Applied Energy 331 (2023) 120437

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Breaking it down: A techno-economic assessment of the impact of battery pack design on disassembly costs

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HIGHLIGHTS

- Detailed economic breakdown of electric vehicle battery pack teardown processes is presented.
- The difference in disassembly cost between battery pack designs varies up to 75%
- Reducing the number of modules and fasteners reduces the battery disassembly cost.
- Automated battery disassembly can achieve cost savings of up to US$190 M by 2040.

ARTICLE INFO

Keywords:
Electric vehicles
Battery pack design
Battery pack disassembly
Techno-economics
Circular economy

ABSTRACT

The electrification of the transport sector is a critical part of the net-zero transition. The mass adoption of electric vehicles (EVs) powered by lithium-ion batteries in the coming decade will inevitably lead to a large amount of battery waste, which needs handling in a safe and environmentally friendly manner. Battery recycling is a sustainable treatment option at the battery end-of-life that supports a circular economy. However, heterogeneity in pack designs across battery manufacturers are hampering the establishment of an efficient disassembly process, hence making recycling less viable. A comprehensive techno-economic assessment of the disassembly process was conducted, which identified cost hotspots in battery pack designs and to guide design optimisation strategies that help save time and cost for end-of-life treatment. The analyses include six commercially available EV battery packs: Renault Zoe, Nissan Leaf, Tesla Model 3, Peugeot 208, BAIC and BYD Han. The BAIC and BYD battery packs exhibit lower disassembly costs (US$50.45 and US$47.41 per pack, respectively), compared to the Peugeot 208 and Nissan Leaf (US$186.35 and US$194.11 per pack, respectively). This variation in disassembly cost is due mostly to the substantial differences in number of modules and fasteners. The economic assessment suggests that full automation is required to make disassembly viable by 2040, as it could boost disassembly capacity by up to 600 %, while substantially achieving cost savings of up to US$190 M per year.

1. Introduction

The automotive industry is rapidly moving towards electric mobility, replacing internal combustion engine vehicles with those powered by lithium-ion batteries – a decisive step towards a green transport sector. However, there are still a number of steps that need to be taken in order to make electric vehicles (EVs) a sustainable solution for clean mobility. Among those is the development of processes linked to the treatment of

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https://doi.org/10.1016/j.apenergy.2022.120437
Received 27 September 2022; Received in revised form 17 November 2022; Accepted 25 November 2022

end-of-life (EoL) battery packs, notably pack disassembly and recycling. It is projected that the annual global EV sales (not including plug-in hybrid vehicles) will increase from 2 million in 2020 to more than 14 million in 2030 [1]. Making a conservative assumption for an average battery lifetime of 10 years and no further second life use after the end of first life in an EV, this would mean that, by 2040, there will be at least 14 million EoL automotive battery packs that need to be dealt with, annually. This represents tonnes of critical and expensive raw materials, including lithium, nickel, cobalt and graphite, potentially going to waste in the coming decades.

Battery EoL management has therefore become an increasingly urgent topic, in both academia and industry, with a clear shift towards efficient EoL disposal strategies and the establishment of a circular economy [2–7]. In this context, EoL options such as repurposing battery packs in second-life applications (e.g. grid storage) and remanufacturing for their original application are being currently explored [8–11].

Eventually, batteries need to be disposed of. Here, battery recycling is a desirable solution as it avoids battery waste mountains with potential risks for health and the environment as well as allows to recover valuable materials including nickel and cobalt [5,8,12,13]. The three main recycling methods are pyrometallurgical, hydrometallurgical and direct recycling [5,8,14–18]. During the pyrometallurgical process, an alloy composing of nickel, cobalt and copper is formed via high-temperature treatments, whereas during the hydrometallurgical process the transition metal salts are recovered via leaching [19–22]. Direct recycling recovers the electrode materials without altering their structure [5,8,20,23,24]. These can then be implemented in a new battery after a re-lithiation step [5,8].

One of the first obstacles towards an efficient recycling process is the large variation in battery pack design across manufacturers, where the lack of standardisation hampers the streamlining of pack disassembly. Despite the importance of battery pack disassembly in the recovery of battery materials, information on pack disassembly processes and associated costs are still scarce in the current literature. Alfaro-Algaba *et al.* [25] offer a step-by-step manual disassembly process of the Audi A3 Sportback e-tron Hybrid, along with a model for disassembly planning of EV battery packs. The paper describes the ideal level of disassembly (i.e. either to module or cell level) and processing method for different states of health of the battery. Rallo *et al.* [26] present quantitative information for the cost of manual disassembly of the Smart ForFour pack, while Bogue *et al.* [27] illustrate the growing role robots are having in the disassembly and recycling industries. A battery disassembly time comparison between manual and automatic disassembly of a small single module battery is proposed in a study by Zhou *et al.* [28], which highlights the large percentage of time saved by automation.

A still existing important knowledge gap in the current disassembly literature is an in-depth comparative techno-economic assessment of the battery disassembly process across various battery pack designs. To the best of our knowledge, the study presented here is the first to provide a comprehensive comparison of the disassembly costs of six commercially available EV battery packs. These include the Renault Zoe (2019), Nissan Leaf (2018), Tesla Model 3 (2020), Peugeot 208 (2020), BAIC BJEV EU5 (2020) and BYD Han (2020). Here, the automotive benchmarking database, A2Mac1 [29], was used to gather detailed information on the battery pack designs and teardown processes. This allowed for the derivation of disassembly procedures and associated disassembly times and costs.

