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“Transport Batteryfication” Analysis of Pre-Recycling Phases of End-of-Life Electric Vehicle Lithium-Ion Batteries from an Irish Perspective

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“Transport Batteryfication”

Analysis of Pre-Recycling Phases of End-of-Life Electric Vehicle Lithium-Ion Batteries from an Irish Perspective

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Abstract

Transport plays a key role in maintaining the economic prosperity of our society. However, transport has remained reliant on fossil fuels, a main contributor to climate change. New EU and Government policies aim to decarbonise the transport sector through batteryfication by shifting to use of electric vehicles. The lithium-ion battery will underpin this strategy.

Lithium-ion batteries have a limited lifespan for automotive applications, this will bring new and unprecedented challenges for end-of-life waste management. The recent growth of electric vehicles is expected to continue exponentially which raises important questions on how to process this new waste stream.

This study investigates the recycling value chain surrounding end-of-life electric vehicle lithium-ion batteries and will highlight best practices of the pre-recycling phases of; safety, disassembly, storage, and transportation which will take place in Ireland

A mixed-methods pragmatic approach was undertaken for this research. To ascertain a holistic understanding of the entire electric vehicle value chain, engagement with wide-ranging interviewees from apprentice to director level from different organisations were conducted to gain varying perspectives.

The findings show that lithium-ion battery waste management is a highly complex field with many different strands still in its infancy. Proposed legislation and production plants will allow the EU to obtain a circular battery value chain in the near future. While all Irish stakeholders interviewed are currently readying themselves to manage this emerging technology. However, many different approaches are being taken.

The author concludes that to reduce the possibility of a serious accident occurring, electric vehicle stakeholders in conjunction with the National Standards Authority of Ireland should develop a standard for operatives working directly on these vehicles. This standard should be compulsory through a statutory regulatory scheme or legislation.

Declaration

I certify that this dissertation which I now submit for examination for the award of Master of Science in Sustainable Transport and Mobility, is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work.

This dissertation was prepared according to the regulations for postgraduate study by research of the Technological University of Dublin and has not been submitted in whole or in part for an award in any other third level Institute.

The work reported on in this dissertation conforms to the principles and requirements of the Technical University of Dublin guidelines for ethics in research.

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04/12/2021

Signature______________________________ Date_________________

Candidate

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Nomenclature and Acronyms

ADR	International Carriage of Dangerous Goods by Road
ATF	Authorised Treatment Facility
BEV	Battery Electric Vehicle
BMS	Battery Management System
BSI	The British Standards Institution
CAP	Climate Action Plan 2019
CCAC	Climate Change Advisory Council
CCPC	Competition and Consumer Protection Commission
CO_2	Carbon Dioxide
CSO	Central Statistics Office
DCCAE	Department of Communications Climate Action and Environment
DECC	Department of the Environment, Climate and Communications
DOE	US Department of Energy
DoT	Department of Transport
DTTAS	Department of Transport, Tourism and Sport
EC	European Commission
EC	European Commission
EEA	European Environment Agency
EGD	European Green Deal
ELVES	End-of-Life Vehicles Environmental Services CLG
ELVs	End-of-Life Vehicles
EoL	End-of-Life
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
EU	European Union
EV	Electric Vehicle
GHG	Greenhouse Gas
ICE	Internal Combustion Engine
IDIS	International Dismantling Information System
IEA	International Energy Agency
IMI	Institute of the Motor Industry
LCO	Lithium-cobalt-oxide battery
LFP	Lithium-iron-phosphate battery
LIB	Lithium-Ion battery (generic)
LMO	Lithium manganese oxide battery
MIT	Massachusetts Institute of Technology
NCA	Lithium-nickel-cobalt-aluminium oxide battery
NMC	Lithium-nickel-manganese-cobalt oxide battery
NSAI	National Standards Authority of Ireland
NTA	National Transport Authority
PHEV	Plug-in Hybrid Electric Vehicle
PPE	Personal Protective Equipment
RO	Research Objectives

SAE	Society of Automotive Engineers
SEAI	Sustainable Energy Authority of Ireland
SoC	State-of-Charge
SoH	State-of-Health
V2G	Vehicle-to-Grid
VRT	Vehicle Registration Tax
WEEE	Waste Electrical and Electronic Equipment
WEF	World Economic Forum
WHO	World Health Organization

1. BACKGROUND AND CONTEXT OF RESEARCH

1.1. Introduction, Summary and Context of Research

Transport plays a key role in maintaining the economic prosperity of a developed society. Traditionally, transport has remained reliant on fossil fuels for energy, which are one of the main contributors to global warming and climate change. To reduce the harmful effects of transport, government policy and legislation is encouraging a shift to zero-emission mobility by electrification of the transport sector.

Electric transport solutions are almost exclusively powered by the lithium-ion battery, which has a limited lifespan when used for automotive applications and as an increasing number of electric vehicles are commissioned on to the roads today, the future prospect of increased amounts of end-of-life waste batteries raises important questions of how societies will process this new waste stream.

1.2. Society, Transport and Climate Change

Industrialised societies have developed to ensure people can move about in the pursuit of goods and services, with transport and its infrastructure a key protagonist within this environment. Since the 1920s academics quantified that transport was a dominant factor in realising a society's economic pursuits (Weber, 1929). The literature since then has supported that a well-developed transport infrastructure is a fundamental facilitator for economic growth and prosperity within an economy (Banister and Berechman, 2000; McEachern, 2006; DTTAS, 2019).

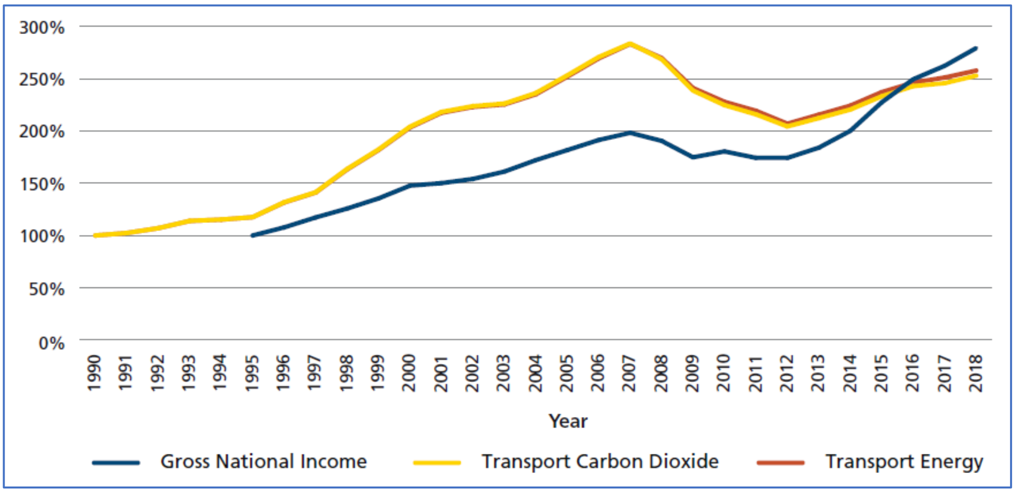
Development of industrialised societies has resulted in a concurrent rise in automobile ownership, with an existing global stock of 1.4 billion vehicles (Ghandi and Paltsev, 2020). The private vehicle allows freedom and autonomy, with many users depending on their vehicle during their daily routine. In Ireland, seventy four percent of the adult population use their car every day (CSO, 2021).

In contrast, automobiles also come with many negative externalities. These include but are not limited to; emissions, damage to the physical and natural environment, traffic accidents, congestion, reduced health levels, noise pollution, infrastructure damage and oil dependency (Parry *et al.*, 2007; Santos *et al.*, 2010).

Harmful exhaust gas emissions released from the internal combustion engine (ICE) through the burning of fossil fuels are having a detrimental impact on society. Nitrous oxides and particulate matter emissions are attributable to millions of premature deaths every year (Liang *et al.*, 2018; WHO, 2018), whilst carbon dioxide (CO_2), is a known greenhouse gas (GHG) and a principal cause of global warming (SEAI, 2020; Shaftel *et al.*, 2021).

The 2015 Paris Agreement is a legally binding, global consensus on climate change which aims to limit global temperature increases to below 2 degrees Celsius above pre-industrial levels. Ireland is a signatory of this agreement, and to meet its obligations the mitigation of GHGs is now at the forefront of the government's policy decisions. This has led to the 2021 Climate Action and Low Carbon Development Bill, a legislative framework to support Ireland's transition to reduce carbon emissions by half over the next decade and achieve net-zero by 2050, which has passed in both Houses of the Oireachtas (Government of Ireland, 2021).

Mitigating the effects of climate change will take far-reaching changes in how societies currently exist. The government's pledge to halve GHGs by 2030 is highly ambitious and challenging, and a feat that no modern economy has yet achieved. With regards to transport, decoupling it from economic growth is a balancing act between the needs of society, the needs of the economy and the needs of the environment. Failure to find a balance will present extensive negative consequences for future generations.



1.2.1. Electrification of Private Vehicles

The transport sector is currently dependent upon fossil fuels for its operation. In 2017, ninety-seven percent of Ireland's transport energy demand was fulfilled by crude oil products (DCCAE, 2019) meaning transport was Ireland's largest contributor of CO_2 emissions. The Sustainable Energy Authority of Ireland (SEAI), disclosed that transport accounted for forty percent of energy-related CO_2 emissions in 2018. This equated to over twelve million tonnes of CO_2 being released into the atmosphere (CCAC, 2020). Within the Irish transport sector, private cars were the largest emitters of GHGs (SEAI, 2020b).

The transport sector has been targeted within the 2021 Climate Action and Low Carbon Bill and the 2019 Climate Action Plan (CAP), as a key area where energy consumption can be reduced and GHGs reduced, using the 'avoid-shift-improve' hierarchy as outlined by the Climate Change Advisory Council (CCAC).

The 'avoid and shift' components within the hierarchy aim to lessen the use of the private car and encourage active mobility and public travel. The CCAC outline frameworks for efficient transport networks such as integrated spatial planning incorporating transit-oriented development. Large scale capital investments projects are already underway and seventy-million euro of funding was allocated to rural councils by the National Transport Authority in March of 2021 for active travel infrastructure, while various public transport improvements such as the Greater Dublin Area public transport capital programme, continue (NTA, 2021).

The 'Improve' strategy aims to progress the energy and carbon efficiency of vehicles through increased engine efficiencies, biofuel use and the employment of electric vehicles (CCAC, 2020). The ultimate goal of the Climate Action Low Carbon Bill and CAP, is to decarbonise Ireland's private and commercial transport fleet. The government have proposed legislation to ban the sales of internal combustion engine vehicles by 2030 to meet CAP objectives, while simultaneously increasing the amount of electric vehicles[1] (EV) on the road to over nine hundred thousand (DCCAE, 2019; Government of Ireland, 2020; Wall *et al.*, 2020).

Reaching the EV target within the next decade will present many infrastructure, monetary and behavioural challenges. The Minster for Transport declared "*…this target is very challenging but indicative of the scale of the transformation that is needed… if Ireland is to reduce national emissions and reach its legally binding emission ceiling…*" (Ryan, 2021). EVs currently

[1] CAP differentiates "Electric Vehicles" as a both; Battery Electric Vehicle (BEV) a pure electric powertrain and Plug-in Hybrid Electric Vehicle (PHEV) which is an ICE coupled with an electric powertrain.

constitute a small fraction of the two-point-seven million vehicles that make up the national fleet (CSO.ie, 2017; SIMI, 2021a), for instance as of July 2021, only forty-one thousand EVs were registered in Ireland (Taylor, 2021). The SEAI estimates, that EV sales will have to increase seventy-five percent per annum for the next decade, based on 2019 figures to meet the proposed targets.

This said, electrification or batteryfication of the transport sector is gathering pace. In 2021 Irish EV sales increased one-hundred and fifty percent on the previous year (SIMI, 2021a), while globally EV growth is increasing exponentially. During the first half of 2021, there was a one-hundred and sixty percent increase in global EV sales on the year previous, which amounted to an increase of over two and half million vehicles (Jones and Fitzpatrick, 2021).

Modelling EV growth based on current sales, technical enhancements, costs, future government policies and legislation, varies. Data from the International Energy Agency predicts global sales of forty-four million EVs by the end of the decade (IEA, 2019). Whereas, the World Economic Forum, estimates sales of thirty-four million within the same period (World Economic Forum, 2019). A report published by the European Commission has stated that the demand for EVs, and the lithium-ion batteries (LIB) that power them, is expected to "*sky-rocket*" by more than thirty percent per year until 2030 (Bobba *et al.*, 2020). Either way, all relevant data suggests a pendulum shift away from the ICE vehicles towards EVs.

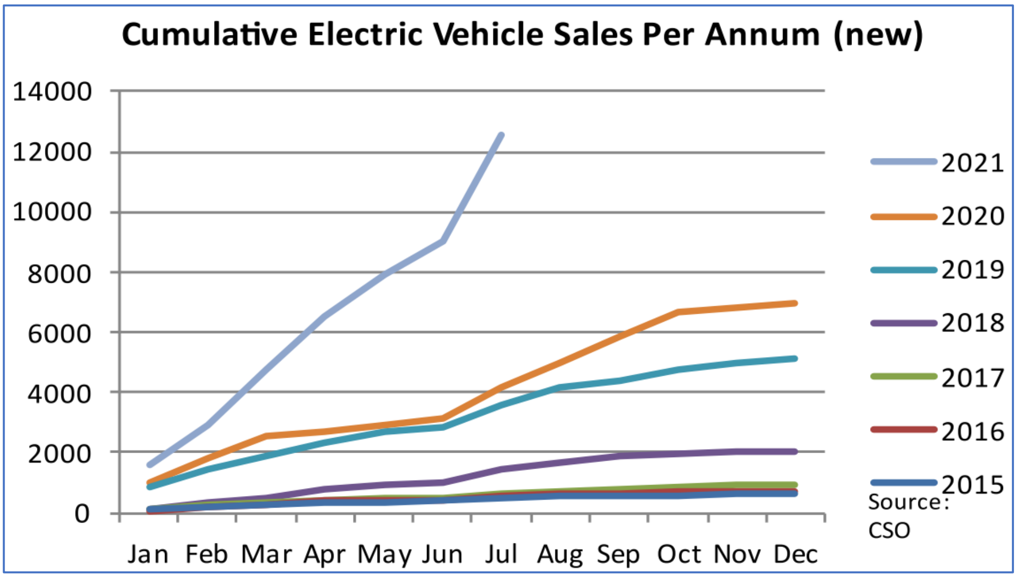


Figure 2: New annual registrations of electric vehicles in Ireland. (CSO, cited by DoT, 2021).

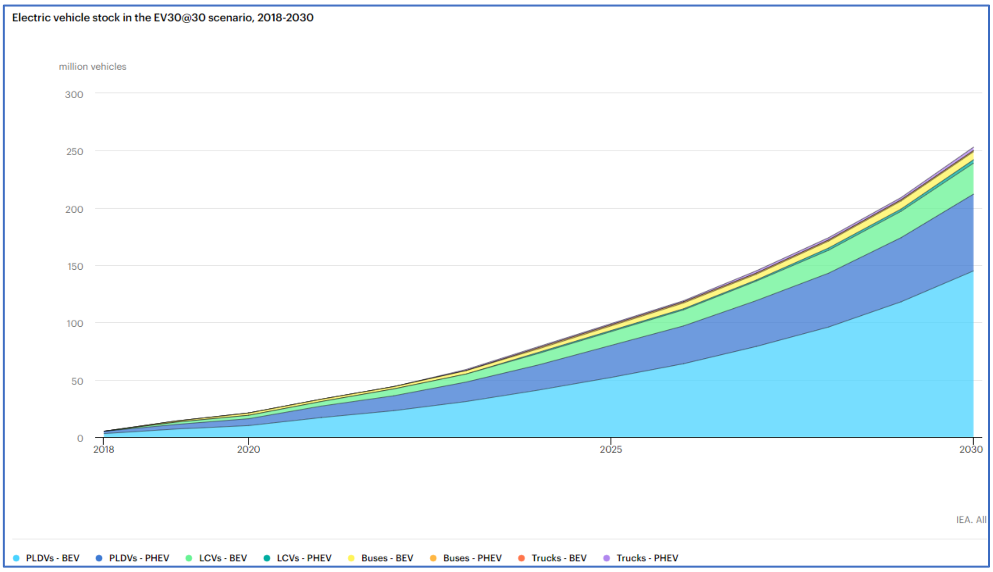


Figure 3: International Energy Agency global EV modelling outlook. Under the EV30@30 Scenario, EV sales reach 44 million vehicles per year by 2030 (IEA, 2019).

1.2.2. End-of-Life Electric Vehicles and their Batteries

The life expectancy of an electric vehicle will be largely determined by its battery. EVs extensively use a lithium-ion battery (LIB) as an energy source to power the traction motor (Beaudet *et al.*, 2020). LIBs are subject to chemical and physical processes known collectively as degradation, which limits their capacity or ability to hold a charge with time. Published literature varies on the estimated lifespan of an EV LIB, with estimates ranging from eight to thirteen years (Guenther *et al.*, 2013; Melin, 2020; Xiong *et al.*, 2020)

A key parameter that quantifies LIBs functionality, efficiency and performance is known as 'state-of-health' (SoH). SoH is the measure of the battery's capacity, in percent, compared to when it was initially manufactured. When new, the expected SoH is one hundred percent (Zubi *et al.*, 2018; Harper *et al.*, 2019).

Degradation is a natural characteristic of LIBs, whereby as the battery ages, its efficiency and capacity deteriorates from its initial condition (Bobba *et al.*, 2018; Hahn and Birke, 2019). As degradation transpires, a point is reached[2] based on the SoH, where the LIBs available capacity will no longer propel a vehicle (Bobba *et al.*, 2018; Zubi *et al.*, 2018; MIT, 2019). At this stage the battery is considered end-of-life (EoL) for automotive applications.

[2] Published literature commonly affirms, that when state-of-health of the battery is between seventy to eighty percent, it is considered end-of-life for automotive application (Tichelen *et al.*, 2019)

Vehicles that reach EoL should enter the appropriate recycling stream. EU directive 2000/53/EC legislates for end-of-life vehicles (ELVs), while EU directive 2006/66/EC is responsible for waste batteries and accumulators. Both directives aim to ensure that ELVs and their batteries, will have a minimal impact on the environment and not end up in municipal waste streams.

