (or scalable) to show the power demands of the system for an entire year.

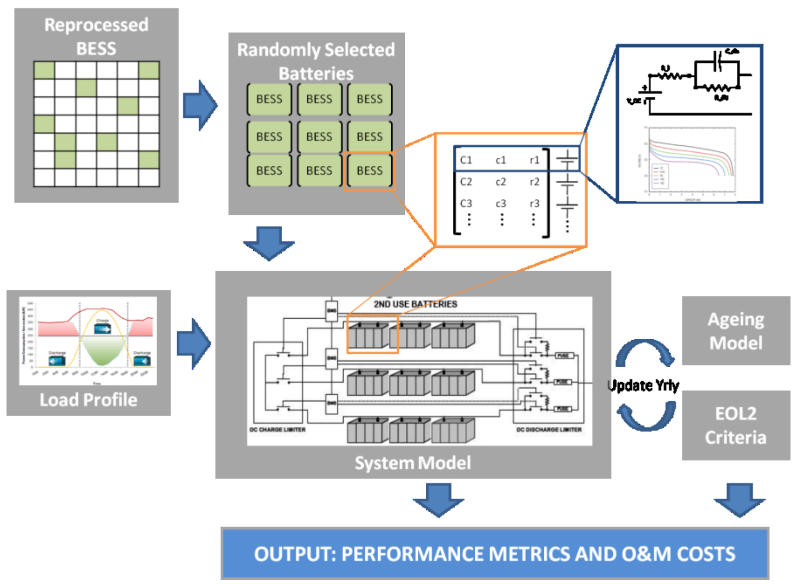


Figure 37: Schematic of Advanced Second Use Model

The properties of the energy storage system include the battery system properties from the Integration main function (system configuration, capacity, internal resistance…), and chemical characteristics of the cell (SOC vs. VOC curve, nominal cell voltage etc).

The model of the energy storage system is a system model that could either be a single cell equivalent representation of the entire system, or a model of multiple cells connected in series or parallel. In single cell representation, the properties of the cell are

determined as follows from the battery parameter matrix from the **Integration** main function.

For series connected systems:

$$R_{s,x} = \sum R_{i,x} \qquad \textbf{Eq. 7}$$

For systems in parallel:

$$\frac{1}{R_{p,x}} = \sum \frac{1}{R_{i,x}} \qquad \textbf{Eq. 8}$$

Advantages of using a multiple cell model include the ability to model a more advanced control strategy and capture effects of having batteries with different properties which includes equalization currents that will flow between battery systems when the batteries are unloaded (I=0). These effects have the potential to affect system aging and overall performance of the system but cannot be captured with the single cell equivalent model.

A simulation of the system using the battery model and application load profile, with a run time of one year, is used to determine the inputs to the aging model and performance metrics of the system. Performance metrics include percent load met, peak system power and full power (dis)charge capacity.

The change in battery parameters due to battery degradation is calculated using the aging model, which then updates the parameter of the battery model and re-runs the simulation until an end-of-life criterion is met. End-of-life criteria can include a performance metric (peak power, usable capacity etc), a battery parameter (capacity, internal resistance,

age), or the end-of-life of the system. If the end-of-life criteria is not the end-of-life of the system the battery system is replaced which returns the properties of the battery to their beginning of second use state, and adds the cost of the replacement to the lifecycle cost of the system.

The simulation will run until the end-of-life of the system, and output the yearly performance of the system and total lifecycle costs.

4.4 Example Analyses Demonstrating Example Tool's Capabilities

The following serves as a demonstration of the developed tool's capability and to illustrate the power of the framework developed. The following analysis consists of three parts:

4.4.1. An uncertainty analysis is performed in order to better define the window of opportunity for battery second use.

4.4.2. Trade off analysis between different reprocessing levels and integration concepts.

4.4.3. Evaluation of potential temporal effects due to changes in battery technology and market price.

The first analysis investigates the level of uncertainty present in today's state of knowledge, sensitivity to contributing parameters, and the bounding conditions (or window of opportunity) for battery second use. The sensitivity analysis and window of opportunity can be used to efficiently prioritize future research. The results can be used as screening criteria and to focus future research to reduce uncertainty of parameters with the highest sensitivity factors, and evaluate technology and applications with parameters that fall into the window of opportunity.

The second analysis shows the flexibility and robustness of the tool. The use of statistics and modularity of the tool allows for the use of methods such as Design of Experiments to identify interrelations among the value chain. In addition, the data rich methods allow for further numerical investigations into these relationships, quantification of their impacts, and evaluation of sensitivities.

The final analysis will demonstrate how battery second use, and the development of a second use strategy, is not a static problem. This analysis will demonstrate that a robust strategy must be dynamic, capable of adapting to and leveraging current market situations. This can only be accomplished by integrating time dependent factors such as market price and properties due to new technology development.

The last two analyses use the base tool described in Section 4.3 while the uncertainty analysis and parameter screening uses a much more simplified model based on the framework presented in Section 4.2.

4.4.1 Identification of Window of Opportunity and Preliminary Evaluation of Problem Uncertainties and Sensitivities

This analysis was performed using data available in literature and collected during internal projects. The purpose of this analysis is to show the range of parameters present in the current state of knowledge, and quantify the resultant amount of uncertainty.

This analysis seeks to answer the following given the state of information available today:

- What is the likelihood of bringing a competitive product to market?
- And under what conditions could this product be competitive?

This analysis uses technology and cost parameters to perform a bottom up calculation which is then combined with a range of market conditions to find the conditions for a profitable second use value chain. The parameter ranges that lead to a profitable scenario are the bounding conditions for the viability of battery second use. The true profitability for individual stakeholders will depend on the operational structure of the battery second use ecosystem.

A schematic overview of the method used to evaluate these questions is presented in Figure 38. More details on the method and input parameters can be found in Section 10.1.

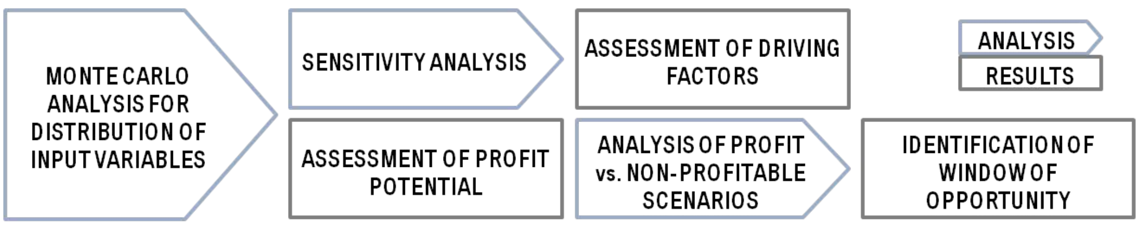


Figure 38: Visualization of Method for Sensitivity Analysis and Identification of a Window of Opportunity.

The following parameters were used for a Monte Carlo Analysis to assess the uncertainty in today's current state of knowledge. Values were derived from literature and pilot projects conducted by BMW. Monte Carlo sampling was used to randomly sample each parameter from the defined distribution with a sample size of 100,000 trials. Triangular distributions are used for parameters with min, max, and best guess estimates, while uniform distributions are used for parameters where a range is available and confidence in one or another value is not possible. The resultant distributions can be seen in Figure 39.

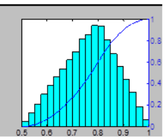
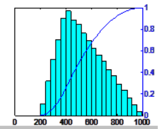
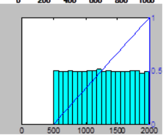
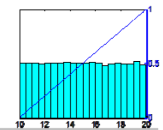
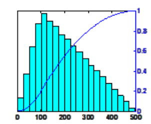
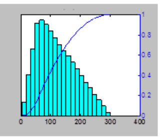
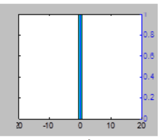
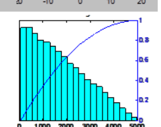
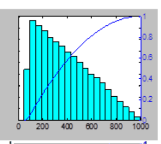
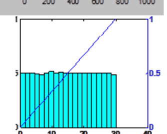
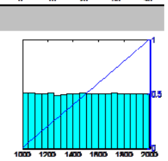
		Level	unit	Distribution	Mean	Param 1	Param2	
SYSTEM PARAMETERS	Capacity at EOLv	rack	%nom cap	triangle	80%	50%	100%	
	Cycles/year	**system**	**cycles**	**triangle**	**400**	**200**	**1000**	
	Remaining useful cycles	rack	cycles	uniform	2000	500	2000	
	System lifetime	**system**	**year**	**uniform**	**15**	**10**	**20**	
COSTS	**Residual Value**	**capacity**	**€/kWh**	**triangle**	**100 €**	**- €**	**500 €**	
	Repurposing	module	€/module	uniform	60 €	3.50 €	300 €	
	Integration	system	€/s	uniform	- €	- €	- €	
		cabinet	**€/cabinet**	**triangle**	**70 €**	**50 €**	**5,000 €**	
		rack	€/rack	triangle	100 €	50 €	1,000 €	
		module	**€/module**	**uniform**	**25 €**	**- €**	**30 €**	
REVENUE	**Market Price**	**Battery System**	**€/kWh**	**uniform**	**1,700 €**	**1,000 €**	**2,000€**	

Figure 39: Distributions of Input Parameters for Initial Monte Carlo Analysis. (Section 10.1.1)

Results of the 100,000 trials can be seen in Figure 40 and quantified in Table 30. The methods by which these results were calculated can be found in Section 10.1.2.

TABLE 30: STATISTICAL OVERVIEW OF POTENTIAL PROFIT FOR PRELIMINARY MONTE CARLO ANALYSIS

PROTFIT POTENTIAL/kWh											
	50% CDF	98% CDF	Point Value	Mean	Std Dev	Range	Min	Max	Stdev %	Range (+) %	Range (-) %
Large	- 600 €	1,073 €	1,130 €	- 1,004 €	1,676 €	19,377 €	- 17,605 €	1,772 €	148%	1657%	57%
Medium	- 591 €	1,095 €	1,130 €	- 991 €	1,667 €	21,393 €	- 19,625 €	1,768 €	148%	1836%	56%
Small	- 789 €	957 €	1,115 €	- 1,196 €	1,710 €	18,298 €	- 16,488 €	1,810 €	153%	1578%	62%

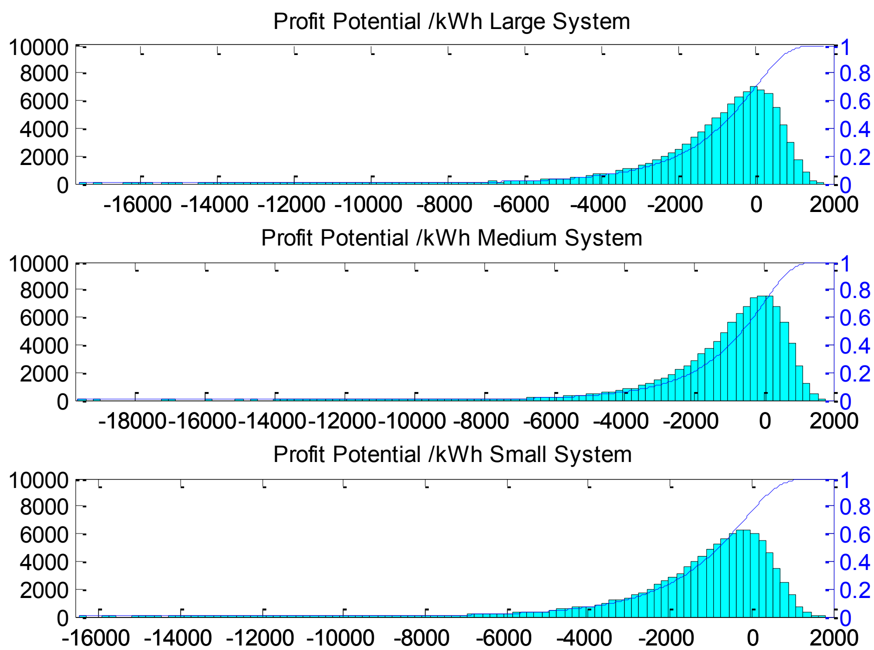


FIGURE 40: POTENTIAL PROFIT DISTRIBUTIONS FROM INITIAL MONTE CARLO ANALYSIS

The profit potential is the difference between the market price of a battery system and the lifecycle cost of the system. Previous studies concentrated on the system costs, assuming the battery system would be sold at a price that would be enough to cover the value chain costs while still remaining under the price ceiling of new lithium ion cells. This study takes a different approach in determining market competitiveness. Here it is assumed that energy storage is a commodity in which the price competitiveness is independent of

technology and solely dependent on lifecycle costs. Therefore the potential profit that can be obtained is the difference between this price ceiling and the lifetime system cost of the system. It is a profit potential since it is the maximum amount of profit that can be made through an end customer sale. In reality a system integrator and all partners between the OEM and end customer in the value chain will take a cut of that profit leaving only a small percentage of the total potential profit for the OEM. The question then is: does that percentage make battery second life attractive enough for an OEM to move forward in a second life strategy?

For the given analysis it can be seen that the potential profit varies dramatically, with an average point estimate of 1,128€/kWh with an 1.5% chance that the profit potential is greater, 28.5% that it is less, and 70% chance that no profit will be made.

From these results it's necessary to understand the sensitivity of the outputs to the input parameters and what range of parameters determine a profitable scenario. A sensitivity analysis was therefore performed by assessing each input parameter distribution's influence on the output distribution. A sensitivity metric was then created using the standard deviation of the input and resultant output distribution for each parameter. More details on these procedures can be found in the Appendix (Section 10.1).

The rating of sensitivity of the problem to the given parameters can be ranked using this sensitivity metric as follows in Table 31.

TABLE 31: RANKING OF RESULTS FROM SENSITIVITY ANALYSIS

	SENSITIVITY COST
Remaining useful cycles	3.24
Cycles/year	0.96
Residual Value	0.80
Capacity at EOLv	0.70
System lifetime	0.57
Integration rack	0.26
Repurposing	0.20
Integration module	0.02
Integration cabinet	0.00
Market Price	0.00
Integration system	0.00

	SENSITIVITY PROFIT
Remaining useful cycles	1.63
Market Price	1.50
Cycles/year	0.48
Residual Value	0.41
Capacity at EOLv	0.35
System lifetime	0.29
Integration rack	0.13
Repurposing	0.10
Integration module	0.01
Integration cabinet	0.00
Integration system	0.00

The problem is most sensitive to the number of remaining useful cycles of the battery which is determined by the aging characteristics of the battery. The market price and residual value of the battery are two other driving factors which will be determined by the development of the battery market. The number of cycles per year is also relatively significant and is dependent of the second life application. All other parameters are more trivial and are mostly attributed to the reprocessing and integration of the electric vehicle system into a stationary system.

Therefore it can be seen that according to this analysis, battery second use will be primarily dependent on the aging properties of the battery and development of the battery market. Previous studies have speculated about this conclusion [41], [42], [46], but here it was proven quantitatively and in proportion to the other parameters. In addition the sensitivity to all parameters have been rated and ranked. This ranking can be used for prioritizing future research.

The second question that stems from the given results is what range of input parameters lend itself to a profitable scenario. To explore this further, the parameters for profitable scenarios were then separated and compared.

By comparing the distributions for profitable and non-profitable scenarios a window of opportunity can be identified. According to this analysis the window of opportunity would lie within the boundaries in Table 32. More information on the method can be found in the Appendix (Section 10.2).

TABLE 32: RESULTS OF ANALYSIS AND LIMITING PARAMETERS FOR PROFITABLE SCENARIOS,

	UNIT	MAX	MIN
Capacity at EOLv	% nom Cap	1.00	0.71
Cycles/year	#/yr	502	200
Remaining useful cycles	cycle #	2000	1318
System lifetime	years	14.70	10.00
Residual Value	€/kWh	197.00	0.00
Repurposing	€/module	114.00	0.00
Integration system	€/module	0.00	0.00
Integration cabinet	€/module	2381.00	0.00
Integration rack	€/module	450.00	0.00
Integration module	€/module	30.00	0.00
Market Price	€/kWh	2000.00	1470.00

Results indicate that the battery system's state of health should have at least 71% of its nominal capacity, which is slightly lower than the generally assumed 80%, and at least 1318 remaining useful cycles. The limits on the number of cycles per year indicate for the range of market prices given the used batteries should not be used in applications with more than 1.38 cycles per day. This will create a limitation for the type of combined applications the system can perform. The limit in market price also indicates that if the market's lifecycle

system cost falls below 1500€/kWh battery second use will not be able to be competitive on a price per unit performance basis.

In order to validate these findings another Monte Carlo simulation was run using the limits for profitable scenarios, the results of which are quantified Table 33 and can be seen in Figure 41.

Table 33: Statistical Summary of Results for Secondary Monte Carlo Analysis

	PROTFIT POTENTIAL/kWh										
	50% CDF	98% CDF	Point Value	Mean	Std Dev	Range	Min	Max	Std dev %	Range (+) %	Range (-) %
Large	1,143 €	1,630 €	1,130 €	1,135 €	259 €	1,918 €	- 25 €	1,892 €	23%	102%	67%
Medium	1,144 €	1,630 €	1,130 €	1,136 €	259 €	1,978 €	- 74 €	1,904 €	23%	107%	68%
Small	1,082 €	1,577 €	1,115 €	1,074 €	264 €	2,027 €	- 161 €	1,866 €	24%	114%	67%

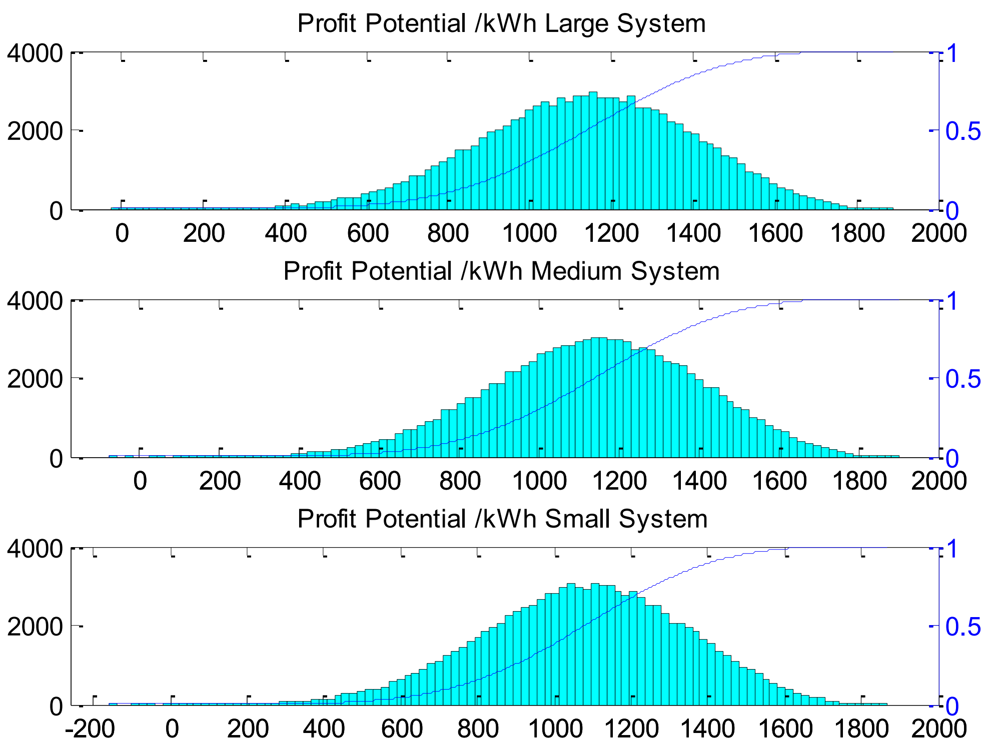


Figure 41: Results of Secondary Monte Carlo Analysis using Identified Limits for the Window of Opportunity

As seen in Figure 41 using the determined parameter windows the majority of scenarios (99.8%) are profitable. The non profitable situations are worst case extremes that require more than five battery replacements, with high system costs. Therefore the given parameters are deemed suitable limits to define a window of opportunity for battery second life.

The results of this analysis can be used as a screening process for the further development of a second use strategy for an OEM. If the profit potential shown in Figure 41 does not provide a suitable incentive for the OEM the further development of a second life strategy should not be perused. Additionally if the technology offerings of the OEM do not align with the window of opportunity shown in Table 32, then a second life strategy should be deferred until more favorable conditions exist. If the potential in Figure 41 appears promising to the OEM they should continue their investigation focusing on the most sensitive parameters identified in Table 31.

4.4.2 *Tradeoff Analysis*

A tradeoff analysis is the next step in understanding the potentials of a battery second life strategy. This type of analysis can evaluate interdependencies that cannot be adequately accounted for in a high level screening. The following example shows the capabilities of the developed framework in investigating and understanding these tradeoffs.

The modular framework allows the combination of the parameters described in Table 34 to evaluate a total of 144 scenarios for battery second use. The use of standardized interfaces between the individual modules then allows deeper investigations to understand the interactions between various parameters along the value chain.

The premises and more details on the modeling methods can be found in Section 10.3.

Table 34: Overview of Scenarios of Tradeoff Analysis

	EOLv		Mod/Pack		BMS		System Size
1	3 years	1	Module	1	Vehicle	1	Large
2	5 years	2	Pack	2	New	2	Medium
3	10 years					3	Small

	Aging Factor		Run Time		# Cycles/yr		Market Price
1	1x Nom	1	10.00 €	1	400.00 €	1	1,500.00 €
2	2 x Nom	2	15.00 €	2	1,000.00 €	2	2,000.00 €
3	3 x Nom					3	3,000.00 €

The results of all 144 scenarios can be seen in Figure 42. It can be seen for the given scenarios there is a wide range of opportunities that must be explored further and better understood.

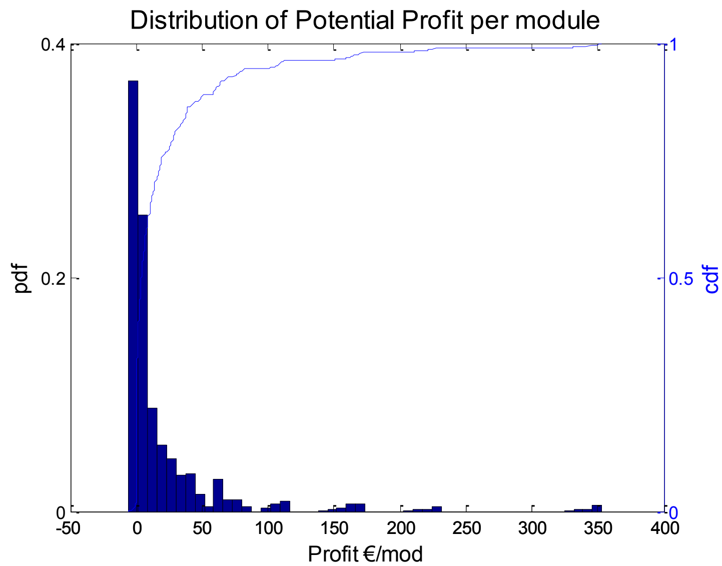


FIGURE 42: DISTRIBUTION OF PROFIT PER MODULE FOR ALL SCENARIOS PROBABILITY (PDF) ON PRIMARY Y-AXIS AND CUMULATIVE DISTRIBUTION FUNCTION (CDF) ON SECONDARY Y-AXIS.

The modular structure allows the use of methods such as Design of Experiments to further breakdown the nature of the interactions along the value chain, and evaluate sensitivities to given parameters. These methods can be used to determine which interactions must be investigated more in detail.

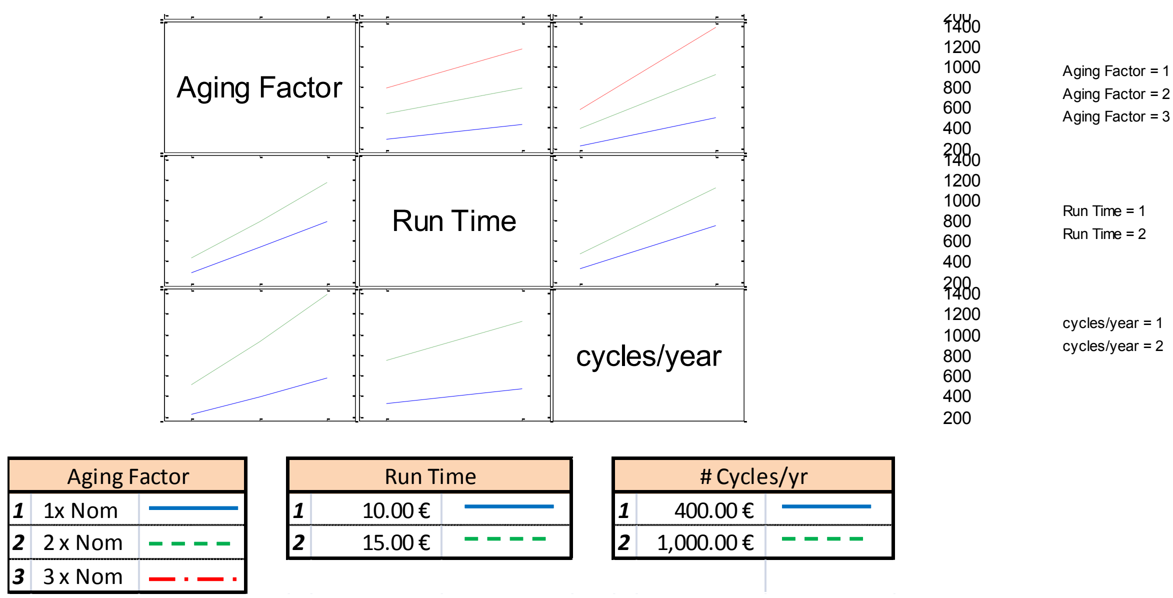


FIGURE 43: EXAMPLE OF INTERACTIONS PLOT FOR TRADEOFF ANALYSIS

From the results of the interaction plots two examples are given to show the types of inquires that can be made and how the results of these inquiries can help an OEM build and optimize their second use strategy

1. The effects of the end-of-life vehicle criteria on the secondary usable system for various system sizes.

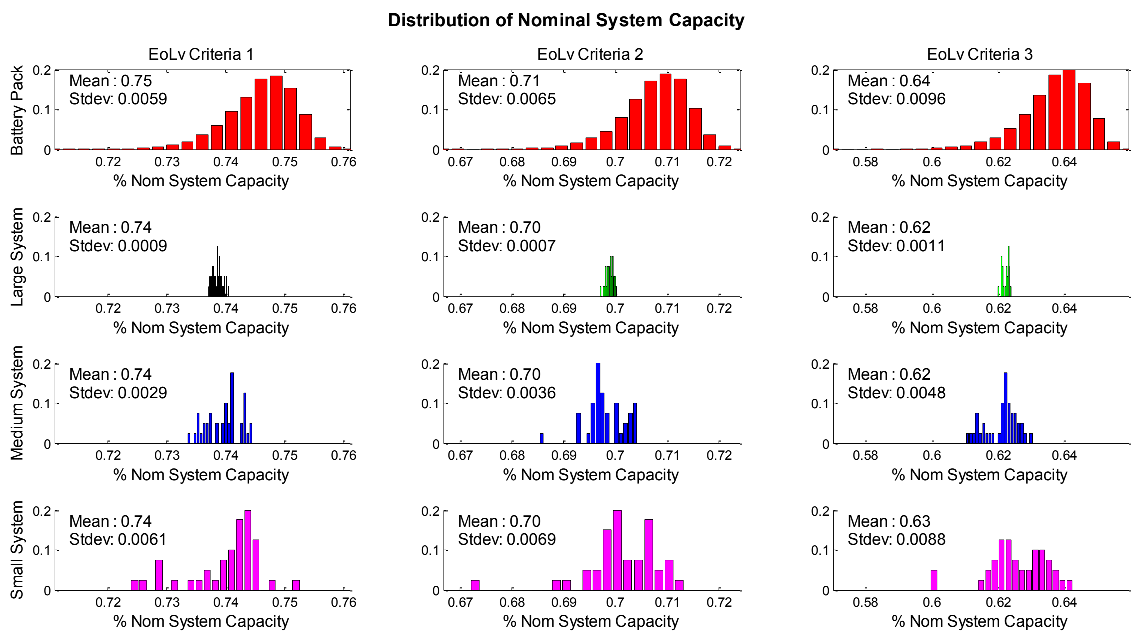


FIGURE 44: USABLE SYSTEM CAPACITY DEPENDENCE ON EOLV CRITERIA AND SYSTEM SIZE

This type of analysis can help determine the type of system the batteries should be used for given different scenarios for taking the batteries out of the vehicle. In addition, it can help with establishing or optimizing, screening requirements, to minimize repurposing costs without negatively impacting the final system performance.

2. Effects of system size and architecture on additional component requirements and integration concepts (Figure 45).

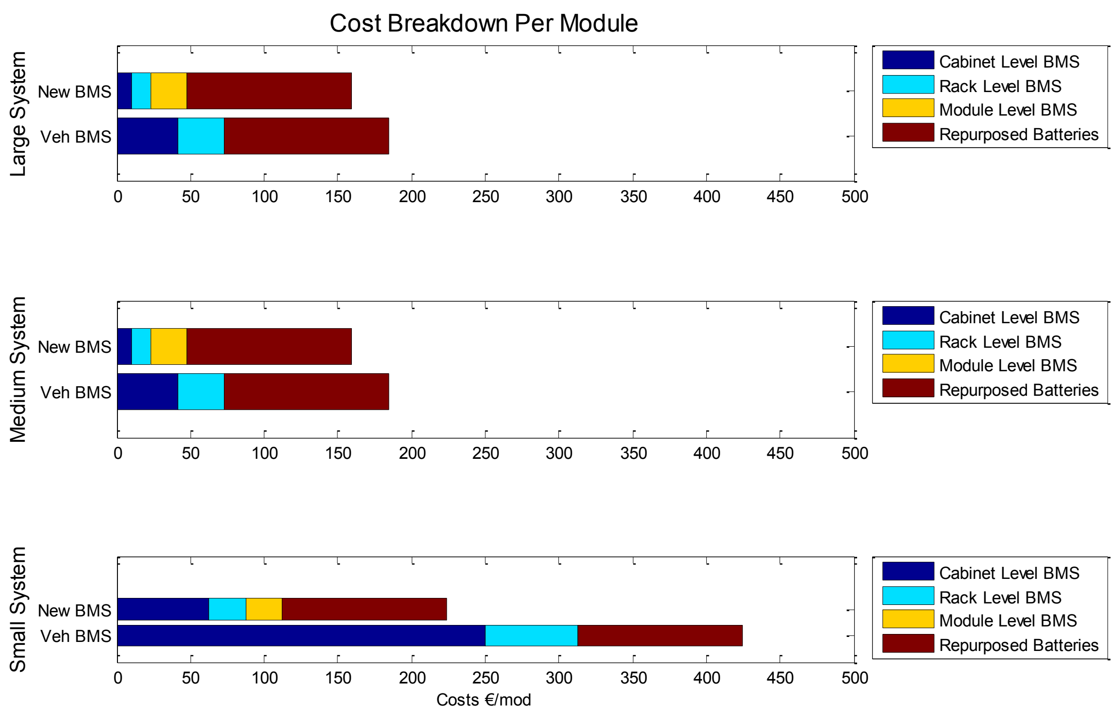


FIGURE 45: ABSOLUTE COST BREAKDOWN PER MODULE FOR EACH SYSTEM SIZE AND INTEGRATION CONCEPT

This type of analysis can help the following:

- Identify the optimal integration concept.
- Assess competitiveness in different scale systems.
- Identify cost drivers.
- Identify optimization opportunities for the final system design.

4.4.3 *ASSESSMENT OF POTENTIAL TEMPORAL EFFECTS ON BUSINESS FEASIBILITY*

A robust strategy will be able to adapt with changing market situations. The following analysis is to evaluate the temporal effects on the costs involved with battery

second use. This includes the effects of technology improvements and cost reductions. By understanding these changing market conditions, the OEM can not only create a robust strategy, but also identify potentials to leverage them.

Using the data from [120] and [109] the following projection of relative EV system capacity and cost is used for the analysis is shown in Figure 46.

