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# In-depth analysis of electric vehicles battery pack structure and disassembly procedure for the application of circular economy strategies

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**Abstract**

The battery pack is the most valuable component of the electric vehicle and its disassembly is the key process to recover the inner value of the product and apply circular economy strategies, from repair to recycling and remanufacturing. Different models of EV battery packs have been analyzed to assess criticalities in the product structure and disassembly procedure. Regardless the absence of a standardized design, some similarities can be identified and considered for the implementation of disassembly procedures. From the comparison of the disassembly procedures of four in-depth analyzed battery pack models emerged that it is possible to identify six disassembly blocks, grouped in two main disassembly stages. The first stage includes the disassembly of the battery covers, the coolant removal (in case of liquid cooling) and the service plug removal, while the second stage involves the removal of the junction block, the battery management system and the modules. The precedencies and criticalities in the execution of the six disassembly blocks were deeply analyzed and the results reported in the paper.



*Keywords:* Batteries; e-mobility; electric vehicles; disassembly; recycling; remanufacturing; circular economy

## 1. Introduction

In the last decade, the automotive industry has faced an increasing transition from the internal combustion engine vehicles (ICEVs) to the Electric (EV) and Hybrid (HEV) vehicles. The shift from Lead Acid batteries to the higher energy-density Li-ion batteries (LIB) allowed the electric vehicles to increase their performances and competitiveness in the car market [1]. The EV sales significantly raised over the last decade and the trend is growing, from 3 million in 2020 to 66 million in 2040, more than two-thirds of passenger vehicle sales [2]. The electric vehicles are mainly composed by the battery pack (which accounts for around 30% of the total car value), the motor, the generator, the inverter, the AC/DC converter and the transmission [3,4]. On average the lifespan of an electric car is estimated to be between 10 and 20 years. Considering the market volume this means that the battery disposal is becoming a concrete issue [5]. In the context of climate crisis and resource scarcity the traditional linear open-ended economic model of "take-make-disposal" is not sustainable anymore and the new restorative Circular Economy (CE) paradigm is taking its place. The CE aims to create inner circles and keep the product circling longer into the system, with the reuse, repair, remanufacture and recycle of the product and its components [6–10]. The Recycling strategy treats the battery in order to release its materials and use them for other manufacturing processes. Battery recycling generally requires the battery discharge and disassembly to reduce the electrical hazards and increase the material separation. Common strategies imply pyrometallurgical treatments, mechanical pre-treatments and hydrometallurgical treatments. The Repurposing aims to reuse the battery for secondary purposes, different from the primary one, such as less demanding electro-mobility or stationary applications. Remanufacturing, instead,


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returns a used product to at least its original performance with a warranty equivalent or better than newly manufactured products. The battery pack is disassembled up to module or cell level, the components are tested to assess the degradation state and replaced, if compromised, to restore the performance of the pack. Key role in these strategies is played by the demanufacturing, which is a breakdown of a product into its individual parts to have access to the residual value, such as reusable components or recyclable materials, and the disassembly is typically its first phase.

### *1.1. EV Battery hierarchical structure*

The EV battery is a hierarchical structure of components. At the lower level there are the battery cells, which are able to store and provide the electrical energy by electrochemical mechanisms [11]. All alone, the energy provided by a single cell is not sufficient to provide the mobility of the vehicle. Average cell voltage range between 3,6V and 3,8V and it strongly depends on the cell chemistry. To increase the power, more cells are connected in parallel to form cell groups, and in series to form a module. In some cases the modules are also grouped into module groups. Moving up to the pyramidal battery levels, more modules (or module groups) are connected in series to increase the battery voltage and with complementary components, such as battery management system, thermal management system, power electronics and junction blocks, they form the whole battery pack. The EV LIB main components inside the EV battery do not significantly change, but the overall pack design is not standardized. The layout is strongly affected by the cell geometry and within the same cell geometry it can vary in relation to the battery manufacturer. Furthermore, different types of junctions are used to link the components. In addition, there is an intrinsic uncertainty of the product End-of-Life (EoL) state due to the different usage condition of the battery pack.