Disassembly cost is particularly a concern in high-labour-cost countries, especially in light of the significant progress in transport electrification and hence the expected substantial demand for retired EV battery treatments [30]. To inform policy makers, industries and stakeholders specifically on domestic EoL capacity building and to outline opportunities on how to reduce disassembly costs (i.e. automation and robotics) in a local context, the geographic boundary of this study was set to the UK as a representative case.

Contrasting the disassembly cost of battery packs from different OEMs, cost-intensive design features are identified, and lessons can be learned from more cost-efficient pack designs. Based on the obtained results, this study suggests alternative design options and enables OEMs to develop future battery packs optimised for disassembly. This will enable a more streamlined disassembly and recycling process and ultimately support a circular economy. In addition, this study provides an exhaustive cost projection of manual, semi-automated and automated disassembly until 2040, emphasizing the necessity of automation for the coming decades. Ultimately, this paper will serve as a reference for battery disassembly and recycling businesses on how to achieve a profitable disassembly process.

2. Methods

For this study, the A2Mac1 database [29] is used to derive battery pack disassembly processes. The A2Mac1 database is unique, as it provides detailed insights into a large number of commercial EV battery packs, from pack down to module and cell level, based on teardown processes performed on those packs. This detailed information in turn increases the accuracy of the disassembly cost assessment. The study presented here analyses the following EV battery packs:

- Renault ZOE R135 Edition One 2019
- Nissan Leaf Tekna 2018
- Tesla Model 3 Standard 2020
- BAIC BJEV EU5 Jing Cai R500 ZhiFeng 2020
- Peugeot 208 e GT 2020
- BYD Han EV ZunGui 2020.

These EVs present a breadth of battery architectures spanning across five major car manufacturers which, together, cover a little more than a third of the global Plug-in EV market [31]. In 2020, the Renault Zoe was the bestselling EV in Europe, followed closely by the Tesla Model 3 (2nd), the Peugeot e-208 (6th) and the Nissan Leaf (7th) [32,33]. In China, BYD and BAIC constitute the leading and 4th largest OEMs respectively [34,35]. Globally, in 2021, the Tesla Model 3 came first in EV sales while the BYD Han placed 7th [36]. Hence, the results obtained in this paper emanate from a wide range of currently commercially available electric vehicles, which are likely to make up a sizeable part of battery packs reaching end-of-life in the years to come.

Characteristics such as energy density, specific energy and weight of the assessed battery packs are given in Table 1. Images of the details of the battery pack designs and the materials of the structural components are given in Figures SI1-6 as obtained from the A2Mac1 database [29].

For each of these battery packs, a detailed disassembly process from pack to cell level is established. Included in the disassembly analysis are the number of screws, welded parts and the number of parts that need to be removed by hand such as wire harnesses, hoses and clips. In addition, the number of tool changes needed throughout the disassembly process is considered to assess the efficiency of each pack design, as well as their suitability for semi-automated and automated disassembly. Each disassembly step is associated to one of four categories: 1) chassis and battery safety, 2) electronic and electric system components, 3) dismantling of other battery parts and 4) separation of modules. The time needed to unscrew, unweld or remove parts by hand ($t_{unscrewed}$; $t_{unwelded}$; $t_{hand\ removed}$) is calculated according to Equations (1a)-c, respectively. Manual disassembly times are assumed to be 40 s for the removal of welded components, 14 s for the removal of a screw and 6 s for hand removed components (Table 2). This ensures that total disassembly time remains in accordance with results found in EV battery pack disassembly literature [26,28]. Equations (1a)-c further consider the sum of those parts across the pack ($\sum i_x$) and the efficiency factor ε, which reflects whether the process is conducted manually or by robots (Table 2). Here, it is assumed that robots are ca. 85 % more efficient than workers, as derived from Zhou *et al.* [28]. The cost to disassemble screwed and welded parts

Table 1
Data sheet of assessed battery packs.

Vehicle	Energy (kWh)	Cell energy density (Wh/l)	Cell specific energy (Wh/kg)	Number of modules	Number of cells	Weight (kg)
Renault Zoe	52	567	262	12	192	327.9
Nissan Leaf	40	445	219	24	192	304.3
Tesla Model 3	52	690	244	4	2,976	327.4
BAIC BJEV	51	488	223	5	90	368.1
Peugeot 208	50	538	239	18	216	344.2
BYD Han	77	335	168	pack-to-cell	178	573.9

Table 2
Input parameters for Eqs. (1)–(8).

Parameter	Input value	Unit	Reference	Comment
$\mathbf{t_{unscrewed}}$	0.0038	hr		14 secs
$\mathbf{t_{unwelded}}$	0.011	hr		40 secs
$\mathbf{t_{hand\ removed}}$	0.0016	hr		6 secs
$\mathbf{i_x}$	see Table SI1	pieces		Number of screws, welded parts and hand removed parts
ε	1 (human) 0.1461 (robot)	–	 [28]	Efficiency factor
$\mathbf{C_{labour,UK}}$	24.88	US$/hr	[37]	
$\mathbf{C_{robot,CAPEX}}$	200,000	US$	[39,40]	
$\mathbf{C_{robot,\ maintenance}}$	14,000	US$	[41]	Maintenance over 5 years
$\mathbf{j_{operation,year}}$	8,760	hr		Operating time per year
σ	0.5	kW	[42]	Average power consumption
$\mathbf{C_{electricity,UK}}$	0.2	US $/kWh	[43]	Average electricity cost
τ	5	years		Robot service life
$\mathbf{R_{pack}}$	0.15	US$/kg		
$\boldsymbol{\omega}_{\mathbf{pack}}$	300	kg		
$\mathbf{N_{EoL}}$	see Fig. SI7	pieces		EoL battery packs predicted

or to remove them by hand ($C_{manual,unscrewed}$, $C_{manual,unwelded}$, $C_{manual,hand\ removed}$) is calculated according to Equations (2a)-c. The total disassembly cost per pack taking into account all three disassembly modes is calculated using Equation (2d). The labour cost, $C_{labour,UK}$, for a manufacturing engineer in the UK is assumed to be US$24.88/h, as of 2021 [37]. It is assumed that a disassembly plant operates 365 days per year, 24 h per day.