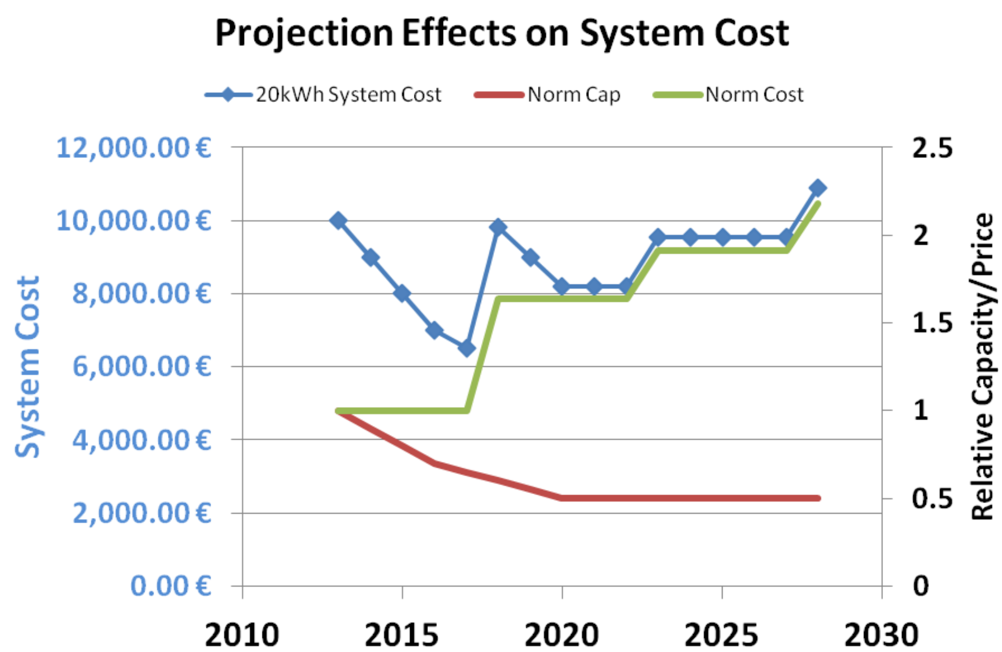


Figure 46: Technology Improvement and Cost Assumptions for Analysis of Changing Market Conditions

Figure 46 also shows the interaction of the two projections by calculating the cost of a system with an original capacity of 20kWh. It is assumed that when the next generation cell is available, the cell is exchanged one for one in the battery system. Therefore in 2018 the 20kWh system increases to a capacity of 32.7kWh, 2023 to 38.2kWh, and in 2028 to 43.6kWh. It can be seen that the largest change in price stability will be between 2013 and 2020.

A subset of data from Section 4.4.2 is used to determine stationary system capacity, repurposing and integration costs, and replacement intervals.

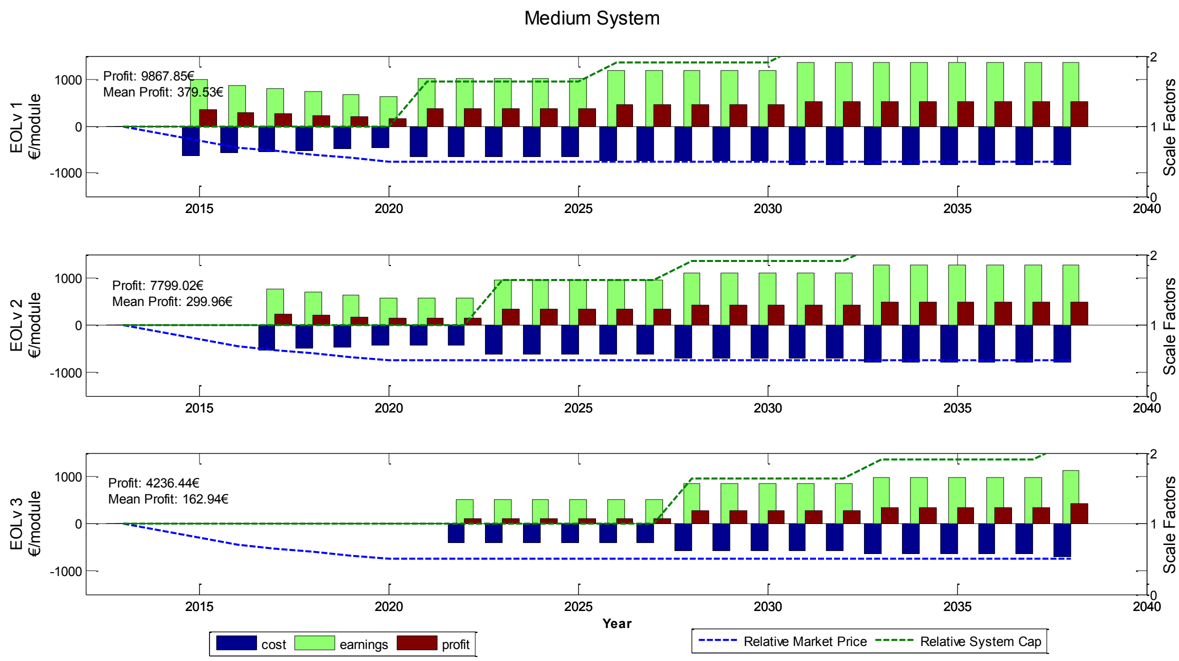


FIGURE 47: CASH FLOW FOR SECONDARY SYSTEMS AS A FUNCTION OF TIME

Figure 47 shows the cost, earnings and profits for systems sold each year for each of the three vehicle return scenarios. For reference, the relative market price and relative system capacity of batteries being integrated into the secondary systems are plotted on the right axis. Both parameters are relative to the price and size (kWh) of the original vehicle system sold in 2013.

Figure 48 shows the potential profit per kWh for the three end-of-life vehicle scenarios as a function of time.

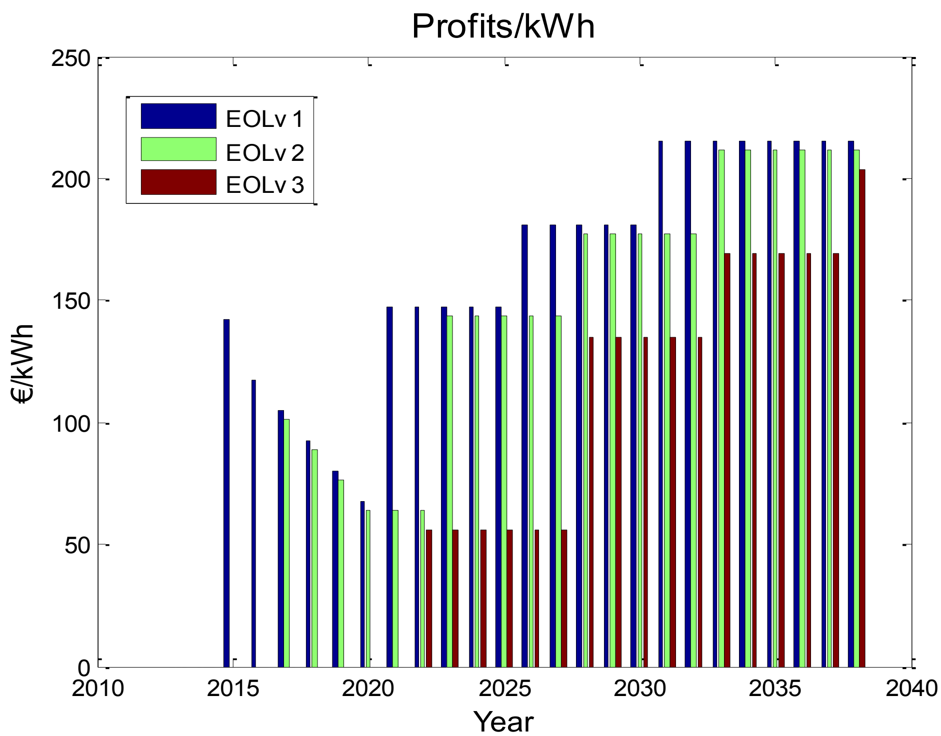


FIGURE 48: SUMMARY OF PROFIT POTENTIAL PER KWH OVER TIME FOR GIVEN MARKET CONDITIONS

This type of analysis can be used to assess:

1. Impacts of various return scenarios
2. Optimal timing for deployment of a B2U strategy
3. Long term contract agreements for the supply of used batteries

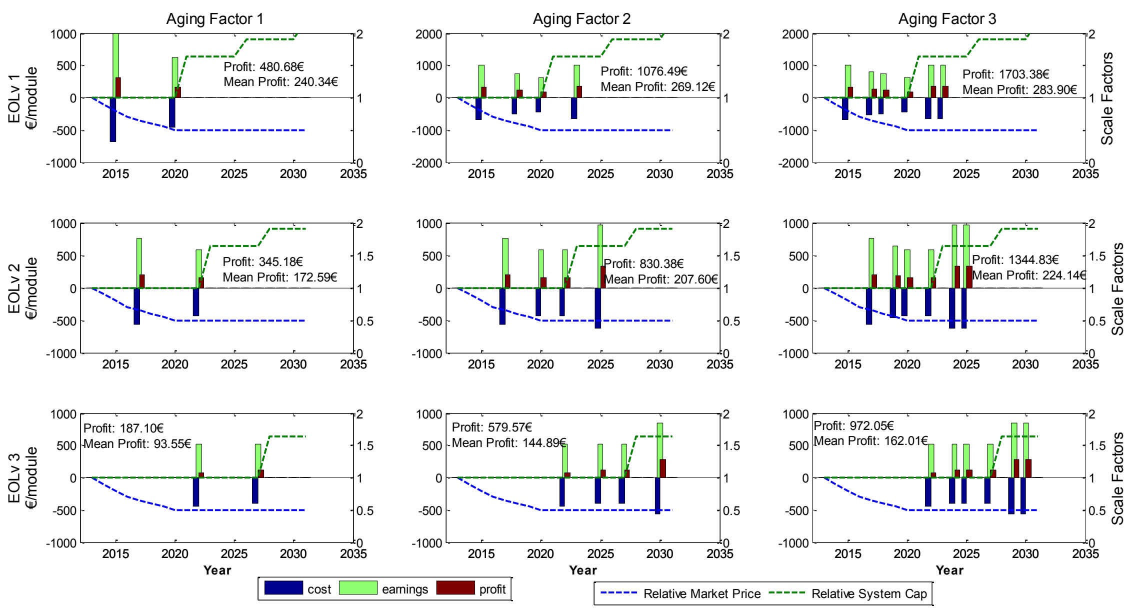


FIGURE 49: EFFECTS OF AGING FACTOR AND REPLACEMENT INTERVALS ON LIFETIME BATTERY SYSTEM COSTS

Figure 49 shows the costs and revenues associated with batteries needed for a given system for a combination of various battery return scenarios and aging rates. The initial system installation occurs the same year the batteries are available, and replacement batteries are taken from the year when the secondary system reaches its cycle life limit.

The results of Figure 49 can be useful in determining the most profitable sales concept for used batteries namely either:

1. Direct customer supply contract, in which a volume of batteries are guaranteed to be supplied at a given price on an agreed upon timeline. This type of contract can be made with either a system integrator or large end consumer such as a utility or energy supplier.
2. Warranty or service contract based on lifetime system cost. This type of contract can be made through the system integrator or directly with the end customer.

For a direct customer supply contract, if you take the scenario depicted in the top right corner of Figure 49 (Battery Return Scenario 1, Aging Rate Scenario 3) the conditions for the contract could be selling the modules over the entire system lifetime for 340€/module. Therefore modules sold for the second through fourth exchange are sold above the system cost, but modules sold at later exchanges are sold to the customer at a discount, relative to their usable capacity.

Warranty or performance based contracts generally mean a higher upfront cost of the system to the end user, which means higher initial revenues, but also potentially lower profit margins The feasibility of a warranty based sales concept or supply contract will depend on the developed market structure and rules, in addition to a cash flow analysis which incorporates the results of this study.

4.5 Using the Framework for Developing a Battery Second Use Strategy

This section outlined the requirements for a framework that would enable the evaluation of process and technical factors, and their contribution to the viability of a battery second life business strategy. From these requirements a framework for a tool was defined, and a base tool created in MATLAB. The functionality of this tool was then demonstrated through a series of three analyses.

The presented analyses showed the capabilities of the method to investigate interdependencies along the value chain and help guide the development of a battery second use strategy. This includes the analysis of multiple scenarios and the integration of temporal data representing changing market dynamics. Given the data to date battery second use shows a potential but must be investigated further.

Ultimately the power of the framework is dependent on the input data; the richer the data set the more powerful the framework. But at the same time, the modular structure allows for preliminary screening based on a limited set of information. The structure also allows the analysis to grow over time without having to adapt the overall methodology. This prevents contradictions to previous findings that can create confusion when communicating to management and key decision makers.

An OEM could use the framework in conjunction with their methods and tools from the vehicle development process in order to first assess the viability of a B2U strategy, similar to the analysis presented in Section 4.4.1. The OEM can then determine the strategic potential using analysis similar to those presented in Section 4.4.2. Then refine its strategy and account for changing market dynamics, similar to the analysis shown in Section 4.4.3.

Ultimately the best strategy for a given OEM will be one that aligns with its unique EV strategy while still meeting market side requirements. These requirements, as discussed in Section 3, include market price, supply volume, integration requirements, and business operational structures. Being as there is currently no B2U market, the rules and requirements for this market are yet to be defined. The following section will discuss factors that will influence the definition of these rules and requirements.

5 Role of the Proposed Framework in the Realization of a Second Use Market

Despite a high level of interest, there is currently no commercial secondary use market, and deployment of used EV batteries has been limited to a select number of pilot projects. This is understandable since the commercial EV market and stationary storage market have only started to approach maturity with respect to their product lifecycle in the last five years [20]. Nevertheless, there have been attempts to understand technical and operational requirements, and the potential benefits of a second use market. But, as discussed in Section 2, the results of these studies are isolated through the methods employed and difficult to extrapolate into actionable business strategy due to large amounts of uncertainty.

Due to these limitations, it is difficult to determine not only the potential societal value of a battery second use ecosystem, but more importantly the shared value between stakeholders. This shared value is integral to the long term competitiveness of the system, which is based on mutual positive economic and social benefits relative to costs [35]. Therefore identifying each shareholder's shared value will naturally drive the maturation of the market, by allowing the transfer of value through the process chain. The developed framework, presented in Section 4, has the capability of aiding not only stakeholders in identifying their individual value potential, but also in evaluating the ecosystem as a whole. Due to the framework's base in the fundamental process and technical requirements, it can adapt with the changing market and environmental conditions.

Currently the OEMs hold the key to the potential value of the market, and in the near term their identification of their potential value will be critical for the early development of

a battery second use market. But as both the vehicle and stationary battery markets evolve so will the roles of the stakeholders along the B2U value chain presented in Section 1. Therefore, it is critical for each party to understand their opportunities along the value chain. Just as the presented framework can be used to leverage the knowledge of the OEM for evaluation of opportunities, it can also help leverage the knowledge of the system integrator, battery repurposer, or any other stakeholder along the operational value chain.

The framework can also aid non-operational stakeholders. For example, the government and regulators can use the framework for collecting and analyzing data required for the development of a regulatory framework that promotes the development of long term societal benefits. In addition, the academic and research community can utilize the structure of the tool to promote collaboration, the development of a cohesive body of knowledge, and identify needs or benefits to society. In turn these activities would further motivate stakeholders along the value chain in the development and promotion of a battery second use market.

This section will discuss the roles of each party above to date, the evolution of their role moving forward, and the ability of the proposed framework to evolve with the changing market conditions and societal context.

5.1 The Continual Evolution of the Vehicle and Stationary Storage System Value Chain

The battery second use ecosystem is an evolutionary system, which means that the current state is dependent on previous states [121], [122]. The viability of the OEM, its battery second use strategy, and the ecosystem as a whole, depends on the co-evolution of each stakeholder over time. By definition, the battery second use ecosystem is an overlap

between the lithium battery, stationary storage, and electrified vehicle ecosystems. Therefore, the evolution of the second use ecosystem is highly coupled to the evolution of these three underlying ecosystems, including their present, past, and future states.

Currently, the stationary storage market, electric vehicle market and non-consumer lithium ion battery cell market, are all in their preliminary growth stage or just starting to reach maturity [123]. Due to growing uncertainties in both the electric vehicle market and battery production markets, individual firms have looked to diversify their roles in order to minimize their risk [109]. Therefore, firms have chosen to move either vertically along the value chain, or horizontally into other markets, or both (Figure 50).

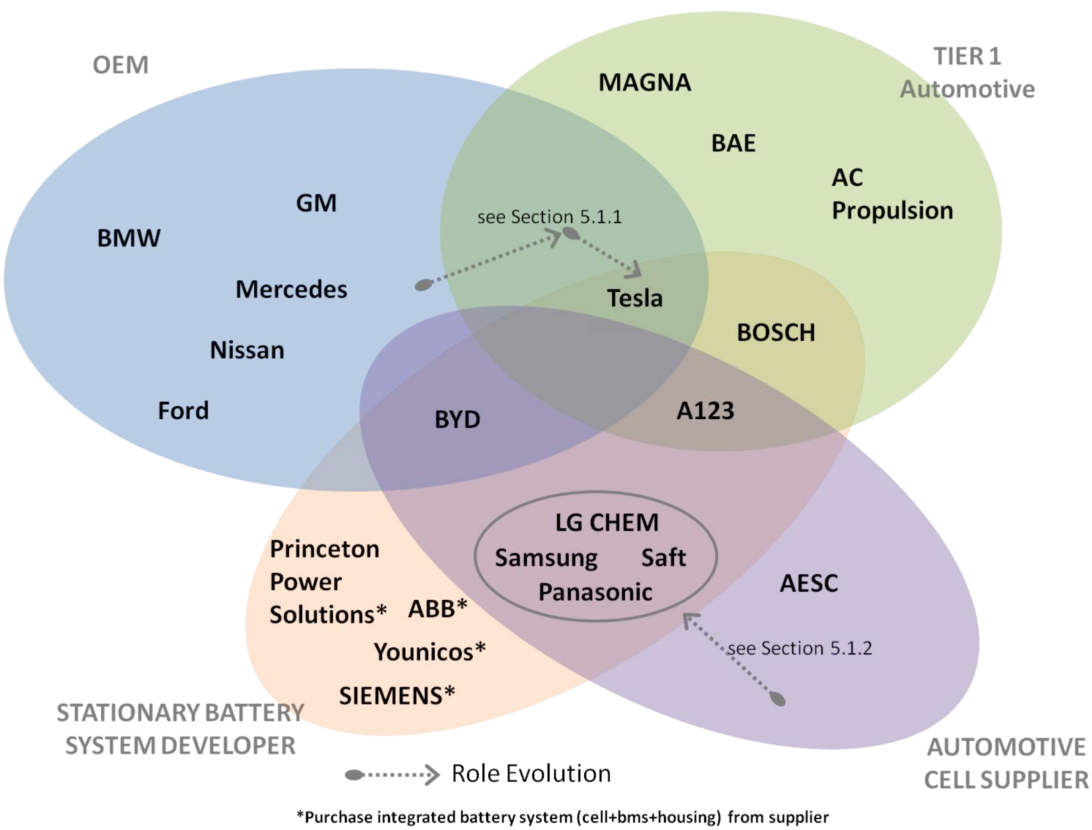


FIGURE 50: EXAMPLES OF ROLE EVOLUTION IN B2U ECOSYSTEM

This section will discuss the changing dynamics in the individual automotive and stationary battery markets, in addition to the interactions where these two markets overlap. Examples are given on how these markets might develop, and how the framework can be used for adopting each stakeholder's individual strategy during these transition phases.

5.1.1 Changing Dynamics in the Vehicle Value Chain

Roles within the vehicle value chain are governed by the amount of control the OEM wants to have in the electric drivetrain development process. The types of development strategies have been discussed in Section 3 and are summarized in Table 16. To date, the main concern of the OEM has been bringing the market a competitive, safe, electrical vehicle with an acceptable level of performance to the customer [85]. Each OEM has made strategic decisions on how to incorporate electrified drivetrains into their current business. The entirety of these decisions is the OEM's electrification or electric vehicle strategy, which includes the architecture of these vehicles and their drivetrains, the design of the battery system, and the battery value chain. This strategy varies broadly between OEMs, is by no means static, and will need to evolve as the electric vehicle market matures. This evolution will involve constantly re-evaluating the technological, market, and economic parameters involved with developing and deploying electrified vehicles.

At early stages of the electric vehicle commercialization, Tier 1 suppliers were critical in bringing EVs to market. Firms like AC Propulsion licensed their technology to OEMs such as Tesla and BMW, helping both companies to launch their own internal electric vehicle programs [124]. Vice versa, Tesla has grown to become the largest supplier of electric drivetrains for OEMs such as Toyota and Mercedes Benz [113].

Currently, the majority of OEMs see the battery system as a key element in the quality and performance of their vehicles. As such they want to gain further experience with the new technology and keep the majority of development related to the battery systems in house. Development is generally performed in close collaboration with the cell providers allowing both parties to learn about the new technology and application requirements.

As the OEMs become more comfortable with the technology, these roles will start to change. With better understanding of the system OEMs can begin to outsource to Tier 1 suppliers in order to save on development costs. As the OEMs start moving up the chain, there will be not only room for traditional Tier 1 suppliers, but also opportunities for cell providers to move up to start providing integrated systems (*i.e.* battery plus BMS) as shown in Figure 51.

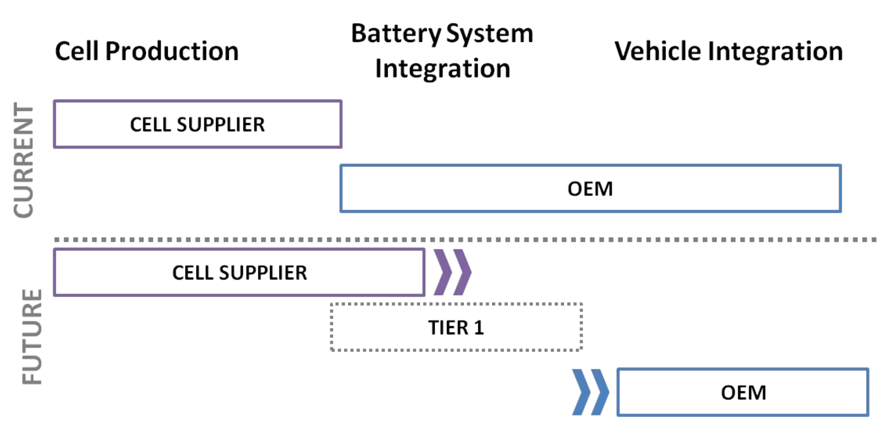


FIGURE 51: CHANGING ROLES ALONG VEHICLE SUPPLY CHAIN [109], [115]

When the OEMs reduce their involvement in the battery system development, they will also reduce their influence on factors effecting second use, and make opportunities for others along the B2U value chain. For example, if the cell suppliers move up the supply chain as battery integrators, they could use the opportunity to standardize product

offerings between stationary and vehicle storage systems. In this case, standardization could help reduce production costs for the cell supplier and could greatly decrease costs along the battery second use process chain. This could allow the cell supplier to gain early market entry into lower valued storage applications without artificially lowering their prices, or depending on government subsidies for economic viability. The structure of the ecosystem could then leverage the use of the OEM's infrastructure to manage the batteries during the vehicle life, and ensure adequate battery returns; and the cell manufacturer's sales network and knowledge for BMS development. OEMs could benefit from a stabilized residual value of the vehicle and the deferral of recycling costs. In such a scenario the framework could be used to determine both profit opportunities and appropriate transfer prices between OEM and cell manufacturer throughout the extended vehicle value chain.

The framework can also be used to evaluate the business case for a third party service provider, for which the market is currently relatively small. These companies provide specialized services such as HV battery service and repair, battery collection and disposal, and potentially battery refurbishment. An example of such a company is ATC New Technologies who offers lifecycle services for OEMs including service and warranty issues [69]. The potential for these types of stakeholders include localized economies of scale through repurposing of multiple types of battery packs. The efficiency of which will ultimately depend on the level of standardization within the second use market.

5.1.2 Changing Dynamics in the Stationary Market

Currently the stationary storage market is very inefficient and dominated by non-commercial systems burdened with high one-off, non reoccurring engineering costs [26].

This is due to the range in size and competency of system integrators in combination with low production volumes, market uncertainty and lack of standardization [20], [26].

Stationary storage providers are mostly technology providers who have moved vertically up the supply chain due to the lack of system integrators on the market offering turnkey storage solutions. For example, STEM created an energy storage system to compliment their advanced energy management algorithm, since their ability to optimize their customers' energy usage and decrease their overall energy consumption has significantly improved with the availability of storage systems. Other companies whose core business was in the sale of inverters, saw a significant market for their inverters for grid services, but couldn't sell into this market due to the lack of system integrators. Therefore, they started developing their own energy storage systems [125].

In the same respect many cell suppliers began developing integrated storage systems for the stationary market. In 2009, the American Recovery and Reinvestment Act's (ARRA) low interest loans helped battery manufacturers in the US to build up capacity necessary to reach economies of scale. Due to low demand from the automotive market at this time, battery manufacturers were forced to search for other sources of revenue in order to pay off their government loans. As a result, many cell manufacturers moved into the stationary storage market, which at the time was strongly supported by R&D funds from the Department of Energy. Due to the lack of structure in the developing stationary market, battery suppliers generally stepped up the supply chain into the role of the system integrator or Tier 1 system supplier [109].

In the near future the market is expected to change due to the development of new regulations, market mechanisms that help monetize the true value of storage, and state

mandated procurement targets such as those recently released by the California Public Utilities Commission [126]. These policies are expected to remove some of the uncertainty that has prevented the investment in storage in the past. This includes promoting not only the financing of projects from banks and private investors, but also the investment of energy storage system providers in the development of commercial turnkey solutions; rather than one-off systems that bear the financial burden of one-off, non-recurring, engineering costs [26]. The volume of deployment is also expected to drive industrial standardization, developing and optimizing industrial best practices and market rules, and in general push the market towards commercialization [127].

As the market stabilizes the framework can be used to evaluate and re-evaluate potential opportunities for battery second use (Figure 52). In addition to new business opportunities that can help stimulate and catalyze markets where systems with new batteries are too expensive or over designed for a given application.

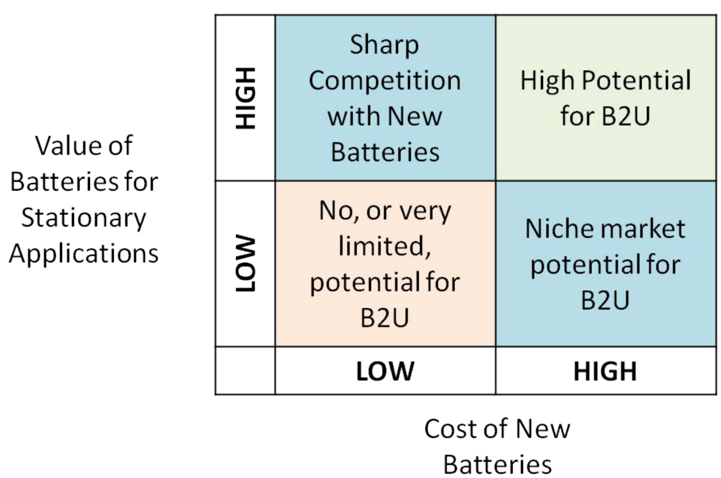


FIGURE 52: POTENTIAL FOR B2U BASED ON MARKET CONDITIONS

5.1.3 Dynamics of Overlap between the Stationary and Vehicle Markets

Although the separated development of both the stationary and vehicle markets is interesting for the development of a B2U market; the overlap of how the two industries influence one another is even more relevant. This section will discuss possible interaction factors, hypothetical strategic options for both vehicle OEM and cell suppliers, and how the framework can aid in evaluating these new market conditions.

A main concern for OEMs and cell suppliers is volume, especially with respects to its supply chain and the ability to make a price competitive product. For OEMs, the higher the volume of production the lower they can drive their supply chain costs and the more influence they can have over their suppliers.

Cell suppliers also need high volumes in order to generate sufficient revenue to offset the capital invest of the production facility. The production of affordable battery cells is highly dependent on process automation. Therefore, cell manufacturing is a very capital intensive industry which depends on high volume demand to be profitable [33]. If demand for batteries is not sufficient in one market or industry, battery manufacturers must search horizontally for new revenue sources [109].

Currently the OEMs have the advantage of an oligopolistic supply chain, placing them in a position of power due to their volume requirements [118]. But as the market develops and OEMs start to get comfortable with the technology, they might start to minimize production risk by diversifying their supply chain. This would decrease their dependence on a single cell supplier [33], [116], [118], and push battery cells into becoming a commodity product. In combination with the expected increase of battery demand for the

stationary storage market (Figure 53), it is possible that not every OEM will be able to bring a vehicle to market at a volume that would make it a prioritized customer to a cell supplier.

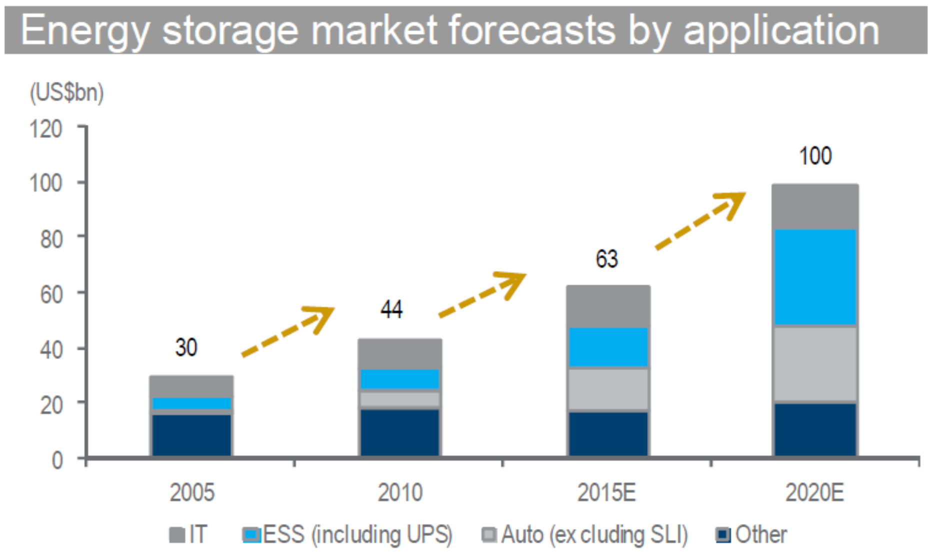


FIGURE 53: MARKET PROJECTIONS FOR ENERGY STORAGE BY APPLICATION [128]

This would make it difficult for the OEM to negotiate prices and push requirements back onto the cell supplier. In this case, an OEM might select one of the following three strategic options shown in Table 35:

TABLE 35: EXAMPLES OF POTENTIAL BATTERY CELL PURCHASING STRATEGIES

OEM Strategy 1: OEM can buy at a higher volume from a single cell supplier, utilize their knowledge about battery systems to develop stationary/other mobile storage systems or other mobile storage systems, and sell these as products to the market.

Potentials	Risk	Example	Implication Second Use
• lower per unit cell price • additional revenues from battery system sales	• Ability to sell and support the battery systems, including market demand, product competitiveness. • Additional operational costs which might off-set the initial benefits.	Tesla who develops vehicle battery systems for other OEMs and stationary systems for Solar City and their own Supercharger Stations [120].	Infrastructure for the sale of new battery systems could also be used to support second use.

OEM Strategy 2: OEMs collaborating on a joint development agreement through which a joint purchasing agreement can be made

Potentials	Risk	Example	Implication Second Use
• split development costs • Combined production volume enough to realize scale effects along the supply chain.	• Agreements between parties on development targets and goals that satisfy both parties' needs. • Historically such agreements don't last more than a few development cycles [115].	Joint Venture between BMW and PSA.	Allow for collaboration in a battery second use strategy.

OEM Strategy 3: OEM joint purchase agreement with a stationary storage system provider, which could then involve joint development of the low level battery management system, and potentially a joint recycling contract.

Potentials	Risk	Example	Implication Second Use
• lower cell cost • split development costs • shared cell testing • potentially lower recycling costs	• Agreement between parties on development targets and goals that satisfy both parties' needs.	None to date with OEM. Tier 1 suppliers such as A123	Joint development of a system compatible with both used and new batteries.

In the future if each market proves to have sufficient volume, and understanding about the intricacies of the electrochemical properties of the cell have improved, battery manufacturers might start to diversify their product offering in order to meet the specific needs of each market. This can already be seen in the difference between cells for Hybrid EVs (HEV) and pure Battery EVs (BEV). HEV cells generally have lower capacity, thinner electrodes, and higher power capabilities than BEV cells.

In a hypothetical case, cells for EVs might tend toward smaller format cells to allow more flexible packaging options in the vehicle, a higher tolerance to temperature, and aging characteristics that maintain a low rate of aging for the first 8-10 years before the cell stops functioning all together. On the other hand, a stationary cell might have a larger format, a lower tolerance to temperature, symmetrical charge and discharge capabilities, and a lifetime of 15-20 years. In this case, the aging properties would make battery second use pointless. Indication of the stratification between stationary and vehicle storage systems can be seen in current research and development targets [129].

