2022

Redesign and benchmarking of electric vehicle batteries for demanufacturing for secondary life applications in the circular economy

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By

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A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Mechanical, Automotive & Materials Engineering
in Partial Fulfillment of the Requirements for
the Degree of Master of Applied Science
at the University of Windsor

Windsor, Ontario, Canada

2022

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August 17, 2022

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Abstract

As per the latest records, the transportation sector is the second largest in energy consumption and plays a major role in air pollution and co2 emission. One solution to curb this pollution and release of hazardous gases is li-ion batteries by electrifying the vehicles. However, these batteries have one factor over here: once EV batteries reach 70-80% charge holding capacity, they are not good enough for traction in the vehicle. Therefore, replacing these batteries with a new ones is necessary. However, these discarded batteries have enough charge holding capacity, which can be used in secondary applications called second-life batteries. It is estimated that there will be 85 million electric vehicles on the road by 2030; given the high demand in the future, we cannot afford to discard these batteries as we cannot meet the demand with material alone. Therefore, we must think about more sustainable ways like reusing multiple applications.

This master's thesis investigates the design guideline for initial design, which will aid in demanufacturing to facilitate disassembly and use the component in the other application as a second life application. It is achieved by an in-depth study of battery's parts, their function, feature, design requirements, and constraints, benchmarked existing high voltage batteries to create a foundation of design guidelines and examine potential future model implementation, analyzed the current level of demanufacturability in existing batteries, provided additional design guideline to meet the demanufacturability, prioritized the design requirements and proposed an EV battery model that will cooperate with the ability to do demanufactured.

Dedication

To my mother Murtee Devi, my father Indrraj Singh, my sisters and friends Neha and Samit, who constantly supported me, and my dearest friends.

Acknowledgments

Taking part in this project was an incredible opportunity for growth, both from academic and personal points of view. The program started and developed under many difficulties due to the ongoing pandemic, but despite that, any challenge was a learning opportunity.

I want to thank the University of Windsor for giving me this possibility.

Thanks to my academic advisor at the University of Windsor, Dr. Beth-Anne Schuelke-Leech. Her support was crucial to keeping me on track during the project's critical phases, helping me foresee possible difficulties, and respecting my timetable. Her guidance toward the right research approach and the suggestion to develop a classification scheme heavily enriched the contents of this work. Thanks again to Dr. Beth Anne Schuelke Leech for the helpful feedback provided during my presentations and the possibility of enlarging my knowledge on the wide range of topics in your research projects.

Thanks to my US advisor Mr. BJ, who introduced me to this research topic and provided constant guidance and support in the most critical moments. His industry insights and suggestions make the study more informative for the industrial partner. Also, I had the chance to explore new topics and gather a huge amount of knowledge I will bring to my future career.

I then would like to express my infinite gratitude to my parents for always supporting me. Thanks for having taught me to be humble and patient, never settle, always strive for the best, be hungry to learn, and be willing to improve when crossing difficult moments.

Thanks, from my heart to my friends Samit, Khusbu and Neha, who supported me throughout the last two years, despite my continuous complaints about the high study workload. They gave me the strength to continue and reach my goals even when it looked too hard or when they realized that I was not the same person under pressure. Thanks for helping me understand my defects and my strengths.Thanks to my friend Aru who guided me throughout my research program and understood my ups and down in last two-year. Thanks to my friend Sara who supported me when I was trying to compile my thesis report.

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List of Abbreviations

ASS	All-Solid-State
BEV	Battery Electrical Vehicle
BMS	Battery Management System
BMU	Battery Management Unit
CE	Circular Economy
°C	Degree Celsius
DFA	Design for Assembly
DFD	Design for Disassembly
DOD	Depth of Discharge
DS	Design Solution
EV	Electrical Vehicle
HEV	Hybrid electric vehicle
HV	High Voltage
HVIL	High Voltage Interlock Loop Current
IC	Internal Combustion
LIB	Lithium-Ion Batteries
LFP	Lithium Iron Phosphate
MSD	Manual Service Disconnect
NCA	Lithium Nickel Cobalt Aluminum
NMC	Lithium Nickel Manganese Cobalt Oxide
OCV	Open Cell Voltage
Ω	Ohm
PAW	Pulsed Arc Welding Resistan

1.0 Introduction

1.1 Background and motivation

Since 2010, attention has been paid to growing pressures on global resources and climate change due to human activities. Products are discarded and replaced due to planned obsolescence, non-repairable failure, outdated technology, and fashion trends. These replacement activities of the product increase resource consumption, which negatively impacts the environment. This trend also threatens the economies and the integrity of the natural ecosystem essential for human survival.

All products have an environmental impact during their development cycles, starting from the extraction of raw material to raw material processing to manufacturing the final product. Thus, minimizing the environmental impact and moving towards a more sustainable society is necessary. The environmental impact refers to global warming and climate change due to the emission of greenhouse gases, water pollution, air pollution, land degradation, and ozone depletion.

Climate change has become one of the most important issues for all economies. The emission of Carbon Dioxide (CO_2) and Greenhouse Gases (GHG) plays a significant role in increasing the overall temperature of the globe. Therefore, these emissions urgently need to be managed [1]. At the COP26 Summit of 2021, hosted in Glasgow, Scotland, the majority of the countries in attendance committed to three key goals: (1) keeping the temperature rise below 1.5°C, (2) working toward a 45% reduction of GHG emission by 2030, and (3) achieving zero carbon emission by 2050 [2]. However, seeing the catastrophic climate reality approaching, these agreement levels are insufficient.

One of the promising ways to reduce the global sustainability pressure is to decrease the use of resources by using current products longer and in new applications, often referred to as a circular economy; a concept that has received increasing attention from policymakers globally as it can help reduce the overconsumption of natural resources while delivering economic benefits. In this context, the EU Commission approved a circular economy action plan COM 614 in 2015 to increase product value by promoting their use for a longer duration. In 2017, a set of measures and an action plan COM was presented in which eco-design is highlighted as a required tool to contribute to the circular economy. The circular economy is an alternative to the traditional linear economy model, which adopts a "take-make-consume-dispose" mentality [3]. In the circular economy, the value of products, materials, and resources is maintained for as long as possible by using them repeatedly to gain additional value, reducing the need for primary material and waste production.

The circular economy principle is most relevant in product development in which the end-of-life (EOL) guidelines aim to reuse, recycle, remanufacture, reconfiguration, and repurpose. These should be integrated from the earlier design stage to keep the product, components, or material circulating and contributing to the economy. The level of circularity can be enhanced if these design guidelines are incorporated from the initial design stage.

The current bottleneck is the lack of implementation of the circular economy principle caused by product design, which hinders product reuse and remanufacturing. However, many products are not designed to allow for easy remanufacturing, reconfiguring, or repurposing. ***Demanufacturing*** is a proposed recovery strategy focusing on retrieving product assets based on a design strategy incorporating a tactic minimum disposal approach. It can be defined as breaking a product into its component pieces to reuse each part while remanufacturing and recycling the remainder of the components. Consequently, it is one of the most novel and critical EOL design guidelines; however, there is a dearth of research on this topic

1.2 EV (Li-ion) batteries Study

A case study involving the Li-ion battery can help to understand how the demanufacturing process can apply the circular economy principle to electric vehicle (EV) batteries. In addition, the Li-ion battery can offer particularly important insight into four considerations: (1) climate change, (2) exponential growth, which has led many batteries to be discarded at the end of their first use, (3) environmental concerns relating to the mishandled discarded batteries, and (4) economic and environmentally friendly second-life opportunities for batteries.

Also, as shown in Figure 1, the market share for the lithium-Ion battery will be 70% of the total rechargeable battery market at the end of 2025, followed by Lead acid batteries at 19.2% [4].

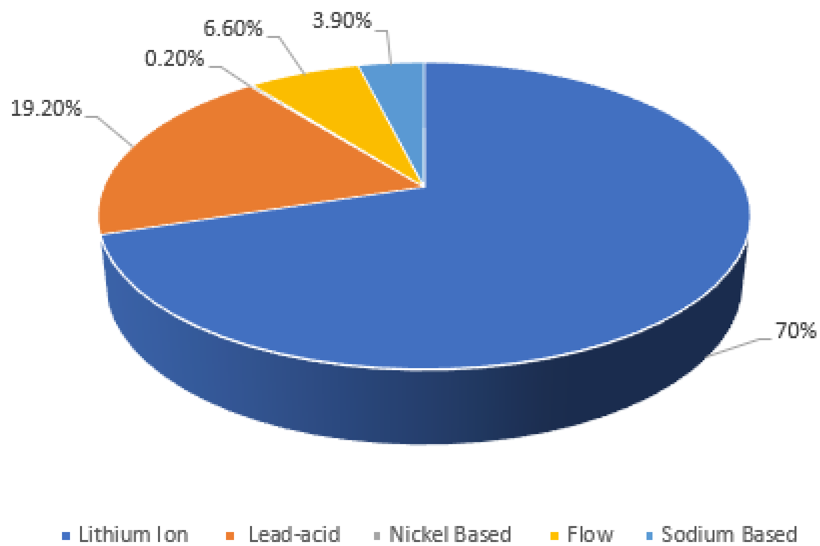


Figure 1. Rechargeable battery market forecast[4]

1.3 Demand for EV

Several factors have increased the demand for electric vehicles worldwide, the most prevalent being rising fuel costs, emerging customer markets, environmental regulations, and growing urbanization trends [5, 6]. As shown in Figure 2, the demand for Plug-In EVs will be 20 million at the end of 2030, which is an exploding situation compared to the 0.56 million vehicles in 2015. There is a growth of almost 40 times in just a span of 15 years. At the same time, the lithium-ion battery market size will jump from 15.9 GWh capacity in 2015 to 93.1 GWh at the end of 2024 only. It is very alarming regarding the volume of used battery generation from these EVs after 5-7 years of use [7].

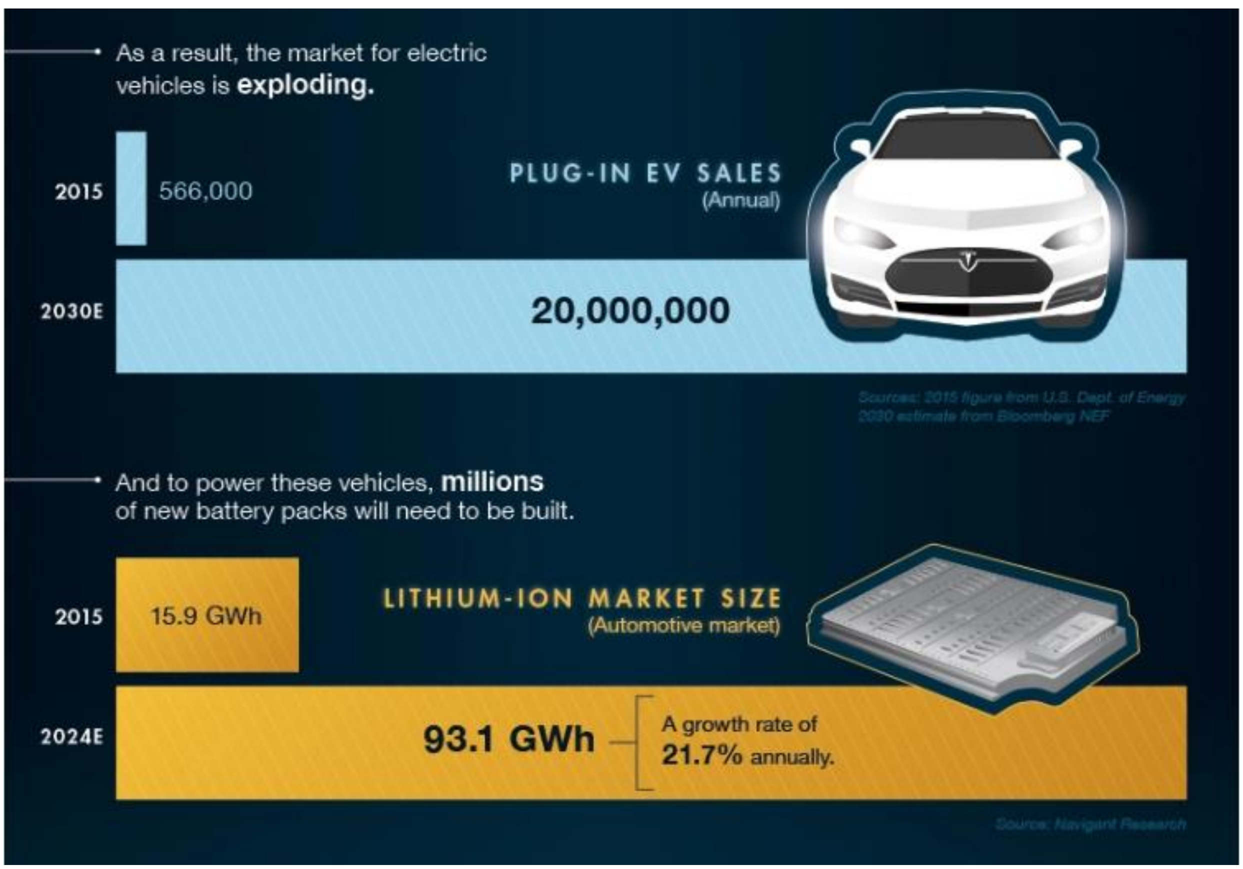


Figure 2. The demand for EVs [4]

1.4 EVs Immediate threat to environment

The environmental impact of EVs is greater than that of the internal combustion engine vehicle during the production phase due to its batteries' manufacturing, which consumes more energy, metal, and minerals than ICE. During the operational phase, however, EV performance is better than ICE vehicles in terms of environmental impact, presuming that the electricity used is from some form of clean green energy. End-of-the-life cycle treatment of EV batteries, like recycling, repurposing, and remanufacturing, helps improve the environmental benefit of the EVs. As an overall performance, EVs have the potential to mitigate greenhouse emissions and fossil fuel consumption. However, they have a higher human toxicity potential (HTP) and eutrophication potential (EP) [7]. In large-scale EV battery production, some factors that play a crucial role are optimizing power structure, upgrading battery technology, and improving recycling. These factors are also crucial for closed-loop production of batteries, sustainable development of the resource's environment and economy [3]

Current EV batteries have limited secondary life applications. As a secondary application, these batteries are currently being used in stationary energy storage applications such as solar energy stores [8], large buildings energy backup storage, renewable power plants [9], and EV charging stations, where these batteries provide reserve energy capacity to maintain a utility's power reliability [8]. As shown in Figure 3, using the end-of-life strategy like remanufacturing or repurposing, used batteries are used in manufacturing the same battery or used in energy storage systems. According to Canal Casals, repurposing EV batteries for stationary energy storage is not the best economical solution. It should be available in secondary electricity market by changing its design to be more sustainable and eco-friendlier [9]. Therefore, to make the EV battery pack more useful in its secondary life, there is a requirement for a design strategy to allow electric batteries to move more easily into the Circular value chain shown in Figure 3.

Figure 3. Circular value chain of retired lithium-ion batteries[10]

1.5 Advantage of battery second life (B2U)

EV manufacturers want to take advantage of the possibility of giving these batteries a second life in so-called Battery Second Use (B2U) applications to open new business opportunities, which could reduce the final EV selling price [11]. The battery cost represents around 30%-40% of the EV's final price [12]. Therefore, reusing these batteries could be a key factor for EVs to overpass conventional ICEVs and accelerate the transport sector's transition into electric-based transportation [5].

Xia & Li have suggested other benefits for second battery life, such as after the first life of electric vehicle batteries, they can be used in secondary applications as they still have 70-80% of charge holding capacity. These batteries can be used in low voltage applications such as grid-connected storage, backup power, auxiliary services, power tools, stationary energy storage system, smart buildings, photovoltaic energy storage, and utility level peak shaving or power load peak shaving (PLPS). A second life battery has been proposed. These batteries are proposed as a potentially expensive, low-carbon energy storage option. In the energy storage application alone, SLB reduces electricity cost by 12-57% and carbon emission by 7-31% compared to new batteries. As per the research, despite manufacturing a new battery, second use of battery has significant environmental impact, and reason behind it is to avoid the production of a new battery. Compared to new batteries produced from raw material and remanufacturing an existing battery, the energy consumption was reduced by 8.55% and 6.62%. The potential cost saving for remanufacturing is approximately $1.82 per kg cell produced. Multipurpose application cases consumes 10-22% lower energy as compared to a single application.[7]

In the case of an automobile, repurposing the battery is a viable business model by extending the battery life in the secondary application shown in Figure 4. An alternate revenue stream can be generated by secondary battery use, and it can also help reduce the upfront cost of EVs. Customers can select this Battery second Use (B2U) as these are cheaper than new batteries and can achieve the performance required by system. Once the cost advantage of these batteries disappears, they can easily choose the new battery. OEM must establish the market for secondary use of the battery. To do this, OEM's will need to consider 2^{nd} life in their battery design so that it can be easily reconfigured in secondary application.

Figure 4. Battery Life cycle[13]

1.6 End-of-life cycle strategy

A critical measure for determining the degree of a battery's performance deterioration and estimating the battery's remaining lifetime is known as state of health (SOH). Depending on the remanufacturing method and the battery's SOH at collection, numerous battery reuse alternatives exist. A summary of the flow diagram that batteries in EVs should follow as they reach the end of their useful life is shown in Figure 4.

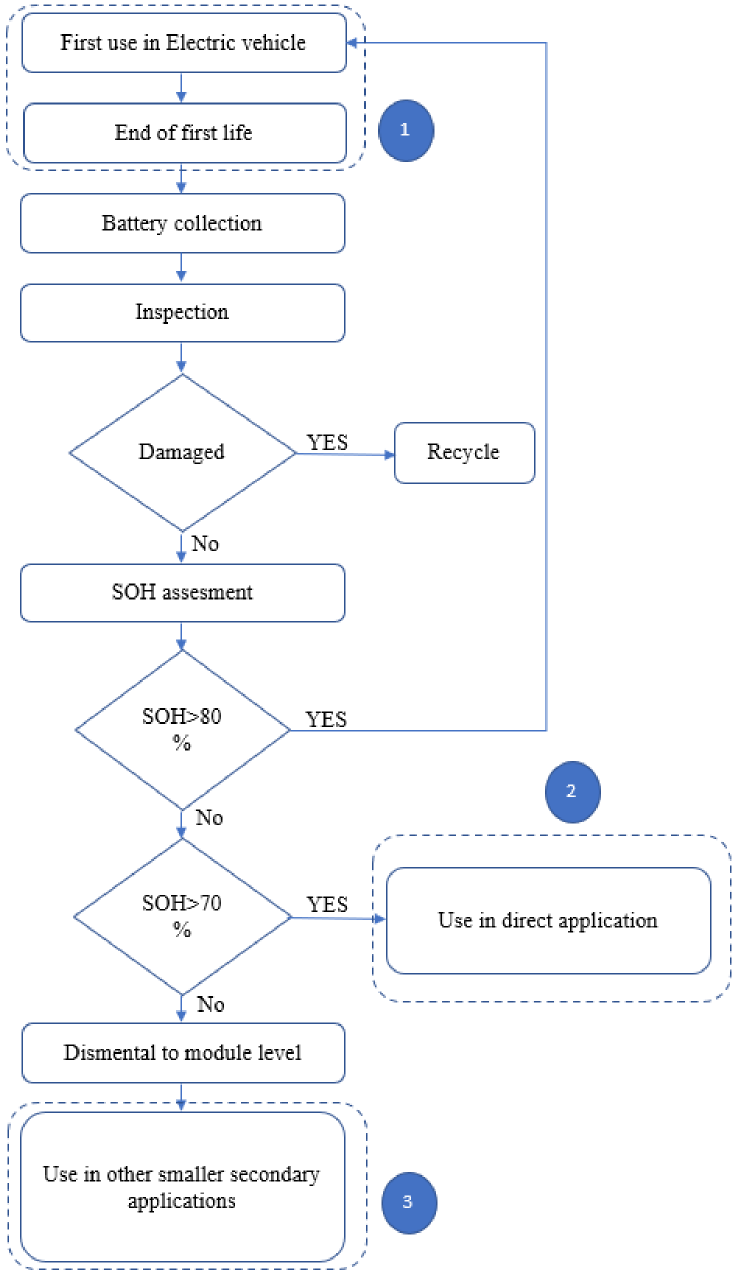


Figure 5. Decision-making flow diagram for secondary application of EV battery [14]

The dashed square in Figure 5 indicates the battery's first life stages. After that, batteries are collected, and the first selection is made. Damaged batteries are deemed useless, and they should be recycled without first having their SOH examined for safety reasons. Next, the remanufacture facility receives functional batteries subjected to SOH tests. Batteries with a SOH of more than 88 percent, denoted by a circled number 1 in Figure 5, can be sent back to the first life as spare components to replace broken or older batteries. The simplest and quickest method to engage in the circular economy is this. Additionally, this battery could later enter the following circular economy cycles.

The second possibility, shown by option number 2 in Figure 5, is that batteries with a SOH of between 88 and 75 percent may be made available for stationary applications. Batteries can be used in a variety of applications, including peak shaving, self-consumption, renewable firming, and uninterrupted power supply systems for commercial buildings and industries. There are also grid-oriented energy services like area or frequency regulation and transmission deferral.

Batteries may also be employed on other transportation services with lesser load requirements if they fall within the 75-88 percent SOH range. Reusing existing batteries to power new hybrid trucks built for urban settings is a possibility that automakers are exploring. These batteries can be employed in city driving cycles where acceleration in first and second gears following traffic lights is typical, noisy, and extremely polluting. Batteries in these situations supply the truck with the requisite acceleration for brief periods before recharging when the internal combustion engine fires up and runs at a more constant rpm. As a result, hybrid trucks would be much more affordable and appealing. When entering and leaving ports, these batteries might be mounted on boats and ferries to be used. This would eliminate noise pollution, which is a major problem [14].

Finally, Figure 5's circled number 3 indicates which batteries are required to be separated into modules or cells. These are the batteries with lower SOH. EV cells are much more advanced than typical batteries for smaller gadgets, such as laptops or electric bicycles, which are more affordable and changeable. As a result, for these devices, old and new EV cells may be compared. Additionally, rather than using real EV batteries, these remanufactured modules from disassembled EV batteries can be used in mobile systems for human assistance, such as cleaning or medical robots, that move about an enclosed space at modest speeds.[14]

1.7 Problem Formulation

The disposal of EV batteries at the end of their automotive lifecycle has emerged as a serious environmental concern. However, due to the current design of these batteries, it is challenging to use in secondary applications. Some of the reasons are the lack of circular economy-oriented design features, bulky module size, lack of standardized design and layout, lack of standardized packaging, different configuration, power output, and different thermal management system designs.

Currently, OEMs are designing the battery pack per the vehicle's design. Every OEM has its design specification and design guideline for EV battery pack related to battery material, battery size, Module size, Thermal management system, electronic system, and safety feature, which all make a battery pack different for different OEMs. Even it is different for the same OEMs for different model variants. It contributes to not standardizing the battery pack's disassembly and using these battery components is difficult due to variation in design. Moreover, no existing EV battery pack is designed considering the end-of-life strategy design.

1.8 Objective

This study examined design guidelines for initial design which will aid in *demanufacturing* to facilitate disassembly and use the component in the other application as a second life application. This is accomplished by benchmarking existing high-voltage batteries to create a foundation of design guidelines and examine potential future model implementation then creating a benchmark of an EV battery that will incorporate the ability to do demanufactured.

1.9 Research Questions

1.9.1 Research question phase 1

In pursuit of environmental concern and economic revenue, the second life of electric vehicle batteries is closer to reality. Common EV battery reaches their end-of-life stage when their charge holding capacity reaches 70-80%. Therefore, it is important to analyze the different end-of-life scenarios according to the battery's remaining capacity and their possible second-life opportunity. Observing the current secondary application of the used EV battery is limited to stationary applications only. To enhance the secondary application for EV batteries, what process can be used for demanufacturing for secondary applications (using electric batteries as the case study)?

1.9.2 Research question phase 2

What benchmark design can be provided to designers and manufacturers for the design of electric batteries which would make them more useable in the circular economy (or for secondary applications) through the demanufacturing process?

1.10 Boundaries of Thesis Research

This research aims to identify the design guideline for demanufacturing through an empirical exploration of EOL strategies and to benchmark the case of EV batteries and their secondary application. Through case studies with nine different OEM batteries, some initial findings were observed regarding key deciding factors for battery demanufacturability. However, this study had some limitations. First, design for demanufacturing is intended to apply to any manufactured product when a secondary life is possible but constrained by the original configuration. Second, the case study is high voltage batteries used in Passengers' cars. Thirdly, EV batteries can be divided into packs, Modules, and cells. Therefore, this thesis will limit the study to pack and module levels. Finally, the focus is on the hardware parts design of the battery.

2.0 Literature Review

2.1 Circular Economy

A circular economy is not a new concept, and the notion may be traced back to several schools of thinking. Ghisellini discussed background of Circular economy [15] and said that Pearce and Turner (1989), environmental economists, were the first to establish the notion of a circular economy, based on prior work by ecological economist Boulding (1966). Boulding's concept of the economy as a cyclical system is considered essential for human existence on Earth's long-term viability (a closed system with practically no exchange of matter with the outside environment). Since the first use of circular economy concept, its terminology has diverged rather than converged. The terms circular economy and close loop can be used interchangeably. [3]

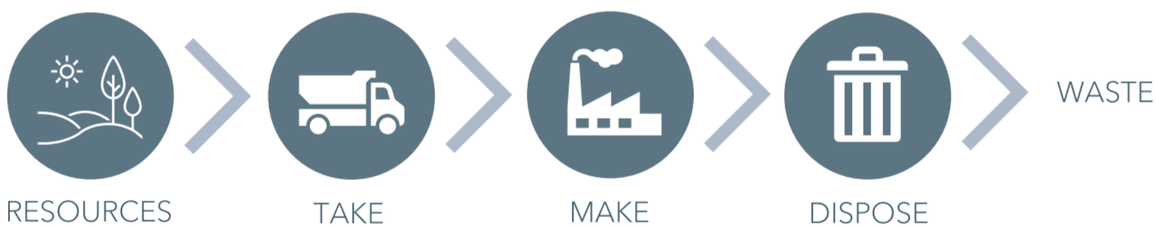


Figure 6. Linear economy, (Ellen MacArthur Foundation, 2018)

The circular economy/ Close loop is the opposite of the linear economy [16]. In a Linear economy, resources are take, make, Dispose of and generate waste, as shown in Figure 6.

A circular economy (CE) is a concept where the value of products, materials, and resources are maintained in the economy for as long as possible, and waste generation is minimized by establishing a circle [17]. In support of this, Bocken [3] defines it in terms of shifting the traditional linear model of take-make-use-dispose to circular model with flow of material and product in a loop. Geissdoerfer defines CE as a regenerative system in which resource inputs are minimized by slowing, closing, and narrowing material and energy loop, which can be achieved by long-lasting design, repair, reuse, remanufacturing, reconditioning, and recycling [18]. Michael Brungart and William McDonough has given the theory of “Cradle to Cradle” with the help of a “Buttery Fly” diagram in which the importance of closing both the technical and biological loop is explained. In the technical cycle, products, components, and materials are kept in circulation in the economy for as long as possible. In biological one, the strategy is to restore nutrients into the biosphere while rebuilding natural capital. The technical cycle is usually for products made from non-biodegrade materials such as Metals. The Most effective technical cycle involves maintaining and reusing products. This way, the product's value is preserved, and its usage length is increased. Once the product is no longer reused, most of its value can still be retained by reconditioning or remanufacturing.

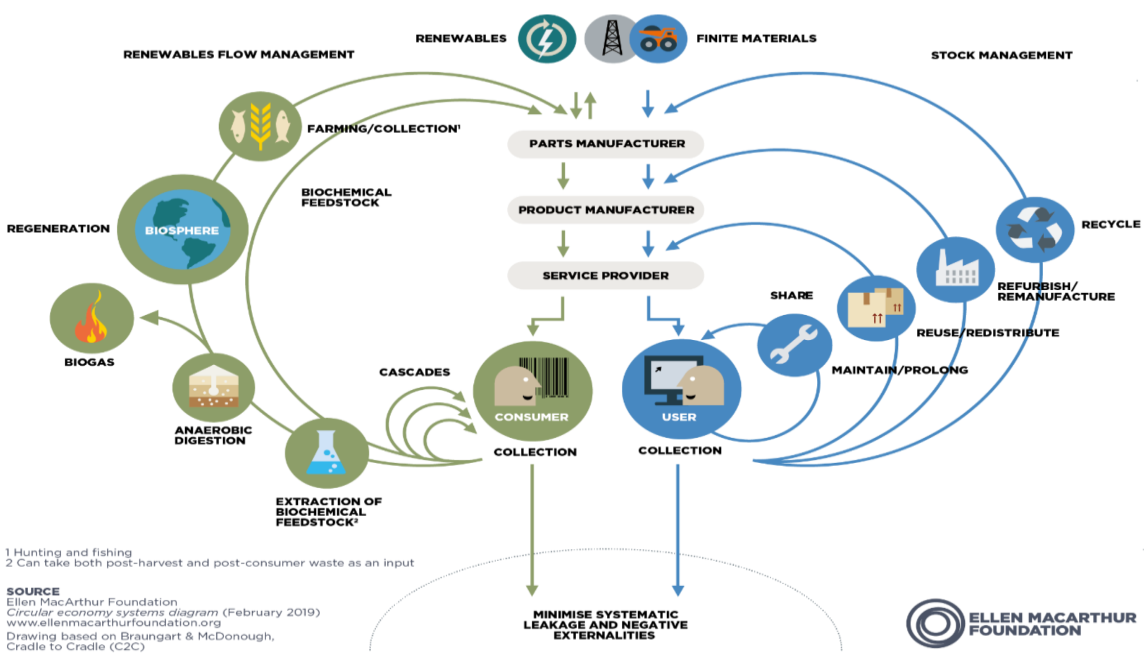


Figure 7. Circular economy “Butterfly” Diagram Ellen MacArthur Foundation. (2017a)

Recently, there has been an increase in interest and development of circular economy (CE) models, which address several issues related to resources and systems in industrial economies. As part of its model, The Ellen MacArthur Foundation (2012) focuses on optimizing resource yields through the circulation of products, components, and materials. The goal is to keep products, components, or materials in circulation and contribute to the economy, among others, by repairing, remanufacturing, refurbishing, or recycling them. To increase the value of products by promoting their use for longer durations, the European Commission approved a Circular Economy Action Plan COM 614 in 2015. An action plan COM 33 in 2017 that focuses on the implementation of that plan was presented in 2017, where eco-design was highlighted as a tool to contribute to the circular economy. However, a need must also be stressed to explore the possibility of developing relevant product guidelines related to durability, reparability, upgradeability, disassembly, reuse, and recycling more systematically for the circular economy.

2.2 Circular Design

It is important to introduce the circular economy concern at the design stage as once the product is manufactured using all the resources like material, process, energy, and resources, it is difficult to make any changes in the product to make it reusable and only minor changes are possible. As John Donahoe rightly said, "The greatest product is the one that already exists because it does not draw on new natural resources to produce."

Product design plays a key role in achieving profitable end-of-life operations [19]. Therefore, product design should prepare products to have multiple life cycles when circular economy is a driver for design. If products are designed for efficient and affordable recovery, they can be valuable for longer. The most stated product features from EOL decision making and EOL management are a product's geometry, the linkages between its components, and how they are arranged as a whole. They influence a product's potential to be recovered after it has been used. It follows then that if these features are settled adequately to match the recovery operation that they will undergo, the process of recovery will turn out to be more efficient, which can be quantified in terms of costs and required time per operation, as well as the product's quality after going through the process. The efficiency of the recovery process relies greatly on whether it has been planned for in the product or not. As the design strategies prescribe, preparing for the recovery operations is also useful to overcome challenges like high labor costs or storage costs associated with remanufacturing and refurbishing. Planning the environmental impact of a product can be reduced by considering, for example, how resource-intensive maintenance operations are required for a product. It also helps avoid unwanted recovery results, like the inability to access a part or requiring a specific unavailable tool. From the design strategies that focus on multiple lifecycles, it has been found that they unclearly state the necessary operations needed for each recovery strategy and the expected output quality. Hence, this translates into bad guidance for designers, given the broad sense of the terms and the inaccuracy in defining the process that products would undergo. Following this idea, this research has been able to point out common critical operations for functional recovery.

Bocken discussed the three loops which can lower the use of natural resources [3]

1. Slowing loop
2. Closing loop
3. Narrowing Loop

A slowing loop means designing a product in such a way that utilization period of the product is extended by reuse, reconfiguration, repurpose, and remanufacturing, which will result in a slowdown of the flow of resources. In the second closing loop, the recycling used product is converted into raw material and can be reused for a new part, hence closing the loop. In the last option, the narrowing loop, fewer resources per part were used, which is a distinct approach from the above two.

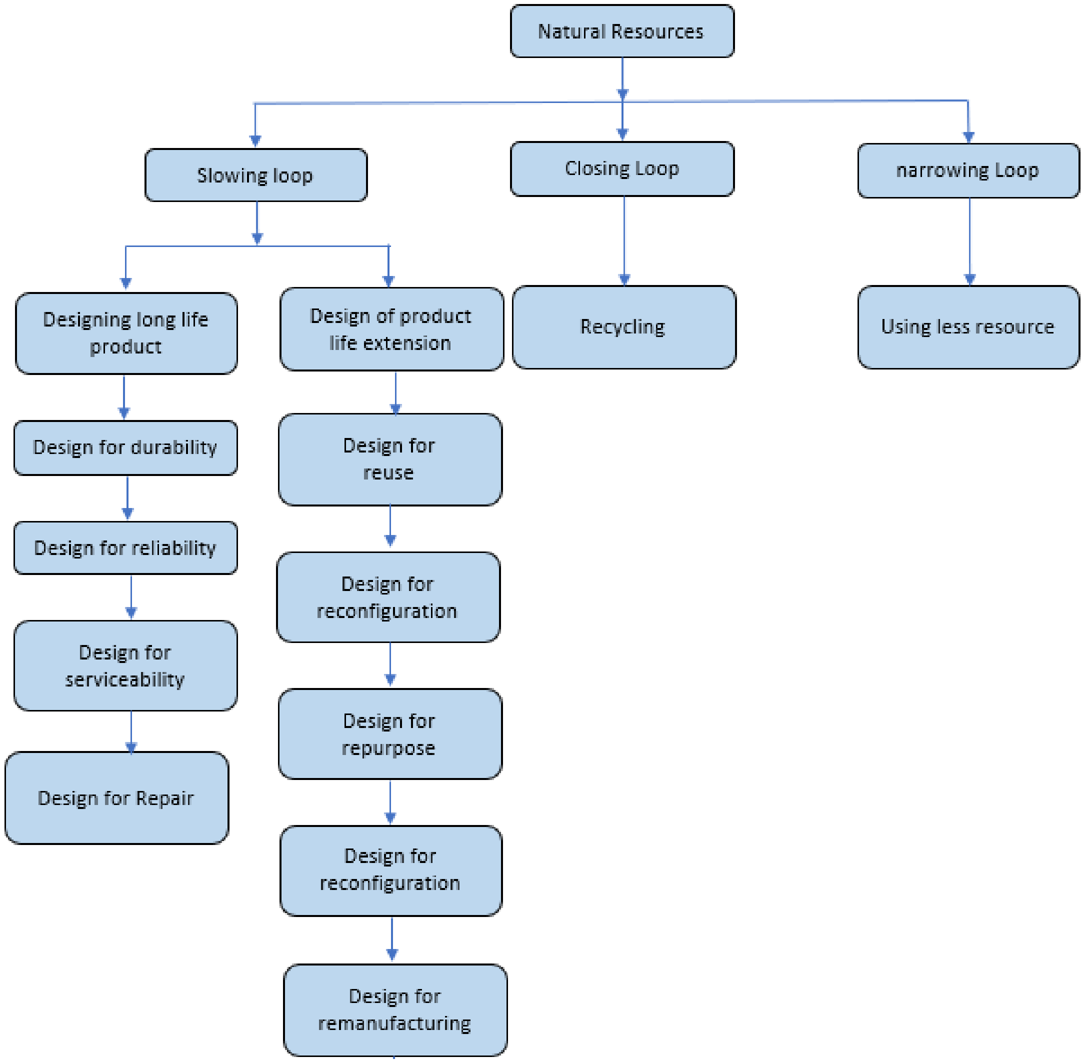


Figure 8. End-of-life strategies for the use of natural resources [3]

2.3 Design paradigms

The term "paradigm" was used by American scientific philosopher Thomas Kuhn in 1962 in his academic work The Structure of Scientific Revolutions. To refers to the shared theories, conceptions, ideas, and practices that one scientific community accepts. The progression of scientific paradigms is "Prescience—Unusual—Crisis—Post-science." Each normal science has a scientific community with one paradigm; the old paradigm only supersedes the previous one when it cannot account for all phenomena, unusual large-scale phenomena, and crises. A new paradigm offers the scientific community a fresher, more direct approach to understanding reality.

This is a general definition of a design paradigm: a design paradigm is the foundation and platform for the design community's normal research. The design community can only conduct in-depth research based on a design paradigm, demonstrating all types of problems raised by the design paradigm.[20]

2.4 Current design paradigm

Different design parameters are used in developing and deploying engineered products. Some of these design paradigms are focused on the end consumer, while others are intended to support the designers and manufacturers. This thesis specifically considers design paradigms that have been introduced to try to support sustainability, cradle-to-cradle, end-of-life designs.

The current design idea for electric vehicle batteries focuses mostly on the following factors: light weight, space layout, and mounting, power output, thermal management, and economical, manufacturable, serviceable, reliable, and safe. These, however, do not fully address the EOL concept of planning for flexibility for reconfiguring and reusing, redeploying, and other applications. [21].

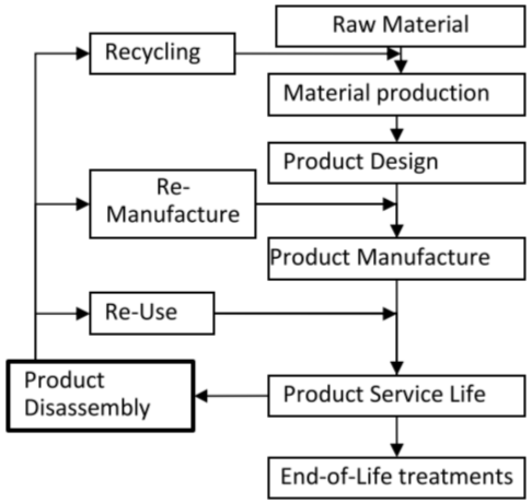


Figure 9. End-of-life treatment for a product[22]

Several end-of-life strategies are available, like design for disassembly, Design for remanufacturing, design for reconfiguration, and design for repurpose. Under all end-of-life strategies, products are disassembled, and their useful components are used again to build the same component, as shown in Figure 7.

2.4.1 Design for Disassembly:

Design for Disassembly (DFD) is a relatively new method included in the design stage to enhance the disassembly of a product. However, this method has been in focus to a greater extent lately due to the environmental awareness in society, and it can be divided into two different categories: total disassembly and selective disassembly. Total disassembly means that the entire product is taken apart into its constituent components; meanwhile, selective disassembly refers to the disassembly of a complex product into non-complex single parts or subassemblies. Selective disassembly is the most common of these two categories since it enables repair and maintenance, material reuse, and creates service parts out of the subassemblies. Here, the purity of the materials is also increased. Meanwhile, total disassembly is time-consuming and not economically feasible.