$$C_{semi,pack}(\$/pack) = \frac{(C_{robot,CAPEX} + C_{robot,operation} + C_{robot,maintenance})}{\sum N_{disassembled,life}} + \left(t_{handremoved}{}^{*}\sum i_{hand}{}^{*}C_{labour,UK}\right) \tag{3}$$

The same method is applied for the calculation of semi- and fully automated disassembly costs per pack, $C_{semi,pack}$ and $C_{full,pack}$ (Eqs. (3) and (4)). The KUKA LBR robot, which is fitted with integrated torque sensors, is used as an example of a disassembly robot capable of performing precise disassembly tasks [27,38]. Assumed end-of-arm tooling includes grippers, screwdrivers and sockets, the latter two being fitted for the respective screws and nuts. It is assumed that the robot arm contains one single tool, which would need to be changed between changing disassembly steps e.g. between removing a screw and a nut. For the semi-automated process, it is assumed that disassembly robots dismantle all fasteners except for hand removable parts, with the latter being handled by workers (Eq. (3)). For the fully automated procedure, it is assumed that robots perform the entire disassembly (Eq. (4)). The cost for the automated disassembly is approximated via the sum of the purchase price for the robot, $C_{robot,CAPEX}$, and the lifetime maintenance and operation costs, $C_{robot,maintenance}$ and $C_{robot,operation}$, divided by the number of battery packs disassembled by one robot over its service life, $N_{disassembled,life}$. $C_{robot,operation}$ is derived from the average power consumption, σ, the UK electricity price, $C_{electricity,UK}$, and the total amount of operating hours during the service life (yearly operating hours $j_{operation,year}$ multiplied by lifetime τ; Eq. (5)). $N_{disassembled,life}$ is calculated taking into account the total amount of operating hours during the service life, τ, divided by the disassembly time per pack, $t_{disassembly,pack}$ (Eq. (6)). The number of packs disassembled per year by one workstation, $N_{disassembled,year}$, is derived from the operating hours per year $j_{operation,year}$ and the disassembly time per pack, $t_{disassembly,pack}$ (Eq. (7)). Further, the number of required workers, robots or hybrid workstations required to disassemble all packs in a given year, $N_{workforce,year}$, was calculated according to Equation (8). N_{EoL} refers to the number of EoL packs in a given year (Fig. SI7). All input parameters to the equations are found in Table 2.

$$t_{disassembly,unscrewed}(hr/pack) = t_{unscrewed}{}^{*}\varepsilon^{*}\sum i_{unscrewed} \tag{1a}$$

$$t_{disassembly,unwelded}\left(\frac{hr}{pack}\right) = t_{unwelded}{}^{*}\varepsilon^{*}\sum i_{unwelded} \tag{1b}$$

$$t_{disassembly,handremoved}\left(\frac{hr}{pack}\right) = \sum t_{handremoved}{}^{*}\varepsilon^{*}\sum i_{handremoved} \tag{1c}$$

$$C_{manual,unscrewed}(\$/pack) = t_{disassembly,unscrewed}{}^{*}C_{labour,UK} \tag{2a}$$

$$C_{manual,unwelded}(\$/pack) = t_{disassembly,unwelded}{}^{*}C_{labour,UK} \tag{2b}$$

$$C_{manual,handremoved}(\$/pack) = t_{disassembly,handremoved}{}^{*}C_{labour,UK} \tag{2c}$$

$$C_{manual,pack}(\$/pack) = C_{manual,unscrewed} + C_{manual,unwelded} + C_{manual,handremoved} \tag{2d}$$

$$C_{full,pack}(\$/pack) = \frac{(C_{robot,CAPEX} + C_{robot,operation} + C_{robot,maintenance})}{\sum N_{disassembled,life}} \tag{4}$$

$$C_{robot,operation}(\$) = \sigma^{*}C_{electricity,UK}{}^{*}j_{operation,year}{}^{*}\tau \tag{5}$$

$$N_{disassembled,life}(packs/lifetime) = \frac{j_{operation,year}}{t_{disassembly,pack}}{}^{*}\tau \tag{6}$$

$$N_{disassembled,year}(packs/year) = \frac{j_{operation,year}}{t_{disassembly,pack}} \tag{7}$$