Such transitions in market dynamics are inevitable, but given the established framework the strategy of the OEM and other stakeholders can be continuously re-evaluated and adjusted to align with the changing market conditions. Battery second use might be a transitory opportunity that can help the stationary and vehicle markets reach maturity; but is a transition that can offer opportunities to all members along the value chain. The developed framework can not only be used to evaluate these opportunities, but also these opportunities as a function of time.

5.2 POTENTIALS FOR BATTERY SECOND USE STANDARDIZATION

The role of standards in the automotive industry is to ensure the safety, quality and effectiveness of products and services [130]. Standardization allows for the interoperability between products which can help build the market, establishing transparent value and thereby reducing risk; and is instrumental in accelerating the adoption rate of a new technology, reducing the amount of one time engineering development needed for new products, and facilitating high volume production, [131].

If implemented correctly, standardization can accomplish two major benefits for battery second use:

1. Decrease costs across the combined value chain
2. Allow for an open battery market for used batteries, eliminating the need for limiting business to business (B2B) relationships along the value chain

Standards have the potential to promote an open battery market would liberate the battery second use ecosystem from constraints of structured B2B relations. Consequently, without standardization there will be multiple battery second use ecosystems each with their unique set and structure of stakeholders. A GM battery second use ecosystem would have different participants than a battery second use ecosystem for Ford or BMW. Each ecosystem will be optimized for that specific battery pack and technology; but a global optimization with access to large economies of scale would not be possible.

Benefits of an open market include scale effects on repurposing procedures, lower costs for standardized components, and new business opportunities for third party service providers. On the downside, an open market will drive profit margins down, making the

battery system an industrialized commodity product. The final product would be valued on performance capabilities rather than on brand name. But free market mechanisms will drive the ecosystem towards its most efficient point which will be necessary to keep used batteries competitive with new batteries and other energy storage systems.

Based on the functional breakdown presented in Chapter 3, the minimal requirements for standardization that would enable an open market are shown in (Table 36).

TABLE 36: BASE STANDARDIZATION REQUIREMENTS FOR OPEN B2U MARKET

Requirement	Description
Standardized communication interfaces	The base unit is able to communicate system data, and receive system commands using a standardized communication protocol at a standardized data rate.
Standardized control architecture	Alignment of stationary and vehicle systems with regards to information flow, location of functionality (*i.e.* SOC estimation).
Standard voltage intervals	Base units are configured so that their voltage is a multiple of a standardized voltage interval (*e.g.* 12V, 24V, 36V…). This will allow for system scalability to match all sizes of power control systems.

Looking at the other relevant B2U parameters described in Section 1.2, further levels of standardization that might prove beneficial can be identified. This includes requiring base units to contain all cell relevant data and parameters including SOC v VOC characteristics, SOC, and the SOH [46]. Having this information readily available can reduce the amount of testing and re-engineering needed per battery system. Physical properties of the base module could also be standardized including standardizing the physical size, or potential size intervals, and electrical and communication interface location. And finally, the

components within the vehicle could be required to meet the safety and electrical standards of secondary systems.

Standards that impact the physical integration, cost, and reliability of the battery system in the vehicle be more difficult to implement. But less resistance to the standard can be expected if the OEMs could see a quantifiable benefit for them when implemented.

The most effective implementation of standards would require an agreement between both the automotive and stationary storage industries. This requires collaboration between industry's standardization bodies predominantly the SAE and IEEE, but possibly also UL for North America, and CE for the European Union.

The developed framework can be utilized to analyze the economic and technical tradeoffs of various levels of standardization. Once the most beneficial level of standardization is identified, the framework can be utilized to communicate and facilitate the development of the most appropriate suite of standards between the various standardization bodies.

5.3 Development of Policy for Battery Second Use

The role of policy is to access potential societal and economic benefits and issue a political framework that enables economic markets to harvest those benefits. According to [132] the four main reasons for issuing policy are:

- Capture positive and negative externalities
- Represent public good
- Imperfect competition
- Incomplete or asymmetric information

To date, policy has been instrumental in the development of both the energy storage and electric vehicle market. In both cases, policy has been used to drive market maturity by encouraging investment, R&D, and market demand. On the supply side this pushes the development of economically competitive systems on a commercial scale, including manufacturing capability, industrial standards and best practices, and technological innovation. On the demand side policy has helped encourage wide spread adoption, which facilitates the development of infrastructure and making these technologies economically sustainable in the future. More information about influential policy in both the automotive and stationary battery markets can be found in Section 8.1.5 and Section 8.2.4 respectively.

Currently it is too early for battery second use specific regulation and policy, as not enough is known about the market dynamics and requirements. Good regulation requires a well defined regulatory objective [114]; therefore a preliminary step would be to validate the assumption that battery second use would provide an overall benefit to economy and

society. This can be accomplished through pilot projects and close collaboration with the OEMs and other stakeholders.

The objective of such a preliminary study would be threefold:

1. Benchmark current situation, quantify potential benefits, and identify key contributing factors.
2. Develop an ideal best case scenario and quantify benefits.
3. Identify barriers to transforming between (1) and (2) and determine if regulatory intervention is necessary.

Benefits in (1) and (2) should include economic, social, and environmental impacts. Factors to be considered in the best case scenario should include reasonable technology capabilities and costs at economies of scale. If the benefits quantified in (2) are deemed unsubstantial, then the intense regulatory intervention should not be perused.

The proposed framework can be used to structure collaboration, collect and analyze data, and prioritize research directions. Preliminary results from the analyses presented in Section 4.3 have also already indicated that, within the current state of knowledge, the key contributing factors will be battery technology and market battery price. This can be used as a starting point, with further analyses focused on performance characteristics of used batteries compared to new batteries.

Apart from the assessment of the need for regulatory intervention, an assessment of current regulation and policy in light of B2U is also required. Mainly, an evaluation of current policy that could potentially undermine the development of a B2U market is necessary. For example the USABC goals that drive development targets for battery

technology, only consider life in vehicle; could be re-evaluated with B2U in mind. In addition, current transportation regulations and the classification of used batteries as hazardous waste or hazardous material should be addressed; as this will significantly affect the processing costs of getting the battery from the vehicle to the stationary application [42], [43].

5.4 Continuous Need for the Research Community and Academia

The role of academia and the research community has been instrumental in the development and maturation of the electric vehicle and grid energy storage markets. Contributions range from identifying the fundamental need for these technologies and their contribution to society; the development of the enabling technologies and methods; the assessment of regulation effectiveness; and identification of deficiencies or needs on a market, societal, or economic level.

To date, the roles of academia and the research community have identified potentials for battery second use, but the results are scattered and non-cohesive. As a result, the research impact is minimal. This is due to (1) the lack of available industry relevant data, (2) the use of methods that isolate the results and therefore potential impact of the study, and (3) the ability to effectively isolate constituent parts of the problem. The first problem can be resolved by a higher level of OEM and supplier cooperation, which would be a potential bi-product of OEMs recognition of the benefits of B2U. The framework proposed in this thesis could then help remediate the second and third problems as it can create a common platform for collaboration and defining the context of constituent research questions.

Moving forward, researchers should work to provide the information for policy development; technological and methodological solutions for problems that arise along the value chain; and evaluation of policy effectiveness. The framework can be used to coordinate this effort, and establish boundary conditions that would enable individual studies to present their findings within the context of the overall value chain.

5.5 Collaboration Needs for Formation of B2U Market

If B2U is to be viable in the future, collaboration to identify the shared value potential between stakeholders could become critical in the next 3-5 years, as the structure of both markets begin to solidify. If battery second use is not considered during this window of opportunity, there is a chance that the vehicle and stationary energy storage market will settle around individual local optimizations. This will inhibit the potential to move towards a societal global optimal without significant market intervention.

Parties involved in this collaboration should be comprised of all stakeholders along the value chain including OEMs, battery suppliers, stationary storage system providers, end users, regulatory bodies, third party researchers and academia. An efficient and effective collaboration will depend on the ability to capture each party's knowledge, objectives, and incites and integrate this information to create a higher level of understanding. This is difficult due to each party's varying level of understanding and involvement in the constituent parts.

The purpose of the framework developed in this thesis is to provide a common platform to evaluate the impacts along the combined value chain for a battery second use strategy. This framework enables the collaboration, conversation, and the communication of

issues between parties and the identification of needs to develop a battery second use market. The structure of the framework allows each player to bring their piece of the puzzle to the table, and set their knowledge into the greater context of the overall value chain. The definition of communized interfaces along the value chain then allows for players to build off others' contributions and generate overarching knowledge and understanding. Therefore, by providing a structure for both the value chain and boundary conditions between the links in the chain, individual contributions can be integrated into a coherent body of knowledge.

6 CONCLUSIONS

The viability of B2U is uncertain and the conclusions about the value of such a market speculative. But as shown in this thesis, there are a wide range of opportunities available. The value of B2U is no longer the re-use of battery cells to reduce the initial price of the vehicle, as indicated in previous works. The potential for B2U is the maximization of the EV's battery system over its lifetime, which can provide both economic and environmental benefits to the members of the battery second use ecosystem.

Unlike the previous research presented in Section 2, this work focuses on the method rather than on the data. The method was developed by first analyzing the technical and process requirements along the value chain as discussed in Section 3. The resulting framework was then built from the understanding of the transfer of factors through the second life value chain; as opposed to being formulated around the type of information currently available. This allows the incorporation of information as it becomes available; enabling a high level screening to transition into a data rich analysis that will be instrumental in understanding the full range of opportunities for battery second use. The structure of the framework also allows individual contributions to be placed in the context of the entire value chain. This not only helps to better understand the value of the contribution with respect to the entire picture, but also allows for the interconnection between studies and the generation of higher level knowledge. A capability that was previously not possible due to constraining boundary conditions and methods.

The main motivation for the development of the framework was to enable an OEM to incorporate technical and process parameters into their evaluation and development of a B2U strategy. Since the OEMs are at the beginning of the value chain their decisions will

dictate the potentials of a B2U value chain. Section 4 presented the framework and showed examples of how OEMs could use the framework to assess B2U opportunities and develop a strategy that best complements their specific EV strategy.

The framework can also be used to structure collaboration between stakeholders in the development and future evolution of a battery second use market. As discussed in Section 5, these types of collaborations will be critical in the next 3-5 years as both the automotive and stationary market start to solidify. Within this time it will be critical to determine the potential social, environmental, and economic impacts; and technical and operational constraints in order to realize the potential of battery second use.

7 APPENDIX: TECHNICAL BACKGROUND INFORMATION ABOUT BATTERY SYSTEMS

This section provides supplementary background information about lithium ion batteries, electric vehicles, and stationary storage systems.

7.1 LITHIUM ION BATTERY TECHNOLOGY

A battery is an electrochemical storage device that is capable of converting chemically stored energy into electricity through oxidation-reduction reactions at the electrodes. Although there are many chemical compositions of batteries the discussion here will be limited to lithium ion based chemistries (LIBs) due to their prevalence in automotive and stationary applications. Li-ion cells are the technology of choice for automotive applications due to their relatively high power and energy densities, good cycle characteristics, and relatively long lifetime [8], [13]. For stationary storage LIBs are favorable for their high round trip efficiency, lack of memory effect, and relatively long cycle life [23]. Disadvantages of LIBs include sensitivity to temperature, damage at high and low levels of SOC, and safety if cells are not properly monitored [34], [89], [106], [133].

It should be noted that the term “lithium ion batteries” refers to a family of batteries characterized by the intercalation mechanism by which lithium ions are shuffled between electrodes (Figure 54).

The cathode half-reaction is :

$$\mathrm{LiMO_2} \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} \mathrm{Li}_{1-x}\mathrm{MO_2} + x\mathrm{Li^+} + \mathrm{xe}$$

The anode half-reaction is : $n\mathrm{C} + x\mathrm{Li^+} + \mathrm{xe} \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} \mathrm{Li}_x\mathrm{C}_n$

Full cell reaction is : $\mathrm{LiMO_2} + n\mathrm{C} \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} \mathrm{Li}_{1-x}\mathrm{MO_2} + \mathrm{Li}_x\mathrm{C}_n$

Figure 54: Generic Intercalation Reaction for Li-ion Battery where M is dependent on the cathode material and N is dependent on the anode material [134].

LIBs include a wide range of battery chemistries with very different properties. This is represented in the equation above where M is a transition metal oxide ($e.g. CoO_2, FePO_2, MnO_2, NiCoMnO_2$) and N represents different anode materials [134]. Nominal characteristics of the most common lithium based cell technologies can be found in Figure 55.

Cell Chemistry Name	Formula	Main Application	Cell Level Energy Density (Wh/kg)	Durability Cycle Life (100% DoD)	Price $ / kWh (Cell Level)	Power C-Rate	Safety Thermal Runaway Onset	Potential (Voltage)	Operating Temperature Range
Lithium Cobalt Oxide	$LiCoO_2$	Consumer Electronics	170-185	500	310-460	1C	170°C	3.6	-20 to 60°C
Lithium Iron Phosphate	$LiFePO_2$	HEV	80-108	>1,000	800-1,200	30C cont. 50C pulse	270°C	3.2	-20 to 60°C
Lithium Iron Phosphate	$LiFePO_2$	EV/PHEV	90-125	2,000	300-600	5C cont. 10C pulse	270°C	3.2	-20 to 60°C
Lithium Manganese Oxide Spinel	$LiMn_2O_2$	EV/PHEV	90-110	>1,000	450-550	3-5C cont.	255°C	3.8	-20 to 50°C
Lithium (NCM) – Nickel Cobalt Manganese	$LiNi_xCo_yMn_zO_2$	HEV	150	1,500	500-580	20C cont. 40C pulse	215°C	3.7	-20 to 60°C
Lithium (NCM) – Nickel Cobalt Manganese	$LiNi_xCo_yMn_zO_2$	EV/PHEV	155-190	1,500	500-580	1C cont. 5C pulse	215°C	3.7	-20 to 60°C
Lithium Titanate Oxide	$Li_4Ti_5O_{12}$	HEV/PHEV	65-100	12,000	1,000-1,700	10C cont. 20C pulse	Not suspectible	2.5	-50 to 75°C

Notes:

DoD	Depth of Discharge
HEV	Hybrid Electric Vehicle
PHEV	Plug-In Hybrid
EV	(Battery) Electric Vehicle

Source: Axeon and Bernstein research.

Figure 55: Common Lithium Battery Chemistries [135]

LIBs are comprised of an anode, cathode, electrolyte, and separator. The type, quality and methods of manufacturing of cell materials will dictate the cost, performance, and

consistency between cells [136]. Aside from performance characteristics, two important attributes on the cell level are safety and aging characteristics.

7.1.1 *Lithium Ion Battery Safety*

Battery safety is a larger concern with LIBs than other battery energy storage technologies. This is due to the higher energy content, and therefore larger potential to release heat, in addition to the flammability of the electrolyte. The main safety concern with LIBs is the induction of an exothermic series of events known as thermal run away [32], [34], [106].

Thermal run away occurs when the cell's internal temperature rises past the operating point of separator (approx 180°C). At this point the separator fails creating an internal short circuit. This results in the direct oxidation/reduction of the electrodes, which creates more heat and further increasing the temperature and pressure within the cell. Eventually the electrolyte begins to decompose, releasing even more heat. These reactions will cause the internal pressure of the cell to increase until the cell bursts, exposing the hot electrolyte, which will ignite when it is exposed to air. This is particularly dangerous when cells are in close proximity to one another as the temperature due to one cell in runaway can induce thermal run away in adjacent cells. The temperature at which thermal runaway is induced is highly dependent on the chemical composition of the cell [81], [106]

Even though a thermal run away event has a low probability of occurrence, the level of risk is high. Cells are therefore designed to have passive safety devices such as positive temperature coefficient (PTC) devices that limit the current through the cell in the case of an external short circuit, pressure vents to prevent extreme internal pressure build up, and mechanical reinforcements to increase the rigidity of the cell [89], [106], [136].

7.1.2 *Battery Aging*

Battery aging is a complex process that is not completely understood [133], [137], [138]. Battery aging has two components: (1) calendaric aging which is dependent on time, SOC, and temperature and (2) cyclic aging which is dependent on temperature, (dis)charge rates, and DOD. Effects of aging are the probability of cell failure; and cell degradation, which results in decreased cell capacity and/or increased internal resistance. Main mechanisms responsible for cell degradation are the loss of active material due to chemical reactions between the electrodes and the electrolyte (formation of the SEI layer); loss of contact between the electrode's active material and the collector plate; and the mechanical degradation of the active material due to the (de)intercalation of the lithium-ions. These mechanisms are almost impossible to observe independently since the rate of each mechanism is interdependent and are simultaneously influenced by numerous factors such as C-rates, temperature, localized voltage, concentration gradients, and chemical composition. Therefore battery aging will be different for each cell chemistry and every use type [34], [133], [134], [139].

7.1.3 *Battery Recycling*

There are some fundamental challenges with the recycling of lithium ion batteries (LIBs). The biggest challenges are the economics of battery recycling. Currently it is not economically favorable to recycle Li-ion batteries as there is not sufficient value in the material components and the processing is complex. Lithium batteries, despite their name contain only about 2-7% lithium by weight and are approximately five times more expensive to recycle than sourcing new material [140]. It has been suggested that lithium is a limited resource which will drive prices up in the future potentially warranting battery recycling [141]. But other sources suggest that lithium is an abundant resource, and there

are sufficient global supplies[142], [143]. The only material that makes recycling financially viable is cobalt in the anode material. However, due to safety issues and in order to reduce manufacturing costs, the use of cobalt based chemistries are gradually being replaced with chemistries using cheaper, more chemically stable, base materials [34], [109], [144], [145].

Therefore significant government regulation will be necessary in order to establish viable LIB recycling infrastructure. Current legislation in effect includes the EU's End of Life Vehicle, which sets requirements for OEMs to recover, recycle, and reuse of vehicles and their components[146]. The EU also passed a directive in 2006 (Directive 2006/66/EC) specifying targets and requirements for the collection and recycling of batteries and accumulators [147]. The directive states that the 'producer' or entity that first places the battery into a product on that market is responsible for ensuring that the battery is collected and recycled. Targets for reclamation are expected to be >80% and recycling efficiency >50%, but ultimate targets are set by the member states. The producer is also responsible for financing any net costs due to the collection, transportation, and recycling of the battery [148]. In the US only the California and New York have legislation regarding the recycling of LIBs [33].

7.2 Advantage of Li-ion over other technologies

The choice of storage technology for a given application is dependent on the requirements of the application and properties of the storage technology. Application requirements include power output, duration of discharge, cycle frequency, and installation requirements. Storage properties include cycle and calendar life, round trip efficiency, operational limitations (e.g. P/E ratios, ramp rate, DOD) and power/energy density.

For stationary systems, due to the vast range of application requirements and storage characteristics, many storage technologies are not in direct competition with one another [23]. Battery or chemical based storage systems offer high energy density, scalability, relative ease of deployment, high round trip efficiency and a fast ramp rate, but are relatively expensive on a per kWh bases when compared to bulk energy storage technologies such as compressed air storage and pumped hydro. For these reasons batteries, specifically li-ion batteries, will almost never be used for the same application as these bulk energy storage technologies [11].

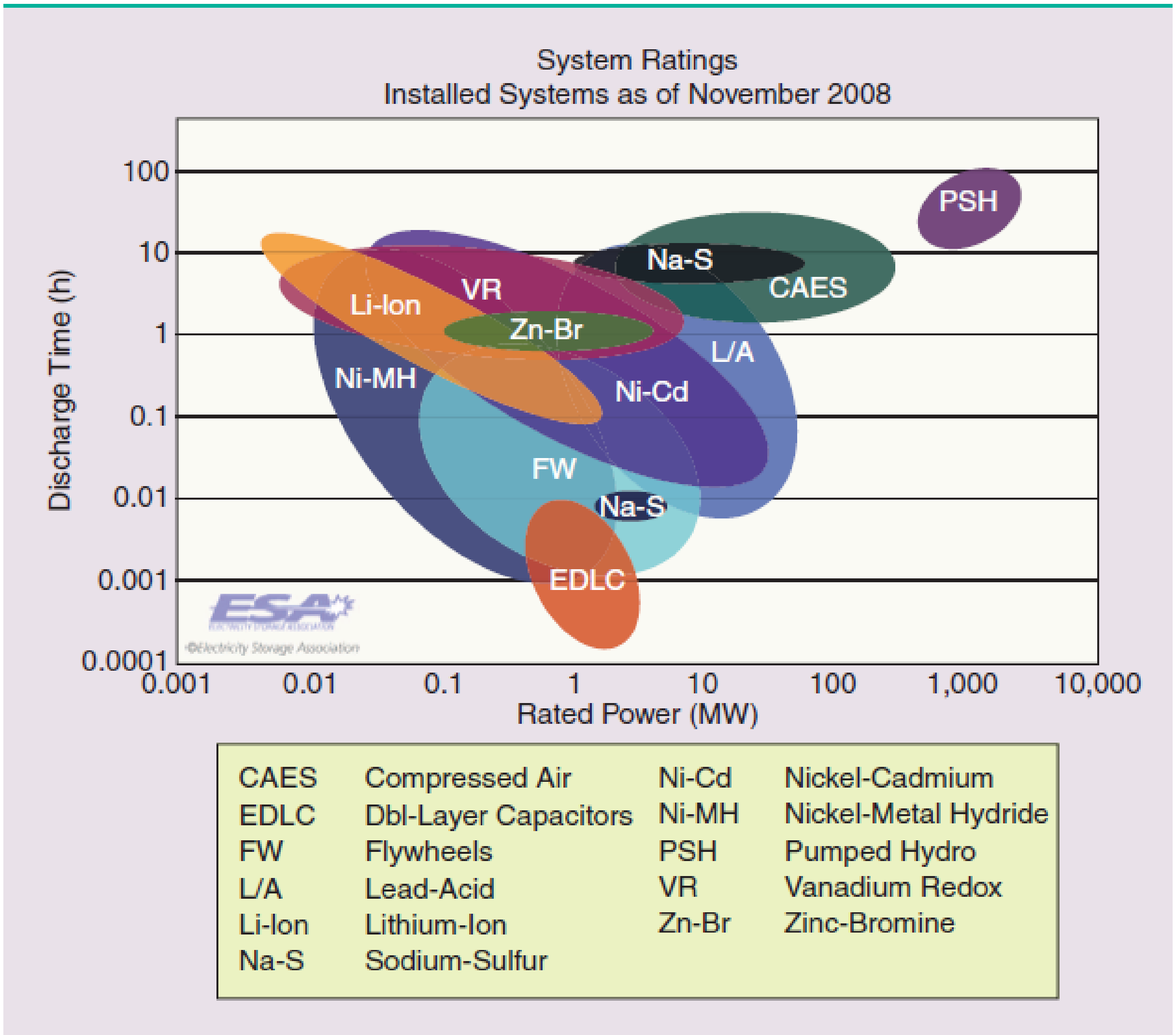


FIGURE 56: STORAGE TECHNOLOGIES CURRENTLY AVAILABLE ON THE MARKET [149]

Li-ion based batteries have a higher energy density, have a higher DOD, and better cycling characteristics than other battery chemistries. But they are also more expensive on a per kWh basis and have inherent safety issues that necessitate integrated monitoring equipment into the storage system to ensure cells are within a safe operating range.

7.3 THE CONTINUOUS TECHNICAL IMPROVEMENTS AND MARKET DEVELOPMENTS FOR LI-ION BATTERIES.

Li-ion based batteries are still considered a relatively new technology, and significant performance improvements and cost reductions are expected over the next 15 years[150].

7.3.1 BATTERY CHEMISTRY

In the next 1-3 years the market will still be dominated by NMC, NCA, and LFP based cathodes. It is predicted that specific capacity improvement of up to 20% will be possible for NMC and NCA based chemistries through refinement of the chemistry, use of nano-coating, and use of new safety devices. This will allow cells to operate with higher voltage range that is currently not possible due to electrolyte decomposition issues. This will be accompanied by a slight drop in overall cell costs due to scales of economy, manufacturing process improvements, and optimization of raw material use [13], [109], [144], [151], [152].

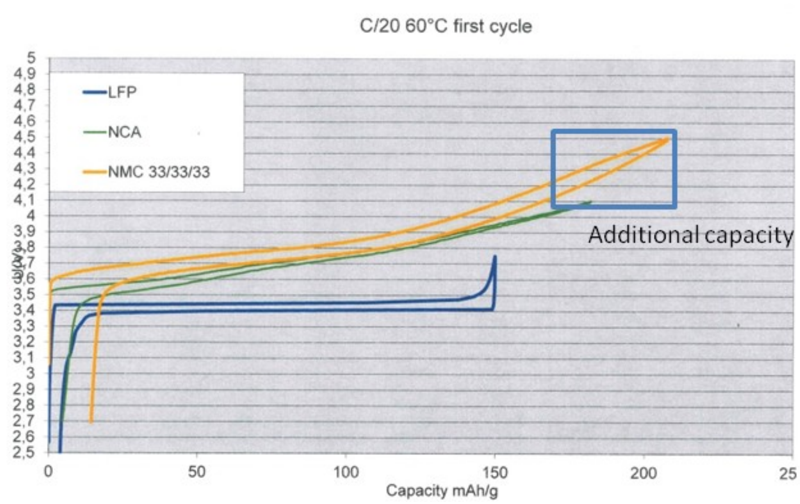


FIGURE 57: OPPORTUNITY TO INCREASE ENERGY DENSITY OF NMC LI-ION CHEMISTRIES [152].

Improvements in the next 3-6 years will involve the use of Li- Sn or Li-S which have a higher specific capacity than the carbon based compounds used today. These materials are currently being developed in laboratories but suffer from cycling and chemical stability issues[144], [153]. This will be accompanied by further improvements in NMC rich, or highly lithiated NMC cathodes and improvements in electrolyte stability to allow operation of even higher voltages.

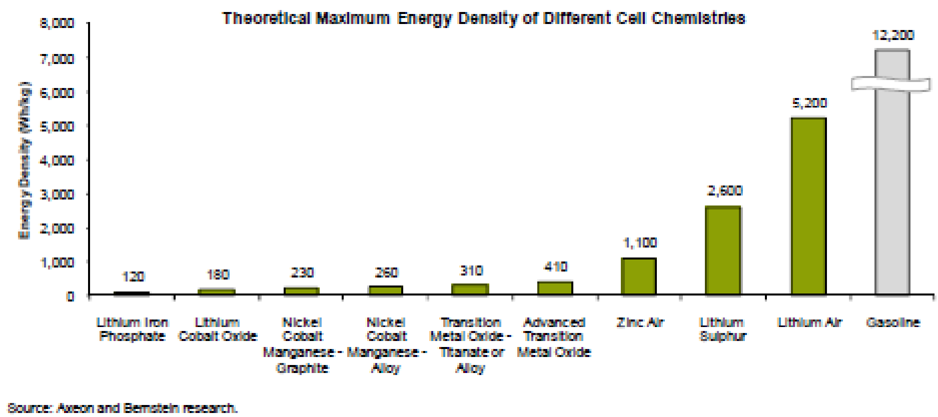


FIGURE 58: COMPARISON OF THEORETICAL ENERGY DENSITIES FOR CURRENT AND FUTURE LI-ION BATTERY CHEMISTRIES [135]

Long term battery chemistries include lithium metal and lithium air. Although these chemistries promise significant improvements in specific capacity (>800Wh/kg versus the 180Wh/kg of current technology), they face significant development challenges and will most likely not become commercialized until after 2030 [144].

7.3.2 Battery System Costs

Currently the cost of Li-ion batteries are too expensive for both stationary and vehicle applications. Cells are approximately $400/kWh while the price of an EV vehicle system is approximately $800/kWh, while a stationary system is estimated to be about $1000/kWh [154]. Currently the majority of system cost comes from the cells where cell costs are driven mainly from cell materials and manufacturing yields [155].

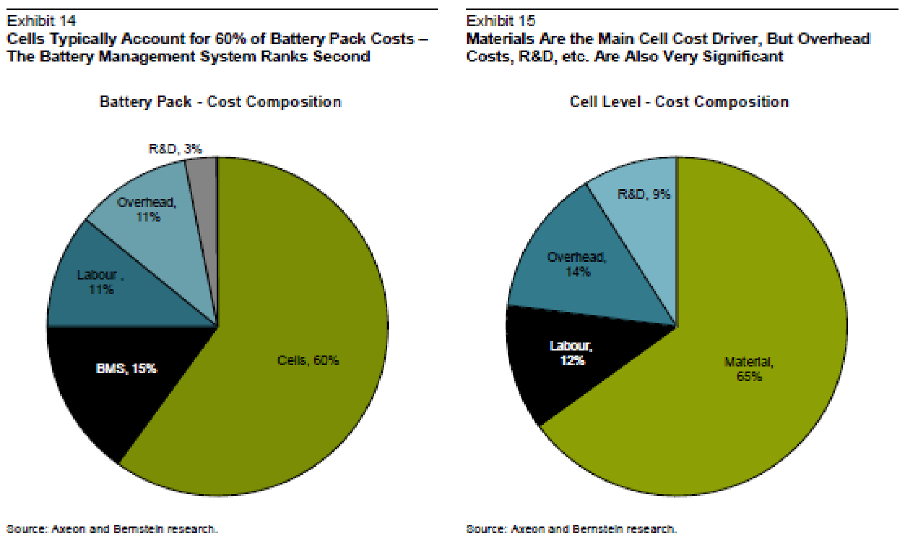


Figure 59: Cost Breakdown for Vehicle Battery Pack and Cells [135]

It is predicted that there is a potential to decrease cell costs by 40-50% by 2025 through improvements in manufacturing, economies of scale and refinements in chemistry in the short to medium term (Figure 60) [67].

Cell Costs	Type of Costs	%	Reduction Potential	Levers	%
	Cell-manufacturing	40 %	High	→ Machine and equipment optimization (learning effects, reduction of variants on single line) → Capacity utilization	17 %
	Cell components	50 %	Medium	→ Shift to better processing techniques / learning effects for new materials processing → Increasing purchasing volumes	25 %
	Raw Materials	10 %	Low	→ Shift to lower-cost primary materials → Increasing purchasing volumes → Intelligent recycling concepts (from Li-Ion-cells and packs after EOL)	8 %

FIGURE 60: POTENTIAL VEHICLE BATTERY PACK COST REDUCTIONS [67]

Additional cost improvements are expected on the pack level driven by short term improvements in BMS design by 2015, and optimized pack assembly due to economies of scale between 2015 and 2025 (Figure 61). These improvements will result in a reduction 50-60% in system level costs[135].

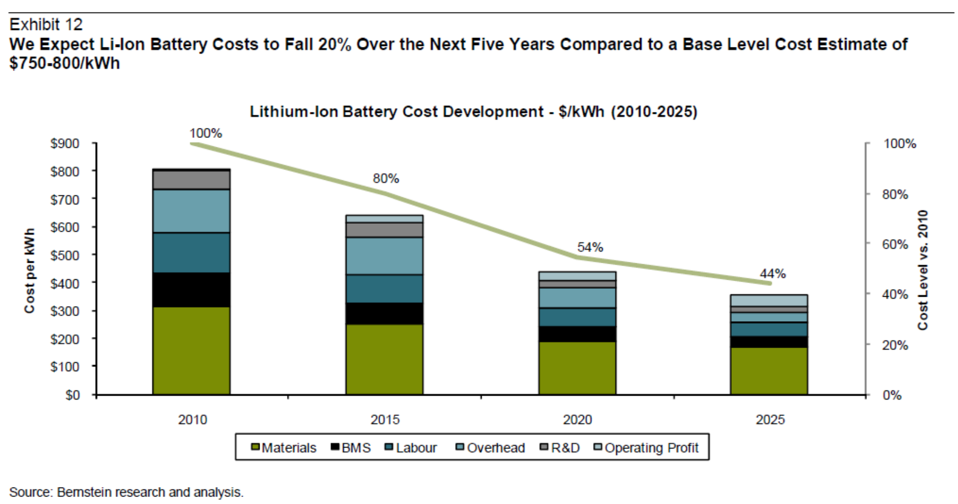


FIGURE 61: PROJECTED COST REDUCTIONS FOR VEHICLE LI-ION BATTERY ENERGY STORAGE SYSTEMS [135]

8 Appendix: Background Information About Battery System Applications

8.1 Developing Batteries for Electric Vehicles

Vehicles are extremely complex systems that must meet an ever increasing number of consumer and regulatory requirements [76], [77].

In order to integrate all of these needs and requirements into one complete package, automotive OEMs have created an integrated vehicle development process that can take from 3-7 years from initial concept to start of production. It is a core competency of an OEM to be able to adequately manage this process [77]. For the last 150 years this process (including tools, metrics, and methods) has been developed and optimized for the production of internal combustion engine (ICE) vehicles [156]. Current expectation is that electric vehicles can be produced with in this same framework, within a comparable timeline, and meet the same standards of traditional vehicles. This poses significant problems along the entire value chain for core systems such as the battery which are reliant on relatively new technology [81].