At the state of the art the disassembly is performed mainly manually [12–18]. Well know case study on battery disassembly was publish by Wegener et. al. [12]. The authors analyzed a manual disassembly of Audi Q5 Hybrid battery pack with a planning approach based on priority matrix and associated disassembly graph, and they investigated the possibility of a semi-automated disassembly station. Similarly, Gumanová et al. [13] analyzed the battery pack disassembly of a Volkswagen Jetta Hybrid to obtain the disassembly sequences with disassembly graph derived from priority matrix. Cong et. al. [18], instead, adopted a Multi-objective mathematical model and hybrid genetic-firework algorithm based on the precedence graph. Virtual disassembly tool based on the MTM-UAS method has been also investigated for the disassembly of the batteries [19].

### *1.2. Scope of the paper*

Given the crucial role of the battery disassembly in unlocking the process of the product EoL value recovery, in this paper an in-depth analysis is performed on different models of EV battery packs to assess similarities and differences between the pack structure and disassembly procedure. The aim is to provide additional inputs on the research in this field to support the implementation of large-scale disassembly strategies and the application of circular economy. The paper proposes a first analysis of the battery pack structure according to the different cell geometries, followed by a detailed analysis of the battery packs disassembly procedures.

## 2. Overview of the 3 types of Li-ion Battery Pack assembly

In order to understand the synergies and differences between the assembly structure and disassembly process requirements for the different battery packs, a first stage of overall analysis of the Li-ion battery assembly structure has been performed and the results were grouped according to the battery cell geometry (cylindrical, prismatic and pouch).

### *2.1. Cylindrical Battery Packs*

In the cylindrical battery packs the bond between the cells is typically by welding. When the cells are positioned one over the other (e.g. the Honda Civic Hybrid 2006) [20,21] they can be bound by projection welding, while when two cells are side by side they can be linked by flat tabs, resistance welding or fuse wire (e.g. Tesla Model S) [22–27]. At module level, the cell groups can be also connected each other by mechanical joints like bolted tabs. At pack level the modules can be stacked one over the other, such as Fiat Ducato EV battery pack, which imply a higher pack height, or generally positioned on the same level, such as the Tesla Model S pack. The connection between the modules is generally achieved with mechanical joints like bolted tabs or cables.

### *2.2. Prismatic Battery Packs*

The connections between the prismatic cells can be both mechanical or welding [20,28–31]. An example of mechanical link with bolted tabs is adopted for the module of the Toyota Prius Prime 8.79kWh, while in the eGolf modules [32] the tabs are connected by ultrasonic welding. In the Prius battery packs the positions of junction block (JB) and Battery Management System (BMS) change among different version of the same electric car model: in the older version ($4^{th}$ generation Toyota Prius 207.2V) or in the Toyota Yaris Hybrid, the BMS and the JB are located at the two sides of the pack, at the same levels of the modules, while in the newer version (Toyota Prius Prime 8.79kWh) they are positioned above all the internal content of the pack. The service plug position is on one side of the pack in case of older Prius model, while it is positioned on the top of the pack in the newer version. The service plug (SP) is a plug generally positioned in the middle of the high voltage electrical circuit of the pack and it can be removed at the early steps of disassembly to splits the electrical circuit and decreasing the maximum voltage inside the system.

### *2.3. Pouch Battery Packs*

The cells of the pouch battery packs are generally connected by resistance welding or ultrasonic welding and a bus bar is used to link the different cell groups [20,33–39]. Given their flexible structure, the cell groups need a supporting and fixing structure such as cartridge, supporting tray and rigid case. The geometry of the modules changes a lot between car models and the link between modules is typically done with bus bars. Also in pouch battery packs the position of BMS, JB and service plug can vary. In the Nissan Leaf, Chevy Volt 1st and 2nd Gen and Chevy Bolt battery packs, for example, the service plug is positioned at the top of the pack but there are other battery models in which it is positioned on the bottom, to be easily removed before the battery pack removal from the EV [33–37].

## 3. Deep analysis of the 3 types of Li-ion Battery packs disassembly

To deeply investigate the disassembly tasks and constraints of the different EV Li-ion battery pack types, four common EV models have been examined in detail. The EV analyzed are:

- Tesla Model S85 2012 for the cylindrical battery;
- Toyota Prius Prime 8.79kWh for the prismatic battery;
- Chevrolet Volt 2nd Gen and Nissan Leaf 24kWh for the pouch battery.