Furthermore, when looking into easy separation, the different materials should be marked, and parts that could potentially damage the machinery should be avoided. For easy handling, it is important that at least one surface is accessible and that non-rigid parts are minimised since they can move. Finally, for easy disassembly, the number of fasteners must be as low as possible and easy to remove, and the fractures, disjoining- and cutting points must be easily accessible. Additionally, the material variety must be low since it enables simpler recycling and less complex movements

DFD was applied at the same time as DFA, namely during both benchmarking and the development of the ideal battery. DFD and DFA go hand in hand, which means that the choice of how a part was assembled was also evaluated from a DFD perspective. It was discovered how important it is to think of DFD when remanufacturing and recycling are becoming a priority

Table 1. List of design guideline for disassembly

S. No.	Design Guidelines	Reference
1	Create a modular design	[23], [24]
2	Minimize the component count	[23]
3	Optimize component standardization	[23]
4	Minimise product variants	[23]
5	Minimise the use of different materials	[23]
6	Use recyclable materials	[23]
7	Eliminate toxic or hazardous materials	[23]
8	Minimise the number of joints and connections	[23]
9	Make joints visible and accessible, eliminate hidden joints	[23]
10	Use joints that are easy to disassemble	[23]
11	Mark non-obvious joints	[23]
12	Use fasteners rather than adhesives	[23]
13	Good accessibility	[23] [25]
14	Low weight	[23]
15	Robust, minimise fragile parts	[23]

17	Preferably unpainted	[23]
18	Design for automated disassembly	[23]
19	Eliminate the need for specialised disassembly procedures	[23]
20	DFD with simple and standard tools	[23] [25]
21	Arrange the sub-assemblies for easy disassembly	[23]
22	Use joints that are easy to separate	[23][25]
23	The joints should have the same life span as the whole product	[23]
24	Minimizing the number of separate components	[26]
25	Avoiding glues, metal clamps, and screws in favor of "push, hook and click" assembly methods	[26]
26	Making fasteners from a material compatible with the parts connected	[26]
27	Designing interconnection points and joints so that they are easily accessible for the opening, loosening, or separating of components by hand	[26]
28	Designing the product as a series of easily accessible "blocks" or module	[26]
29	Using in-mold identification symbols for plastic resins (based on ISO 11469 [ISO 2000])	[26]
30	Minimizing the number of different materials used	[26]
31	Locating non-recyclable parts in one area that can be quickly removed and discarded	[26]
32	Locating parts with the highest value in easily accessible places	[26]
33	Ensuring that assembly and disassembly can take place with simple tools	[26]
34	Standardizing as many elements as possible, thus avoiding tool changes during assembly and disassembly	[26]
35	Keeping assembly and disassembly methods to a minimum so as to improve efficiency	[26]
36	Ensuring that fixings and fasteners are easily accessible	[26]
37	Keeping the number of fixings and fasteners to a minimum	[26]
38	Designing for ease of separation so that damage to components is eliminated	[26]
39	Minimise the number of different types of material.	[26]
40	Make subassemblies and inseparably connected parts from the same or a compatible material.	[27]
41	Mark all plastic and similar parts for ease of identification.	[27]
42	Use materials that can be recycled.	[27]
43	Use recycled materials.	[27]
44	Ensure compatibility of ink where printing is required on plastic parts.	[27]
45	Eliminate incompatible labels on plastic parts.	[27]
46	Hazardous parts should be marked and easily removed.	[27]
47	Minimise the number of fasteners	[27]
48	Minimise the number of fastener removal tools needed.	[27]
49	Fasteners should be easy to remove.	[27]
50	Fastening points should be easy to access.	[27]
51	Snap-fits should be located and able to be disassembled using standard tools.	[27]
52	Try to use fasteners of material compatible with the parts connected.	[27]
53	If two parts cannot be compatible, make them easy to separate.	[27]

54	Minimise the number and length of interconnecting wires or cables used.	[27]
55	Connections can be designed to break as an alternative to removing fasteners.	[27]
56	Minimise the number of parts.	[27]
57	Locate unrecyclable parts in one area which can be quickly removed and discarded.	[27]
58	Locate parts with the highest value in easily accessible places.	[27]
59	Design parts for stability during disassembly.	[27]
60	Avoid moulded-in metal inserts or reinforcements in plastic parts.	[27]
61	Access and break points should be made obvious.	[27]
62	Eliminate adhesives unless compatible with both parts joined.	[27]
63	Make designs as modular as possible, with separation of functions.	[27]
64	Use of simple product structure	[22]
65	Minimum number of different parts and materials	[22]
66	Minimal use of force is recommended	[22]
67	A simple mechanism is preferable	[22]
68	Standard tools are preferable to specialized ones	[22]
69	Repetition of parts should be minimised for easy identification	[22]
70	Recognisability of disassembly points	[22]
71	Product structure: simple structures are preferable	[22]
72	The use of toxic material is not recommended	[22]

2.4.2 Design for Remanufacturing

Remanufacturing is defined as “the process of returning a used product to at least its Original Equipment Manufacturer's (OEM) performance specification from the customers’ perspective, and giving the resultant product warranty that is at least equal to that of a newly manufactured equivalent” [28]. Remanufacturing is done using the industrial process and technical specifications. Remanufacturing has greatest work content among reconditioning and repair work as all components need to be dismantled, and restoration and replacements need to be done. In addition, there are important requirements for remanufacturing; ease of disassembly and separation, ease of access, ease of cleaning, ease of handling, ease of sort and identification, ease of inspection, and ease of reassembly[29].

Figure 10. Examples of remanufacturing (alternator, vehicle door) [30]

The steps are taken during remanufacturing the products, as shown below in Figure 12.

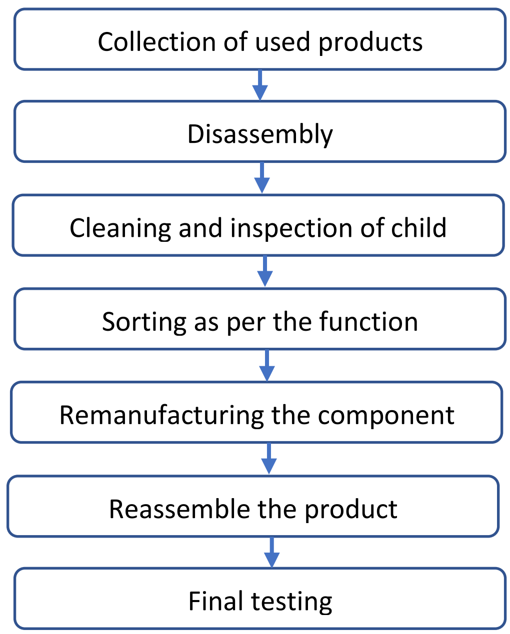


Figure 11. Steps have been taken in remanufacturing

Table 2. List of design guidance for remanufacturing

S. No.	Design Guidelines	Reference
1	Minimize the number of different incompatible or dissimilar materials	[31]
2	Markings on parts should withstand cleaning	[32]–[34]
3	Use of only environmentally friendly cleaning agents should be required	[33]
4	Surfaces to be cleaned should be smooth and wear resistant	[33]
5	All deposits and impurities removable without damage to parts	[33]
6	Similar-looking parts should be identified for easy sorting and classification	[33]
7	The same function should either be identical or be identifiable as being different	[33]
8	Wear and corrosion of parts should be easy to verify	[33]
9	Data such as material properties, load limits, tolerances, and adjustments should be available	[33]

10	Avoid Nondurable material that may lead to breakage during refurbishment	[28]
11	Avoid Joining technologies that prevent the separation of components	[28]
12	Avoid Features that require banned substances or processing methods	[28]
13	Make exchange and faulty components easily accessible	[31]
14	Make it easy to clean the product and its components	[31]
15	Make it easy to disassemble the product and its components non-destructively	[31]
16	Use durable and robust components and materials, e.g., corrosion-resistance	[31]
17	Use fasteners and connectors that can be easily opened and closed multiple times	[31]
18	Design with standardized fasteners and components across different products and models	[31]
19	Design the product with a focus on functionality and upgradability	[31]
20	Make it easy to inspect the product and its components	[31]
21	Use fasteners and connectors that can be easily opened and closed multiple times	[31]
22	Design with standardized fasteners and components across different products and models	[31]
23	Design to use standard tools across different products and models	[31]
24	Make spare parts and exchange components easily available	[31]
25	Adapt a modular design	[31]
26	Investigate current and upcoming laws and regulations	[31]
27	Focus mainly on functionality and quality performance	[31]
28	Make it easy to identify the materials and relevant information	[31]
29	Consider the toxicity and other environmental aspects of the materials	[31]
30	Provide repair manuals and documentation	[31]
31	Think about activity support in the operational stage	[31]
32	Focus on fulfilling the customer’s requirements and value creation	[31]
33	Consider the timeless design, emotional attachment and compatibility	[31]
34	Treat remanufacturing waste appropriately	[31]
35	Try to use digitalization, ICT, and IoT solutions	[31]
36	Design using renewable materials	[31]
37	Design using recyclable and secondary (recycled) materials	[31]
38	Favor cleaner production, processes, machines, and equipment	[31]
39	Design for reduced energy consumption and usage of renewable energy	[31]

2.4.3 Design for Reconditioning:

Reconditioning is a process in which the used product is restored to a satisfactory working condition that may be inferior to the original specification. In the case of reconditioning, the product warranty is less than the newly manufactured product. However, the warranty is provided for all major wearing parts. In reconditioning, work content will be lower than the remanufacturing but more as compared to repair. All the major components that are failing or about to fail are generally rebuilt or replaced. Rebuilding major components to working condition is usually expected to be inferior to the original model along with less warranty period.[35]

Table 3. List of design guideline for reconditioning

S. No.	Design Guideline	Reference
1	The shape of the parts should permit the use of jigs and fixtures for reconditioning	[32]
2	Threaded bushings should be easily replaceable	[32]
3	Surface and shape defects removal,	[32]
4	Material addition and deposition	[32]
5	Material properties restoration	[32]
6	Surface finishing	[32]

2.4.4 Design for Repurpose:

Design for Repurposing, a novel approach to integrating the idea of reusing in product design, strive to increase items' usefulness by purposefully including features or specifics that make repurposing easier. Repurposing is transforming goods or their components to serve a new use after being used for a previous one.

Table 4. List of design guideline for repurposing

S. No.	Design Guideline	Reference
1	Minimizing the number of separate components	NA
2	Avoiding glues, metal clamps, and screws in favor of “push, hook and click” assembly methods	NA
3	Making fasteners from a material compatible with the parts connected	NA
4	Designing interconnection points and joints so that they are easily accessible for the opening, loosening, or separating of components by hand	NA
5	Designing the product as a series of easily accessible “blocks” or module	NA
6	Using in-mould identification symbols for plastic resins (based on ISO 11469 [ISO 2000])	NA
7	Minimizing the number of different materials used	NA
8	Locating non-recyclable parts in one area that can be quickly removed and discarded	NA
9	Locating parts with the highest value in easily accessible places	NA
10	Ensuring that assembly and disassembly can take place with simple tools	NA
11	Standardizing as many elements as possible, thus avoiding tool changes during assembly and disassembly	NA
12	Keeping assembly and disassembly methods to a minimum so as to improve efficiency	NA
13	Ensuring that fixings and fasteners are easily accessible	NA
14	Keeping the number of fixings and fasteners to a minimum	NA
15	Designing for ease of separation so that damage to components is eliminated	NA
16	Design for Repurposing Checklist (Batch Production) Steps to get started	NA
17	Components can be separated through simple processes/tools	NA
18	Materials and components are durable and capable of functioning well in another role	NA
19	The designer provides cues and clues of symmetry, holes, Contour/edge, flanges, panels, and sharp edges	NA
20	Products designed for repurposing strive to be safe, for instance, from toxicity	NA

NA- Not Available

Of course, this limits the application of disassembled components to that product only.

2.4.5 Need of other End of life design strategy

Product management aims to design for disassembly, remanufacturing, reconditioning, and repurpose. These ideas have the potential to reduce the rate of landfill usage. When worn goods end up in landfills, they waste precious resources and poison soil and water over a long period of time with dangerous substances, which is highly bad for the environment. It is preferable to investigate more options for disassembly, remanufacturing, and reconfiguration than to do nothing, given the current rate of depletion of landfills. New advancements in these technologies have the potential to turn garbage into treasure and result in resource reincarnation [36].

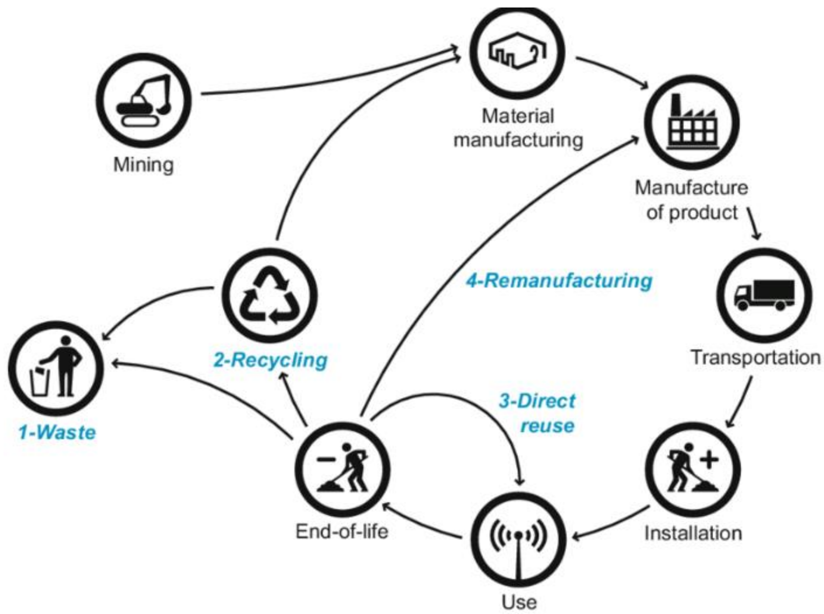


Figure 12. End of the life cycle of a product[37]

Given the current need for trash management, the 3R (Reduce, Reuse, Recycle) waste reduction approach has been expanded to 9R. The extended Reduce category involves rethinking, redesigning, and reconfiguring product design so that minimum waste should be produced. This needs the highest level of innovation in product design and enabling technology, which will provide better manufacturable technology and product which can be used smartly in many secondary applications after first use. In addition, end-of-life strategies support in product second life; design for disassembly, reuse, remanufacturing, design reconfiguration, design for reconditioning, and design for repurpose.

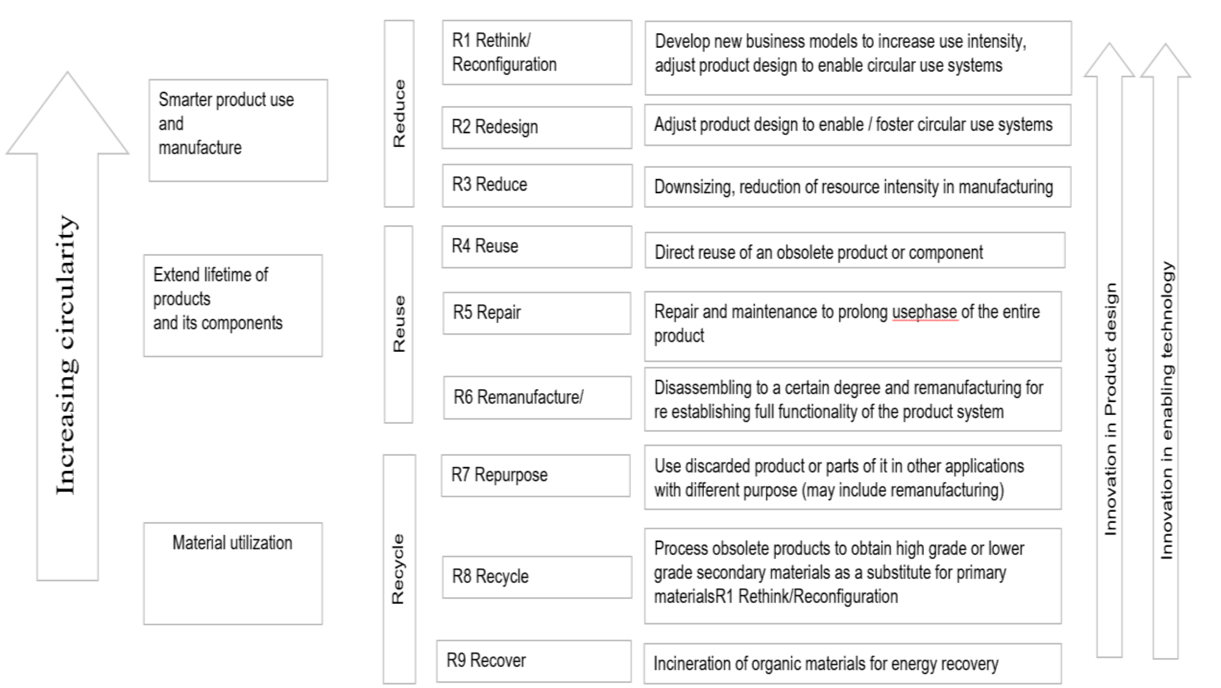


Figure 13. Levels of circularity adopted from[38]

There is a need to design the components which meet all the criteria for currently existing EOL strategies and can be used in multiple other applications. Therefore, there is a need for strategy which can meet this requirement, which is proposed in this thesis: Demanufacturing.

2.4.6 Design for Demanufacturing

Demanufacturing is a design strategy in which a product is designed with its full lifecycle in mind, including the ability to disassembly, reconfigure, and redeploy after its primary application has finished. This can be achieved by standardizing its components design for ease of disassembly, ease of reconditioning or reconfiguration, ease of testing, and incorporating other provisions to assist in the assembly for secondary applications. Once the product is disassembled in its sub-module, the sub-module does not need to be used in similar way again; it can be used in multiple other applications. To make this concept applicable, important changes must be made during the product's design, however. This thesis analyzes and discusses those required changes.

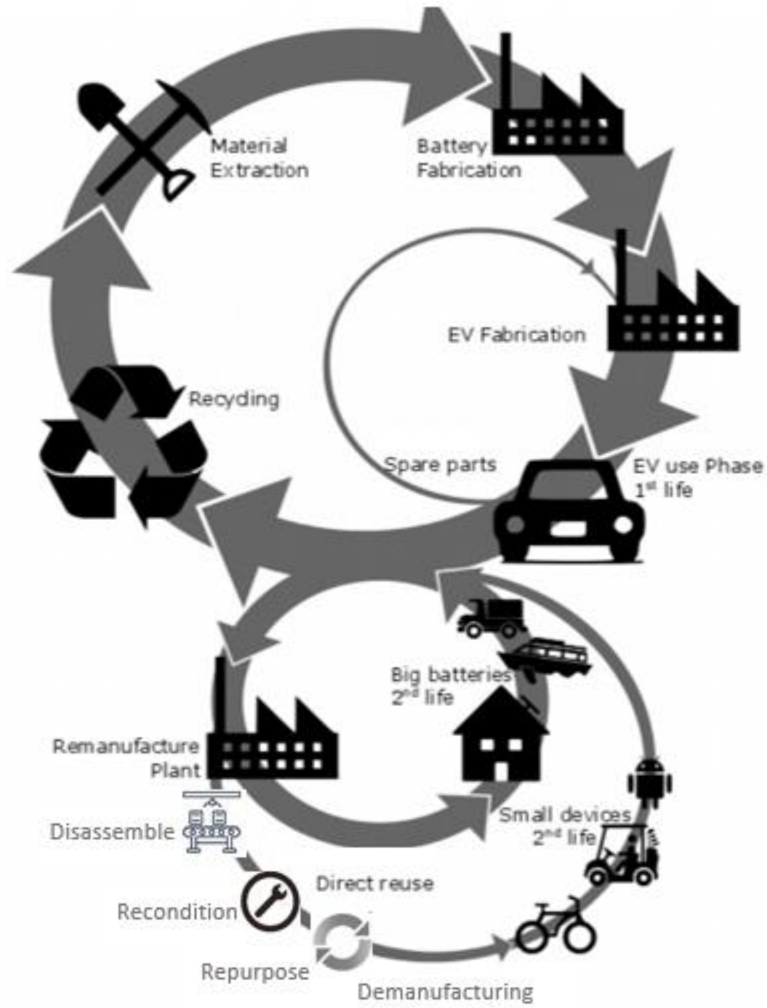


Figure 14. Demanufacturing in the Circular Economy

The demanufacturing process can be defined as breaking down a product into its parts for remanufacturing, reusing, and recycling the reminder of the components [40,41]. Demanufacturing covers the design strategies, guidelines, and product features that enable functional recovery operations like remanufacturing, reconditioning, repurpose and recycle. It is very important to keep a product and its component as valuable as possible for a longer period of time. Therefore, recovery operation should be easy to perform in an efficient manner, which is influenced by product design.

The functional recovery guideline for the product design is related to end-of-life decision making; product structure, number of parts, number of modules, disassembly level and sequence, joining and geometrical relationship among the component, direction, and force for disassembly. Another product design guideline related to ease of cleaning, which refers to the removal of an external, undesired element from the product, Ease of diagnosis refers to physical inspection to quick check the condition of components and functionality testing of components; disassembly guideline refers to deconstructing the product in a no destructive manner and ease of storage refers to an operation to keep valuable parts safe for future usages.[34]

Peeters compiled broad design standards for several demanufacturing techniques, emphasising that standards for disassembly frequently conflict with those for dismantling, smashing, or shredding. But given the disassembly procedure, it was also acknowledged in this instance that fasteners are crucial for products that need to be fixed, refurbished, or remanufactured. Following their analysis, they classified three separate product categories as part of the demanufacturing process[39].

There are the following types of demanufacturing process

-Non-destructive demanufacturing (manual, Auto, or active disassembly)

-Semi-destructive demanufacturing (for components and fasteners)

-Destructive demanufacturing (smashing and shredding)

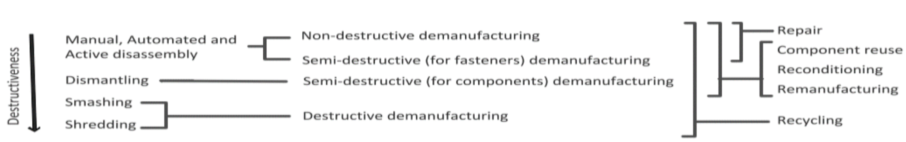


Figure 15. Different demanufacturing processes

As per Tang, very little focus has been placed on demanufacturing from a system standpoint. However, in reality, a demanufacturing system's resource allocation is crucial to smooth operations. Therefore, the demanufacture of products for component and material recovery is an emerging field of research. [40]

Tolio discussed the challenges faced by demanufacturing system in the current scenario. Demanufacturing systems need special kinds of flexibility and reconfigurability due to the trend toward increased product variety and a rapid pace of product model substitution in manufacturing. Additionally, the high degree of variability in the post-use product circumstances necessitates data collection and monitoring solutions, as well as the adaptability of the demanufacturing system. Additionally, this would facilitate a controlled flow of returned goods into the system, which is necessary for the Circular Economy business model to be profitable. [30]

Table 5. Challenges for demanufacturing[30]

Global trends	Challenges
Short life cycle of products and high product variety	Flexibility and reconfigurability
High variability in the conditions of post-use parts	Variability of process sequences and processing times
Poor information about return products	Need for Information and Communication Technology (ICT) solutions and big data management Need for in-line part and materials inspection
Increasing product complexity High fluctuation in materials' value	Increasing quality requirements on recovered materials and components
Pressure on costs and efficiency	Need for knowledge-based tools Involvement of the manufacturer
Increasing attention to safety and ergonomics	Need for process automation, repeatability, and quality assurance
Emphasis on business models, inventory, and production planning Need for hybrid automation solutions	Need for the human-centric design of disassembly and sorting workstations

2.5 Design criteria for Demanufacturing

Based on the end-of-life strategies like design for disassembly, Design for remanufacturing, design for reconfiguration, and design for repurpose, Design guideline for demanufacturing is compiled. As discussed in the literature review, Demanufacturing combines all such EOL strategies. Therefore, this is a "Design criteria" by which to compare existing designs to paradigm and strategy.

Table 6. Demanufacturing's place in the EOL Design paradigm and strategies

S. No.	Design guideline	Disassembly	Remanufacturing	Reconditioning	Repurpose	Demanufacturing
1	It has a modular design	O	O			O
2	Minimum Use no of parts	O			O	O
3	Ensure resistance to dust accumulate		O			O
4	use standardised components	O	O			O
5	minimise product variants	O	O			O
6	Improve the ratio between the labor required to retrieve a component and its value	O	O	O	O	O
7	Avoid welding and fusion of joints	O	O	O		O
8	Consider the use of active disassembly	O	O			O
9	Use of standard joints	O	O	O		O
10	Prioritize latching to screws and bolts	O	O	O		O
11	Unify screw heads	O	O			O
12	Minimise type of connection	O	O			O
13	Use fasteners rather than adhesive	O	O		O	O
14	make joints visible and accessible	O	O			O
15	use fasteners that are easy to remove	O	O	O		O
16	Minimise the no of joints and connections	O	O		O	O
17	minimise the no of tools and use the push/pull process	O	O	O		O
18	use material resistance to cleaning processes for components to be reused	O	O	O	O	O
19	use components with verified reliability	O	O	O	O	O

20	Do not Combine components that have different life spans	O	O	O	O	O
21	minimise length of wires and cables	O	O			O
22	Use components sized for easy handling	O	O			O
23	maximise the accessibility of components	O	O	O	O	O
24	Avoid dismantling part from opposite direction	O	O			O
25	simplify the product structure	O	O			O
26	build monitoring equipment into the system	O	O	O	O	O
27	Ensure that the fewest possible operators are required to perform a disassembly task	O	O	O	O	O
28	eliminate the need for special disassembly procedures	O	O			O
29	use simple and standard tools	O	O	O		O
30	use durable and robust component	O	O		O	O
31	make fasteners that are easy to open	O	O	O		O
32	design with standardized fastener and component	O	O	O		O
33	design to use standard tool	O	O	O		O
34	investigate how current and upcoming laws and regulations affect the design product	O	O	O	O	O
35	design the product with a focus on functionality	O	O	O	O	O
36	Easy inspection of the products	O	O	O	O	O
37	provide disassembly manual	O	O			O
38	treat remanufacturing waste properly	O	O			O
39	use digitalization ICT and IoT solution	O	O		O	O
40	use the same type of material	O	O			O
41	Predesign for easy cleaning	O	O	O	O	O
42	reduce sharp corner	O	O	O	O	O
43	Avoid long disassembly path	O	O	O		O
44	design multiple detachments with single operation	O	O	O		O
45	avoid permanent joints	O	O	O		O
46	the surface should be worn resistant from cleaning liquid	O	O	O	O	O
47	design smooth surface for less dust accumulation	O	O	O	O	O
48	mark/eliminate hidden joints	O	O	O		O
49	Mark testing points	O	O	O	O	O
50	easy access to fasteners	O	O	O		O
51	easy identification of fasteners	O	O	O		O
52	easy access to the subsystem	O	O	O		O
53	easily remove subsystem	O	O			O

54	labels and instructions withstand the cleaning process	O	O	O	O	O
55	simple and fewer variation methods for cleaning	O	O		O	O
56	surface is worn resistance	O	O		O	O
57	no secondary finish			O	O	O
58	plastics surface is not coated			O	O	O
59	surface treatment last enough through refurbishment			O	O	O
60	texture area is furnishable			O	O	O
61	prevent the corrosion of parts			O	O	O
62	less hazards material		O	O	O	O
63	avoid bulky overdesign	O	O	O	O	O
64	sufficient clearance and support at the base to avoid damages during transportation	O	O	O	O	O
65	ease of classification of the component	O	O	O	O	O
66	all similar parts are identified or marked for easy sorting	O	O	O		O
67	ease of accessing the part condition	O	O	O		O
68	testing points are easy to access	O	O			O
69	testing should be quick and simple	O	O			O
70	mounting points are easily accessible	O	O	O	O	O
71	mounting points are easily identified	O	O		O	O
72	Feature provided for reuse	O	O	O		O
73	Easy to separate the subcomponent	O	O	O		O

O-Present

3.0 Methodology

The methodology used in this research is divided into the six major steps, as illustrated in Figure 16.

Step 1- Understanding the Battery parts, their function, and design factors

Step 2- Design analysis of current product design by reverse engineering

Step 3- Analyze the current products for demanufacturability

Step 4- Design requirement for Demanufacturing

Step 5- Prioritizing the design requirements using a house of quality

Step 6- Proposed a new battery design as per demanufacturing

Methodology

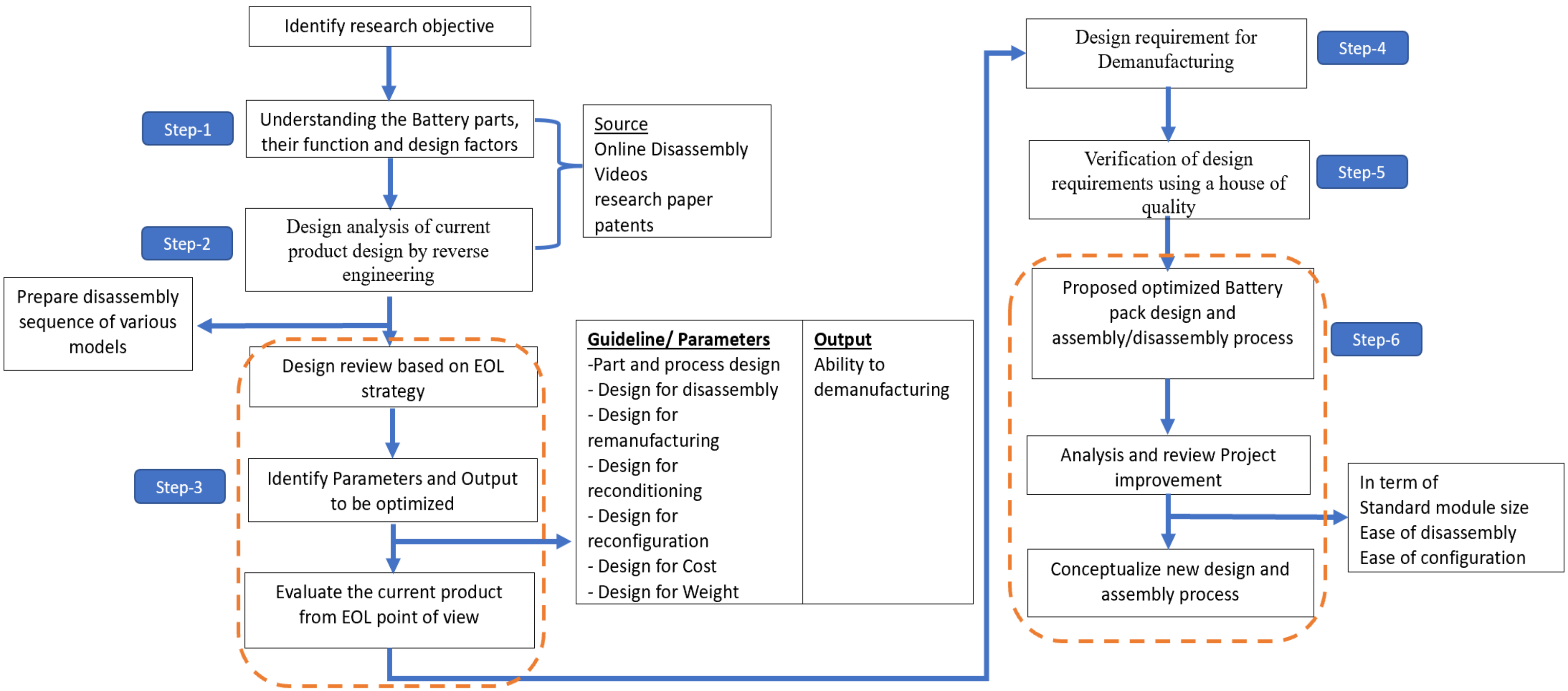


Figure 16. The schematic diagram for the research methodology

The Above figure is explained in the following six steps.

Step 1: Understanding the Battery parts, their function, and design factors:

This part will go through the philosophy of EV battery design and concentrate on the vital component systems, like their requirement in the system features, function, constraints, and criteria. The information has been collected for each type of battery and their parts. To understand the factor which is affecting a battery design, all factors are divided into eleven different structural modules, which are

1. Vehicle structure,

2. Cell structure

3. Cell material structure

4. Electronic structure

5. Thermal management structure

6. Mechanical structure

7. Safety structure

8. Testing structure

9. Battery charging structure

10. Battery nomenclature structure

11. Battery assembly methods and their structure.

Step 2: Design analysis of current product design by reverse engineering

Benchmarking study is conducted to understand the design philosophy of existing products in a better way. In this section, disassembly of various EV batteries like Chevrolet Bolt 2017, Chevrolet Bolt 2018, Tesla Model S, Tesla Model Y, Tesla Model M, Volkswagen ID 4, Toyota Prius 4Th generation, Mustang Mach E, BMW i3 has been studied, and learning/ observations have been jotted down. In addition, data collection has been performed by conducting a literature analysis of current batteries from various OEMs. Finally, observations have been taken by watching online blogs and YouTube videos; because of covid restrictions on travel and interaction, it was impossible to see the batteries directly.

Step 3: Analyze the current products for demanufacturability:

To find the level of demanufacturability of existing batteries, a method has been used which represents the results in the form of a spider net. To achieve this visual graph of demanufacturability, design guidelines are identified for demanufacturability in a product. Then parameters are defined: margin of improvement (MI) and relevance (R). Finally, criteria are defined to measure the parameters. Based on the parameter values, demanufacturability has been plotted against all seven battery packs and tried to identify how demanufacturable these batteries are.

Step 4: Design requirement for Demanufacturing

Additional design requirements are suggested to make the current design product more demanufacturable in the following upgraded or newer version. These design guidelines should be incorporated from the initial stage of design.

Step 5: Prioritizing the design requirements using a house of quality

House of the quality tool establishes and verifies the relation between designing and engineering specifications. The designing specifications/guidelines are collected from the end-of-life strategies that support the demanufacturing and engineering specification from the background study of EV battery parts. As a result, important guidelines are identified based on the relation between designing specification and engineering, which helped further propose a new battery design for demanufacturing.

Step 6: Proposed a new battery design as per demanufacturing

Based on the background study related to the EV batteries and its parts design and their specification, feature, and criteria, benchmarking study for various OEM EV batteries, and End of life requirements, a new battery design has been proposed which meets most of the guidelines for demanufacturability. In addition, the proposed design will help to use the battery and its components in the secondary application more effectively.

Data

To collect the data, extensive research is conducted using publicly available information sources, such as academic and industry publications, patents in the public domain, company news releases, and videos showing battery disassembly. An electronic databased has been used called Scopus for finding the related research papers, journals and patents. The keywords which are used to find the related papers were “Electric vehicle battery”, “Product design” , “Design Guideline” , “End of Life strategy” , and “Demanufacturing”. Total of 342 papers were shortlisted, reviewed and finally 83 papers are used in this research. To build the advanced knowledge, enrolled and studied in a master level course named “Advanced energy storage system”.

Table 7. Benchmarking model details

Electric Battery primary application	Description	Data sources used
Tesla S 2014	Tesla S was the first sedan that Tesla designed from the ground up, and it was released in 2012. The 2014 version of the Tesla S has a capacity of 85 kWh and 400V Max and is an assembly of thousands of cells. The battery pack weighs approx. 1200 lb (540 Kg).	Munro Live is world-renowned engineering and manufacturing consulting firm governed by Mr Sandy Munro. Blog "Throtl" with approx. 2 Million subscriber Video Link -[41],
Tesla M3	Tesla's Model 3 "long-range version" is the company's third-generation electric vehicle, launched in 2017. This vehicle has a range of nearly 576 kilometers on a single charge, 74 kWh (0.02 kWh/cell) capacity, and an energy density of 168 Wh/kg.	Munro Live is world-renowned engineering and manufacturing consulting firm governed by Mr Sandy Munro. Video Link- [42]
Chevrolet Volt (2018)	The Chevrolet Volt EV battery is a plug-in hybrid vehicle launched in 2018. It is also called an extended-range electric vehicle. It has a capacity of 18.4 kWh and a total weight of 197 kg, consisting of 96 cells arranged in 9 modules. This vehicle has a range of 40-80 Km.	A video Blog by Professor John D. Kelly at Weber State University (WSU) - Davis Campus in Layton, Utah, U.S.A Video Link: [43]
Chevrolet Volt (2016)	The Chevrolet Bolt EV battery is the vehicle's second-generation battery pack, launched in 2016. It has a capacity of 57 kWh (0.19 kWh/cell) and a total weight of 435 kg, thanks to using 288 pouch cells with the chemistry NMC. In addition, this vehicle has a range of 320 Kms.	A video Blog by Professor John D. Kelly at Weber State University (WSU) - Davis Campus in Layton, Utah, U.S.A Video Link- [44]
BMW i3 2015	The BMW i3 is an electric vehicle released by BMW in 2011. The battery is located beneath the floor. The battery weighs 230 kg and has a range of 160 Kms. It has a capacity of 18.8 kWh (0.19 kWh/cell).	Munro Live is world-renowned engineering and manufacturing consulting firm governed by Mr Sandy Munro. Video Link-[45]
Toyota Prius (Plug-In- Hybrid)	Toyota Prius is a second-generation plug-in hybrid vehicle with a Lithium-ion battery. The battery is located under the back seat and rear cargo floor. The battery range is 40 Km with a weight of 120 kg. It has a capacity of 8.8 kWh. It was launched in 2016.	A video Blog by Professor John D. Kelly at Weber State University (WSU) - Davis Campus in Layton, Utah, U.S.A Video Link-[46]
Mustang MACH-E	Mustang Mach E is an electric compact SUV introduced in 2019. The	Munro Live is world-renowned engineering and manufacturing

	power of battery is 68 KWh with 485 Kg of weight.	consulting firm governed by Mr Sandy Munro. Video Link-[47]
Volkswagen ID.4	Volkswagen ID4 is the first fully electric compact SUV by Volkswagen. The model was launched in September 2020. The range of the battery is 346 Kms with 82 KWh power. The battery pack sits in the vehicle’s underbody.	Munro Live is world-renowned engineering and manufacturing consulting firm governed by Mr Sandy Munro. Video Link-[48]

4.0 Result

Step 1: Understanding the Battery parts, their function, and design factors:

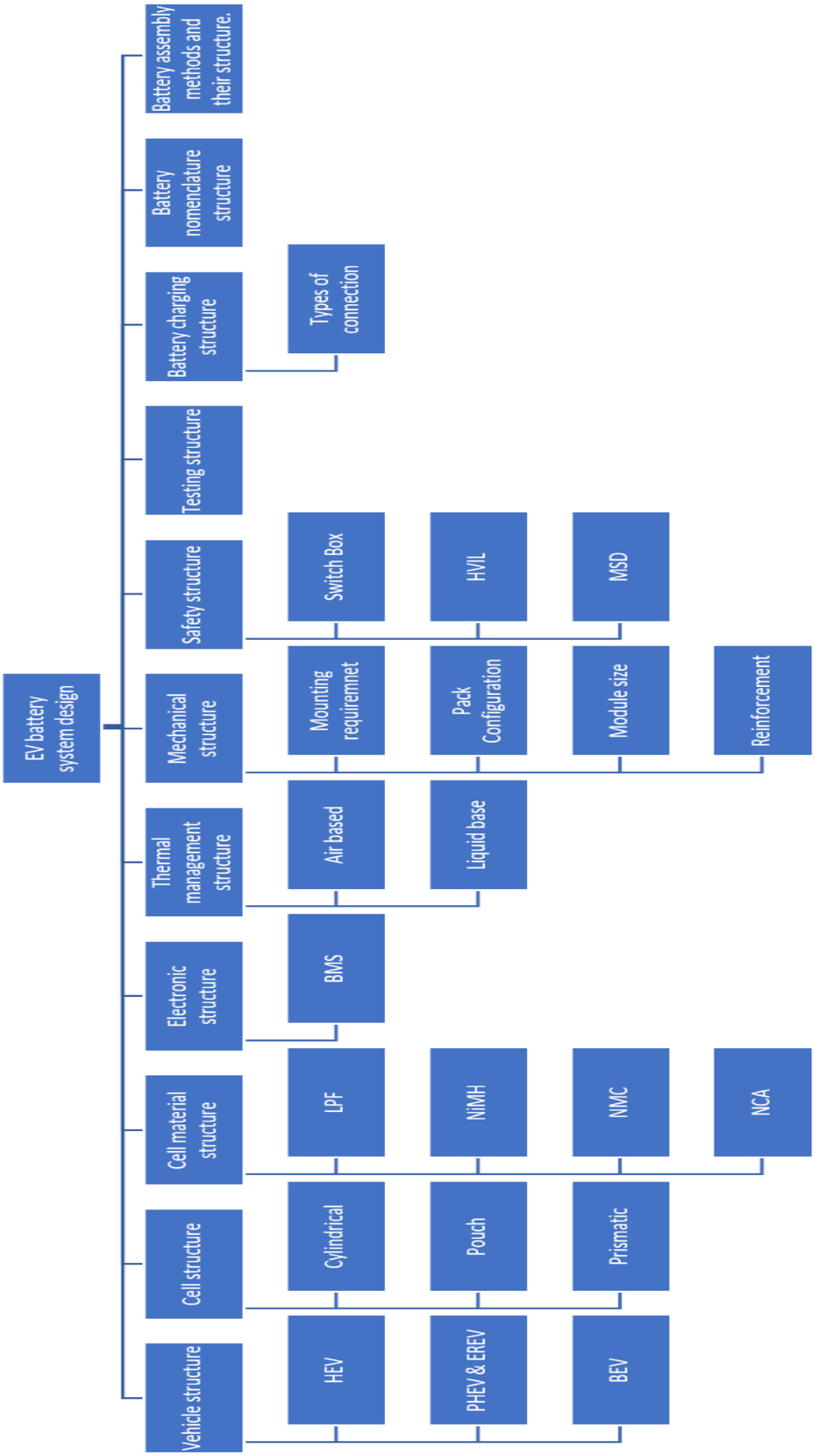


Figure 17. Sub structure of EV batteries

This part will go through the philosophy of EV battery design and concentrate on the vital component systems, like their requirement in the system features, function, constraints, and criteria. To understand the factors affecting a battery design from a demanufacturing perspective, all factors are divided into eleven different structural modules, which are 1. Vehicle structure, which includes Hybrid electric vehicle (HEV), Plug-in hybrid electric vehicle/ Extended range electric vehicle (PHEV/EREV), BEV (Battery electric vehicle) 2. Cell structures like Cylindrical, Prismatic, and Pouch 3. Cell material structure like Lithium-ion phosphate (LPF), Nickle metal hydride (NiMH), Lithium Nickle Manganese Cobalt Oxide (NMC), Lithium Manganese Oxide (LMO), and Nickle Aluminium oxide (NCA) discussed their specific energy and energy density 4. The electronic structure includes a Battery management system (BMS) and contact system 5. Thermal management structure includes Air-based and liquid-based 6. The mechanical structure includes housing and its material requirements 7. Safety structures installed in the battery system include a Switch box, High Voltage switch, Connectors and Fuse, Manual Service Disconnect (MSD), and High Voltage interlock loop (HVIL) 8. The testing structure includes test driving cycles 9. The battery charging structure includes the charger and its capacity of 10. Battery nomenclature structure includes state of charge (SOC) and state of health (SOH), end of life (EOL) 11. Battery assembly methods and their structure.