Some examples of how this drastic change in core competence effects the vehicle lifecycle can be seen in Figure 62.

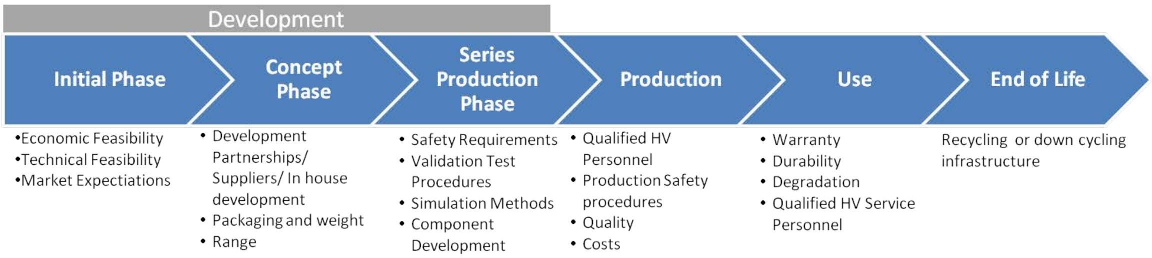


FIGURE 62: CHALLENGES DURING THE LIFE-CYCLE OF AN EV RELATIVE TO A TRADITIONALLY POWERED VEHICLE, LIST IS NON-COMPREHENSIVE [67], [81], [157]

In order to ensure the battery system can meet vehicle requirements numerous vehicle and system level tests are preformed throughout the development cycle. Examples of such tests can be seen in Figure 63.

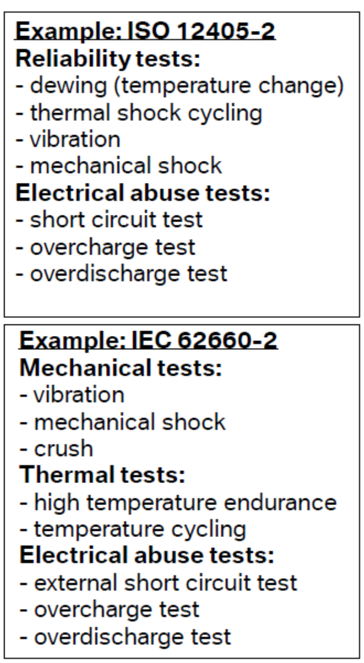


Table 2. EUCAR Hazard Levels and Descriptions

Hazard Level	Description	Classification Criteria & Effect
0	No effect	No effect. No loss of functionality.
1	Passive protection activated	No defect; no leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell reversibly damaged. Repair of protection device needed.
2	Defect/Damage	No leakage; no venting, fire, or flame; no rupture; no explosion; no exothermic reaction or thermal runaway. Cell irreversibly damaged. Repair needed.
3	Leakage Δ mass < 50%	No venting, fire, or flame*; no rupture; no explosion. Weight loss <50% of electrolyte weight (electrolyte = solvent + salt).
4	Venting Δ mass ≥ 50%	No fire or flame*; no rupture; no explosion. Weight loss ≥50% of electrolyte weight (electrolyte = solvent + salt).
5	Fire or Flame	No rupture; no explosion (*i.e.*, no flying parts).
6	Rupture	No explosion, but flying parts of the active mass.
7	Explosion	Explosion (*i.e.*, disintegration of the cell).

FIGURE 63: EXAMPLE OF SYSTEM LEVEL TESTS FOR AN EV BATTERY SYSTEM [81]

8.1.1 *DEVELOPMENT CHALLENGES*

Model and simulation driven development has become a key enabler for the reduction of vehicle development time and cost. These tools rely on years of data and experience to provide relevant information about system performance for the entire lifetime of the vehicle. The development of effective simulation and modeling methodologies involves optimizing procedures in the modeling process in terms of cost, performance and time. Procedures include: the level of detail used in the model for a given point in the development process; the test procedures needed to parameterize the model; methods for extrapolating results, and validation methods [158].

Since the LIB market was previously dominated by consumer electronic industry the tools needed for developing a battery system that can meet automotive safety and quality requirements did not exist. Therefore OEMs and Tier 1 suppliers are currently working closely with cell suppliers in order to develop the necessary tools and procedures [13], [33], [67], [159]. Since adequate testing protocols and analysis techniques are being developed in parallel to the normal development process current EV battery development is very expensive and time intensive [157].

Current modeling techniques require the parameterization of empirical models based on large quantities of test bench data [93], [134]. Testing is very time and resource intensive as stress factors must be tested in isolation and measurements can only be taken after suitable resting intervals[139]. Extrapolation of the data to real life conditions is limited in applicability due to the empirical method employed; and techniques to analyze field data in order to validate the models are still in development [60], [62], [160].

Characterization Tests	Capacity Characteriyation	For capacity characterization, the cell was fully charged and then discharged at rates of 6C, C/2 and C/20. At each rate, two cycles were recorded and the capacity from the second cycle was used as the cell capacity
	Relaxation test	For the relaxation test, a fully charged cell was discharged for a period of 24 min at C/2 rate, and then followed by a 2 h rest before the subsequent discharge. The test was plete when the discharge voltage reached 2V
	Electrochemical Impedance Spectroscopy (EIS)	The EIS characterization was performed at 40% state of the charge (SOC) which was defined as 72 min of discharge at C/2 rate of a fully charged cell. The EIS measurement was carried out in a frequency range between 0.01 and 100 kHz and AC amplitude of 5mV.
	Hybrid Pulse Power Characterization	For HPPC characterization, prior to a pulse power sequence, a fully charged cell was discharged to 10% DOD at 1C rate, and then rested for 1 h. The pulse power sequence was composed of three steps: (1) 5C discharge for 18 s, (2) rest at OCV for 32 s, and, (3) 3.75C charge for 10 s. After the pulse sequence, the cell was immediately discharged to 20% DOD and rested for 1 hr before the pulse power sequence was repeated. The cell was tested at 10% DOD increments until reaching the cut-off voltage of 2V.

	Temperature °C												
DOD (%)	-30		0		15		25		45		60		C-rate
90	1	1	2242	2240	2144	2130			1796	1661	754	518	C/2
80	1	1	2520	2520	2390		2439	563	2120	2123	1011	1006	
50	13	15	3976	3965	3827	3804			3387	3317	3355	3963	
20	2662	4979	9625	9652	9234		4711	2211 2204	8374	8379	9801	9821	
10	9678	12082	18579	18534	18067	17940			16235	16571	19098	19385	
	-30		0		15		25		45		60		
90	26	40							4492	4048	1276	1594	2C
80			2249 2315	1931 2197									
50					3532 3784	3671 6763							
20													
10	38733	29511									54934	54943	
	-30		0		15		25		45		60		
90			3795 1723	1207 409	700 480	1222 418							6C
80									1479	1355			
50	1114	641			4017 5887	8242 9290					1428	1854	
20													
10					36151	35898							
	-30		0		15		25		45		60		
90	56	1									274	228	10C
80			611 1076	1135 1304					683	691			
50					9648	6696							
20													
10	1	1									17511	16848	

Test Stopped   Test Ongoing

Fig. 1. Test matrix for accelerated cycle life study. Two cells were tested at each condition. The numbers in the test matrix indicate the number of cycles attained by the cell. Cells highlighted in green were still cycling when this manuscript was written, and cells highlighted in red have reached the defined end of life condition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

FIGURE 64: EXAMPLE TEST MATRIX FOR DEVELOPING A BATTERY AGING MODEL, CHARACTERISTIC TESTS WERE PERFORMED AT REGULAR INTERVALS DURING CYCLING [134]

8.1.2 BATTERY WARRANTY PREDICTIONS

Currently, one of the largest risks for automotive OEMs is battery warranty[134], [138]. The battery is one of the most expensive components of the vehicle [159] and degradation of the battery system is dependent on the driving character of the driver, ambient temperature, and frequency of use[60], [62]. Every battery is going to age differently depending on driver characteristics and geographical location. It is therefore

necessary to incorporate this information to determine if batteries will fail to meet their warranty requirements. An example of current warranty prediction technique can be seen in Figure 65 [44], [63].

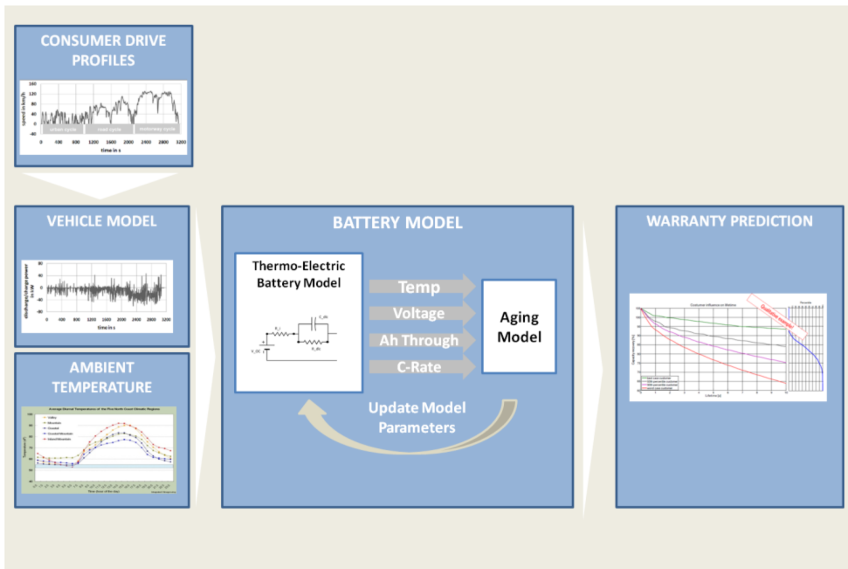


FIGURE 65: EXAMPLE METHOD FOR ESTIMATING DEGRADATION OF BATTERY IN VEHICLE [63], [161]

In this method driver profiles are collected and characterized according to driving intensity, duration, and frequency. Typical driving profiles are then combined with a vehicle model to determine the load profile for the battery[62]. The load profile in combination with different ambient temperature profiles are inputs to a thermo-electrical model of the battery system. An aging model runs in parallel to the battery model and updates battery characteristics at regular intervals throughout the simulation of the battery's life in the vehicle[63]. By combining different combinations of driving profiles and thermal profiles, a statistical distribution of battery characteristics as a function of time can be developed [161].

8.1.3 Responsibilities and Requirements for an OEM to Build a Sustainable Vehicle

Recently consumers, government agencies, the public sector, and society in general have become more aware of sustainability factors. This has led many industries including automotive, to evaluate the operations along their value chain with more scrutiny with respect to its environmental, social, and economic impacts [36]. This is particularly true for companies that emphasize the sustainability and environmental friendliness of their products, such as automotive OEMs selling electric vehicles.

MATERIAL USE AND WASTE REDUCTION

Looking at the vehicle value chain the most heavily scrutinized environmental impacts are generally manufacturing and end of product life [146], [162]. Impacts of the manufacturing phase can be reduced through the choice of sustainable materials, energy sources, and manufacturing practices. The end of life procedure for the vehicle and its components can be subjected to one of the following in the waste reduction hierarchy. Listed in order of increasing environmental impact: 'Reduce, Reuse, and Recycle'.

The first option 'Reduction' means the amount of energy and materials initially invested in the product is reduced. This includes material and energy used during the manufacturing phase in addition to non valuable waste at the end of product life. In the second option 'Reuse' the remaining value from the product or product components is extracted after its original intended use for another application. This option may include additional repurposing, rejuvenating, or remanufacturing steps to bring the product into a 'like-new' condition or a quality sufficient for its secondary application. The last option

‘Recycling’, breaks down the system into its component parts, reclaims any useful material, and disposes of the remains in the most environmentally cautions fashion.

The most environmentally friendly option for the electric vehicle and its battery system is the re-use of the battery system. This would also be the most economic sensible due to the current state of large format lithium ion recycling, which can cost around $3.85/lbs or $800-1000/pack [42], [69].

ECONOMICS OF USE STAGE

In the last few years there has been a slow paradigm shift between the concepts of the vehicle as a product to mobility as a service. Or more specifically services that enable mobility. This concept started as early as 1919 when automotive OEMs started adopting their own financial service entities in order to help customers finance their vehicles. Since then financial services and leasing services have grown significantly to include additional vehicle services such as full service leasing, insurance packages, and fleet management. Currently these business areas represent 50% of an OEM’s total assets and 13% of their total revenues (Figure 66). Recently new sustainable mobility concepts have been introduced such as car sharing, with joint financing between the OEM and a strategic partner generally in the form of an automotive rental company [163].

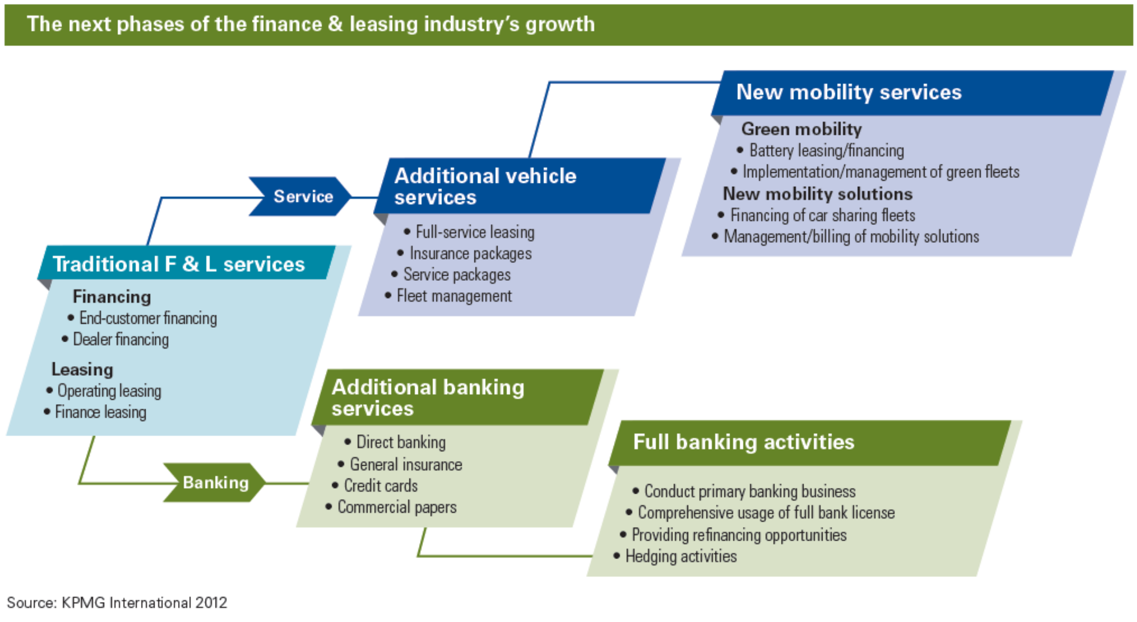


FIGURE 66: EXPANSION OF AUTOMOTIVE FINANCIAL SERVICES [163]

The majority of these financial and leasing services depend on the ability of the OEM to predict the residual value of the vehicle after a given amount of time. This is particularly problematic for EVs. A significant portion of the vehicle's overall cost (approx 1/3) is the battery, which is associated with a large amount of uncertainty in terms of performance capability and value in the next 3-10 years. For example, after a 3-5 year lease period the battery in the vehicle might only be degraded 5-10%, but a new battery pack will have a higher performance at a much lower cost due to improvements in cell chemistry and manufacturing processes. This creates a lot of risk in the calculation of the vehicles residual value. Similar risks, dependent on the residual value of the vehicle at the end of the contract agreement, are also present in determining the financing terms for car sharing and fleet vehicles.

Strategies to mitigate this risk include stabilizing the residual value through a battery upgrade after the lease or contract period, or decoupling the price of the vehicle and battery through a separate battery leasing program. In either case battery second use has the potential to offset the associated costs, and further mitigate the associated risk.

8.1.4 *Example Electric Vehicle Architectures*

To date all battery systems available are unique. The following provides an overview of the battery systems currently available and publically available information about their architecture and construction.

<u>TESLA ROADSTER (2008-2012)</u>

The Tesla roadster is a conversion vehicle produced by Tesla Motors between 2008 and 2012. The Roadster is a conversion vehicle which uses a modified body and chassis from the Lotus Elise. In converting this vehicle, the battery was packaged into the rear of the vehicle which was previously occupied by the engine and powertrain.

The Roadster's battery has a nominal capacity of 56kWh and is constructed of 6831 (18650 format) cells. The pack is divided into 11 sheets (modules), with an overall voltage of 375V. Based on this information and the knowledge that NMC cells have a nominal voltage of 3.7V the following can be said about the architecture.

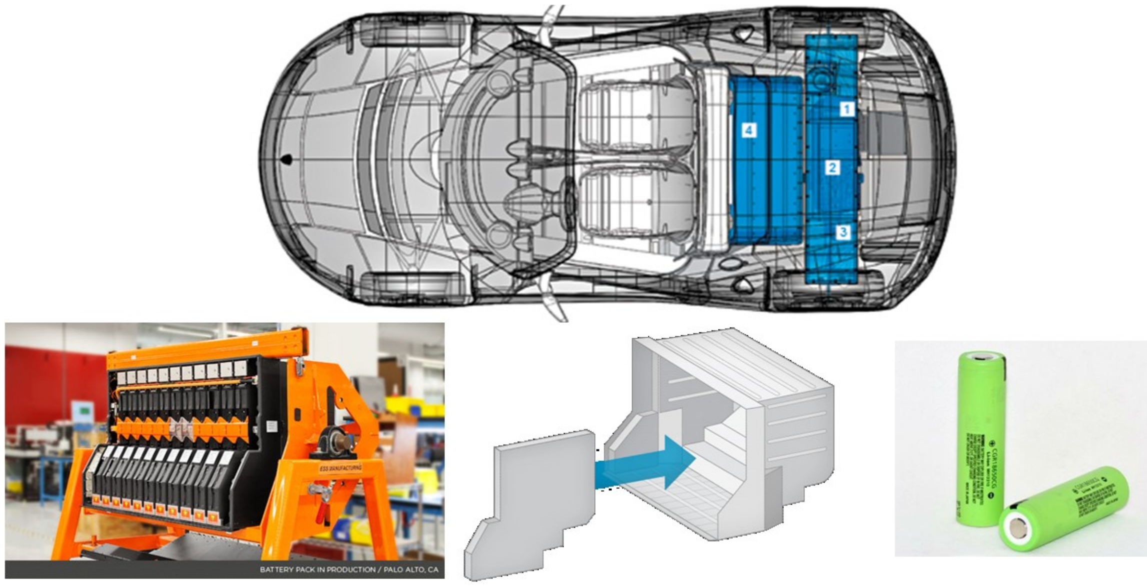


FIGURE 67: TESLA ROADSTER BATTERY ARCHITECTURE

Each of the 11 sheets consists of 621 cells, with 69 cells connected in parallel and 9 in series (69P9S). Each sheet is equipped with its own PCB and microcontroller for communicating module voltages and temperatures, an integrated conduit for the liquid thermal management system, and main fuse to prevent a short circuit across the pack. Cell level protection includes two fuses per battery cell (positive side and negative) in addition to safety devices integrated into the cell to reduce the probability and severity of a thermal event.

The pack level integrates the individual modules into a system housing that is electrically isolated from the pack, in addition to adding sensors for smoke, humidity, moisture, crash, or roll over. [102], [164], [165]

NISSAN LEAF (2010-)

The Nissan Leaf was one of the first widely accepted mass produced series production EV. The Leaf is a purposed built vehicle, where the air-cooled battery is integrated under the passenger cabin.

The battery has a nominal capacity of 24kWh and is constructed of 192 pouch cells. Each cell has a nominal capacity of 33Ah and is connected in a 2P2S configuration to form a module. 48 modules are then connected in series to form the pack [65], [99].

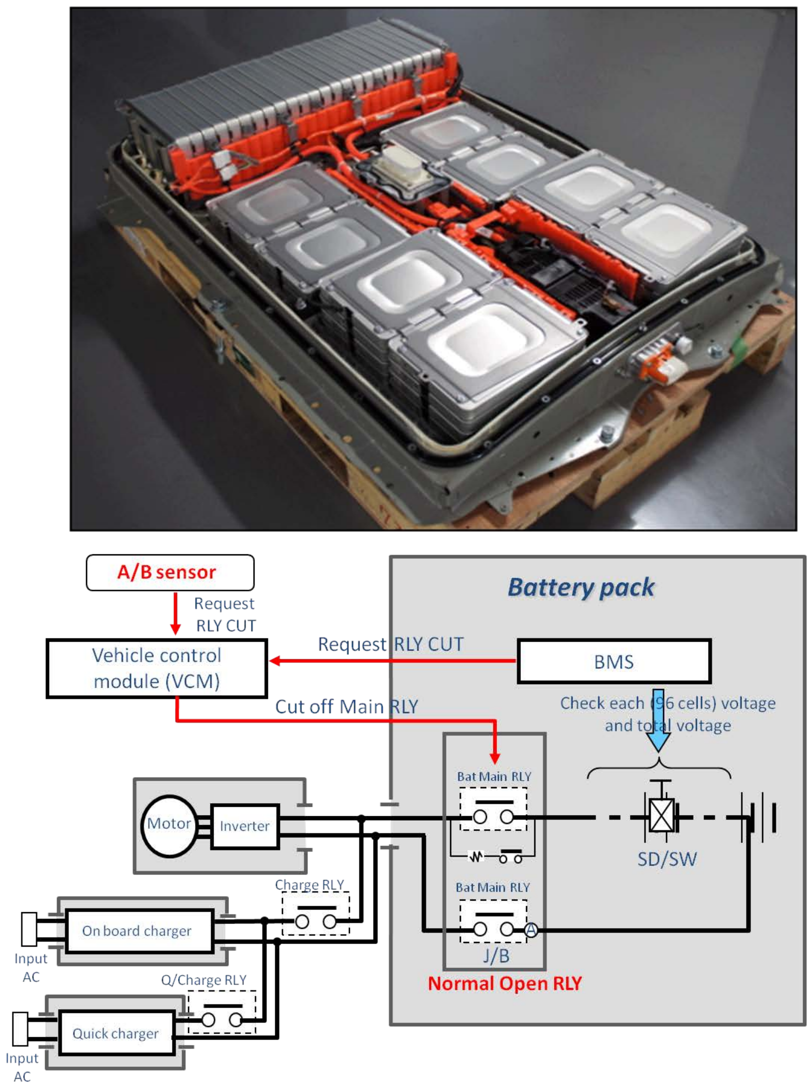


FIGURE 68: PICTURE AND ELECTRICAL SCHEMATIC OF NISSAN LEAF

CHEVY VOLT (2011-)

The Chevy Volt is a good example of a distributed system designed for a conversion vehicle, as it highlights some of the tradeoffs between packaging and standardization. The Chevy Volt is designed from Chevrolet's Delta II platform, which is also used for conventionally powered vehicles such as the Chevy Cruze, Buick Verano, and Opel Astra. Therefore the battery needed to be designed to occupy the area in the vehicle normally dedicated to the engine, powertrain and gas tank. The result is a t-shaped pack consisting of four sub-packs, located in the transmission tunnel and under the back passenger seats

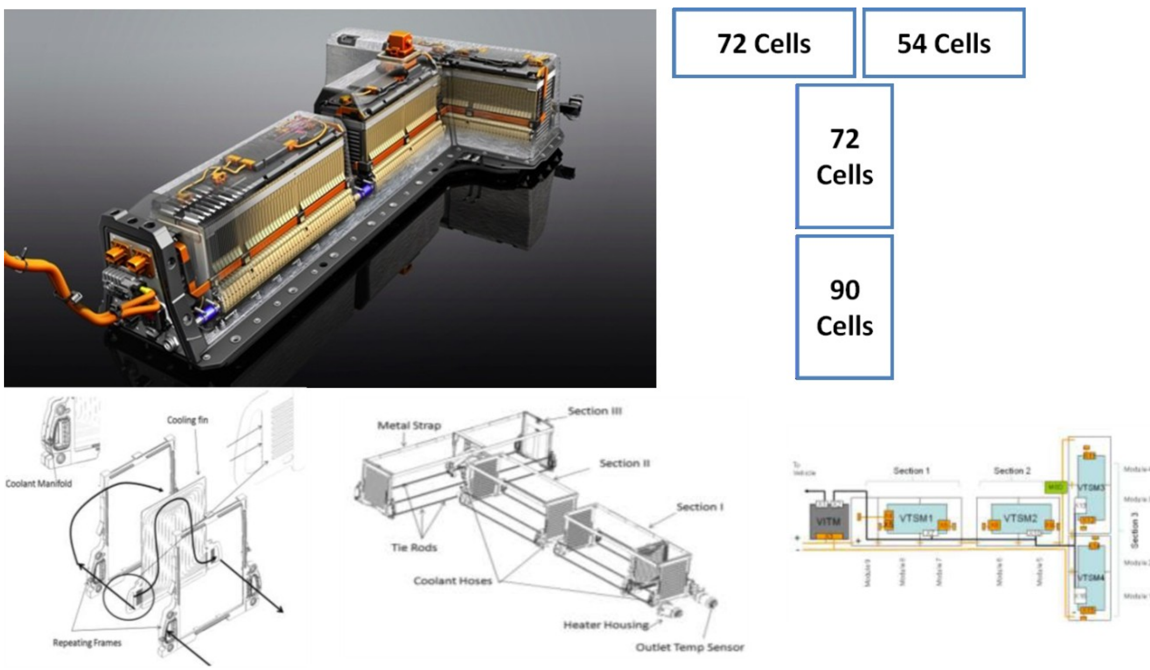


FIGURE 69: CHEVY VOLT BATTERY SYSTEM

The sub-packs consists of 54, 72, or 90 pouch cells. Cells within the packs are grouped in a 3P module. There are a total of 96 modules connected in series, and 288 cells in the pack.

Throughout the entire battery pack cooling elements are sandwiched between the cells for the liquid thermal management system. [66], [84].

BMW I3 (2013-)

The BMW i3 is the first purposed built EV from the BMW Group and the first vehicle for the BMW-i sub-brand. The 22kWh battery pack consists of 96, 60Ah prismatic cells configured into 8 modules, each with 12 batteries connected in series. The battery is a self contained unit, including a liquid cooling system, which is integrated into the Drive Module of the vehicle [166].

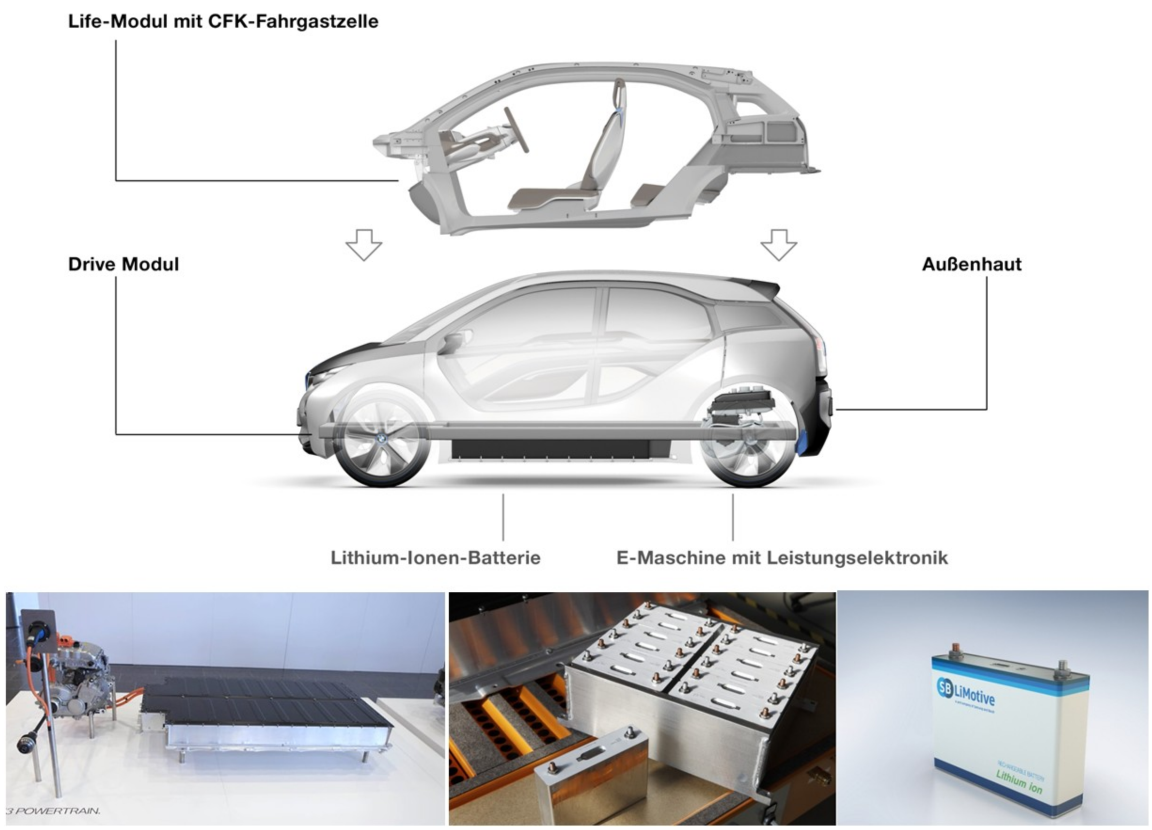


FIGURE 70: BMW I3 BATTERY SYSTEM AND INTEGRATION CONCEPT

8.1.5 *POLICY CONTRIBUTING TO THE DEVELOPMENT OF THE ELECTRIC VEHICLE MARKET*

Important policies for the development and usage of electric vehicles include the California Air and Resource Board's ZEV mandate, the American Recovery and Reinvestment Act (ARRA), and federal and state EV incentive programs (Table 37).

TABLE 37: EXAMPLES OF INSTRUMENTAL POLICIES FOR THE DEVELOPMENT OF THE EV MARKET

Program	Influence on Development of EV Market
ZEV Mandate	The ZEV mandate requires car manufacturers earn credits by selling given percentages of low emission and zero emission vehicles per year. IF an OEM fails to meet their ZEV requirement, they are subjected to a penalty of $5,000 per credit not fulfilled. This policy has been instrumental in encouraging OEMs to develop and produce low emission and zero emission vehicles, specifically EVs, at significant volumes [123].
The American Recovery and Reinvestment Act (ARRA),	Also known as the stimulus bill, was passed in 2009 to help the US out of the recession by using public funds to compensate for the lack of private investment. Out of the $831 billion allocated for the bill, $2.4 billion in grants were allocated to support the development of lithium ion battery manufacturing capabilities in the US. The purpose of investment would be to build up an American based supply chain for the production of electric vehicles. Of the allocated funds, $1.5 billion went to the development of a domestic battery supply chain, including the development of manufacturing plants mostly around the Detroit, Michigan, area. Another $500 million was allocated for the production of electric drive components, and $400 million for the purchase of PHEVs, charging infrastructure for demonstrative purposes, and training of workforce personnel for supporting this new technology. The ARRA helped provide the capital necessary to create the infrastructure to support the commercial production of electric vehicles, in addition to help reduce system costs through economies of scale [167].
Local Incentives	Local and federal incentives have also played a significant role on both the supply and demand side of the market. On the demand side, incentives have helped by making electric vehicles price competitive with traditional vehicles through tax exemptions and rebate programs. Non-monetary benefits such as unlimited access to the HOV lane or priority parking make using EVs more practical and desirable [123].

8.2 Scales and Applications for Stationary Battery Energy Storage Systems

Defining a storage application involves defining where and which benefit, or collection of benefits, it will be used for. Applications will vary with market structure and location. EPRI defined ten general storage applications (Figure 71). Although this is not a comprehensive list it is representative of the storage market today and in the near future.