From Ireland's perspective, this legislation necessitates that pre-recycling phases of the recycling process, such as discharging and removal of the battery are carried out onsite. The LIB will then continue its journey along the recycling value chain. As EVs are relatively new to the market and few have reached EoL, it may be assumed that a skills gap surrounding the technology and hazards posed by LIBs exists.

Regardless of the estimated lifespan of an EV and their LIBs, the new technologies bring new EoL challenges. The expected market proliferation of EVs within the next decade will ensure that actors within the Irish ELVs domain, must ready themselves to work with the emerging technology in new ways.

1.2.3. European Green Deal, Electric Vehicles and the Circular Economy

The European Green Deal (EGD) was published by the European Commission (EC) in December 2019 and sets out the European Union (EU) commitment to tackling climate change, while also ensuring a prosperous resource-efficient society and economy (EC, 2019b). The EGD outlines a framework of both legislative and non-legislative proposals, with the ultimate goal of achieving climate neutrality within the union by 2050 (McLoughlin and Deane, 2020). The EGD is now central to the government's objectives, outlined within the 2021-2030 National Development Plan.

The EGD focuses on many areas from energy supply to taxation. For transport, a stated objective detailed is that transport emissions are reduced by ninety percent by 2050 (EC, 2019b). Electrification of the transport sector and an accelerated shift to zero-emission mobility is essential in delivering this goal. In parallel, a strategic industry action plan for batteries is advocated within the Green Deal. The EGD battery action plan demands an industry that provides a safe, circular and sustainable value chain for all batteries including the growing market of EVs. A proposed battery regulation to support the EGD is in the preliminary stages of the legislative process. Fundamental to the new legislation is the end-of-life management of EV batteries (EC, 2020d).

Central to the EGD policy is a move towards a circular economy. The EC stated that the EU's industry remains too 'linear', as only twelve percent of goods come from recycling (EC, 2019b). A new circular economy action plan was published in conjunction with the EGD prioritising reduction and reuse of materials before recycling them, and where waste cannot be avoided, its monetary worth should be recovered and its environmental impact lessened (EC, 2021).

Transport electrification is seen as a key enabler to allow the EU meet its objectives of becoming a climate-neutral circular economy. The EGD and its concurrent action plans, affirm that batteries are a key tool in this transition. The EC, having stated that batteries are of 'strategic importance' (EU, 2021b), are proposing a legislative framework to ensure a battery's life-cycle becomes a circular process. This will ensure new challenges for all stakeholders within the industry, including EoL management.

1.3. Research Question, Purpose and Objectives

1.3.1. Research Question

"A research question is a question that provides an explicit statement of what it is the researcher wants to know about" (Bryman, 2012, p. 9).

Based on the context outlined in section 1.1 to 1.2.3, the author will research the recycling value chain surrounding end-of-life (EoL) electric vehicle (EV) lithium-ion batteries (LIB).

The author's specific area of study is to analyse the pre-recycling phases of; safety, disassembly, storage, and transportation of EV LIBs within the recycling process, from an Irish perspective.

1.3.2. Purpose of the Research

EV LIB pre-recycling phases are particularly important steps within the recycling process, as they are the first phases in moving batteries away from a linear to a circular value chain. The establishment of a circular value chain for EV batteries will have both environmental and economic societal benefits. It is also a key objective within European Green Deal, to necessitate a prosperous society and competitive economy, that is decoupled from resource use (European Commission, 2020b).

From an Irish context these steps are also significant, as the pre-recycling phases will take place in Ireland before the batteries are shipped to Europe for recycling or second use. Therefore, it is of great importance that all actors within the Irish EV domain are fully aware of the issues surrounding pre-recycling that will transpire as traction batteries reach their EoL, and are fully equipped to deal with the expected proliferation as Irelands fleet becomes electrified.

1.3.3. Research Objectives

The objectives for the author's area of study are twofold. As far as the author is aware there is no published literature in relation to the proposed topics of pre-recycling EV LIB from an Irish viewpoint, while EV battery recycling topics as a whole in Ireland, are also understudied. Internationally there is a plethora of literature surrounding EV LIB recycling, however common areas of study generally focus on the technical aspects of battery recycling efficiencies, and not solely pre-recycling.

The author's initial literature review revealed a knowledge gap with regards to the outlined pre-recycling themes. The proposed dissertation research findings will add knowledge to the area which is presently in need of further study.

The author is aware of the significant personal health and safety risks associated with EV LIBs. These hazards demand study, understanding and awareness from all stakeholders within the EV field. They are of particular importance to technicians and transporters, who will be directly involved in the pre-recycling phases of EV LIBs, yet there are few academic papers pertaining to this area. From the dissertation findings, the author proposes to present a best practice methodology regarding the safety aspects of pre-recycling operations.

Research Objectives (RO)	
RO1	Identify and analyse electric vehicle lithium-ion battery recycling methods.
RO2	Appraise the current domain for end-of-life electric vehicle lithium-ion batteries in Ireland.
RO3	Evaluate and assess national and international end-of-life electric vehicle lithium-ion battery pre-recycling practices.
RO4	Identify and discover Ireland's electric vehicle lithium-ion battery recycling barriers and enablers, if any.
RO5	Formulate a health and safety best practice methodology for pre-recycling operations of end-of-life electric vehicle lithium-ion batteries.

Table 1: Primary research objectives.

2. LITERATURE REVIEW

2.1. Introduction

The purpose of this study is to investigate the recycling value chain surrounding the end-of-life (EoL) electric vehicle (EV) lithium-ion battery (LIB), and suggest a best practice methodology for pre-recycling operations thereof, from an Irish perspective.

Before undertaking the data investigation, the author carried out a literature review of previous research on the subject. The objective of the literature review was to provide the author with a background contextual understanding of the entire process surrounding EV battery recycling. Pertinent literature was critically analysed in order to obtain an in-depth comprehension of the topic before a concept of investigation was considered.

2.2. Electric Vehicle Market and End-of-Life Batteries

Numerous studies have demonstrated and quantified the environmental benefits of EVs when compared to Internal Combustion Engine (ICE) vehicles (Nykvist, Sprei and Nilsson, 2019; Ortar and Ryghaug, 2019). Furthermore, if EVs can be charged with renewable energy, additional decarbonisation can be achieved (Sharma and Strezov, 2017).

For these reasons, EVs have become a cornerstone for governments globally, who have committed to reducing their emissions and seek to decarbonise their transport systems. One of the major announcements from COP26 in Glasgow 2021, was the prioritisation of sustainable transport. This led to thirty countries comprising the world's largest automotive markets, agreeing to make zero emission vehicles more accessible, affordable and sustainable in all regions by 2030 (United Nations, 2021).

The global transition to EVs is already well underway. Exponential growth in the sector over the last number of years, has led to the global number of EVs on the road surpassing ten million for the first time in 2020 (Fleischmann *et al.*, 2021). This growth will eventually translate into an increase in EoL EV LIBs, which will in-turn require treatment through processes of waste management. Models predict, that one million spent EV LIBs will require treatment in 2030, with this number rising to one-point-nine million by 2040 (Chen *et al.*, 2019).

2.3. Introduction to the Lithium-ion battery

The advancement of consumer electronics in the 1980s necessitated the need for a more suitable power source. Established rechargeable batteries at this time consisted of lead-acid, nickel-cadmium and nickel-metal hydride types, however their use was limited as their energy density corresponded to their size and weight (Yoshino, 2014). Research commenced to provide a suitable battery for the growing electronics market. This led to the development of the rechargeable lithium-ion battery (LIB), and commercialization was first achieved by Sony Corporation in 1991 (Yoshino, 2014; Marinaro *et al.*, 2020; Sony, 2021).

The benefits of the LIB when compared to other available battery systems are many. Mossali *et al.* (2020) state the advantages being high energy density and low atomic weight, low self-discharge rate and high recharge cycle rate. Fill (2019) accentuated upon their greatly improved safety, longevity and reliability aspects, while Kraytsberg and Ein-Eli (2012) stress the high voltage, high capacity and design flexibility of the LIB as its major advantage.

Yoshino (2014, p.5), emphasise the importance of cost, stating that *"LIBs have historically achieved an astonishing level of price reduction…The achievement of such a low price…made LIB affordable for medium and large-scale applications such as electric vehicles and storage batteries for residential use"*.

These characteristics have led to the LIB becoming the dominant energy source not only for portable electronics, but more recently for the electric vehicle and stationary grid storage markets globally (Placke *et al.*, 2017; Birke and Schweitzer, 2019).

The basic structure of a LIB as illustrated in Figure 4, is typically comprised of four principal components; cathode, anode, electrolyte and separator (Dunn, *et al*. 2011). The LIB charging and discharging cycle is a reversible process because the anode and cathode electrodes allow for the release and storage of lithium. Internally, a separator prevents short circuits between the anode and cathode, whilst allowing an electrolyte solvent mixture to carry positively charged lithium-ions from the anode to cathode and vice versa in a chemical process known as intercalation (Kraytsberg and Ein-Eli, 2012; Yoshino, 2014; Chen *et al.*, 2021). As the lithium-ions move, free electrons are formed which generate a charge, thus allowing the LIB to power electrical consumer products (U.S. Office of Energy, 2017).

Noteworthy here, is the difference between primary and secondary lithium battery types. Primary lithium batteries are non-rechargeable that may be found in small electronic devices such as a vehicle remote central locking keys or digital watches, whereas secondary lithium batteries are rechargeable batteries typically found in laptops and EVs (Horn *et al.*, 2019). Secondary lithium batteries used in EVs may also be referred to as 'industrial batteries', as denoted within framework documents of the European Union (EU) and European Commission (EC) (EC, 2020c)

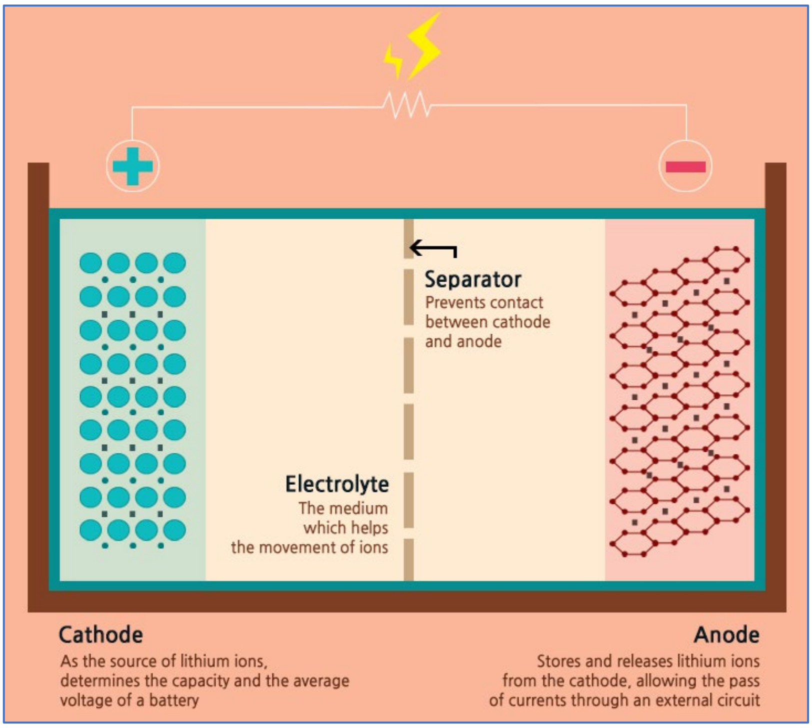


Figure 4: Four major components of a lithium-ion battery cell: 1. Cathode, 2. Anode, 3. Separator and 4. Electrolyte (SAMSUNG SDI CO, 2016)

2.4. Overview of the Electric Vehicle Lithium-ion Battery

The EV LIB battery pack is of a modular design, which denotes that it's fundamental elements are mechanically independent of one-another, but work together as a whole (Arora and Kapoor, 2018). Saw, Ye and Tay (2016) affirm that EV battery packs, as illustrated in Figure 5, are typically described by three different levels; the cells, the module pack and the battery back. The individual lithium-ion cells are connected together to create the module pack, each module pack has their own monitoring and thermal management components. The module packs are then linked to form the single high-voltage battery pack which can then power the EV traction motor.

Figure 5: Modular design of a Nissan Leaf lithium-ion battery pack: 1.Pouch cell, 2. Module pack and 4. EV battery pack (Adapted image; Nissan Motor Corporation, 2018)

2.4.1. Cathode Materials

There are a wide range of LIBs available in the market, from small consumer electronics to larger-scale transport and grid storage applications. However, the type of LIB is dependent on the cathode chemistry and each class will have different performance attributes as shown in Table 2. Manthiram (2020) observes, that out of all the elements involved in the make-up of a LIB, the positive cathode currently limits the energy density and dominates the battery cost.

Cathode material	Specific capacity [Ah/kg]	Average voltage [V]	Energy density [Wh/kg]
LCO ($LiCoO_2$)	145 - 160	3.9	566 - 624
NCA ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$)	180 - 200	3.7	666 - 740
NMC ($LiNi_xMn_yCo1_{-x-y}O_2$)	160 - 170	3.7	592 - 629
LMO ($LiMn_2O_4$)	100 - 120	4.1	410 - 492
LFP ($LiFePO_4$)	160	3.4	544

Table 2: Characteristics of commercialized cathode materials (Elwert, Hua and Schneider, 2019).

The different cathode chemistries determine the amount of precious metals within the battery and this will directly affect the recycling process, from both a technical and economic standpoint. As an example, for batteries with high quantities of cobalt, the pyrometallurgical recycling method, is technically straightforward and economically viable. However, for LIBs with lesser cobalt amounts, the separation and extraction process is more complicated and costly (Melin, 2019). Various finite materials are combined within the LIB cathode collector, these can include; Manganese (Mg), Lithium (Li), Cobalt (Co), Nickel (Ni), Aluminium (Al) and Iron (Fe) (Placke *et al.*, 2017).

The chemical make-up of the cathode will denote the commercial name of the LIB (Table 2). As an example, lithium-cobalt-oxide cathodes (LCO battery) are commonly found in mobile phones and laptops. Cells in LCO batteries may contain up to twenty percent cobalt, which is the most valuable element in a LIB (Melin, 2019; Zeng *et al.*, 2019).

Zubi *et al.* (2018) and Melin (2019) point out that four different LIB cathode chemistries currently dominate the EV market: lithium-iron-phosphate (LFP), lithium-manganese-oxide (LMO), lithium-nickel-manganese-cobalt-oxide (NMC) and lithium-nickel-cobalt-aluminium-oxide (NCA). LFP batteries see popular use in Chinese EVs and electric buses and contain no cobalt which reduces the cost of the battery, however this also limits the range of the EV (Rathi, Murray and Dottle, 2021). LMO batteries were used in first generation EVs such as the Nissan Leaf, although they were commonly used in conjunction with NMC batteries. Today, it is the NMC along with NCA batteries that have become the dominant LIB chemistry for EVs in Europe and the United States. Both NMC and NCA contain cobalt quantities of between two and six percent (Wentker, Greenwood and Leker, 2019). Depending on the recycling process used, all of the cathode elements mentioned have the potential to be recovered.

2.4.2. Cell Design

LIB cell designs come in varied shapes and sizes. Within the automotive industry, three types have been commercialised as shown in Figure 6; cylindrical cell, prismatic cell and pouch cell (Birke and Demolli, 2019). The vehicle type and required performance will determine which cell type a manufacturer will gravitate towards, however Warner (2014) notes that there is currently no consensus between EV manufacturers on the optimal cell type.

Manufacturers connect single lithium-ion cells in series and parallel configurations to form a module pack which are then connected with bus bars to from an EV battery pack (Arora, Kapoor and Shen, 2018). A Tesla model S battery pack for example, is comprised of over seven thousand NCA cylindrical cells which are assembled into sixteen modules and joined to form a single pack (Saw, Ye and Tay, 2016; Harper *et al.*, 2019). Whilst a Nissan Leaf uses four pouch cells per module and combines forty-eight modules within its battery pack (Milojevic *et al.*, 2021). The BMW i3 LIB employs ninety-six prismatic cells contained in eight modules for its battery pack (Miri, Fotouhi and Ewin, 2021).

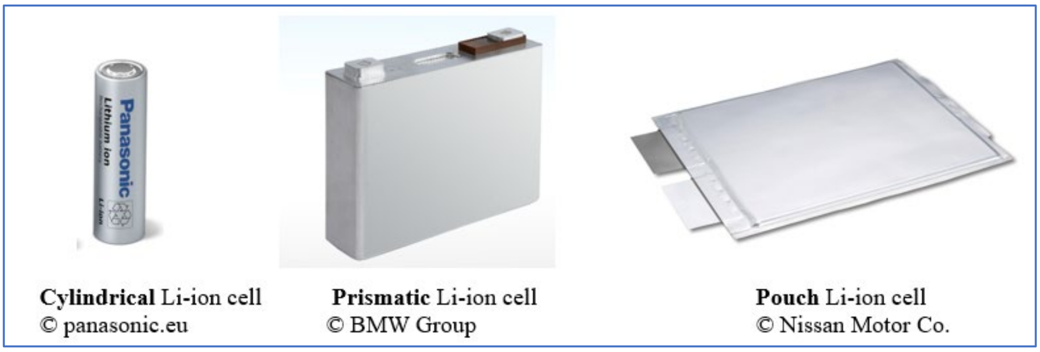


Figure 6: Lithium-ion cell types used within electric vehicle module battery packs. Cylindrical, Prismatic and Pouch type Li-ion cells (Adapted images; Panasonic, BMW, Nissan)

The different lithium-ion cells present different recycling challenges. Harper *et al.* (2019) asserts that the epoxy resin used to bond the cylindrical cells is difficult to remove or recycle, whilst the physical make-up of their module packs also presents problematic issues for dismantling, especially if direct recycling is desired. Prismatic cells require special tooling to open them and the pressure inside the cells creates an additional hazard. The pouch cell used by Nissan presents the fewest technical challenges for recyclers, however due to the high manganese content within, it makes the reclamation less profitable.