The internal and external design of all battery packs is different. Some methods install the batteries directly into the mechanical enclosure, while others employ a variety of modules and monoblocs to subassembly the cells. Some systems divide the battery into numerous "packs" at various locations around the vehicle, while others combine all components into a single "pack." Some systems include cell balancing and monitoring electronics in the modules, while others include cell balancing and monitoring in the main BMS circuits. Finally, some systems employ heated or chilled air thermal management devices, but others do not actively maintain the battery system.

4.1 Vehicle structure:

The battery pack system is designed differently based on the vehicle architecture and expected system performance, such as whether it is a completely new EV or an existing vehicle architecture that has been effectively converted to an EV. Based on this, EVs are classified into three types: hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV). In these EVs, the electric motor assists a traditional ICE or drives the vehicle alone. The difference in power-to-energy ratios between BEV, PHEV, and HEV batteries is mostly due to the different consumption patterns discussed below. 1.1 Vehicle structure

Figure 18. Types of Electric Vehicles[49]

When considering the performance requirements of various battery designs, energy and power density are crucial elements. The more energy a vehicle can carry aboard, the longer its driving range can attain. However, one of the most important issues for system designers is the necessity to keep the battery as small as feasible. This is advantageous for two reasons. First, the bigger the battery, the more space it takes up in the vehicle, reducing cargo and carrying capacity and necessitating more challenging integration exercises. Second, the bigger the battery, the more expensive it is. As a result, system designers are always looking for new ways to minimize battery size and weight while improving energy. As a result, energy densities (Wh/l) and specific energies (Wh/kg) increase.

4.1.1 HEV

A hybrid electric vehicle's battery size and capacity are smaller than the other EVs. HEVs have ICE as the main drive unit and an electric drive train. HEV takes power from ICE during medium and high speed, whereas the battery powers the vehicle during the stop-and-go traffic and assists in the vehicle's acceleration. This battery pack is charged by the ICE and regenerative braking system. There is no plug-in option for this EV to get the charge directly from an external source. The most common location for the battery mounting is in the tunnel or fuel tank area. The advantage of this battery pack is that it can be packaged in a small area due to its smaller size. The shorter driving range is the disadvantage of these batteries before the engine turns on to provide the charging to the batteries. In HEV, existing space is being used for packaging the battery.

Example: Toyota’s Prius (2015 model year) provides a milage of 50 mpg with milage with 4.3 KWh li-Ion battery.

4.1.2 PHEV and EREV

Differing battery pack designs are employed to suit the performance needs of PHEVs and EREVs since they have different use and power profiles than BEVs. A PHEV operates like an HEV at times and like a BEV at others. PHEVs and EREVs must have enough useable energy onboard to meet the electric driving range, often between 15 and 65 kms. Once this range has been reached and the battery pack capacity has been reduced to a predetermined level, the PHEV works on ICE power, with the battery operating in a hybrid or charge-sustaining mode, powering the vehicle and accessories during pauses. When the EREV battery achieves this minimal capacity, the ICE does not directly power the wheels. Instead, it supplies consistent power to the motor(s) to drive the vehicle and power the accessories. Combining a Li-ion battery and an electric drive system with an ICE allows PHEVs to attain combined electric and ICE vehicle ranges of 500–650 Kms or more, equivalent to ICE cars. These consumption profiles tend to necessitate a greater power-to-energy ratio in PHEV applications. Depending on the intended electric driving range, PHEV batteries range in capacity from roughly 5 kWh to 15 kWh. The sizes of EREV batteries range from 16 kWh to 20 kWh, with the majority lying at the lower end of that range.

This vehicle's battery is larger than that of an HEV but smaller than that of a BEV. As the size is larger, it can carry more energy and power. Depending on the intended electric driving range, PHEV batteries range in capacity from roughly 5 kWh to 15 kWh. Unlike the HEV, the PHEV's battery may be charged using an external energy source and the ICE. The PHEV has a power-to-energy ratio of around 12:1 or less and can operate at up to roughly 80% of its SOC, allowing it to achieve up to 4000 cycles throughout the life of the battery.

4.1.3 BEV

In BEV, there is no ICE to function as a backup power source; it necessitates a bigger battery, which means that the whole driving range must be met with onboard battery power and energy from braking regeneration. Power requirements become less critical as battery size increases since the larger the battery, the more power it contains. This is not because BEVs use less electricity but because larger batteries deliver more power. Many BEV batteries have 20–24 kWh of onboard energy and, depending on the size of the vehicle, can have up to 50 kWh for performance vehicles and up to 100 kWh for some light commercial vehicles, such as all-electric vehicles. Nissan Leaf is a different design: a full EV with no ICE engine. It is completely running on battery power, which requires a larger battery pack (24 KWh as compared to 16KWh in volt). Moreover, provide a greater electric drive range (160 Kms compared to 65 Kms). The leaf platform is the same as the existing versa model and requires packaging the battery in the existing space. Therefore, the core structure of the body space is used to achieve the minimum changes, like underneath the floor and under the seats.

Many BEV batteries have 20-24 KWh of onboard energy and, depending on the vehicle size, can have as much as 50 KWh for performance vehicles and even up to 100 KWh for some light commercial vehicles such as electric delivery vans. Table 8 shows the typical difference between various EVs design and their working. It shows that BEV are having the maximum range while HEV are having minimum range. BEV completely drive on electric battery.

Table 8. Typical differences between various EVs design and their working

Type of vehicle	Platform	Battery	ICE engine	Location for battery	Battery Range (KWh)	Remarks
HEV	Common	O	O	Tunnel/ fuel tank area		ICE act as a generator to charge the battery
PHEV	Common	O	O		5-15	ICE power to the vehicle once the battery is discharged to a predefined level
EREV	Common	O	O		16-20	ICE provides power to the motor to drive the vehicle
BEV	Common/ New	O	X	Underneath floor and seat	20-118	The battery provides the power to the vehicle

O-Present X-Not present

4.2 Cell Material Structure

It is important to discuss the material of the cell as many of the important design factors of EV batteries, like the weight of the battery pack, energy density, charge-to-weight ratio, energy storage capacity, and price, depends on its material as shown in the Table 9.

Table 9. Cell Material characteristic for battery for demanufacturing

Parameter	Impact on design
Safety	The higher the operation stability at a higher temperature, the safer the battery will be and the longer the battery life.[50]
Green Product	It depends upon whether the material used in the battery is environmentally friendly. Therefore, deciding the end-of-life strategy for that product is a factor.
Charge at high temperatures	Operation ability at a higher temperature from thermal runaway point[50]
Memory effect	Defines the rate of gradually losing maximum energy holding capacity during repeatedly recharging without being discharged. The lower the memory effect, the higher will be battery life.
Nominal voltage	Charging voltage
The energy density (Wh/kg)	Amount of energy held by battery. Measured in Wh/Kg. Higher the energy density value higher the energy a battery can store, which can be used in multiple higher energy applications. [50]
Life cycles	No of a full cycle, a battery can charge and discharge. Higher the life cycle, the more the battery life. [50]
Life in service (continuous use)	The complete life of the battery cell.
Charging efficiency	It is a ratio of energy that can be taken from charged battery to the energy required to charge it. The more the ratio better the efficiency will be. [51]
Charging and discharging time (hours)	The rate of charging and discharging is given in proportional to C. So, the charge rate of C/5 means the constant current to discharge the battery within 5 hours fully.
Self-discharge (monthly)	Automatic depletion of stored energy without the use [52]. Lower the self-discharge rate, charge sustain for a longer period
Nominal Mass (g)	Mass of the battery material, Lower the mass lighter the battery
Acceptable Temperature (°C)	Range of temperature battery can work efficiently, Wider the acceptable temperature, wider the use in a number of applications

Based on the cell cathode chemistry, batteries can be classified into four major categories are

1. Lithium-iron-phosphate (LPF)
2. Nickel-Metal hydride (NiMH)
3. Lithium nickel manganese cobalt oxide (NMC)
4. Nickle aluminum oxide (NCA)

4.2.1 Lithium-Ion Batteries (LFP)

Lithium-Ion batteries (LIB) are most common in EVs at present. One of the types of LIB is Lithium Iron Phosphate (LFP). The positive electrodes (cathode) consist of Lithium iron phosphate ($LiFePO_4$), and the negative electrode is made of graphite carbon electrode with stored lithium [53]. LFP batteries are cobalt free. LFP batteries are currently at 125 watt hours (Wh) per kg, up to possibly 160 Wh/kg with improved packing technology, compared to over 300 Wh/kg for the highest NMC batteries. [54].

Table 10. Characteristics of LFP batteries[50], [55]

Types of batteries	**LFP**
Year of marketing	2004
Chemical formula	LiFePO4
Safety	Excellent
Green Product	Yes
Charge at high temperatures	Good
Memory effect	No
Nominal voltage	3.2V
Operating range [V / cell]	2.0–3.65
The energy density (Wh/kg)	90–160
Life cycles (download 1C)	2,000–7,000
Life in service (continuous use)	5-6 years
Charging efficiency	0.95
Charging time (hours)	0.25-1
Self-discharge (monthly)	0.80%

Nominal Mass (g)	39
Acceptable Temperature (°C)	−30 to 60
Major OEM used	Tesla Model 3, Nissan Leaf, Porche Taycan,

Table 11. Advantages and Disadvantages of LFP

Advantages	**Disadvantages**
High energy ratio and Voltage The high charge weight ratio Light weight Competitive in price Lack of memory effect Longer life cycle (2000-7000) High current rating (Large capacity) Good tolerance for abuse	Difficult to control cell balancing Temperature sensitive Need for thermal management system Need for battery management system Difficult to recycle Recharge capacity is limited High production cost

Due to the high energy and charge weight ratios, these batteries are lightweight and price competitive. Lack of memory defines the lower rate of gradually losing maximum energy holding capacity in case of repeatedly recharging without being discharged. Also, When used, the voltage remains stable for a long time. Still, once the power is exhausted, the voltage will be Sub-lower to 0 (no memory effect at all). Due to this, these kinds of batteries have a longer life cycle. In addition, good tolerance for abuse leads to enhanced safety. Poor charging or incomplete discharge will not affect the battery capacity; therefore, good tolerance to abuse.[56]

Continuously decreasing the rate of charging and discharging of battery due to aging; therefore, balancing the cell is difficult. In addition, LIBs are temperature sensitive, and the rate of aging increases as the temperature rises above 25 degrees Celsius. Therefore, LIBs need to have a cooling and heating system to keep the change in temperature within the range of 2-3 degrees throughout life. To monitor and control the internal cell temperature and their uniform charging and discharging rate, there is a need for a different system called battery management system (BMS). Waste batteries seriously pollute the environment; therefore, recycling is difficult.

4.2.2 Nickel manganese cobalt oxide (Li-NMC)

For moderate load conditions, NMC in a 18650 cell has a capacity of about 2,800mAh and can deliver 4A to 5A. However, because of the high cost of cobalt, battery manufacturers are shifting away from cobalt systems and toward nickel cathodes.

Table 12. Characteristics of NMC batteries[50], [54]

Types of batteries	**LiMn (NMC)**
Year of marketing	1997
Chemical formula	LiNixMnyCozO2 (Ni:Mn:Co = 1:1:1, 6:2:2, or 8:1:1)
Safety	Almost good
Green Product	Yes
Charge at high temperatures	Very bad
Memory effect	No
Nominal voltage	3.7V
Operating range [V / cell]	3.6–4.0
The energy density (Wh/kg)	160–230
Life cycles (download 1C)	2,000–3,000
Life in service (continuous use)	Two years
Charging efficiency	0.9
Charging time (hours)	2-4
Self-discharge (monthly)	0.1
Nominal Mass (g)	47
Acceptable Temperature (°C)	−5 to 50
application	“BMW i3”, “Audi etron GE,” “BYD Yuan EV535”, “BAIC EU5 R550”, “Chevrolet Bolt,” “Hyundai Kona Electric,” “Jaguar I-Pace”, “Jiangling Motors JMC E200L”, “NIO ES6”, “Nissan Leaf S Plus”, “Renault ZOE”, “Roewe Ei5”, “VW e-Golf”, “VW ID.3”

Table 13. Advantages and Disadvantages of NMC

Advantages	Disadvantages
high power and capacity	Sensitive to high charge, which can cause thermal runaway
Low self-heating rate Max temp range is 210 degrees	the life cycle of 1000-2000 cycle
Major Manufacturers using: Volvo, BMW Active E, BMW i3, Chevrolet Bolt, VW ID3	

4.2.3 Nickel Cobalt Aluminium (NCA)

The chemical formula is $LiN_{0.8}Co_{0.15}Al_{0.05}O_2$. This chemistry is also regularly used in EV batteries but has become out of the race due to high costs and higher chances of fire. There is a high risk of a thermal runaway due to the low maximum temperature (150 degrees as compared to the 260 degrees in LFP). It has a lower life cycle of 400-1000 cycles. The energy density of Panasonic's "2170" NCA batteries used in 2020 in Tesla's Model 3 is around 260 Wh/kg.[54]

Table 14. Characteristics of NMC batteries[50], [54]

Types of batteries	**LiCo (NCA)**
Year of marketing	1992
Chemical formula	$LiN_{0.8}Co_{0.15}Al_{0.05}O_2$
Safety	Very bad
Green Product	No
Charge at high temperatures	Almost good
Memory effect	No
Nominal voltage [V / cell]	3.7V
Operating range [V / cell]	3.0–4.2
The energy density (Wh/kg)	200–260
Life cycles (download 1C)	400–1,000
Life in service (continuous use)	Two years
Charging efficiency	0.9
Charging time (hours)	2-4
Self-discharge (monthly)	0.1
Nominal Mass (g)	48.5
Acceptable Temperature (°C)	0 to 45
Major Manufacturers using	Telsa, such as "Model 3", or "Model X"

Table 15. Advantages and Disadvantages of NCA

Advantages	Disadvantages
High specific energy and power Long life span.	High cost per Kwh High risk of a thermal runaway Lower life cycle

4.2.4 NiMH batteries

This kind of technology in the EV was the first step currently being used as Li-ion batteries. The positive electrode is Nickle Oxide hydroxide (NiOOH), and the negative electrode is a hydrogen-absorbing alloy. These batteries have a good energy consumption of 15.7 Kwh/100kms with increased energy density and power.

Table 16. Characteristics of NMC batteries[57]

Types of batteries	**NiMH**
Year of marketing	1990
Chemical formula	NiMH
Safety	Good
Green Product	Yes
Charge at high temperatures	Mediocre
Memory effect	Ni (very small)
Nominal voltage	1.25V
Operating range [V / cell]	
The energy density (Wh/kg)	80
Life cycles (download 1C)	500–1500
Life in service (continuous use)	Three years
Charging efficiency	0.7
Charging time (hours)	4
Self-discharge (monthly)	0.3
Nominal Mass (g)	NA
Acceptable Temperature (°C)	−20 to +60
application	Toyota Prius (HEV)

Table 17. Advantages and Disadvantages of NiMH

Advantages	Disadvantages
Able to use the regenerative energy Excellent thermal properties Simpler battery management system Battery charging and discharging safety	Heavyweight Obsolete technology Harmful waste material for the environment Lower voltage
Major OEM using: Toyota Prius (HEV)	

NiMH batteries can use the regenerative energy recovered from braking. Also, have excellent thermal properties ranging from -30 degrees to +70 degrees. It has a more straightforward battery management system than a Li-Ion battery.

4.3 Cell structure

In this section, the next important factor will be discussed in battery pack designing, i.e., the type of cell used. The cells are used to store the electrical energy, and that can be recharged. These cells are connected in parallel/series to increase the pack capacity and meet the requirement for power and energy. For example, Tesla Model S has a total battery pack power of 85KWh and uses 74 no of cells with a current-carrying capacity of 3.1 Ah (Ampere-hour) in one module unit. Ninety-six nos. of such modules are again connected in the series.

The important parameter that can be used in the design of demanufacturing are mentioned in the table below.

Table 18. Cell structural characteristic for battery for demanufacturing

Parameter	Impact on design
Energy Density	According to the shape of cells used in the module, energy density changes in a module. Higher the energy density, the higher the capacity of a battery pack
Lifeline	The higher the lifeline, the better the battery is
Space Utilisation	Space utilisation in a module, Higher the space utilisation more energy can be stored
Design Flexibility	Design of cell as per the requirement
Mechanical Stability	Stability is retaining its shape during pressure, stiffness, and tightness. Higher mechanical stability better the life of a cell

The Li-ion cell comes in many shapes and sizes. OEMs design the outer shape and size of the cell per the design requirements. Majorly, cell design can be divided into three types i.e.

1. Cylindrical,
2. Pouch and
3. Prismatic.

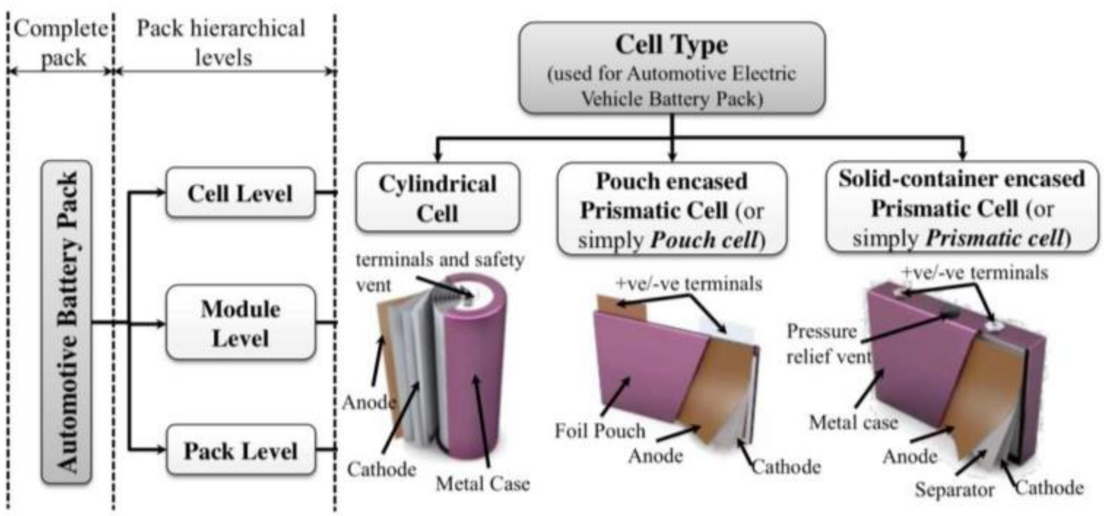


Figure 19. Cell types[58]

The battery pack design mostly depends on the type of cell used. The design of major components like mechanical structure, battery management system, thermal management system, and overall packing is decided by the type of cell used. Another major factor that helps select the number of cells and type of cell in the battery pack is the amount of current flow in the pack.

An arrangement has been shown for all three types of cells in the Tesla Model S, BMW i3, and Nissan Leaf battery pack. Where Tesla uses a cylindrical, BMW I3 and Nissan Leaf use prismatic and pouch cells, respectively. The battery pack using cylindrical cells is found to be slim with 127mm thickness compared to the Prismatic and pouch cell battery pack, which are 265 mm and 259 mm in thickness, respectively. Also, the weight of the Cylindrical cell battery pack is much higher, i.e.530 kgs, compared to the prismatic and pouch types as 235 kg and 294 kgs, respectively. Also, Tesla uses more cylindrical cells as 7000 in one battery pack, whereas many fewer cells are used in BMW and Nissan as 96 Prismatic cells and 192 Pouch cells, respectively.

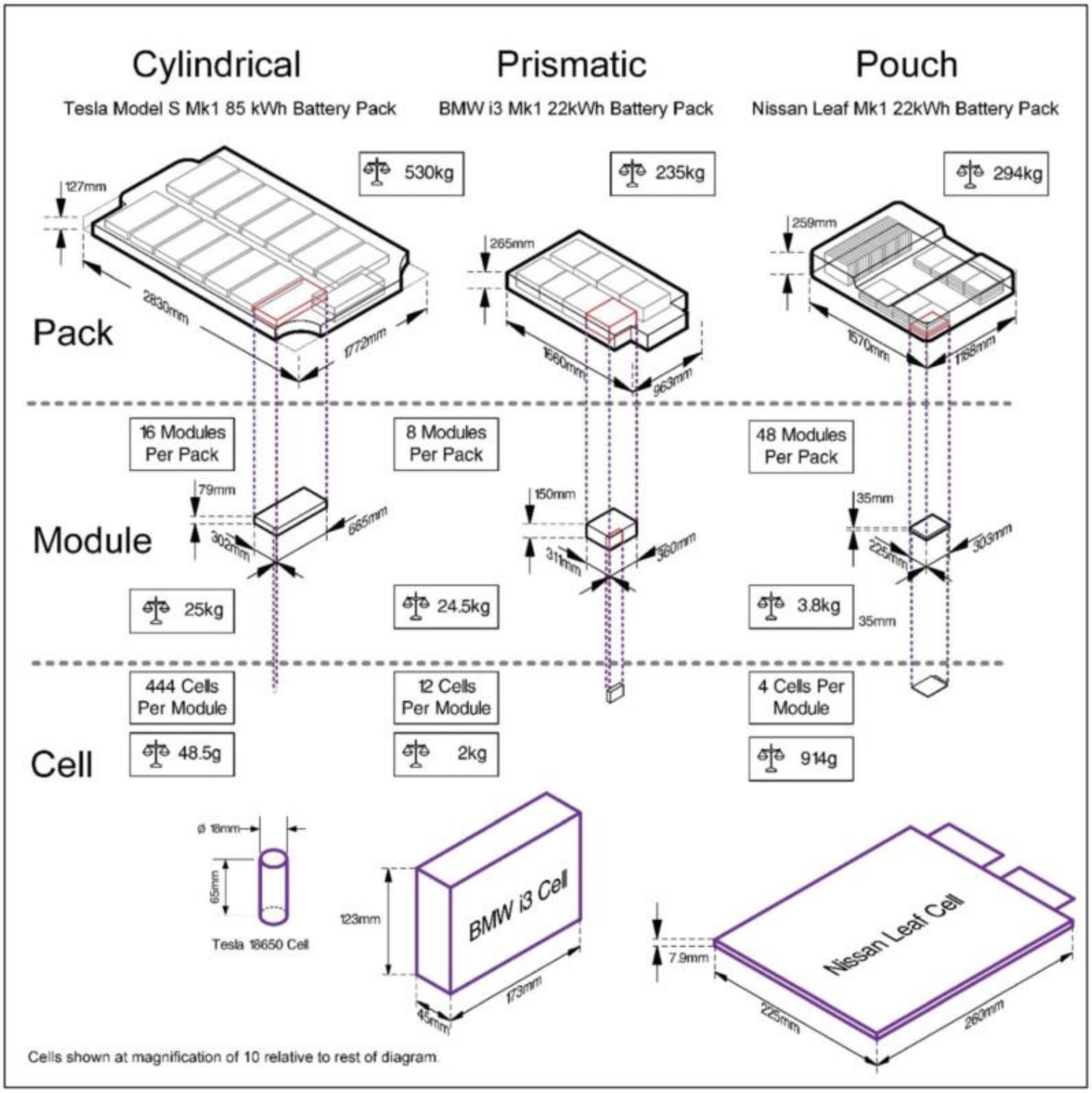
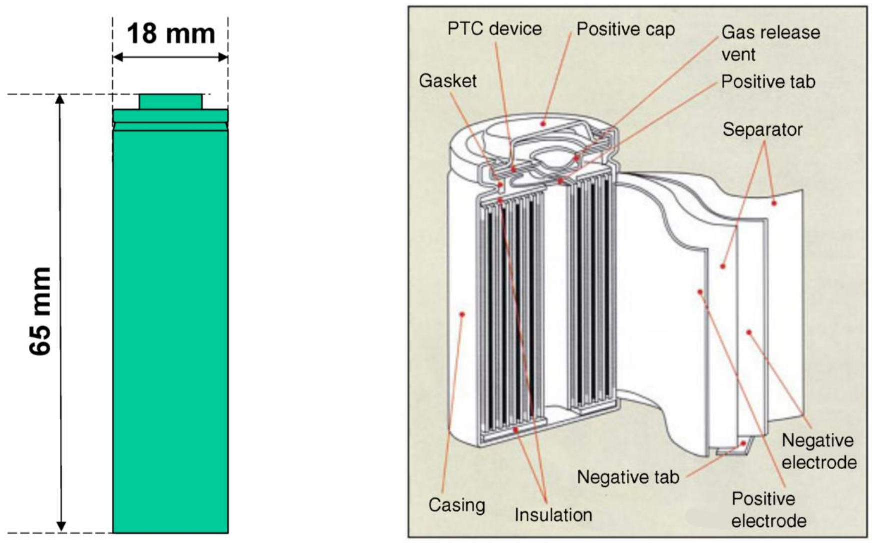


Figure 20. The systematic arrangement of different cells in the Battery pack[59]

4.3.1 Cylindrical cells:

Due to the shape of such kinds of cells are called cylindrical cells. The most used cell in EVs these days is 18650. The name of these cells defines the dimension of the cell-like 18mm in diameter and 65mm in length. This cell is widely used in all types of electronic items. The capacity of these cells varies from 2Ah~3.5Ah. Due to their capacity, an EV uses approx—7000~8000 cells in its battery pack.



(a) 18650 Cylindrical cell

(b) Anatomy of cylindrical cell
(Reproduced with permission from Cadex Electronics, Inc.)

Figure 21. Cylindrical Cell Li-Ion[60]

Table 19. Cell structural characteristic for cylindrical battery

Parameters	**Cylindrical Cell**
Energy Density	Low in module
Packaging Density	High
Lifeline	Good
Capacity	3-6 Ah
Housing	Metal
Space Utilisation	Does not fully utilize the space
Design Flexibility	Low
Mechanical Stability	Tolerates pressure High stiffness High tightness
Deformation	High resistance toward deformation
Temperature	For cells with high capacity, the heat dissipation is low

Table 20. Advantages and Disadvantages of Cylindrical Battery Cells

Advantages	Disadvantages
- Good mechanical stability - Long life than the other type of cell. - Built-in safety features - Avoiding cascading failure propagation - Easy to the bin and short - Reducing the cell balancing operation - Cost is lower than other types of cells.	-Inefficient from a packaging perspective
Major OEM using: Tesla (Model S, Model X, Model Y)	

As shown in Table 20, cylindrical cells have a long life as they are resistant to deformation due to their hard outer shell and cylindrical shape and good heat dissipation capability. They have built-in safety features such as a temperature-driven resettable thermal fuse, a pressure-driven interrupt device, and a vent. It can reduce the impact of single-cell failure by avoiding cascading failure propagation. Due to being small in size and accessible to handle, these cells are easy to bin and short according to their voltage capacity during manufacturing. Therefore, it is better to have cells with almost equal capacity in one module to enhance the overall capacity of the module. Also, if all cells have a similar capacity in a single application, it reduces the cell balancing operation, reducing the heat generation in the pack. Due to mass production capability, these cells have lower costs than the other types of cells. On the other side, one major disadvantage of these cells is not being efficient in packaging. The maximum volumetric cylindrical efficiency is 78.5%.

4.3.2 Pouch/polymer/laminated cell:

These cells are designed like a pouch. These types of cells have flexibility in terms of shape by maintaining consistent chemistry and internal structure. In this, the anode, cathode, and separator are assembled in Z fold, in which all three sheets are folded continuously to form a single cell. These stacked sheets are welded together, packed in an aluminum pouch, and sealed with adhesive. Pouch cells have a large cell capacity of , up to 20~40 Ah, and even more for some special applications of, up to 100 Ah. These cells need to be enclosed in an aluminium pouch.

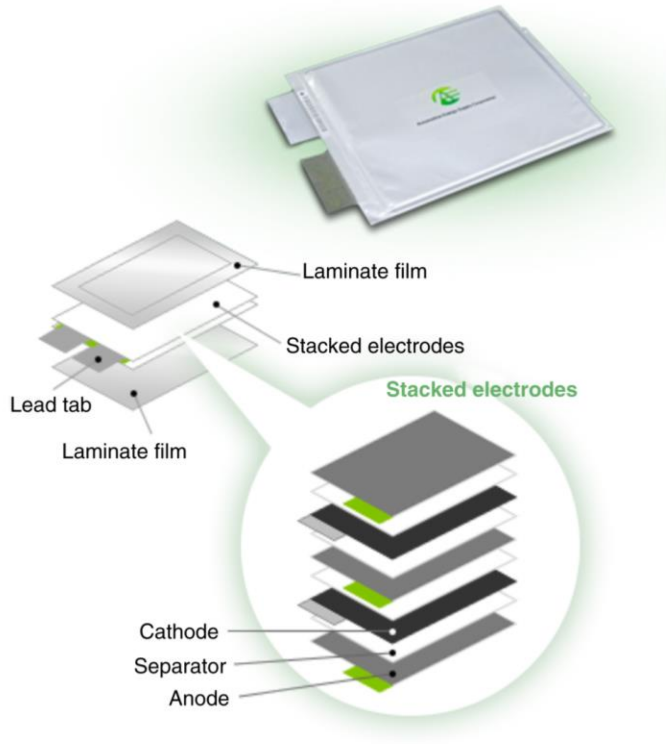


Figure 22. Pouch Cell[60]

Table 21. Cell structural characteristic for Pouch battery

Parameters	**Pouch Cell**
Energy Density	High in module
Packaging Density	Low
Lifeline	Medium
Capacity	40 Ah
Housing	Soft bag
Space Utilisation	Space between every cell for possible swelling
Design Flexibility	High
Mechanical Stability	Swells Low stiffness Low tightness
Deformation	Low resistance towards deformation
Temperature	Efficient cooling good surface-volume ratio

Table 22. Advantages and Disadvantages of Pouch Cell

Advantages	Disadvantages
Less No cells required Higher reliable battery pack Lower cost of a battery pack Higher energy density More efficient in cooling	Risk of damage as a soft outer casing Lower mechanical stability Lack of integrated safety Risk of cascading failure Difficult to meet safety test
Major Manufacturers using: GM (Chevy Bolt), Audi (e-Tron), Ford (Focus electric)	

Table 22 lists the advantages and disadvantages of pouch cells. Due to higher energy density per cell, fewer cells are required in a battery pack. As the number of cells is less in a battery pack, the battery pack is highly reliable, lower in cost, and has higher energy density. The surface area of a pouch cell is more than a cylindrical cell; these types of cells are more efficient in cooling. On the other hand, there are some disadvantages of such cells. The outer skin is soft; there is a high chance of cell damage. Due to excessive flexibility and softness, pouch cells have dimension and alignment issues and need holding components. Such holding components include a frame, rigid cases, and a supporting tray. Also, passing stringent tests like the nail penetration abuse test is difficult. These cells have lower mechanical stability and deform if the temperature rises. There is a lack of integrated safety; therefore, an external device must extract stacked pressure on the cell. As the energy density is higher per cell, there is a risk for cascading failure propagation if a single cell fails.

4.3.3 Prismatic:

These cells have an upper edge due to their design flexibility, long life, and mechanical stability. However, the design and style of these cells can vary as an outer casing of either plastic or aluminum can be used. In this kind of cell, as per the size requirement, the anode, cathode, and separator may use a Z fold or stacked one or rolled type configuration. Once all three layers are rolled together with the help of a spindle, called jelly rolled, it is compressed to get an oblong or flat kind of structure. The capacity of these cells covers a wide range starting from less than 4 Ah to 250 Ah and more.

Major Automotive OEM using: BMW

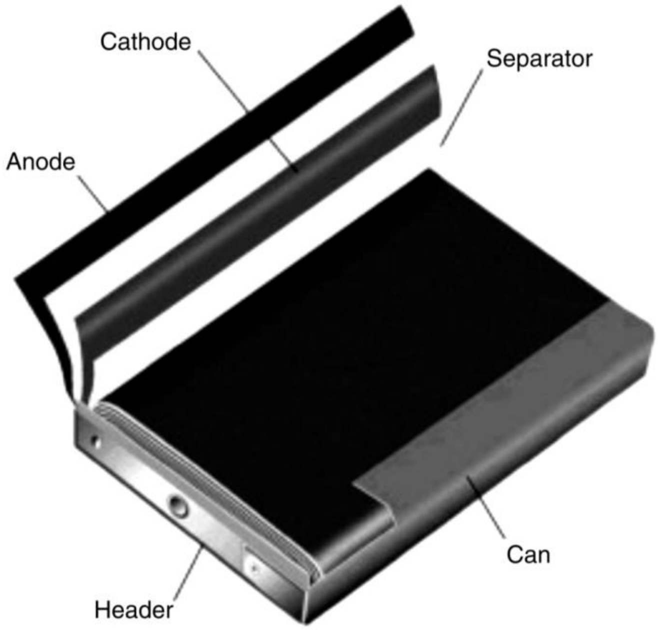


Figure 23. Anatomy of Prismatic cell Li-Ion[60]

Table 23. Cell structural characteristic for Prismatic battery

Parameters	Prismatic Cell
Energy Density	Middle in module
Packaging Density	High
Lifeline	Good
Capacity	20-50 Ah
Housing	Metal/plastic
Space Utilisation	Fully utilize the space
Design Flexibility	High
Mechanical Stability	Tolerates pressure Medium stiffness High tightness
Deformation	Medium resistance towards deformation
Temperature	Good surface-volume ratio

Table 24. Advantages and Disadvantages of Prismatic Cell

Advantages	Disadvantages
Better space utilisation Has a good long life Higher capacity Inbuild safety Mechanical connection can be used	Risk of cascading failure Medium resistance towards deformation. Mass production setup will take time The quality of the cell is also lower
Major Manufacturers using: Nissan (Leaf), BMW (X6, Mini), Chrysler (200C EV), Honda (Civic, Insight), Mitsubishi (I-MIEV)	

The advantages and disadvantages of prismatic cells are mentioned in the table 24. Due to the shape of these cells, it can be packed effectively. The prismatic cell can be customized as per requirement. Prismatic cells have safety features like venting and thermal fuse. A mechanical connection can connect two cells that avoid busbar welding. There are some disadvantages of these type of cells. There is a risk of cascading failure as higher energy per cell if a single cell fails. The quality of the cell is also lower than the cylindrical cell.

4.4 Module structure:

Modules connect the cells structurally into a single electromechanical unit for a specific electric power and energy capacity. Cells can be connected in series, parallel, or mixed configurations according to the capacity requirement. The number of cells installed in a module is limited by the monitoring capability of the battery management system at the module level [61]. According to the design of the battery pack, each module may have its monitoring, electrical and thermal management components. A combination of such modules makes a battery pack. Therefore, the module facilitates the scale-up of the battery pack and simplifies the battery function control.

According to the cell design, cells' mounting strategy differs in every module. In addition, module shape and size depend on the type of cell used, amount of current required, class of the vehicle, and thermal management system. For example, there is a need for frame type structure of metal or plastic for pouch cells to mount, protect, and apply required pressure on the cells in a module, whereas there is no such requirement for a prismatic cell. For instance, Interconnect board (ICB) is enough in the prismatic cell to provide a mechanical structure. All these attributes make modules different for different manufacturers, even different for the same manufacturers for the different models of vehicles. Therefore, there is no industry standard for module shape and size.

Although modules come in various sizes, the process involves the same elements, including connecting the cells, assembling them into mechanical structures, integrating the cells or modules, monitoring and balancing the electronics, and integrating a thermal management system. Another concept is Monoblock, or the simple use of welded busbar, a small mechanical package with the thermal management system built-In.

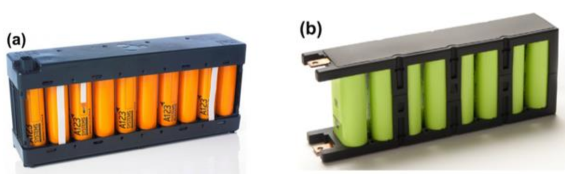


Figure 24. (a)Image of 6.6 V, 8.8 Ah Nano phosphate source: A123 (b) 3.7 V, 35 Ah Boston power swing key block (Source: Boston-power)

Another crucial point to be considered in module design is the serviceability and disassembly of the module. Some battery manufacturers design a module in which cells are interconnected with mechanical joints like use of bolts and nuts. The advantage of such mechanical joints is that cells can be repaired or replaced easily in case of failure throughout the module's life. However, the disadvantage is that mechanical joints may get loose over time, which results in increased resistance and can increase the chances of failure in the module. On the other hand, another manufacturer prefers permanent joints like welding to interconnect cells in modules. The advantage of having permanent joints is material saving, cost saving, weight saving, less no of components (no nuts and bolts) in the module, and high reliability (no looseness of joints). However, the disadvantage is that in case of a cell failure, the faulty cell cannot be repaired or replaced, and the entire module needs to be replaced.

Table 25. Module design characteristic for battery for demanufacturing

Parameter	Impact on design
Type of cells	The design of modules depends on the type of cell chosen
No of cells	The size of the module depends on the of cells used in a module
Orientation of cells	according to the capacity requirement, cells are connected in series, parallel, or combination
Interconnection of cells	Method to connect the cells like welding or using nut/bolt
Thermal management	integrated thermal management with module or not
Capacity	According to the requirement of total capacity, it is required.
Monitoring Components	May have integrated BMS or separated one

Table 26. Important Features of Module

Important Features	Potential Problems
Module size depends on the type of cell use	No industry standard for the module shape and size
Size changes as per current and voltage requirement	Collecting the current from a different cell is difficult
The module can have its own BMS or be connected with a central one	No common standard for cell mounting

4.5 Pack configuration:

Battery main contains many components such as cells, modules, thermal management system, battery management system, wiring harness, busbars, etc. The battery pack design is not standard as it varies with the original equipment manufacturer (OEM) and even within the same OEM with every car model. Battery design mostly depends on the requirement of OEMs to develop a new design that meets the requirements of crash safety, body weight balance of vehicle (center of gravity), space efficiency, and serviceability. These contrasting design elements lead to an inefficient disassembly that is not optimized for demanufacturing. [62]

The battery pack can be a single pack or multi-pack design, depending upon the space availability in the vehicle. Also, the way cells are installed in the battery pack, either in a standardized module, or in a Monoblock design, or directly into the pack structure. The smaller the battery, the less space required for battery packaging in the vehicle, increasing the payload and carry capacity and helping in easy integration exercise.

Table 27. Important Features of a battery pack

Important Features	Potential Problems
can be single pack and multi pack	Bulky in size
The cell can be installed in the module or directly	
Easy and quick connection of coolant	
Safe and secure connection of battery pack	

4.6 Thermal Management Structure

A thermal management system is responsible for keeping the cell temperature in the battery pack nearly at room temperature i.e., 25 degrees, with a constant variance of 2 degrees to 5 degrees for optimal battery life in low and high-temperature environments. High temperatures, in particular, degrade the life of the batteries, while cold temperatures reduce their power and energy capabilities. Therefore, the thermal management system must be compact, lightweight, low cost, and easy to pack inside the vehicle.

In addition, it must be reliable and accessible for maintenance. In general, a thermal management system may use air or a liquid to maintain the battery pack at the specified temperature, and it may be passive (only the ambient environment is used) or active (a built-in source provides heating and cooling depending on the actual battery temperature)

Four major factors impact the design of the thermal management system

1. Ambient Temperature: The ambient temperature in which the vehicle operates is a major factor in designing the thermal management system. The thermal management system heats the cells when the ambient temperature is cold and cools down the cells when the ambient temperature is hot. A constant higher or lower ambient temperature negatively impacts the battery life. Due to extreme temperature, the internal resistance and impedance increases within the cell. The higher the resistance, the higher the heat generated (can be calculated by I2R), which further reduces the active capacity of a cell. Therefore, the vehicle that will operate in the colder place might need less cooling but additional heating to avoid the freezing of coolant. Whereas in the extremely hot place, liquid cooling is used. As a designer, if a vehicle is about to go globally, both extreme temperature conditions must be met.
2. Pressure Drop: The pressure drop of air or liquid can be calculated by measuring the pressure difference between the inlet and outlet valve. The pressure difference will depend on the amount of hindrance air or liquid face passing through the channels. If air/liquid passes freely, the pressure difference will be low across both valves resulting in even flow. The even flow of air/liquid will helps the even cool/heating of all the cells in the battery, which results in even aging of the cells, thereby preventing the premature reduction in

capacity. Therefore, the medium flow should be smooth in the thermal management system for optimal battery life.