Application	Description	Size	Duration	Cycles	Desired Lifetime
Wholesale Energy Services	Arbitrage	10-300 MW	2-10 hr	300-400/yr	15-20 yr
	Ancillary services [2]	See note 2	See Note 2	See Note 2	See Note 2
	Frequency regulation	1-100 MW	15 min	>8000/yr	15 yr
	Spinning reserve	10-100 MW	1-5 hr		20 yr
Renewables Integration	Wind integration: ramp & voltage support	1-10 MW distributed 100-400 MW centralized	15 min	5000/yr 10,000 full energy cycles	20 yr
	Wind integration: off-peak storage	100-400 MW	5-10 hr	300-500/yr	20 yr
	Photovoltaic Integration: time shift, voltage sag, rapid demand support	1-2 MW	15 min-4 hr	>4000	15 yr
Stationary T&D Support	Urban and rural T&D deferral. Also ISO congestion mgt.	10-100 MW	2-6 hr	300-500/yr	15-20 yr
Transportable T&D Support	Urban and rural T&D deferral. Also ISO congestion mgt.	1-10 MW	2-6 hr	300-500/yr	15-20 yr
Distributed Energy Storage Systems (DESS)	Utility-sponsored; on utility side of meter, feeder line, substation. 75-85% ac-ac efficient.	25-200 kW 1-phase 25-75 kW 3-phase Small footprint	2-4 hr	100-150/yr	10-15 yr
C&I Power Quality	Provide solutions to avoid voltage sags and momentary outages.	50-500 kW	<15 min	<50/yr	10 yr
		1000 kW	>15 min		
C&I Power Reliability	Provide UPS bridge to backup power, outage ride-through.	50-1000 kW	4-10 hr	<50/yr	10 yr
C&I Energy Management	Reduce energy costs, increase reliability. Size varies by market segment.	50-1000 kW Small footprint	3-4 hr	400-1500/yr	15 yr
		1 MW	4-6 hr		
Home Energy Management	Efficiency, cost-savings	2-5 kW Small footprint	2-4 hr	150-400/yr	10-15 yr
Home Backup	Reliability	2-5 kW Small footprint	2-4 hr	150-400/yr	10-15 yr

1. Size, duration, and cycle assumptions are based on EPRI's generalized performance specifications and requirements for each application, and are for the purposes of broad comparison only. Data may vary greatly based on specific situations, applications, site selection, business environment, etc.
2. Ancillary services encompass many market functions, such as black start capability and ramping services, that have a wide range of characteristics and requirements.

Figure 71: Potential storage applications for present day grid [18]

Battery storage will not be suitable for all applications. Battery storage should be used for fast ramping and distributed storage applications; whose value is dependent on delivering power when and where it is needed [11]. Such applications include renewable integration,

distributed energy storage systems (DESS), transportable systems for grid support, frequency regulation, or for commercial and residential energy management[168]. These applications can then be grouped by system size in order to specify general requirements for the range of applications (Figure 72).

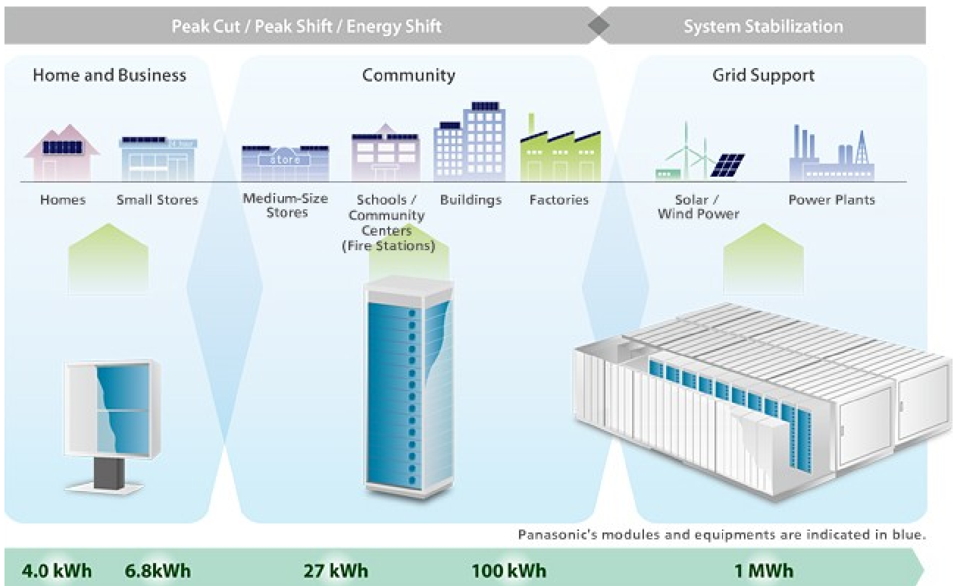


FIGURE 72: SYSTEM SIZES FOR STATIONARY BATTERY STORAGE SYSTEMS [79]

8.2.1 *SMALL SYSTEMS FOR RESIDENTIAL AND SMALL COMMERCIAL END USERS*

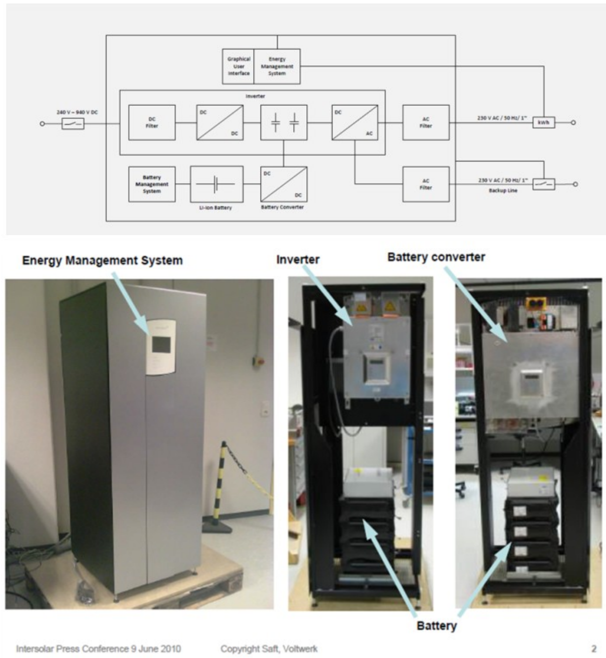


FIGURE 73: EXAMPLE SMALL BATTERY ENERGY STORAGE SYSTEM [169]

Small BESSs will be nominally 10-50kWh with a peak power of around 10kW. The battery system will probably contain 1-10 modules with an integrated battery management system, and be designed to change out the entire battery system if needed. Systems will need to be self contained, have very little maintenance requirements; be easy to install; meet standard residential electrical standards and connection requirements (e.g. 120V or 240V single phase for US); and be integratable into a Home Energy Management System (HEMS). System should also have proper metering and switching capability (Figure 74) to

allow customer to qualify for appropriate tariffs[17] from the utility and provide islanding capabilities [15].

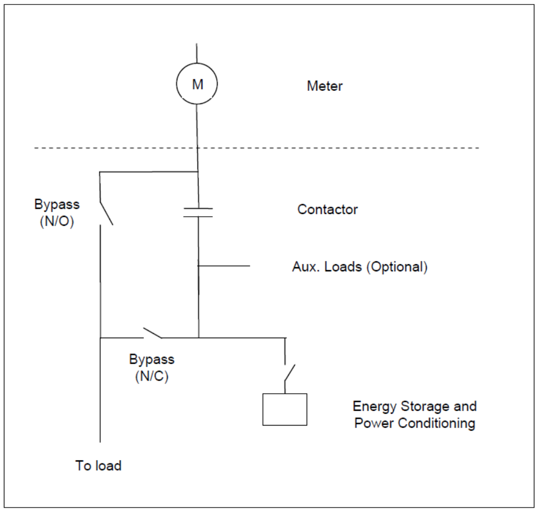


FIGURE 74: SINGLE LINE FOR CONSUMER CITED ENERGY STORAGE SYSTEM [15]

Small BESSs are currently on the market today and generally integrated into a solar system installation. There is a potential in the future that these systems will be available as a standalone system that can be integrated into a home energy management system (HEMS) to allow for the optimization of the consumer's electricity use (also known as Demand Side Management), or provide energy reliability for customers whose peak energy demand exceeds the capability of the local grid [168].

8.2.2 *MEDIUM COMMERCIAL, COMMUNITY, OR SMALL INDUSTRIAL SYSTEMS*

Medium BESSs can be owned by either a utility, private commercial or small industrial end user. Systems will be between 50 to 500kWhs with a power rating of 25-200kW and a single or three phase connection of up to 480V. A common use for a utility is a

[17] California Performance Based Incentive Program allows consumers to sell excess solar power to the grid which requires a net metering device and switches to ensure an installed battery system is not feeding energy into the grid.

community energy storage system (CESS), which can provide power quality and reliability services for a community of houses or a small commercial business park.

Figure 3: Layout of CES Installation and Its Main Components - from Revision 2.2 of Functional Specification For Community Energy Storage (CES) Unit

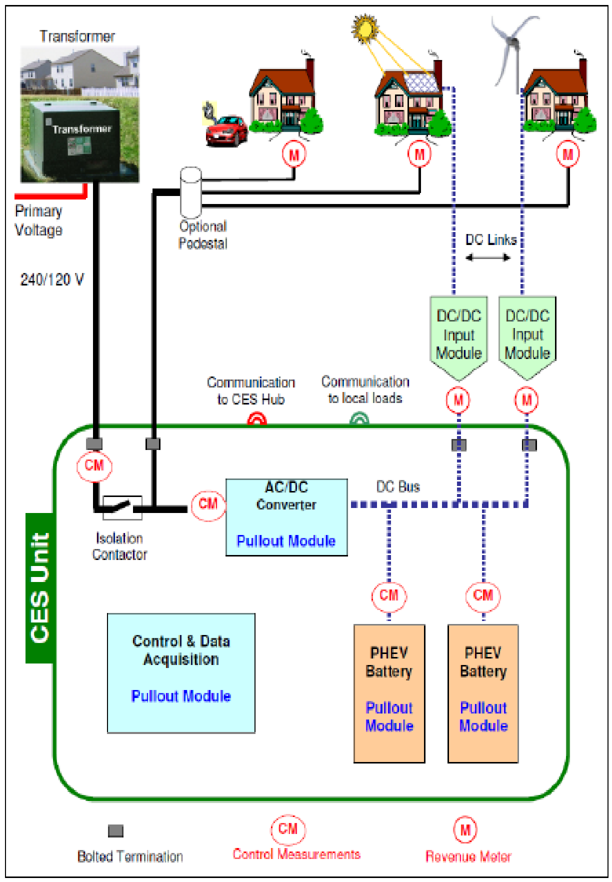


FIGURE 75: EXAMPLE CONFIGURATION OF CESS (SOURCE: AEP)

CESS are self contained units located outdoors, generally pad mounted between the utility's transformer and meters. The system should include a module battery system that can allow the disconnection or service and maintenance of part of the battery system without shutting the entire system off (i.e. hot swap capabilities). A summary of applications for this type of

system can be found in Table 38. Systems could also be controlled by the utility from a centralized location to create a virtual power plant.

TABLE 38: CESS APPLICATION FUNCTIONS [15]

Grid functions: *1) Serve as a load leveling, peak shaving device at the station level* *2) Serve as a power factor correction device at the station level (VAR support)* *3) Be available for ancillary services through further aggregation at the grid level* *Local functions:* *4) Serve as backup power for the houses connected locally* *5) Serve as local voltage control* *6) Provide efficient, convenient integration with renewable resources*

8.2.3 LARGE COMMERCIAL, INDUSTRIAL, AND UTILITY SYSTEMS

Large BESSs have 500kWh-10MWh of energy with a power rating of 1-4MW and can have connection voltages of 240V to 52kV depending on grid location. Due to their size, systems will generally be cited outside or in a dedicated building. Current system suppliers use a modularized concept that allows for easy scalability, installation, and transport [88], [170], [171]. Systems of this scale also require hot swap capabilities in addition to a more complex power conditioning systems using multiple power inverters with synchronization capabilities.

FIGURE 76: EXAMPLE OF DESIGN FOR LARGE STATIONARY BATTERY ENERGY STORAGE SYSTEM [172]

8.2.4 POLICY CONTRIBUTING TO THE DEVELOPMENT OF A MARKET FOR STATIONARY STORAGE SYSTEMS

Policy for the energy storage market started with the funding of pilot and demonstration projects. These projects are instrumental in driving change and effective policy by providing the information needed to assess the inadequacy of current energy and market policy for energy storage and derive future research needs. Examples include FERC 733 and 784, local and state incentive and financing programs, creation of forums for collaboration and information exchange, and the new California procurement mandate.

Currently, one of the largest hindrances to the wide adoption of energy storage is inability to monetize the real value the stationary storage [85].This is due to the market mechanisms such as tariff structures, wholesale market rules, and utility regulations being designed for operation of traditional energy systems, without advanced energy storage.

FERC 755 and 784 is an example of a regulatory change made specifically to help monetize the true value of energy storage (see Sidebar 1). These regulations have not only helped make a favorable business case for stationary storage systems in parts of the US but are also a precedent to encourage other reforms worldwide [17].

In addition, demonstration programs have played a significant role in the development of the storage industry, specifically energy storage and research programs funded through the DOE [16]. Given the energy markets today, policy change and decisions are just as important as technological advancement. In addition regulator can only respond once assets are deployed, and a need for regulator change is proven[26]. Therefore these demonstration projects are instrumental in stimulation regulatory change. Such projects include demonstration projects such as the Beacon Power flywheel projects which were instrumental in the development of FERC 755, and the Duke Energy's Notrees ERCOT project. Results from these projects, combined with market research being done through the national labs, have helped identifying opportunities for storage and policy needs for deployment [21], [26].

Incentives and low interest government loans have also played a key part in the development of the energy storage market. One of the most notable for driving consumer demand is the California Self Generation Incentive Program (SGIP). This program incentivizes self-generating technology on the consumer side of the meter including solar, wind, gas turbines, and advanced energy storage [20].This program reduces the initial capital cost of the system and creates a positive business case for storage.

Another more recent demand side regulation is the California energy storage procurement mandate. This mandate passed in October 2013 requires 1.3 GW of storage to

be deployed onto the CA grid by 2020. Exact procurement targets are divided among the state's investor owned utilities, subdivided across different grid domains (transmission, distribution, and consumer), and separated into yearly deployment targets (Table 39)

TABLE 39: CPUC ENERGY STORAGE PROCUREMENT TARGETS [126]

Proposed Energy Storage Procurement Targets (in MW)[22]

Storage Grid Domain Point of Interconnection	2014	2016	2018	2020	Total
Southern California Edison					
Transmission	50	65	85	110	310
Distribution	30	40	50	65	185
Customer	10	15	25	35	85
Subtotal SCE	**90**	**120**	**160**	**210**	**580**
Pacific Gas and Electric					
Transmission	50	65	85	110	310
Distribution	30	40	50	65	185
Customer	10	15	25	35	85
Subtotal PG&E	**90**	**120**	**160**	**210**	**580**
San Diego Gas & Electric					
Transmission	10	15	22	33	80
Distribution	7	10	15	23	55
Customer	3	5	8	14	30
Subtotal SDG&E	**20**	**30**	**45**	**70**	**165**
Total - all 3 utilities	**200**	**270**	**365**	**490**	**1,325**

The goal of the mandate is to "transform how the California electricity system is conceived, designed, and operated" and create an environment in which a mature energy storage market can compete to provide services alongside traditional resources [127].

9 APPENDIX: LITERATURE REVIEW

This Section provides a brief description of studies that were discussed in Section 2.

9.1 CATEGORY 1 STUDIES

This category consists of research that try and quantify the benefits of battery second use. These analyses generally include techno-economic or techno-environmental evaluations of the second-life value.

Paper	Author	Year	Description
Electric Vehicle Battery 2nd Use Study	Pinsky[40]	1998	Performance evaluation to assess if used NiMH batteries could compete with new Lead Acid batteries in stationary storage applications
Technical and Economic Feasibility of Applying Used EV Batteries in Stationary Applications	Cready et al. [41]	2002	Economic evaluation building on work by Pinksy et al to assess if used NiMH could be cost competitive with new Lead Acid Batteries in stationary applications assuming the cost of the used NiMH battery would make the Life Cycle costs for Electric Vehicles cost competitive with traditional ICE vehicles. Structure of assessment and assumptions made are basis for majority of Second Life Studies to follow
Economic Analysis of Deploying Used Batteries in Power Systems	Narula et al. [43]	2011	Assessment of 2nd Life battery competitiveness in power grid applications using updated information about storage market from Eyer and Corey [45], and extending reprocessing costs from Cready et al. Looks explicitly at sensitivity to different battery life and discount rates, analyzes entire system costs in terms of high and low best guess approximations.
Analysis of the Combined Vehicle and Post Vehicle Use Value of Lithium Ion Plug in Vehicle Propulsion Batteries	Williams et al. et al. [46]	2011	Update and extension of Cready et al. Study based on new information including a more detailed reprocessing cost model, identification and more detail about potential second use applications from work done by Eyer and Corey [45], and use of actual PEV battery packs for base of analysis. Used a Monte Carlo Simulation to analyze the sensitivity of point estimates on the battery lease payment for a Chevy Volt.

A Techno- Economic Analysis of PEV Battery Second Use: Repurposed-Battery Selling Price and Commercial and Industrial End-User Value	Neubauer , J. Persaran, A. Williams et al., B. [42]	2012	Integration and update of methods from Neubauer, 2011 and Williams et al., 2011 to determine selling price of used batteries to stationary storage system integrators and price at which the battery can be bought from EV owner. Extension of repurposing model to include cell fault rate and assumed improvement in testing requirements. Based on analysis price for repurposed batteries will cost between $38/kWh-$132/kWh and buying price from EV owner will range from $20/kWh-$100/kWh
Feasibility analysis of second life applications for li-ion cells used in electric powertrain using environmental indicators	Cicconi, P. Landi, D. Morbidoni, A. Germani, M. [47]	2012	Looks at environmental impacts of battery second use. Shows that repurposing and transportation, and the need for a battery replacement in second life do not have significant contributions to the environmental balance sheet. The LCA shows that there is a 25% overall environmental gain through battery second use due to the manufacturing savings of displacing the production of a new battery system.

9.2 CATEGORY 2 STUDIES

These studies contribute qualitative incites about key parameters and opportunities for B2U..

Paper	Author	Year	Description
An Economic Assessment of "Second Use" Lithium-Ion Batteries for Grid Support	Wolfs [48]	2012	Evaluation of used of used battery packs in stationary storage for Australian market. Shows potential revenues for medium sized grid support systems and distributed systems with a 5,10, or 20 years service life. Speculates that new batteries will not be economic for either application. Presents methods of evaluating and determining SOH and aging characteristics but doesn't appear to use methods in evaluation.
Life Cycle Costs of Electric and Hybrid Electric Vehicle Batteries and End-of-Life Uses	Price, B. Dietz, E. Richardson, J. [49]	2012	Discusses four potentials for offsetting high initial purchase price of electric vehicle through use of the battery system either (1) for V2G during vehicle use; (2) Grid Storage or (3) telecommunication power back up as a second use potential; or (4) recycling value. Provides a literature references to discuss factors contributing to the viability of the four proposed life-cycle management options.

9.3 Category 3 Studies

Category 3 studies look at tradeoffs along the entire value chin or sections of the value chain.

Paper	Author	Year	Description
The ability of battery second use strategies to impact plug-in electric vehicle prices and serve utility energy storage applications	Neubauer, J. Pesaran, A. [44]	2011	Development of method to determine the salvage value for used Li-ion batteries, based on the current price of equally capable new batteries discounted by a used product discount factor, battery health factor, and the repurposing cost of the battery or the potential revenue available through recycling the battery. Using their method they concluded that an EV battery will never be retired from the vehicle due to financial reasons. In addition there is a very low likelihood that a Battery Second Use Strategy will have a significant impact on today's battery pricing and under certain conditions B2U stands to reduce battery prices in 2015 by up to 11%.
Second Use of Transportation Batteries: Maximizing the Value of Batteries for Transportation and Grid Services	Viswanthan [50]	2011	Analyzes tradeoffs between time spent in vehicle and stationary use in terms of maximizing battery value to determine when to remove the battery from the vehicle. Author constructs optimization problem based on % battery capacity degradation per year in vehicle use and earnings from providing regulation energy ($/MWh/yr). Does sensitivity analysis based on different regulation pricing.
Second Use of Retired Lithium-ion Battery Packs from Electric Vehicles: Technological Challenges, Cost Analysis and Optimal Business Model	Lih [51]	2012	Present qualitative requirements for battery second use, quantitative evaluation criteria for determining the value of the battery pack throughout its life time, and methods for assessing optimal use strategy between first and second use stages based on costs.

Valuation of electric vehicle batteries in vehicle-to-grid and battery-to-grid systems	Hein [52]	2012	Business case evaluation extending Cready analysis into a system dynamics model evaluating competitiveness of stationary battery systems using new batteries, used batteries and vehicle to grid for 2020-2050. Study shows that given the assumptions presented installation of used battery systems will stagnate in 2030 at 200 batteries but the use of EVs for V2G will continue to grow.

9.4 Category 4 Studies

Category 4 Studies concentrate on the use of the battery in a secondary system, focusing on either system architecture, control algorithms, or system sizing.

Paper	Author	Year	Description
Optimal Use of Second Life Battery for Peak Load Management and Improving the Life of the Battery	Keeli [55]	2012	Creates optimization problem in order to properly size a 2nd life battery system to maximize battery life and energy savings through a peak shaving application. Study does not take into account overall system costs, battery pricing, or battery degradation. Battery State of health is determined by calculating the remaining amount of energy throughput.
An Economic Analysis of Used Electric Vehicle Batteries Integrated Into Commercial Building Micro-grids	Beer [68]	2012	Evaluation of three different business models for incorporating a used EV-Stationary stationary storage system into a commercial building micro-grid. Extends use of resource sizing tool to include participation in regulation market to find optimal size for battery system. Found that use of old EV batteries could be profitable if used for Regulation and managing the building's energy use.
Current Sharing Control for Cascaded H-Bridge Applied to Secondary Used Batteries in Community Energy Storage Systems	Lomaskin, M. Bai, S. Lukic, S. [72]	2012	Presents a cascaded H-bridge inverter topology and control method that allows use of individual battery systems according to their capacity and SOC. This allows battery packs of different capacity to be integrated into a single system.

Off-grid photovoltaic vehicle charge using second life lithium batteries: An experimental and numerical investigation	Tong, S. Same, A. Kootstra, M. Park, J. [54]	2013	Looks at using a second life EV battery pack in an off-grid PV charging station. This study created an experimental system using differently aged cells, that were configured into a pack by mixing the capacity of series connected cells. The experimental set up was used to parameterize a battery model used to evaluate the potential performance of the system. The study claims the methods used to combine the used cells and applied BMS technique can create a battery system with equivalent performance capabilities to new batteries at a lower cost. Further studies will look at lifecycle characteristics for the given system.
Modular ESS with Second Life Batteries Operating in Grid Independent Mode	Mukherjee, N. Stickland, D. [53]	2012	Proposes a modular multi-scale cascade inverter (MMCC) based energy storage system using second life batteries. Features of this topology include increased system reliability, intelligent control capabilities to maximize system output, and ability to optimize system design by reducing output filter size which can result in a reduction in overall system cost. Through simulation, proves that a system using the MMCC design has a comparable performance capability to a conventional topology.
Modeling, Controls, and Applications of Community Energy Storage Systems with used EV/PHEV Batteries	Onar, O.C. Starke, M. Andrews, G.P. Jackson, R. [56]	2012	Developed control algorithm for aggregation of multiple CES systems providing service to multiple households. Uses a simulation model to evaluate system's effectiveness of providing multiple services.

9.6 Category 5 Studies

Category 5 studies provide periphery information about technical and operational aspects that will affect B2U.

Paper	Author	Year	Description
Remanufacturing for the automotive aftermarket-strategic factors: literature review and future research needs	Subramoniam, R. Huisingh, D. Chinnam R.B. [36]	2009	Investigates strategic drivers and operational barriers for the development of a remanufacturing process. Develops seven major propositions regarding the strategic factors that guide decision making with respect to remanufacturing.
A review on lithium-ion battery aging mechanisms and estimations for automotive applications	Barre, A. Deguilhem, B. Grolleau, S. et al. [57]	2013	Overview of battery aging research and knowledge to date. Including electrode aging mechanisms and resulting impacts on cell performance, methods for estimating and predicting battery aging, evaluation of effectiveness of methods, and practicality of methods for in vehicle implementation.
DESA: Dependable, Efficient, Scalable Architecture for Management of Large Scale Batteries	Kim, H. Shin, K. [58]	2012	Presents a hierarchical battery management system (DESA) consisting of local controllers that autonomously manage small arrays of battery cells and a global BMS that orchestrates connectivity of individual arrays to optimize overall system performance. Shows this new configuration increases initial manufacturing costs but has a large potential to decrease service costs associated with failed modules or cells.
A High-Efficiency Grid-Tie Battery Energy Storage System	Qian, H. Zhamg, J. Lai, J. Yu, W. [59]	2010	Describes BMS and control system requirements for a stationary storage system. Including BMS configuration, SOC estimation techniques and challenges; cell balancing techniques; requirements for the power control system, system control and power management

10 APPENDIX: DETAILED INFORMATION FOR ANALYSES PRESENTED IN SECTION 4

The following provides the input assumptions, boundary conditions and details about the methods and analysis performed in Section 4.4.

10.1 IDENTIFICATION OF WINDOW OF OPPORTUNITY AND PRELIMINARY EVALUATION OF PROBLEM UNCERTAINTY AND SENSITIVITY

The purpose of this analysis was to benchmark the current state of knowledge based on data presented in literature, supplemented with data from internal pilot projects.

10.1.1 INPUT DATA

Below Table 40 displays the input parameters for the preliminary uncertainty analysis, followed by the reasoning for the selection of these parameters. It should be noted for this preliminary analysis all input variables are considered independent, and therefore are modeled and sampled independently of one another.

TABLE 40: INPUT VALUES FOR SENSITIVITY ANALYSIS

SYSTEM PARAMETERS	Level	unit	Distribution	Mean	Param 1	Param2
Capacity at EOLv	rack	%nom cap	triangle	80%	50%	100%
Cycles/year	system	cycles	triangle	400	200	1000
Remaining useful cycles	rack	cycles	uniform	2000	500	2000
System lifetime	system	year	uniform	15	10	20
COSTS						
Residual Value	capacity	€/kWh	triangle	100.00 €	- €	500.00 €
Repurposing	module	€/module	triangle	60.00 €	3.50 €	300.00 €
Integration						
	system	€/s	uniform	- €	- €	- €
	cabinet	€/cabinet	triangle	70.00 €	50.00 €	5,000.00 €
	rack	€/rack	triangle	100.00 €	50.00 €	1,000.00 €
	module	€/module	uniform	25.00 €	- €	30.00 €
REVENUE						
Market Price	Battery System	€/kWh	uniform	1,700.00 €	1,000.00 €	2,000.00 €

CAPACITY AND EOLV (END-OF-LIFE OF THE VEHICLE).

Currently vehicle warranties guarantee the battery for 100,000 miles, 8 years with a remaining capacity of 80% [84]. Therefore it is expected that the majority of batteries will be returned when they reach around the 80% of their original nominal capacity. This assumption is consistent with assumptions found in literature. Therefore 80% is chosen as the point value estimate.

It is also possible that the batteries will come out of the vehicle either before or after the 80%. For instances where the customer wants to upgrade their battery to the newest technology, batteries might be returned at 90% of their original nominal capacity. In cases where the customer is satisfied with the performance of their battery, or are outside of their warranty period, batteries might come back with a much lower capacity. Therefore upper and lower bounds are chosen to be respectively 90% and 50% of the original nominal capacity.

A triangular distribution was chosen since it is believed that the majority of returning batteries will be around 80% rather than at the extremes.

CYCLES PER YEAR

The number of cycles required per year is determined by the application or service the storage installation is to provide. This was determined from the cycle requirements reported in [20]. As seen in Figure 71 the cycle number per year can vary between less than 50 to over 8000 cycles. The majority of applications require around one full cycle (full charge and discharge) per day, therefore a point value of 400 was chosen, representing a daily average of 1.10 cycles. The lower value was chosen to represent a lower utilized system, with the assumption that systems deployed for applications with a low utilization

factor will be employed for multiple applications and therefore a cycle number of less than 200 cycles per year is not practical. The upper value was limited to 1000 since the majority of high frequency applications have short duration discharges (15mins). For a system employing second life batteries it assumed that the maximum power will be limited to a 1C discharge, which means that the system will be sized with a maximum power to energy ratio of one (i.e. 1 MW/1MWh). Therefore for a short duration discharge will result in a micro-cycling of the battery system, instead of a full cycle discharge. Preliminary analyses using derived load profiles for frequency regulation it was found that these micro-cycles equate to less than one cycle per day with respect to the amp-hour throughput. Based on the results of these analyses 1000 full cycles per year is considered an appropriate upper limit.

A triangular distribution was chosen in since the majority of applications are closer to the one cycle per day requirement.

REMAINING USEFUL CYCLES

Lithium ion batteries have a cycle life of approximately 2000-3000 cycles before they degrade to 80% [173]. For this preliminary analysis it is assumed that for a secondary application the batteries will be allowed to degrade to 80% of their original installed capacity before needing to be replaced (Figure 77).

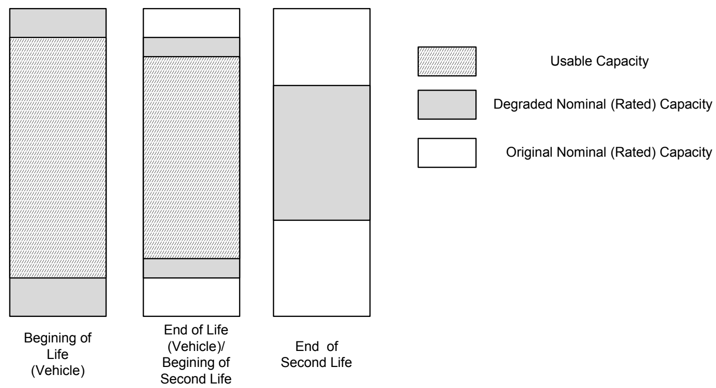


FIGURE 77: VISUALIZATION OF USABLE BATTERY CAPACITY THROUGHOUT BATTERY LIFETIME

This is consistent with current industry standards and warranties for stationary systems [18], [85]. Therefore 2000 cycles is taken as the point estimate and upper limit. It is also known that lithium ion batteries go through various stages of aging and experience a more rapid rate of degradation at later stages of the aging process [138]. Therefore a lower limit of 500 remaining cycles was chosen to represent a worst case scenario of rapid degradation four times higher than normal beginning of life degradation rate. A uniform distribution was chosen since there is currently no information available that would justify a biased distribution.

SYSTEM LIFETIME

System lifetime was determined from Figure 71. A point estimate of 15 years was taken as an average, between the two extremes of 10 and 20 years. A uniform distribution was chosen since there is no information that can justify a biased distribution.

RESIDUAL VALUE/ BUY-DOWN

The residual value of the battery is determined from the market price of lithium ion batteries (/kWh) and a used product factor. This number represents the amount to be paid to the customer for the return of the battery. The average market price of a battery system

from 2012 until 2020 is about 400€/kWh [120], which is used as an upper bound. The lower estimate is the best case scenario in which the batteries are returned for free (*i.e.* the EV user does not require payment in exchange for the battery). A point estimate of 100€/kWh is chosen as a conservative point estimate, which is also consistent with values found in literature (Table 41). A triangular distribution was chosen due to the evidence presented in literature.

TABLE 41: BUY-DOWN PRICE FROM LITERATURE (EXCHANGE RATE 1€=$1.30)

	Cready	Narula High	Narula Low	Williams	Neubauer High	Neubauer Low
Battery Buy Price	57.69 €	169.23 €	57.69 €	142.69 €	76.92 €	15.38 €

REPURPOSING COST

Repurposing costs were derived from values found in literature (Table 42). High value approximation comes from the study by Cready et al. , low estimate from the study by Narula et al, and point estimate from the most recent study by Neubauer et al. Values from these studies were converted to Euros and renormalized to a per module basis based on the initial nominal capacity of the i3 battery module. A uniform distribution was chosen since based on the range possible repurposing scenarios all costs between the two extremes are expected.

TABLE 42: REPURPOSING COSTS FROM LITERATURE (1€=$1.30, 1 MODULE=2.7KWH @BOL)

	Cready	Narula High	Narula Low	Williams	Neubauer High	Neubauer Low
Repurposing (€/kWh)	55.38 €	1.94 €	1.29 €	48.08 €	24.62 €	13.85 €
Repurposing (€/module)	149.54 €	5.23 €	3.49 €	129.81 €	66.46 €	37.38 €

INTEGRATION COSTS

The integration costs are derived from internal BMW data for both the vehicle and quotations from pilot projects, in addition to commercially available systems. Lower

estimates represent minimal additional part requirements, while upper limits represent the highest estimate in the table below. Point estimates were set to represent the best guess of what a series production part would cost.