Other elements found within the LIB to consider in the recycling process are copper, graphite, carbon and steel, generally used for the current collectors and negative anode. The battery casing may contain aluminium, stainless steel and various plastics, while the electrolyte can also be extracted and recycled for reuse in new batteries and other manufacturing processes, if economic to do so (Gaines, 2014; Elwert *et al.*, 2016).

2.4.3. Electric Vehicle Battery Pack

The design and location of an EV LIB pack must also be considered, as removal of the battery pack is a principal step in the recycling process. EV LIB packs will generally contain four key components; the battery cells, battery management system (BMS) electronics, a thermal management system and the mechanical structure (Elwert *et al.*, 2016; Bolsinger, Berner and Kai, 2019). Warner (2014) observes that EV battery pack architecture is mainly influenced by the type of lithium-ion cell used. This is because, the cell type will determine the mechanical structure of the battery modules, the BMS type, the thermal management system, and the overall packaging.

In addition, Warner states that the battery pack design will also vary depending on vehicle architecture and crucially whether the specific vehicle was an originally-designed EV or an ICE vehicle that was retrofitted to become an EV. For example, the Volkswagen e-Golf was designed as an ICE vehicle and later converted to an EV by Volkswagen, whereas their ID range is a ground-up designed EV (Volkswagen AG, 2019). This leads to two differently designed battery packs as illustrated in Figure 7, which present different challenges for removal. This example is not specific to only Volkswagen, and is a common practice with all automotive manufactures.

Figure 7: Different battery pack designs. e-Golf - a retrofitted EV, versus ID. - a original designed EV (Volkswagen, 2021).

As there is currently no standard EV battery pack design, complications arise when recyclers need to remove the battery packs, which is currently a manual task carried out by trained personnel (Harper *et al.*, 2019; Rastegarpanah, Gonzalez and Stolkin, 2021). Gaines (2014) remarks, that if EV battery packs were designed for EoL recycling, with removal measures standardised, the recyclability of the batteries would be greatly improved. Norgren *et al.* (2020) counter-argue this, saying that because an EV battery is specific to particular manufacturers, its recyclability will be improved as only trained personnel will attempt removal, which enhances overall safety and control standards during the recycling process.

The differences and variation of EV LIB packs also limits the possibility of automating battery pack removal using robotics (Wegener *et al.*, 2015). A Harper *et al.* 2019 paper in *Nature* outlines examples of automated recycling processes for LIBs and indicate the benefits as enhanced safety for recycling operators and time efficiencies. Automated systems currently in use by recyclers are largely for specific small consumer electronic batteries. Apple for instance has set up an automated recycling disassembly line where robots can dismantle iPhones into parts (Vonk, 2018). Harper *et al*. do discuss the possibility of ‘collaborative human-robot co-working’ which allows a human operator to share a workload using a new generation of force-sensitive robotic arms, which are currently being used in other industries, but the removal of an EV battery pack is a predominantly a manual process carried out by skilled workers.

2.4.4. Summary: Electric Vehicle Lithium-ion Battery

The EV industry is continually developing its batteries to achieve greater capacity to improve range, reduce charging times and increase longevity to meet consumer demand whilst simultaneously trying to drive down their manufacturing costs. This has led to several types of varying battery pack designs, cell types and chemistries available in today’s market that is constantly evolving.

The assorted EV LIB in use have made the recycling process highly complex and cathode chemistries largely determine the economic value of LIB reclamation. This poses a difficulty for the recycling industry as different recycling methods are required dependent on the cathode. For example, pyrometallurgical recycling (smelting) is economically viable for NMC or NCA batteries as they contain cobalt and / or nickel in the cathode. However, pyrometallurgical recycling is not suited for LMO or LFP batteries as they contain no cobalt or nickel, so direct recovery recycling is cost-effective and worthwhile for these batteries (Gaines, 2018).

A further consideration for recyclers is the speed at which the industry is advancing. The NMC is one of the most common LIB used in EVs today, yet it was only invented and the patent filed in 2001 (M. Li *et al.*, 2018). Presently, researchers are focusing on cell chemistries, in particular on lessening the precious metal content and thus, cost. Cost and sustainability become critical in the large-scale deployment of EVs, and Manthiram (2020) states that concerted efforts are underway to make cobalt free batteries. In conjunction with evolving cell chemistries, new types of LIB such as, solid-state and lithium-air batteries are being forecast as next generation technologies (Mizuno, Yada and Iba, 2014; Toyota Ireland, 2021). Conversely, this leads to more multifaceted cathode chemistries and increased variation of batteries types, which elicits more taxing and complex recycling methods that may be economically inefficient for recyclers in the future (Wang *et al.*, 2014).

2.5. Lithium-ion Battery Degradation

The life expectancy of an electric vehicle will be largely determined by the life expectancy of its battery and due to the chemical and physical characteristics of LIBs, they degrade naturally with age (Bobba *et al.*, 2018). Hahn and Birke (2019, p.141) confirm, stating that, "*battery aging in general has revealed itself to be inevitable*".

Edge *et al.* (2021) note that LIB degradation is a complex issue, affected by multiple factors such as chemical composition, calendar ageing, usage and cycle-life (number of charge-discharge cycles). They affirm that the degradation process is not obvious physically, as it occurs within the battery cell, however its most noticeable effects are realised only when the usable capacity and power of the battery diminish.

The LIBs state-of-health (SoH) is a measure of the battery's usable capacity and power at a given time compared to when it was new (Zubi *et al.*, 2018). This key parameter quantifies the LIBs functionality, efficiency and performance against its usage time. Literature varies, however most research suggests that automotive EV LIBs reach their end-of-life when the SoH drops to between eighty and seventy percent (Bobba *et al.*, 2018; Skeete *et al.*, 2020; Kamran, 2021). At this point, the EV LIB is no longer able to propel a vehicle efficiently. The time taken for a LIB to reach end-of-life status is difficult to predict, as competing factors will influence the SoH degradation. Studies suggests the estimated lifespan of a EV LIB is anywhere between eight to thirteen years (Hahn and Birke, 2019; Skeete *et al.*, 2020; Xiong *et al.*, 2020).

2.6. Waste management and Electric Vehicle Batteries

Worrell and Reuter (2014) define recycling as, the recovery of materials from end-of-life products, that are then reprocessed and returned to the supply chain. They assert that recycling is now critical for our society, as the current linear economy is at its limits, due to the enormous demand for materials, driven by an increasing population.

Waste management hierarchy may vary, however in general terms the following basis exists;

1. Prevention or avoid (preferred option)
2. Reuse the product
3. Recycle
4. Energy recovery
5. Treatment, disposal and landfilling (last resort)

(Worrell and Reuter, 2014; Cole et al., 2019)

Figure 8: Waste hierarchy (EC, 2020c)

Waste batteries and accumulators cannot be disposed of in municipal landfill because of the environmental hazard posed. The EU Batteries Directive 2006/66/EC regulates for the collection and recycling of batteries. The Directive has ensured a highly successful recycling rate of lead-acid automotive batteries, with one-point-four million tonnes recycled in the EU in 2018 (EUROSTAT, 2021). EU Eurostat reporting currently makes no distinction on EV batteries, therefore statistics are not available on the amount of EV LIBs entering the EU waste stream.

EV batteries will pose a significant waste problem in the near-to-medium future. However, there is significant possibility that EoL EV LIBs can help with further decarbonisation due to second use in the energy sector, which is discussed in section 2.7.

Once EV batteries reach EoL after reuse, they will represent a valuable source of materials. A World Economic Forum model (2019) shows that if half of the LIBs expected to reach EoL in 2030 were recycled, it would provide seven percent of global materials required for battery production. Recycling of EV LIBs is currently in its infancy, with no large scale operation yet underway (Melin, 2019). However, many researchers, companies and high-level institutes, are working to ensure EoL EV LIBs will have a life-cycle that is circular through new recycling approaches and legislation.

2.7. Reuse of Electric Vehicle Lithium-ion batteries

EV LIBs have great potential with regards to reuse and second life. Various automotive manufacturers can currently repair and reuse their EV batteries (Warner, 2014). The modular design of the battery pack and the battery management software, as presented in section 2.4.3, allows for faulty modules to be identified and replaced. However, it should be noted this is currently a specialist repair (Denton, 2016; IMI, 2019).

When EV LIBs reach their EoL for automotive use they can potentially assume a second life as a stationary grid storage battery. Kamran, Raugei and Hutchinson (2021) note that repurposing EV LIBs will allow transport to become more sustainable with respect to lessening energy demand. Repurposed LIBs will also reduce demand for materials, as the amount of new storage batteries required will be reduced.

In Ireland, the SEAI are also aware of the significant value EoL EV batteries pose and are funding research in the area. They note that a removed EV battery is a valuable asset, which could allow emergency backup for the provision of additional electricity storage for the national grid (SEAI, 2021).

A report from the European Environment Agency (2018, p 49) reaffirms this, citing that EoL EV batteries "*offer significant circular economy opportunity through their second-use applications, especially in energy storage systems*". The report outlines how LIBs are particularly suited for integration with renewable energy systems as they facilitate storing of intermittent energy (wind and solar), which allows better management during supply and demand spikes. This sentiment is echoed in a number of academic journals, including papers by, Hesse *et al.* (2017), M. Li *et al.* (2018), and Dehghani-Sanij *et al.* (2019).

2.8. Recycling Electric Vehicle Lithium-ion Batteries: Introduction

Currently the main focus of EV LIB recycling methods is largely driven by market value of the precious metals within the battery (Wang, Gaustad and Babbitt, 2016). Within the EU, the value of the recovered materials from an EV LIB, is often less than the labour required to process the material. Drabik and Rizos (2018) argue that this leaves no business case for recycling EV LIB at present. Whilst Velázquez-Martínez *et al.* (2019) outline that LIB recycling methods are extremely 'resource-intensive', and their viability is therefore firmly influenced by economic constraints.

Yet the assessment by these academics has not deterred a number of commercial businesses from setting up facilities in the EU, U.S. and Asia, in anticipation of the upsurge in EoL EV LIBs to come. The EU has stated that a sustainable battery value chain including as showing in Figure 9, of design, manufacturing, second use, recycling and disposal within a circular economy context, is a '*strategic imperative*' for Europe in the context of its clean energy and clean mobility transition (EC, 2018).

Although commercial recycling of EV LIBs is still within its developmental stage (Gaines, Richa and Spangenberger, 2018), the expected market growth of EVs and their associated need for environmentally and economically sustainable raw materials, will ensure a major expansion within the EV LIB recycling industry. This expansion is already happening with battery manufacturing plants popularly termed 'Gigafactories' presently under construction in Stockholm (Northvolt) and Berlin (Tesla), which will include in-house recycling facilities (Lambert, 2021; Northvolt, 2021). Ortiz and Careaga (2021) affirm, that plans have been announced for the development of twenty battery manufacturing plants in the EU over the coming years, and although not all will have the capacity to recycle LIBs, it can be assumed that EV LIB recycling facilities will develop in parallel.

Recycling an EV LIB is challenging. Complex cell chemistry, diverse battery pack design, lack of standardisation, absence of identification labelling, safety hazards, shortage of skilled workers, environmental risks, coupled with inadequate recycling infrastructure are just some of the considerable barriers involved. Yet researchers, regulatory authorities and industry are readying themselves for the challenges to come, as the expansion of EVs continue.

There are two main recycling methods currently employed by commercial enterprise; pyrometallurgical or hydrometallurgical processing.

The pyrometallurgical process sees the EV batteries fed into high-temperature furnaces, where the valuable metals are reduced to a mixed alloy which can be processed to recover the individual metals elements for reuse. Pyrometallurgical recycling is a relatively straightforward and proven process and has the advantage that it can accept different battery chemistry types (Beaudet *et al.*, 2020). However Gaines (2019) notes that the economic viability of the pyrometallurgical process depends on the recovery of the cobalt, and manufactures are actively reducing the cobalt content levels within their batteries.

In the hydrometallurgical recycling process, the batteries are shredded. Metal foils are then screened for recovery, which leaves a black mass. The black mass is then treated with acids and solvents to extract the cathode metals as salts, which can then be reused for making new cathodes (Gaines, 2019). This process is already operational in large-scale commercial enterprises in Asia, where capital costs are lower, although its mainly used for consumer electronic LIBs (Gaines, 2019; Melin, 2019). A small number of state-of-the art facilities are operating commercially in the EU and U.S. for EV LIB recycling (Harper *et al.*, 2019). Although hydrometallurgical material recovery is a more complicated process when compared to pyrometallurgical, it can extract more usable materials, with some companies claiming they can recover up to ninety-five per cent of the base components from a spent EV LIB (Lithion Recycling, 2019).

A third recycling option gaining traction, but still in the non-commercial developmental stage is direct recycling. With direct recycling, the battery's cathode materials are recovered in close to usable form using a physical extraction process, meaning they can then be used directly for the production of new battery cathodes with minimal intervention (Sloop *et al.*, 2020). Gaines (2019) states that direct recycling has the potential to be economically viable for batteries with low-value cathodes. The direct recycling process also lends itself to recycling at a smaller scale, which will benefit local plants with reduced infrastructure and transport costs while also improving the overall environmental credentials of the LIB life-cycle.

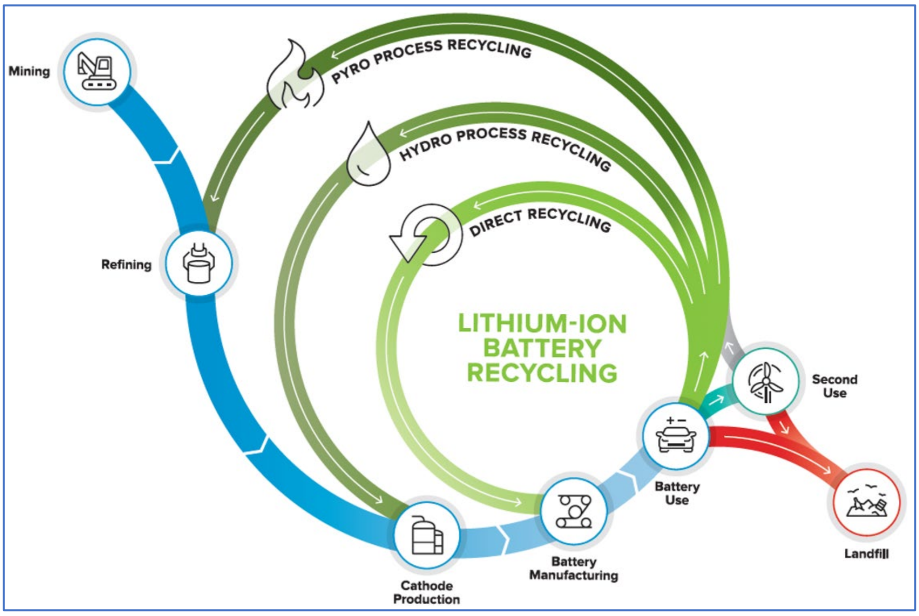


Figure 9: Lithium-ion battery life-cycle. (Gaines *et al.*, 2021)

2.8.1. Recycling Process and Methods

Gaines (2018) and Velázquez-Martínez *et al.* (2019) affirm that the recycling process can be broadly classified into four main areas; pre-processing (manual disassembly and categorisation), pyrometallurgical (smelting), hydrometallurgical (leaching) and direct recycling (physical processes) methods. Gaines notes that because of the complexity of recycling EV LIBs, different recycling processes may be combined, depending on aspects such as battery characteristics, quantity available and the value of material obtainable for recovery. The literature tends to agree with Gaines, advocating that an amalgamation of recycling processes combining direct recycling, hydrometallurgical and pyrometallurgical are required to obtain the highest quality materials suitable for reuse in LIBs and other industries (Xu *et al.*, 2008; Melin, 2019; Velázquez-Martínez *et al.*, 2019; Sommerville *et al.*, 2021).

For a fuller understanding of the subject, the literature surrounding the following recycling processes and methods were researched. These were: pre-processing, pyrometallurgy, mechanical processing, hydrometallurgy and direct recycling.

2.8.1.1. Pre-processing

Pre-processing or pre-treatment is considered a key step to the successful recovery of cathode materials, especially for hydrometallurgical and direct recycling methods (Xu *et al.*, 2008; Gaines, 2018; Larouche *et al.*, 2020).

Any process that does not alter the battery's cell structure is considered pre-processing. This may include: the deactivation or powering down of the vehicle's high voltage electrical system before removal, discharging the entire LIB system, battery modules or cells after removal from the vehicle, disassembly of the battery pack, removal of BMS or thermal management system, and the mechanical separation of structural components. This facilitates for recycling of steel, aluminium, plastics and electronics contained within the pack. Modules and cells are then evaluated and sorted dependant on their chemistry for pyrometallurgical or hydrometallurgical treatment or direct recycling (Elwert *et al.*, 2016; Romare and Dahllöf, 2017; Tichelen *et al.*, 2019).

Pre-processing of an EV LIB is presently a highly manual process that requires specialist tools because of the associated health and safety hazards such as the battery size and weight, electric shock, thermal runaway (fire / explosion) and chemical dangers (inhalation / burns) (Beaudet *et al.*, 2020; Tan *et al.*, 2021). Because of these hazards, pre-processing must only be carried out by specially trained operators who are qualified to work on EV high voltage batteries (Denton, 2016; Elwert *et al.*, 2016; Institute of the Motor Industry, 2019).

Battery labelling, or lack thereof, is another issue which if addressed, has the potential to significantly enhance pre-processing methods. Richa *et al.* (2017) contend that specific labelling via barcode or RFID chip placed on the LIB pack components during production, thus verifying chemistry, capacity and materials, could facilitate for more efficient sorting, remanufacturing and recycling. Romare and Dahllöf (2017) also note that if recyclers are to extract the right materials in the correct form, clear information about the battery composition is imperative and battery markings could provide this detail. Thus far, there is no requirement for standardised labelling to be placed on EV LIBs, however the EU's new proposed regulatory framework for batteries intends to make battery labelling mandatory from 2027 (EU, 2021).