The analysis of the selected battery pack included: product analysis to identify the different components of the battery pack; Identification of precedence between the components; Formalization of tasks to remove each the component.

### *3.1. Cylindrical Battery Pack: Tesla Model S85 2012*

The Tesla Model S85 2012 is a full EV with cylindrical 18650 cells. The battery pack thermal control adopts a liquid cooling system. With information gathered from publicly available image and video database of a Tesla Model S disassembly process [22–27] and the internal expertise it was possible to identify the battery pack components, the tasks required for the dismantling and derive the disassembly graphs. As reported in the pack level disassembly graph of Figure 1, the pack dismantling process can start both with the safety fuse and covers removal (steps from #1 to #11) and the coolant removal (step #2). In the disassembly sequence from #1 to #11 it is first required to remove the cover of the safety fuse (steps #1 to #2), then remove the safety fuse (which, once removed, has the same effect of the service plug removal, absent in this battery pack). Once removed the fuse the dismantling can proceed with the battery pack main covers removal (steps from #5 to #11). After steps #11 and #12 it is possible to perform the modules removal operations (steps #13 to #44) in parallel with the junction block (JB) disassembly (steps #45 to #48, #50 and #51). The BMS removal tasks (#49, #52, #53) can be performed only after step #48 and the JB removal can be concluded only after the beginning of BMS removal (step #49). The pack disassembly terminates with the dismantling of the remaining cable components and the battery tray.

### *3.2. Prismatic Battery Pack: Toyota Prius 8.79kWh*

The Toyota Prius 8.79kWh is a Plug-in HEV with a pack of five modules of prismatic cells. The cooling of the battery is obtained by air entering from one side of the car and flowing through cooling tubes inside the pack. The heating system consists in a serpentine positioned under the five modules. From the publicly available information on the Toyota Prius Hybrid battery structure and disassembly process [28–31], the battery disassembly operations performed at the Circ-eV lab of Politecnico di Milano [40] and interviews of battery dismantlers during the DigiPrime project coordinated by Politecnico di Milano [41], the pack disassembly process has been derived and formalized into the disassembly graph of Figure 2. The Toyota Prius 8.79kWh battery pack is a layered structure. The disassembly can be seen as a series of three main stages: a first phase of covers and SP removal (from step #1 to #12 in Figure 2); a second phase of BMS, JB and pack internal holding fixture removal (from step #13 to #48) and the last phase (from steps #49 to #76) which includes the modules removal. In the first disassembly phase, step #8 is dedicated to the SP disconnection and the rest to the covers removal. In the second disassembly phase, junction block removal (steps from #29 to #36) can be performed in parallel with the BMS removal (steps #22 to #25). Before starting the last phase, the remaining pack internal holding fixture have to be removed. Last phase is mainly focused on modules removal (steps from #49 to #73). The dismantling finishes with the removal of the battery heaters below the modules and the battery tray (steps #74, #75, #76).

### *3.3. Pouch Battery Pack: Chevrolet Volt 2nd Gen*

The Chevrolet Volt 2nd Gen is a full EV with a pouch battery pack of three module groups: the 3 module groups have different voltage, 2 of them are made of 2 modules and 1 is composed by 3 modules. From the analysis of publicly available image and video database on Chevrolet Volt 2nd Gen battery structure and disassembly operations [20,33,34], and interview of battery dismantlers during the DigiPrime project [41], the pack battery components and precedence relations has been identified. The graph related to the pack disassembly is reported in . The cooling of the system is liquid and requires the coolant removal (step #3 of ). In parallel it is possible to remove the system casing cover (steps #1 & #2) and the SP circuit (step #4). After the system casing cover removal, the three module groups, the BMS and the JB are clearly visible. To continue, before proceeding with any cables disconnection, it is necessary to first disconnect the monitoring circuit cables from the BMS (step #5) to avoid possible its misread of absent signals and erroneous countermeasures [33,34]. After that the BMS removal activities can be concluded (steps #17 to #19). The removal of the JB (steps from #6 to #11) can be performed after step #5, in parallel to the module groups removal operations (steps from #20 to #32). Given their high weight, the lift of the system casing cover and the module groups requires a hoist.