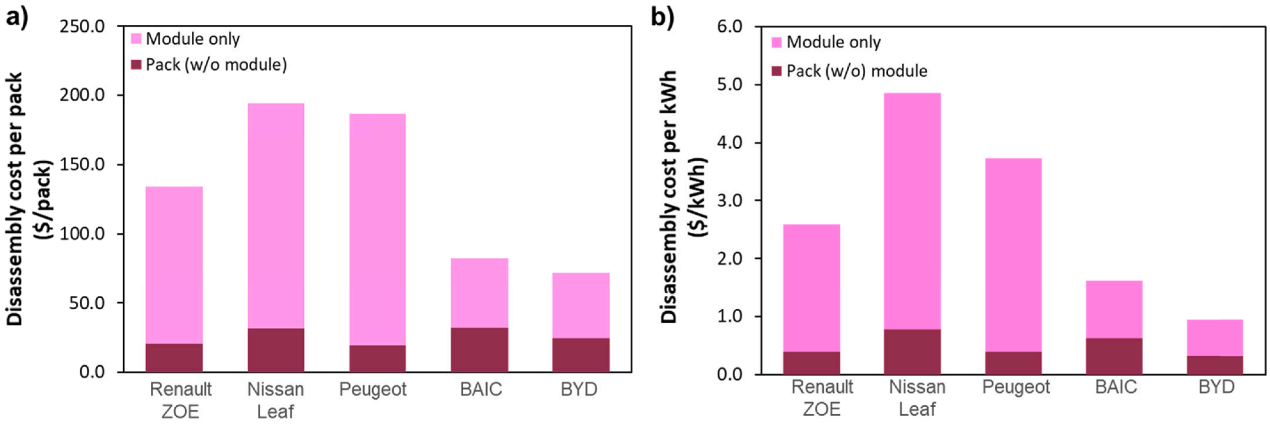

Fig. 1. Disassembly cost (in US$) per pack (a) and per kWh (b) from pack to module level (purple bars) and module to cell level (pink bars) using manual disassembly. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

$$N_{workforce,year} = \frac{N_{EoL}}{\sum N_{disassembled,year}} \tag{8}$$

3. Results

3.1. Disassembly cost

a) Disassembly from pack to module level: The calculated disassembly times and associated cost from pack to module level for the assessed commercial battery packs are shown in Fig. 1 (purple bars). The highest disassembly costs per pack were obtained for the BAIC (US$31.86/pack; US$0.62/kWh) and Nissan Leaf (US$31.24/pack; US$0.78/kWh), followed by the BYD (US$24.59/pack; US$0.32/kWh) and Renault ZOE (US$20.30/pack; US$0.39/kWh). The least cost-intensive disassembly processes are obtained for the Peugeot 208 (US$19.41/pack; US$0.39/kWh) and Tesla Model 3 (US$15.59/pack; US$0.30/kWh). The results are summarised in Tables SI1 and SI2. Note that, on a kWh basis, the BYD pack was the second cheapest to disassemble.

To identify the most cost-intensive battery parts to be dismantled, the disassembly cost was further broken down into the following categories: *chassis and safety*, *electronics*, *module separation* and *other components* [44]. The contribution of each category to the total disassembly cost is shown in Fig. 2. It can be stated that no trend could be derived across the various battery packs and that, due to the large differences in pack design, each pack has its own cost hotspots. *Chassis and safety* is the hotspot for BYD, Renault Zoe and Tesla Model 3. *Electronics* is difficult to deal with in Nissan Leaf and Peugeot 208, the latter having also a high contribution of *module separation*. The disassembly cost of the BAIC pack spreads evenly across categories.

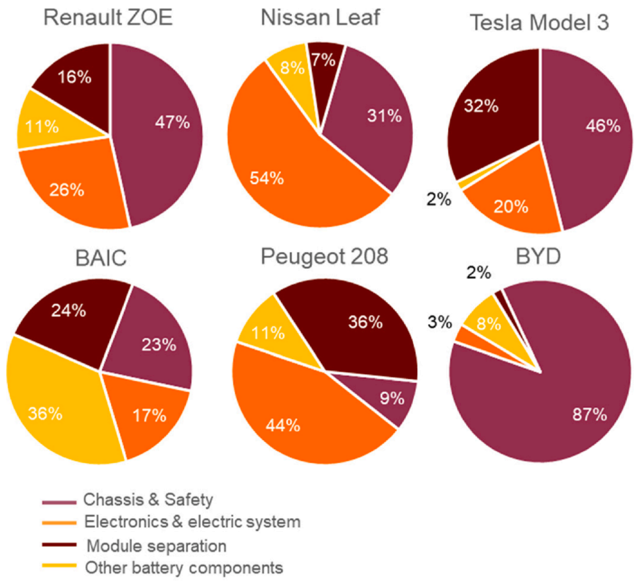

Fig. 2. Contribution of pack design categories to the total disassembly cost.

The inhomogeneity in cost contribution in turn makes it difficult to establish a generalised cost optimisation strategy. Instead, each pack needs to be optimised individually to reduce the respective disassembly costs. The BYD pack, for example, uses 206 of the overall 222 screws at pack level for the *chassis and safety* components, with the largest part used for the pack enclosures. If the number of screws was decreased and/or partially replaced by alternative fasteners, such as clips, without compromising stability and safety, the overall disassembly time and cost could be reduced. The Nissan Leaf pack, on the other hand, would need to be optimised for its *electronics* components, with a focus on the reduction of bus bars (discussed in more detail in Section 3.1d).

b) Disassembly from module to cell level: In a next step, the disassembly process from module to cell level was assessed. Again, the number of screws, hand-removed parts and welded components was derived. Details are summarised in Table SI1, together with the disassembly time and cost per module and total disassembly time for all modules. Note that the Tesla Model 3 was omitted in this step of the analysis since no details on the debonding method of the strong structural glue (polyurethane) [45] and the cell separation process for this pack could be found. In general, debonding techniques for structural adhesives can include thermal treatment and solvents, but ultimately the debonding method will vary as a function of composition and application of the adhesives [45].

With respect to disassembly times per module, the BYD takes by far the longest time to dismantle (114 min). This is due to the large number of welded cells. The fastest module to disassemble is the Nissan Leaf (16.4 min), even though it has the highest number of screws per module (62) across all packs. However, the avoidance of welding makes this pack more advantageous.