2.8.1.2. Pyrometallurgy

Pyrometallurgical recycling is a thermal process where LIBs, generally after disassembly to module level, are fed into a furnace with a slag-forming agent at elevated temperatures to smelt the batteries. The ignition of the batteries electrolyte and construction plastics supply additional energy to the thermal process, therefore making the process more energy efficient (Gaines, 2014; Horn *et al.*, 2019; Velázquez-Martínez *et al.*, 2019). Conversely, this means that the plastics, electrolytes and other organic components which make up a large proportion of the battery are lost (Lv *et al.*, 2018). The elevated temperatures of the pyrometallurgical process also merges the precious metals, namely cobalt, copper, nickel and iron into an alloy which may be used directly by industries for the remanufacturing of, for example stainless steel, or refined further to extract specific materials (Larouche *et al.*, 2020). Gaines (2014) also notes that hazardous gas toxins are generated when LIBs are smelted and gas clean-up steps are necessary to avoid the release of harmful pollutants in to the atmosphere.

The pyrometallurgical recycling process is particularly economically efficient because of its simplicity and its capability to except mixed cathode LIBs. Batteries which contain greater amounts of cobalt and nickel in their cathodes make the operation especially worthwhile due to economic value of the reclaimed materials (Gaines, 2018; Velázquez-Martínez et al., 2019).

Within the standard pyrometallurgical process, materials such as lithium, iron-phosphate, aluminium, silicon, calcium, manganese and graphite that where present in the cathode are incinerated and reduced to slag which makes them difficult to recover and they frequently end up in landfill or alternatively they can be used in the cement industry (Gaines, Richa and Spangenberger, 2018; Harper *et al.*, 2019; Tichelen *et al.*, 2019). The employment of hydrometallurgical processes can be further utilised to the alloys and slag to allow for individual metal retrieval (Gaines, 2014; Elwert, Hua and Schneider, 2019). The combined processes are commonly used in series by industry to allow for maximum retrieval of the precious metals.

Pyrometallurgical recycling is one of the most universal LIB recycling methods used today, coming about as a natural progression from the established lead-acid battery recycling model (Gaines, 2014; Harper *et al.*, 2019). Companies such as Umicore (Belgium) have expanded their existing lead-acid recycling business and now have the ability to process thirty-five thousand tonnes worth of EV LIB batteries a year (Umicore, 2021). There are associated drawbacks with pyrometallurgical recycling, namely the high energy and capital expenditure requirement and generation of toxic gases.

2.8.1.3. Mechanical Processing

Mechanical process recycling is when materials are liberated, concentrated and classified without changing their chemical makeup and is also referred to as comminution (Velázquez-Martínez *et al.*, 2019; Cleary *et al.*, 2020). Comminution usually occurs before hydrometallurgical recycling where the EV LIBs are dissembled, typically to their modules, and fed into a mechanical crusher or shredder, reducing the batteries into smaller fragments. This happens in a protective atmosphere where an inert gas of argon or CO_2 mitigates the risk of fire or explosions (Vezzini, 2014; Diekmann *et al.*, 2016).

After comminution the materials are physically separated dependent on their size, density, magnetic conductivity, electrical properties and/or hydrophobicity. The separation process involves sieves, magnets and shaker tables to yield what's called a black mass, constituting a mixture of residual cell material of electrode coating materials, a concentration of plastics, casing materials and metal foils (Harper *et al.*, 2019; ReCell, 2021; Sommerville *et al.*, 2021).

Vezzini, (2014) and Diekmann *et al.* (2016) affirm that mechanical processing should be thought of as an intermediary stage of the recycling process, because comminution does not completely separate all materials. Therefore pyrometallurgical, or most likely hydrometallurgical, is required after the mechanical processing of EV LIBs. Commercially, a number of companies such as Duesenfeld (Germany) and RECUPYL (France) follow the mechanical and hydrometallurgical process which allows them to recover not only the conversion metals but also graphite, electrolyte and lithium.

2.8.1.4. Hydrometallurgy

Hydrometallurgical recycling is a chemical process which involves the use of an aqueous solution of acids and reducing agents to leach the compound metals from the cathodes (Gaines, 2018) . Generally, industrial hydrometallurgy is employed to process the black mass generated during the mechanical processing of the EV LIB. The leaching produces dissolved metals in the aqueous solution in ionic form, which are separated and recovered by solvent chemistry extraction and selective precipitation (He *et al.*, 2017; Duesenfeld, 2021; Recupyl, 2021).

Iron, copper and aluminium are easily reclaimed as pure metals once the hydrometallurgical process is completed (Gaines, Richa and Spangenberger, 2018). He *et al.* (2017) note that depending on the acid solution ratio, solution temperature and time spent in the solution, different material may be reclaimed and their purity grade will be altered.

Hydrometallurgical recycling is extremely efficient when compared to pyrometallurgical recycling in terms of the quality of the material recovered. Gaines, Richa and Spangenberger (2018) also state that the ability to recover the cathode's lithium and transition metals using the hydrometallurgical process, as significant when compared to pyrometallurgical.

Commercial firm, Duesenfeld, have developed a patented hydrometallurgical process (Figure 10) which has a ninety-one percent material recovery rate. Their method recovers cobalt and nickel as well as iron, copper, aluminium, lithium, manganese and graphite (Duesenfeld, 2021). Whilst Lithion (Canada) state their innovative hydrometallurgical process can recover ninety-five per cent of an EV battery's materials, which can be reused for new battery production (Lithion Recycling, 2019). Also noteworthy, as outlined by Gaines, Richa and Spangenberger (2018) is that hydrometallurgical recycling is potentially more economically viable than pyrometallurgical recycling because of the reduced capital set-up cost, while also exhibiting a smaller environmental footprint with low energy use due to the non-requirement of smelting.

Nevertheless, the chemicals used in the aqueous solution for the hydrometallurgical process contain extremely hazards environmental toxins, and the process necessitates high water consumption (Larouche *et al.*, 2020).

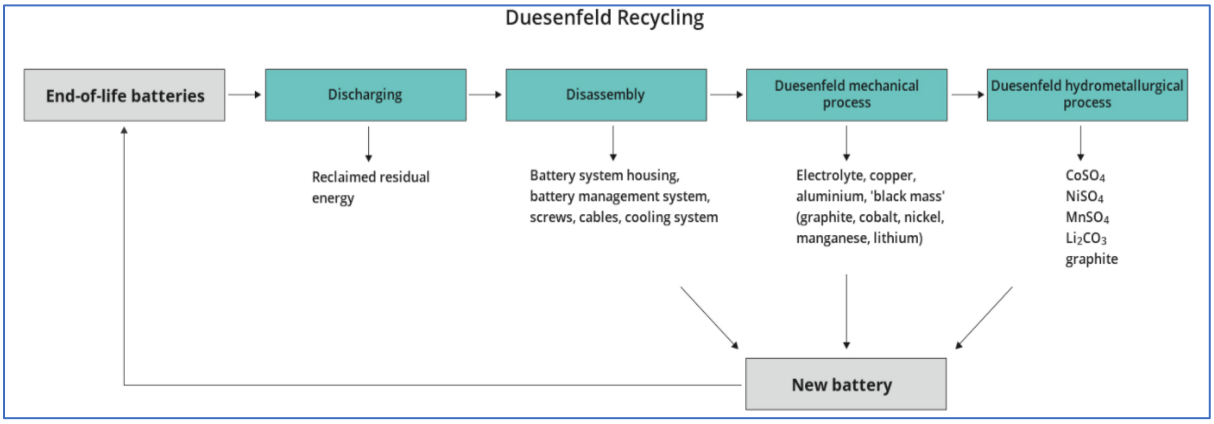


Figure 10: Material recovery with the Duesenfeld recycling method (Duesenfeld, 2021)

2.8.1.5. Direct Recycling

Direct recycling is a non-destructive approach that involves the removal of the cathode or anode material in a useable form by maintaining its original chemical structure and reusing them directly in the production of remanufactured LIBs (Harper *et al.*, 2019; Spangenberger, 2021).

Direct recycling is a similar process to hydrometallurgical, however direct recycling does not use acid leaching agents. Instead of dissolving the cathode or anode active material from the black mass, a mechanical separation of the materials occurs through flotation, magnetic separation and sieving. This process then refreshes and reactivates the cathode materials to recover properties lost during the batteries life-cycle due to battery degradation (Gaines, Richa and Spangenberger, 2018; Larouche *et al.*, 2020). Generally, the reactivation of the cathode will require its lithium content to be replenished (re-lithiated), to offset its losses (L. Li *et al.*, 2018; Shi, Chen and Chen, 2018). As well as allowing the recovery of the battery's cathode materials intact, direct recycling also allows for the recapture of valuable elements such as; aluminium, copper foils, electrolyte salts and anode graphite.

Direct recycling is particularly promising for LIBs with a lower economic cathode value, such as LFP and LMO because of its more direct process path when compared to hydrometallurgical. Gaines, Richa and Spangenberger (2018) and Larouche *et al.* (2020) both argue, that direct recycling is currently the only economically viable recycling route for LIBs with a low-value cathode chemistry.

Argonne National Laboratory of the University of Chicago, who are at the forefront of research within this subject, declare that direct recycling poses a range of benefits when compared to pyro / hydro metallurgical processes. They note that direct recycling of the cathode eliminates the need to remanufacture/reform the material back into structure, which reduces cost, and also the recovered active cathode materials are worth twice as much as the raw materials required to make them. Argonne perceive that the enhanced economics associated with direct recycling will lead to greater EoL value of LIBs, which will in-turn increase recycling rates and the accompanying benefits. It is thought that the improved recycling economics will ultimately lead to lower cost batteries and EVs (Spangenberger, 2021).

It should be observed that direct recycling is only in its developmental stage and although there are many research case studies within the direct recycling spectrum, such as that conducted by Sloop *et al.* (2020), it remains to be demonstrated that direct recycling is industrially scalable for EV batteries. To date, there are no commercially operating organisations using the direct recycling processes (Gaines *et al.*, 2021).

2.8.2. Recycling Electric Vehicle Lithium-ion Batteries: Conclusion

Recycling EV LIBs is a technically complicated process which requires large resources, whilst also being energy intensive. Pyrometallurgical recycling is the most straight forward process commercialised today and highly effective at recovering precious metals and alloys such as, cobalt and nickel. A major disadvantage is that it is not selective, i.e. the recovery of specific metals is extremely difficult (Horn *et al.*, 2019) and lithium and other cathode elements are generally lost to the slag heap. However, several reports claim pyrometallurgical is the most sustainable industrial scale EV LIB recycling process available today (Kwon and Sohn, 2020; Holzer *et al.*, 2021).

Hydrometallurgical recycling is an exceptionally selective process which can recover a large amount of the batteries elements with high purity rates. Companies such as Northvolt and Lithion maintain they can recover up to ninety-five per-cent of a battery's components using the hydrometallurgical recycling process. With regards to a sustainable circular economy, this is very promising. However Dunn *et al.* (2021) note that these recycling efficiency rates represent best-case scenarios, assuming that all EoL EVs end-up in a state-of-the-art recycling facility. In practice they affirm, that EoL vehicles follow many different unregulated recycling pathways.

Direct recycling promises to be the most environmentally friendly recycling method for EV LIBs because the recovered cathode materials are of high purity and can be used directly for new cathode production without the need for complex synthesis and remanufacture. This allows for a closed loop battery production model to be employed, which will reduce resource and energy consumption while also improving economic efficiency. It is noted that the direct recycling process is still in its infancy and is not yet fully commercialised.

Observers note that a global megatrend of EV mobility is already underway (Dhawan *et al.*, 2019). To facilitate this growth, the specific elemental constituents such as lithium, cobalt and nickel, will be required to ensure state-of-the art LIBs are available to enable society to make the transition to EV. The elemental building blocks of LIBs are finite however, and the supply of these critical raw materials is not guaranteed. Many of the materials are sourced from countries where conflict, governance, social and environmental issues exist (EU, 2021). Therefore, as well as the environmental and economic benefits associated with the reusing, repurposing and recycling LIBs, it is critical that a functioning end-of-life management system is in place for EV LIBs to facilitate a closed loop circular economy.

2.9. Electric Vehicle Lithium-ion Battery Hazards: An Overview

LIBs are generally considered safe, however as with any components containing an electrical energy power source, hazards do exist. Chen *et al.* (2021) contend that the reputation of the LIB has been severely damaged in recent years due to a number of accidental fires and large-scale safety recalls.

In 2020, automotive company, Hyundai recalled some eighty-two thousand 'Kona' model EVs worldwide after reports of fifteen fires which were initiated by the LIB (Aalund *et al.*, 2021; Yang, 2021). The recall affected nearly seventeen-hundred Irish customers (CCPC, 2020). Reports of a number of incidents involving the flagship EV company, Tesla have also added to the negative perception of LIB safety. In 2019, the battery unit apparently spontaneously ignited in major cities of Shanghai, San Francisco and Hong Kong, garnering considerable media attention for Tesla, and EVs in general (Goh and Sun, 2019; Sun *et al.*, 2020).

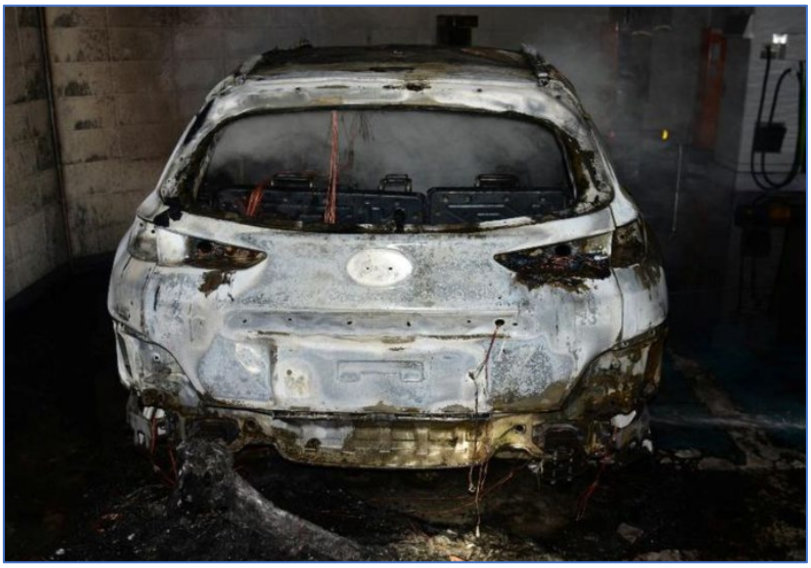


Figure 11: The burnt wreckage of a Hyundai Kona EV, Daegu, South Korea, October 4, 2020. Likely caused by a LIB thermal runaway incident (Daegu Fire & Safety Department, via REUTERS, 2021, 2021)

Outside of the automotive industry, LIB fire safety issues have also occurred. In 2006, ten-million laptop batteries used by a multitude of manufacturers such as Dell, Sony and Apple where recalled due to risk of internal short-circuiting (Zhang, Ramadass and Fang, 2014). While Boeing airlines grounded its entire fleet of 787 Dreamliners in 2013 because of an LIB fire on one of the aircrafts (Williard *et al.*, 2013).

In contrast, Abada *et al.* (2016) assert that the increase of negative media currently associated with EV LIBs can be correlated to their increasing market share. Context is also important when discussing EVs safety issues. Media outlets consistently report on EV battery fires because they are new technology, yet Christensen *et al.* (2021) note that on average there are sixty-five conventional ICE vehicle fires in the United Kingdom (UK) every day, which receive little or no attention. A meta-analysis by Bravo Diaz *et al.* (2020), regarding fire safety issues of LIBs across all industry sectors, acknowledged that when one considers the immense amount of LIBs in circulation today, fires are statistically rare.

It is noteworthy that both the UK Health and Safety Executive (2021) and the Irish Health and Safety Authority (2021) outline the primary personal dangers associated with EV LIBs as the potential releases of harmful gases and liquids and risk of explosion if a fire does occur, and not battery self-ignition fire itself. They also note the obvious high-voltage hazard, capable of delivering a fatal electric shock, is present even when the battery is powered down. LIBs and EVs also generate electromagnetic forces that can interrupt the operation of personal medical devices such as pacemakers. While manual handling risks associated with EV battery removal is another factor to consider, as some battery packs weigh in excess of five-hundred kilograms (Harper *et al.*, 2019).

In addition to the personal hazards, EV LIBs also pose a substantial risk to the natural environment. Papers by Christensen *et al.* (2021) and Dehghani-Sanij *et al.* (2019), outline the significant environmental impact that LIBs pose throughout their life cycle. For example, mining of raw materials, manufacturing, first-use, second-use and EoL will each denote different environmental challenges. They note that environmental land damage caused by mining, and pollutants such as hazardous waste, greenhouse gas emissions and toxic gases are just some of the negative environmental externalities associated with EV LIBs.

The current EU battery directive 2006/66/EC was enacted to mitigate the environmental risks posed by EoL batteries, particularly to ensure they would not end up in landfill. While, the EU's new proposal for a regulation concerning batteries and waste batteries aimed at repealing

2006/66/EC, will assess the environmental impact of the battery during its whole life-cycle (European Commission, 2020e).

2.9.1. Thermal Runaway

A fire in a LIB generally stems from a process known as thermal runaway. Thermal runaway is the primary safety issue for an LIB, which under certain conditions can lead to a build-up of pressure, causing the rupturing of the battery pack and releasing corrosive hot toxic gases, fire and potentially, explosion (Wang *et al.*, 2012; EC, 2020e; Chen *et al.*, 2021).

Thermal runaway occurs when a single battery cell overheats and transfers or propagates the heat to the cell next to it. The increasing temperature then leads to a chain reaction within the surrounding cells, then modules, then to the whole pack (Kong *et al.*, 2018). Chen *et al.* (2021), state the main causes of thermal runaway are, battery chemistry, its operating environment, and the abuse tolerance, for example: a defective cell separator (will cause internal short circuit), electrical abuse by overcharging (causes electrolyte decomposition), mechanical abuse to the battery pack casing caused by accidental damage (may cause a short circuit). All of these issues could lead to rapid discharging of the energy within the battery, unwanted chemical reactions and the generation of immense heat, which may manifest into a fire.