### *3.4. Pouch Battery Pack: Nissan Leaf 24 kWh*

The Nissan Leaf 24 kWh is a full EV with pouch cells. The pack is made of three module groups, where two of them have a mirrored structure. From data available on public sources [35–38] and disassembly activities performed on batteries at the Circ-eV lab of Politecnico di Milano [40], the components list and the disassembly graph of the Nissan Leaf 24 kWh have been formalized (Figure 4). The first operations to perform in the pack disassembly are the removal of the SP (step #1 in Figure 4) and the removal of the upper casing cover (from step #2 to #5). After that, 3 disassembly blocks are available for dismantling: the BMS removal (from step #6 to #8); the 3 module groups removal (respectively from step #9 to #15 for one module group; from #16 to #23 for another module group; from #24 to #29 for the other module group); and the JB removal (steps from #37 to #49). There are no physical constraints between them, therefore they could theoretically be performed in parallel. After the removal of the 5 disassembly blocks, what remains to be dismantled are battery pack internal holding fixture and remaining cables (steps from #30 to #36 and from #50 to #52).

## 4. Disassembly comparison

From the comparison of the battery packs disassembly operation of the four battery, six common disassembly blocks (DBs) have been identified (Figure 5): the cover removal DB; the SP removal DB; the coolant removal DB; the BMS removal DB; the modules removal DB and the JB removal DB. The covers of the battery pack physically protect the components inside of it, therefore their removal (cover removal DB) always happens in the first phase of dismantling. The battery pack service plug (or safety fuse in case of Tesla model) splits the high voltage circuit to reduce as soon as possible the electrical hazard. For this reason, it is quickly accessible since the beginning (after a small cover removal if hidden). The coolant removal DB (in case of a liquid cooling) can be as well a starting point of the pack disassembly (this is reasonable to avoid unseemly liquid losses). After the execution of these three disassembly blocks there is the second phase of dismantling, which involves the JB removal DB, the BMS removal DB and the modules (or module groups for the pouch pack) removal DB. The JB is generally accessible immediately after the first phase. The Chevrolet Volt disassembly requests to firstly disconnect the monitoring circuit cables from the BMS before proceeding with the dismantling, while for the other battery packs no anticipated BMS monitoring cables disconnection requirement has been found. BMS removal is another phase generally possible immediately after the initial phase, with exception for the Tesla Model S pack (where a partial JB dismantling is necessary). The module or module group removal BD can be performed immediately after the initial phase, except for Toyota Prius 8,79 kWh for which this DB is accessible only in the last stage of the process. In terms of disassembling reversibility, the best case is the Toyota Prius, because no-destructive disassembly are required from pack to cells level, while, on opposite side, the Tesla pack is the worst due to extensive usage of adhesive bonding (starting from the main cover closure), and welding linkages (from module level).

## Conclusion and further developments

The analysis performed on the selected battery packs confirmed that the LIB design is not standardized: the main components are generally the same, but the layout strongly changes depending on the cell types and battery manufacturer. Furthermore, different types of junctions are used to connect the components (cables, bolts, nots, welding, glues, etc). In addition, there is an intrinsic uncertainty of the battery EoL state due to the different driving conditions in the usage phase. Lack of information exchange between the product manufacturer and the companies treating the good at the end on its life, and lack in the traceability of the pack, slow down the innovation process and the automation of operations.