TABLE 43: BMS COST ESTIMATION

	Company	Description	Unit Price	Source
BMS CABINET	Orion BMS	108 cells	1,310.00 €	http://elithion.com/comparison.php
	Lithiumate	108 cells	1,196.00 €	
	EMUS	255 cell master unit	299.00 €	http://www.nothnagel-marine.de/index.php?cat=c266_EMUS-BMS-System.html
	REC		359.00 €	http://www.nothnagel-marine.de/product_info.php?info=p3612_REC---BMS-Slave-Unit-7S--4S---14S-Cells--incl--temp--sensor--LiIon--LiFePO4.html
	BMW P0		100.00 €	INTERNAL
	BMW P1		495.00 €	INTERNAL
	BMW P2		2,500.00 €	INTERNAL
	BMW P3		1,499.23 €	INTERNAL
BMS RACK	Orion BMS	108 cells	1,310.00 €	http://elithion.com/comparison.php
	Lithiumate	108 cells	1,196.00 €	
	EMUS	255 cell master unit	299.00 €	http://www.nothnagel-marine.de/index.php?cat=c266_EMUS-BMS-System.html
	REC		359.00 €	http://www.nothnagel-marine.de/product_info.php?info=p3612_REC---BMS-Slave-Unit-7S--4S---14S-Cells--incl--temp--sensor--LiIon--LiFePO4.html
	BMW P0		223.00 €	INTERNAL
	BMW P1		493.00 €	INTERNAL
	BMW P2		950.00 €	INTERNAL
	BMW P3		418.46 €	INTERNAL
	PARTS		50.00 €	INTERNAL
BMS MODULE	EMUS	Cell monitoring and balancing	15.50 €	http://www.nothnagel-marine.de/index.php?cat=c266_EMUS-BMS-System.html
	BMW P0		24.00 €	INTERNAL

MARKET PRICE

The market price of the battery system is assumed to include the initial purchase price of the battery system (cells, BMS, housing, internal DC wiring) and replacement batteries over the system lifetime. Prices used were determined from the system costs reported in [20] and commercial system benchmarks (Table 44).

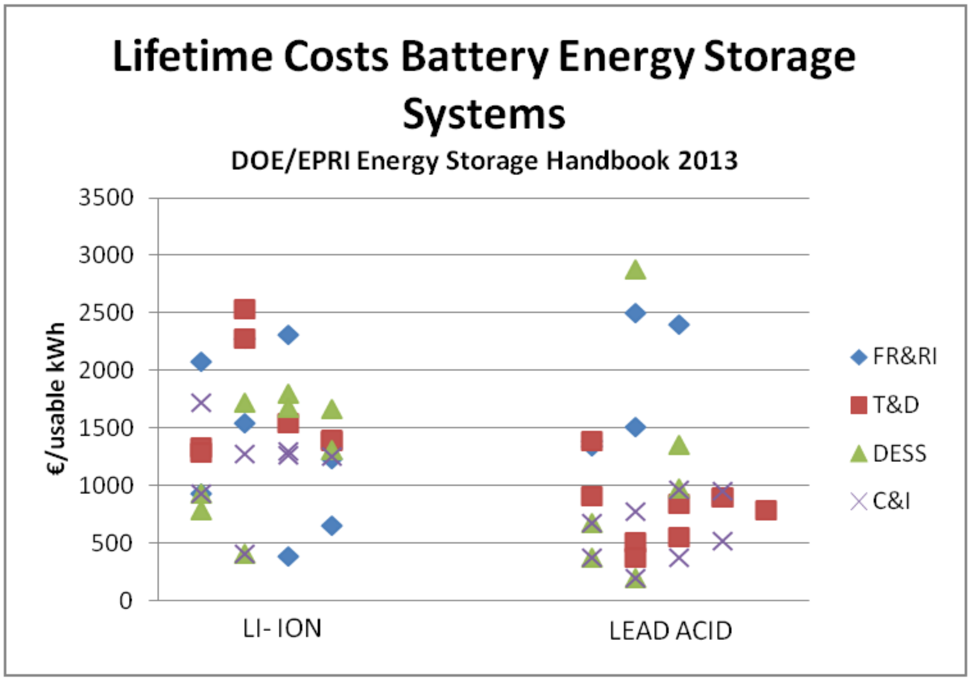


FIGURE 78: LIFETIME SYSTEM COSTS FOR STATIONARY BATTERY ENERGY STORAGE SYSTEMS AS REPORTED IN [20](1€=$1.30)

Prices reported in Figure 78 are for the purchase price of the battery system (battery cells, BMS, housing) plus replacement battery systems over the system lifetime. It can be seen that the cost of lithium-ion based systems are between 500-2500€/kWh, while lead acid batteries are generally cheaper and range from 250-2800€/kWh. The large range of values reported can be attributed to the pilot project/ “one off” nature of the documented systems, in addition to the generic assumptions about battery aging and cycling requirements.

TABLE 44: COMMERCIAL SYSTEM COSTS (SOURCE: INTERNAL BMW)

			System Price ($/kWh)	BMS ($/kWh)	Battery ($/kWh)	Battery+ BMS ($/kWh)	PCS ($/kWh)	PCS ($/kW)
SYSTEM	Supplier ID					**Default 70% System		
Small	S1		1,089.45 €			762.61 €		
	S2	lead	1,152.61 €			806.83 €		
	S3	lead	806.83 €			564.78 €		
	S4	lead	1,169.56 €			818.69 €		
	S5	lead	1,408.34 €			985.84 €		
	S6	li-ion	3,012.50 €			2,108.75 €		
	S7	li-ion	1,735.20 €			1,214.64 €		
	S8	li-ion	3,745.98 €			2,622.18 €		
	S9	LFP	1,048.20 €	178.20 €	600.00 €	778.20 €	155.00 €	258.33 €
Medium	M1	Lithium(LFP	9,166.67 €			6,416.67 €		
Large								
	L1	Lithium(LFP	673.63 €	101.04 €	404.18 €	505.22 €	168.41 €	6,183.22 €
	L2	Lithium(LFP	863.66 €	129.55 €	518.20 €	647.74 €	215.91 €	5,285.00 €
	L3	Lithium(LFP	1,105.97 €	165.90 €	663.58 €	829.48 €	276.49 €	5,075.83 €
	L4	Lithium(LFP	1,179.52 €	176.93 €	707.71 €	884.64 €	294.88 €	3,608.94 €

Prices reported in Table 44are the pure capital costs of the system. Prices of the systems reported are from systems currently available on the market. Since most system suppliers don't break out the cost of the inverter and battery system, it is assumed that the battery and BMS are approximately 70% of the system cost when no cost breakdown is given.

For each trail values were randomly selected from each input distribution to calculate the lifetime system cost and profit potential as follows

$$COST_{LIFE} = COST_{BATT} + COST_{SYS} + COST_{REPLACE} * \ [\#_{replace}] \quad \textbf{Eq. 9}$$

$$COST_{kWh_{LIFE}} = \frac{COST_{LIFE}}{[\%nom\ Cap]\ [CAP_{nomsys}]} \quad \textbf{Eq. 10}$$

$$PROFIT = PRICE_{kWh} - \ COST_{kWh_{LIFE}} \quad \textbf{Eq. 11}$$

Where

$$COST_{BATT} = [VALUE_{RESID}][\%nom\ Cap]\ [CAP_{nomsys}]$$ **Eq. 12**

$$COST_{PROCESS} = [\ Repurp_{Mod}]\ [\#_{mod}]$$ **Eq. 13**

$$COST_{SYSTEM} = Integ_{sys} + Integ_{cab} * [\#_{cab}] + Integ_{rack} * \ [\#_{rack}] + Integ_{mod} * [\#_{mod}]$$ **Eq. 14**

$$COST_{REPLACE} = \ [Integ_{rack}][\#_{rack}] + [Integ_{mod}][\#_{mod}] + \ COST_{BATT}$$ **Eq. 15**

$$\#_{Replace} = ceil(\ cyc_{yr} * \frac{Sys\_life}{remainlife_{cyc}})$$ **Eq. 16**

<u>*PARAMETERS:*</u>
Sys_life: Lifetime of system [years]
cyc_{yr}; Number of system full cycles per year
CAP_{nomsys}: Nominal system capacity assuming new batteries [kWh]

$\%nom\ Cap$: Percent remaining capacity relative to capacity at beginning of vehicle life
$remainlife_{cyc}$: Number of cycles remaining in battery
$VALUE_{RESID}$: Residual value of battery, dependent on new battery price and potentially a used battery discount factor.

$COSTS_{BATT}$: Purchase price of one system worth of used batteries
$COST_{PROCESS}$: Reprocessing costs for one system worth of batteries
$COST_{SYSTEM}$: Capital cost of system
$COST_{REPLACE}$: Cost for replacement battery system
$COST_{LIFE}$: Lifetime system costs
$COST_{kWh_{LIFE}}$: Lifetime system cost per usable kWh

$Repurp_{Mod}$: Cost to repurpose single module
$Integ_N$: Integration costs per [N: System/Cabinets/Racks/Modules]

$\#_N$: Number of [N: Cabinets/Racks/Modules] required for stationary battery system
$\#_{Replace}$: Number of battery system replacements required over system lifetime

$PRICE_{kWH}$: Market Selling price of battery system [Price/kWH]

Integration costs are dependent on system configuration. The following three system configurations were used to represent a small (10kWh) system, medium (100kWh) system, and large (1MWh+). Configurations parameters were derived from internal pilot projects.

TABLE 45: SYSTEM CONFIGURATIONS FOR MONTE CARLO ANALYSIS

		Small (~10kWh)		Medium (~100kWh)		Large (1MWh+)		
System	0	**S**	**P**	**S**	**P**	**S**	**P**	
Power Cabinet	1	1	1	1	1	1	20	Cabinet/System
Rack	2	1	1	1	3	1	3	Racks/Cabinet
Module	3	8	1	16	1	16	1	Modules/Rack
Cell	4	12	1	12	1	12	1	Cells/Module

Numbers in the 'S' and 'P' columns represent the number of sub-systems connected in series and parallel for that given system level. For example for the large system there are 12 cells connected in series to form a module; 16 modules in series to create a rack; three racks connected in parallel to form a power cabinet; and 20 power cabinets connected in parallel to form the entire system.

10.1.2 DETAILED RESULTS OF UNCERTAINTY ANALYSIS

Results of the 100,000 trials can be in Figure 40. The mean values in Table 40 were also used to calculate point values as means of comparison. Results of these point value estimates in addition to characteristics of the distributions shown in Figure 40 can be found in Table 46 for comparison.

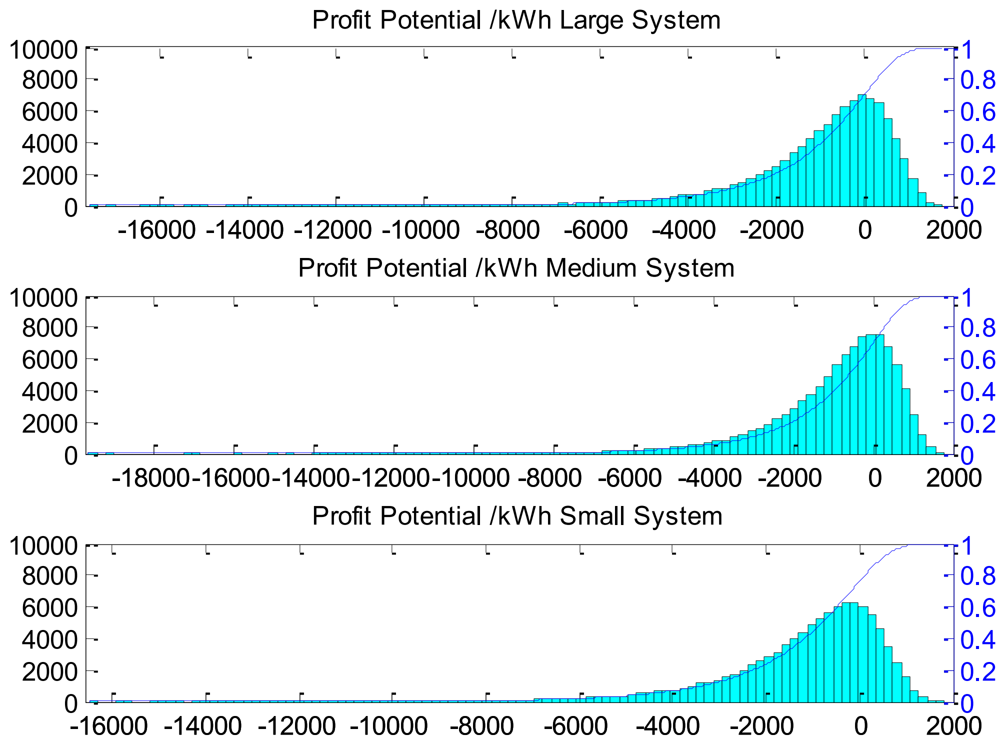


FIGURE 79: POTENTIAL PROFIT DISTRIBUTIONS FROM INITIAL MONTE CARLO ANALYSIS

TABLE 46: STATISTICAL OVERVIEW OF POTENTIAL PROFIT FOR PRELIMINARY MONTE CARLO ANALYSIS

PROTFIT POTENTIAL/kWh											
	50% CDF	98% CDF	Point Value	Mean	Std Dev	Range	Min	Max	Stdev %	Range (+) %	Range (-) %
Large	- 600 €	1,073 €	1,130 €	- 1,004 €	1,676 €	19,377 €	- 17,605 €	1,772 €	148%	1657%	57%
Medium	- 591 €	1,095 €	1,130 €	- 991 €	1,667 €	21,393 €	- 19,625 €	1,768 €	148%	1836%	56%
Small	- 789 €	957 €	1,115 €	- 1,196 €	1,710 €	18,298 €	- 16,488 €	1,810 €	153%	1578%	62%

PROTFIT POTENTIAL/kWh											
	50% CDF	98% CDF	Point Value	Mean	Std Dev	Range	Min	Max	Stdev %	Range (+) %	Range (-) %
Large	- 600 €	1,073 €	704 €	- 1,004 €	1,676 €	19,377 €	- 17,605 €	1,772 €	238%	2602%	152%
Medium	- 591 €	1,095 €	704 €	- 991 €	1,667 €	21,393 €	- 19,625 €	1,768 €	237%	2889%	151%
Small	- 789 €	957 €	680 €	- 1,196 €	1,710 €	18,298 €	- 16,488 €	1,810 €	251%	2525%	166%

The profit potential is the difference between the market price of a battery system and the lifecycle cost of the system. Previous studies either concentrated on the system costs, assuming the battery system would be sold at a price that would be enough to cover the

value chain costs while still remaining under the price ceiling of new lithium ion cells. This study takes a different approach in determining market competitiveness in that we are assuming that energy storage is a commodity in which the price competitiveness is independent of technology and is solely dependent on lifecycle costs. As shown in Figure 78 energy storage is expected to be between 1000-3000€/kWh . Therefore the potential profit that can be obtained is the difference between this price ceiling and the lifetime system cost of the system. It is a profit potential since it is the maximum amount of profit that can be made through an end customer sale. In reality a system integrator and all partners between the OEM and end customer in the value chain will take a cut of that profit leaving only a small percentage of the total potential profit for the OEM. The question then is does that percentage make battery second life attractive enough for an OEM to move forward in a second life strategy.

For the given analysis it can be seen that the potential profit varies dramatically, with an average point estimate of 1,128€/kWh with an 1.5% chance that the profit potential is greater, 28.5% that it is less, and 70% chance that no profit will be made .

From these results it's necessary to understand the sensitivity of the outputs to the input parameters and what range of parameters determine a profitable scenario.

10.1.3 Sensitivity Analysis

A sensitivity analysis was performed from the Monte Carlo analysis as follows:

Equations 9-11 were re-calculated using the point estimate values for all input variables except one for which the randomly sampled values were used in place of the point estimate. Therefore the variation of the resulting distributions will be due to the variable of the non-

point estimate variable only. The variance between the results and the original point estimate for lifetime system costs and profit was calculated as follows

$$VAR_{x,i} = \frac{CALC_{x,i} - POINT_x}{POINT_x}$$ **Eq. 17**

Where $CALC_x$ is the vector of calculated values using the point values of all variables except for i, $POINT_x$ is the point value of output variable x and VAR_x is a vector of percent change in the output variable x due to the variance of one input variable i.

Results of these calculations show the largest contributing factors are the number of cycles per year, remaining cycles of the battery, residual value of the battery pack, repurposing costs, and rack integration costs..

What is still unclear is to which parameters are the lifetime system cost and profit potential the most sensitive to. Since each input distribution has its own variance, it is not clear if the variance of the outputs is due to the sensitivity of the problem to that given parameter, or is due to the variance of the original input distribution.

The standard deviation of the distributions can be seen as a proxy metric for variation which can be normalized by the point value to allow for comparison between the input parameters.

$$Stdev\,\%_i = \frac{Stdev_i}{POINT\_VALUE_i} * [100\%]$$ **Eq. 18**

The normalized standard deviation of each input and resultant cost and profit distributions were calculated. A metric for sensitivity is calculated as the ratio of the normalized standard deviation of the output to the normalized standard deviation of the input parameter. Or more explicitly

$$SENSITIVITY\ COST = \frac{COST\ Stdev\%_i}{Stdev\%_i} \qquad \text{Eq. 19}$$

$$SENSITIVITY\ PROFIT = \frac{PROFIT\ Stdev\%_i}{Stdev\%_i} \qquad \text{Eq. 20}$$

Results of these calculations can be seen in Table 47.

Table 47: Overview of Results of Sensitivity Analysis. Green highlighted are most influential factors, grey do not apply to given Analysis

	Std dev %	COST Stdev %	SENSITIVITY COST	PROFIT Stdev %	SENSITIVITY PROFIT
Capacity at EOLv	13%	7%	0.57	4%	0.29
Cycles/year	43%	41%	0.96	21%	0.48
Remaining useful cycles	22%	70%	3.24	35%	1.63
System lifetime	19%	16%	0.80	8%	0.41
Residual Value	108%	76%	0.70	38%	0.35
Repurposing	107%	21%	0.20	11%	0.10
Integration system	0%	0%	0.00	0%	0.00
Integration cabinet	1653%	2%	0.00	1%	0.00
Integration rack	218%	58%	0.26	29%	0.13
Integration module	35%	1%	0.02	0%	0.01
Market Price	17%	0%	NA	26%	1.50

It can be seen that for some parameters, such as the module integration cost, have a large variance as an input parameter, but results in lower variance in the output resulting in a sensitivity metric of less than 1. Other parameters have a lower normalized standard

deviation than the resulting output standard deviation creating and therefore have a sensitivity metric of greater or equal to one.

It's interesting to note that of the three parameters affecting the battery exchange rate (cycles/year, remaining useful cycles, system lifetime) remaining useful cycles has the highest cost sensitivity metric of all the parameters, while the other two have a cost metric closer to 1. This is due to the role of the point estimate in the calculation of the variance distributions. For example the cost calculation when only the number of cycles per year was varied, the system lifetime and number of remaining useful cycles were held constant. Since the point estimate for the remaining useful cycles was taken as the distributions maximum, and assumed best case scenario, all scenarios calculated were limited to replacement requirements based on this extreme.

This can be seen in Figure 80 where over the range of inputs for number of cycles/year results in a number of lifetime replacements between 2 and 8, and for the range of System Life inputs between 3 and 4 replacements, while the range of replacements for number of remaining cycles is between 4 and12.

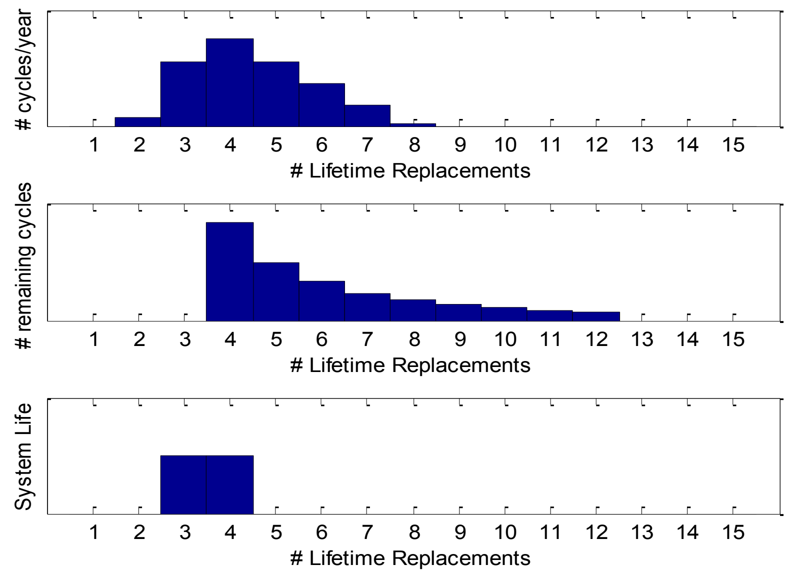


Figure 80: Histogram of Replacement Requirements for Sensitivity Analysis

10.2 Identification of Window of Opportunity

The second question that stems from the given results is what range of input parameters lend itself to a profitable scenario. This was done by separating the results shown in Figure 40 into two separate data sets (1) where profit is greater than zero named [PROFIT] and (2) where profit is negative of zero [NO PROFIT]. The distribution of input parameters for these two datasets were then compared (Figure 81).

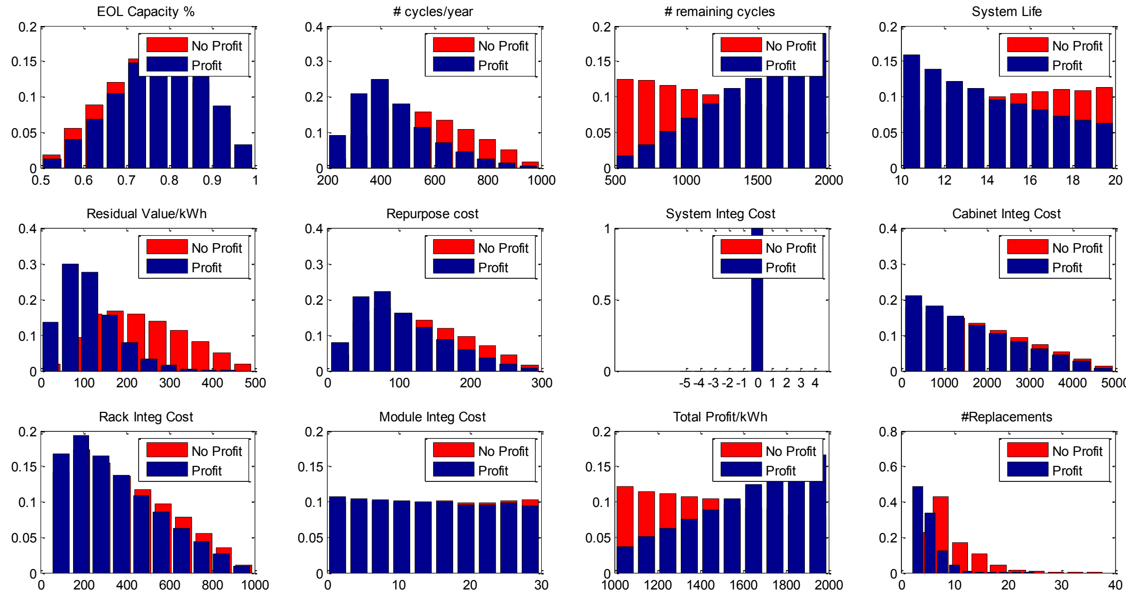


Figure 81: Comparison of Distributions of Input Variables for Profitable and Non-Profitable Scenarios

It can be seen that non-profitable scenarios are generally associated with systems using batteries with a slightly lower capacity, higher residual value, in applications with more cycles per year and longer system lifetimes where more replacement batteries are needed, and in a market with a lower system price ceiling.

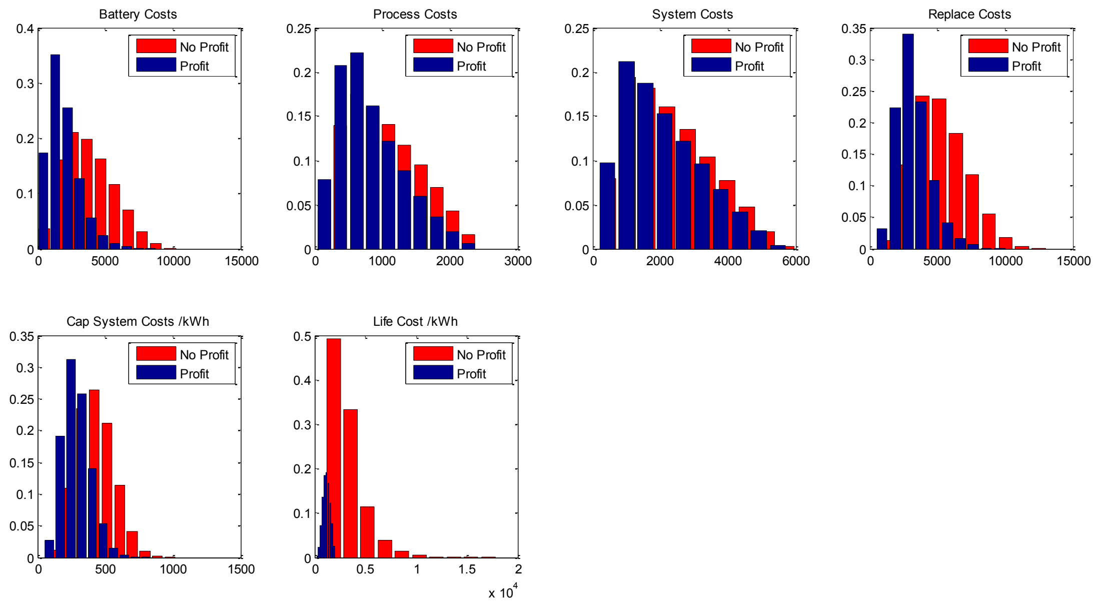


FIGURE 82: COMPARISON OF DISTRIBUTIONS OF COST OUTPUTS FOR PROFITABLE AND NON-PROFITABLE SCENARIOS

Looking at the comparison of the cost outputs in Figure 82, the largest discrepancy seems to be in number of replacement systems over the system lifetime, which would support the findings of the sensitivity analysis of the high dependence of profit and system cost on the number of remaining life cycles. Returning again to the number of replacements required (Figure 83). It can be seen that in some situations the system can be profitable even with five or more battery exchanges throughout the system lifetime. For a system life of ten years that would equate to a battery exchange every two years or more. From a customer's perspective this is assumed to be unacceptable. Therefore it is assumed that scenarios requiring more than five battery exchanges are impractical. A new data subset is then created that consists of scenarios that are both profitable and practical (number of replacements <=5) this subset will be referred to as [PROBABLE].

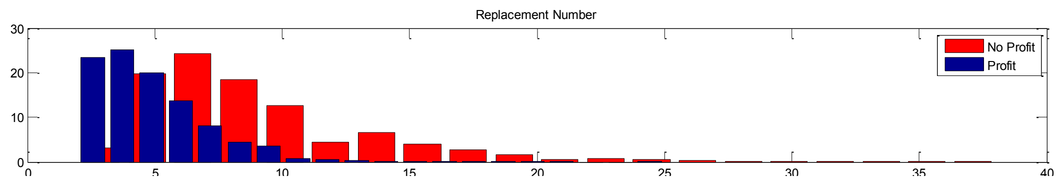


FIGURE 83: COMPARISON OF REPLACEMENT REQUIREMENTS FOR PROFITABLE AND NON- PROFITABLE SCENARIOS

The distribution of input variables that resulted probable scenarios can be seen in Figure 84.

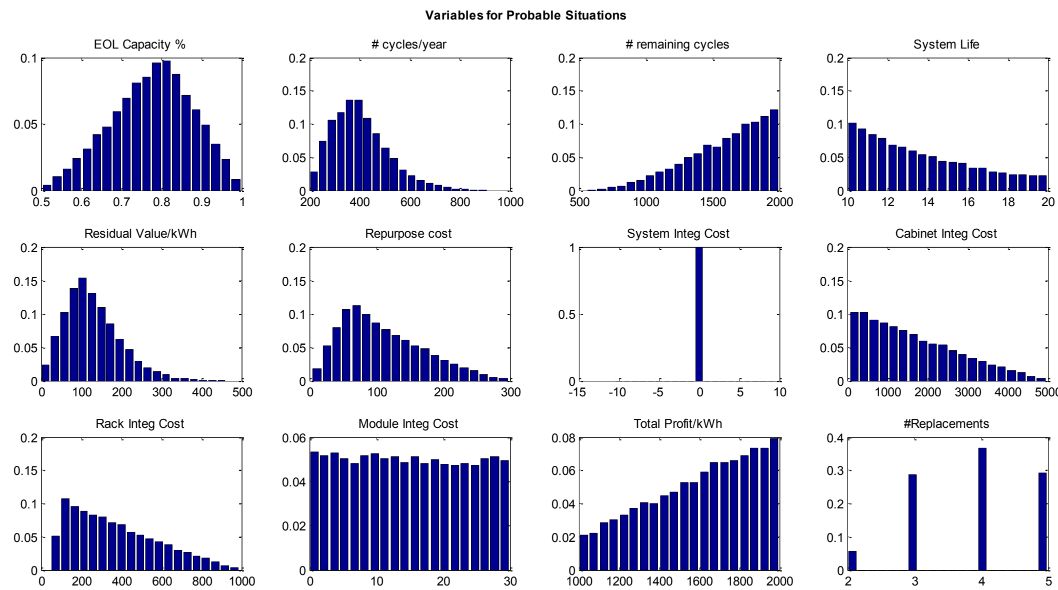


FIGURE 84: DISTRIBUTION OF INPUT PARAMETERS FOR PROBABLE SCENARIOS

From all scenarios calculated, 30% are profitable and 16.5% are probable. In order to determine what range of parameters will make a scenario profitable or not the original distribution (Figure 39) was normalized by the distribution in Figure 84. The results of which can be found in Figure 85.

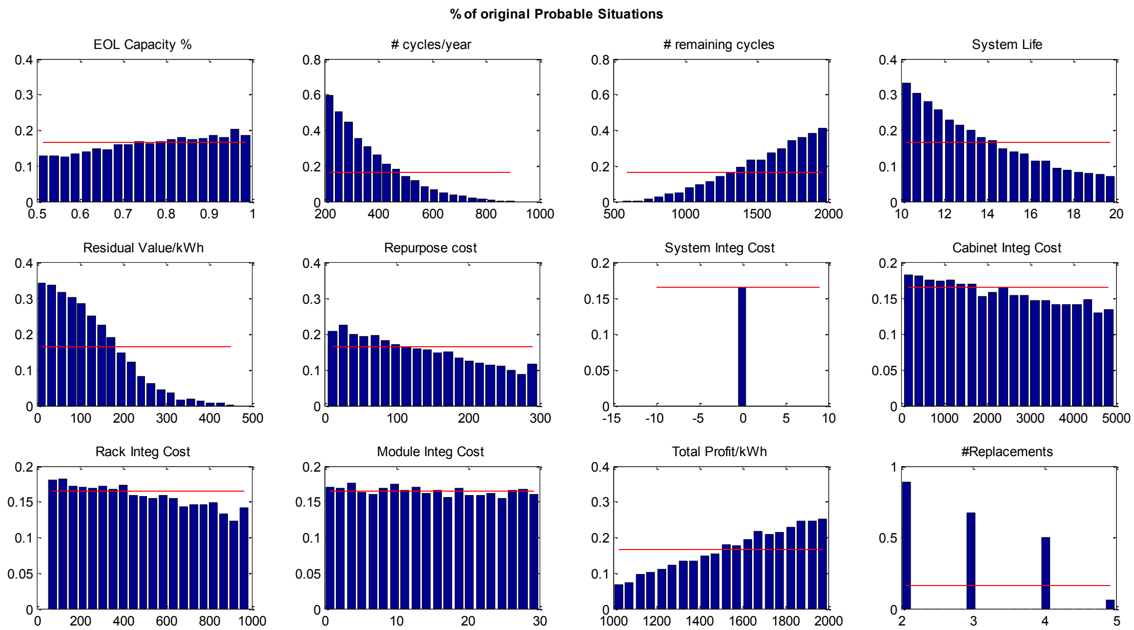


FIGURE 85: ANALYSIS OF DISTRIBUTIONS OF INPUT PARAMETERS FOR PROBABLE SITUATIONS

The y-axis is the percent of original scenarios for each bin in the histogram represented in the [PROBABLE] subset. The closer this value is to one, indicates its influence on making the scenario probable. That is to say for that given parameter, independent of the other parameters considered, the scenario will be in the [PROBABLE] subset. If a value of a given parameter (x-axis) does not contribute to making a scenario probable or not it will be around 16.5% (represented by the red line). Values less than 16.5% indicate that at value of that parameter it is not likely that the scenario will be [PROBABLE].

By comparing the distributions for profitable and non-profitable scenarios a window of opportunity can be identified. According to this analysis the window of opportunity would lie within the boundaries in Table 32.