Corrosive toxic gases are another hazard associated with EV LIB fires. Under certain conditions, gassing products such as hydrofluoric acid, carbon monoxide and carbon dioxide may be produced (Sturk *et. al.*, 2015; Christensen *et al.*, 2021). These gases are extremely hazardous to both humans and the environment.

Another risk linked to thermal runaway is explosion. Christensen *et al.* (2021) reviewed a number of LIB incidents that led to explosions. One event in Flagstaff, Arizona detailed how two firefighters were thrown over twenty meters and received chemical burns and broken bones while responding to a fire involving a LIB used for grid storage, when it exploded. While such events as the one in Flagstaff, have yet to be reported with regards to EV LIBs, it’s a real possibility that does exist, particularly in the event of a severe road vehicle collision and with EoL wastes management.

2.9.2. High Voltage

EV high voltage ranges differ from the commercial and domestic electrical supply. UN and EU regulation ECE R100 classifies automotive EV high voltage as; greater than sixty volts direct current (DC) and greater than thirty volts alternating current (AC) (United Nations, 2010; ECE/UN, 2016). A EV powertrain traction-motor works using AC voltage with many motors operating at six to seven hundred AC volts when fully loaded (Wen *et al.*, 2012; Denton, 2016). Whereas, an EV battery works using DC voltage typically in the range of four-hundred-volts (Audi AG, 2021). In both instances, these voltages far exceed the ECE R100 high voltage thresholds.

The high voltage contained within an EV LIB poses various hazards such as electric shock, electrical burns, arc flash (electric explosion), fire and electrocution (Denton, 2016; Harper *et al.*, 2019; Chombo and Laoonual, 2020; HSE, 2021). Manufactures design their EVs and allied high voltage technologies to operate safely, however extreme care is always required when working on EV powertrain systems.

Industry bodies such as the Institute of the Motor Industry (IMI) and the Society of Automotive Engineers (SAE) have recommenced guidelines (SAE J-2344) to follow to allow for EV safe working practices, which include removal of the battery from the EV at EoL. A number of countries such as France, Germany and Canada have already adopted a mandatory qualification approach to ensure technicians are competent to work with high voltage technologies due to the associated electrocution hazards (Institute of the Motor Industry, 2020). Other countries are also following this route, and it may be assumed that an EU regulatory framework maybe forthcoming within this area.

Crucially with respect to EoL EV LIBs, they retain significant capacity at the end of their first life, which is still very much capable of electrocution (Bandelier *et al.*, 2020; Dawson, Ahuja and Lee, 2021).

2.9.3. Lithium-ion Battery Safety Standards

Various safety hazards clearly exist with EV LIBs. Yet as detailed, LIBs are generally considered safe, and accidents are rare. To mitigate the potential risks, stringent safety standards are imposed on battery manufacturers by policymakers. Extensive health and safety legislation encompass all areas of the battery's value chain, which include UN Reg. No.100.02 [73], UN-ECE GTR No.20 and SAE J2464 as examples.

The ECs impact assessment report, SWD (2020) 335 concerning batteries and waste batteries, repealing Directive 2006/66/EC, summarises various safety concerns that can take place through-out a battery's lifecycle, from manufacturing, use-phase, transport, recycling and disposal. However, the Commission warns that ‘despite proper design, quality control and assurance measures... failures can and will occur’ with LIBs. Consequently, state-of-the-art safety and testing requirement methodologies, have been recommended within the EU’s new battery directive. These are summarised in Table 3., and will ensure acceptable safety during what is considered both normal and abnormal operation of LIBs.

Normal operating conditions of LIBs are a set of predetermined values and parameters where the battery is designed to work safely within specified ranges. Abnormal operating conditions are when the battery operates outside of these ranges, particularly with regards to temperature and voltage, caused by either internal or external factors (EC, 2020e). An abnormal condition may occur in the event of a road crash for example, which can lead to hazardous scenarios such as thermal runaway. The Commission’s proposed safety testing procedures and subsequent legislation classifies both normal and abnormal operation of EV LIBs.

	Test name	**Evaluation**
1	Thermal shock and cycling	Evaluate changes in the integrity of the battery arising from expansion and contraction of cell components upon exposure to extreme and sudden changes in temperature
2	External short circuit protection	Evaluate the safety performance of a battery when applying an external short circuit
3	Overcharge protection	Evaluate the safety performance of a battery in overcharge situations
4	Over-discharge protection	Evaluate the safety performance of a battery in over-discharge situations
5	Over-temperature protection	Evaluate the effect of temperature control failure
6	Thermal propagation	Evaluate the safety performance of a battery in thermal propagation situations
7	Mechanical damage by external forces (drop and impact)	Simulate one or more situations in which a battery accidentally drops or is impacted by a heavy load
8	Internal short circuit	Evaluate the safety performance of a battery in internal short-circuit situations
9	Thermal abuse	The battery shall be exposed to elevated temperatures which can trigger exothermal decomposition reactions

Table 3: EC battery safety parameter tests. Amended safety annex V, from COM (2020) 798, (EC, 2020a).

2.9.4. Electric Vehicle Lithium-ion Battery Hazards: Conclusion

EV LIBs pose numerous environmental concerns and personal safety hazards throughout their entire life-cycle, which must be considered.

With regards to EoL recycling, the risk of electric shock from residual charge and thermal runaway denote an immediate threat to technicians, transporters and recyclers. A recent report by the United States EPA highlighted the growing trend of consumer product LIB fires in recycling facilities. The report found that two-hundred and forty-five fires occurred between 2013 and 2020, that were 'caused by, or likely caused by' LIBs (O'Connor and Wise, 2021). Although EV LIBs EoL accidents are unusual, this is likely due to the small numbers currently presenting for EoL treatment at this time. Couple the fire risk with the high voltage also present in EV LIBs, and a significant personal safety hazard exists, in addition to the environmental hazards.

The literature review of section 2.9 relating to EV LIB hazards has identified a knowledge gap, specifically in relation to the battery's high voltage risks. Twenty-one academic peer-reviewed papers on EV LIB safety were studied and only three where identified by the author that referenced the hazards associated with high voltage, specifically electrocution. Harper *et al.* (2019) noted the potential of electrocution for technicians and recyclers. While Chombo and Laoonual (2020) and Christensen *et al.* (2021), briefly discuss the risk of electrocution to first responders. A mandated study by Propulsion Québec affirmed that the risk of electrocution during dismantling was a barrier to recycling (Bandelier *et al.*, 2020).

The majority of papers reviewed, focused on the fire hazards that EV LIBs pose, and how thermal runaway occurs. Whereas, industry publications from the IMI, the SAE, and textbooks such as Danton's *Electric and Hybrid Vehicles* along with manufacturer methodologies, concentrate on personal health and safety, and specifically the high voltage capacity of EV LIBs. A clear difference emerged between industry publications and research articles, with regards to EV LIB safety priorities during the literature review.

To reduce the knowledge gap of the personal hazards associated with EV LIBs, research, training and education and legislation strategies should be continually developed within this area.

2.10. Transportation and Storage of Electric Vehicle Lithium-ion Batteries

When an EV reaches EoL, their batteries must be removed for reuse, repurposing or recycling, as EU battery legislation 2006/66/EC, prohibits the disposal of LIBs in landfills (EUR-Lex, 2006). Depending on where the EoL EV resides, which would typically be an automotive dealership or an authorised treatment facility (ATF), the LIB must be handled and transported to a different facility to perform these operations. In Ireland's case, the LIBs usually have to be transported overseas to a country such as France, Belgium or Germany to facilitate this repurposing or recycling (Chen *et al.*, 2019), however the transportation of LIBs poses difficulties.

EV LIBs are considered dangerous goods, and legal provisions exist to ensure they are transported safely (HSA, 2012). A UN and EU legislative agreement known as the International Carriage of Dangerous Goods by Road (ADR), classifies LIBs as 'Class 9…dangerous articles', while EV LIBs also come under a specific code within the ADR regulations; No.3090 and No.3091 (United Nations, 2019). ADR regulations mandate particular standards surrounding the packaging and labelling of the goods, the vehicle transporting the goods, and all persons involved in the movement of the goods (HSA, 2012). The main goal of ADR regulations is to ensure safe passage of dangerous goods to their destination. The shipment of EV LIBs from Ireland to the EU for processing, also falls under the International Maritime Dangerous Goods Act (IMDG), the maritime equivalent of ADR legislation (International Maritime Organization, 2019).

Ireland's own Health and Safety Authority (2012), also affirms that EV LIBs are a dangerous good when in transit and present a risk to people, property and the environment. Because of the hazards associated with LIBs, transporting the batteries requires the contractor to pay utmost due diligence to safety legislation and accountability. This inevitably increases transportation costs, accounting for a large percentage of the overall recycling outlay (Chen *et al.*, 2019; Dawson, Ahuja and Lee, 2021; Gaines *et al.*, 2021). Transporters must also take into consideration the size, weight and extensive variations in design of EV LIBs which add additional layers of complication, in conjunction to the safety aspects.

2.10.1. Extended Producer Responsibility

Dawson (2019) asserts that extended producer responsibility (EPR) is a regulatory tool which aims to realise circularity through the "polluter pays" principle. Dawson states that since EPR was first established in Sweden during the 1980s, it has grown to encompass over four-hundred schemes globally. EPR ensures that manufacturers are responsible for the entire life-cycle of their product. Forslind (2005) outlines that EPR incentivises a producer to consider the negative environmental effects of their product through monetary tools, particularly once the product reaches its end-of-life.

EPR is widely used by the EU as a policy to mitigate environmental impact of waste and reduce waste through circularity of repair, reuse and recycling. Unlike the linear waste model, the financial burden is placed on the producer (Forslind, 2005; Dawson, Ahuja and Lee, 2021). EPR was first introduced in Ireland in 2005, while directive 2012/19/EU on Waste Electrical and Electronic Equipment (WEEE), set minimum annual collection rates for EU member states from 2019 (WEEE Ireland, 2020). Bandelier *et al.* (2020) and Dawson, Ahuja and Lee (2021) both affirm that EPR measures are an effective tool for ensuring high recovery and recycling rates for materials such as batteries and electronic waste.

Ireland has so-far enacted EPR measures for packaging, batteries, WEEE, end-of-life vehicles (ELVs), tyres and farm plastic waste streams (DECC, 2021). With regard to EVs and their batteries, EPR principles are applicable to both the vehicle and the battery under separate directives. Directive 2000/53/EC legislates for the ELVs, while directive 2006/66/EC is responsible for EV's waste batteries and accumulators. Both directives require comprehensive modernising to deal with the emergence of EVs, and a 2019 report *COM166* by the EC, acknowledges this. Dawson, Ahuja and Lee (2021) acknowledge that the current EPR framework for vehicles and batteries was developed for ICE vehicles and not EVs. As an example of the conflict between the two directives, the ELVs legislation stipulates that eighty-five-percent of the vehicle weight must be reused or recycled, while the EV battery, which comes under different legislation, weighs on average twenty-two-percent of the vehicles total weight (EUR-Lex, 2006; Nykvist, Sprei and Nilsson, 2019; Dawson, Ahuja and Lee, 2021).

The EU commission is aware of the shortcomings within the current waste battery directive, with respect to EVs and their batteries, and a complete evaluation was undertaken in 2019. This evaluation led to a new draft regulatory framework for batteries, *COM798*, which was published in December 2020. The draft framework has been comprehensively updated to take into consideration the current and future move towards electrification of the transport sector (EU, 2021). The proposed regulation outlined, strengthens the principle of EPR by assigning additional responsibility to battery manufacturers, with respect to the battery-life-cycle and the EU Green Deal (EC, 2020b).

2.11. Literature Review Conclusions

2.11.1. Literature Review Overview

The strive to reduce carbon emissions and mitigate the effects of climate change has instigated a global shift to EVs in effort to decarbonise transport and the growth in EVs creates increased demand for raw materials required to produce their primary power source; the LIB. LIBs are also subject to natural degradation, which will result in a vast amount of spent automotive batteries requiring waste management in the near-to-medium future.

Technological advancements in recycling methods and proposed EU legislation aim to create a truly circular battery value chain, from production through to EoL, however due to the associated safety hazards posed by LIBs, stakeholders must give serious thought and consideration to the challenges this emerging field will bring.

2.11.2. Literature Review Findings

The literature regarding EoL EV LIBs was thoroughly researched and critically analysed, and revealed a knowledge gap within the LIB recycling value chain. The knowledge gap regards specifically, the high voltage safety risks surrounding the pre-recycling steps encompassing disassembly, storage and transport of LIBs. The author recommends further research around these topics and this study aims to add further knowledge to this area of the literature.

3. RESEARCH METHODOLOGY

3.1. Introduction

The primary aim of this action research is to understand the recycling value chain encompassing end-of-life (EoL) electric vehicle (EV) lithium-ion batteries (LIB), specifically during the pre-recycling phases that will be necessary in Ireland. These phases encompass the removal of the LIB from the EV as presented at EoL, along with the battery's storage and transportation as it embarks into a developing circular life-cycle product chain. Each stage will come with inherent health and safety implications, so the research will propose a best practice to adopt in regard to each of the aforementioned stages.

The technical nature of this study lent itself to a mixed-methods pragmatic paradigm research approach.

The following sections will elaborate and present this research methodology, in terms of how data was collected and analysed, in addition to the logic and justification for using these methods.

3.2. Research Philosophy

Saunders, Lewis and Thornhill (2007, p.101), state that the term 'research philosophy' simply translates to, "*the development of knowledge and the nature of that knowledge*". The development of knowledge is a natural outcome when any research study is undertaken, but specifically, Bryman (2012) highlights the importance of research philosophy definition for the social researcher, as it provides a rationale and framework to benchmark the increased knowledge against, throughout the undertaking.

The nature of knowledge advancement typically falls into two categories within social science; positivism or interpretivism which denote the philosophical assumptions a researcher brings to the study (Creswell, 2009). The theory and research of a subject make for either a deductive or inductive approach. Bryman (2012) affirms that, the relationship between these areas will determine a quantitative or qualitative research approach.

Due to the technical nature and processes occurring within the field of EoL EV LIB recycling, and owing to the subject being a relatively modern phenomenon, an epistemological deductive-based positivism action approach was undertaking. This approach enabled the author to gain factual knowledge through the observation of the research topic.

The deductive-based positivism approach lent itself to the use of qualitative research methods. However, as the study progressed, a small-scale quantitative survey was considered advantageous. This led to a mixed-methods research study, combining both quantitative and qualitative data, or a pragmatic-paradigm approach.

3.3. Action Research

Saunders, Lewis and Thornhill (2007), affirm that a research strategy will be dictated by its research question and objectives, and whether they can be fulfilled. Coghlan and Brannick (2005) state that action research is the resolution of organisational issues and the implications of change for those who directly experience the organisation affected (cited in, Saunders, Lewis and Thornhill, 2007).

The author aims to lead a change in the EV LIB pre-recycling stages by increasing awareness and formulating best-practice approaches surrounding the safety hazards associated with EoL EV LIBs. To facilitate change in this field, the author will develop a measured health and safety best practice methodology for the pre-recycling phases for all stakeholders in the current Irish process chain. This undertaking lends itself to an action research-based strategy.

3.4. Research Process and Methodology

The research process and methodology are important parts of the conception of a multi-stage strategy-based research project and they are both conceived before the research proper. This enables the researcher to keep focus on their research goals as the project passes through the varying stages that may each require differing methods for differing scenarios, in order to reach their end-objective (Saunders, Lewis and Thornhill, 2007).

The author’s research process and methodology for this dissertation is summarised in Table 4.

1. Research topic	Selected a relevant topic within sustainable transport and mobility area, worthy of research and of interest to the author.
2. Define research question	To research the recycling value chain surrounding end-of-life (EoL) electric vehicle (EV) lithium-ion batteries (LIBs) and specifically, to study and analyse the pre-recycling phases of: safety, disassembly, storage and transportation of EV LIBs within the recycling process, from an Irish perspective.
3. Outline research objectives	Five primary research objectives, (RO1-5) are stated in Table 5. within section 3.7.
4. Conduct literature review	A comprehensive literature review was undertaken.
5. Methodology: mixed methods pragmatic paradigm.	Qualitative data: semi-structured interviews with key actors in the EV sector. Quantitative data: survey actors who may be involved in the EV LIB pre-recycling phases.
6. Analysing data	Reflect on data and concepts uncovered and write dissertation
7. Contribution of Research	Dissertation findings will fill in the knowledge gap and add to the subject field. Present a best practice methodology regarding the safety aspects of pre-recycling operations of LIBs in Ireland.

Table 4: Outline of research process and methodology leading to author's dissertation.

3.5. Research Rationale

The battery value chain is now acknowledged to be of strategic importance within the European Commission and Government policy as Ireland moves towards an electrified transport network. To exemplify this importance, forthcoming new battery legislation will ensure stringent lifecycle regulations, from design to production, through its working life and possible second life, culminating in EoL recycling.

Within the Irish market, the pre-recycling phases of LIB removal and storage must occur on the island, before the batteries can be shipped to Europe for completion of the recycling process. Therefore, it is of great importance that all actors within the Irish EV domain are fully aware of the concerns and issues that may arise during the pre-recycling phases of EoL EV traction batteries.

The rationale for carrying out this research is twofold. Firstly, the pre-recycling aspects of EV batteries are understudied. And secondly, there are significant personal health and safety risks associated with EV LIBs that the author felt they could add a meaningful value to society in addressing.

On the under-study of the EV LIB recycling value chain, a research review by Melin (2019), commissioned by the Swedish Energy Agency investigating the recycling value chain, concluded that studies surrounding the EV LIB recycling pre-treatment phases were "*completely lacking*". The author's own secondary research confirmed Melin findings. While completing the literature review for the dissertation, the author specifically found a knowledge gap concerning the pre-recycling phases of, safety, disassembly, storage, and transportation of EV LIBs within the recycling process. This study will add significant knowledge to this area.

From an Irish perspective, research encompassing the recycling and pre-recycling of EV LIBs is wholly lacking. The author did not find any published literature relating to the pre-recycling topics of EV LIBs from an Irish source. The dissertation findings will be one of the first on the island of Ireland and start the process of filling the information void.