Looking at the disassembly time for all modules, the trend changes. Indeed, the BYD comes out as the best battery pack (114 min) as it has no actual modules (pack-to-cell design), resulting in a disassembly cost for all modules of US$47.41/pack; US$0.62/kWh. The Nissan Leaf and Peugeot 208, on the other hand, take the longest to dismantle (392.6 min and 402.5 min, respectively), with disassembly costs of US$162.88/pack or US$4.07/kWh for the Nissan Leaf and US$166.94/pack or US$3.34/kWh for the Peugeot 208. This can be explained by the large number of modules in the Nissan Leaf and Peugeot 208 (24 and 18, respectively). The cost of module-to-cell disassembly is shown in Fig. 1 (pink bars).

c) Total disassembly cost: The total disassembly cost per pack, from pack down to cell level, as calculated from Equation (2d), is shown in Fig. 1. In total, the BAIC (US$50.45/pack; US$1.61/kWh) and BYD (US $47.41/pack; US$0.94/kWh) battery packs have the most cost-efficient disassembly processes from pack to cell level, whereas the Nissan Leaf (US$194.11/pack; US$4.85/kWh) and Peugeot 208 (US$186.35/pack; US$3.73/kWh) are the most expensive ones (Tables SI1 and SI2). Compared to the Nissan Leaf, the disassembly cost per pack of the BAIC is reduced by ca. 75 %. This highlights the importance of an optimised pack design to achieve cost-efficient disassembly.

d) Discussion of design features for rapid disassembly: From the disassembly analysis, several cost-intensive design features have been identified. For instance, the costly disassembly of the Nissan Leaf pack can be explained by the excessive use of screws (322 pre-module disassembly, 1810 total), mostly due to the complex bus bar design. The bus bars are spread out across the pack and require, on average, 19 screws per bus bar compared to an average of six screws for all other component types. This design inefficiency is particularly apparent when comparing the share of disassembly costs by component type for the Nissan Leaf. While bus bars make only 1 % of the pack's total weight, electronic and electrical system components account for 54 % of the pre-module disassembly costs. The modules of the Peugeot 208 are similarly spread across the pack. Consequently, the pack requires 24 bus bars, which is more than twice as much as most other packs; the Tesla Model 3, for instance, only needs two bus bars.

Comparing the pack designs of the Nissan Leaf and Peugeot 208 to the Tesla Model 3 highlights the benefits of Tesla's linear design. Here, all bus bars are contained together in a "bus bar assembly" at one end of the pack. Not only does this reduce the number of screws for electronic components to 31, but also streamlines the disassembly workflow, making the overall process more time efficient. This is especially important for business models which repurpose EoL battery cells and packs, where partial disassembly and easy access to certain battery components is required. Packs will therefore need to be designed in a flexible manner, with components being easily interchangeable. Here, the Model 3's "bus bar assembly" is a good example, as it enables the disassembler to have quick access to the modules.

To decrease the number of screws, several alternatives have been identified in some of the examined battery packs. These could include straps for electronic components, as done in the Renault ZOE pack, clips or readily soluble or debondable adhesives.

To further reduce the overall disassembly time, the dismantling of the modules and cell separation need to be optimised. Those steps are important for direct recycling and repurposing strategies. Especially undoing welded parts is a time-consuming step. This is reflected in the high module disassembly times for the BYD, Peugeot 208 and Renault ZOE, with a high number of welded parts on cell level compared to the Nissan Leaf, which does not use welding at all. Here, potential alternatives could be wire bonding, debondable adhesives and clips [45–47]. An interesting design approach is the use of tape to hold cells together, as done in the BAIC, for instance. This avoids the use of strong structural adhesives such as used in the Tesla Model 3, for example, and makes it faster to tear the cells apart [45]. However, it should be pointed out that structural adhesives provide module and pack stability and thus improve the overall pack safety [48]. It is therefore crucial that the overall pack safety is carefully assessed for each specific pack, when alternatives to structural adhesives are implemented.

Further, the number of modules in a pack significantly impacts the overall disassembly costs. Even though the Nissan Leaf module is the quickest to dismantle, its 24 modules per pack increase the overall disassembly time, resulting in the highest disassembly cost amongst the studied battery packs. The BYD pack structure is especially interesting, as it does not have modules like other designs, but instead, uses the so-called "blade cells", therefore having a direct pack-to-cell hierarchy (as opposed to a pack-to-module-to-cell one). Therefore, although the BYD pack is slow to open, since there is no further need to disassemble modules, it comes out the most time- and cost-efficient, overall. Similarly, the BAIC, with only five modules, has a low total disassembly cost. This shows that limiting the number of modules, or even avoiding them altogether, if possible, will positively impact disassembly costs.

An additional obstacle towards a streamlined disassembly process needs to be highlighted at this stage, namely the large number of required tools and associated tool changes (Table SI3). The highest number of tool changes was counted for the BAIC and Peugeot, for instance. One issue is the use of different types of fasteners and screws. Tool changes require time and add unnecessary cost. Moreover, looking towards an automated disassembly process, which is discussed in more detail in the following section, tool changes and the use of a variety of tools further complicate the process. For instance, a KUKA LBR robot requires approximately 1 min for a tool change, which decreases the overall disassembly efficiency and capacity of a disassembly plant [28,38,42]. Here, the standardisation of screws and fasteners can make the dismantling process more time- and cost-efficient.

The design features which are the most cost-intensive, from a disassembly perspective, and their potential alternatives are summarised in Table 3. In addition, risks to pack safety and stability that could occur from the pack modifications are indicated.