Table 48: Updated Input Parameters for Second Monte Carlo Analysis

SYSTEM PARAMETERS	Level	unit	Distribution	Mean	Param 1	Param2
Capacity at EOLv	rack	%nom cap	triangle	80%	71%	100%
Cycles/year	system	cycles	triangle	400	200	502
Remaining useful cycles	rack	cycles	uniform	2000	1318	2000
System lifetime	system	year	uniform	15	10	15
COSTS						
Residual Value	capacity	€/kWh	triangle	100.00 €	- €	197.00 €
Repurposing	module	€/module	triangle	60.00 €	3.50 €	114.00 €
Integration						
	system	€/s	uniform	- €	- €	- €
	cabinet	€/cabinet	triangle	70.00 €	50.00 €	2,381.00 €
	rack	€/rack	triangle	100.00 €	50.00 €	450.00 €
	module	€/module	uniform	25.00 €	- €	30.00 €
REVENUE						
Market Price	Battery System	€/kWh	uniform	1,700.00 €	1,470.00 €	2,000.00 €

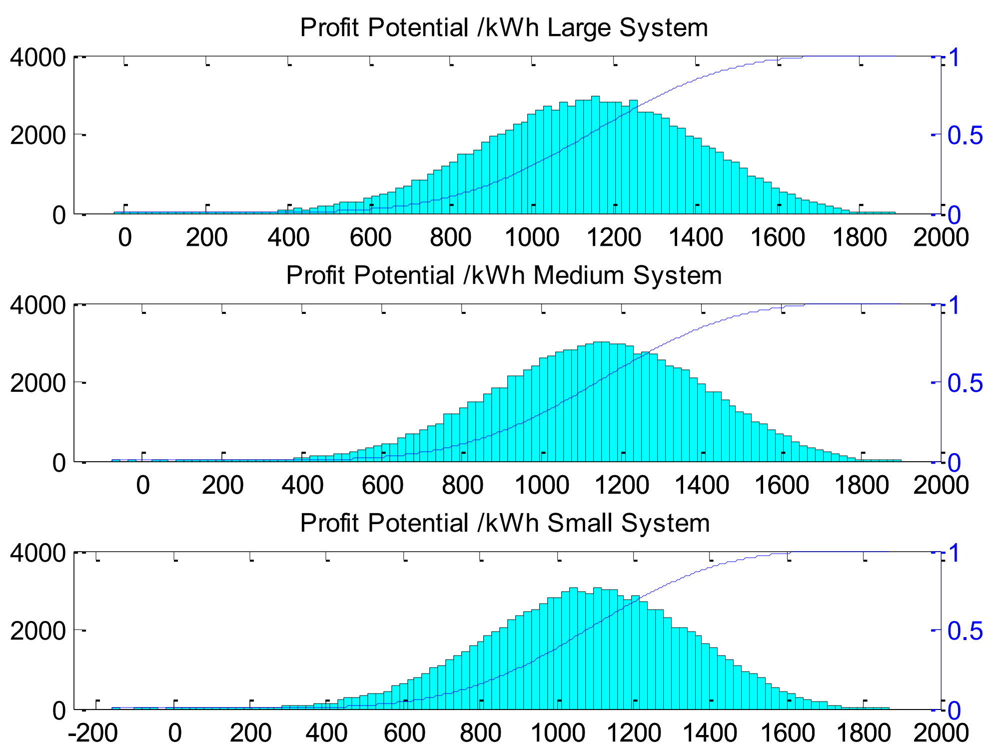


Figure 86: Results of Secondary Monte Carlo Analysis

TABLE 49: STATISTICAL SUMMARY OF RESULTS FOR SECONDARY MONTE CARLO ANALYSIS

	PROTFIT POTENTIAL/kWh										
	50% CDF	98% CDF	Point Value	Mean	Std Dev	Range	Min	Max	Std dev %	Range (+) %	Range (-) %
Large	1,143 €	1,630 €	1,130 €	1,135 €	259 €	1,918 €	- 25 €	1,892 €	23%	102%	67%
Medium	1,144 €	1,630 €	1,130 €	1,136 €	259 €	1,978 €	- 74 €	1,904 €	23%	107%	68%
Small	1,082 €	1,577 €	1,115 €	1,074 €	264 €	2,027 €	- 161 €	1,866 €	24%	114%	67%

As seen in Figure 41using the determined parameter windows the majority of scenarios (99.8%) are profitable. The non profitable situations are worst case extremes that require more than five battery replacements, with high system costs. Therefore the given parameters are deemed suitable limits to define a window of opportunity for battery second life.

10.3 TRADEOFF ANALYSIS

The following study was performed as an example to the type of trade off analysis needed in analyzing the potentials for a battery second life business strategy. The analysis consists of different battery return, repurposing, integration and second life scenarios. A summary of the scenarios can be found in Table 50.

TABLE 50: OVERVIEW OF SCENARIOS OF TRADEOFF ANALYSIS

	EOLv
1	3 years
2	5 years
3	10 years

	Mod/Pack
1	Module
2	Pack

	BMS
1	Vehicle
2	New

	System Size
1	Large
2	Medium
3	Small

	Aging Factor
1	1x Nom
2	2 x Nom
3	3 x Nom

	Run Time
1	10.00 €
2	15.00 €

	# Cycles/yr
1	400.00 €
2	1,000.00 €

	Market Price
1	1,500.00 €
2	2,000.00 €
3	3,000.00 €

The trade off analysis is accomplished by running each main function described in Section 4.3 once per scenario for each scenario input. For example if there are three battery return scenarios and two repurposing scenarios then the Battery Return main function will run for three iterations and the Repurposing main function will run for six iterations (See Table 51).

TABLE 51: SUMMARY OF SCENARIO NUMBER AND ITERATION REQUIREMENTS

Main Function	Battery Returns	Repurposing	Integration	Second Use
Scenarios	3	2	4	6
Iterations	3	6	24	144

The results of each iteration can then be compared and analyzed for each main function individually or across the entire modeled value chain.

10.3.1 VALUE CHAIN ASSUMPTIONS AND PREMISES FOR ANALYSIS

The purpose of this analysis is to evaluate the lifecycle and value chain costs. Therefore the time value of money and third party margins are not taken into account. It is assumed that the battery is to be returned to either a dealership or vehicle recycling facility, at which point the battery or vehicle owner might be compensated for the return of the battery based on its state of health and market price of the battery.

The battery is then shipped to a local refurbishment center, no more than 400km away. The refurbishment center is assumed to be similar to the one defined by Cready et al., capable of processing 2,500 EV battery packs per year. [18]

[18] Cready specified a facility of to process 62,500 modules per year and assumed a battery back consisted of 25-30 modules

After the batteries are refurbished the batteries are integrated into battery racks, retrofitted with new components when necessary and then shipped to the system integrator located no more than 400km away for final system assembly.

It is assumed that the second life battery system will be sold to the system integrator and not the final customer. Therefore the final cost of the system for this analysis is the final battery system cost, which does not include the price of the power electronics, enclosures, and other balance of system components. Operation and maintenance costs are those relating only to the battery system, specifically to need to exchange packs or modules during the entire system's lifetime.

A summary of costs and revenues for the value chain described above is illustrated in Figure 87.

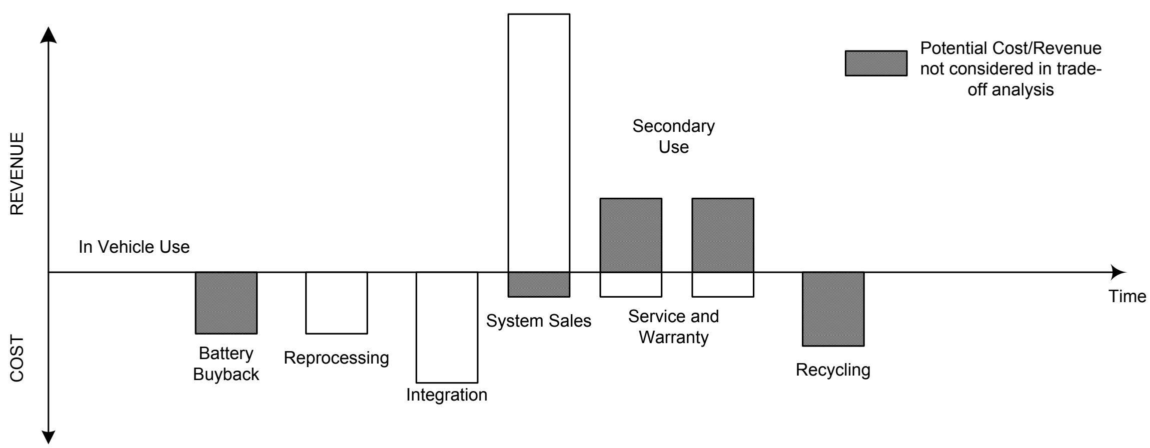


FIGURE 87: OVERVIEW OF CASH FLOWS FOR VALUE CHAIN BEING ANALYZED

BATTERY RETURN SCENARIOS

This analysis will evaluate the impact of the batteries coming back after three, five, and ten years in the vehicle. The capacity of the battery is modeled as a Weibull distribution defined base shape and scale parameters that change as a function of time.

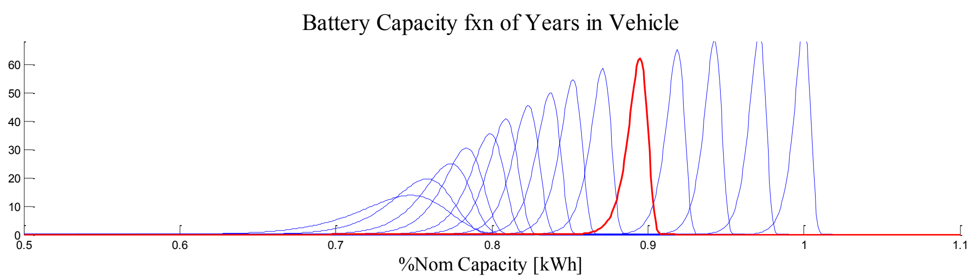


FIGURE 88: EXAMPLE OF MODEL USED FOR BATTERY RETURN MODEL

Parameters for the Weibull distributions were extrapolated from results of a warranty prediction analysis similar to the one described in Section 8.1.2. For proprietary reasons the number have been altered slightly, but are still considered sufficient for the level of analysis conducted here.

It is assumed that the buyback price of the packs is zero, and all packs returning are of the same battery system design with the following parameters.

TABLE 52: VEHICLE BATTERY SYSTEM ARCHITECTURE

			S	P	
SYSTEM LEVEL					
	Pack	2			
	Module	3	8.0	1.0	Modules/Pack
	Cell	4	12.0	1.0	Cells/Module

	Cap [kWh]	Cap [Ah]	V nom [V]
Cell	0.22	60.00	3.72
Module	2.68	60.00	44.64
Pack	21.43	60.00	357.12

BATTERY REPURPOSING SCENARIOS

The effects of two generic battery repurposing scenarios will be analyzed; namely the reuse of the entire battery pack or just the battery modules. The main difference between these two reprocessing scenarios is the additional disassembly needed for module level repurposing.. Cost assumptions for the two scenarios can be found in Table 53.

TABLE 53:REPURPOSING PARAMETERS

PROCESS	€/pack	Source
Transportation to Reprocessing Facility	133.00 €	BMW Project 1 (400km, 400€/ton)
Disassembly	95.00 €	2.5 hrs @ 38€/hr
Testing and Inspection	532.00 €	Based on repurposing procedure described by Neubauer et al. 24.62€/kWh @21.4kWh/battery
Transportation to System Integrator	133.00 €	See transportation assumptions above
TOTAL	893.00 €	

INTEGRATION SCENARIOS

For this analysis a total of 12 different integration scenarios were considered.

TABLE 54: INTEGRATION SCENARIO INDICES

SCENERIO NUMBER	LARGE SYSTEM (~2MWh)		MEDIUM SYSTEM (~100kWh)		SMALL SYSTEM (~ 10kWh)	
	PACK	*MOD*	*PACK*	*MOD*	*PACK*	*MOD*
VEH BMS	1	7	2	8	3	9
NEW BMS	4	10	5	11	6	12

The system architecture for each given system size can be found in Table 55. Numbers in the 'S' and 'P' columns represent the number of sub-systems connected in series and parallel for that given system level. For example for the large system there are 12 cells connected in series to form a module; 16 modules in series to create a rack; three racks connected in parallel to form a power cabinet; and 20 power cabinets connected in parallel to form the entire system.

TABLE 55: OVERVIEW OF SYSTEM ARCHITECTURES USED IN TRADE OFF ANALYSIS

SYSTEM ARCHITECTURE					
SMALL SYSTEM (~ 10kWh)	*System*	0	**S**	**P**	
	Power Cabinet	1	1	1	Cabinet/System
	Rack	2	1	1	Racks/Cabinet
	Module	3	8	1	Modules/Rack
	Cell	4	12	1	Cells/Module
MEDIUM SYSTEM (~100kWh)	*System*	0	**S**	**P**	
	Power Cabinet	1	1	1	Cabinet/System
	Rack	2	1	3	Racks/Cabinet
	Module	3	16	1	Modules/Rack
	Cell	4	12	1	Cells/Module
LARGE SYSTEM (~2MWh)	*System*	0	**S**	**P**	
	Power Cabinet	1	1	20	Cabinet/System
	Rack	2	1	3	Racks/Cabinet
	Module	3	16	1	Modules/Rack
	Cell	4	12	1	Cells/Module

The architectures were chosen as representative of what a small, medium, and large system might look like. It should be noted that actual system architectures will be subjected to technical limitations mentioned in Section 3.

Costs associated with using a new BMS or adapting components from the vehicle can be found in Table 56.

TABLE 56: OVERVIEW OF COST PARAMETERS FOR INTEGRATION SCENARIOS

		Component	Price	Qty/System level	System level
NEW BMS	1	Cabinet Level BMS	500.00 €	1	1
	2	Rack Level BMS	200.00 €	1	2
	3	Module Level BMS	25.00 €	1	3
VEH BMS(M)	1	Cabinet Level BMS	2,000.00 €	1	1
	2	Rack Level BMS	500.00 €	1	2
VEH BMS(P)	1	Cabinet Level BMS	2,000.00 €	1	1
	0				

Number chosen from above are from best guess estimates based on numbers reported in Table 43.

For each scenario 10 storage systems will be modeled in order to capture the variances in secondary system capacity due to the variance in the capacity of battery systems returning from vehicle use.

SECOND USE SCENARIOS

For this analysis a total of 36 second life scenarios were considered, which consists of three different aging rates; two overall system lifetimes; cycle requirements for two different types of applications; and three different competitive pricing scenarios (Table 57).

TABLE 57: OVERVIEW OF PARAMETERS FOR SECOND LIFE MODELS

Aging Factor	1	2	3
System Run Time	10	15	
Application cycles/year	400	1000	
Market Competitive Price	2,000.00 €/kWh	3,000.00 €/kWh	1,500.00 €/kWh

The aging factor is a multiplication factor of the original cell aging rate specified in the vehicle design input parameters. The original cell specification is 2000 cycles until it degrades to 80% of its nominal original capacity and if the aging factor is two, then the battery will degrade to 80% of its nominal original second life capacity in 1000 cycles.

The system run time is the lifetime of the entire energy storage system, not just the run time of the batteries. And will be used to determine the number of battery replacements required.

Application cycles per year are the average number of yearly cycles the system is expected to perform over its lifetime. The values chosen represent high and low cycle applications. For more information about the types of applications these numbers correspond to can be found in Figure 71.

The market competitive price represents the maximum lifetime sales price of a battery system including required battery exchanges over the system lifetime. These

numbers are similar to those used in the preliminary screening analysis (See Section 10.1.1).

10.3.2 Results

The following will review the results of the tradeoff analysis. Figure 89 shows an example interaction plot of the input variable on the mean cost per kWh for the ten systems modeled in each scenario.

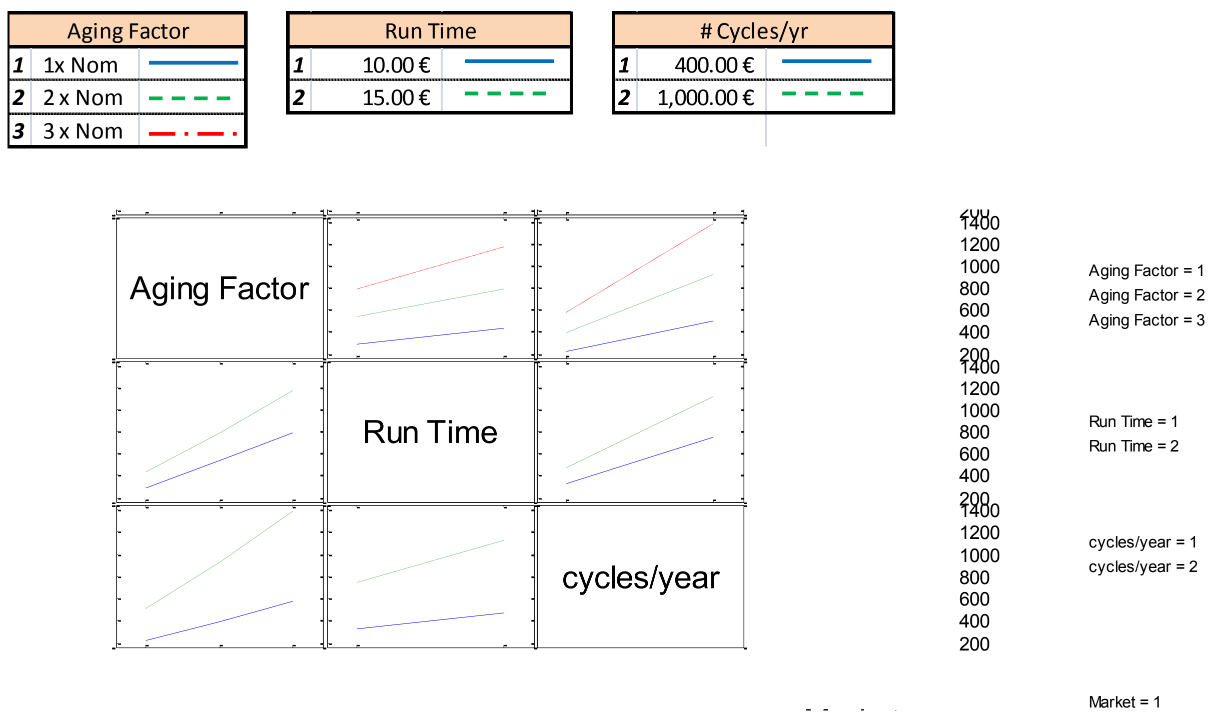


Figure 89: Example of Interactions Plot for Tradeoff Analysis

Figure 42 shows the potential profit per module which was calculated as follows

$$PROFIT_{Mod} = \frac{PROFIT_{Sys}}{\#mod_{sys} * \#batt_{exchange}}$$ **Eq. 21**

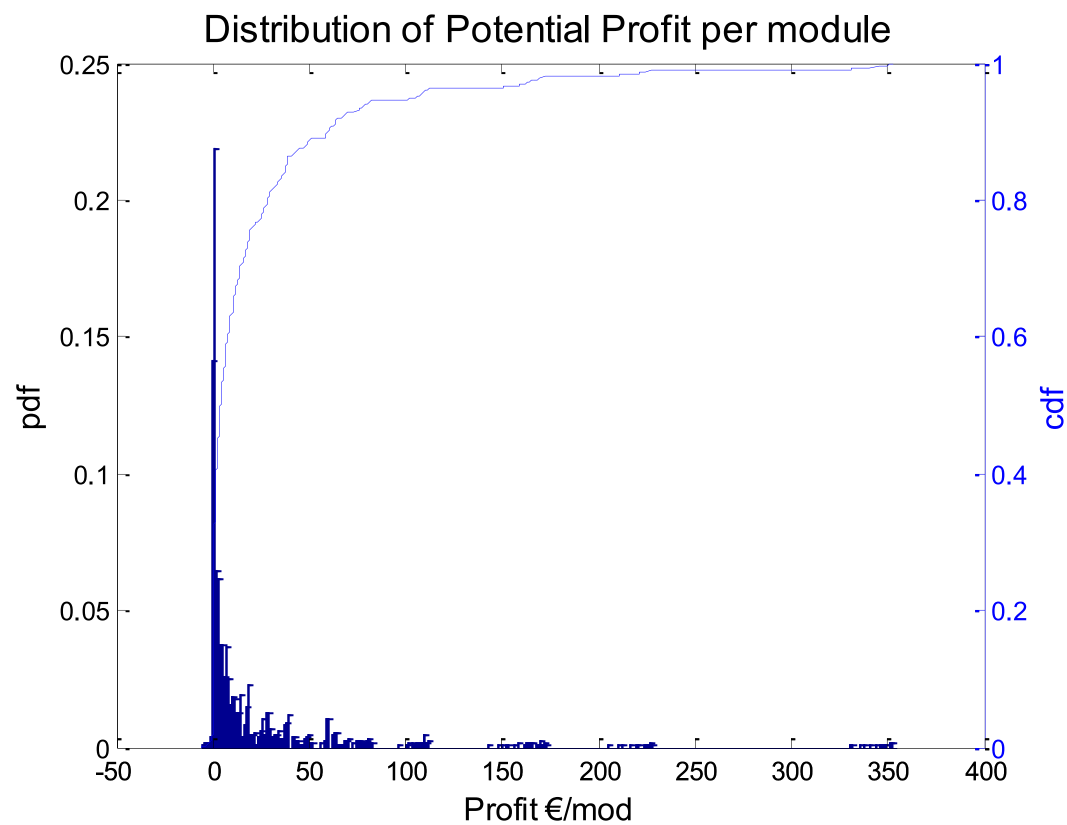


FIGURE 90: DISTRIBUTION OF PROFIT PER MODULE FOR ALL SCENARIOS

It can be seen that about 80% of scenarios result in a per module profit of less than 28€. Scenarios clustered around 350€/module and 200€/module correlate to modules used in the large system, with a 2000 cycle life, and are sold for 3,000€/kWh and 2,000€/kWh respectively.

To better understand the interaction of the input parameters the details of these results will be further discussed in the following sections.

Tradeoff Analysis 1: Effects of battery return capacity and system capacity
Tradeoff Analysis 2: Effects of system size and component requirements
Tradeoff Analysis 3: Aging factors and replacement requirements
Tradeoff Analysis 4: Market Price

Tradeoff Analysis 1: *Effects of battery return capacity and system capacity*

Figure 91shows the distribution of system capacities for each system size. It can be seen there are three distinct distributions for each system size which corresponds to the three different vehicle return scenarios.

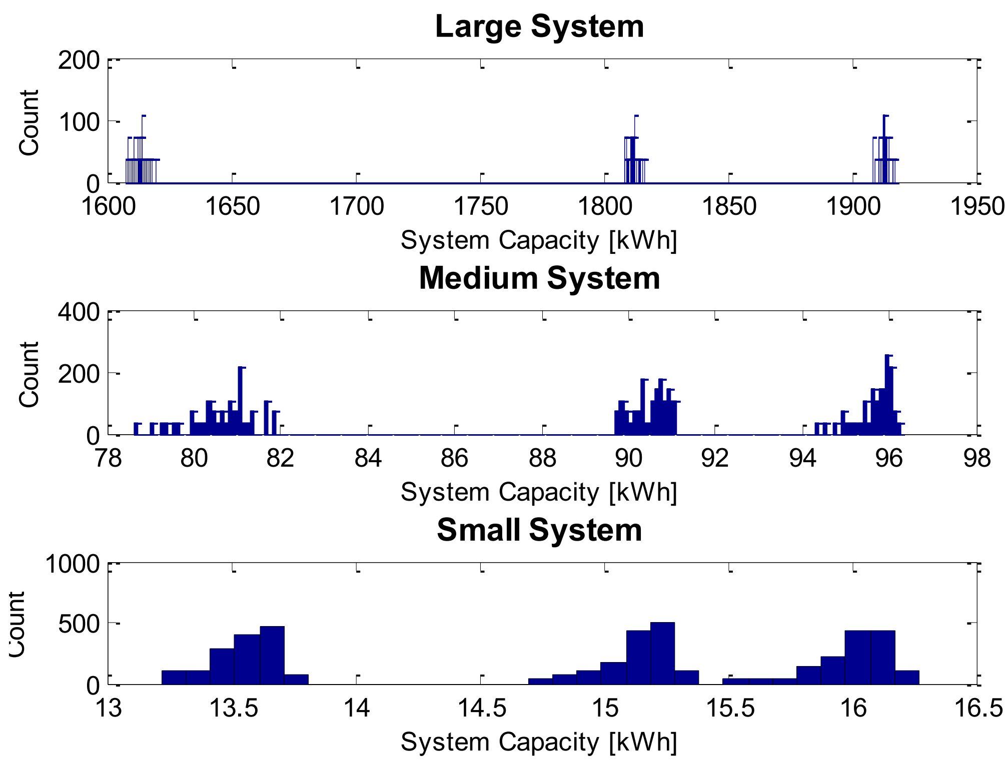


Figure 91: Distribution of Secondary System Capacities

The plots show that for all three system sizes, the variations for the distributions furthest to the left are the largest, which corresponds to the scenarios where batteries return after 8 years in the vehicle. This corresponds to the variation in the capacity variation of the returning packs, which increases the longer the batteries stay in the vehicles.

The first row of distributions in Figure 92, shows the capacity of battery packs for the given end-of-life criteria (left to right 3,5 and 10 years), relative to the initial rated capacity of the vehicle battery system. The second through fourth row of Figure 92 shows the relative usable capacity of the systems using randomly selected battery packs or modules from the packs represented in row one. Where the percent capacity shown in rows two to four are relative to a system being built with new batteries.

For example the small system would have a rated capacity of 21.4kWh if it were to use a new battery which is considered here to be the "Nominal System Capacity". With used batteries the system has a rated capacity of 16kWh and therefore is 74,7% of the nominal system capacity.

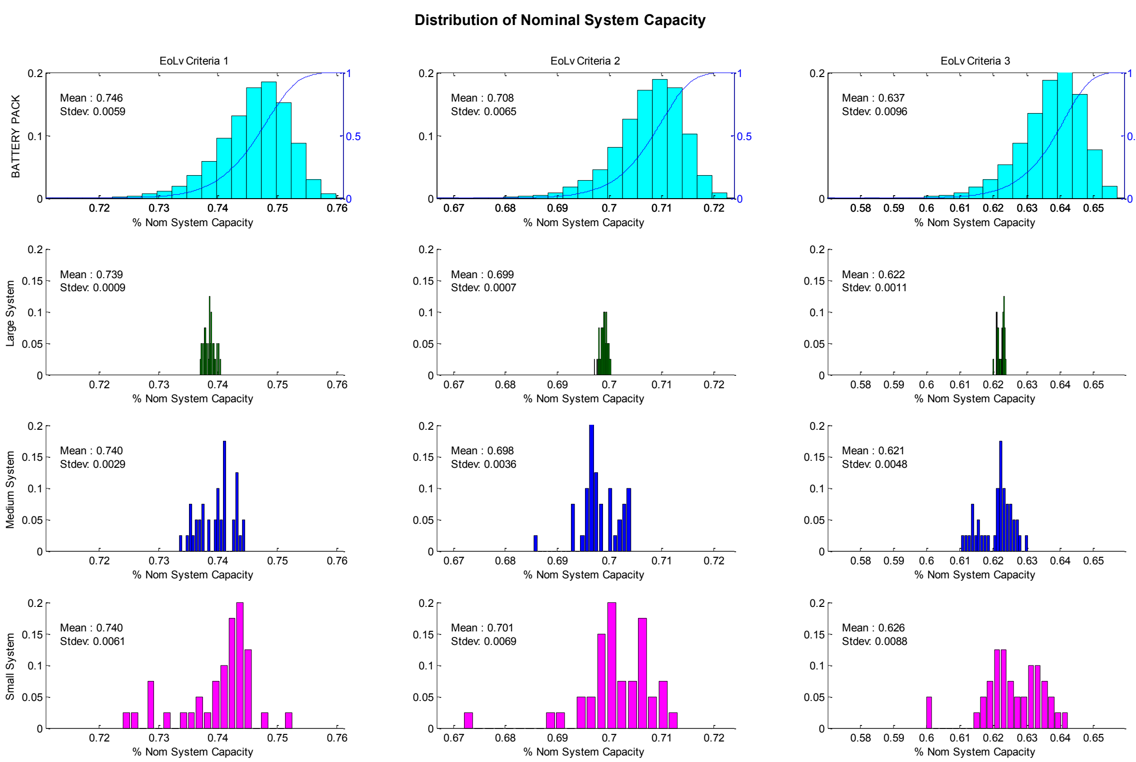


FIGURE 92: COMPARISON OF RELATIVE VEHICLE SYSTEM CAPACITY TO RELATIVE SECONDARY SYSTEM CAPACITY

It can be seen that the random combination of packs or modules into a system results in an overall stationary system capacity that is generally lower than the capacity of packs coming out of the vehicle. In all cases the average capacity of resultant stationary storage system is around the tenth percentile of the capacity of returned batteries. For the given analysis the effects aren't drastic, due to the relatively low standard deviation in the capacity of the returning batteries. But it suggests that if the variance in capacities were higher, a pre sorting of the batteries according to aged properties would be necessary.

This phenomenon can also potentially have a negative effect on the profitability of a battery second use strategy if the batteries are purchased from the vehicle owner for a price dependent on the usable capacity of the vehicle battery system, and the stationary system is sold at a price dependent on its usable capacity.

For the given example the resulting profit loss could be seen as, for the most part, negligible, due to the low variability in the SOH of returning batteries. Looking at the worst case scenario (10 years in the vehicle and integrated into a small system), and assuming no used product discount factor

$$[LOSS]_{kWh} = \left([\%\ mean\ cap]_{vehbatts} - [\%\ mean\ cap]_{system}\right) * [PRICE_{market}]_{kWh} \quad \text{Eq. 22}$$

the average loss would be 1.1% of the market price. Assuming a capital cost of 600€/kWh losses would be 6.60€/kWh or approximately 132€/pack. This implies that even if no reprocessing was performed and there were no addition component, logistics, or labor costs the value of all battery systems would lose an average of 132€/pack when integrated into a secondary application.

This is an extreme scenario and it will most likely be the case that the battery return price will be a percentage of the market price. But if the variance between battery systems is relatively large this type of analysis would be helpful in determining additional requirements for battery testing and sorting in addition to justifying the additional associated costs. This also implies that if the variance between packs is small enough, extensive battery testing will not be necessary, which can reduce costs by eliminating the need for battery testing equipment, facilities, and labor.

Tradeoff Analysis 2: *Effects of System Size and Component Requirements*

The following will look at the influence of component requirements and their capital costs for different system sizes. It should be noted that the cost of repurposed batteries does not include a battery buyback from the vehicle owner. Therefore if the batteries must be purchased from the vehicle owner the cost associated with the repurposed batteries is expected to increase significantly. Since it is currently uncertain what types of incentives (if any) are to be used for ensuring battery returns, this parameter was omitted in order not to obstruct the analysis of the other contributing factor. When more information is available the effects of the buyback price of the battery can be included.

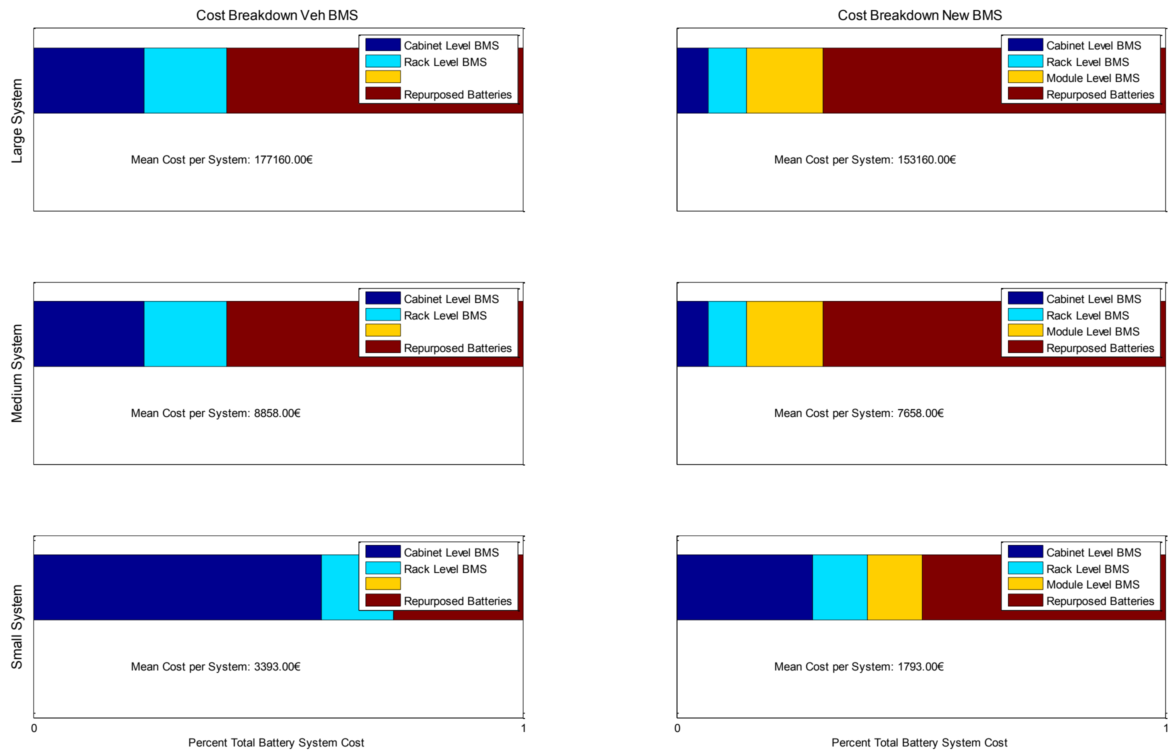


FIGURE 93: RELATIVE COST BREAKDOWN PER SYSTEM FOR EACH SYSTEM SIZE AND INTEGRATION CONCEPT

Figure 93 shows the cost breakdown for each system size using the vehicle BMS or a new BMS. It can be seen in most cases the total price of the system is driven by the cost of the repurposed batteries, which accounts for approximately 50-70% of the system cost . The exception to this is a small system using the vehicle BMS (where the batteries are only 30% of the total system costs) which is driven more by the cabinet level BMS. In all cases the cost of the system using a new BMS is cheaper than systems utilizing the BMS from the vehicle.