On the topic of personal health and safety, the inherent hazards of working with LIB traction batteries demand study, understanding and awareness, and must be relayed to all stakeholders within the EV field in as clear a manner as possible. From an Irish viewpoint, actors within the industry will be the ones tasked with completing the pre-recycling phases when EVs reach EoL, so this research will impact and assist the Irish recycling platform to mitigate injury and environmental damage as much as possible. As the EV market is still emerging in Ireland, few EV LIBs have reached EoL so it may be assumed that a skills and knowledge gap exists within the area. To alleviate this, the author proposes to formulate and present a best practice methodology regarding the safety aspects of EV LIB pre-recycling operations from the dissertation findings.

3.6. Research Question

The author will research the recycling value chain surrounding end-of-life (EoL) electric vehicle (EV) lithium-ion batteries (LIB). The specific area of study is to analyse the safety implications of the pre-recycling phases of EV LIBs during removal and disassembly, storage and transportation, from an Irish perspective.

3.7. Research Objectives

Research Objectives (RO)	
RO1	Identify and analyse, electric vehicle lithium-ion battery recycling methods.
RO2	Appraise the current domain for end-of-life electric vehicle lithium-ion batteries in Ireland.
RO3	Evaluate and assess, national and international end-of-life electric vehicle lithium-ion battery pre-recycling practices.
RO4	Identify and discover, Ireland's electric vehicle lithium-ion battery recycling barriers and enablers, if any.
RO5	Formulate a health and safety best practice methodology for pre-recycling operations of end-of-life electric vehicle lithium-ion batteries in Ireland.

Table 5: Author's primary research objectives

3.8. Secondary Research

It is deemed essential to engage in associated readings, as to be informed and stimulated by your developing knowledge if completing a research project (Blaxter, Hughes and Tight, 2013).

The topic of recycling EoL EV batteries was new to the author, therefore an extensive amount of research reading has been completed since the undertaking of the study.

Secondary research constituted a comprehensive literature review, primarily using TU Dublin's online library resources. Search criteria focused on keywords from the research question and the sources and papers selected for study were principally peer-reviewed journals published within the last three years. The Google Scholar system was also employed when keyword searches provided limited results. Relevant published literature, Government and European official communications, and industry data was also read, analysed and reviewed.

3.9. Primary Research

Saunders, Lewis and Thornhill (2007, p.5) describe research as, "*something that people undertake in order to find out things in a systematic way, thereby increasing their knowledge*".

A pragmatic paradigm mixed-method research approach was undertaken by the author for the study's primary research data. Once the research question and objectives where established and the secondary research literature review was drawing to a close, the author initiated primary research.

Qualitative data was collated by conducting interviews with key actors within the EV market and its battery value chain nationally and internationally. As the research progressed, a small-scale survey targeted at technicians, who will potentially be tasked with physically conducting the pre-recycling phases, was also undertaken. The initial data was then analysed in a logical, methodical way and a concept was formed.

3.9.1. Qualitative Research

The topic of recycling EoL EV batteries is technically complex, involving many different processes, phases and stakeholders. Because of this, the author performed a qualitative research strategy primarily. Qualitative research methods typically put the emphasis on descriptions, concepts and words in the collection and assessment of data (Bryman, 2012). Creswell (2009) delineate that researchers typically gather several formats of source data such as interviews, documents and observations, rather than focusing on a single data set when researching qualitatively.

The author followed Bryman (2012) systematic qualitative research process, presented in Figure 12. below, as it provided a logical sequence for the study. Pursuing Creswell's (2009) research philosophies, stakeholders within the EoL EV LIB recycling value chain where specifically pre-identified and selected for being best-placed help the author understand the subject, and answer the research question.

To gain a holistic understanding of the wide-ranging and varying perspectives of the interviewees from different organisations, the interviews were carried out in a semi-structured manner. This would allow some degree of freedom for the author to draw out themes and gain a comprehensive understanding of real-life issues within the industry, and not a rigid pre-prescribed set of similar interviews.

Bryman (2012) points out that a researcher’s list of specific questions when conducting semi-structured interviews for qualitative research should only serve as a guide. This is because the interviewees will have a varying scope on how to reply and indeed, the author found this assessment to be accurate. Several interviews led to new avenues of research outside the initial questions and introductions to new people within the industry. While, three interviews also led to site visits based on this approach.

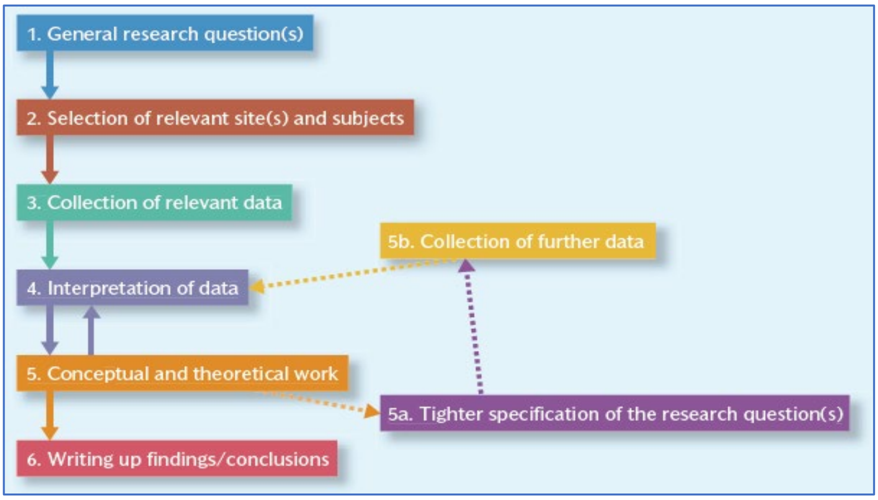


Figure 12: Outline of the main steps of qualitative research was followed by the author (Bryman, 2012).

Fourteen interviews were conducted for this study comprising diverse stakeholders in the field of study. See table 6, below. The stakeholders were interviewed using various media: seven face-to-face interviews where completed, with three occurring in their place of business, along with phone and electronic interviews, both synchronous and asynchronous. The site visits were particularly useful; seeing the practical processes faced day-to-day by those working first-hand on EVs and their batteries, provided contextual experience for the author.

Bryman (2012) notes that when carrying out an interview, the interviewee is unlikely to mention something that they consider standard or normal behaviour, so having the opportunity to interview formally deviated from their norm and created a more detailed knowledge transfer.

To ensure a logical approach to the design and implementation of the interviews and processing of data, the author utilised Kvale's (2011) seven-step structure to interviewing (Figure 13).

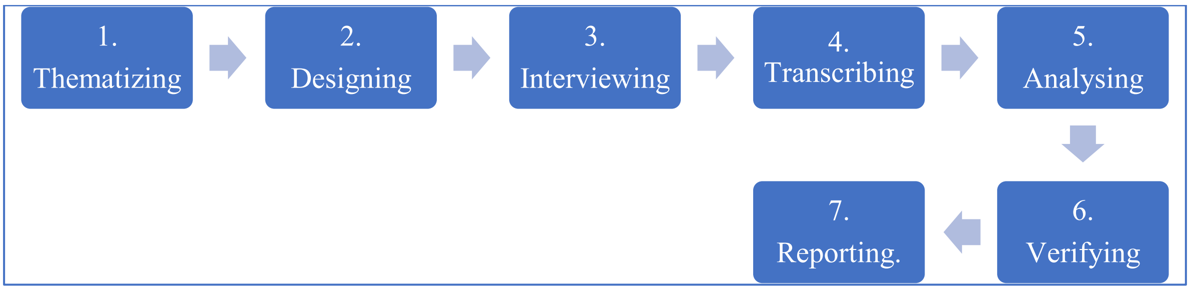


Figure 13: Seven stages of an interview inquiry. Adapted from 'Planning An Interview Study', in *Doing Interviews* (Kvale, 2011b).

Interviewee	Organisation	Industry / business role	Position	Length	Date	Interview form	Recorded & transcribed
Denis McCrudden	Hyundai Ireland	EV sales, repair & EPR. Private business.	National Service Training Manager	1h50m	02/09/2021	Site Visit. Hyundai IRL, Dublin 12 & Asynchronous	NO
John Dockrell	ScrapMyCar.ie	ELVs Treatment EoL EV & LIBs. Private business.	Authorised Treatment Facility Owner	0h16m	06/09/2021	Phone Interview	NO
Elena Wrelton	ELV Environmental Services CLG	ELVs compliance for IRL. Non-profit company	Environmental Compliance Manager	0h52m	07/09/2021	In person. Rush, Co. Dublin & Asynchronous	YES
Martin Dunne	Peugeot Ireland	EV sales, repair & EPR. Private business.	Country Technical Coordinator	0h24m	16/09/2021	Phone interview & Asynchronous	NO
Maurice Brady	TU Dublin	Transport expert ADR / IMDG. Public sector.	Assistant Lecturer	0h35m	21/09/2021	In person. Bolton Street City Campus	YES
Ken Byng	CarTake Back.com (United Kingdom)	ELVs Treatment EVs & LIBs. Private business.	Senior Business Manager	0h22m	01/10/2021	Synchronous Microsoft Teams & Asynchronous	YES
Joe Greene	Citroen Ireland	EV sales, repair & EPR. Private business.	Aftersales Manager	0h21m	04/10/2021	Phone interview & Asynchronous	NO
Robert Guy	Volkswagen Group Ireland	EV sales, repair & EPR. Private business.	Director of Group Aftersales	0h32m	14/10/2021	In person. Bolton Street City Campus	YES
Alan McDermott	Nissan Ireland	EV sales, repair & EPR. Private business.	Head of Aftersales	1h40m	05/11/2021	Site visit. Nissan Academy, Naas & Asynchronous	NO
John Gaffney	Nissan Ireland	EV sales, repair & EPR. Private business.	Technical Advisor	1h40m	05/11/2021	Site Visit. Nissan Academy, Naas	NO
Tadgh Cronin	Technical Training Manager	EV sales, repair & EPR. Private business.	Volkswagen Group Ireland Ltd.	2h40m	26/11/2021	Site Visit. VW National learning centre	NO
Johannes Chatzis	IDIS Management (Germany)	EoL EV disposal methods. Non-profit.	Project Manager	N/A	05/10/2021	Asynchronous : email	N/A
Fredericq Peigneux	WATT4EVER bv (Belgium)	Repurposing EV LIBs. Private business.	Business Intelligence Officer	N/A	13/10/2021	Asynchronous : email	N/A
Conor Leonard	WEEE Ireland	Non-profit organisation, electrical waste	Battery Operations Manager	N/A	11/10/2021	Asynchronous : email	N/A

Table 6: List of semi-structured interviews completed. Interviewees, firms, titles and type of interview.

Kvale's (2011) seven-step structure to the interviewing process is expanded upon for this study below.

3.9.1.1. Thematizing

The reason for the interviews was to acquire knowledge to fulfil the outlined research objectives, so the author established a theme using the research question. The questionnaire themes focused on the barriers and enablers of safety, disassembly methods and transport of the EoL EV LIB value chain.

3.9.1.2. Designing

The interview design and planning varied slightly based around the stakeholder categories. Interviewees ranged from large multi-national companies to small family businesses to non-profit organisation and academics. Once a stakeholder agreed to be interviewed, a questionnaire was designed with the specific interviewee in mind.

Themes that would emphasise the interviewee's area of expertise were planned specifically, based on the author's research question. Due to the technical nature of the recycling of EoL EV LIBs, succinct questions, following a logical order were composed.

While the wording varied, and some of the questions evolved as a greater understanding of the research topic ensued, the main themes remained consistent.

An example of the questions and themes initiated for one of the interviewees is presented in Table 7. below. These questions were posed to Nissan Ireland, before a site visit, and as can be seen they were tailored to Nissan, but the themes remained.

1.	What is the current process a Nissan dealer follows if an electric vehicle (EV) lithium-ion battery (LIB) is to be replaced?
2.	What happens to the replaced high voltage battery?
3.	Have the Nissan network been trained to remove an EV high voltage battery?
4.	What are the protocols a Nissan dealer follows, if they store an EV battery on their premises?
5.	What specific special tooling do Nissan recommend using, for working with EV LIB?
6.	Do Nissan repair EV batteries (replace modules / battery management systems units etc.)?
7.	Do Nissan use different LIB cathode chemistries, for example NMC or NCA etc.?

8.	Do Nissan use a pan-European transport company for returning EV batteries for recycling / refurbishing to Europe?
9.	Do Nissan Motor Corporation currently have a facility to recycle EV batteries?
10.	What are the current or future barriers (if any) you envision, concerning recycling and disposal of EVs batteries from an Irish perspective?
11.	Do you think legislation, should be introduced for technicians who work on high voltage components of EVs?

Table 7: Questions sent to Nissan Ireland prior to an onsite meeting.

3.9.1.3. Interviewing

Participants were fully informed for the reason of the interview and the objective of the research. Every interviewee received a declaration from the author (see appendix, Figure 34), confirming that all information provided would be treated with confidentiality and only used for the purpose of the MSc research. Questions were provided to the participants before carrying out the in-depth semi-structured interviews. This was to ensure the interviewees were comfortable with the topics to be covered. Some participants noted that receiving the questions beforehand allowed them to carry out additional research in areas of their business that they were not fully familiar with.

Interview methods varied and included face-to-face interviews, site-visits, phone interviews and electronic interviews, both synchronous using Microsoft Teams and asynchronous using email. Due to the different interview methods and the participants personal preferences, only four interviews were recorded. The author generally recorded a 'Voice Memo' immediately after all face-to-face and phone interviews while the information was still fresh. This ensured all themes were fully documented for further analysis.

3.9.1.4. Transcribing

Three interviews were recorded using the iPhone Voice Memo application, while another was charted using Microsoft Teams. The audio M4A files were converted to a text file using the Microsoft Office 365 'Transcribe' application.

The author reviewed the transcribed text line-by-line, as there were numerous grammatical errors. An example is shown in the appendix, Figure 35. Although this process was painstaking, the transcribe software saved the author a significant amount of time. The transcribed interviews amounted to fifty-three pages of dialogue, containing just under twenty-one thousand words. The author would not have been able to complete this process manually without losing focus of the theme.

The author conducted three site visits, which were especially beneficial for gaining an insight into the safety and repair methods being employed by industry, however the environment of these meetings did not facilitate recordings being made of the conversations. Notes were made, and questionnaires were answered asynchronously by email, with the same approach taken for phone interviews.

3.9.1.5. Analysing

Kvale (2011a) affirms that there are no simple shortcuts when analysing qualitative data from an interview and there is no standard approach. However, Kvale does state that quality analysis depends on aptitude, knowledge of the research topic and an understanding of language surrounding the topic.

The author carried out analysis of the data by thematic coding, see appendix Figure 36, 37 and 37 as an example of thematic coding. This process involves assigning keywords to a text segment, in order to permit later identification of a statement, and opening the data to possible quantification (Kvale, 2011a). Thematic analysis involved searching all of the primary data set to find repeated patterns or themes that represent something significant about the research question or objectives (Braun and Clarke, 2006).

Fourteen interviews were thematically coded in a deductive or “top-down" approach. Braun and Clarke (2006, p.12), deduce that a deductive top-down thematic analysis is “*driven by the researchers theoretical or analytic interest in the area”*. They note that this analyst-driven method allows for a detailed examination of aspects of the data, which facilitates coding toward a specific research question.

The author’s manual coding process was as follows, see also Figure 14:

1. The primary data set from the transcribed interviews and asynchronous responses were reviewed using Microsoft Word, and a text code added to a line of text using the ‘Review and New Comment’ function within Word.
2. A software add-on for Microsoft Word called, ‘DocTools - ExtractData’ created by Lene Fredborg, was used to extract all the coded text into a Word table format.
3. This file was exported from Word to an Excel document, where the coded words could be quantified.
4. The quantified words were categorised into themes using colour identification.

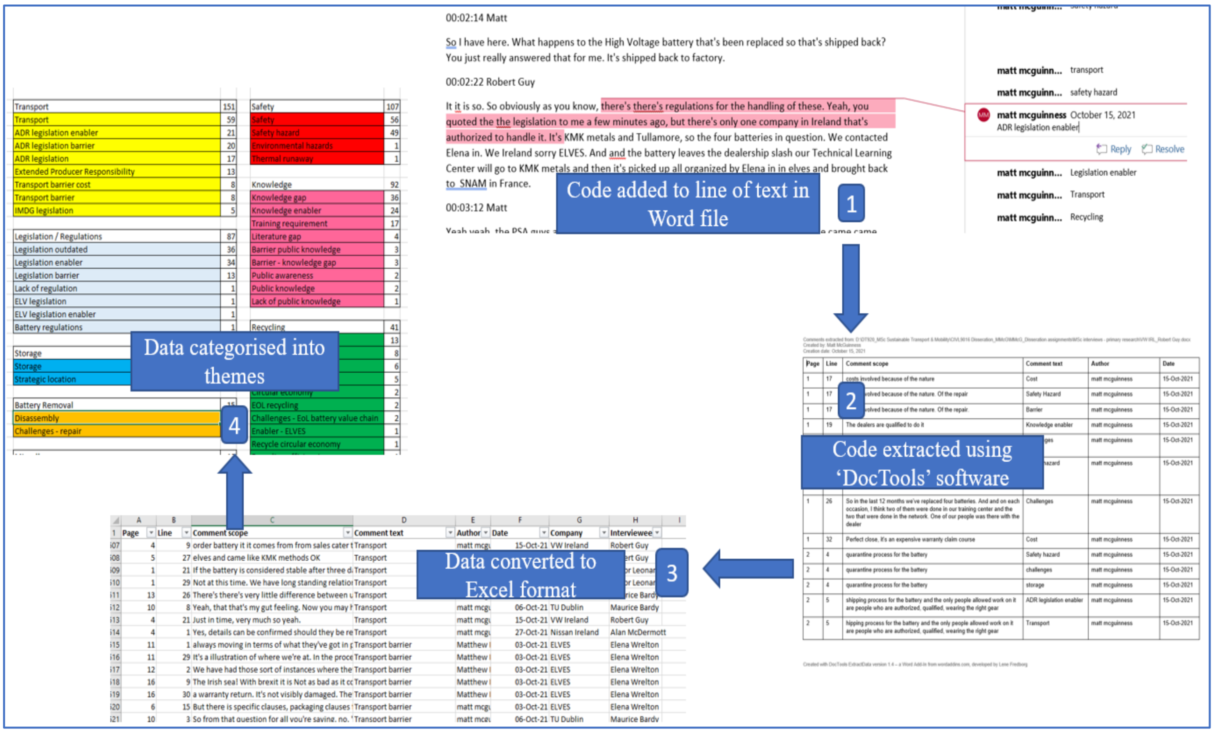


Figure 14: The author's approach to thematically coding the primary research data.