To account for rapid evolution in battery pack design and associated uncertainties for future disassembly cost developments, a sensitivity analysis was conducted on the BAIC BJEV pack. The BAIC BJEV was chosen as an example, since it has the lowest disassembly cost amongst packs having a traditional cell-module-pack set up (in contrast to the BYD Han). For the sensitivity analysis, the number of modules, screws, hand-removed and welded parts was separately increased and reduced by 50 %, respectively, and the impact on the total manual disassembly cost was evaluated. The time and cost of disassembly were calculated according to Equations 1 and 2. Fig. 3 depicts the change in disassembly cost for the various design modifications and the values are summarised in Table SI4. It can be stated that to further reduce the cost of the BAIC BJEV in the future, the biggest impact can be made by decreasing the number of modules and screws. This can lead to disassembly cost reductions up to 24.3 % and 29.7 %. On the other hand, reducing the number of hand-removed parts has only a minor impact on the overall disassembly cost. Note, that this sensitivity analysis is specific to the BAIC BJEV and that for other battery packs, depending on the base case, the trend might be different. However, using this kind of analysis can be a powerful tool for battery OEMs to decide on the best cost optimisation strategy for a pre-defined battery pack.

Table 3
Summary of cost-intensive battery pack design features, design alternatives and potential risks associated with the pack modifications.

Cost-intensive design features	Alternatives	Potential risks
High number of screws	Straps, clips, adhesives	Potential compromise of pack stability and safety; safety assessment by manufacturer required
Welding	Wire bonding, adhesives (thermoplastics) and clips	
Structural adhesives (e.g. epoxy resin in Tesla)	Readily debondable adhesives, tape adhesives (e.g. BAIC)	
Complex design; electronic components (bus bars) spread across pack	Linear design; similar components bulked together (e.g. Tesla)	No potential risk identified
High number of modules	Reducing number of modules (e.g. BAIC, BYD)	Loss of compartmentation; potential risk of thermal propagation in case of thermal runaway
Different tools and often tool changes	Standardise screws and fasteners	No potential risk identified

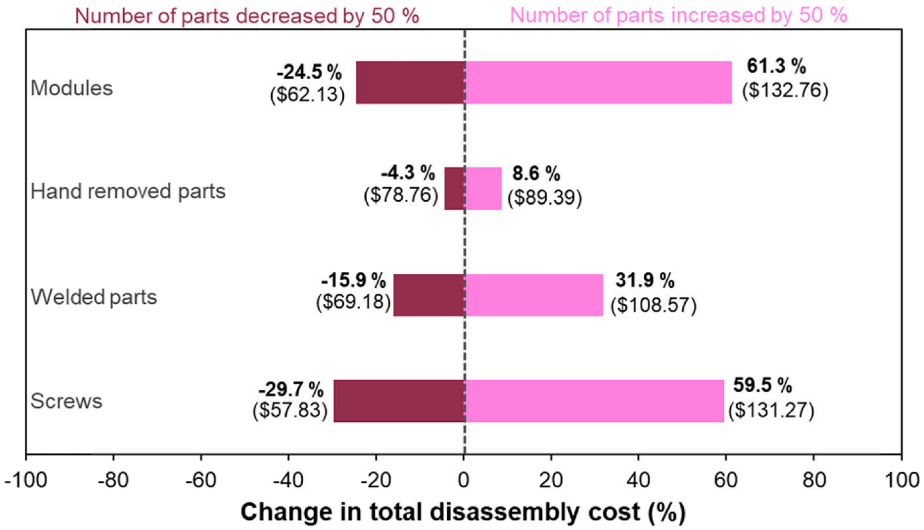

Fig. 3. Sensitivity analysis of the total disassembly cost as a function of the number of fasteners and modules of the BAIC BJEV. The change of disassembly cost is given in %. The number of parts is increased (pink bars) and decreased (purple bars) by 50 % with respect to the original number of parts as given in Table SI1. The grey dashed line indicates the base disassembly cost (US$82.31). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.2. Automation of the disassembly process

The results discussed above assume purely manual battery pack disassembly. However, in the future, automated disassembly processes might be introduced to increase efficiency and reduce costs, as well as to minimise safety risks for technicians, associated with the handling of EoL battery packs. It is therefore crucial to be able to predict the impact of automation on the cost of disassembly ($C_{semi,pack}$ and $C_{full,pack}$).

Fig. 4a compares the disassembly times per pack of a semi- and fully automated disassembly process to a manual one, as calculated according to Equation (1a)-(1c). It can be seen that by moving from manual to a semi-automated process, a time saving up to 78 % can be achieved and a further 10 % by moving onward to a fully automated process. This, in turn, reduces the labour cost of the disassembly process by 76–87 % (*e.g.* US$134.3/pack to US$23.4/pack for a Renault Zoe) for a semi-automated process and by 97 % for a fully automated process (Fig. 4b, c). The results are summarised in Table SI5.

The costs and cost savings calculated here refer only to the labour cost contribution of the disassembly process. The total cost and profitability of battery disassembly depend on a variety of factors, including capital costs, operation and maintenance costs, administrative fees, materials costs, revenue, etc., which are not included in this analysis.

It was recently proposed by Thompson *et al.* that to be economically viable to recycle a US$100/kWh battery, total recycling costs would need to be in the region of US$2–6/kg [7]. This study did not, however, include disassembly or labour costs. Taking a Nissan Leaf as an example, the disassembly costs for a manual process in the UK would add US $0.64/kg to the total recycling costs, whereas an automated process would add only US$0.02/kg. The reduced disassembly cost could thus affect the recycling profitability.