3. Mounting of battery pack: Another design aspect in designing the thermal management system is mounting a battery pack as a single pack or multi-pack. It is easier and cheaper to meet the requirement in single-pack mounting than in multi-pack mounting. Mounting of the pack is dependent on the availability of space in a vehicle. For Single-pack mounting, the air system is better, whereas, for multi-pack mounting, the liquid system is better.
4. Medium of temperature control: Thermal management systems use two types of medium to control the battery pack temperature

   1. Air-based 2. Liquid base

Table 28. Comparison of mediums of TMS

Liquid base	**Air-based**
A thermal conductive cooling plate must be installed between cells that act as a heat sink. These plates are connected to a cooling line. Liquid passes through these lines, which are further connected with the radiator/ evaporator to reduce the temperature of the liquid. For cold places, a separate heating element is required.	Air is channeled from the heat exchanger into the series of a duct that drives the air through the cells or modules, forcing the heat /air out of the battery pack
It is more efficient as liquid transfers the heat more effectively as compared to air	Less effective in transferring the heat
Costlier as it has the cooling line, radiator, and use of aluminum as a heat exchanger	Less expensive as only ducts are required to guide the air
It can be designed in a closed loop system where it does not require or draw liquid from the outside of the system	It is an open loop system where air needs to be sucked inside for circulation

Various cooling and heating system elements are used in the liquid-based system, but the most common use is a 50-50 mixture of water and glycol.	Only air is used.
An active thermal management system (the built-in system is used) uses a liquid-based system. The pack is designed with an aluminum heat exchanger throughout the battery pack to pull the excess heat from the cells during operation.	A passive type thermal management system (only ambient environment) uses an air-based system in which chiller air is blown through the battery pack on the feedback from the sensor mounted at various spots in the battery.
Major OEM Using:	Major OEM Using:

Table 29. Advantages and Disadvantages of Thermal Management system

Advantages	Disadvantages
Maintain the battery temperature in the operation range	Occupies space in battery pack
Reduce the battery aging	Add weight to a battery pack
Maintain the battery performance at an optimal level	Add cost
Control the fire chances in the battery	Effective packaging is difficult
Major Manufacturers using:	

Table 30. TMS design characteristics from the demanufacturing point of view

Parameter	Impact on design
No of mounting	The number of mountings for cooling plates needs to be a minimum or zero to make assembly and disassembly easy and quick
No of connection	The number of connections of a different cooling plate with the main supply of coolant needs to be minimum.
Type of connection	The connection between the supply line and cooling plates needs to be fit and disassemble quickly without any efforts
Number of cooling plates	Depending on the number of battery packs or type of layout, cooling plates will be required
Number of parts	Minimise the number of parts in a thermal management system
Contact area with cells	For better heat collection from the cells, a max contact area of cells needs to be connected with cooling plates

Temperature control	the temperature of cells needs to be maintained at 25 C for a good battery lie
Ambient temperature	According to the ambient temperature, a Thermal management system shod have the capability to cool and heat the cells
Medium of temp control	The required medium for temperature control can be decided
Pressure control	It is necessary to have uniform pressure in cooling channels as pressure differences can create an uneven flow which can result in uneven cooling of the cell

4.7 Mechanical Structure

The mechanical structure includes housing the battery pack, which plays a vital role in the safety and handling of the battery back. The design of mechanical structure depends on many factors as whether the battery pack is a single pack or multi-pack, whether it is integrated with the vehicle frame or separate body structure, material Type, Mass Impact, Crash Requirement, electromagnetic compatibility, Shockproof, Vibration resistant, Humidity proof, Liquid intrusion. Most of the requirements vary from vehicle to vehicle.

Table 31. Design characteristics of housing for demanufacturing

Parameter	Impact on design
No of packs	More no of a battery pack, more time to disassemble it from vehicle
Integration with body	Integration with body will make it difficult to replace, prefer to make separate unit
Material selection	Along with strength, cost, and weight requirement of material, select a material that has possibility of integrating different mounting features to reduce the number of parts
Crash requirement	Extra reinforcement can be provided with the minimum number of mountings
Corrosion resistance	For longer life of the battery, compatible material needs to be selected
Fire retardant	Use material that supports the fire elimination
Coating	For longer life of component by protection from environment and isolation of electric component
Sealing	Sealants should protect sufficiently from water and dust intrusion but should separate easily during disassembly.

Depending on the availability of space in the vehicle, battery pack can be mounted in Trunk space, under the front or rear seat, and under the floor. Batteries pack can be integrated with the body frame or a removable type. If battery pack is interchangeable, a new set of requirements are needed; battery pack needs to be rigid enough during replacement and transportation. Also, high voltage connection, vehicle to battery connection, and thermal management system connection need to connect automatically with high accuracy during replacement.

The housing is the external safety component of a battery that provides crash protection and prevents leaking. Therefore, it is critical that the housing be sturdy for the duration of the battery's life and of high quality, mainly to seal the housing after assembly. Another critical feature of the housing is that it has good gripping areas for raising it when mounting or dismounting it from the vehicle.

Material selection of large-weight items like the housing of Li-ion cells is another factor. Keeping the same energy level and reducing the mass is a significant challenge; achieving this can increase the driving range. Some options are steel, aluminum, fiberglass, and composite material. In most cases, a combination of these materials is used in the battery pack design.

Some of the materials are discussed below:

Stamped steel

Stamped steel have an advantage like strength and relatively low cost. However, the steel enclosure needs welded nuts and mounting attachments or may need an additional structure to achieve the required strength. These additional components are either welded with a base plate or have mechanical joints like bolts and nuts, which further add the processing time and more numbers of components, respectively. It also increases the assembly and disassembly time.

Aluminum

Aluminium offers a lower weight than steel but needs additional material thickness to achieve the required strength. Two aluminum variants can be used as encloser material: stamped aluminum and die-casted aluminum. In die-casted aluminum, high-pressure die casting (HPDC) is a better choice due to its best strength, porosity, and surface quality. Still, there is a disadvantage as it is costly from a tooling perspective. On the other hand, sand casting is a less expensive tool, but surface equality is low, due to which additional surface finishing operation is required.

Plaster Casting

Plaster casting is a better option compared with aluminium, as it is relatively low cost to tool and offer a good surface finish as offered by HPDC. However, there is a quality-related issue as plaster casting has a porosity of the flow, creating a weak spot that makes it least preferable for the big-size battery pack.

There is another requirement for metal housing is coating. There are two reasons for coating: 1. To prevent grounding and shorting of electronics and battery cells (for isolation purposes), 2. To provide environmental protection. The filmed-based coating is used for isolation purposes, with adhesive on one side that can be directly applied in the critical area. In contrast, liquid-based or powder-based coating is used for environmental protection.

Additional structural reinforcements are mostly used to meet the strength requirement in the metal housing. These additional metal components might be bolted or welded, and for cast enclosure, it may be added as an additional rib into the design. Some other analyses need to be done for the addition of reinforcement, like finite element analysis, shock analysis, and vibration analysis.

Special attention needs to be made while using dissimilar materials. Dissimilar materials can create a chemical reaction and cause one of the materials to corrode, known as galvanic corrosion. It is especially critical in an electric system as such corrosion results from electric charge and can cause long-term reliability issues as metal corrodes over time.

Fire Retardant:

Another requirement for battery housing material if a plastic or composite material is used that should be fire retardant. For example, in most cases, a battery cover is used of composite material with a base tray of metal. The material should have a rating from V0 to V2, where V stands for vertical flame retardancy and "Zero" is less susceptible to fire. This rating is based on the Under-laboratory UL-94standard (UL protector, 2014). In case of a thermal runaway event, it is crucial to control the initial spreading of fire.

Sealing requirement:

Another requirement is sealing the battery housing. It is essential to meet the internal protection/ingress protection (IP) rating. In Automobile, the battery pack must be sealed against dust (physical particle) and liquid intrusion known as IP6K9. The first digit represents protection against dust or physical particle and the second digit represents protection against water intrusion. It is developed under Internal Electrotechnical Commission (IEC) standard 60529.

Table 32. International protection classes

Level	Dust and object protection	Level	Liquid protection
0	No protection	0	No protection
1	Protection against body surface touch	1	Protection against dripping water
2	Protection against finger insertion	2	Protection against dripping water at 15° tilt from a normal position
3	Protection against tools and thick wires	3	Protection against spraying water

4	Protection against small parts—wires and screws	4	Protection against splashing water
5	Dust ingress not entirely protected, no contact	5	Protection against water jets at 30 kPa
6	No ingress of dust, no contact	6	Protection against powerful water jets at 100 kPa
		6K	Protection against powerful water jets at 1000 kPa
		7	Protection from immersion up to 1 m
		8	Protection from immersion beyond 1 m
		9K	Protection against powerful high-temperature water jets

Another rating is used for electrical equipment installation in outdoor or indoors: National Electric Manufacturing Association (NEMA) rating. NEMA testing evaluates the degree of protection against mechanical damage to equipment, risk of explosion, or conditions such as moisture, corrosive vapor, and fungus.

Table 33. NEMA Enclosure Rating

Protection against	1	2	4	4X	5	6	6P	12	12K	13
Access to hazardous components	√	√	√	√	√	√	√	√	√	√
Ingress of solid foreign objects (falling dirt)	√	√	√	√	√	√	√	√	√	√
Ingress of water (dripping and light splashing)		√	√	√	√	√	√	√	√	√
Ingress of solid foreign objects (dust, lint, fibers)			√	√		√	√	√	√	√
Ingress of water (hose down and splashing)			√	√		√	√			
Oil and coolant seepage								√	√	√
Oil and coolant spray and splashing										√
Corrosive agents				√		√				
Ingress of water (occasional temporary submersion)					√	√				
Ingress of water (occasional prolonged submersion)						√				

√ - Present

Table 34. Important Features

Important Features	Potential Problems
Provides rigidity in crash	High weight
Sealing the battery pack from water and dust	Large size
Can be integrated or interchangeable	High Voltage and high current

4.8 Electronic Management Structure (EMS)

The electronic management system is responsible for monitoring the temperature, voltage, and current of the cell, block, and module within the pack and preventing the battery pack from failing and aging. Also, it plays a vital role in the balancing of cells. In addition, EMS includes a Battery Management System (BMS), a switch box, and other safety-related equipment.

4.8.1 Battery Management System (BMS)

BMS acts as a brain for the battery pack. It delivers the status of battery capacity and health to the user. It protects the battery when limits are reached during charging/discharging or failure occurs. It is responsible for main system monitoring and controlling the battery behavior in different load conditions, including state of charge (SOC), state of health (SOH), state of life (SOL), Depth of discharge (DOD), safety circuitry, and multiple fuses. Also, responsible for monitoring the temperature, voltage, and current of the cell and module within the battery pack. It plays a vital role in balancing the cells in the pack by ensuring that all cells work at the same capacity. Balancing the cell is very important in the battery pack as the pack's capacity is defined by the lowest capacity cell in the pack. Balancing of the cell is required due to the variance in the voltage and capacity of the individual cells. The variance in capacity is in the manufacturing and chemical formulation of individual cells. This divergence increases with each cycle of charging/discharging and can cause the capacity fade of the whole pack over the life of the pack.

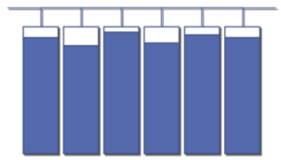


Figure 25. Unbalance cells with different charged conditions

Table 35. Important Features and potential problems of BMS

Important Features	Potential Problems
Act as the brain of the battery	Need to be connected with each cell
Control and monitor SOC, SOH, SOL, and DOD for battery pack	Need to mount on a secure location
Monitor Temperature, Current, and voltage for each cell	
Balance the cell during charging and discharging	
Control and monitor coolant temperature	

Balancing can be done by following two methods.

1. Active balancing: The system keeps monitoring the capacity of every cell and moves energy from one cell to another to keep them balanced with the help of transformers, conductors, or capacitors. It is costly as each grouping of cells requires a separate set of hardware.
2. Passive Balancing: The system monitors each cell's capacity, and excessive energy of a higher-capacity cell is burned off in heat by using a resistor to maintain the capacity of cells at the same level. As this system generates heat in the battery and may cause cell heating, the thermal management system needs to be considered

There are three types of design for BMS in a battery pack.

1. Centralized Type BMS: Hardware and software are designed into a single physical control unit with the sensor mounted through the battery system to provide feedback on battery performance.
2. Distributed Type BMS: The main controller is mounted in one location with cell balancing and monitoring circuitry and a slave board located separately from the host controller and often mountain on or near the module or cells.
3. Modular type BMS: There are multiple host controllers, each with the ability to monitor a limited no of cells or modules. A modular system encompasses aspects of both the centralized and distributed system with more wiring than a distributed system but more control circuits than a centralized one.

4.8.2 Contacting System

To connect the cells, a contacting system is required. This system must measure, for instance, the heat impact and voltage on the cells and send the information back to the BMS.

4.8.3 Switch Box

The switch box holds High voltage switches, current, voltage sensors, contactors, and fuse. The high voltage switches are used to disconnect the battery pack from the vehicle.

A current sensor monitors the total current in the battery pack. Voltage sensors evaluate the current sensor and communicate the result to the BMS. The contactor is an electromagnetic operator switch capable of carrying high currents. Fuse, as the battery store a high amount of energy, the fuse prevents the direct short across the positive and negative connections in the system. Without the fusing device, the battery would be short and continue to supply the power until it experiences irreversible damage.

Table 36. Important Features of Switch Box

Important Features	Potential Problems
- Used to disconnect the battery from the vehicle	- Need to be secure as high voltage current passes
- Holds major electric components like current sensor, voltage sensor, contactor, and fuse	- No water intrusion
- It needs to be easily accessible for the operator	- Should have a warning label for high voltage

4.8.4 Manual Service Disconnect (MSD)

MSD is a safety feature that divides the pack capacity into half or more miniature sub-packs of lower potential and prevents contact with high-voltage electrical devices and components during installation, service, and repair. MSD should be accessible without opening the complete battery pack and exposing the high voltage system. The fuse can be integrated with MSD in the BEV battery pack. In most cases, MSD is accessible from the cabin of the vehicle.

Table 37. Important Features of MSD

Important Features	Potential Problems
Divides the battery pack in half pack capacity	Mounting inside the cabin needs to be secured from occupants due to high voltage.
Accessible without opening the pack	

4.9 Safety Structure

In this section, the discussion will be done on the equipment that provides the battery pack's safety.

4.9.1 Crash Requirements

Meeting the safety standard in a side crash is essential for the battery pack. Additional structural reinforcement in the housing is required if the battery is placed/mounted in the truck, underbody, or under the seating area, as this mounting area comes under the side crash zone.

Table 38. An important feature and a potential problem for crash requirements

Important Features	Potential Problems
To meet the crash requirement	Increase no of parts in the battery
Separate battery pack during thermal runaway	Increase battery pack weight
It can be used to clamp the modules	Cross members occupy crucial space in pack
	Make difficult to assemble the cooling line

From the above analysis, the necessary Lithium-ion battery criteria have been listed down for demanufacturing. All mentioned criteria are directly related to the components' demanufacturing and secondary use.

Table 39. Important Battery Criteria for Demanufacturing

S.No.	**Criteria**	**Important Feature**
1	Vehicle Type	The capacity of a battery pack
		Location of battery pack mounting
2	Cell Material	Safety
		Green Product
		Charge at high temperatures
		Memory effect
		Nominal voltage
		The energy density (Wh/kg)
		Life cycles
		Life in service (continuous use)
		Charging efficiency
		Charging and discharging time (hours)
		Self-discharge (monthly)
		Nominal Mass (g)
		Acceptable Temperature (°C)
3	Cell Structure	Energy Density
		Packaging Density
		Lifeline
		Capacity

		Housing
		Space Utilisation
		Design Flexibility
		Mechanical Stability
		Deformation
		Temperature
		Type of cells
4	Module Size	No of cells
		Orientation of cells
		Interconnection of cells
		Thermal management
		Capacity
		Monitoring Components
5	Thermal Management	No of mounting
		No of connection
		Type of connection
		Number of cooling plates
		Number of parts
		Contact area with cells
		Temperature control
		Ambient temperature
		Medium of temp control
		Pressure control
6	Mechanical Structure	No of packs
		Integration with body
		Material selection
		Crash requirement
		Corrosion resistance
		Fire retardant
		Coating
		Sealing
7	Electronic Management	Complexity
		Cooling
		Independent Operation
		Reliability
		Installation and maintenance
		cost
8	Safety Structure	No cross member used
		Orientation of cross members
		Integrated or bolted

Step 2: Design analysis of the current product by Reverse engineering

Benchmarking is a technique for analyzing existing market solutions and determining how far ahead the competition they are. Benchmarking research uncovers areas where the firm has to improve and forces it to identify its competitive advantages. It allows for the identification of new technologies that may subsequently be used in new products; as a result, it is a continuous process that requires constant updating. Benchmarking helps identify the area of improvement and forces the designers/Policy maker to apply new technology / concepts over and above the existing product to enhance their performance. It can be said that benchmarking is a well-developed strategy within many industries, mainly automobiles, where it is vital to design a product that matches precise user expectations at minimal cost by applying the best technology available worldwide.

In this section, batteries from seven different OEM's/models are considered Chevrolet Bolt 2017, Chevrolet Bolt 2018, Tesla Model S, Tesla Model Y, Tesla Model M, Volkswagen ID 4, Toyota Prius 4Th generation, Mustang Mach E, BMW i3. The reason to select different OEMs or models is that all these models have different built structures like T shape, Spine type, and cell structure like cylindrical, pouch, and prismatic. The cell type of structure further differentiates the cell joining method in Module and Modules in Pack.

General Disassembly process:

Steps to follow before dismantling the battery

- Check the battery pack if there is any residual charge within the battery. If yes, the battery needs to be discharged.
- Coolant needs to be removed from the battery
- Screws and adhesives used are removed to dismantle the battery casing.

- All tools must be anti-statics
- Gloves need to be worn, which should tell me shock proof
- External components within the battery system, which are the BMS, power electronics, and heating/ cooling system, are disconnected and removed.
- Additional wires, cables, and connectors are cut and removed.
- Disassembled the holder holding the module to get take out the module

Batteries

Tesla S/X 2014

Figure 26. Tesla Model S[63]

<u>Cell Structure design observation</u>

Cylindrical type cells number 18650 are used. Each cell has 3.7 V and a capacity of 3.4 Ah [64].

<u>Cell Material Structure observation</u>

Nickle Cobalt Aluminium material combination is used where the anode is made up of graphite/Silicon and the cathode is made of Nickle-cobalt-aluminium. There is an aqueous electrolyte with lithium-ion as a charge carrier. It uses 80% Nickel, 15% Cobalt, and 5% Aluminium. [4]

Module Design observation

Each module has a 74P6S configuration, which means cells are arranged in 74 Parallel and six series combinations to achieve desired voltage and capacity. Each module has 444 nos. of cells (74*6). The capacity of each module is 5.3 KWh. The module has a dimension of 685mm*300mm*75mm with a weight of 25Kg.[65] The module size is average, making it not difficult to handle.

In a parallel connection, the positive terminal of one cell is connected with the positive terminal of another. Similarly, the negative terminal of one cell is connected with the negative terminal of another. In a parallel connection, Capacity (voltage) remains the same for each cell, whereas power (current) is added to individual cells. In a series connection, one cell's positive terminal is connected with another cell's negative terminal. In a series connection, each cell's capacity (voltage) is added up, whereas the power (current) remains the same. Therefore, in the Model S module, 74 cells have the same voltage as an individual cell which is 3.8 V, and six numbers of 74 cell groups are connected in series, added up the individual voltage to make the module voltage 22.8 V (3.8 V*6).

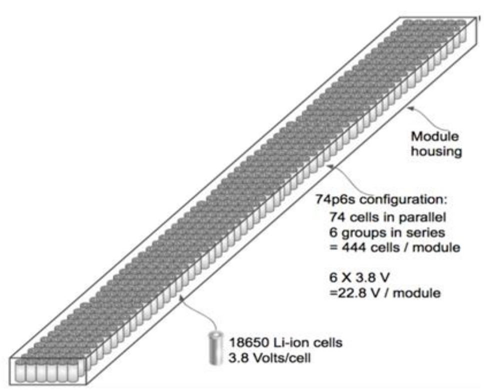


Figure 27. Tesla Model S (74P6S) battery module Schematic[66]

74P6S configuration has been divided into six different sections within a module where the positive terminal of half of the cell is on one side, and the rest are in the opposite direction. As shown in the image below, all red cells have their positive terminal on the top side, and all white cells have their positive terminal on the backside. This eases the connection of adjacent modules in series and will reduce the length of connecting wire to them.

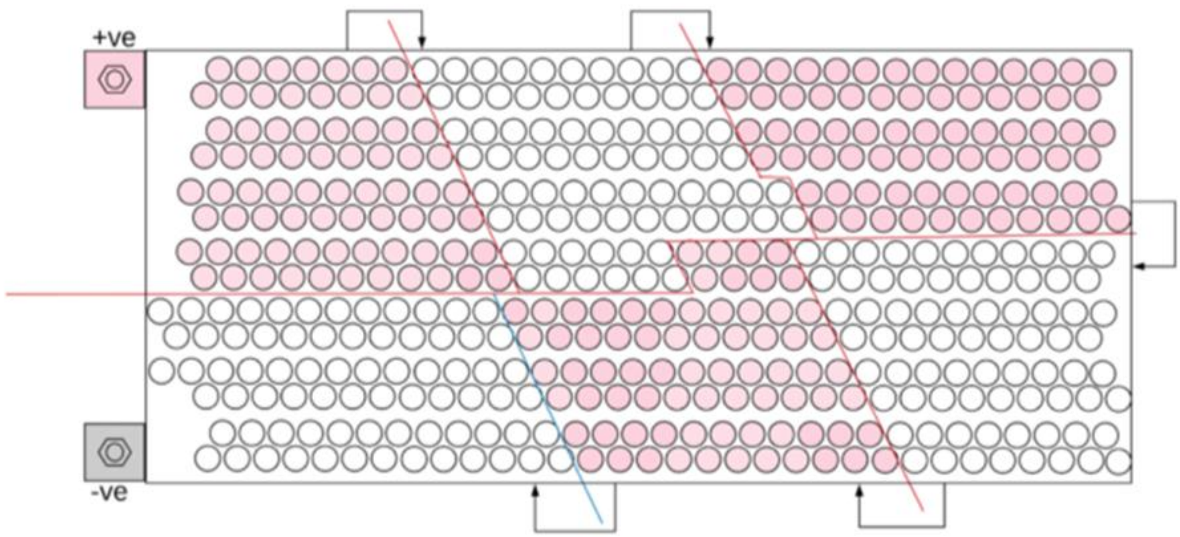


Figure 28. Tesla Model S, 74p6s Battery Module Cell Stacking Arrangement[66]

Disassembling the modules into smaller modules is very difficult. There are many reasons for this; all cells are placed inside a cell holder at both ends and glued, a continuous cooling channel passes, touching all cells, and the current collecting plate is wire bonded with the cells. All six sections (group of 74 parallel connected cells) connected in series are not of standard shape and size. The Actual module has been shown in the blow image along with a cad model.

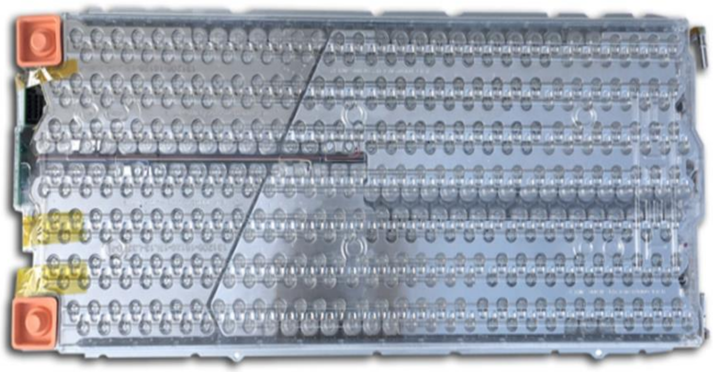


Figure 29. Tesla Model S Battery Module[66]

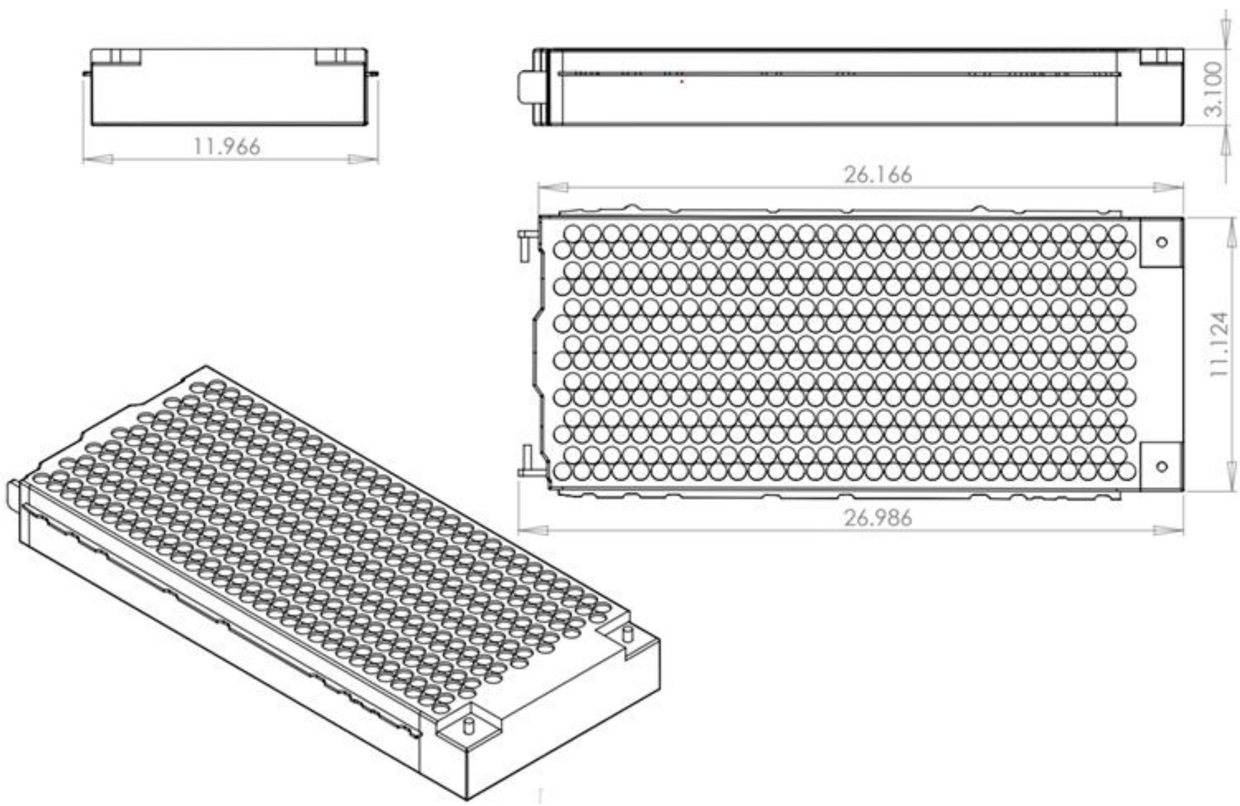


Figure 30. Dimension of module[66]

Pack design observation

It is composed of 16 modules with 444 cells approx of the type 18650, resulting in a total of 8256 cells in each battery pack [67]. Modules are also connected in series only. The total capacity of the pack is 100KWh, 400 V, and 252 Ah. The pack's dimension is 1660mm*964mm*174mm with a weight of 550Kg [67]. The battery pack is mounted under the floor of the car. The layout modules in a battery pack are mostly in single layers except for two modules placed on one another.

Figure 31. Battery pack Model S[68]

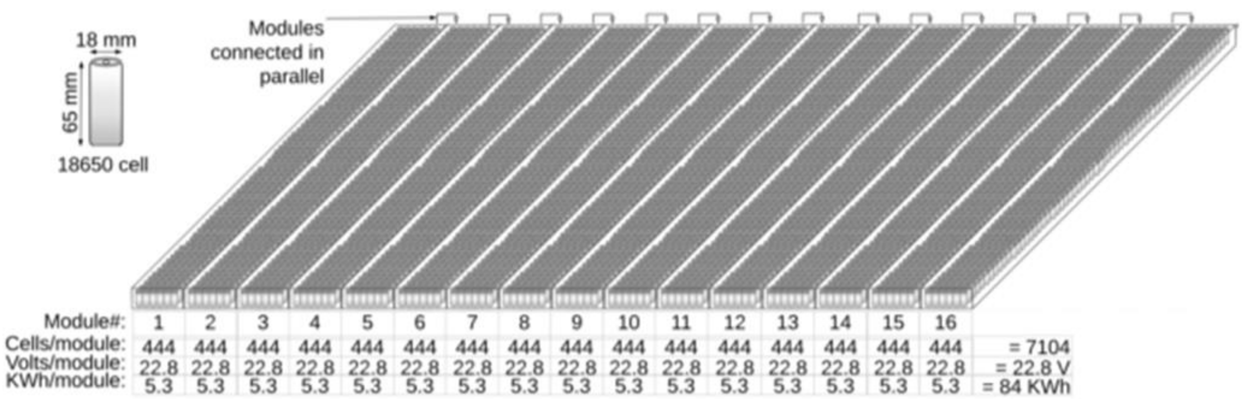


Figure 32. Tesla Model S (74P6S) battery Pack Schematic[66]

<u>Electronic Management System design observation</u>

Each module has its individual BMS linked to the central BMS in front of the pack. BMS in each module is connected with two rubber rivets. By providing the individual BMS for each module, the number of harnesses has been reduced significantly to connect each cell with the centralized module. However, no BMS units are increased.

Manual Service Disconnect

A fuse of 130 Amp has been installed, which can be accessed from outside the battery pack. It is properly sealed with sealant and with nine bolts. This fuse is used to divide the battery pack into half.

Thermal Management System design observation

The battery's cooling system consists of two cooling loops in each module, with glycol as the coolant and each loop cooling half of the cells. This coolant passes from the main line into the module with a quick type connector, reducing the assembly time and operator's efforts. Tesla built a more effective cooling system by providing more contact area between the cell surface and cooling channel and boosting the cells' safety by employing two cooling tubes. The loops are drawn within the modules and around the cells. To heat the battery during cold weather, Tesla reuses waste heat from the drive motor and power electronics, eliminating the need for a heat pump to keep the battery at the proper temperature range.

Every module is connected with the primary coolant line with the help of two quick connectors, where one acts as an inlet, and another acts as an outlet. It increases the number of joints in the battery pack, increasing the number of parts.

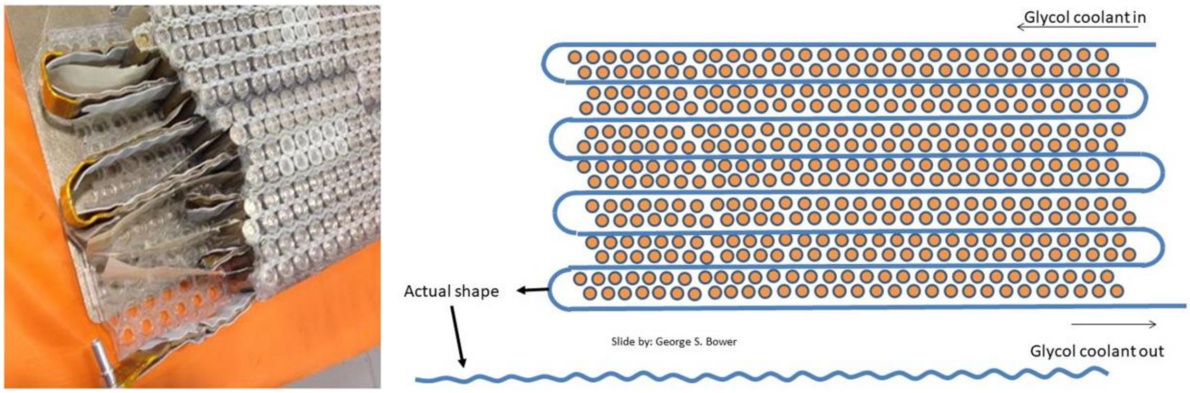


Figure 33. Cooling channel

Housing design observation

The battery that powers Tesla S Long Range has a housing made from metal, both lid and bottom tray. The lid is divided into two parts. The front lid protected the front two modules placed on one another and the coolant connection system. The Front lid is fixed with 50 screws with the bottom tray. The back lid secures the remaining 14 modules from the outer environment. The lid is fixed with the bottom tray with the help of more than 400 screws and a sealant between them to make it water and dustproof but make it difficult to disassemble.

Mounting Requirements observation

Module to base tray: Modules are mounted with the base with the help of 2 M8 Type bolts. These bolts are also used for connecting the terminals of adjacent modules.

Safety design observation

Crash Requirements:

For side crash safety, seven cross members and one longitudinal member is provided to make the bottom tray more rigid.

Fire Safety:

Tesla has installed a fire-retardant sheet over the battery pack for two reasons 1. Avoid transferring heat or fire (in case of an accident) from the battery pack to the cabin area. Additionally, one electromagnetic sheet is provided above each module. This sheet is assembled with the battery pack with the help of guide pins (12 Nos). These guide pins guide the pack during installation in the vehicle

Manufacturing Process-related observation:

It is difficult to disassemble the battery module in smaller module further as cells are welded together. The little wire linked to each cell has two purposes: it connects to the main bus and acts as a safety fuse if the cell is destroyed.

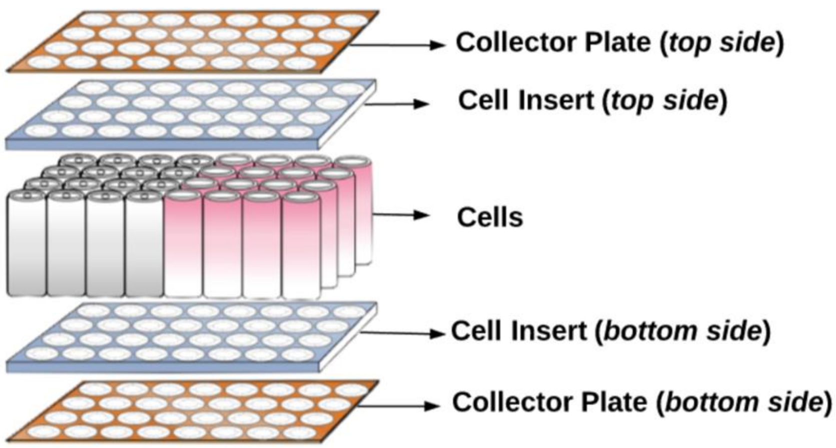


Figure 34. Battery module key component[66]

Battery Pack

Front of the car is having coolant nozzle

Remove fire redundant sheet

Guide pin which allow the pack to guide while assembly.Total 12 Nos. (8 in middle ,2 in front, 2 in back)

Taking the fuse box out, mounted with 9 bolts

130 Amp fuse, mounted with 2 bolts

cover is mounted by 50 bolts approx. with sealant in middle

EM shield Sheet (electric magnetic shield) insulation

2 out of 16 modules

To make it water tight and dust tight more sealant are used which is making it more difficult to take it apart

After removal of top cover

All 16 models are visible

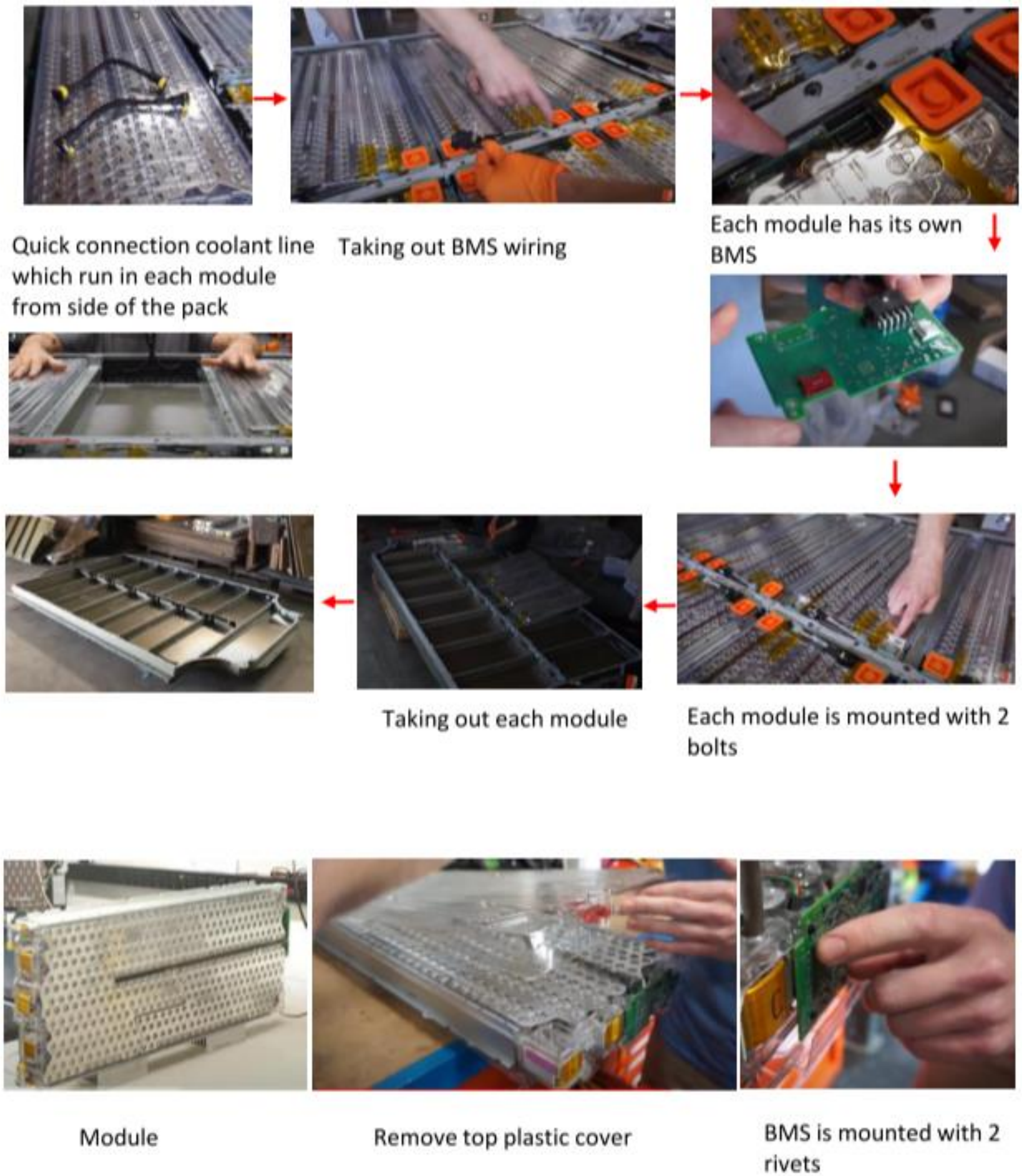


Figure 35. Disassembly for Tesla S/X[41]

Tesla Model 3/ Y

Figure 36. Tesla Model 3 battery pack[69]

Cell Structure

Similar to model S, Model 3 also uses cylindrical type cells number 2170. Each cell has 3.7 V. Each cell can store up to 4800 mAh and weigh 68 grams. The size of this cell is 21 mm dia and 70 mm in length, which is slightly larger than the Tesla Model S cell. The Bigger cell helps Model 3 to further optimized the volumetric energy density.

Cell Material Structure

The cell used is the 2170 Lithium Ion rechargeable batteries of material configuration as LFP. [69]

Module Size

The battery in this automobile is a significant advance over the battery in the Model S, and instead of 16 smaller modules linked to each other, it has four larger ones. The number of parts is reduced significantly. Among four modules, there are two different capacity modules used, increasing the number of variants of components in the pack. Many bricks house the cells within these four modules [69]. The size of the module is very bulky, which makes it difficult to handle.

Figure 37. Module for Model 3[70]

The interior of the modules is a printed flexible circuit board with an insulated copper wire linked to each cell and a temperature sensor attached to this connection to monitor the cell's temperature.

Cells are placed vertically in each brick. All these cells are glued together to secure their position tightly to avoid breakage of connections due to vehicle vibrations. Also, as cooling lines are passing through by touching each cell, the cell must remain at its place firmly to continuously transfer the heat from the cell to the cooling lines.

Pack Configuration:

The battery is made up of two smaller modules with 23 bricks each and two larger modules with 25 bricks each, with each brick storing 46 cells, for a total of 4416 cells in the battery. Therefore the total is 96 groups of 46, each weighing 480 Kgs in 0.40 m3 volume density and density is 150 Wh/Kg. The dimension of the battery pack is 2180mm*1500mm*330mm. All modules are connected in series producing a total power of 74 Kwh, 208 Ah, and 355V [69].