3.9.1.6. Verifying

To ensure reliability and validity of the data, various stakeholders from diverse backgrounds within the electric vehicle, lithium-ion battery and ELVs (End-of-Life Vehicles) recycling value chain were interviewed along a consistent theme. Eleven interviews were conducted with Irish actors from private, public and non-profit organisations, while three interviews were conducted with international establishments from the UK, Germany and Belgium.

The author did contact other actors, including a company currently shipping EoL EV LIBs from Ireland, a public sector body, institutes working within the battery recycling value chain research sector, and LIB recycling companies. However, due to time constraint and their other commitments, it was not possible to obtain interviews with these stakeholders. This may lead to omission, particularly with the lack of engagement from research institutes, which the author believes would have been especially insightful for this study.

Engagement with key stakeholders from diverse positions, along with the additional data set from a quantitative survey, the author ensured efforts were made throughout the study to warrant a reliable data set and a verified interpretation.

3.9.1.7. Reporting

Results are reported in section four, Data Analysis and Findings.

3.9.2. Quantitative research

A quantitative research strategy in social science is described as necessitating the collection and analysis of a numerical data set, to show the relationship between theory and research, using a deductive positivism approach (Bryman, 2012).

As the research progressed, the author deemed it essential to obtain data from actors who may be directly involved with the manual task of removing and storing an EV battery and their concerns regarding training and the inherent health and safety hazards. While qualitative data was obtained from fourteen key stakeholders working within a position of authority within the industry, a quantitative approach was undertaken with actors working at the ground level, of whom there would be more people, and industry over-views wouldn't be as relevant. A quantitative survey was carried out with these actors, in the whole, making for a mixed-method pragmatic paradigm approach to the research question.

A small-scale convenience sample survey was carried out. A convenience sample is a survey that is available to the researcher by virtue of its accessibility (Bryman, 2012). The author had direct access to light vehicle automotive apprentice students from TU Dublin and fifty-eight apprentices were surveyed. They were asked to consider one open-ended, and eight closed-ended questions, which can be viewed in Table 13.

The author understood that in general automotive apprentices would not be tasked with working directly on high voltage electric vehicle systems, however they may have been exposed to EVs within their workplace. For this reason, the author deemed it beneficial to gain an understanding of their experiences.

The quantitative survey along with the qualitative data, assisted the author in answering research objectives two, four, and five, re-capped in Table 8 below for convenience.

RO2	Appraise the current domain for end-of-life electric vehicle lithium-ion batteries in Ireland.

RO4	Identify and discover, Irelands electric vehicle lithium-ion battery recycling barriers and enablers, if any.
RO5	Formulate a health and safety best practice methodology for pre-recycling operations of end-of-life electric vehicle lithium-ion batteries.

Table 8: Research objectives 2, 4 and 5.

3.10. Limitations

The author aimed to undertake an extensive review and obtain representative data from diverse stakeholders within the electric vehicle value chain, and this was largely achieved, however there were limitations to this study.

The main limitation associated with this research related to timescale. The author wished to interview more actors within the field, specifically international academic institutes specialising in EV battery recycling and an Irish transport company shipping LIBs. Although every effort was made, it was not feasible to obtain interviews with all the stakeholders contacted. This could potentially lead to omissions within this study.

3.11. Conclusion

The research methodology section has outlined the author's research question and objectives, and described the rationale for carrying out this study. It has also classified the philosophical standpoints, alongside the research process and logic, and presented the methods of collecting and analysing the data set.

Due to the technical nature of the study, a mixed-methods pragmatic paradigm action research approach was employed to achieve the research objectives and fulfil the research question.

In order to gain a full understanding of the entire LIB value chain and collect primary data, the author carried out a series of interviews, site visits and a convenience survey, across a diverse array of stakeholders within the electric vehicle domain.

4. DATA ANALYSIS AND DISCUSSIONS

4.1. Introduction

This chapter will present the author's primary data analysis and findings, which aimed to resolve the research question and objectives outlined in section 3.6. and 3.7. The qualitative data from the semi-structured interviews is discussed under nine central themes relating to this research, and the quantitative data from the convenience survey are summarised and explained. In addition, two case studies from Volkswagen and WATT4EVER will highlight the best practices for training and battery repurposing.

4.2. Qualitative Research Analysis

The qualitative research for this study consisted of fourteen interviews with key actors within the EV field, both nationally and internationally. The stakeholders were categorised as public state bodies, vehicle importers and distributors, authorised treatment facilities, economic actors, non-profit companies and industry experts. The interviews were conducted either face-to-face, synchronously over Microsoft Teams, or asynchronously through email. Three of the interviews involved site visits, allowing the author to observe industry best practices first-hand.

Five hundred and forty-three statements relevant to this research were identified using a semantic approach and coded, which is displayed in Table 9. Analysis of reoccurring codes, as explained in the methodology chapter, led to key themes emerging which were colour-coded and grouped under headings shown in Table 10.

The nine key themes which emerged from the semi-structured interviews were:

1. Transport
2. Safety
3. Knowledge
4. Legislation and Regulations
5. Recycling
6. Storage
7. Battery removal
8. Miscellaneous
9. Battery characteristics

Row Labels	Count of Comment text
Transport	60
Safety	58
Safety hazard	51
Legislation outdated	36
Knowledge gap	36
Legislation enabler	34
Knowledge enabler	27
ADR legislation enabler	21
ADR legislation barrier	20
Training requirement	19
Storage	18
ADR legislation	17
Disassembly	15
Extended Producer Responsibility	13
Legislation barrier	13
Recycle	13
Transport barrier cost	8
Recycling barriers – cost	8
Transport barrier	8
Recycle reuse	6
Barrier - cost of recycling	5
IMDG legislation	5
Literature gap	4
Barrier public knowledge	3
LIB chemistry	3
Barrier - government resources	3
Barrier - knowledge gap	3
Technology evolution	3
Special tooling	3
Circular economy	2
EOL recycling	2
Public awareness	2
Challenges – EoL battery value chain	2
LIB chemistry not currently an issue	2
Public knowledge	2
Battery manufacturing	1
Lack of regulation	1
Enabler – ELVES	1
ELV legislation	1
ELV legislation enabler	1
Environmental hazards	1
Battery regulations	1
Initial idea the start of the MSc research – proved wrong	1
Same response form ELVES	1
Recycle circular economy	1
Strategic location	1
Challenges - repair	1
Thermal runaway	1
Battery classification	1
Recycling efficiencies	1
Imported vehicles	1
EOL EV	1
Lack of public knowledge	1
Grand Total	**543**

Table 9: Data corpus thematic analysis. Coded text and number of recurrences compiled from semi-structured interviews – colour coded using a semantic analytic process.

Transport	152
Transport	60
ADR legislation enabler	21
ADR legislation barrier	20
ADR legislation	17
Extended Producer Responsibility	13
Transport barrier cost	8
Transport barrier	8
IMDG legislation	5

Legislation and regulations	87
Legislation outdated	36
Legislation enabler	34
Legislation barrier	13
Lack of regulation	1
ELV legislation	1
ELV legislation enabler	1
Battery regulations	1

Storage	19
Storage	18
Strategic location	1

Battery Removal	19
Disassembly	15
Challenges - repair	1
Special tooling	3

Miscellaneous	10
Barrier - government resources	3
Technology evolution	3
Initial idea the start of the MSc research	1
Same response form ELVES	1
Imported vehicles	1
EOL EV	1

Safety	111
Safety	58
Safety hazard	51
Environmental hazards	1
Thermal runaway	1

Knowledge	97
Knowledge gap	36
Knowledge enabler	27
Training requirement	19
Literature gap	4
Barrier public knowledge	3
Barrier - knowledge gap	3
Public awareness	2
Public knowledge	2
Lack of public knowledge	1

Recycling	41
Recycle	13
Recycling barriers - cost	8
Recycle reuse	6
Barrier - cost of recycling	5
Circular economy	2
EOL recycling	2
Challenges - EoL battery value	2
Enabler - ELVES	1
Recycle circular economy	1
Recycling efficiencies	1

Battery characteristics	7
LIB chemistry	3
LIB chemistry not currently an issue	2
Battery manufacturing	1
Battery classification	1

Table 10: Data corpus thematic analysis. Coded text compiled from semi-structured interviews. The numeric indicator represents the number of times that code appeared. Codes were then colour coded using a semantic analytic process into themes.

4.3. Qualitative Research Findings

Analysis and findings from the nine key themes.

4.3.1. Transport

The transport supply chain plays a crucial role, importing new, and returning EoL LIBs to Europe for recycling. LIBs are considered dangerous goods (section 2.10), therefore transport companies must adhere to ADR and IMDG legislation, which aims to ensure the batteries are transported safely.

Regarding the transportation of LIBs, it became clear that the legislation is effective, and manufacturers are adhering to the regulations. ADR and IMDG legislation has ensured only a few select companies in Ireland can transport EV batteries, and these companies have gained the trust of industry to do so on their behalf. For example, both ELVES and Volkswagen Group use KMK Metals Recycling, while Hyundai use MOBIS for transporting their LIBs. Figure 15 shows the typical shipping precaution stipulated by ADR for shipping LIBs that lead to high costs.

Extended Producer Responsibility (EPR) (section 2.10.1) has also assured that only reputable transport companies will be used by manufacturers and vehicle recyclers, as it is the manufacturers that are liable if the battery falls into the wrong waste stream.

Ireland's geographical nature being an island inflates transportation costs associated with the safe movement of LIBs, and concern was raised by stakeholders about this. Elena Wrelton from ELVES, discussed the hurdles encountered when returning EV batteries from Ireland to the EU:

"*a lot of manufacturers would have a pan-European contract like PSA, where they have an agreement with the recycler. And, that recycler has an agreement with the collection agent. However, the pan-European contracts, they've been written from a European perspective, you know, and it's lovely. If you need a battery collected in France, great. They sort of forget that we're in Ireland and the Irish sea! ... I think for us one of the challenges is the fact that we're in Ireland*."

Ken Byng, from CarTakeBack.com, who are the largest car recycling network in the UK, spoke about the high costs of shipping LIBs and how it may lead to unsafe practices:

"*We've got an agreement in place with a big logistics company and everything that they do is all ADR compliant and it's not cheap, but we only ever use them. There are companies out there transporting batteries illegally, we stay well away from that. It's worth Googling, electric vehicle battery transport fire and there are some videos where a truck goes up in flames and things like that. So yeah, that's exactly what we want to avoid*."

Figure 15: Hyundai EV battery pack ready for shipment. The steel create packaging is an ADR / IMDG requirement, which warrants a high transport cost. Note the "UN3481" ADR designation warning on the box, which will cover the crate. (MMcGuinness, 2021).

4.3.2. Safety

All stakeholders spoke in part or at length about the health and safety aspects associated with EV LIBs. The vehicle importers and distributers interviewed all have similar processes in place to ensure personnel in their distribution and dealer networks, when working with EV batteries, are equipped to do so safely. Training courses are conducted centrally for knowledge-consistency, and technicians are taught the correct health and safety procedures and how to apply them. An importance is also placed on supplying the recommended tooling and providing training of how to work safely when in the vicinity of an EV high voltage components.

A safety point of note that emerged during the analysis, was that industry training focused more on the high-voltage hazard of LIBs than anything else. Of the five manufacturers interviewed, the central focus of their EV technician training was to inform of the high voltage risk associated with an EV, and how to mitigate the danger of electric shock. Although this may seem obvious, the main safety themes that emerged during the literature review was risk of thermal runaway, and not high voltage. This highlights an area that requires further academic research.

The questions surrounding safety also affected authorised treatment facilities (ATFs), and a knowledge gap was identified by this study. ATFs do not have direct access to manufacturer's technical data, which is required if they are dismantling a vehicle safely. ATFs use a system known as IDIS (International Dismantling Information System), which was set up under ELVs directive. Both ELVES and CarTakeBack.com, whom represent a large number of ATFs, stated that the information available on IDIS has shortcomings.

One interviewee said the information on the IDIS system is "hit or miss", and that IDIS was "*a box ticking exercise for manufacturers to say yeah, look, we've complied with the ELV directive*".

IDIS will become a critically important information source for ATFs as the EV market grows in Ireland. It provides information about correct methods of power down, and how to make an EV safe before removal of the battery, so all interested stakeholders should ensure that IDIS is fully functional going forward to mitigate the risk of accidents.

Divergent safety methodologies employed by different organisations while working on EVs became apparent during the interviews and site visits. Certain equipment is legislated and standardised, for example, insulating latex class-00 gloves, EN60900 insulating hand tools and warning signage for working on or around EV live circuits. However, the commonalities do end when manufacturer-specific methodologies come into effect. As an example, different manufactures and even different models from the same manufacturer, have different processes to 'lockout'[3] an EV, Figure 16 highlights the different lockout service plugs.

The author perceives the study's findings relating to safety as an issue of concern for personnel working on EVs in the future. Specifically, this concern centres upon organisations outside of the automotive main dealer / repairer franchise, such as independent repairers and ATFs. If technical information is not readily available, up to date or accurate on generic systems such as IDIS, the potential for accidents to occur will exist. This may present a barrier in the future to a circular EV battery value chain.

[3] Electric vehicle lockout, is a process where an EV is made safe to work on. A technician follows a number of steps to remove a service plug which powers down the high voltage battery and lock it out, so it can not be powered up accidently.

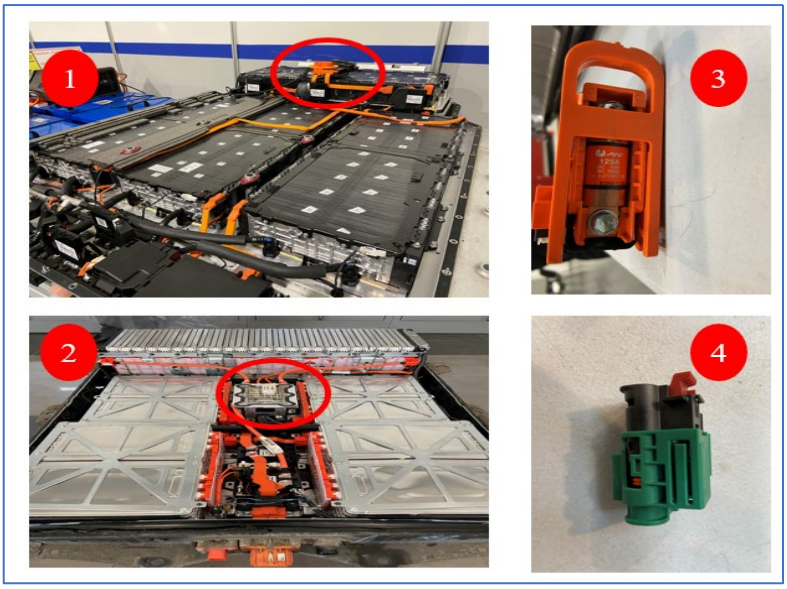


Figure 16: Example of different EV LIB packs and service plug locations (1-Hyundai; 2-Nissan) and lockout plugs (3-Toyota & 4-Volkswagen). Lack of standardisation is a potential safety hazard. Items viewed by the author during site visits (MMcGuinness, 2021).

4.3.3. Knowledge

All automotive manufacturers and ELV organisations interviewed, reiterated how essential EV safety training was for their operation. Denis McCrudden of Hyundai, stated that "*EV training and health and safety knowledge is extremely important*" as an enabler to allow the dealer network to operate autonomously.

It was noted that because the EV industry is relatively new, some manufacturers are further developed in delivering EV training than others. Nissan, who were first to mass market an EV with the Leaf, have a well-established curriculum. Their Aftersales manager, Alan McDermott said, "*all Nissan dealers are both trained and certified to remove the complete high voltage battery pack*". While Hyundai, who also have a large EV fleet on Irish roads, have two different levels of EV technician: HVT and HVDT, which qualifies them to repair LIB packs if required. Other manufactures who are only now bringing EVs to market are in the process of developing, standardising and improving the training of their networks with regards to EVs.

Both ELVs companies interviewed said they are currently running EV awareness training for their networks. When asked what the training entails, Elena Wrelton, who organises EV training for Irish ATFs said:

"*it covers the key risks in terms of things like high voltage arcing, fire, puncturing of the battery, that kind of thing. And the basic steps of shutting the vehicle down yeah, but always with* *reference to IDIS, because each vehicle is different. Umm, it goes through a little bit of first aid, and it also goes through things like the PPE needed*".

Knowledge gaps also presented themselves during the research. One organisation stated that only seven percent of their network were trained to process EoL EVs, however it was acknowledged this was sufficient to provide their coverage, as they operated a 'hub and spoke' type network.

Elena Wrelton also spoke about the disruption of COVID. She said ELVES had not carried out face-to-face training since 2019, a point echoed by John Gaffney of Nissan and Robert Guy of Volkswagen.

Ken Byng spoke about the lack of general awareness around EoL EV LIBs as a major barrier. He stated: "*there does seem to be a real lack of knowledge amongst the general public, and even some ATFs as to the correct course of action for an end of life EV battery, which is another barrier*". He believes a combined approach from industry and government to publicise the hazards of EV LIBs, and how to correctly dispose of them would be beneficial. He added: "*But it's very difficult. You know, the people who are charged with looking after anything end-of-life you know, vehicle related. They're underfunded and under resourced. It's really difficult, and they're fighting fires really*."

The author hadn't previously considered the implications surrounding lack of public knowledge regarding EoL LIBs. This discussion led to the private buying and selling of second-hand EV batteries and the serious safety hazards this practice poses to the public. Ken Byng described how internet sites like eBay advertise EV LIBs for sale (Figure 17 and 41) and there are no regulations around this cottage industry. This was a new finding for the author, which was also reiterated by John Dockrell the Managing Director of an ATF in county Dublin. John said that if he scrapped Toyota Prius models, he can sell the used nickel-cadmium batteries to an operator in Carlow, who reconditions them for resale.