The reduced disassembly times shown in Fig. 4a will, in turn, increase the overall disassembly capacity of a disassembly facility. This is crucial given the steep increase of predicted EoL battery packs (N_{EoL}) to up to more than 14 million worldwide, annually [1]. Since the geographical boundary of this study is the UK, in the following analysis, N_{EoL} equals the amount of EoL battery packs available in the UK. The annual UK EV sales will reach 1.4 million by 2030, which means that in 2040, 1.4. million EoL battery packs will need to be dealt with (assuming a battery lifetime of 10 years) (Fig. SI7) [49]. The annual disassembly capacity of one worker, hybrid workstation or robot ($N_{disassembled,year}$) was derived based on the disassembly times for a manual, semi- and fully automated process, respectively, and the yearly operating time (Eq. (7)). The disassembly capacities for the three processes are shown in Figure SI8 and are summarised in Table SI6. On average, the number of disassembled battery packs per year increases from 1,918 for a manual process, to 7,829 and 13,129 for a semi- and fully automated disassembly process, respectively, an increase of nearly 300 % and 600 %. Fig. 5a shows the disassembly costs in a given year. The results are further summarised in Table SI7. The cost is derived from the cost for one pack upscaled to the expected number of EoL packs. These numbers provide an outlook on the potential disassembly costs (labour and costs for robots) that disassembly and recycling facilities will face in the coming decades. Manual disassembly can lead to labour costs of almost US$200 M by 2040, while switching to a fully automated process can achieve cost savings of up to almost US$160 M for a hybrid process and $190 M for full automation in 2040 (Fig. 5b). The associated cost savings were calculated by subtracting the semi and fully automated pack disassembly costs, respectively, from the manual disassembly cost.

To be able to achieve full disassembly capacity, the amount of workforce $N_{workforce,year}$ needs to be matched to the number of EoL battery packs increasing the overall disassembly cost. To avoid high disassembly and recycling costs, it might thus seem preferable for disassembly/recycling facilities to export EV battery waste to countries with low labour costs for manual disassembly. However, it is difficult to monitor the working conditions in disassembly factories abroad, which creates a blind spot for inappropriate and unethical working conditions and potentially puts at risk the health and safety of the factory workers. Automation could help to prevent this, by significantly reducing the cost of disassembly in the UK. Figure SI9 shows the average number of workers, hybrid workstations and robots depending on the process (manual, semi- or fully automated) necessary to fulfil the yearly disassembly demand (Eq. (8)). It can be stated that whilst the number of hybrid workstations and robots rises only slightly, the number of workers increases significantly from ca. 250 in 2030 up to 3300 by 2040.

The techno-economic assessment of automated battery pack disassembly shows that automation can indeed decrease costs compared to manual disassembly. This, in turn, might lead to reduced gate fees paid to off-set expenses of the recycling facility or, in the best-case result, in a profitable EV battery recycling process. There are, however, still a number of problems that need to be ironed out for that to happen efficiently. First, the lack of linearity in the disassembly workflow for a majority of the packs is a hindrance, especially to the implementation of automated disassembly, as this requires several tool changes, which increases the disassembly time, for instance. Here, besides streamlining the pack design, also a multi-head tool arm for robots could be envisaged, which would shorten the time for tool changes [50]. Second, the lack of standardisation between battery packs requires the robot to be reprogrammed for different dismantling procedures, depending on the

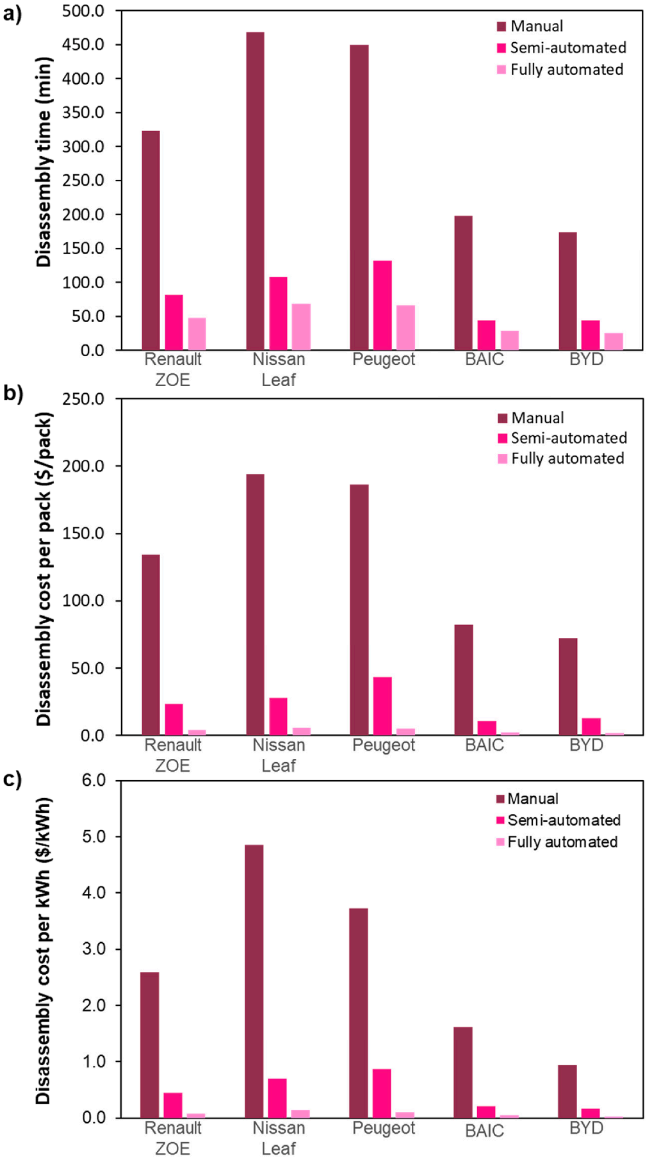

Fig. 4. Comparison of disassembly times (a), costs (in US$) per pack (b) and costs per kWh (c) for manual, semi- and fully automated disassembly processes for selected commercial battery packs.

pack manufacturer. Reprogramming the robots is time consuming and costly. Here, bar codes or QR codes could provide the robot with the battery pack model and the associated step-by-step teardown process [51]. This would allow for the same robot to disassemble multiple different packs in the same shift. Moreover, deep learning methods for the detection of fasteners by the robot could improve accuracy and time efficiency in the disassembly process [52].