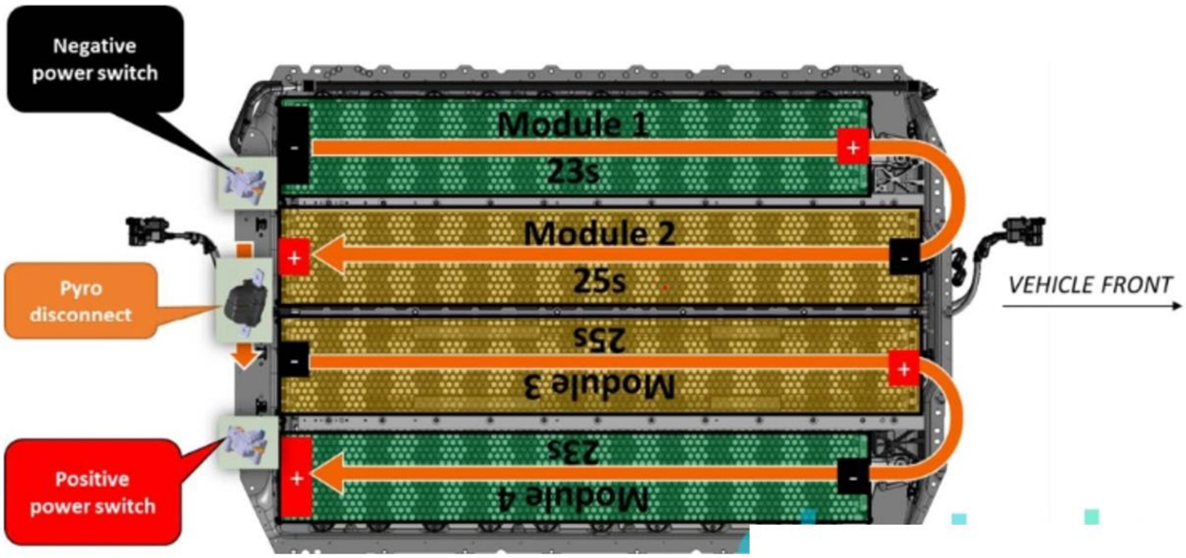


Figure 38. Cell Distribution schematic for Model 3[71]

Electronic Management System

When looking at the battery's BMS, each module has one circuit board, and the high voltage control board and the main BMS board are connected. The BMS is responsible for controlling the temperature in each cell, and Tesla answers that if a thermal runaway occurs, that specific cell will get a current that burns up the connecting wire. As a result, the cell is separated from the system and is no longer usable. By providing the individual BMS for each module, the number of harnesses has been reduced significantly to connect each cell with the centralized module.

The figure shows the number of electric components the Model 3 battery pack has, including 1. Charge port connector 2. Fast charge contactor assembly 3. Coolant line to PCS 4. PCS – Power Conversion System 5. HVC – High Voltage Controller 6. Low voltage connector to HVC from vehicle 7. 12V output from PCS 8. Positive HV power switch 9. Coolant line to PCS 10. HV connector to cabin heater and compressor 11. Cabin heater, compressor, and PCS DC output fuse 12. HV connector to rear drive unit 13. HV pyro fuse 15. HV connector to the front drive unit 16. Negative HV power switch 17. Connector for 3-phase AC charging

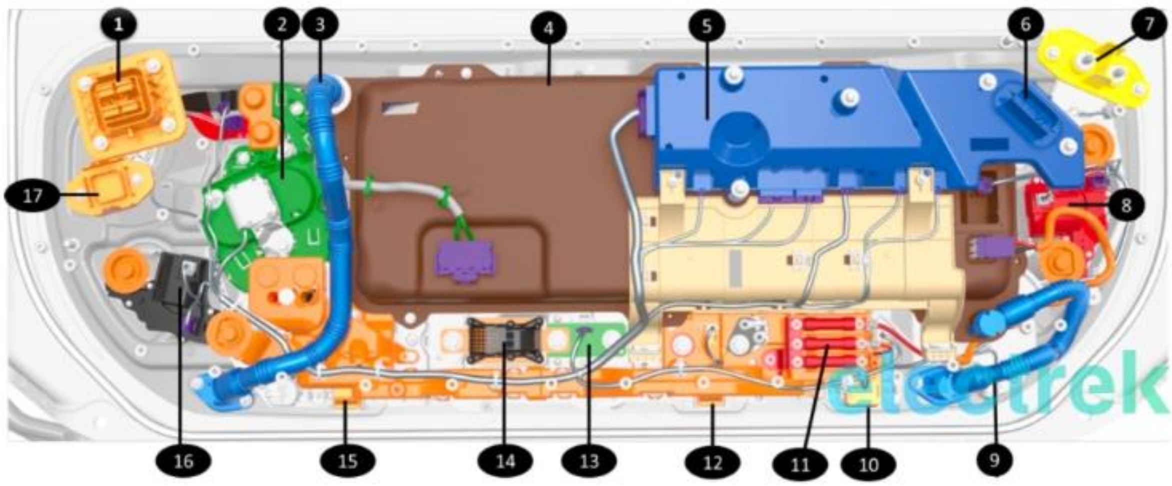


Figure 39. Main electronic components for model 3 Battery pack[72]

Thermal Management System

The cooling system in Model 3 is an improvement over that in Model S. The new cooling system employs a manifold-based design, with the cells linked to the cooling tubes, resulting in a more effective battery cooling system. The tubes cover a larger cell surface and do not need to chill as many cells as the Model S. This allows more coolant to travel through, allowing more heat to be transferred away from the cells. Furthermore, the cooling system is one solid section rather than being separated into numerous individual tubes, reducing the number of parts in the system. For example, no quick connectors are used, and despite that, the main coolant pipe is directly connected with cooling channels in which coolant passes from one side of the module and another, as shown below. There are approx. Seven channels, each one of which cooled down 164 cells.

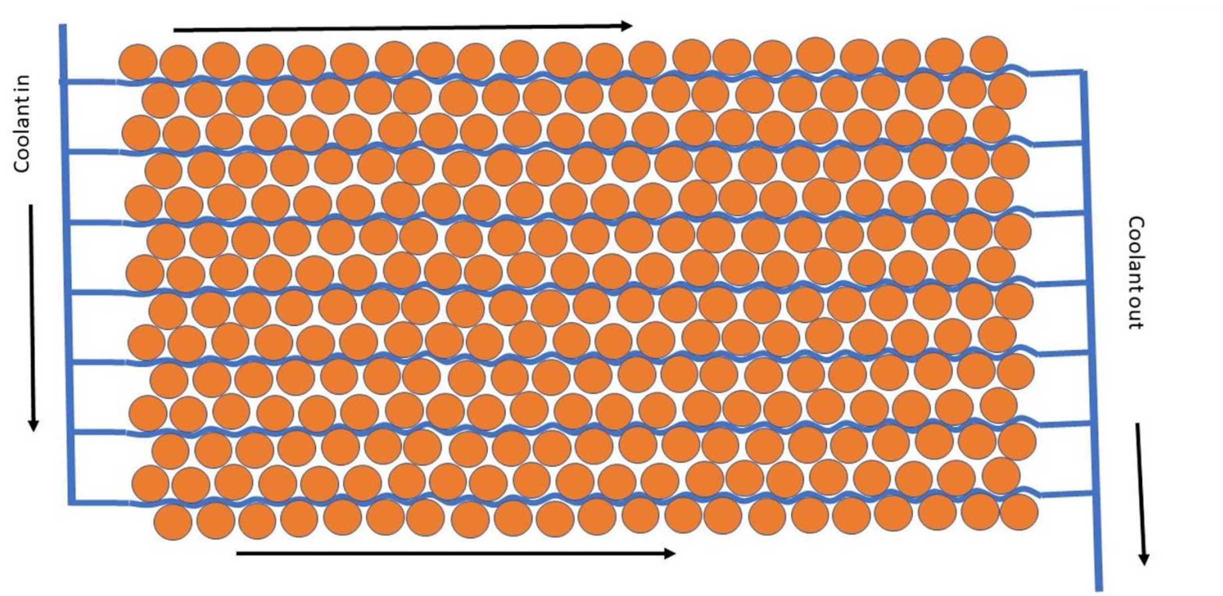


Figure 40. Cooling pattern in Model 3 [73]

Model 3 does not have an external pack heater to save weight and cost. Instead, model 3 can heat the pack using heat provided by the powertrain even when a car is parked by using a thermal controller, which sends the signal to the powertrain inverter to start powering up and passes enough current to the motor to produce sufficient heat to warm the cells without producing torque.

Housing

The bottom tray and top tray are of metal. The lid is fixed with the bottom tray with the help of bolts and a sealant between them to make it water and dustproof but make it difficult to disassemble.

Mounting Requirements

Ten bolts mount side modules from one side, and the other side is held by a metal rail. The middle two modules are held by two rails. By this design, it is tried to minimize the number of mounting points.

The battery pack is mounted so that it can be swapped easily. This is because some bolts are accessible by removing the interior trims of the car in case the battery pack is removed.

Safety Structure

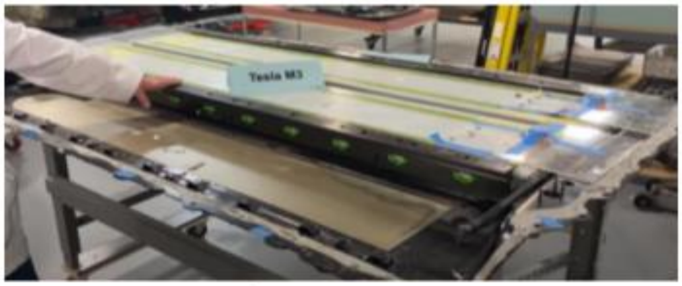
A vibration cushion fitted to the shell on top of the modules reduces vibrations from the outside, reaching the modules and, eventually, the cells.

Manufacturing Process:

The wire bonding technique is used to connect the cells with the battery. Also, glue is used to make the module rigid and cells in their position irrespective of the vehicle vibration.

Battery Charging Structure

Tesla has engineered their vehicle so that heat waste from the powertrain may be utilized while moving and stationary, such as during a supercharge. This is an important function since the battery's charge-rate drops if it is too cold. This also means that there is no external battery heater in the car and that Tesla relies on the software to control and adjust the temperature of the cells



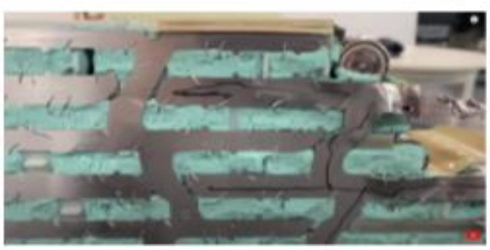
Battery Pack

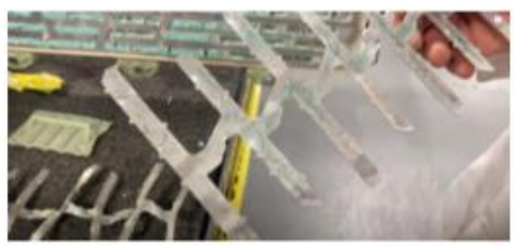
4416 cell , called the brick and there are 3 bricks

Cooling plate around each cell

cooling pipes are glued to-gather not easy to get out

way the cooling channels are connected





tiny aluminium wires to wire bonded to the back side of the collector

Cylindrical Cell

Figure 41. Disassembly for Model 3[42]

Tesla Y

Battery pack

Upper cover

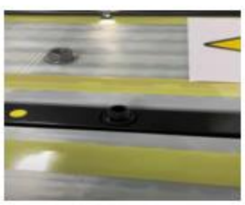
electronics bay

Taking electronic plate out

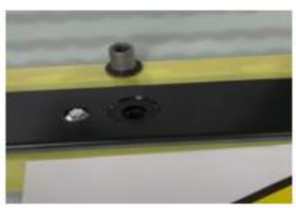
All bricks are connected in series

Brick is connected with base with side bolt 10 no and other side with mounting rail

Tip of the tin pan



Jack nut with hexagonal head , holding the battery pack with lid



to avoid the shock while tightening of bolt, plastic part is introduced

Cooling plates connection

Run away solenoid only 3 stud with bolt are used

Figure 42. Disassembly for Model Y[42]

Chevrolet Volt (2018):

Cell Structure

Pouch type cell is used. Each cell has 3.6 Volts. The nominal Capacity is 60 Ah. The net weight is 820 grams.

Cell Material Structure

The material used for such kind of cell is NMC.

Module Size:

There are seven modules. Each cell is assembled in a frame, with a cooling plate and a foam pad in a module. These repeating frames and plastic end separate the modules' cells. These injection molded frames are made from BASF nylon 6/6 grade and ultra mid 1503-2F NAT, which is 33% glass filled, and hydrolysis stabilized. Rubber sealers are also used between two cell casings to avoid coolant leakage. Cell groups in one module are assembled with the help of two long bolts. Therefore, a very high number of parts are used in each module. Also, all modules have a different number of cells, hence having a different capacity, resulting in more numbers of module variants in the pack. Moreover, the module's size is very bulky, making it difficult to handle.

Pack Configuration:

The complete battery pack is divided into three sections with a T-shaped structure. Ninety-six cells are used in the battery pack packed under seven modules. Adjacent modules are connected with a bus bar in which the negative terminal of one model is connected with the positive terminal of the adjacent module. Similarly, all modules are connected in series. As a result, the total voltage of the battery pack is 355.2 V, whereas the total power is 18.4 KWh.

Table 40. Battery pack configuration for Volt 2018 Model

Section	Module No.	No of Cell	Voltage (Volt)	Power (KWh)
Section 1	Module 1	16	162.8 V	8.4 kWh
	Module 2	12		
	Module 3	16		
Section 2	Module 4	12	103.6 V	5.4 KWh
	Module 5	16		
Section 3	Module 6	12	88.8 V	4.6 kWh
	Module 7	12		
Total		96 Cells	355.2 V	18.4 KWh

Electronic Management System

There is one centralized BMS used in the battery pack. The BMS is mounted over one of the modules in a bracket. The BMS fitted in the bracket with the eight snaps. BMS bracket is fitted over the module with the help of four bolts. BMS has eight electric connecting ports, which are used for high voltage sensor connectors, low voltage sensor connectors, temperature sensor connectors, current sensor connectors, awake signal connectors, GM landline connectors, communicating line connectors, and ignition connectors. By providing the central BMS, the number of harnesses has been increased significantly to connect each cell with the centralized module.

Each module is connected with one circuit by rivets for voltage and current sensing.

Several cables are used, like voltage sensing cable, temperature sensing cable, and high voltage sensing cable. Harnesses are properly routed with the battery pack so that they should not rub with the walls of the cover. There are 13 electrical connections.

Major electronic contactors are mounted in the front of the battery with the help of 2 studs on an aluminum contactor plate. On this contactor plate, an electronic plate is assembled with three bolts. Electronic have several electronic items like contractor relay assembly, current sensor, charging system connector, positive contactor plug (connects the positive terminal of the battery with the positive terminal of the motor), Transistor module (controls the current for coolant heater), High voltage fuse, relay assembly, High voltage terminal, coolant Hodge, Coolant heater (1750 W) and three small electrical connectors.

Thermal Management System

Pouch cells are vertically installed in the modules. Between two pouch cells, one coolant plate is instated. These coolant plates are connected with the main coolant channel from one side as an inlet and another side as an outlet. Along with each cooling plate, one foam pad is installed between two cells. This foam pad provided the space for the cell for its expansion and contraction during charging and discharging.

For transferring a coolant between two cell groups, the rubber seal is used, which is tightened by two long bolts in each module. For transferring the coolant between two modules, a connector pipe of rubber material is used, which is tightly secured with clips to avoid any leakage.

At the end of each module, one temperature sensing sensor is installed to monitor the module's temperature.

There is a heater used to heat the coolant in cold ambient conditions. Coolant is forced to pass through the heater before entering the battery pack to attain an optimum temperature to keep the cells at normal working temperature.

Housing

The bottom tray is made of metal, whereas the lid is made of composite material to reduce the overall battery pack weight. The bottom tray and lid are fitted together with bolts and sealer tape. It is not that difficult to open the battery pack and access its components. There is a seat mounting provided at the rear top cover too.

Mounting Requirements

The battery pack is mounted at the vehicle's underbody with the help of 22 bolts. Modules in the battery packs are mounted with the help of a metallic retainer. This Retainer is fixed with a base tray with 40 bolts from one side and clamps the module's edge from another side. High numbers of bolts are used to mount all modules.

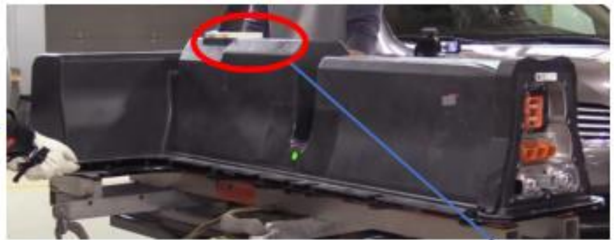
Safety Structure:

HVSD: High Voltage service disconnect feature is installed in this battery. This switch is mounted under the console area.

Manufacturing Process:

Two adjacent pouch cells are welded together with the help of a copper bus bar. In the first generation, three pouch cells are connected in parallel, while in the current generation battery pack, two cells are welded together.

Battery pack Mounted at bottom with 22 bolts



Complete battery pack after taking out from vehicle

High voltage Service plug disconnect under console area

7 modules once upper cover is removed

voltage sensing cable
temp sensing cable

Orange high voltage cable

High voltage DC connector

Coolant IN

Coolant OUT

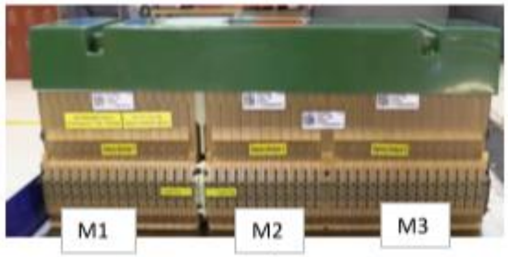
Connect the cooling passessage

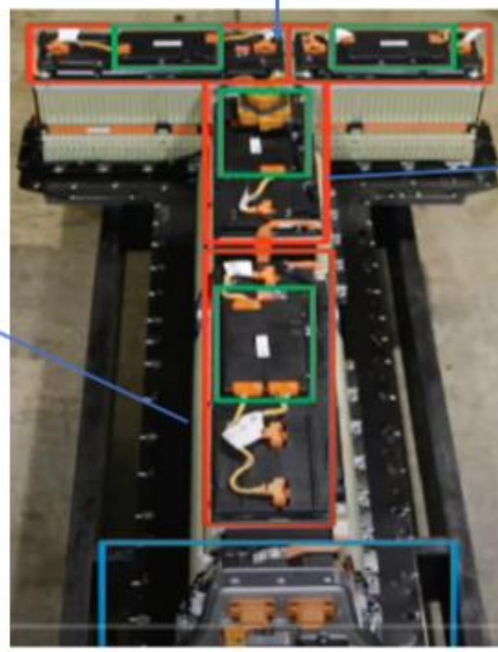
Front bracket to stop moving the battery in front mounted with 2 stud

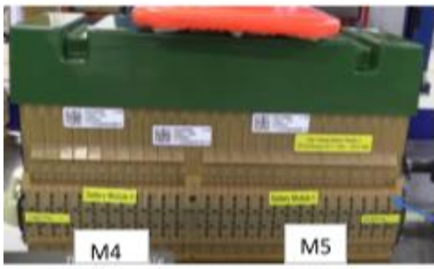
Module 1 ->16 cell groups
Module 2 ->12 cell groups
Module 3 ->16 cell groups

96 cells group (3.7 V cell each)->162.8 Volt

Module reading is 3.1 KWh
Battery section 8.4 KWh



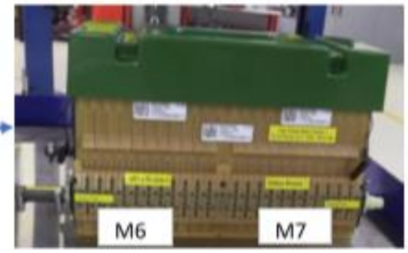




Module 4 ->12 cell groups
Module 5 ->16 cell groups

28 cells (3.7 V cell each)->103.6 Volt

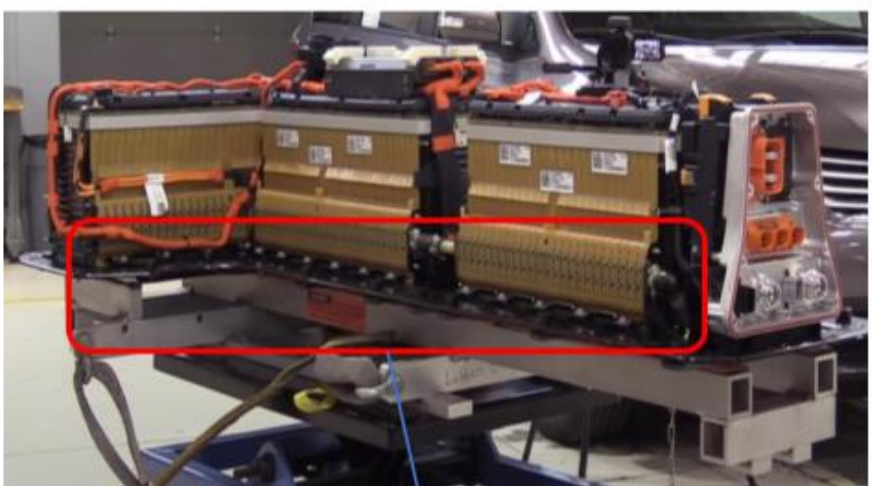
Module reading is 3.1 KWh
Battery section 5.4 KWh



Module 6 -> 12 cell groups
Module 7 -> 12 cells group
24 cells (3.7 V cell each)->88.8 Volt

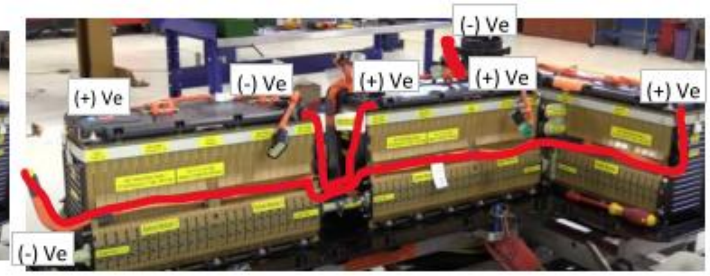
Module reading >-2.3 KWh (each)
Section 1- 4.6 KWh

T shaped Battery tray



All Modules are mounted with 40 bolts with help of clamp tray/Retainers at the edge.

clamp tray/Retainers at the edge



13 electrical connector
Proper routing and grove for wire harness so that it should not rub on any thing and interfere with surrounding parts

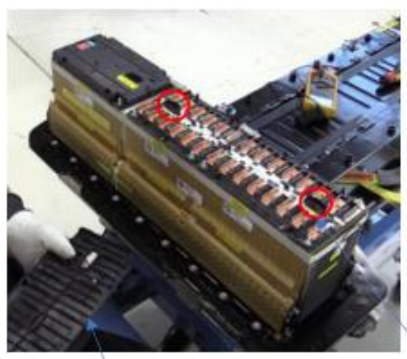
Routing of Harness to make all modules in series

BMS, snap fitted in the bracket

Bracket is mounted with 4 bolts

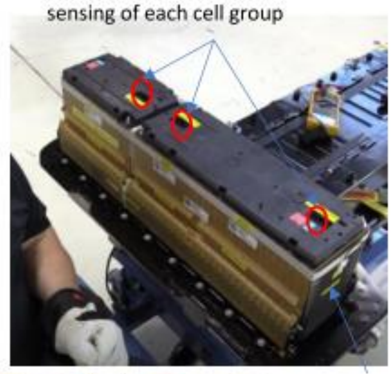
BMS: 8 electrical connectors : voltage sensing connecting
except 2 7 and 8 low voltage -Temp sensor and current sensor in contactor assembly 8 communication line , GM land line, wake signal , ignition

Two adjacent cell groups are welded together with copper bush bar



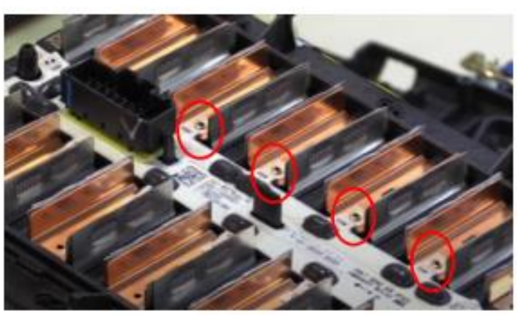
Top connections are covered by plastic cover

Electrical connectors for voltage sensing of each cell group



Temp section on each side

Temp sensor



circuit is connected with each individual pack by rivets

2 cell together parallel in latest generation

3 cell together parallel in 1st generation

Connection of 2 adjacent module with bus bar -ve of one module to + of module another module. Similarily all are connected in series

cell group of 2 or more cell in

All cell groups are mounted together with help of long bolt on both side.

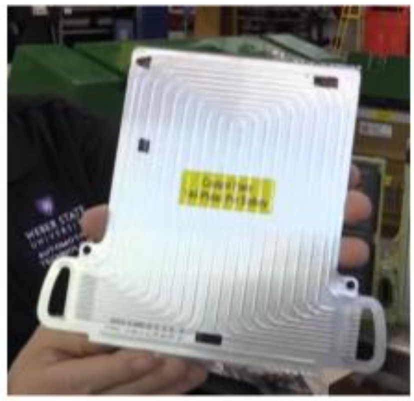


Plate is sandwich in-between the cells

first generation - 3 cell are used in parallel in one group increase capacity without increasing the voltage
1 cell can give 55 amp per hour

Second generation is using 2 cell in parallel welded together

Coolant passage

Battery contactor assembly is mounted by 2 studs

Mounted with 3 bolt

current sensor

charging system contactor

+ve contactor (connector of +ve cable to +ve outside cable) plugs in serviceable

transistor module control the current for coolant heater

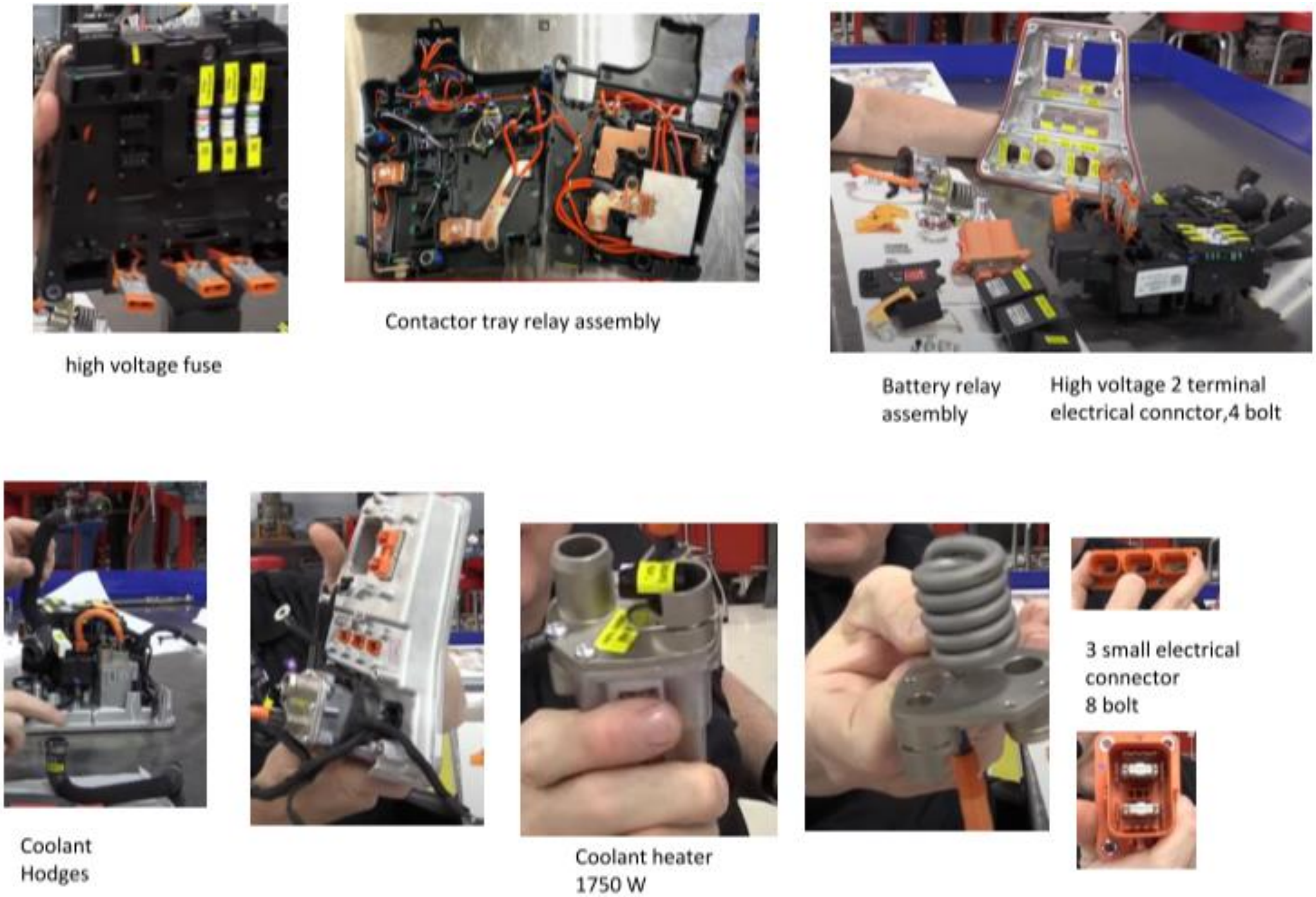


Figure 43. Disassembly of Chevy Volt 2018 [44]

Chevrolet Bolt (2016)

Figure 44. Battery pack[74]

Cell Structure:

Pouch cells are placed in an aluminum casing. It is the most expensive way to make a pack size.

Cell Material Structure

The chemistry NMC is used in cells.

Module Size

There are two sizes of modules used in the battery pack:30 cells module and 24 cells module. The cells in this battery are packed together, specifically three in parallel. Such a group of three cells is connected in series to achieve the required voltage and capacity. All these combinations are held together in a metal enclosure with four long bolts at each corner. The module's size is very bulky, making it difficult to handle.

Pack Configuration:

The 288 pouch cells used in the battery pack provide a total power of 60 Kwh. The pack includes ten modules separated into two rows and two levels, with the bottom modules holding 30 cells and the top modules comprising 24. For the module mounted on the upper level, a separate platform is created with the help of two side brackets and one metal plate. The reason for creating a separate platform is to avoid the heat and weight transfer to the lower module and to provide support to the cooling plate.

Electronic Management System

The BMS and power relays are located within the pack. Hi-voltage DC and high voltage AC connectors are provided at the front of the battery to connect the battery pack with the motor.

One Centralised BMS is used in the battery pack, with six connecting slots. By providing the central BMS, the number of harnesses has been increased significantly to connect each cell with the centralized module. These connecting slots are used for high-voltage battery cell monitoring circuits. In addition, BMS is snap-fitted in a bracket further mounted on one of the modules.

Bush bars are used to connect the Module in series. A negative terminal of one module is connected with the positive terminal of another. The length of the Bus bar is very high.

Thermal Management System

Thermal management comprises thermistors attached to the end of the module that sense the temperature of the cells and modify it as needed. There two sizes of cooling plates are used, one large plate for eight modules and another smaller one for upper-level modules. Both upper and lower cooling plates are connected with a rubber hose with clamps. No of the parts has been reduced by providing one signal large cooling plate for major numbers of modules. These cooling pads have liquid coolant channels. Above these cooling plates, heating pads are used for effective heat transfer from cells to coolant plates. Finally, Aluminium sheets in between the cell packages help transport the heat from the cells to the base. Each layer has its cooling system with hoses to the coolant loop and a lower cooling plate base

Figure 45. Heat Transfer plate in Module [61]

Housing

The housing of the battery pack is separated into two parts: upper- and lower casing, with the lowest section made of steel and the top part made of lightweight vinyl ester resin that contains hyalite nano clay filler and 40% fiberglass to reduce the overall battery pack weight [60]. Chevrolet has put silicon between the two components to provide particle and humidity isolation. Both the upper and lower cover are bolted together. It makes it easy for the operator to open the battery pack and access its components

Mounting Requirements

Each module is clamped on the base tray with the help of U-shaped clamps at four locations. These U-shaped clamps are further tight with three bolts on the cross member fitted in the tray for the crash requirement. As these bolts are fitted inside the U-shape bracket, they are not easily visible and accessible, making it difficult to disassemble.

Safety Structure:

A safety feature is provided as a service disconnect plug mounted under the rear seat. This plug divides the battery pack voltage in half during service, repair, or installation.

Four cross members are provided in the battery tray to provide rigidity during side crashes and the mounting space for module clamping brackets.

Manufacturing Process:

Pouch cells are welded together with bus bar, making it impossible to separate the cells without damage.

Battery pack

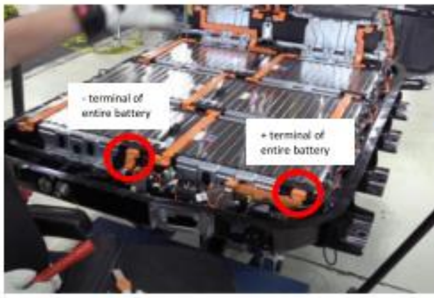
remove service plug

remove upper cover

Remove sealer between upper and lower cover

disassemble high voltage DC connector

disassemble high voltage AC connector



Disconnect -ve and + terminal

Put special connector with inlet value and suck the coolant while creating vacuum and close the outlet valve to create the vacuum in cooling plates

Disconnect BCM with all wire harness connection in specific order there are 6 connector

Disconnect High voltage battery cell monitoring circuit

Disassemble BMS

disassembly all bush bar as all modules are connected in series each bush bar is connected from -ve terminal of one module with + terminal of next module

Disassemble rear two brackets

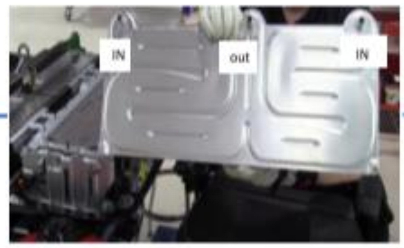
Disassemble upper plate

Disassemble upper Module

Disassemble module mounting bracket (6 bolt front 6 back and 3 on other side each

Disassemble all 3 modules

Disassemble heating pad

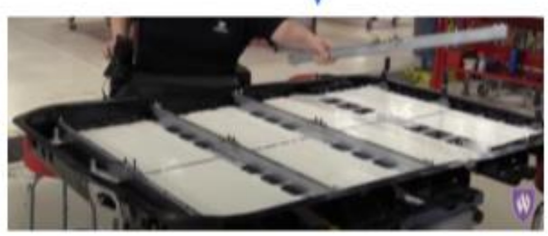


Disassemble cooling pad

Disassemble heat insulating sheet

Disassemble bracket between section 4 and 5

Remove last module



Remove module mounting bracket

Remove absorbing pad

Disassemble cooling pad

under cover (Battery tray)

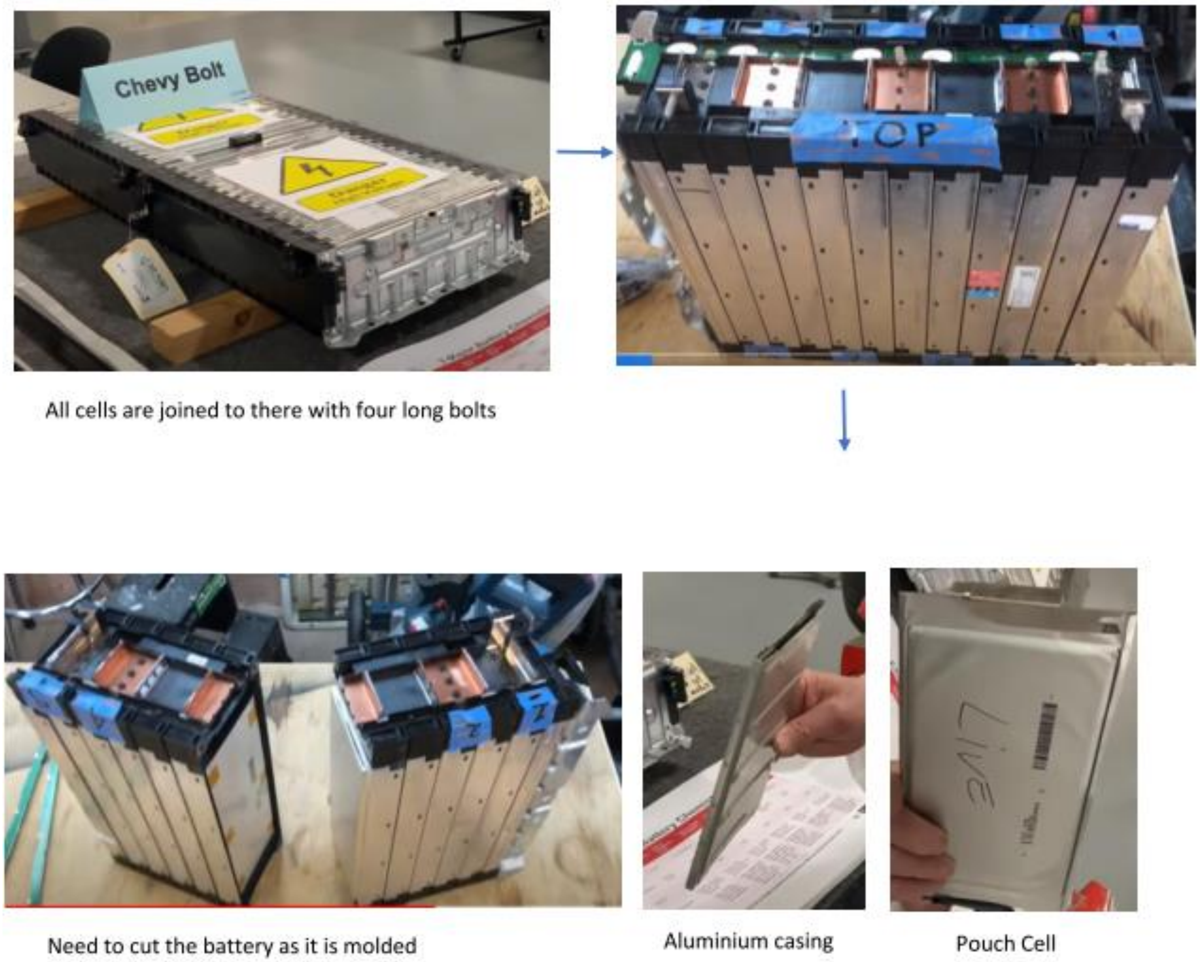


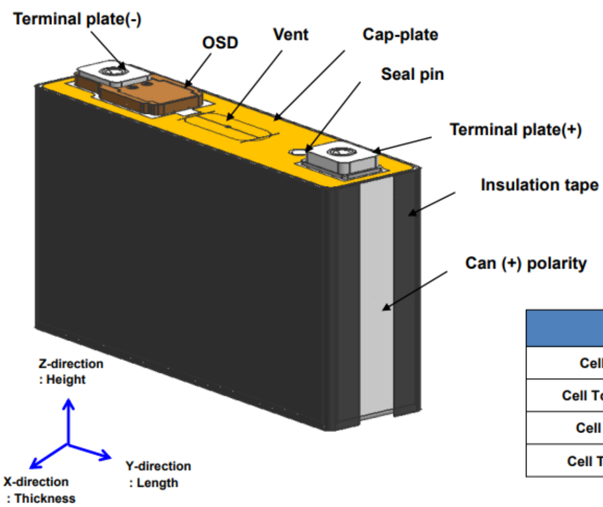
Figure 46. Disassembly sequence of Chevrolet Bolt 2016 [44]

BMW i3 2015

Figure 47. BMWi3 battery pack[75]

Cell Structure

Prismatic type cell structure is used. Each cell has 3.7V. [76]



Items	Characteristics
Cell Height (Z)	125mm
Cell Total height (Z)	133mm (Rivet)
Cell Length (Y)	173mm
Cell Thickness (X)	45mm

Figure 48. Prismatic cell of BMW I3[64]

Cell Material Structure:

The material structure is NCM. [76]

Module Size

Figure 49. Module of BMW i3[77]

The modules are connected by a cable that may be plugged in on the positive side and permanently attached on the negative. The size of module is average which makes it not difficult to handle.

In addition, the modules include a solid metal wall on two sides for maximum protection during usage and a plastic cover on top. A laser-welded connecter connects the cells within each module, and each module includes 12 prismatic Lithium-ion cells, bringing the total number of cells in this battery to 96. The total capacity of the module is 4.1 KWh, 94 Ah and 44V. The module has dimension of 387mm*300mm*150mm. with total mass of 29.8 Kg. [78]. All modules are of the same size and spec, lowering the number of variants in the pack.