For medium and large systems using a new BMS, of the three BMS components, the module level BMS is the predominant cost factor at 15% followed by the rack level BMS at 7% and cabinet level at 6%.

The similarity in price distribution between components for the large and medium system is due to the chosen system architecture in which the large system is a scaled version of the mediums system where in both use the same base architecture.

Figure 45 shows the same cost breakdown but on a per module basis.

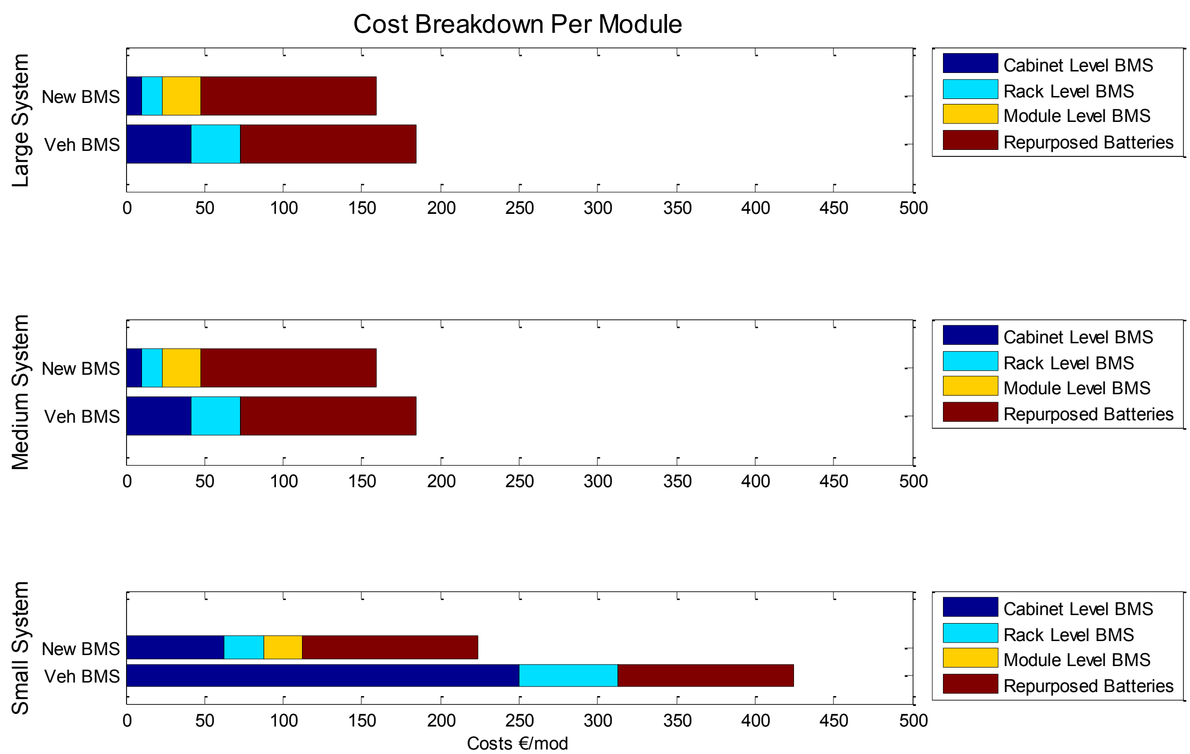


Figure 94: Absolute Cost Breakdown per Module for Each System Size and Integration Concept

For the medium and large systems the per module cost difference is 28€ between the vehicle and new BMS scenarios, while the difference for the small system is 200€. The per module cost for the small system is 64€ and 312€ more expensive than the other two systems when using a new BMS and the vehicle BMS respectively.

It should be noted that the prices used for system integration using the vehicle BMS are representative of low volume systems, and therefore due to the absence of economies of scale are relatively high. In the same respect the order of magnitude would also be representative of scenarios where custom interfaces are required for each battery system. Explicitly when there is no industry standardized interface for used or new battery systems. If there was a standardized interface it would be logical to assume the cost of the vehicle based BMS would drop below the costs of the new BMS system.

Tradeoff Analysis 3: *Aging Factors and Replacement Requirements*

The following shows the relationship between the three input parameters affecting the number of battery replacements

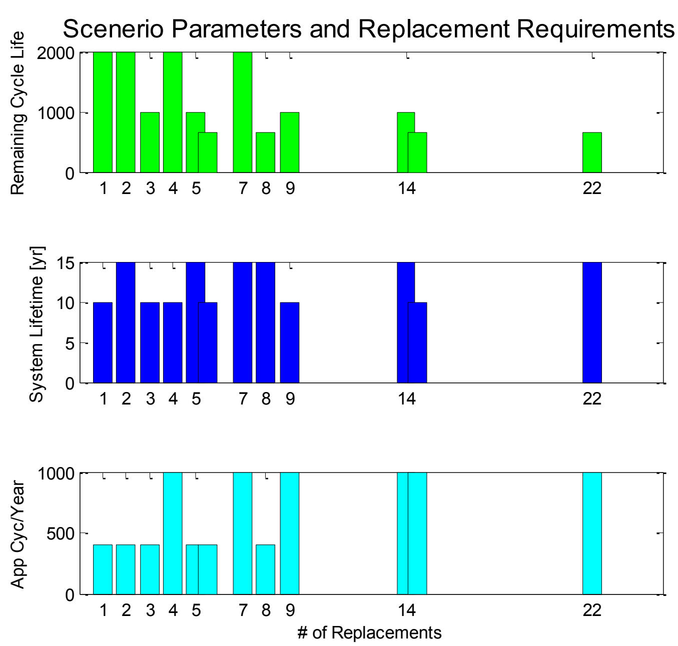


FIGURE 95: RELATIONSHIP BETWEEN LIFECYCLE FACTORS AND REPLACEMENT REQUIREMENTS

It can be seen that for the12 given aging scenarios (2 system lifetime, 2 application cycles/year, and 3 remaining life cycles) only half meet the “practical criteria” of five exchanges during the system lifetime or less. And of those six only one scenario allows the higher cycle number per year, and two for a longer system lifetime of 15 years. This is consistent with the findings in the preliminary parameter screening in Section 10.2.

Looking at the effects of battery replacement on overall lifetime system cost, it is obvious the more battery exchanges required the larger the influence of the replacement cost of the batteries.

10.4 Assessment of Potential Temporal Effects on Business Feasibility

The following analysis is to evaluate the temporal effects on the costs involved with battery second use. This includes the effects of technology improvements, cost reduction, and various end-of-life vehicle scenarios.

10.4.1 Inputs and Assumptions

This study is conducted from the point of view of an OEM engaging in a battery second use strategy or third part reseller who purchases batteries from electric vehicle owners or dealerships. In either case the OEM or reseller repurposes the packs and then sells them to a system integrator at the market price for lithium ion battery systems. The option of selling the batteries directly to the end customer as part of a service contract is also discussed.

This analysis uses two projections for the development of lithium ion battery technology in addition to subset of the analysis from Section 4.4.2.

The first projection is for the market price of electric vehicle battery systems. Due to the lack of other indicators and simplicity for this analysis it is assumed that the market price of an electric vehicle battery is also representative of the market price for stationary storage systems. The decrease in cost is presumed to be due to improvements in both manufacturing capability and in cell chemistry (*i.e.* higher energy density).

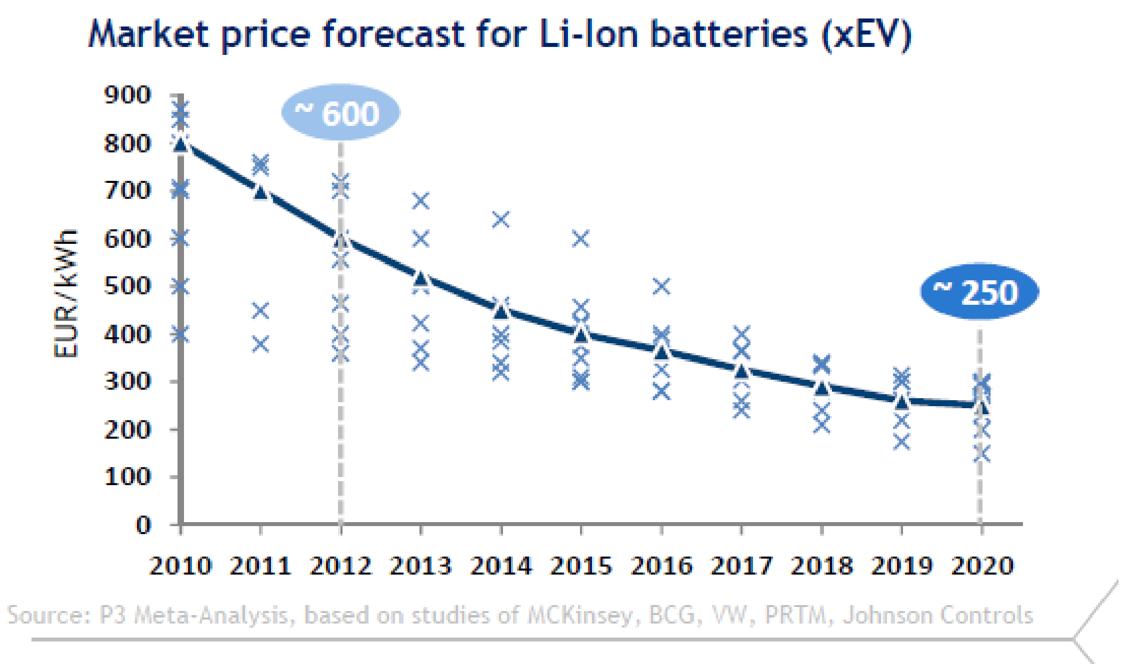


FIGURE 96: MARKET PRICE FORECAST FOR EV LI-ION BATTERIES USED FOR ANALYSIS [120]

Given the data from Figure 96, it is assumed that after 2020 the cost of Lithium ion battery systems will remain at 250€/kWh. It should be noted that the market price used in this analysis is the initial purchase price of the battery and not the lifecycle system cost of the battery as assumed in Section 10.1.

In Section 10.1 it was assumed that the customer would only buy the battery system if it met the lifetime cost and performance level of competitive technologies. For a given

business case scenario this would correspond to a supply or warranty agreement made with the initial purchase of the stationary system. For this analysis a slightly different sales concept is assumed in which batteries are assumed to be a commodity. As such it is assumed that they will be sold at the market price at the point in time which they are removed from the vehicle and placed into a secondary application. This method is used for this analysis in order to assess if a supply contract or warranty agreement would make sense given the changing dynamics of the market; and the terms of such a contract if it appears to be a logical business decision.

For this analysis it is assumed that the battery will be purchased from the vehicle owner for 50% of the current market price, and the secondary stationary storage system sold at the full market price.

The second projection is for the improvement in battery technology (i.e. energy density or specific energy capacity). For this analysis it is assumed that improvements in technology are for energy density only and does not influence the cycle life of the battery. If the lifecycle of the system were under investigation it would be critical to include the effects of improving lifecycle. This study only considers the initial purchase price and therefore lifecycle is not a contributing factor.

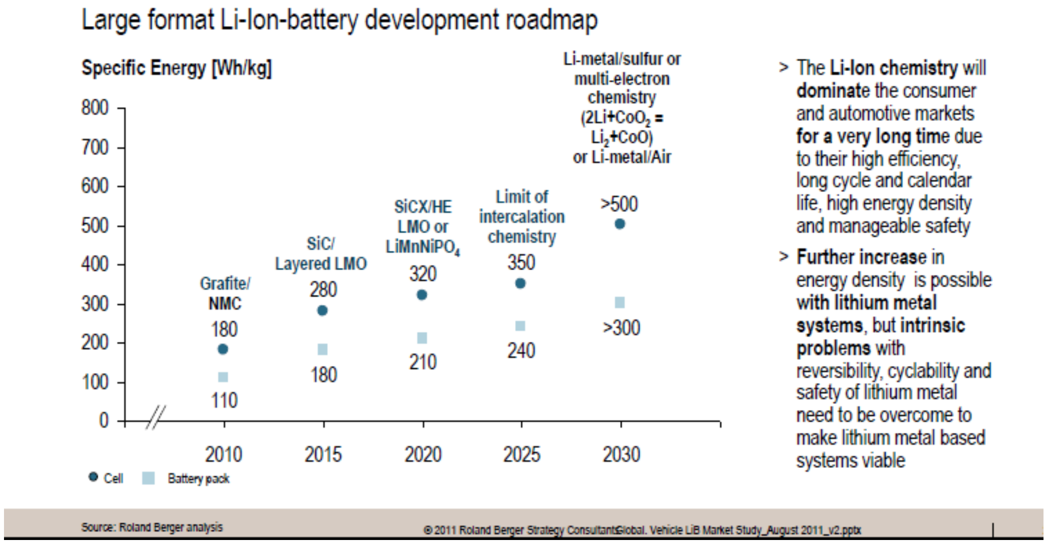


FIGURE 97: LI-ION TECHNOLOGY DEVELOPMENT FORECAST [109]

Assuming the architecture of the battery pack in question doesn't change, it is assumed that an improvement in energy density will increase the usable capacity of the battery pack. For example a battery system originally with 20kWh capacity (with Graphite/NMS) will have a technological successor with a capacity of 32.7kWh using the next generation cell (SiC/layered LMO).

For this analysis it is assumed that there is a three year delay between the introduction of a new battery technology into the market and the availability of that technology in a vehicle. For example the Fig X shows SiC/Layered LMO cells will become commercially available in 2015, it is assumed that the first vehicle using this technology will not come onto the market until 2018.

Using the data from Figure 96 and Figure 97, the following projection of relative EV system capacity and cost is used for this analysis Figure 46.

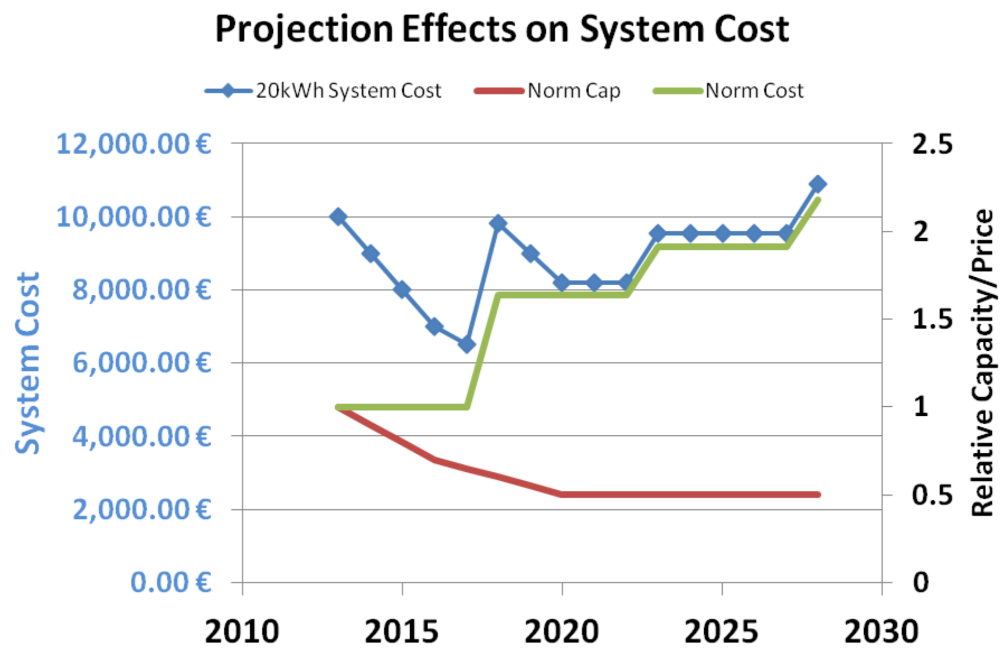


FIGURE 98: TECHNOLOGY IMPROVEMENT AND COST ASSUMPTIONS FOR ANALYSIS LOOKING AT EFFECTS OF CHANGING MARKET CONDITIONS

Figure 46 also shows the interaction of the two projections by calculating the cost of a system with an original capacity of 20kWh. It is assumed that when the next generation cell is available, the cell is exchanged one for one in the battery system. Therefore in 2018 the 20kWh system increases to a capacity of 32.7kWh, 2023 to 38.2kWh, and in 2028 to 43.6kWh.

It can be seen that the largest in price stability will be between 2013 and 2020 when both technology and price will be changing the most drastically.

A subset of data from Section 0 is used to determine stationary system capacity, repurposing and integration costs, and replacement intervals. For this analysis data was limited to scenarios with the following parameters.

TABLE 58: REDUCED SCENARIO SET FOR FURTHER ANALYSIS; SCENARIOS IN GREY HAVE BEEN REMOVED FROM THE DATASET

	EOLv
1	3 years
2	5 years
3	10 years

	Mod/Pack
1	Module
2	Pack

	BMS
1	Vehicle
2	New

	System Size
1	Large
2	Medium
3	Small

	Aging Factor
1	1x Nom
2	2 x Nom
3	3 x Nom

	Run Time
1	10.00 €
2	15.00 €

	# Cycles/yr
1	400.00 €
2	1,000.00 €

	Market Price
1	1,500.00 €
2	2,000.00 €
3	3,000.00 €

10.4.2 METHOD

This analysis looks at the amount of potential profit per module dependent on how long the battery was in the vehicle and the current market price for the battery.

It is assumed that the first vehicles are sold starting in 2013. The time, at which the batteries from these vehicles are bought back, repurposed, integrated into a new system, and sold to the final customer, is dependent on the vehicle return scenario. The relationship between vehicle sell date, vehicle return scenario, and secondary system sell date can be seen in Figure 99.

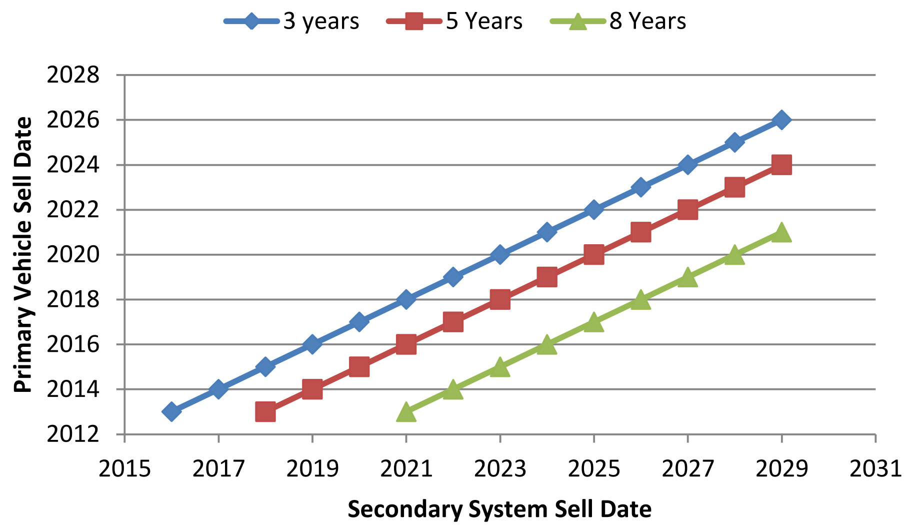


Figure 99: Battery Availability Based on Sale Date of Vehicle and End-of-life Criteria

Therefore secondary systems sold in 2021 will contain battery systems from vehicles sold in 2013 assuming an initial vehicle life of 10 years, 2016 for a return scenario of 5 years, and 2018 for a return scenario of 3 years.

The cost for purchasing the batteries from the vehicle owner is determined by the market price (€/kWh) and the remaining capacity of the battery (kWh). The remaining capacity is determined from the purchase date of the vehicle and the number of years the battery was in the vehicle.

The relative remaining capacity of the battery is available from the analysis in Section 10.3, which can be scaled by the vehicle system size and technology improvement factor.

$$Cap_{veh} = [\%\ Nom]_{Eolv}[Tech]_{veh\_sell}[CAP_{nomsys}] \quad \textbf{Eq. 23}$$

Where

$[\% \, Nom]_{Eolv}$: is determined in the Battery Return Model (Section 10.3)

$[Tech]_{veh\_sell}$: is the relative technology capacity improvement factor (Figure 46)

$[CAP_{nomsys}]$: Nominal system capacity of the original vehicle battery system

It is assumed that the used battery can be purchased at 50% of the market price. Therefore the buyback price of the battery is

$$COST_{purchase} = Cap_{veh}[Price_{market}]_{kWh}[50\%] \quad \textbf{Eq. 24}$$

Earning generated through the sale of the secondary battery system can be calculated as follows

$$EARNINGS_{sys} = [Price_{market}] * [Cap_{System}] \quad \textbf{Eq. 25}$$

The profit for the system is calculated as follows

$$PROFIT = EARNINGS_{sys} - \sum Price_{purchase} - Cost_{refurb} - Cost_{integ} \quad \textbf{Eq. 26}$$

The refurbishment costs and integration costs are determined from the data from Section 0.

10.4.3 Results

The method was used to analyze all three system sizes from Section 0, for three vehicle return scenarios. The results of one system size will be discussed here in detail. The results of the other two scenarios are very similar and can be found in the Appendix.

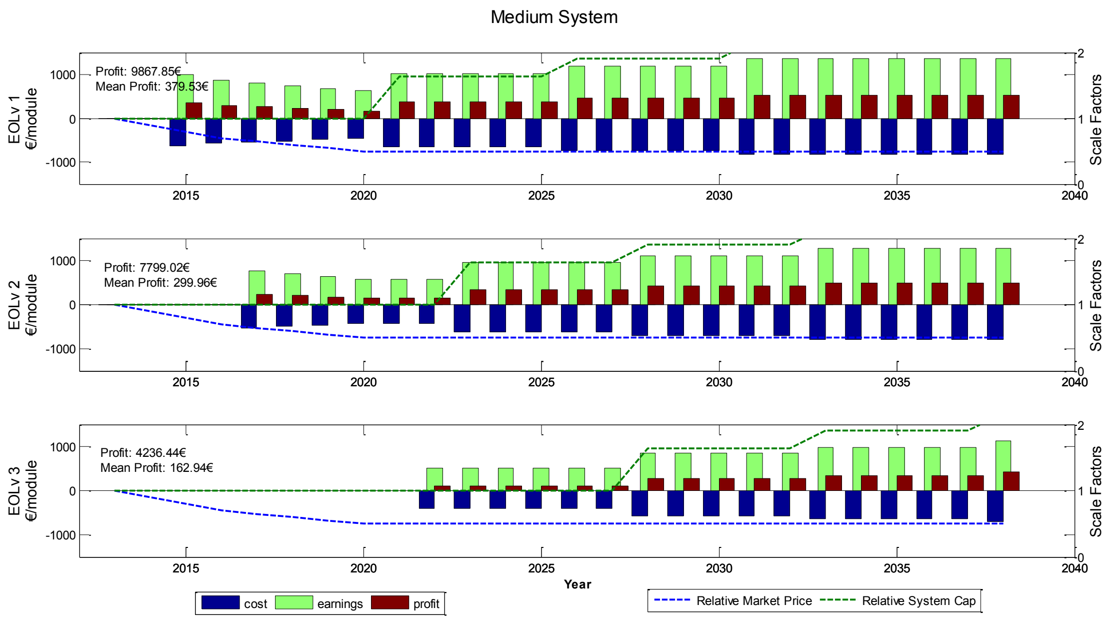


Figure 100: Cash Flow for Secondary Systems as a Function of Time

Figure 47 shows the cost, earnings and profits for systems sold each year for each of the three vehicle return scenarios. For reference the relative market price and relative system capacity of batteries being integrated into the secondary systems are plotted on the right axis. Both parameters are relative to the price and size (kWh) of the original vehicle system sold in 2013.

It can be seen that for the battery return scenario of three years (EOLv 1), second generation systems are first available at the end of 2015. Between 2015 and 2020 the amount of potential profit per module steadily decreases from 313€ to 168€. In 2021 the first second generation batteries are available increasing the usable capacity of the

stationary storage system. At this point the market price of the battery has stabilized and the potential profit per module remains at 366€ (118% increase from 168€) until 2025 when the generation three batteries become available. The third generation batteries provide a profit of 450€/module, a 23% increase from generation two. Over the time period analyzed the average profit per module is 379€/module.

For the second battery return scenario (EOLv2), in which the batteries return after five years. The first batteries return in 2017 and bring in a potential profit of 196€/module. This is about 25% lower than the potential profit of the three year old batteries returning the same year at 261€/module, due to the lower usable capacity per module of the older batteries. Between 2017 and 2022 the profit per module decreases to 150€/module when the market price stabilizes in 2020. In 2023 the second generation batteries become available for secondary use increasing profits by 124% to 336€/module. Prices remain steady until 2028 when the availability of the third generation batteries increases profits by 24% to 415€/module. Over the period analyzed the average profit per module is 300€.

The final battery return scenario (EOLv3) has the batteries returning after 10 years of vehicle use, which means the first batteries are not available until 2022. At this point the price of the battery market is stable and potential profits hold steady at 73€/module, almost 50% less than the profit from 5year old modules sold in the same year due to a lower usable capacity. For this battery return scenario, second generation batteries become available in 2028, increasing profits by 282% to 278€/module. Generation three batteries do not become available until 2033. Over the period analyzed the average profit per module is about 163€.

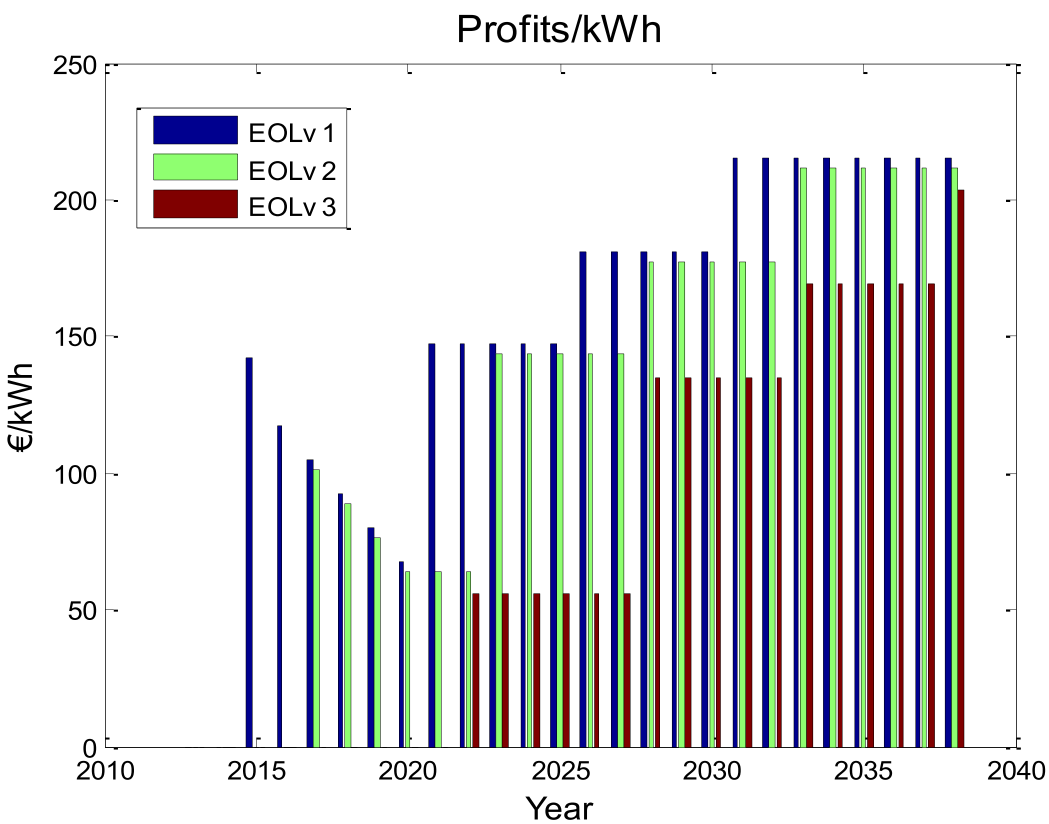


FIGURE 101: SUMMARY OF PROFIT POTENTIAL PER KWH

This type of analysis can be used to assess:

1. Impacts of various return scenarios
2. Optimal timing for deployment of a B2U strategy
3. Long term contract agreements for the supply of used batteries

Figure 101 shows the profits from Figure 100 per kWh. It can be seen in general vehicles returning after 3 years (EOLv1) have a slightly higher profit per kWh due to their higher capacity to cost ratio. This is due to repurposing and integration costs being independent of the system capacity.

How the market dynamics can affect the nature of system sales and sales contract can be seen in Figure 102.

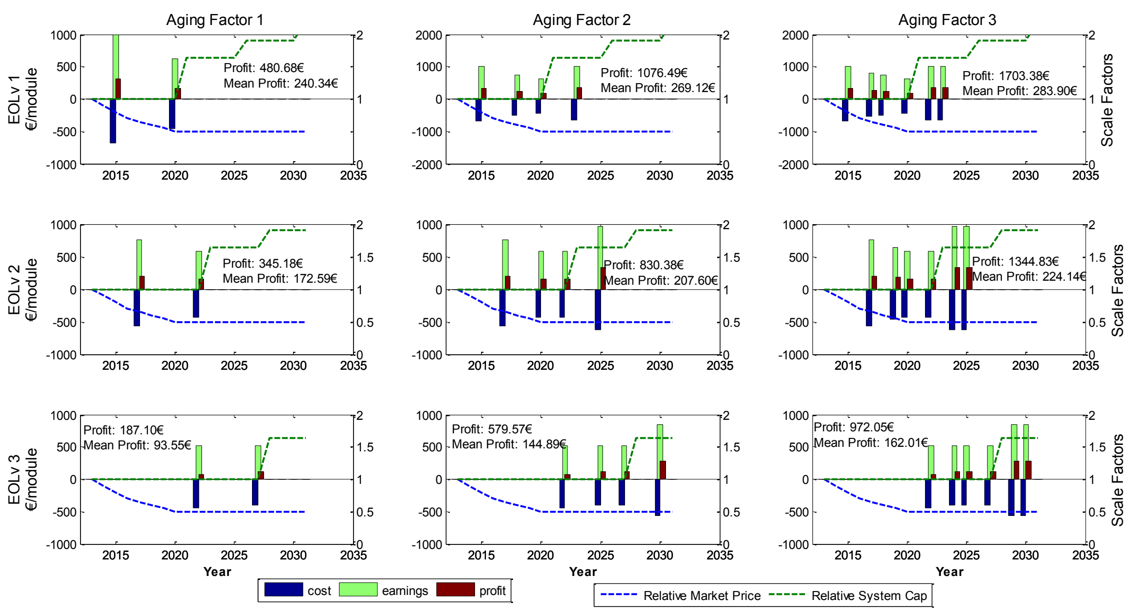


FIGURE 102: EFFECTS OF AGING FACTOR AND REPLACEMENT INTERVALS

Figure 102 shows the costs and revenues associated with batteries needed for a given system for each battery return scenario and aging rate scenario. Therefore initial system installation occurs the same year the batteries are available, and replacement batteries are taken out of the vehicle and repurposed when the secondary system reaches its cycle life limit. The cycle life limit is determined by the 400 cycles a year, nominal number of cycles until 80% of the stationary rated capacity is reached (2000 cycles) and aging scaling factor. It can be seen that the most profitable scenarios is dependent on the combination of end-of-life, market, and aging factors.

In all cases the earlier the batteries come out of the vehicle the more profitable the scenario relative to the other vehicle return scenarios. For vehicle return Scenarios 1 and 2

the less replacements required the more profitable the scenario. That is due to the placement of at least two battery replacements during the least profitable window for the faster aging rates. Vehicle return Scenario 3 is the only scenario in which more battery replacements increase (slightly) the average profit since later replacements occur after the market price has stabilized and the second generation batteries come on to the market.

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