Therefore, at the state of the art the disassembly is performed manually. Nevertheless, from the comparison of the disassembly procedures of four selected battery models emerged that it is possible to identify six common disassembly blocks, grouped in two main disassembly stages. The first stage includes the disassembly blocks of covers removal, coolant removal (in case of liquid cooling system) and the SP removal (safety fuse in case of Tesla pack), while the second stage involves the JB removal DB, the BMS removal DB and modules (or module groups) removal DB. The covers removal and coolant removals operations can be started since the beginning, while the SP removal requires sometimes partial covers removal steps. Regarding the second phase of the disassembly, for cylindrical and pouch batteries the modules removal tasks can be addressed as soon as the first phase is finished (exception for step #5 of Chevrolet Volt), and it can be concluded regardless the execution of the JB and BMS removals (except for step #20 of the Chevrolet Volt). The JB removal DB can be performed at the beginning of the second disassembly phase in all the four battery models (exception for step #5 of Chevrolet Volt) and can be finished regardless the execution of modules removal DB. For the Nissan Leaf and Toyota Prius the JB removal DB is also independent from the BMS removal. A multi-layered structure of the battery pack, as for Toyota Prius Prime 8.79kWh, implies that the module removal DB is executed after all the other disassembly blocks. The analysis of battery pack disassembly criticalities and similarities proposed in this paper aimed to provide additional inputs on the research in this field to support the development of common disassembly strategies to foster the operations automation and the development of tool & methodologies for the disassembly optimization. A work in this direction is on-going for the development of a safety-oriented decision support tool for the remanufacturing and recycling of post-use HEV&EV Lithium-Ion batteries. Some results have been already achieved during the master thesis work at Politecnico di Milano [42] and shared in the CIRP conference paper [15], and they are planned to be widening with the disassembly analysis and application to other types of battery packs.

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## Annex

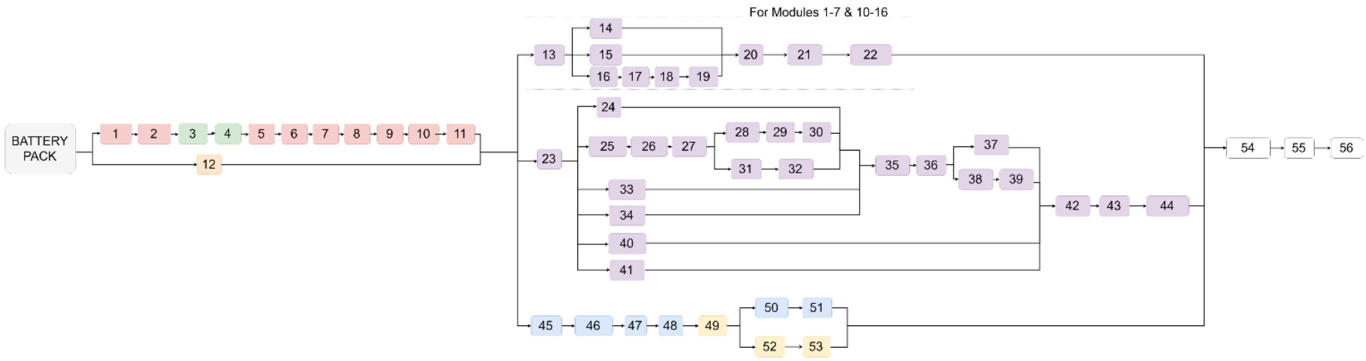


Figure 1: Tesla Model S85 disassembly graph at pack level: red = covers removal block; green = safety fuse removal block; orange = coolant removal block; blue = junction removal block; yellow = BMS removal block; purple = modules removal block