Pack Configuration:

There are 8 Modules in the pack. The pack capacity is 40KWh and 120Ah and maximum voltage is 352 V. The cell is connected in series, thus it is a 96S (96s series) cell connection pack. The size of pack is 1660mm*964mm*174mm. The weight of the battery is 290 kg [76]. The housing houses a BMS, a cooling system, a charger, a DC/DC converter, and a BMS salve.

Electronic Management System

By providing the central BMS, number of harnesses has been increased significantly to connect each cell with the centralised module.

Figure 50. The battery management system of BMW i3[77]

Figure 51. Connector of each module of BMW i3[77]

Thermal Management System

The cooling system is liquid, with tubes covering the bottom of the pack. As a result, the tubes provide support for the modules.

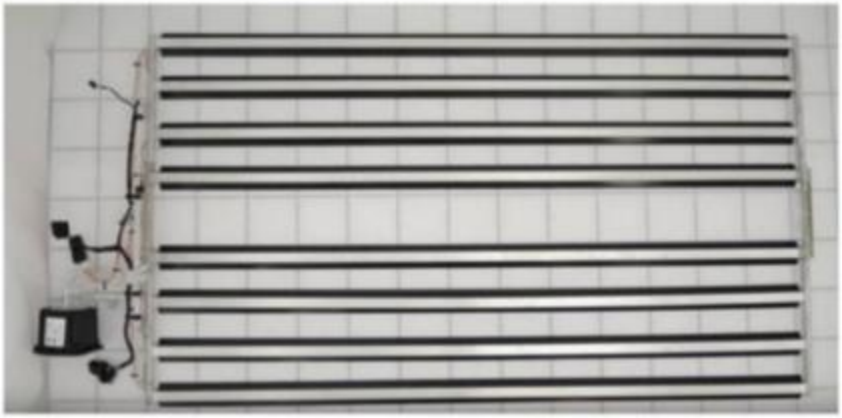


Figure 52. Cooling system[79]

Housing

The housing is made of metal, and the top features a gasket to keep the battery safe from the elements. Upper cover of battery pack is made of composite material to reduce the overall weigh of battery pack. Screws are used to secure the lid to the bottom of the car. It makes easy for the operator to open the battery pack and access it components.

Mounting Requirements

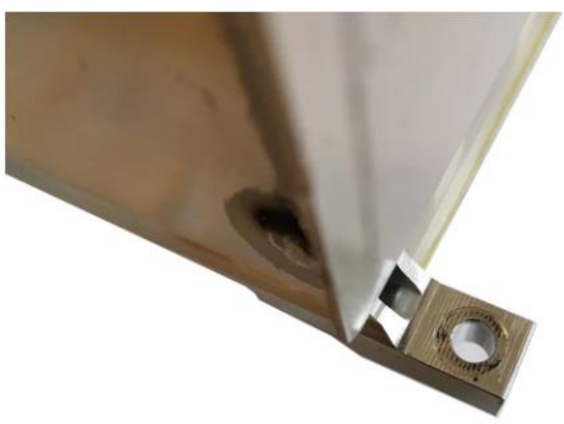


Figure 53. Mounting of module with battery tray[77]

Manufacturing Process:

Even prismatic cells are used here but two adjacent are connected by welding.

Toyota Prius

Cell Structure

The prismatic type cells are used.

Cell Material Structure

The cell material structure is NMC

Module Size

There are 28 numbers of lithium-ion cells used in each module. Each cell has 3.7 volts. Cell connections are covered with separate plastic covers. The module size is small, making it easy to handle.

Pack Configuration

Two separate modules are stacked together in the battery pack, where each module has 103.6 volts. These modules are connected in series. Making the total power of the battery pack is 207.2 V.

Electronic Management System

The battery pack has a high voltage junction box, current sensor, pre charge contactor, BMS, negative contactor, positive contactor, and pre-charge resistor.

BMS monitors the voltage and temperature of the cell connected through wire with each cell and; increases the harness length. Three bolts mount the BMS unit. BMS is protected by a separate metal cover, mounted by three bolts and a plastic cover.

The high voltage battery pack junction is fitted with four bolts. The service plug grip connector is assembled with one bolt. The junction box is fitted with one bolt. A high voltage fuse of 125 Amp is connected with a positive terminal held by one clip.

Thermal Management System

Air-based cooling is when a fan takes the air from the cabin and blows in the battery to keep it cool. A plastic duct is used to spread the air through both modules with two openings at the outlet.

Housing

Housing is made up of metal assembled in three pieces: Front Cover, Upper cover, and Lower tray. The front cover is provided to access the battery's electronic circuit, and the upper cover is used to protect the module. Bolts mount all parts. All bolts used in the battery pack are of the same dimension.

Mounting Requirements

Four bolts mount modules with the base tray.

Safety Structure

A high voltage warning sticker and contact information for recycling are mentioned on a label on the battery pack.

A service grip must be used to open the front cover and access the high voltage circuit as a safety feature during servicing and repairing work. The service grip needs to be inserted in the lock and rotated. It is a safety method that reminds the operator that there is a high voltage circuit under the front plate, and they need to wear a high voltage PPE kit.

service plug grip- to access open 10 mm nut

4th generation 3rd generation 2nd generation

need the service grip to open the lock , insert and rotate to remind that there are high voltage under this cover

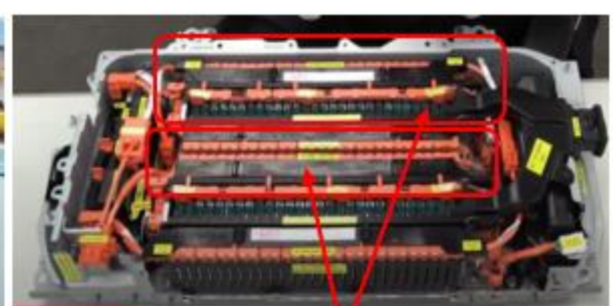
all nut and bolt are same except 2 bolt

high voltage warning and phone no for battery recycling

lift cover

After removal of top cover

fan take the air from the cabin and blow it in the battery to keep it cool from this housing



2 separate battery stack and air pass through batteries (103.6 volt each , 28 Nos. of 3.7 volt lithiun Cells are welded together in the housing
2 stacks of batteries are in series

battery computer or BMS system under this plastic

remove the duct by removing this 2 piece clip

high voltage battery junction box, current sensor, pre charge contactor

6 harness connected to the batteries outside of each stack has individual wire connected to the each cell to check voltage of each cell

remove high voltage battery junction box which is fitted with 4 bolt

remove service plug grip connector mounted by one bolt

Takeout cover which are snap fitted

-ve contactor, +ve contactor, pre charge + contactor, current sensor, resistor, pre charge register,

Junction box tray fixed with one bolt

inlet duct split in two

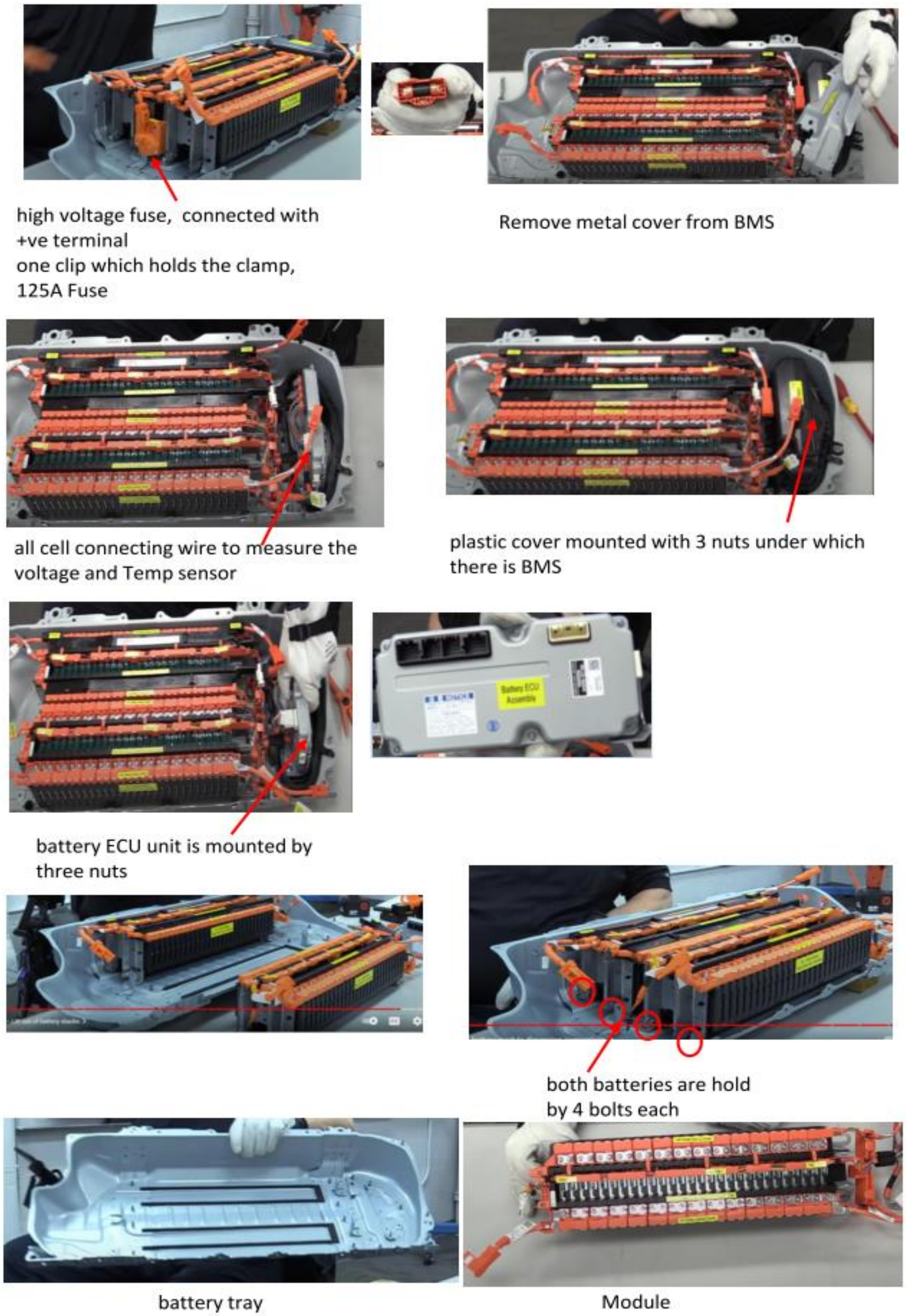


Figure 54. Disassembly sequence of Toyota Prius [47]

Mustang MACH-E

Cell Structure

Pouch cells are used with an aluminum casing outside. The cells used in mustang and Chevrolet Volt are almost identical in shape and size. But the only difference is in the current collector plate.

Cell Material Structure

The material used for such kind of cell is NMC.

Module Size

Two specifications of modules are used; 24 cells and 30 cells. Therefore increases the number of variants in the module. All cell connections are protected and covered by a separate plastic cover that is snap-fitted. Cells are fitted in the injection molded part with an aluminum plate and a foam pad. Therefore, each cell has three more parts, increasing the number of parts in the module. Cells are stacked and assembled with four long bolts and two end caps. One end cap is having thread and acting as a nut. This is cost saving idea implemented in this module. In the module, the collector pack is made of copper and nickel. The module's size is very bulky, making it difficult to handle.

Pack Configuration:

Modules are connected with long bus bars like the Chevrolet Volt 2016 model.

Electronic Management System

All wire harnesses are routed in the center only. Ribbon cables collect the cell’s information like temperature and voltage. By providing the central BMS, the number of harnesses has been increased significantly to connect each cell with the centralized module.

Thermal Management System

A thermal interface conductive material layer is applied between the module's bottom surface and the top surface of the cooling plate. This material ensures that the cell surface is always in contact with the cooling plate to transfer heat from cells to cooling plates effectively. For cost saving, the layer is applied in a zig-zag pattern.

There are two coolant pipes layout in the center of a battery pack, one is for the inlet, and another is for the outlet. Cooling pipes are connected with the cooling plate with quick connections. There are ten quick connectors used for five different cooling plates.

The bottom side of the cooling plate has a dimple-type structure to make the coolant flow turbulent so that it can absorb more heat or excite the transfer of heat and cold. In addition, a foam pad provides extra cushion and space between two pouch cells to expand the battery pouch cell during charging.

Aluminum plates are used between two pouch cells to collect the heat and transfer it to the bottom. The bottom surface of the aluminum plate is in touch with the cooling plate, which extracts heat from it.

Housing

The upper cover of a battery pack is made of composite material to reduce the overall weight of the battery pack. The bottom tray and lid are fitted together with bolts and sealer tape. The operator can easily open the battery pack and access its components.

Mounting Requirements

The pack is mounted by the sides only. Therefore, there is no side and front mounting used. On the front side, metal guide brackets are given to assist during the battery pack assembly. Six bolts from both sides mount each module.

Safety Structure

A battery pack's side walls have an aluminum extrusion structure for providing a crumble zone during a side crash. Also, five cross members are welded with the battery tray to provide stiffness during a side crash.

Battery pack-upper cover is of com-posite material to reduce the weight

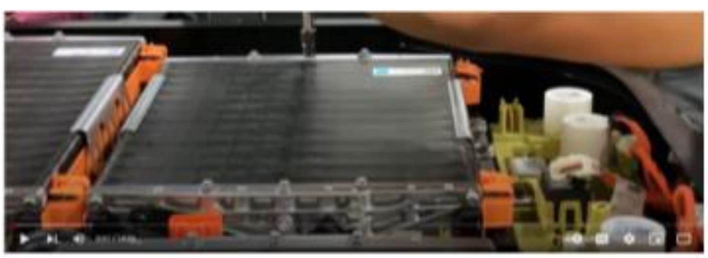
Fasteners in sides only .no front and rear fasteners

Front battery connection

Side rail aluminium extrusion structure for improving crash worthiness

Front guide bracket during assembly

High voltage bush routing

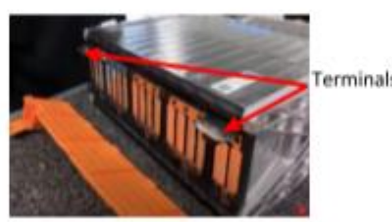


After removal of top cover

Each module is mounted by six bolts from both side

Removal of one module

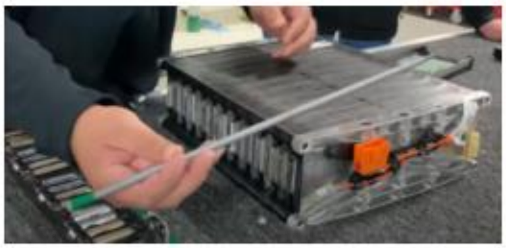
Application of conductive layer of paste for better heat transfer



Terminals and protective cover in orange color

After removal of top plate

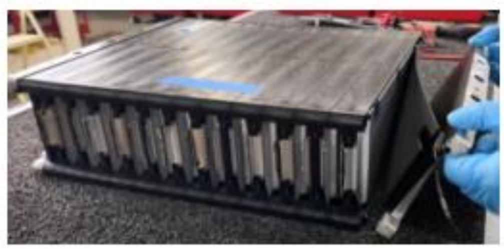
All cells are tighten together with 4 bolts



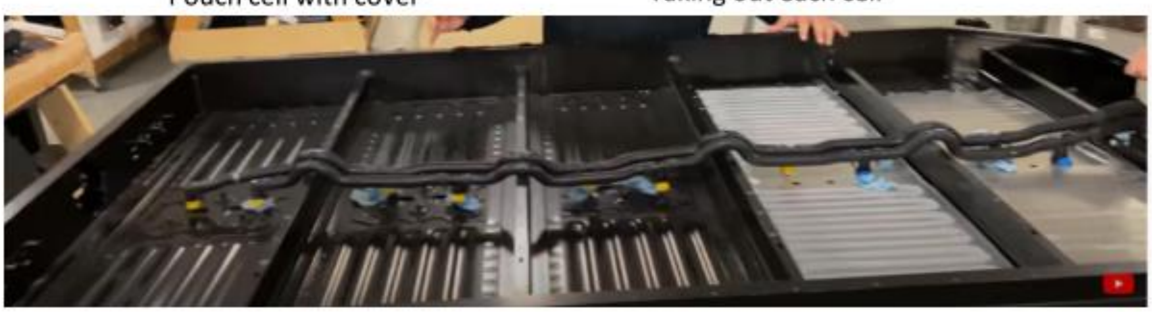
All cell are joined together with help of Long fasteners

In end cap is self tapped which eliminate a need of extra nut (as chevy bolt) . 24 and 30 cells in battery

Pouch cell with cover



Taking out each cell

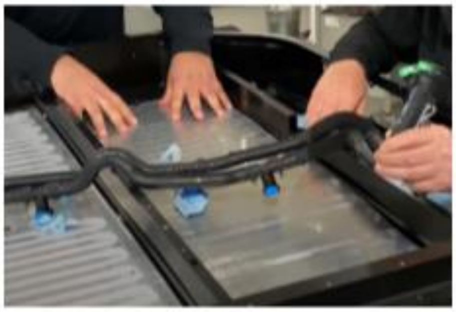


Cooling channel in center and 5 bays - Reinforcement in the bottom

self piercing rivet attached to the battery try

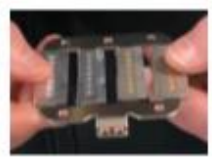
Two different size of cooling plates ,thermal interface compound which is in gray paste , helps in transferring the heat from battery module to the cooling plate

Quick connect to snap the cooling pipe in the place -10 quick connect



No mounting for these cooling plate, just holded in the studs which are used to mount the modules .

Back side of cooling plate is having dimple to make the flow of fluid turbulent so that it can absorb the more heat or excite transfer of heat and cold



Collector plates made of copper and nickel plated

Ribbon cable used for circuit board

Foam to allow some expansion in pouch cell

Aluminium plate is collecting the heat from the cell and transfer to the bottom which further transfer to cooling plate beneath it

Aluminium plate with injection molded piece with aluminium

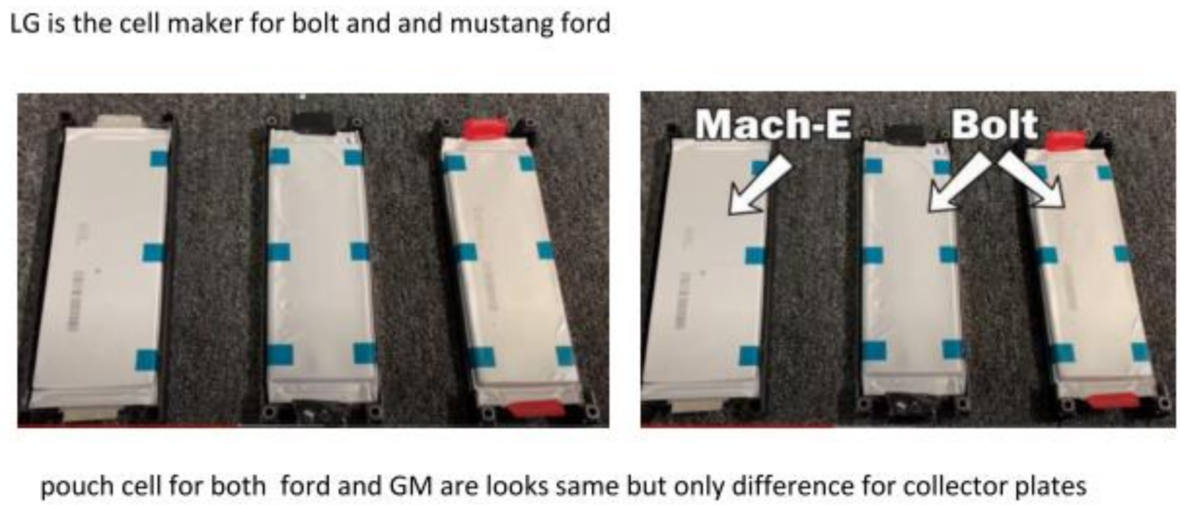


Figure 55. Disassembly sequence of Mustang Mach-E [47]

Volkswagen ID.4 2020

Figure 56. Pack Configuration of ID4[80]

Cell Structure:

Prismatic-type cells are used. Each cell is having capacity of 78Ah.

Cell Material Structure

The material used for such kind of cell is NMC.

Module Size

The capacity of one module is 234 Ah. The capacity is 29.6 Ah. Therefore, one module has 24 cells providing a total capacity of 23 Ah and voltage of 29.6V. Cells are arranged in 8S3P configuration (8 series and three parallel). Cells are packed in a rectangular aluminum casing. All modules in one battery pack are of the exact specification and configuration, which increases the number of module variants in the pack. Also, all bus bars connected to the modules have the same shape and size.

Figure 57. Module of ID4[77]

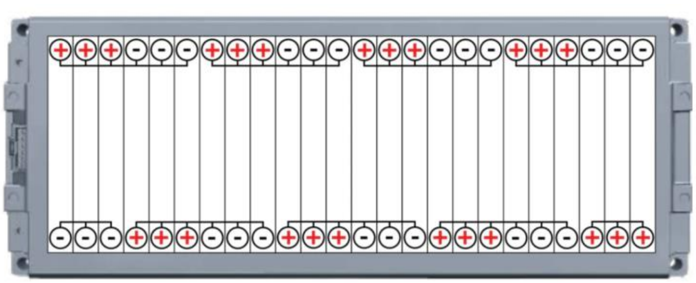


Figure 58. 8S3P Cell circuitry in Volkswagen ID4 battery module[81]

Pack Configuration:

There are 12 modules in a battery pack providing a total capacity of 82 KWh, 408V, and current 201 Ah. The total pack weight is 309 kg. This design which has all harness connections in the center and modules on the side, is known as spine design. [77]

Electronic Management System

By providing the individual BMS for each module, the number of harnesses has been reduced significantly to connect each cell with the centralized module. In addition, the module size is small, making it easy to handle.

Thermal Management System:

A thermal management system is designed to keep the battery temperature at 25 degrees. In addition, there is a liquid cooling system used.

Housing

The battery has a housing made from metal, both lid and bottom tray. The lid secures the remaining 12 modules from the outer environment. The lid is fixed with the bottom tray with the help of more than 80 screws and a sealant between them to make it water and dustproof but make it difficult to disassemble.

Mounting Requirements

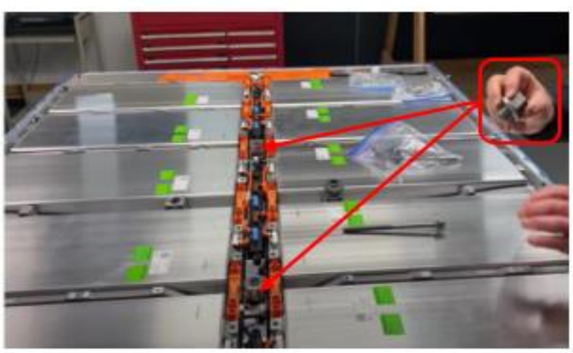
The battery pack is mounted in the vehicle's underbody.

Safety Structure

Casted cross members are used in between the modules in the battery pack

Spine design for the connectors

Casting and welding of cross members



two nuts and bolts goes inside of it

Through out bolt

Figure 59. Disassembly sequence of Volkswagen ID.4 2020 [48]

Step 3: Measure the current products level of Demanufacturability

It's not easy to evaluate a product's demanufacturability performance. Meanwhile, it is becoming increasingly important for enterprises and industrial practitioners who want to take advantage of the circular economy's promises with demanufacturing strategy. As a result, offering methodologies and tools for evaluating and improving product performance—in the context of extending product life by reusing —becomes a crucial yet under-explored issue.

A three-stage methodology has been proposed by Bovea & Pérez-Belis [82] to check the circularity of the existing product by evaluating its design based on the existing design guideline, and a similar method can be used to measure the demanufacturing by adding guidelines related to the demanufacturing.

Stage 1- The design guideline, which is required for circular design, along with demanufacturing guideline, are identified and classified according to the objective and principle defined in the end-of-life strategy framework

Stage 2- Criteria are defined to measure the margin of improvement based on the level of compliance of each demanufacturing design guideline. Also, define the criteria for the level of relevance for each demanufacturing design guideline group for the product.

Stage 3- Both criteria, margin of improvement (MI) and Relevance (R), are used together to check the demanufacturability of the product.

Stage 1:

Considering the principle of circular economy and demanufacturing, the guideline shown in the Table 41 is grouped as per the demanufacturing framework in Table 44. Groups are mentioned below

1. Extending life: The guideline ensures the product's long life and durability by adapting its design and studying the possibility of providing the feature which can support timeless design.
2. Disassembly: The guideline which is related to product structure and its connecting system

   Junction: It includes the guideline related to the connecting system.

   Architecture standardization includes design guidelines related to the accessible location of parts.
3. Components reuse: The guideline which facilitates the reuse of the product's components.
4. Safety: The guideline facilitates the safety from high voltage for secondary use.
5. Components retesting and revalidation: The guideline facilitates retesting and revalidation for secondary use.

Table 41. Benchmarking of design guidelines with various models

S. No.	Product characteristic	Tesla S 2014	Tesla Model 3	Tesla Model Y	Chevrolet Volt 2018	Chevrolet Volt 2016	BMW i3 2015	Toyota Prius	Mustang MACH-E	Volkswagen ID.4 202	Remarks
1	It has a modular design	O	O	O	X	O	O	X	O	O	Separate units of a module in a battery pack
2	Use minimum no of parts	O	O	O	X	O	O	X	O	O	Due to pouch cells, no frames, cooling plates, or foam pads are used
3	Ensure resistance to dust accumulate	O	O	O	O	O	O	O	O	O	the battery is properly sealed
4	use standardised components	X	X	X	X	X	O	O	O	O	Use uniform size module
5	minimise product variants	O	X	X	X	X	O	O	X	O	Modules used in battery pack are of same size and capacity
6	Improve the ratio between the labour required to retrieve a component and its value	X	X	X	O	O	O	O	O	X	amount of labour required to open the top cover as the sealant seals it
7	Avoid welding and fusion of joints	X	X	X	X	X	X	X	X	X	Interconnection of cells
8	Consider the use of active disassembly	X	X	X	X	X	O	O	O	O	use quick connect for coolant flow
9	Use of standard joints	X	X	X	X	X	X	X	X	X	Use welding to join the cells
10	Prioritize latching to screws and bolts	X	X	X	X	X	X	X	X	X	no latch concept is observed
11	Unify screw heads	X	X	X	X	X	X	O	X	X	One type of bolts /screw head is used
12	Minimise type of connection	O	X	X	X	X	X	X	X	X	due to distributed BMS, less number of harness connections are used
13	Use fasteners rather than adhesive	X	X	X	O	O	O	O	O	X	pack cover and tray are joined together with sealant; also, cells in

											modules are glued together
14	make joints visible and accessible	O	O	O	O	X	O	O	O	O	U-shaped brackets used for clamping the modules are mounted with two bolts that are not visible.
15	use fasteners that are easy to remove	O	X	X	X	X	X	O	O	O	half threaded fasteners are used
16	Minimise the no of joints and connections	X	O	O	X	O	X	O	X	O	providing a distributed type of BMS no of electrical connections are reduced
17	minimise the no of tools and use the push/pull process	X	X	X	X	X	X	X	X	X	No push-pull process is used
18	use material resistance to cleaning processes for components to be reused	O	O	O	O	O	O	O	O	O	related to reusing the component
19	use components with verified reliability	O	O	O	O	O	O	O	O	O	cell performance is checked
20	Do not Combine components that have different life spans	X	X	X	X	X	X	X	X	X	According to a difference in manufacturing, cells have different life
21	minimise length of wires and cables	O	O	O	X	X	X	X	X	O	due to distributed BMS, harness length is reduced
22	Use components sized for easy handling	O	X	X	X	X	O	O	X	O	Module size is not that bulky
23	maximise the accessibility of components	X	X	X	O	O	X	X	X	O	
24	Avoid dismantling part from opposite direction	O	O	O	O	O	O	O	O	O	No opposite direction is used
25	simplify the product structure	O	O	O	X	O	X	X	X	O	The module design is very complex due to pouch cell
26	build monitoring equipment into the system	O	O	O	O	O	O	O	O	O	BMS is used

27	Ensure that the fewest possible operators are required to perform a disassembly task	X	X	X	O	O	X	X	X	O	standardised module and screw fitting of the top cover
28	eliminate the need for special disassembly procedures	X	X	X	X	X	X	X	X	O	need special tools for opening the assembly
29	use simple and standard tools	X	X	X	X	X	X	X	X	O	
30	use durable and robust component	O	O	O	X	X	O	X	O	O	Use a cell with a hard covering
31	make fasteners that are easy to open	X	X	X	X	X	X	X	O	O	special fasteners are used to assemble the cells without nut
32	design with standardized fastener and component	X	X	X	X	X	X	O	X	X	The same kind of bolts are used
33	design to use standard tool	X	X	X	X	X	X	O	X	X	
34	investigate how current and upcoming laws and regulations affect the design product	O	O	O	O	O	O	O	O	O	Meeting current safety design guidelines
35	design the product with a focus on functionality	O	O	O	O	O	O	O	O	O	
36	Easy inspection of the products	X	X	X	X	X	X	X	X	X	module terminals are given
37	provide disassembly manual	O	O	O	O	O	O	O	O	O	Information is not available
38	treat remanufacturing waste properly	X	X	X	X	X	X	X	X	X	Limited applications are there
39	use digitalization ICT and IoT solution	X	X	X	X	X	X	X	X	X	No such information found
40	use the same type of material	O	O	O	O	O	O	O	O	O	All cells are made up of the same material in one battery
41	Predesign for easy cleaning	O	O	O	X	O	O	X	O	O	Module and other components of standard shape so easy to clean

42	reduce sharp corner	O	O	O	O	O	O	O	O	O	sharp corners are avoided generally
43	Avoid long disassembly path	O	O	O	X	O	O	X	O	O	easy to access modules one upper cover is removed
44	design multiple detachments with single operation	X	X	X	O	O	O	O	O	X	Cells are assembled with a long bolt in a module. Once the bolt is removed, all cells are free from one end but welded from other ends
45	avoid permanent joints	X	X	X	X	X	X	X	X	X	Cells are joined by welding
46	surface should be worn resistance from cleaning liquid	X	O	O	X	X	O	X	X	O	the outer surface of modules is of metal and closed from all side
47	design smooth surface for less dust accumulation	X	O	O	X	X	O	X	X	O	The module surface is not smooth
48	mark/eliminate hidden joints	X	X	X	X	X	X	X	X	X	No such marking is observed
49	Mark testing points	O	O	O	O	O	O	O	O	O	Terminal are marked
50	easy access to fasteners	O	O	O	O	O	O	O	O	O	
51	easy identification of fasteners	O	O	O	O	O	O	O	O	O	
52	easy access to the subsystem	O	O	O	X	O	O	X	O	O	easy access to a module
53	easily remove subsystem	O	O	O	X	O	O	X	O	O	easy removal of a module
54	labels and instructions withstand the cleaning process	X	X	X	X	X	X	X	X	X	No such instruction observed
55	Meet safety criteria	O	O	O	O	O	O	O	O	O	Safety components or coating are used
56	surface is worn resistance	X	O	O	X	X	O	X	X	O	Metal outer surface
57	no secondary finish	O	O	O	O	O	O	O	O	O	
58	plastics surface is not coated	X	O	O	X	X	O	X	X	O	
59	surface treatment last enough through refurbishment	NA	NA	NA	NA	NA	NA	NA	NA	NA	No information available

60	texture area is furnishable	O	O	O	O	O	O	O	O	O	No texture area is available
61	prevent the corrosion of parts	O	O	O	O	O	O	O	O	O	Corrosion resistance material is used in joining the cell connection
62	less hazards material	X	O	O	X	X	X	X	X	X	Cobalt-free material is used
63	avoid bulky overdesign	O	X	X	X	X	O	O	O	O	Design of module
64	sufficient clearance and support at the base to avoid damages during transportation	O	O	O	O	O	O	O	O	O	Hard outer housing supports the battery pack
65	ease of classification of the component	X	X	X	X	O	O	O	X	O	Integrated cooling channel makes it difficult to classify
66	all similar parts are identified or marked for easy sorting	X	X	X	X	O	O	O	X	O	The integrated cooling channel makes it difficult to sort
67	ease of accessing the part condition	X	X	X	X	X	O	X	X	O	Accessing the cells is difficult
68	testing points are easy to access	O	O	O	O	O	O	O	O	O	Yes, once the battery pack is open
69	testing should be quick and simple	O	O	O	O	O	O	O	O	O	Yes, once the battery pack is open
70	mounting pints are easily accessible	O	O	O	O	O	O	O	O	O	
71	mounting points are easily identified	O	O	O	O	O	O	O	O	O	
72	Feature provided for reuse	X	X	X	X	X	X	X	X	X	No such feature provided
73	Easy to separate the subcomponent	X	X	X	X	X	X	X	X	X	Disassembly of module

O- Present X-Not Present NA- Not Available

Stage 2: The evaluation of product design is based on two criteria.

<u>The margin of Improvement</u>:

It is based on compliance with the design guideline mentioned in Table 41. By determining how much a product conforms to these design guidelines, we can assess whether improvements need to be made to incorporate those that are not fully addressed from a demanufacturable perspective. The Grade of Margin of Improvements is mentioned in Table 42, Where 3 represents the guideline is not present and there is a highest requirement of the guideline in the current product, while 1 represents the lowest requirement as the current design is fully meeting with design guideline.

Table 42. Assessment of the degree of Margin of Improvement (MI) criterion

Grade of MI	Value	Description
High	3	The design guideline is not presented or is very slightly met in the product design
Medium	2	The design guideline is fairly met in the product design
Low	1	The design guideline is fully met in the product design

<u>Relevance:</u>

It is defined based on the importance of the demanufacturing design guideline. It is not enough to incorporate the level of compliance of the demanufacturing design guideline because it depends on the different OEM batteries, which may be more or less significant. Therefore, adding additional criteria, including the relevance of each demanufacturable design guideline group on the product under study according to its disassembly, life span, component reuse, safety, and testing, is important. The grades for relevance assessment are given in Table 43. If the design guideline has the highest relevance, three will be given; one will be given if the guideline is not or less relevant.

Table 43. Assessment of the Relevance (R) criterion

Grade of R	Value	Description
High	3	When considering the battery's disassembly, life span, component reuse, safety, testing, etc., the demanufacturing design guidelines group will be highly significant.
Medium	2	When considering the battery's disassembly, life span, component reuse, safety, testing, etc., the demanufacturing design guidelines group will be highly significant.
Low	1	When considering the battery's disassembly, life span, component reuse, safety, testing, etc., the demanufacturing design guidelines group will be of high low significance.

The average margin of improvement is calculated by number of design guidelines which are present for particular product and degree of Margin of improvement for that guideline. It is observed that design guideline related to Junction type and architecture are least present in the product are having highest average margin of improvement as shown in Table 45.

Table 44. Average margin of improvement for each product category (MI)

Demanufacturing design guidelines group		Code of design guidelines group	Tesla S	Tesla Model 3	Tesla Model Y	Chevrolet Volt 2010	Chevrolet Volt 2016	BMW i3 2015	Toyota Prius	Mustang MACH-E	Volkswagen ID.4 202
Extension of life		ELl	1.0	1.0	1.0	3.0	2.0	2.0	2.0	1.0	1.0
		EL2	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Disassembly	Junction	DJl	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
		DJ2	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5	3.0
		DJ3	3.0	3.0	3.0	2.5	2.5	2.5	2.5	2.5	3.0
		DJ4	1.8	1.8	1.8	1.5	1.8	1.5	1.5	1.5	1.8
		DJ5	2.0	2.0	2.0	1.0	1.0	1.0	1.0	1.0	2.0
		DJ6	3.0	3.0	3.0	3.0	3.0	3.0	2.0	2.0	2.0
		DJ7	1.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
		DJ8	3.0	1.0	1.0	3.0	1.0	3.0	1.0	3.0	1.0
		DJ9	3.0	3.0	3.0	3.0	3.0	3.0	2.0	3.0	3.0
		DJ10	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	2.0
	Architecture standardization	DASl	1.0	1.0	1.0	2.0	1.0	1.0	2.0	1.0	1.0
		DAS2	1.0	1.0	1.0	3.0	1.0	1.0	3.0	1.0	1.0
		DAS3	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
		DAS4	2.8	2.8	2.8	2.8	2.8	2.7	3.0	3.0	2.0
		DAS5	2.5	3.0	3.0	2.0	2.0	1.5	1.3	1.3	2.3
		DAS6	2.0	2.0	2.0	1.0	1.0	2.0	2.0	2.0	1.0
		DAS7	1.0	1.0	1.0	3.0	3.0	3.0	3.0	3.0	1.0
		DAS8	1.0	3.0	3.0	3.0	3.0	1.0	1.0	2.0	1.0
		DAS9	1.0	1.0	1.0	2.5	1.0	1.0	2.5	1.0	1.0
		DAS10	1.0	1.0	1.0	2.0	1.0	1.0	2.0	1.0	1.0
		DAS11	2.0	2.0	2.0	3.0	2.0	2.0	3.0	2.0	2.0
Component reuse		CRl	2.0	2.0	2.0	2.0	2.0	1.0	1.0	1.0	1.0
		CR2	2.5	2.0	2.0	2.8	2.5	2.0	2.8	2.5	2.0
		CR3	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
		CR4	1.0	3.0	3.0	3.0	3.0	1.0	1.0	3.0	1.0
safety		S1	3.0	3.0	3.0	3.0	1.0	1.0	1.0	3.0	1.0
		S2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Components retesting and revalidation		CRR1	2.5	2.5	2.5	2.4	2.4	1.5	2.5	2.5	1.3
			2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
		CRR2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Relevance for each group of design guidelines are mentioned in Table 46 for a assessed product. It is based on design of the product.

Table 45. Relevance of each design guidelines group for each product category

Demanufacturing design guidelines group		Relevance R							
		Tesla S	Tesla Model 3	Tesla Model Y	Chevrolet Volt 2010	Chevrolet Volt 2016	BMW i3 2015	Toyota Prius	Mustang MACH-E
Extension of life		3	3	3	3	3	3	3	3
Disassembly	Junction	3	3	3	3	3	3	3	3
	Architecture standardization	2	2	2	2	2	2	2	2
Component reuse		3	3	3	3	3	3	3	3
safety		2	2	2	2	2	2	2	2
Components retesting and revalidation		2	2	2	2	2	2	2	2

<u>Product design level of demanufacturable improvement</u>

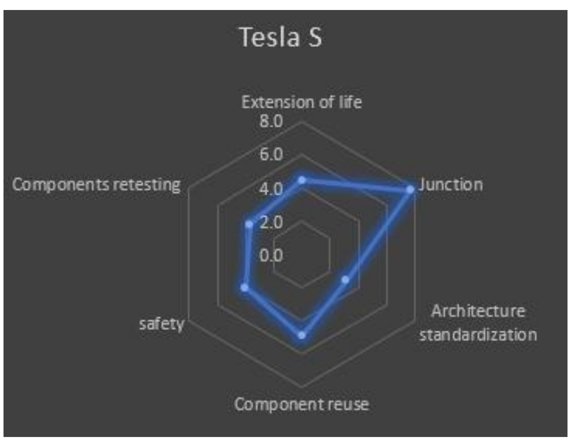
After calculating the MI (Table 45) and R (Table 46) for each battery, the Level of demanufacturing can be calculated now by multiplying MI*R. Final values are available in Table 47. Taking the average of each design group will decide the demanufacturability of that battery pack on a 1-9 scale. Higher the number, the less demanufacturable the battery is. There is a need for the highest improvement requirement from the demanufacturing point of view if the value is nine or close to 9. The lowest value means the product is already meeting the demanufacturability criteria in the existing design.