4. Industry, research and policy implications

Improving the battery pack design is a joint effort between researchers, industry developments and policy support. The above-described findings imply that battery OEMs should strive towards the reduction of modules in the battery pack, as has been done in the BYD pack, for instance. Furthermore, current fasteners should be replaced with more efficient solutions, such as clip fasteners for cell, module and pack joining, to avoid lengthy unscrewing processes and the tearing apart of welded parts. Moreover, also the overall standardisation of screws is proposed. A streamlined pack design where similar parts are clustered, instead of being spread across the pack, will further facilitate a quick and easy disassembly process. The overall feasibility of suggested alternatives should be assessed by battery and car manufacturers and further optimised.

Research of various disassembly sequences, the understanding of general bottlenecks in the automated disassembly process, as well as the programming of the robots and improvement of their precision and speed is an important contribution towards the development of an efficient disassembly process. Also, the improvement of currently known structural adhesives with regards to their strength-solubility trade-offs is an important research direction, with regards to battery pack design and disassembly.

Current efforts to develop not only an efficient disassembly process but a recycling industry more generally need to be supported also by policy makers. This could include, for example, extended producer responsibilities that require battery OEMs to ensure the appropriate end-of-life treatment of their batteries either via second life applications or recycling. This could incentivise battery manufacturers to consider easy and cost-efficient battery disassembly in their design process to reduce the incurred costs at the end of the battery life. Moreover, legislations that require battery OEMs to label their packs with QR codes, which could be read by disassembly robots, will further support the disassembly process.

5. Conclusions

This paper is the first to present a holistic, techno-economic comparison of the disassembly process of several commercial EV battery packs. The assessed EVs include the Renault Zoe, Nissan Leaf, Peugeot 208, Tesla Model 3, BAIC and BYD. Based on detailed pack design information obtained from the A2Mac1 database, disassembly processes were established and associated disassembly times and costs were modelled. Overall, the Nissan Leaf (US$194.11) and Peugeot 208 (US $186.35) came out to have the highest disassembly cost per pack, whereas the BAIC (US$50.45) and BYD (US$47.41) battery packs were highly cost-efficient. The Tesla Model 3, while having pack design aspects that are beneficial, could not be fully analysed on module and cell level due to the lack of information on the handling of the structural adhesives. The numbers of screws, welded parts and modules in a pack contribute the most towards increasing disassembly cost. Here, efficient alternatives could include clip fasteners and debondable structural adhesives to minimse the number of screws and welded parts.

Further, the impact of automation in the disassembly process was analysed. Here, three scenarios were developed with a purely manual dismantling process, a hybrid semi-automated workstation (worker paired with one robot) and a fully automated process. Implementing an automated process decreases the labour cost of disassembly by 97 % per pack and significantly increases the annual disassembly capacity, which consequently might have an impact on the overall profitability of battery disassembly.

Note that while reduced disassembly costs can indeed decrease the overall recycling cost, ultimately the metal content in the cathode materials and the market price of the recovered materials (e.g. cobalt, nickel, lithium) will decide over the financial viability of EV battery recycling and materials recovery. Those factors including cell chemistry, recycling cost and revenue generated from recovered materials have not been included in this analysis, which puts the spotlight on the pack design and disassembly step of the recycling process. In addition, this study focused on the labour cost associated with the disassembly process. Other cost points, such as capital investment, administrative fees, interest fees etc. were out of scope of this study.

It is further worth mentioning that a limitation of this study is the safety aspect of the proposed design alternatives, especially with regards to adhesives and welding. Rigorous testing is required from OEMs to evaluate if those design options are viable, not only from a cost perspective, but also from a safety point of view.

Fig. 5. a) Disassembly costs (in US$) caused by dismantling the predicted amount of EoL battery packs in year 2030, 2035, 2037 and 2040. b) Cost savings (in US$) generated by shifting from manual to semi- and fully automated disassembly.

This study shows that pack design optimisation following the paradigm "design for disassembly" would have a significant impact on the time- and cost-effectiveness of disassembly processes and should therefore be more rigorously followed in early pack development stages. In addition, looking towards the future, automated disassembly will prove more financially viable. However, to achieve the full potential efficiency of automated disassembly, battery packs need to be optimised for a streamlined workflow. Furthermore, standardisation across packs of different manufacturers would reduce time losses and increase revenue from the disassembly process. As a next step, the manufacturing cost of those optimised battery packs for easy disassembly should be evaluated to ensure financial viability of those designs, not only at end-of-life but across the entire value chain.

CRediT authorship contribution statement

Laura Lander: Conceptualization, Methodology, Formal analysis, Writing – original draft, Funding acquisition. **Chris Tagnon:** Methodology, Formal analysis, Writing – original draft. **Viet Nguyen-Tien:** Writing – review & editing. **Emma Kendrick:** Writing – review & editing. **Robert J.R. Elliott:** Writing – review & editing. **Andrew P. Abbott:** Writing – review & editing. **Jacqueline S. Edge:** Conceptualization, Writing – review & editing, Supervision. **Gregory J. Offer:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

L.L., J.S.E., and G.J.O. would like to thank the Faraday Institution for their support through the 'Multi-scale Modelling (MSM)' project (Grant No. FIRG025). C.T. thanks the funding for his undergraduate research opportunity through the Mechanical Engineering Department at Imperial College London. Funding from the Faraday Institution project, ReLiB (Grant No. FIRG027), is also acknowledged.

Data availability statement

Access to the A2Mac1 database (https://www.a2mac1.com/) including images and battery pack information is restricted by license. All information relevant to this study is available in the main text and supporting information.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2022.120437.

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