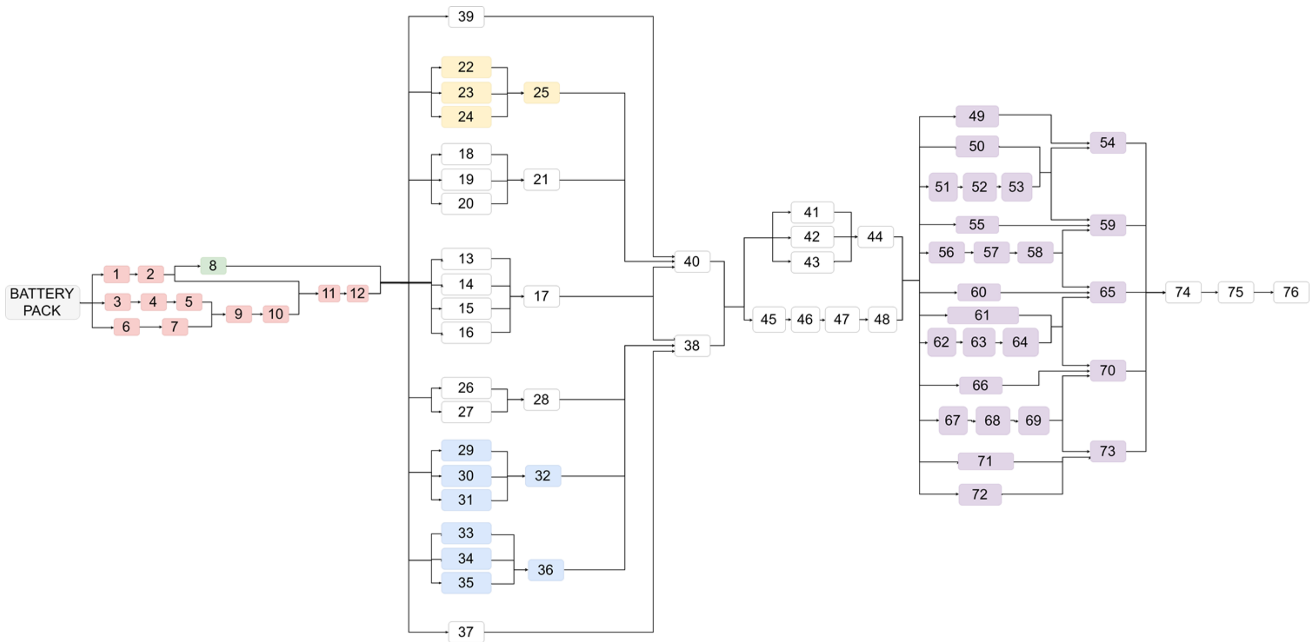


Figure 2: Toyota Prius 8.79kWh disassembly graph at pack level: red = covers removal block; green = service plug removal block; blue = junction removal block; yellow = BMS removal block; purple = modules removal block

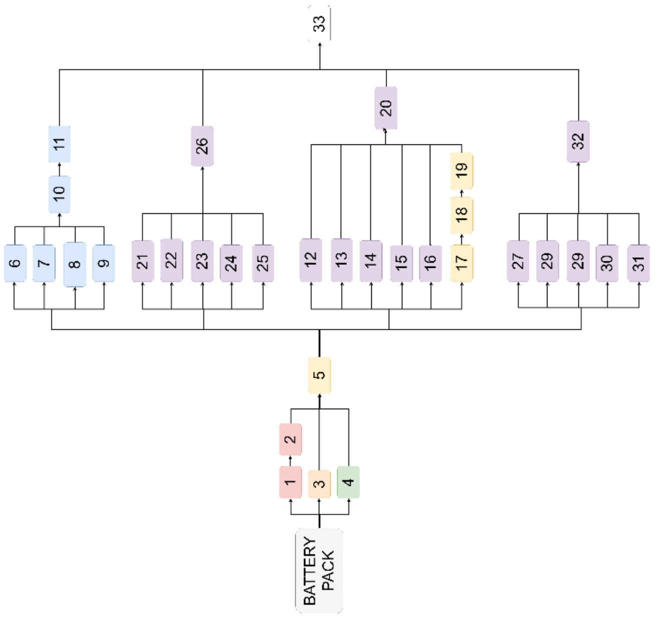


Figure 3: Chevrolet Volt 2nd Gen disassembly graph at pack level: red = covers removal block; green = safety fuse removal block; orange = coolant removal block; blue = junction removal block; yellow = BMS removal block; purple = modules removal block