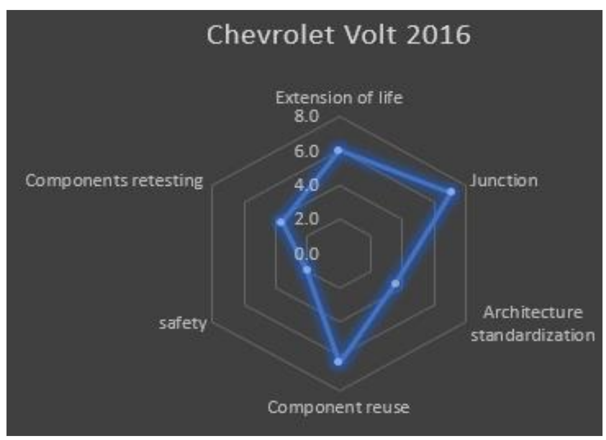
*Table 46. The margin of improvement for each product category (MI*R)*

Demanufacturing design guidelines group		Code of design guidelines group	Tesla S	Tesla Model 3	Tesla Model Y	Chevrolet Volt 2010	Chevrolet Volt 2016	BMW i3 2015	Toyota Prius	Mustang MACH-E	Volkswagen ID.4 202
Extension of life		ELl	3	3	3	9	6	6	6	3	3
		EL2	6	6	6	6	6	6	6	6	6
Disassembly	Junction	DJl	9	9	9	9	9	9	9	9	9
		DJ2	9	9	9	7.5	7.5	7.5	7.5	7.5	9
		DJ3	9	9	9	7.5	7.5	7.5	7.5	7.5	9
		DJ4	5.25	5.25	5.25	4.5	5.25	4.5	4.5	4.5	5.25
		DJ5	6	6	6	3	3	3	3	3	6
		DJ6	9	9	9	9	9	9	6	6	6
		DJ7	3	9	9	9	9	9	9	9	9
		DJ8	9	3	3	9	3	9	3	9	3
		DJ9	9	9	9	9	9	9	6	9	9
		DJ10	9	9	9	9	9	9	9	9	6
	Architecture standardization	DASl	2	2	2	4	2	2	4	2	2
		DAS2	2	2	2	6	2	2	6	2	2
		DAS3	4	4	4	4	4	4	4	4	4
		DAS4	5.6	5.6	5.6	5.6	5.6	5.4	6	6	4
		DAS5	5	6	6	4	4	3	2.5	2.5	4.5
		DAS6	4	4	4	2	2	4	4	4	2
		DAS7	2	2	2	6	6	6	6	6	2
		DAS8	2	6	6	6	6	2	2	4	2
		DAS9	2	2	2	5	2	2	5	2	2
		DAS10	2	2	2	4	2	2	4	2	2
		DAS11	4	4	4	6	4	4	6	4	4
Component reuse		CRl	6	6	6	6	6	3	3	3	3
		CR2	7.5	6	6	8.25	7.5	6	8.25	7.5	6
		CR3	3	3	3	3	3	3	3	3	3
		CR4	3	9	9	9	9	3	3	9	3
safety		S1	6	6	6	6	2	2	2	6	2
		S2	2	2	2	2	2	2	2	2	2
Components retesting and revalidation		CRR1	5	5	5	4.8	4.8	3	5	5	2.5
			4	4	4	4	4	4	4	4	4
		CRR2	2	2	2	2	2	2	2	2	2

Graphical representation

The results are presented in the spider net diagram in Figure 60. The Graph shows the demanufacturable improvement for each battery pack on six criteria. By analyzing the level of demanufacturability for each battery, it is observed that their type of connection is the major reason for not meeting the demanufacturable criteria. All EV models have a value close to 9, indicating that immediate attention is required to make a design change or add a design guideline to change the method of connection. Most of these connections are cell-to-cell connections, cell-to-current collectors, or cell-to-module connections. The next major outcome of this analysis is that current batteries are not meeting the design requirement for reusing its component in the secondary application, as the demanufacturability value for most batteries lies between 6-8. At the same time, BMW and Volkswagen ID4 models have less value which shows that components of these models can be easily reused.





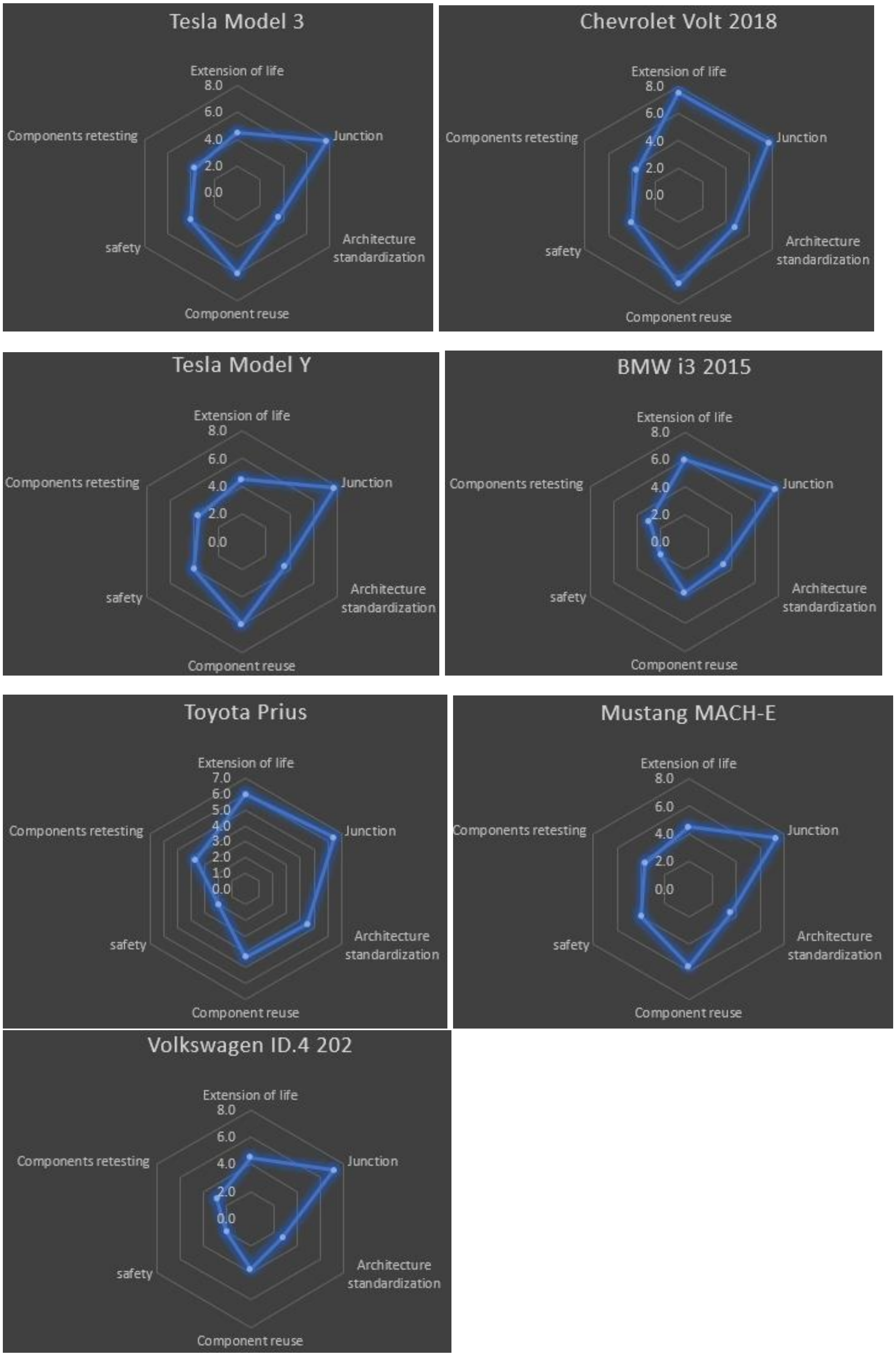


Figure 60. Level of demanufacturing for various Battery packs

Step 4: Additional Design requirements for Demanufacturing

As observed in Figure 60 in step 3, Current products are not meeting the demanufacturability criteria. Therefore, there is a need for more design guidelines to make them more usable at the end of their first life. Some of the previous guidelines, along with new design requirements, have been mentioned below.

Step 1: Analyse the product platform form thoroughly based on end-of-life recovery

- Analyze and structure product platform
- Analyze disassembly and reconfiguration task

Step2: Determine the degree of disassembly and reusability of product and components

- Develop disassembly and reusability criteria
- Evaluate various designs for disassembly and reusability
- Document potential improvement
- Carry out the required improvement

Step 3: Establish a network between production and EOL processing

- Organize the return of products from consumers by using the existing and alternative distribution and collection channels
- Develop the technology and equipment for the return logistics
- Develop an information system for the return flow to provide feedback to the designers
- Generate a plan for internal and external information and material flow
- Transfer knowledge from CIM (computer integrated manufacturing) to CIR (Computer integrated recycling)

Step 4: Develop and design reliable and visionary solutions for disassembly and reconfiguration

- Plan technical and time capabilities
- Determine suitable disassembly, and reconfiguration processes
- Evaluate economic benefits
- Establish future technical, economic, ecological, and environmentally friendly goals for reconfiguration
- Integrate production, usage, and end-of-life processing

Step 5: Prepare comprehensive guidelines for future demanufacturable product design

- Prepare product structure guideline
- Prepare fixture and joining technique guideline
- Recommended an appropriate configuration for the product platform
- Prepare demanufacturable process guideline
- Prepare economic evaluation guideline
- Document important design measure
- Establish the curriculum to train product designers in the technique of demanufacturing and manufacturing

Step 5: Prioritizing the design requirement using a house of quality

The term "House of Quality" refers to a well-known method of product development that is based on the resources and capabilities of the business striving to satisfy customer needs and is motivated by their aspirations for new products or processes[83]. It involves listening to customers, turning their wishes into a written plan, ranking execution steps according to what matters to them most, and creating a practical strategy on paper. House of quality connects the engineering specification with the consumer specification. Here, the buyer wants the product to be easier to demanufacture. The user's requirements and the engineering specifications should be integrated into the product design, and the impact of customer requirements on engineering specifications should be quantified. The roof matrix, which assesses the interdependence of engineering requirements and completes the design support tool, is another aspect of this methodology.

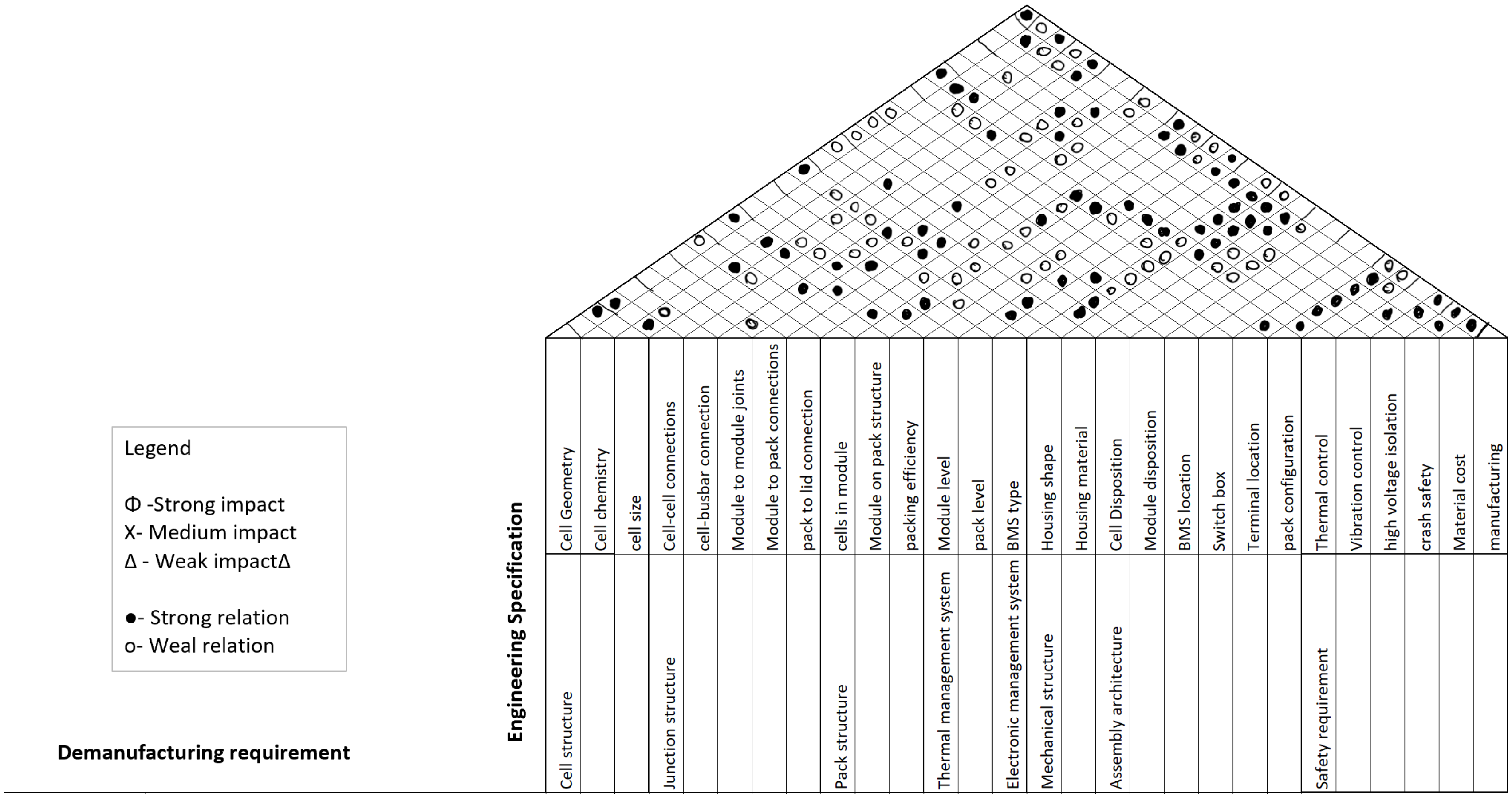
In recent years, is has been necessary to established guidelines in order to enable the creation of a product that is by design intended to be reused, repaired, remanufactured, reconfiguration, repurposed, and demanufactured, end-of-life strategy specific. The demanufacturing requirements are used in this study to substitute the customer need under an evaluation matrix. In order to drive product demanufacturability throughout the design phase, this permits the systematic examination and prioritising of engineering specifications.

The Engineering specification is shown in the row, while the Demanufacturing Requirements are represented in the column. Cell structure, junction structure, pack structure, Thermal management structure, electronics management structure, mechanical structure, and assembly structure are the several categories under which engineering specifications have been separated. On the other hand, the guidelines relating to the extension of product life, disassembly requirements, safety, and component reuse and revalidation have divided the demanufacturing requirements.

Outcome:

The HoQ technique has been used to evaluate the most significant design interventions after the technical requirements for the production of an EV LIB pack and the redesign needs obtained to enable End of life strategies like reuse, remanufacturing, and recycling were determined. HoQ was used to process all of the input data in order to produce a single, comprehensible, and highly visual framework summarising all ramifications. The end result is a set of characteristics of a hypothetical product, specified beforehand with regard to the effective manufacture and weighted according to their impact on CE management of End-of-Life LIBs, according to internal correlations and expert evaluations..

The evaluation matrix outcome is focusing on to the junction type under the disassembly section. Designers must put maximum effort into junction type, directly affecting the product's easiness and recovery efficiency. Another focus area will be the architecture standardization battery pack, where more focus is provided on the modular design of the battery pack, simplification of the battery design, and providing the design which can be quick separate.


Legend
Φ -Strong impact
X- Medium impact
Δ - Weak impactΔ
●- Strong relation
o- Weal relation
Demanufacturing requirement
Engineering Specification
Cell structure
Cell Geometry
Cell chemistry
cell size
Junction structure
Cell-cell connections
cell-busbar connection
Module to module joints
Module to pack connections
pack to lid connection
Pack structure
cells in module
Module on pack structure
packing efficiency
Thermal management system
Module level
pack level
Electronic management system
BMS type
Mechanical structure
Housing shape
Housing material
Assembly architecture
Cell Disposition
Module disposition
BMS location
Switch box
Terminal location
pack configuration
Safety requirement
Thermal control
Vibration control
high voltage isolation
crash safety
Material cost
manufacturing

Continued….

Extension of life		Timeless design				Φ	Φ	X	X	Δ														Φ
		Feature compatible for secondary use	Δ	Δ	X	Φ	Φ	Φ	X	Δ				X		Φ							X	
Disassembly	Junction	Use standardised joints				Φ	Φ	Φ	Φ	X							Δ							
		Avoid rivets and temper resistance screw								Φ														
		avoid welding					Φ	Φ	Φ															
		avoid hidden and non accessible joints					Φ	Φ	Φ	Φ	X	X								X	X	X	X	
		avoid glue and adhesive (sealant)									Φ					X								
		Use screws with the same metrics						Φ		Φ							X							X
		Minimise type of joints	Φ					Φ	Φ	X	X	X												
		Minimise the number of joints	Φ		X	X	Φ	Φ	Φ	Φ	Δ	X		Δ	Δ	X			X	X	X	X	X	
		Minimise the number of tools to be used				Φ	Φ	Φ		Φ				Φ	X		Δ			X	X	X	X	Φ
		Use standardised tools				Φ	Φ			Φ	X	X	X	Δ	Δ	Δ	Δ		Δ	Δ	Δ	Δ	Δ	Δ
	Architecture standardization	Adopt modular designs	Φ		Φ	Φ	Φ	Φ	Φ	Δ	X	X		Φ	Φ	Φ	Φ	Δ	X	X	X	X	X	X
		Minimise the number of components	X		Φ	X	X	X	X	X	X	X		X	X	X								
		group similar component	Φ	Φ		X					Φ	Φ												
		Maximize the architecture simple	Φ		Φ	Φ	Φ	Φ	Φ	Φ			Φ	Φ	Φ	Φ			Φ	Φ	Φ	Φ	Φ	Φ
		Provide quick separation	Φ		Δ		Φ	Φ	Φ	Φ		X	X	X	X	Φ	Δ		Φ	Φ	Φ	Φ	Φ	Δ
		Be able to quickly identify disassembly joints																						
		Minimise length of wires and cables				Φ	X	X								Φ			X	X	X	X	X	
		Avoid bulky size components for easy handling						Φ			Φ	Φ												
		Facilitate the accessibility of essential components																	X	Φ	Φ	Φ	Φ	Φ
		Minimise disassembly direction	Φ			Φ	X	X						X	X				X	X	X	X	X	X
		Design to make disassembly automatic				Φ	Φ	Φ	Φ	Φ	Φ	Φ	Φ	X	X				Φ	Φ	Φ	Φ	Φ	Φ
Component reuse		Use standardised components	Φ	Δ	X						Φ	Φ		Φ	Φ	X								
		Use materials that overcome cleaning processes	X		X	X	X	X	X	X	Δ	X	X	X	X	Φ	Φ		X	X	X	X		
		label components for identification of function		Φ							Φ	Φ		Φ	Φ									
		Minimise component variations	Φ	Φ	Φ						Φ	Φ				Φ								
safety		Identify high voltage components						Φ	Φ		Φ	Φ											Φ	
		Minimize short circuit triggering				Φ	Φ	Φ																
Components retesting and revalidation		Provide accessible electrodes -Module level												Φ	Φ		Φ						Φ	
		Inbuilt monitoring in components											Φ								Φ	X		Δ
		Provide testing parameter												Φ	Φ									

Figure 61. House of quality for demanufacturing requirements

Step 6: Proposed battery design as per demanufacturing

As discussed above, the design of demanufacturable products is of great value both for the customer and the OEMs. A battery has many ways to implement the design of a demanufacturable concept in its components. Some design concepts need to be incorporated from its initial design stage to make the product design more reconfigurable for secondary applications. Some of these design guidelines are related to standardizing, component reuse, disassembly, and testing ease, and some are making provisions in design for ease of disassembly after their first use.

A battery design has been proposed, as shown in the 3D model in Figure 50. This design met the maximum demanufacturing guidelines and incorporated all demanufacturable ideas observed in benchmarking design.

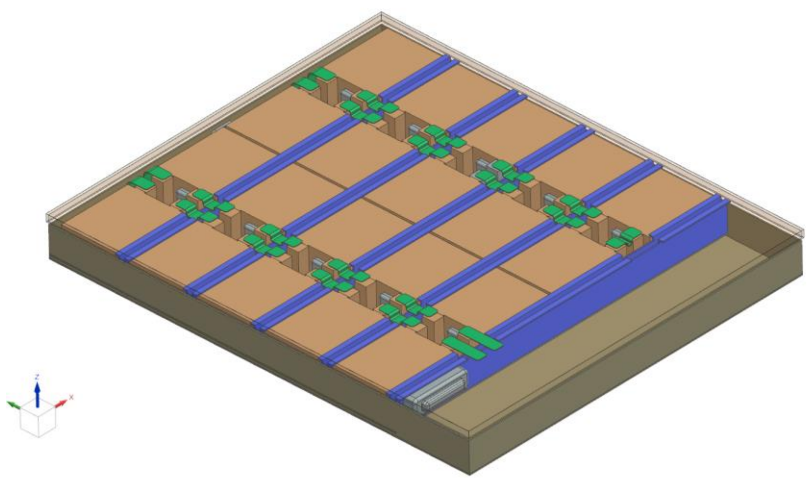


Figure 62. 3D model for proposed battery

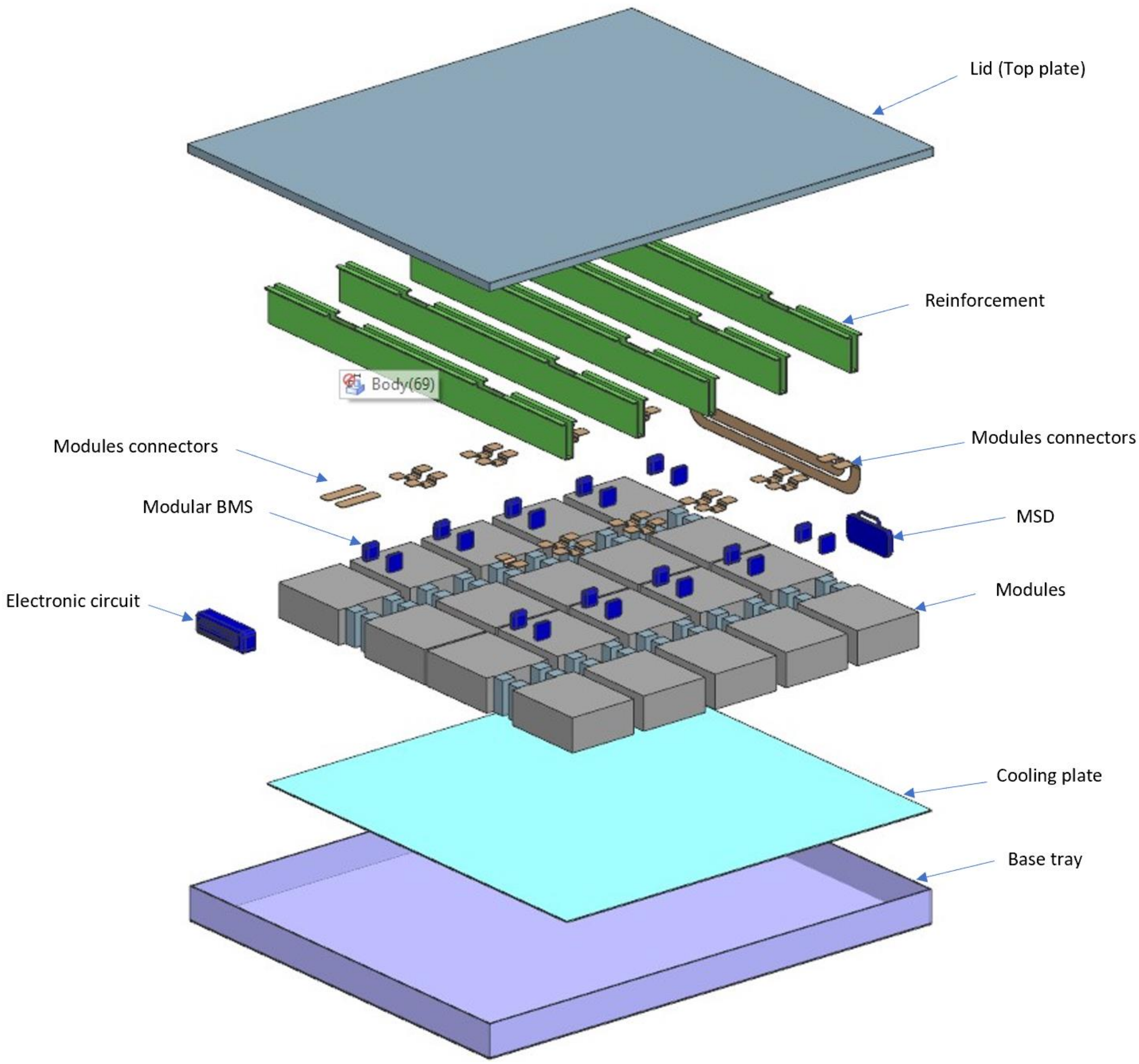


Figure 63. Exploded view of the proposed battery

Guidelines for battery design and its components

1. Vehicle structure

As the majority of OEMs are moving towards full electrification of the vehicle. A large battery capacity is used to increase driving range. BEVs have the most significant battery size, providing them with a more extended range of drivability. For example, Lucid Air Grand has a battery capacity of 118 KWh which can provide approx. 830 kms of range of battery power. This is equivalent to 1.8lt/100 km of gasoline.

Therefore, it will be good to consider the BEV battery design here. The body design of the BEV vehicle will be done considering the whole battery pack installation in the vehicle. Therefore, the underbody will be the most suitable location for such a significant component.

2. Cell material structure

As discussed in section 1.2 under the methodology section and benchmarking data, LFP cell chemistry is the preferable cell chemistry for demanufacturing. As shown in below comparison table, LFP is safer chemistry due to low toxicity, capability to operate under a broader range of temperatures (-30º C to 60º C), charging capability at high temperatures, and lower chances of thermal runaway. LFP is also a green product, making it easy to handle for end-of-life strategy. LFP battery has the best life period, up to 5-6 years or 2000-7000 cycles of charging and discharging, as these batteries are charged at high temperatures without chemistry deterioration, no memory effect, and the least self-discharging rate. The efficiency of the LFP battery is also superior, with 95% charging efficiency and less charging time, which makes it suitable for many secondary applications. Furthermore, LFP can provide a more extended driving range in cars and portable secondary applications with a lower weight. Therefore, it also increases its applications in portable secondary applications.

Table 47. Comparison of the cell performance table

Types of batteries	**NiMH**	**LiCo (NCA)**	**LiMn (NMC)**	**LiFePo4 (LFP)**
Safety	Good	Very bad	Almost good	Excellent
Green Product	Yes	No	Yes	Yes
Charge at high temperatures	Mediocre	Almost good	Very bad	Good

Memory effect	very small	No	No	No
Nominal voltage	1.25V	3.7V	3.7V	3.2V
The energy density (Wh/kg)	80	167	110	115
Life cycles (download 1C)	500	>500	>500	>2000
Life in service (continuous use)	3 years	2 years	2 years	5-6 years
Charging efficiency	0.7	0.9	0.9	0.95
Charging time (hours)	4	2-4	2-4	0.25-1
Self-discharge (monthly)	0.3	0.1	0.1	0.0080
Energy density	NA	260Wh/Kg	300Wh/Kg	160 Wh/Kg
Nominal Mass (g)	NA	48.5	47	39
Acceptable Temperature (°C)	NA	0 to 45	−5 to 50	−30 to 60

Table 48. Benchmarking table of cell material used by OEMs

Important Feature	Tesla S	Tesla Model 3	Tesla Model Y	Chevrolet Volt 2018	Chevrolet Volt 2016	BMW i3 2015	Toyota Prius	Mustang MACH-E	Volkswagen ID.4 202
LFP		√	√						
NiMH							√		
NCA	√								
NMC				√	√	√		√	√

√ - Present

Therefore, it is best to consider the LFP cell chemistry for a demanufacturable battery.

3. Cell structure

As discussed in section 1.3 and benchmarking data, prismatic cells outperform other structural cells in terms of demanufacturing. It has been discovered that the larger the cell, the greater the energy. As a result, a fewer prismatic cell are required to store more energy in a battery pack. In prismatic cells, the design is also adaptable. These cells have a higher packaging density due to better space utilisation. Another significant advantage from the standpoint of demanufacturing is the cell-to-cell connection type. A mechanical joint can be used to connect cells in a module or battery pack. Which is simple to disassemble after testing and validation for reuse in secondary applications. Its mechanical properties, like high tightness, pressure tolerance, stiffness, and resistance to deformation, make it easy to handle when preparing and testing cells for secondary application. One point which needs to be taken care of from a demanufacturing point of view is the standardization of the shape of the cell to make it compatible with multiple secondary applications.

On the other hand, a cylindrical cell can also be considered with a higher capacity; for example, the recently developed Tesla 4680 (46mm diameter and 80 mm length). It has approximately a capacity of 26 Ah, and energy of 96-99 Wh will be a much better option than 18650 cells in terms of fewer cells needed for the same capacity and energy storage. As shown in the benchmarking table below, Tesla needs to use approx. 7000 cells for 100 Kwh power. For secondary use, pouch cells will be considered least as they require a frame structure to maintain their shape, a heat transferring plate between two cells to transfer heat to the cooling plate, and a foam pad to allow for swelling during usage, resulting in a higher number of parts. Another significant issue is the soft outer cover, which makes it challenging to handle and use in the secondary application.

Table 49. Design characteristics of different cells

Parameters	**Cylindrical Cell**	**Pouch Cell**	**Prismatic Cell**
Packaging Density	High	Low	High
Lifeline	Good	Medium	Good
Capacity	3-6 Ah	40 Ah	20-50 Ah

Housing	Metal	Soft bag	Metal/plastic
Space Utilisation	Docs not fully utilise the space	Space between every cell for possible swelling	Fully utilise the space
Design Flexibility	Low	High	High
Mechanical properties	Tolerates pressure High stiffness High tightness	Swells Low stiffness Low tightness	Tolerates pressure Medium stiffness High tightness
Shape stability	High resistance towards deformation	Low resistance towards deformation	Medium resistance towards deformation
Heat Transfer	For cells with high capacity, the heat dissipation is low	Efficient cooling good surface-volume ratio	Good surface-volume ratio

Table 50. Benchmarking table of cell structure used by OEMs

Important Feature	Tesla S	Tesla Model 3	Chevrolet Volt 2018	Chevrolet Volt 2016	BMW i3 2015	Toyota Prius	Mustang MACH-E	Volkswagen ID.4 202
Cylindrical Cells	√	√						
Pouch cells			√	√			√	
Prismatic Cells					√	√		√
Battery pack Power (Kwh)	100	150	18.4	60	40	NA	NA	82
No of cells	8256	4416	96	288	96	56	NA	288
Cell Size	D18*L65	D21*L70	NA		173*45 *125 m m	NA	NA	NA
cell capacity (Ah)	3.4	4.8			NA	NA	NA	NA

D-Diameter L-Length NA- Not available

Therefore, the preference of cell structure will be as shown below for demanufacturable battery with Prismatic cell being the most preferred choice whereas pouch type is the least one.

Prismatic type > Cylindrical Type >Pouch Type.

4. Module Design:

The demanufacturing capability of the battery pack mostly depends on the designing factors of a module, such as the capacity of a module, orientation of cells, type of monitoring system, method of cell interconnection, thermal management system and its connection, routing of harness, mounting with battery pack and assembly of all these different elements together.

The current size of the module makes its secondary use for limited applications only. The benchmarking Table 52 shows that various OEM modules are very bulky in size and heavy weight. Cells inside these modules are connected through different types of welding, either spot welding, wire welding, or laser welded. Further, to secure the position of cells in their position Tesla glued the cells to the module's frame. Chevy Bolt and ford Mustang connect the cells by spot welding the cell's terminal with a U shape connector. These U shape connectors are injection molded with the current collector plate. In such condition, these modules need to be used as it is or needs to be scrapped to recover the material. There is no option to make or separate a smaller module from these large modules.

Electronic components like BMS in modules must be either distributed or modular. This will reduce the number of electric connections and harnesses used for measuring each cell's current, voltage, and temperature within the battery pack. This will increase the cost per module but will make the module a separate unit for secondary applications.

A module's required capacity is achieved by connecting the cells in either parallel, series, or a combination of these. From the demanufacturing point of view, all parallel cell connections should be assembled as a submodule and letter connected in series to achieve the required output. For Example, Tesla Model S has a module configuration 74P6S means 74 cells in parallel, and such six cell groups are connected in series in a very arbitrary shape, as shown in the Figure 26. Another way these submodules can be designed with 74 parallel cells and such submodules than further connected in series. So that during disassembly, these submodules can be recovered and used in the secondary application. Alternatively, a combination of the large capacity of the prismatic cell can be used, which is easy to disassemble. For example, as used in Volkswagen ID4 or BMW i3 series.

The thermal management system should not be a part of module design as it makes the module assembly very complex and makes disassembly almost impossible as done in Tesla model S and M. Instead, it is better to have an independent cooling plate-like chevy Bolt, as shown in Figure 52. Only one cooling plate is used for all one layer of cells.

Figure 64. Chevy Bolt cooling plate

The number of mounting points of modules with battery packs can be minimized. The cross members, which are used for strength, can be used to clamp the modules as done in Tesla Model 3 and Model Y and as shown in Figure 65.

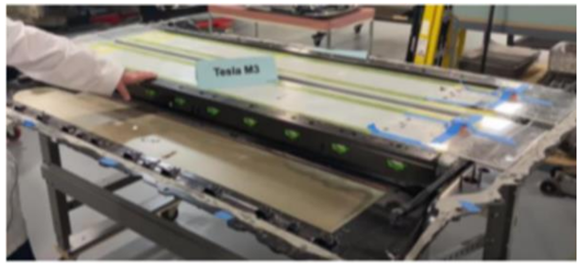


Figure 65. Multipurpose design of Cross member

Table 51. Benchmarking for module specification

Important Feature	Tesla S	Tesla Model 3	Tesla Model Y	Chevrolet Volt 2018	Chevrolet Volt 2016	BMW i3 2015	Toyota Prius	Mustang MACH-E	Volkswagen ID.4 202
Capacity of module (KWh)	5.3			8.4		4.1			
No of cells (Max)	444	1158	1158	16	30	12	28	30	24
No of modules	16	4	4						
Combination of cell	74P6S	46P25S	46P25S						8S3P
Module Size	N-Uni	N-Uni	N-Uni	N-Uni	N-Uni	Uni	Uni	N-Uni	Uni
Dimension (mm)	685* 300* 75					387* 300* 150			
Weight (Kgs)	25kgs					29.8			
BMS	Int	Int	Int	N-Int	N-Int	N-Int	N-Int	N-Int	Int
Thermal Management system	Int	Int	Int	Int	N-Int	N-Int	N-Int	N-Int	N-Int
No of mounting	2	9	9	10	12	4			4

N-Uni->Non-Uniform, Uni-> Uniform,
Int->Integrated, N-Int->Non-Integrated

5. Thermal management structure

As discussed in section 1.6 and benchmarking data, design requirements need to be met to meet demanufacturability criteria. The design of TMS is judged based on the medium of temperature control, number of mountings required, number of connections, Types of connections, number of cooling plates used, the contact area of the cell with cooling plate, pressure variation control, and ambient temperature.

The most suitable design is observed for Volkswagen ID4 TMS from the demanufacturing point of view. The reason behind it is medium of cooling is liquid which is more efficient than air. The second reason is that no mounting is required to mount the cooling plate. The cooling plate is placed below the module and gets fixed with the weight of the modules. The third reason is that no connection required between the cooling channel as there is only one large cooling plate is used, which reduces the total number of parts in a battery pack. However, contact between cells and cooling pate is at the bottom only, which makes it less efficient. This issue can be solved by placing aluminum plates between cells and transferring more heat to the bottom, as used in the chevy volt 2016 model and also shown in the Figure 66.. Also, as only one cooling plate is used to cool all cells, there might be a pressure difference at the inlet and outlet, which can cause uneven cooling, resulting in a different rate of cell aging. This issue can be resolved by providing bead type structure at the bottom of the cooling plate to make the coolant more turbulent and make it capable of extracting more heat from the cell. On the other side, Chevy Volt 2018 model considers the least priority design for demanufacturing point due to its complex structure and many parts

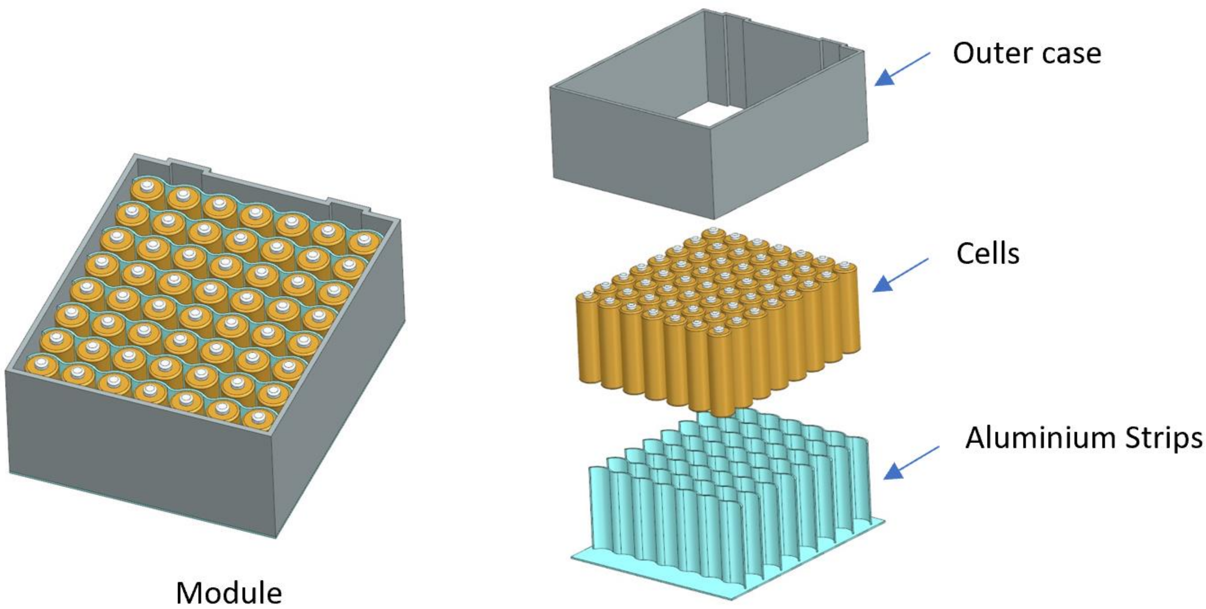


Figure 66.Proposed design for Thermal Management system

Table 52. TMS Benchmarking for different OEMS

Parameter	Tesla S 2014	Tesla Model 3	Tesla Model Y	Chevrolet Volt 2018	Chevrolet Volt 2016	BMW i3 2015	Toyota Prius	Mustang MACH-E	Volkswage n ID.4 202
Medium of temp control	Liquid	Liquid	Liquid	Liquid	Liquid	Liquid	Air	Liquid	Liquid
No of mounting required for TMS	integrated with module	integrated with module	integrated with module	integrated with module	0	0	4	0	0
No of connection (both inlet/outlet)	18	6	6	196	2	NA	2	10	0

Type of connection	quick connector type	quick connector type	quick connector type	Fixed with module	rubber pipe with clip	NA	using duct	quick connector type	no need
Number of cooling plates	16 cooling channels	21 cooling channels	22 cooling channels	96 cooling plates	5 cooling plates	8 cooling channels	2 air ducts	5 cooling plates	1 cooling plate
Contact area with cells	along length	along length	along length	along surface	At bottom	At bottom	full body	At bottom	At bottom
Temperature control	More efficient	More efficient	More efficient	More efficient	Medium	less efficient	More efficient	less efficient	less efficient
Pressure difference (PD)	may have PD	less chances of PD	less chances of PD	less chances of PD	More chances of PD	less chances of PD	less chances of PD	less chances of PD	may have PD

6. Mechanical structure:

As discussed in section 1.7 and benchmarking data, it is observed that house is the second largest contributor in the weight of the battery pack. Therefore, a light material needs to be selected. However, that material needs to have enough strength to hold the battery during all driving, testing, and crash condition. One of the variants of aluminium HPDC can be consider suitable for housing material as used in the Volkswagen ID 4. With HPDC, feature like mounting feature, air flow channel, structural ribs, and support can be integrated into the casting with additional advantage of being the light weight. This will reduce the total number of parts in the battery pack. However, in future, composite material with glass filled can be a best option to achieved mush lighter battery housing with required strength. On the other side most of the OEMs are using composite material LID which is a better weight saving idea. However, Lid material needs to pass fire safety test or should have fire retardant characteristics.

Housing needs to be corrosion resistance, compatible with other material, and coated for electric shock and environmental protection. For sealing purpose of the housing, its better to use a rubber seal which makes it easy while disassembly of the battery pack. Paste type sealant makes separation of Lid and base tray very difficult.