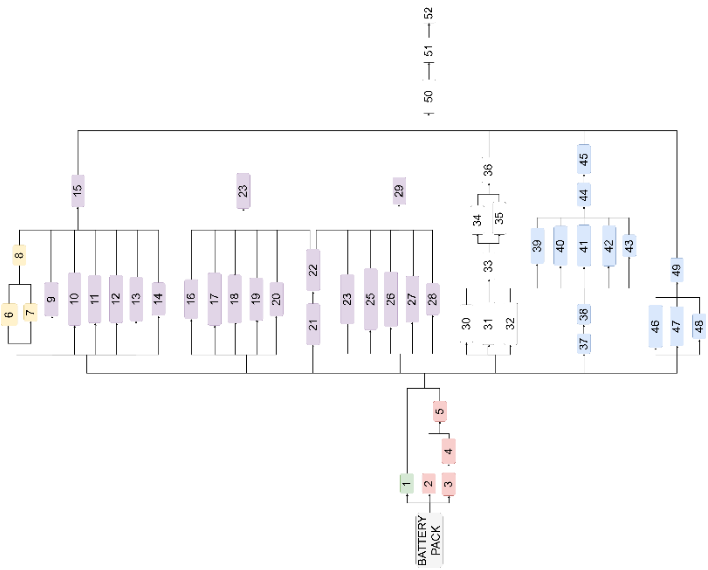


Figure 4: Nissan Leaf 24 kWh disassembly graph at pack level: red = covers removal block; green = service plug removal block; blue = junction removal block; yellow = BMS removal block; purple = modules removal block

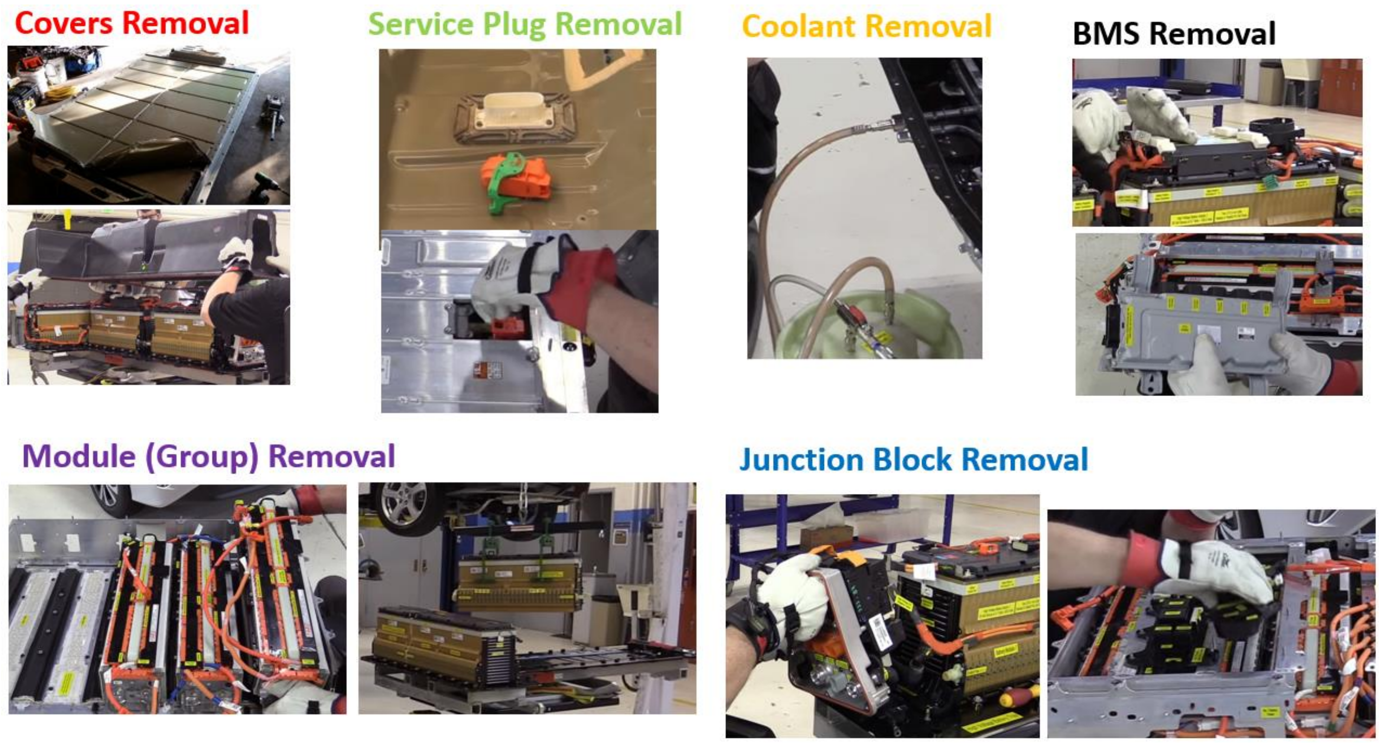


Figure 5: Battery pack disassembly blocks