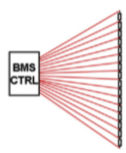
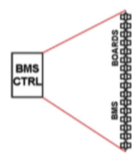
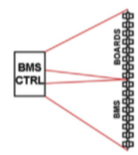
Table 53. Benchmarking for Mechanical structure for different OEMS

Parameter	Tesla S 2014	Tesla Model 3	Tesla Model Y	Chevrolet Volt 2018	Chevrolet Volt 2016	BMW i3 2015	Toyota Prius	Mustang MACH-E	Volkswagen ID.4 202
No of packs	1	1	1	1	1	1	1	1	1
Integration with body	Non -Int	Non -Int	Non -Int	Non -Int	Non -Int	Non -Int	Non -Int	Non -Int	Non -Int
Base Material selection	Steel	Steel	Steel	Steel	Steel	Aluminium	Steel	Steel	Aluminium
Lid Material selection	Steel	Steel	Steel	Composite material	Composite material	Composite material	Steel	Composite material	Aluminium
Corrosion resistance	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fire retardant	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Coating	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Sealing	paste type sealant	paste type sealant	paste type sealant	Rubber sealant	Rubber sealant	Rubber sealant	NA	Rubber sealant	paste type sealant
Crash requirement	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

7. Electronic structure

As discussed in section 1.8 and benchmarking data, four significant components come in the electronic system: BMS, Switch box, MSD, and harness. Among these, BMS plays a vital role in an electronic management system. As there are three types of BMS available, the modular type of BMS is preferable as it makes less complex the battery pack by reducing the number of harnesses and connections, can work independently, and is most reliable. Furthermore, modular type BMS is most suitable for demanufacturing perspective as it enables each module to work independently once reused in a secondary application, and no separate BMS is required. On the other hand, Centralised BMS is low-cost and is preferred by some OEMs, as shown in the below-benchmarking table. Therefore, to have a balance, distributed type BMS may be used to meet the demanufacturability criteria; however, it needs a master BMS system while used in secondary applications.

Table 54. Characteristics of Different types of BMS

Parameters	Centralised	Distributed	Modular
Topology			
Complexity	High	Low	Low
Cooling	Easy	Difficult	Difficult
Independent Operation	No	No	Yes
Reliability	Low	Low	High
Installation and maintenance	Difficult	Depend on type of cell	Depend on type of cell
cost	Low	High	High

Along with BMS, a switch box must be present to provide the platform to connect battery terminals with motors. Another essential feature is MSD, which is needed during battery installation; service and repair must be fitted inside the cabin. The location MSD is provided away from average reach, either under the rear seat or console area.

Table 55. Benchmarking table for electronic system in various OEMs

Important Feature	Tesla S	Tesla Model 3	Tesla Model Y	Chevrolet Volt 2018	Chevrolet Volt 2016	BMW i3 2015	Toyota Prius	Mustang MAC H-E	Volkswagen ID.4 202
Centralized Type BMS				√	√	√	√	√	
Distributed Type BMS	√	√	√						√
Modular type BMS									
Switch Box	√	√	√	√	√	√	√	√	√
Manual Service Disconnect	√	√	√	√	√	√	√	√	√

√- Present

8. Safety structure

Crash Requirement: Most OEMs prefer to give cross members to meet the crash requirement, as shown in the benchmarking Table 57. These reinforcement members can be used to clamp the modules, which will reduce the number of mounting as well as reduce the number of bolts shown in Figure 67. Integrated-type reinforcement is better for demanufacturing but will make installing one big cooling plate impossible. Ford and Volkswagen have added an integrated channel on the housing side to provide extra protection from the side crash.

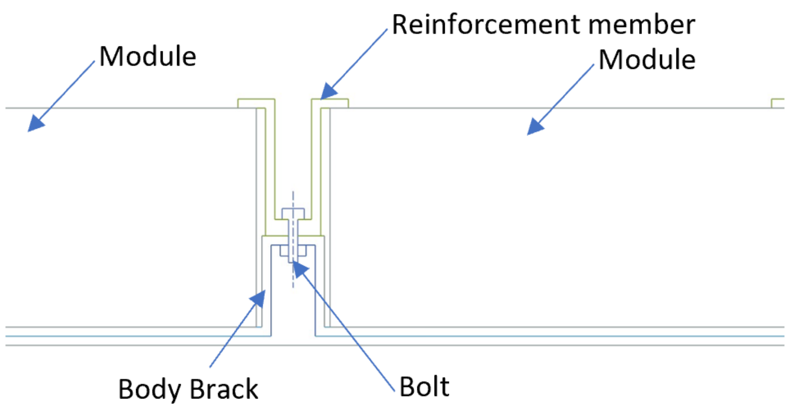


Figure 67. Section of Clamping reinforcement cross member

Table 56. Benchmarking for reinforcement in different OEMS

Parameter	Tesla S 2014	Tesla Model 3	Tesla Model Y	Chevrolet Volt 2018	Chevrolet Volt 2016	BMW i3 2015	Toyota Prius	Mustang MACH-E	Volkswagen ID.4 202
No of cross member used	7+1	3	3	0	3	NA	NA	5	6
Orientation of cross members	Both	Longi-tudinal	Longi-tudinal	0	cross	NA	NA	cross	cross
Integrated or bolted	Integrated	Bolted	Bolted	0	Bolted	NA	NA	Integrated	Integrated

5.0 Conclusion

This thesis has sought to give insights into the current product design, impact on second life management, current level of demanufacturability of the batteries, additional guidelines to make future batterie more compatible with demanufacturable, prioritize of the guideline using the house of quality, and finally proposed a battery design which meets maximum demanufacturing design guidelines.

The report encompasses information and knowledge regarding the battery packs used for electric vehicles with data from public resources. An investigation is made of the current battery solution for different EV cars of their way of solving different functions. The gained knowledge is stored in an enhanced benchmarking model and further assessed concerning its compatibility with end-of-life strategies like a design for disassembly, remanufacturing, reconfiguration, and repurposing characteristics to develop the ideal battery design for demanufacturing.

5.1 Major findings:

After going through the various existing end-of-life strategies like a design for disassembly, remanufacturing, reconditioning, and repurposing, it is observed that these design guidelines are not enough to handle the current level of waste. Instead, these guidelines focus on disassembling the used components and building the same component again. The major difference between these End-of-life strategies is about quality and warranty of the rebuilt product. Existing guidelines majority focus on the ease of disassembly, reducing the number of components, reducing the number of operations, minimize the number of tools. There is an urgent need for an end-of-life strategy like demanufacturing, which includes the design requirement at the design stage for reusing the components for secondary use after their first use.

For demanufacturable battery design, the selection of cell material can be made based on important parameters like low toxicity, broader operating range of temperature, higher energy density, higher life of service, higher charging efficiency, and memory effect. Selection of cell structure can be made based on important factors like cell-to-cell connections, packaging density, charge holding capacity, space utilization, design flexibility, mechanical property like tolerance, high stiffness, high tightness, shape stability, and a higher rate of heat dissipation

The demanufacturing capability of the battery pack mostly depends on the designing factors of a module, such as the capacity of a module, orientation of cells, type of monitoring system, method of cell interconnection, thermal management system and its connection, routing of harness, mounting with battery pack and assembly of all these different elements together.

The design of TMS depends on the medium of temperature control, number of mountings required, number of connections, Types of connections, number of cooling plates used, the contact area of the cell with cooling plate, pressure variation control, and ambient temperature.

Housing of the battery pack is the second largest contributor to the weight. Therefore, lightweight material needs to be selected, such as aluminum HPDC, which should also have enough strength and corrosion resistance.

Modular type of BMS needs to be used to reduce the number of harnesses, making less complex structure in the battery pack. The design of TMS is depends on the medium of temperature control, number of mountings required, number of connections, Types of connections, number of cooling plates used, the contact area of the cell with cooling plate, pressure variation control, and ambient temperature.

Housing of battery pack is second largest contributor in the weight therefore light weight material needs to be selected such as aluminium HPDC which should also have the enough strength, corrosion resistant. For electronic system management, modular type of BMS needs to be used to reduces the number of harness, making less complex structure in the battery pack

5.2 Contribution

Batteries are evaluated based on demanufacturing design guidelines and observed that all existing batteries which are considered in the study are not meeting the design of demanufacturing criteria. The major reason for not meeting the design of demanufacturing criteria is a method of joining cell to cell and cell to modules along with other factors like battery architecture, design factor responsible for extension of life, reusability of components, and their retesting and revalidating capabilities makes the disassembly of bulky modules next to impossible.

A new End of Life strategy, "Design for Demanufacturing," is introduced, incorporating the design guideline for the second use of a product and its component in multiple applications from the initial design stage. In addition, it incorporates necessary design guidelines for existing End of life strategies and new additional guidelines. New guidelines majorly focus on designing a product for standardized design for multiple use applications, analyzing the product platform based on disassembly and reconfiguration, Modular design, the establishment of return logistics, and enhancing the capability of the product design engineer in the technique of demanufacturing.

Based on the understanding developed during the literature review about the various parts used in the batteries, their design requirement, feature, specification, and criteria, benchmarking observation and a new battery design have been proposed which meet maximum design guideline of demanufacturing. It is recommended that the battery module's design be optimized in power capacity, smaller size, and with standardized connection points similar to the benchmarked

Volkswagen ID4 model. Due to the smaller size, the number of secondary applications will be more. Also, it is recommended that each module have its own BMS to work independently during first use as a module in an EV battery pack and during secondary application. The connection of modules needs to be standardized and easy to access, as provided in the Volkswagen ID 4 modules. These connection points can be used as module mounting points with the base try, as done in Tesla Model S.

To make the assembly and disassembly easy, the focus needs to be put on designing the parts in such a way that the majority of parts should perform additional tasks along with the primary task. For example, cross reinforcements are used to provide strength. In the proposed design, a minor modification can be done in reinforcement design and used as a clamping member for surrounding modules. Thus the architecture of the battery can be made simple, reduce the number of parts, and eliminate mounting requirements for the module. A similar concept has been used in the Tesla Model M and Tesla Model Y.

It is recommended that a single cooling plate be provided for a thermal management system which will reduce the number of quick connectors and the number of connections of cooling pipes to cooling plates. It will ease the disassembly as well. Similar concepts have been used in Chevrolet Bolt 2016 model. However, providing the cooling channel through modules makes the module structure very complex, bulky, and difficult to use in the secondary application as used in Tesla Model S and Model M.

For the sealing of the Lid and base tray of the battery pack, it is recommended to use the rubber sealer along with the bolt for achieving the required sealing same used in the Chevrolet Bolt 2016 module. Using the adhesive-based sealer makes the disassembly of the Lid very difficult and, in some cases, next to impossible as used in Tesla Model S, Tesla Model M. To make the overall assembly of the battery pack lighter, special attention needs to be given to the material selection of the Lid and tray, such as glass fiber and aluminum, respectively, as used in the BMW I3 model. Using the aluminum material for the tray will reduce the number of parts as a mounting feature; air vent and structural ribs can be added to the design and incorporated during casting.

Heads of all mounting screw/bolts needs to be the same size to reduce the number of tools required during disassembly, as followed in the Toyota Prius HEV model

5.3 Limitation

This study has some limitations, which are discussed in this section. Lithium-ion batteries' technology is still subject to change, and updates contribute to difficulty in predicting the future. New technology also implies that all products must be updated, involving all factors in the product life cycle. Therefore, tracking this ongoing technological improvement is crucial to staying competitive in the industry.

Another limitation is that due to the ongoing Coronavirus Pandemic, it was impossible to travel for an industrial visit and observe the actual assembly and disassembly of EV batteries.

The EV models considered in the study are limited to the models with teardown (disassembly) details on online platforms. Generally, such videos are uploaded after 1-2 years of the model launch; therefore, the models used in this research are not the latest ones.

5.4 Area of Application

The data is collected about the design requirements of battery parts, their design feature, specification, constrain, and limitation. This data can be valuable for other researchers. The benchmarking study has been conducted for nine different OEM’s EV batteries, and the disassembly sequence has been plotted. This study can be useful for analyzing further investigation related to part assembly, disassembly, design feature in the child part, and the number of mounting points.

Methodology, the analysis, design guidelines, and proposed battery design could aid other researchers in increasing the demanufacturing for secondary applications and decreasing their end-of-life impact on the environment.

Also, it can be used by Automobile OEMs to make a necessary structure for the return logistics of a used battery. It will be a Win-Win situation for both customers and OEMs to reduce the overall cost of the battery and generate additional revenue by selling the used battery module for secondary applications.

Also, it can be used by Automobiles OEM’s to make necessary structure for return logistics of used battery. This will be a Win- Win situation for both customer and OEMs to reduce the overall cost of the battery as well as generative addition revenue by selling the used battery module for secondary application. It can be possible when necessary, design correction are done the battery design.

5.5 Future work

There is a need to build the proto type of the proposed battery and verify the assembly and disassemble easiness. Standardized size and capacity of modules needs to be finalised which can be suitable for multiple secondary application. Reconfiguration of actual battery needs to be done. Impact of cost needs to be calculated for the proposed battery design as per demanufacturability. Impact on warranty needs to be checked for the proposed design. Trade off between redeploying in second life vs reclaim recycling needs to be analysed.

References

[1] P. Saisirirat, J. F. Rushman, K. Silva, and N. Chollacoop, “Contribution of Road Transport to the Attainment of Ghana’s Nationally Determined Contribution (NDC) through Biofuel Integration,” *Energies*, vol. 15, no. 3, Art. no. 3, Jan. 2022, doi: 10.3390/en15030880.

[2] Y. A. Chávez-Juanito, J. M. R. Marín, and M. E. M. Cueva, “COP26 de Glasgow: ¡Nueva utopía tecnológica y política!,” Feb. 2022, doi: 10.5281/ZENODO.5979738.

[3] N. M. P. Bocken, I. de Pauw, C. Bakker, and B. van der Grinten, “Product design and business model strategies for a circular economy,” *Journal of Industrial and Production Engineering*, vol. 33, no. 5, pp. 308–320, Jul. 2016, doi: 10.1080/21681015.2016.1172124.

[4] F. Lambert, “Breakdown of raw materials in Tesla’s batteries and possible bottlenecks,” *Electrek*, Nov. 01, 2016. https://electrek.co/2016/11/01/breakdown-raw-materials-tesla-batteries-possible-bottleneck/ (accessed Jul. 17, 2022).

[5] H. Rallo, L. Canals Casals, D. De La Torre, R. Reinhardt, C. Marchante, and B. Amante, “Lithium-ion battery 2nd life used as a stationary energy storage system: Ageing and economic analysis in two real cases,” *Journal of Cleaner Production*, vol. 272, p. 122584, Nov. 2020, doi: 10.1016/j.jclepro.2020.122584.

[6] J. Warner, “7 - Lithium-Ion Battery Packs for EVs,” in *Lithium-Ion Batteries*, G. Pistoia, Ed. Amsterdam: Elsevier, 2014, pp. 127–150. doi: 10.1016/B978-0-444-59513-3.00007-8.

[7] X. Xia and P. Li, “A review of the life cycle assessment of electric vehicles: Considering the influence of batteries,” *Science of The Total Environment*, vol. 814, p. 152870, Mar. 2022, doi: 10.1016/j.scitotenv.2021.152870.

[8] H. Engel, P. Hertzke, and G. Siccardo, “Second-life EV batteries: The newest value pool in energy storage,” p. 9.

[9] L. Canals Casals, M. Barbero, and C. Corchero, “Reused second life batteries for aggregated demand response services,” *Journal of Cleaner Production*, vol. 212, pp. 99–108, Mar. 2019, doi: 10.1016/j.jclepro.2018.12.005.

[10] Y. Hua *et al.*, “Sustainable value chain of retired lithium-ion batteries for electric vehicles,” *Journal of Power Sources*, vol. 478, p. 228753, Dec. 2020, doi: 10.1016/j.jpowsour.2020.228753.

[11] N. Jiao and S. Evans, “Secondary use of Electric Vehicle Batteries and Potential Impacts on Business Models,” *Journal of Industrial and Production Engineering*, vol. 33, no. 5, pp. 348–354, Jul. 2016, doi: 10.1080/21681015.2016.1172125.

[12] L. Canals Casals, A. M. Schiffer González, B. Amante García, and J. Llorca, “PHEV Battery Aging Study Using Voltage Recovery and Internal Resistance From Onboard Data,” *IEEE Transactions on Vehicular Technology*, vol. 65, no. 6, pp. 4209–4216, Jun. 2016, doi: 10.1109/TVT.2015.2459760.

[13] A. Q. Pan *et al.*, “The applications of echelon use batteries from electric vehicles to distributed energy storage systems,” *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 354, no. 1, p. 012012, Oct. 2019, doi: 10.1088/1755-1315/354/1/012012.

[14] L. Canals Casals, B. Amante García, and L. V. Cremades, “Electric vehicle battery reuse: Preparing for a second life,” *JIEM*, vol. 10, no. 2, p. 266, May 2017, doi: 10.3926/jiem.2009.

[15] P. Ghisellini, C. Cialani, and S. Ulgiati, “A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems,” *Journal of Cleaner Production*, vol. 114, pp. 11–32, Feb. 2016, doi: 10.1016/j.jclepro.2015.09.007.

[16] M. Moreno, C. De los Rios, Z. Rowe, and F. Charnley, “A Conceptual Framework for Circular Design,” *Sustainability*, vol. 8, no. 9, Art. no. 9, Sep. 2016, doi: 10.3390/su8090937.

[17] D. R. Pamminger, S. Glaser, D. W. Wimmer, and G. Podhradsky, “GUIDELINE DEVELOPMENT TO DESIGN MODULAR PRODUCTS THAT MEET THE NEEDS OF CIRCULAR ECONOMY,” *2018*, p. 12, 2018.

[18] M. Geissdoerfer, P. Savaget, N. M. P. Bocken, and E. J. Hultink, “The Circular Economy – A new sustainability paradigm?,” *Journal of Cleaner Production*, vol. 143, pp. 757–768, Feb. 2017, doi: 10.1016/j.jclepro.2016.12.048.
[19] K. Ramani *et al.*, “Integrated Sustainable Life Cycle Design: A Review,” *Journal of Mechanical Design*, vol. 132, no. 9, p. 091004, Sep. 2010, doi: 10.1115/1.4002308.
[20] X. Zhang, Y. Sun, and F. Zhang, “Design paradigm and its development phases,” in *2009 IEEE 10th International Conference on Computer-Aided Industrial Design & Conceptual Design*, Nov. 2009, pp. 288–291. doi: 10.1109/CAIDCD.2009.5374978.
[21] A. Dettmann *et al.*, “Comfort or Not? Automated Driving Style and User Characteristics Causing Human Discomfort in Automated Driving,” *International Journal of Human–Computer Interaction*, vol. 37, no. 4, pp. 331–339, Feb. 2021, doi: 10.1080/10447318.2020.1860518.
[22] A. Ziout, “Innovative Design for Active Disassembly and Sustainable Product Recovery,” p. 254.
[23] R. Bogue, “Design for disassembly: a critical twenty-first century discipline,” *Assembly Automation*, vol. 27, no. 4, pp. 285–289, Oct. 2007, doi: 10.1108/01445150710827069.
[24] M. S. Tavakoli, J. Mariappan, and J. Huang, “Design for Assembly Versus Design for Disassembly: A Comparison of Guidelines,” in *Design Engineering, Volumes 1 and 2*, Washington, DC, USA, Jan. 2003, pp. 389–395. doi: 10.1115/IMECE2003-43951.
[25] C. Favi, M. Germani, M. Mandolini, and M. Marconi, “Promoting and Managing End-of-Life Closed-Loop Scenarios of Products Using a Design for Disassembly Evaluation Tool,” in *Volume 3: 38th Design Automation Conference, Parts A and B*, Chicago, Illinois, USA, Aug. 2012, pp. 1339–1348. doi: 10.1115/DETC2012-70997.
[26] “Design + Environment: A Global Guide to Designing Greener Goods,” *Routledge & CRC Press*. https://www.routledge.com/Design--Environment-A-Global-Guide-to-Designing-Greener-Goods/Lewis-Gertsakis-Grant-Morelli-Sweatman/p/book/9781874719434 (accessed Jul. 29, 2022).
[27] “http://www.meceng.uct.ac.za/~mec450z/local/enviro/documents/REP,” p. 10.
[28] J. Kauffman and K.-M. Lee, Eds., *Handbook of Sustainable Engineering*. Dordrecht: Springer Netherlands, 2013. doi: 10.1007/978-1-4020-8939-8.
[29] X. Zhang, S. Zhang, L. Zhang, J. Xue, R. Sa, and H. Liu, “Identification of product’s design characteristics for remanufacturing using failure modes feedback and quality function deployment,” *Journal of Cleaner Production*, vol. 239, p. 117967, Dec. 2019, doi: 10.1016/j.jclepro.2019.117967.
[30] T. Tolio *et al.*, “Design, management and control of demanufacturing and remanufacturing systems,” *CIRP Annals*, vol. 66, no. 2, pp. 585–609, 2017, doi: 10.1016/j.cirp.2017.05.001.
[31] S. Shahbazi, K. Johansen, and E. Sundin, “Product Design for Automated Remanufacturing—A Case Study of Electric and Electronic Equipment in Sweden,” *Sustainability*, vol. 13, no. 16, Art. no. 16, Jan. 2021, doi: 10.3390/su13169039.
[32] M. Hundal, “Architecture DESIGN FOR RECYCLING AND REMANUFACTURING.”
[33] W. L. Ijomah, “Addressing decision making for remanufacturing operations and design-for-remanufacture,” *International Journal of Sustainable Engineering*, vol. 2, no. 2, pp. 91–102, Jun. 2009, doi: 10.1080/19397030902953080.
[34] B. Pozo Arcos, A. R. Balkenende, C. A. Bakker, and E. Sundin, “PRODUCT DESIGN FOR A CIRCULAR ECONOMY: FUNCTIONAL RECOVERY ON FOCUS,” 2018, pp. 2727–2738. doi: 10.21278/idc.2018.0214.
[35] W. L. Ijomah, S. Childe, and C. Mcmahon, “Remanufacturing: A Key Strategy for Sustainable Development.”
[36] P. Veerakamolmal and S. Gupta, “Design for Disassembly, Reuse, and Recycling,” in *Green Electronics/Green Bottom Line*, Elsevier, 2000, pp. 69–82. doi: 10.1016/B978-075069993-8/50159-0.

[37] T. Bauer, G. Mandil, É. Naveaux, and P. Zwolinski, “Lifespan Extension for Environmental Benefits: A new Concept of Products with Several Distinct Usage Phases,” *Procedia CIRP*, vol. 47, pp. 430–435, Jan. 2016, doi: 10.1016/j.procir.2016.03.079.
[38] J. Kirchherr, D. Reike, and M. Hekkert, “Conceptualizing the circular economy: An analysis of 114 definitions,” *Resources, Conservation and Recycling*, vol. 127, pp. 221–232, Dec. 2017, doi: 10.1016/j.resconrec.2017.09.005.
[39] J. Peeters, P. Vanegas, W. Dewulf, and J. Duflou, “Design for Demanufacturing: A Life Cycle Approach,” *undefined*, 2012, Accessed: Mar. 24, 2022. [Online]. Available: https://www.semanticscholar.org/paper/Design-for-Demanufacturing%3A-A-Life-Cycle-Approach-Peeters-Vanegas/6f3ca8e961b1f2ce6c1f274291fcf469910f89ac
[40] Y. Tang, M. Zhou, and R. J. Caudill, “An integrated approach to disassembly planning and demanufacturing operation,” *IEEE Transactions on Robotics and Automation*, vol. 17, no. 6, pp. 773–784, Dec. 2001, doi: 10.1109/70.975899.
[41] *What’s Inside a Tesla Model S Battery Pack -- World’s FIRST Tesla Swapped Nissan 350Z - Part 9*, (May 29, 2020). Accessed: Aug. 01, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=ENu8uuPIss8
[42] *Model Y E32: High Voltage Battery Comparison - Cylindrical vs. Prizmatic vs. Pouch*, (May 04, 2020). Accessed: Aug. 02, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=4JiDZVO9NdM
[43] *2018 Chevrolet Volt 355.2V Li-Ion Battery - Deep Dive*, (Dec. 11, 2017). Accessed: Aug. 01, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=eWYtq0hxhQg
[44] *Chevrolet Bolt EV Battery Disassembly*, (Feb. 19, 2018). Accessed: Aug. 01, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=ssU2mjiNi_Q
[45] *BMW i3 60Ah Battery Pack Disassembly*, (Dec. 15, 2019). Accessed: Aug. 02, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=LB6WI8cRzgs
[46] *2016 - 2022 Toyota Prius Li-Ion Battery*, (Oct. 17, 2017). Accessed: Aug. 01, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=BYSE4Yedeus
[47] *Mach-E: Battery Tray and Battery Cell Features*, (Jul. 23, 2021). Accessed: Aug. 01, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=4vRjo0gaG1g
[48] *2021 Volkswagen ID.4: Battery Teardown*, (May 28, 2021). Accessed: Aug. 01, 2022. [Online Video]. Available: https://www.youtube.com/watch?v=1hPe82cGLOE
[49] “Types of Electric Vehicles: BEVs, PHEVs, HEVs - What’s the Difference?” https://www.evgo.com/ev-drivers/types-of-evs/ (accessed Apr. 20, 2022).
[50] S. Windisch-Kern *et al.*, “Recycling chains for lithium-ion batteries: A critical examination of current challenges, opportunities and process dependencies,” *Waste Management*, vol. 138, pp. 125–139, Feb. 2022, doi: 10.1016/j.wasman.2021.11.038.
[51] “Charge Efficiency - an overview | ScienceDirect Topics.” https://www-sciencedirect-com.ledproxy2.uwindsor.ca/topics/earth-and-planetary-sciences/charge-efficiency (accessed Jul. 23, 2022).
[52] G. Zhao, X. Wang, and M. Negnevitsky, “Connecting Battery Technologies for Electric Vehicles from Battery Materials to Management,” *iScience*, p. 103744, Jan. 2022, doi: 10.1016/j.isci.2022.103744.
[53] M. C. Rao, “Novel Cathode Materials for Rechargeable Batteries,” p. 3, 2013.
[54] Y. Preger *et al.*, “Degradation of Commercial Lithium-Ion Cells as a Function of Chemistry and Cycling Conditions,” *J. Electrochem. Soc.*, vol. 167, no. 12, p. 120532, Jan. 2020, doi: 10.1149/1945-7111/abae37.

[55] "The rise of LFP batteries in electric vehicles | Electronics360." https://electronics360.globalspec.com/article/18081/the-rise-of-lfp-batteries-in-electric-vehicles (accessed Jul. 17, 2022).
[56] A. Cao, "Battery Features and Characteristics: What You Need to Know When Selecting a Battery," *Insight Solutions Global*, Nov. 12, 2018. https://insightsolutionsglobal.com/battery-features-and-characteristics-what-you-need-to-know-when-selecting-a-battery/ (accessed Jul. 17, 2022).
[57] J. Warner, "Lithium-Ion and Other Cell Chemistries," in *The Handbook of Lithium-Ion Battery Pack Design*, Elsevier, 2015, pp. 65–89. doi: 10.1016/B978-0-12-801456-1.00007-5.
[58] A. Das, D. Li, D. Williams, and D. Greenwood, "Joining Technologies for Automotive Battery Systems Manufacturing," *WEVJ*, vol. 9, no. 2, p. 22, Jul. 2018, doi: 10.3390/wevj9020022.
[59] D. L. Thompson *et al.*, "The importance of design in lithium ion battery recycling – a critical review," *Green Chem.*, vol. 22, no. 22, pp. 7585–7603, 2020, doi: 10.1039/D0GC02745F.
[60] S. Li, H. Wang, Y. Lin, J. Abell, and S. J. Hu, "Benchmarking of High Capacity Battery Module/Pack Design for Automatic Assembly System," in *ASME 2010 International Manufacturing Science and Engineering Conference, Volume 1*, Erie, Pennsylvania, USA, Jan. 2010, pp. 505–517. doi: 10.1115/MSEC2010-34114.
[61] L. H. Saw, Y. Ye, and A. A. O. Tay, "Integration issues of lithium-ion battery into electric vehicles battery pack," *Journal of Cleaner Production*, vol. 113, pp. 1032–1045, Feb. 2016, doi: 10.1016/j.jclepro.2015.11.011.
[62] W. J. Tan, C. M. M. Chin, A. Garg, and L. Gao, "A hybrid disassembly framework for disassembly of electric vehicle batteries," *Int J Energy Res*, vol. 45, no. 5, pp. 8073–8082, Apr. 2021, doi: 10.1002/er.6364.
[63] "Tesla Model S/X Pack - 75kWh / 214Ah / 350V," *Second Life EV Batteries Ltd*. https://www.secondlife-evbatteries.com/products/tesla-75kw-pack (accessed Jul. 16, 2022).
[64] "Tesla Model S battery module, 24V, 250Ah, 5.3kWh 12kW, 444 Panasonic 18650," *Kilowattpack.ca*. https://kilowattpack.ca/products/tesla-model-s-battery-module-24v-250ah-5-3kwh-444-panasonic-18650 (accessed Jul. 23, 2022).
[65] "Tesla 5.3 kWh Modules | 22.8V | 232Ah - Tested Used EV Modules," *Second Life EV Batteries Ltd*. https://www.secondlife-evbatteries.com/products/tesla-5-3-kwh-electric-vehicle-battery (accessed Jul. 16, 2022).
[66] A. Sharma, P. Zanotti, and L. P. Musunur, "Enabling the Electric Future of Mobility: Robotic Automation for Electric Vehicle Battery Assembly," *IEEE Access*, vol. 7, pp. 170961–170991, 2019, doi: 10.1109/ACCESS.2019.2953712.
[67] "Tesla Model S/X Pack - 100kWh / 252Ah / 400v," *Second Life EV Batteries Ltd*. https://www.secondlife-evbatteries.com/products/tesla-100kwh-pack (accessed Jul. 16, 2022).
[68] "Tesla Panasonic Quietly Outmaneuver All Lithium Battery Manufacturers," *InsideEVs*. https://insideevs.com/news/338268/tesla-panasonic-quietly-outmaneuver-all-lithium-battery-manufacturers/ (accessed Aug. 14, 2022).
[69] "Tesla Model 3 Pack - 74kWh / 208Ah / 355V," *Second Life EV Batteries Ltd*. https://www.secondlife-evbatteries.com/products/tesla-model-3-75kwh-pack (accessed Jul. 16, 2022).
[70] "2017-2021 TESLA MODEL 3 AWD BATTERY PACK ASSEMBLY OEM 1104422-00-T DAMAGED," *eBay*. https://www.ebay.com/itm/403623210911 (accessed Aug. 14, 2022).
[71] "Tesla Model 3: Exclusive first look at Tesla's new battery pack architecture | Electrek." https://electrek.co/2017/08/24/tesla-model-3-exclusive-battery-pack-architecture/ (accessed Aug. 14, 2022).

[72] F. Lambert, “Tesla Model 3: Exclusive first look at Tesla’s new battery pack architecture,” *Electrek*, Aug. 24, 2017. https://electrek.co/2017/08/24/tesla-model-3-exclusive-battery-pack-architecture/ (accessed Jul. 07, 2022).
[73] “Tesla Model 3 Battery Can Transfer Twice The Heat Of Model S P100D.” https://insideevs.com/news/339220/tesla-model-3-battery-can-transfer-twice-the-heat-of-model-s-p100d/ (accessed Aug. 22, 2022).
[74] “Tesla Model 3 & Chevy Bolt Battery Packs Examined - CleanTechnica.” https://cleantechnica.com/2018/07/08/tesla-model-3-chevy-bolt-battery-packs-examined/ (accessed Aug. 14, 2022).
[75] “BMW i3 Pack - 33kWh / 94Ah / 398V,” *Second Life EV Batteries Ltd*. https://www.secondlife-evbatteries.com/products/bmw-i3-94ah-33kwh-pack (accessed Jul. 16, 2022).
[76] “BMW i3 Pack - 40kWh / 120Ah / 352V,” *Second Life EV Batteries Ltd*. https://www.secondlife-evbatteries.com/products/bmw-i3-120ah-40kwh-pack (accessed Jul. 16, 2022).
[77] “BMW i3 | 44V | 94Ah Module - Re-rated Capacity: 3933Wh,” *Second Life EV Batteries Ltd*. https://www.secondlife-evbatteries.com/products/bmw-i3-module-samsung-sdi-94ah (accessed Jul. 16, 2022).
[78] “BMW i3 120Ah Battery module - Tested Used EV Modules | Battery | EV Project,” *Second Life EV Batteries Ltd*. https://www.secondlife-evbatteries.com/products/bmw-i3-44v-120ah (accessed Jul. 16, 2022).
[79] “How BMW and LG Chem Surpass Tesla’s Battery Thermal...,” *GM Volt Forum*. https://www.gm-volt.com/threads/how-bmw-and-lg-chem-surpass-teslas-battery-thermal-management-system.337853/ (accessed Aug. 14, 2022).
[80] “VW ID Pack - 82kWh / 201Ah / 408V,” *Second Life EV Batteries Ltd*. https://www.secondlife-evbatteries.com/products/vw-id3-82kwh-pack (accessed Jul. 15, 2022).
[81] “VW ID4 Modules battery 6.85kWh - EV Project | PowerWall | Energy Storage,” *Second Life EV Batteries Ltd*. https://www.secondlife-evbatteries.com/products/vw-id4-battery-module (accessed Jul. 15, 2022).
[82] M. D. Bovea and V. Pérez-Belis, “Identifying design guidelines to meet the circular economy principles: A case study on electric and electronic equipment,” *Journal of Environmental Management*, vol. 228, pp. 483–494, Dec. 2018, doi: 10.1016/j.jenvman.2018.08.014.
[83] H. Darmawan *et al.*, “Product development strategy with quality function deployment approach: A case study in automotive battery,” *10.5267/j.msl*, pp. 601–610, 2017, doi: 10.5267/j.msl.2017.8.005.

Appendix A: Glossary and Term Explanation

Performance and cost are essential aspects of a battery that must be considered during design and development. In this section, factors related to batteries are identified, which needs to be controlled for optimal health of batteries.

Ampere-hour capacity:

The entire charge quantity released from a fully charged battery under defined conditions is represented by the Ampere-hour (Ah) capacity. The rated Ampere hour capacity is the nominal capacity of a fully charged new battery under the manufacturer's set circumstances; for example, a typical nominal condition might be described as a temperature of 20 °C and a rate of discharge of 1/20 C. The Watt-hour capacity may also be used to describe battery capacity: it is defined as the product of the Ah Capacity and the Voltage level of the cell.

C-rate

It is used to represent a charge or discharge rate (current magnitude) equal to the capacity of a battery deliverable in one hour. For a 1.6 Ah battery, C refers to a charge or discharge of the cell at 1.6 A; correspondingly, 0.1C is equivalent to 0.16 A rate, and 2C to a current of 3.2 A. Higher the C rate faster the power is being charged and discharged. Initial vehicle acceleration and regenerative braking events can produce discharge and charging rates up to 5C rate for a time of about 5-10 sec.

Specific energy

It is used to determine how much energy a battery can store per unit mass. It is also known as gravimetric energy density. It is given in Watt-hours per kilogramme and is a critical quantity to consider because it directly impacts the distance the vehicle can travel in a charge depleting mode as well as the mass of the battery pack.

Specific power

The peak power per unit mass of a battery, also known as gravimetric power density. It is stated in Watts per kilogramme and provides information about the torque boost performance of a certain HEV.

Energy and power densities:

The ratio between the nominal battery energy or power and the associated battery volume is specified as the volumetric energy and power densities. Their units of measurement are Wh/l and W/l, and they show how large the battery must be to provide the required energy and power levels.

Internal resistance:

It is the total equivalent resistance within the battery; it varies with charging and discharging events, can alter as operating conditions change, and dictates the amount of power wasted over time for the Joule effect.

State of charge (SOC)

It is defined as a battery's residual capacity in comparison to its original state of charge, and it is impacted by module operating circumstances such as load current and temperature. It may be thought of as the battery pack's equivalent of a gasoline gauge in a battery or hybrid electric vehicle; its mathematical representation is given by

$$SOC = \frac{RemainingCapacity}{RatedCapacity}$$

The state of charge is a vital condition parameter for battery management; correct measuring of SOC is difficult due to material, temperature, and capacitance yet important to achieve healthy and safe battery operation.

Depth of discharge (DOD)

The depth of discharge indicates the proportion of total battery capacity that has been drained and is therefore defined as the one's complement of the battery state of charge.

State of health (SOH)

SOH describe how well a battery works over a period of time and defined as the ratio of an aged battery's maximum charge capacity to the maximum charge capacity of the battery when it was new. It is a critical measure for determining the degree of a battery's performance deterioration and estimating the battery's remaining lifetime.

$$SOC = \frac{AgedEnergyCapacity}{RatedEnergyCapacity}$$

Cycle life

It specifies the number of discharge/charges cycles the battery can withstand at a given DOD (usually 80%) before failing to fulfil particular performance parameters. The charging and discharging rates, as well as other factors such as temperature, all have an impact on the battery's actual functioning life. Obviously, the greater the DOD, the shorter the cycle life; therefore, a larger battery can be utilised for a lower DOD during typical operations to attain a higher cycle life.

Calendar life:

The calendar life is the battery's estimated life span under storage or periodic cycling settings; it may be described as the battery's capacity to tolerate deterioration over time. It is highly tied to temperature and should be as high as feasible in order to extend the calendar life of the complete BEV/HEV system.

Efficiency:

The battery's efficiency is defined as the ratio of electrical energy delivered by the accumulator during discharge to electrical energy supplied to the accumulator during recharge. In fact, an accumulator cannot transfer all the energy acquired during charge during discharge since some of this energy is converted to heat or lost due to leakage currents occurring inside the internal structure of the cell.

State of Function

State of Function (SOF) is defined as the ratio of the battery's capacity to its remaining available charge and is therefore a mix of SOC, SOH, the charge/discharge history, and the operating temp erature. The procedure is used to assess a battery's readiness and mechanical integrity

Appendix B: Meeting regulations and standards

Testing Structure

Test Driving cycle:

Design consideration for Li-Ion batteries include factors such as the driving cycle that is to be tested. For example, government driving cycle included the US06, the Urban Dynamometer Driving school and the new European Driving Cycle (NEDC)

These cycles are originally designed for emission certificate testing are representing of specific regional driving scenario. US 06 test cycle for instance is designed to replicate a combination of aggressive low speed “city type” driving and high speed “highway” type driving. NEDC also include both type of driving scenario but have city drive first so it’s us considered a good cycle for testing EV.

Testing and validation fall in two categories:

1. Performance testing: To check the how the battery will perform under a variety of condition and usage model

   - Life Cycle Testing of Electric Vehicle Battery Modules (SAE J2288)

   - Vibration Testing of Electric Vehicle Batteries (SAE J2380)

   - Recommended Practice for Performance Rating of Electric Vehicle Battery Modules (SAE J1798)

   - Determination of the Maximum Available Power from a Rechargeable Energy Storage System on a Hybrid Electric Vehicle (SAE J2758)

2. Abuse testing: To check how the battery will react to various abuse situation such as crash impact penetration rollover and high temperature.

Some abuse test protocols are (which are jointly designed by OEM, battery manufacturers, and government organisation)

- Freedom CAR Electrical Energy Storage System Abuse Test Manual for Electric and Hybrid Electric Vehicle Applications
- US Advanced Battery Consortium Electrochemical Storage System Abuse Test Procedure Manual (SAND99-0497)
- SAE J2464, Electric and Hybrid Electric Vehicle Rechargeable Energy Storage System (RESS) Safety and Battery Abuse Testing

Other industry group and organisation have begun addition regional safety

- ANSI/UL 1642, ANSI/UL 2054
- IEC 60086-1, 60086-2, 60086-3; IEC 62133; IEC 61851, 61951, 61960, 62196
- IEEE 1625, 1725
- UL2202, UL2231, UL2251
- ANSI C18.1 Part 1, ANSI C18.3 Part 1
- UN Transportation Testing (38.3 T1-T8)
- SAND99-0497
- SAE J2464 EVB
- Nordic Ecolabel (White Swan)

Standardization: Standardization of test and validation procedure still in process and many agencies are working on this such as SAE (society of automobile engineering), OIS (organisation of international standard), IEC (international electrotechnical commission) and ANSI (the American national standard institute)

In 2012, SAE released standard J2464 "EV & HEV Rechargeable Energy Storage System (RESS) Safety and Abuse Testing Procedure". This is an attempt to standardize the safety and abuse testing on EV batteries and builds on the work done under the US government sponsored "Freedom CAR" program as well as the US Automotive Battery Consortium (USABC). USABC was created in 1991 with a goal of helping to drive the development of advanced high-performance batteries for EVs.

Appendix C: Battery charging structure

There are three types of chargers ranging from 110V to 400V.

Leve 1: This type of charging unit plugs into the standard household outlet using 110 V and offer about 3.3 kW of power to the vehicle.

Level 2: It offer 6.6 kW of power and required 220-240 V. It can charge the battery in half the time of level 1 but must be installed professionally

Level 3: use 480 V and charge the battery in 10 mins. Due to high voltage these types of charging unit cannot be installed in house and majorly for public places charging.

Table C1. Level of Charging

	Voltage (V)	Current (A)	Power (kW)	Type
Level 1	110	16	1.9	AC
Level 2	208/240	32	19	AC
Level 3	480	400	240	DC

Next level of charging which is under development is wireless/inductive charging system. Some inductive charging has been used in the low volume vehicle like GM EV1 and Toyota RAV4. During the charging by induction vehicle need to come in proximity of inductive charger where electromagnetic current pass through them to charge the battery. Here half the electromagnet is placed in the car and other half is placed in the charging station. It is not that efficient process as its efficiency is 75-85%. One safety advantage is that there is no risk of electric shock as there is no physical connection and touch

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