The author also deems of significant interest that the foremost comment from industry in relation to the 'knowledge' theme, was the concerted effort to ensure all actors within their own networks were familiar with the safety hazards posed by EV LIBs and address any internal knowledge gaps. The second-hand market surrounding used EV batteries was a new finding for the author, as it did not emerge during the literature review, yet no-one has a vested interest to train, warn and close the knowledge gap in this unregulated area

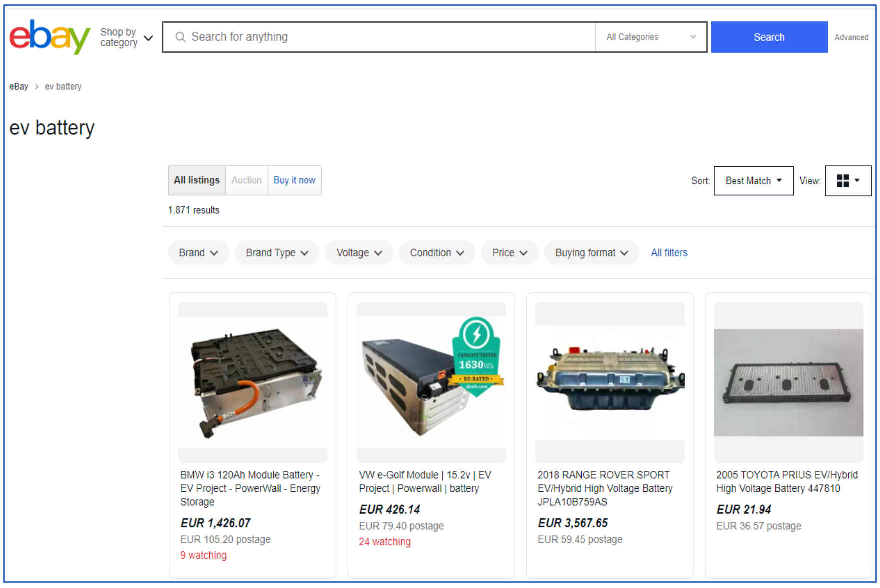


Figure 17: Second-hand EV batteries for sale on eBay. Lack of public awareness around the EoL LIBs was highlighted as a barrier to a correctly functioning circular battery value chain (ebay.ie, 2021).

4.3.4. Legislation and regulations

The main findings regarding legislation and regulations is that they are working, but they need modernizing to avoid contradiction. This theme had emerged during the literature review and was confirmed when speaking to industry stakeholders. Due to the fact that EVs are an emerging technology, they are covered by a number of different regulations, as displayed in Table 11.

Directive 2006/66/EC; batteries and accumulators and waste batteries and accumulators.	2006
Directive 2000/53/EC; on end-of life vehicles (ELV Directive)	2000
Directive 2012/19/EU; on waste electrical and electronic equipment (WEEE) (Extended producer responsibility - EPR)	2012
ADR: Agreement concerning the International Carriage of Dangerous Goods by Road	Introduced 1985, regularly updated
IMDG: International Maritime Dangerous Goods Code	Adopted 1965, mandatory 2004
Proposal for a Regulation concerning batteries and waste batteries, repealing Directive 2006/66/EC and amending Regulation (EU) 2019/1020 (New battery regulations)	Proposed December 2020, under review

Table 11: EV batteries fall under a number of different legislative and regulatory requirements.

Some stakeholders commented that the evolving nature and amount of the legislation can cause barriers. The main criticisms aimed at EoL EV regulations is that EVs fall under the various protocols of ELVs, EPR and the battery directive, which were published before the proliferation of EVs. Elena Wrelton said "*there are gaps, which they're (EU Commission) obviously very aware of, which is part of the reason why they're revising both at the moment*" in relation to the current legislation.

This said, the current regulations are having the desired effect; that being, improving rates of correct disposal of EoL EV batteries, while mitigating safety and environmental risk.

Johannes Chatzis, a Project Manager with IDIS explained that the ELV directive legally obligated automotive manufactures in the EU to make their technical data available to all actors within the ELVs domain. And Maurice Brady of TU Dublin, noted that transporters are now forced to follow strict protocols when shipping LIBs because they are a 'Class 9' dangerous good, under ADR and IMDG legislation.

A trend that surfaced during the interviews, specific to Ireland and legislation, was in relation to UK imported vehicles. Conor Leonard, a Battery Operations Manager at WEEE Ireland outlined the topic. *"Under WEEE directive 2002/96/EC, when a distributor sells a battery, they must make a payment, which is used to fund a sustainable approach to waste management. In Ireland this fund is managed by WEEE with a system known as Blackbox. EV batteries are included in this scheme."*

The issue raised by Conor Leonard was that the Irish car market includes vast amounts of UK imported or, '*orphaned*' vehicles as he referred to them, which have not contributed to the Blackbox scheme at start-of-life. Conor said, "*orphaned or imported vehicles, are a huge issue for the Irish motor industry. Who will cover the cost of the imported vehicles when they reach EoL or require a battery replacement?*"

Robert Guy also touched on the same point and suggested the governmental bodies will expect industry to pay for the waste management cost of UK vehicles, which he argues against. "*A lot of people imported them (used cars from UK) and have not paid their fair share. People will look for a vehicle certificate of destruction at EoL and they say, well, hang on, you (person who imported vehicle) didn't pay your subscription and I think the legislators will come to the OEM and say this is your baby and I'll say well it is not. It's not big thing, but it's another layer. It should be a barrier to registering an imported vehicle."*

The EU commissions new draft regulatory framework for batteries (see section 2.10.1) published in December 2020, should help to reduce many of the current issues discussed.

4.3.5. Recycling

EV LIBs have a relatively long lifespan. This, coupled with the fact that Ireland's EV market is still in its infancy, means few batteries have yet to reach EoL. John Dockrell a scrap yard operator, confirmed he has yet to be presented with an EV at his premises.

The EPA currently report the recycling efficiency rates for automotive lead-acid and consumer lithium-ion batteries (EPA, 2021), however there is no specific data on the amount of industrial EV batteries recycled, as they get counted in with consumer LIBs. Conor Leonard of WEEE Ireland agreed with this sentiment, stating that the actual amount of EV LIBs returned for recycling is "*difficult to pin down*", but through information from WEEE contractors, he estimated approximately four batteries per annum are returned from EoL EVs.

This estimation does not consider LIBs returned under warranty. Hyundai, Peugeot and Volkswagen said they have returned LIBs to their respective recycling centres under warranty, which would not be recorded with either EPA or WEEE. Nissan stated that they only return the individual battery modules for recycling, and not full battery packs, as they opt to repair before replacing entire units.

The manufacturers interviewed confirmed that they each carry out different work-flows for the pre-recycling steps. For instance, the Hyundai dealer network are each authorised to remove LIBs themselves and return the EoL unit directly to Germany for recycling, while other manufacturers require that the vehicle is returned to their head office first, where specialist trained EV technicians remove the batteries. The author contends that because Nissan and Hyundai have been selling EVs longer than the other manufactures interviewed, their high voltage training program is further developed to facilitate battery removal. The other vehicle distributors confirmed that as their EV footprint grows, it is likely that their dealer network will carry out the pre-recycling operations of removal and transport from site.

4.3.6. Storage

Generally, the stakeholders interviewed did not consider the storage of EV LIBs to be a major issue, which ran contrary to the literature review research. None of the manufacturers that the author spoke to currently store new, used or EoL LIBs on their premises.

All five manufacturers affirmed that if a traction battery is to be replaced on an EV, the actor involved simply orders a new one through their parts chain, which is then delivered from Europe or the UK. When the new LIB arrives, it is immediately fitted to the vehicle and the defective/expired LIB is returned for recycling, generally by the same transporter on the same day.

Tadgh Cronin, Technical Training Manager form Volkswagen, provided additional information on storage. Table 12 below, outlines the specific conditions in which LIBs should be stored to ensure utmost safety and associated risks are mitigated.

Requirements	Temperature	• Between 5 & 20°C, recommended 20°C.
	Light	• No direct sunlight
	Area	• LIBs need to be stored in a designated area. • Sorting of LIB in office building strictly prohibited.
	Packaging	• LIBs have to be stored in original transport packaging. • Damaged packaging has to be replaced immediately by qualified staff.
	Damage	• Moving damaged LIBs only allowed by qualified staff. • Follow rules for noncritical LIBs. • Status warning LIBs need to be stored in quarantine zone outside of the warehouse. • Do not try to fix LIB in the warehouse.
Recommendations	Area	• Quarantine zone for all LIBs. • LIBs should be 2.5 metres in distance from warehouse materials. Or separated by flame-retardant wall. • Do not store LIBs with other dangerous goods. • Quarantine zone recommended >5 meters away from building.
	Equipment	• Sprinkler protection
	State of Charge	• SoC should be monitored. Deep discharge avoided.

Table 12: Volkswagen aftersales: Required and Recommended storage conditions for Lithium-ion Batteries – country specific (adapted from interview, Volkswagen, 2021)

4.3.7. Battery removal

Removal of the EV LIBs is a key step in the pre-recycling process, and one that will take place onsite, in Irish automotive repairers and ATFs. The main themes to emerge around this topic were having access to valid technical documentation in the case of ATFs, addressing the knowledge gap generally and access to special tooling required for automotive repairers and ATFs.

If an ATF needs to remove a battery, they currently access the 'IDIS' system, which will provide the technical steps and safety requirements to follow. However, being generic, there are shortcomings within the IDIS system as previously outlined in the safety section 4.3.2. Again, the knowledge gap has been discussed in this regard. Generally, all organisations interviewed have already trained, and continue to train their respective networks on all aspects and stages of battery removal.

The removal of EV LIBs also requires an assortment of special tooling as showing in Figure 18, which may prove a barrier for some businesses within the field. Tadgh Cronin, stated the importance of safety around everything Volkswagen do in relation to removal of LIBs and pointed out that the personal protective equipment (PPE) alone required for their high-voltage trained technicians costs one-thousand euro per-person, because they are working on batteries with up to eight-hundred volts. All manufactures noted that their networks require heavy-duty lifting tables to remove EV LIBs and Martin Dunne from Peugeot Ireland stated that the tables cost over four-thousand euros.

The high cost of special tooling, which is deemed essential to mitigate the safety risks associated with EV LIBs, may be an inhibitor to correct removal, especially for independent repairers and ATFs where the removal might occur less frequently than for a manufacturer's dealer network. The author foresees a potential risk for any actors who are tempted to remove a battery without the correct tooling, as a serious accident becomes all-the-more likely.

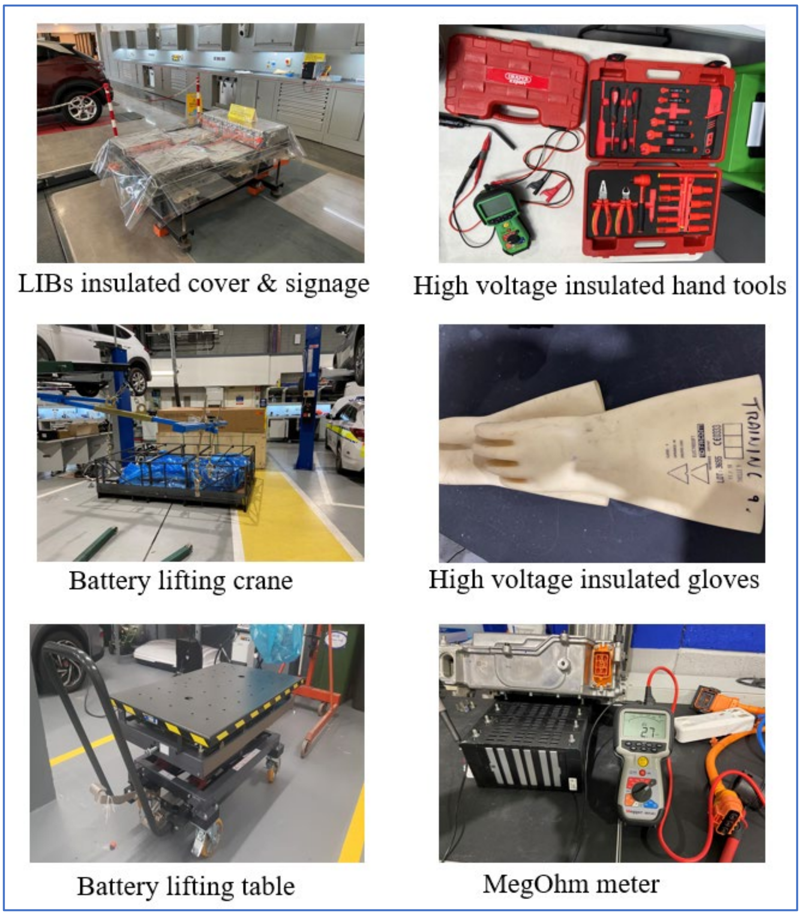


Figure 18: Examples of special tooling and PPE required when working on, or removing EV batteries. The various items are of a considerable cost, which may entice actors to cut corners. The items are from different manufacturers, viewed by the author during site visits (MMcGuinness, 2021)

4.3.8. Miscellaneous

Themes that emerged during the data analysis that were points of interest to the author, but did not fall under other codes were deemed miscellaneous.

A comment from Robert Guy about the rapid EV market growth within the last twelve months, led to a discussion around the challenges that have arisen from this. He said the swift advancement of technology has presented a large workload in all areas of his company generally. New operational standards were necessary, and education for both staff, customers and the general public were required.

Elena Wrelton and Alan McDermott both spoke about having to train staff online because of COVID. Alan and his colleague, John Gaffney were unsure about how effective this type of training can be, because working on LIBs is a physical and hazardous operation. They stated that working with the required PPE restricts normal movement and requires actual practice to achieve the dexterity needed in hand and body movement. They added that anyone in their network, who all online EV training, will have to complete the same training again in person.

4.3.9. Battery characteristics

The author invested significant effort during the literature review to understand the varying physical and chemical characteristics of the LIB. This was due to the fact that the cathode type is a key factor when considering the type of recycling process the battery may undergo at EoL. However, this topic did not figure largely while speaking to industry stakeholders.

When asked if the cathode chemistry determines where a LIB is sent for recycling, WEEE Ireland said it does not at this time. They stated that they have two processors in Germany that all LIBs handled by them are returned to for recycling, but that the recycling companies themselves sort the LIBs based on chemical make-up.

The same question was put to the automotive manufactures, who generally did not know what type of cathode chemistry was prevalent in their EV LIBs. If they needed to return a LIB, it was arranged through their supply chain, so the battery characteristics were not relevant.

Conor Leonard of WEEE, also mentioned that LIB recycling in Europe is currently at capacity, but there are plans to build specialist recycling plants, which was highlighted in the literature review. He also said that some recycling plants who specialise in certain cathode types may begin to align themselves with particular manufacturers, however as with the EV topic as a whole, Conor noted that "*lithium recycling is still at a global development phase*".

4.4. Quantitative Research Analysis

The stakeholders interviewed for the qualitive data analysis generally represented individuals whom held high-level positions within the EV field.

The author also took the opportunity to conduct a small-scale convenience survey, participated in by fifty-eight light-vehicle automotive apprentice students from TU Dublin. The rationale for this survey was to ensure the validity of the qualitative data surrounding EV health and safety with a quantitative contrast in attempt to gain an understanding of the level of awareness of front-line workers in the field.

Some of the automotive apprentices would have been exposed to EVs within their places of employment. This survey assessed the apprentice's rudimentary knowledge of the risks associated with EV LIBs in order to create a quantitative critique of the EV health and safety topic 'on the ground'.

1. Do you work for a franchised main dealer?	YES	NO	I don't know
2. Have you received electric vehicle **health and safety** training?	YES	NO	I don't know
3. Have you received electric vehicle "**Lock-out**" training?	YES	NO	I don't know
4. At which **voltage ranges,** do electric vehicle **batteries** operate?	50 – 200v DC	50 – 400v DC	I don't know
5. At which **voltage ranges** do electric vehicle **traction motors** operate?	50 – 200v AC	50 – 800v AC	I don't know
6. At which threshold can **AC current** cause **electrocution**?	0.5 Amps	5 Amps	I don't know
7. Would you attend electric vehicle high voltage training, if the opportunity presented itself?	YES	NO	I don't know
8. Do you intend to work with electric vehicles in the future?	YES	NO	I don't know
9. Please name **five** pieces of **automotive high voltage PPE**?			

Table 13: Automotive apprentice questionnaire.

The apprentices were asked one open-ended and eight close-ended questions shown in Table 13. Questions four to six are basic EV health and safety information that would typically be taught in a foundation EV course.

4.5. Quantitative Research Findings

An overview of the apprentice survey responses is displayed in Table 14 below. The individual questions were analysed in further detail in Figures 19 through 24. The survey suggests that in relation to EV health and safety, there is a marked benefit to working within a franchised main dealer.

In summary, the main findings to emerge from the apprentice survey were;

- Apprentices employed by franchised main dealers have greater opportunity for continued professional development, compared to those working for an independent repairer.
- There is a lack of understanding surrounding the electrocution threshold current.
- Apprentices employed by a franchised main dealer are more likely to have been exposed to EVs and their safe working practices.

Automotive apprentice questionnaire regarding Electric Vehicle health & safety working practices				
Row Labels	Sum of **Yes**	Sum of **No**	Sum of **I don't know**	Sum of **Total responses**
Have you received electric vehicle health and safety training?	10	48	0	58
Please name five pieces of automotive high voltage PPE?	11	47	0	58
Have you received electric vehicle "Lock-out" training?	3	55	0	58
Would you attend electric vehicle high voltage training, if the opportunity presented itself?	53	5	0	58
Do you work for a franchised main dealer?	31	26	1	58
Do you intend to work with electric vehicles in the future?	43	7	8	58
Row Labels	Sum of **Correct**	Sum of **Incorrect**	Sum of **I don't know**	Sum of **Total responses**
At which voltage ranges, do electric vehicle batteries operate?	36	4	18	58
At which voltage ranges do electric vehicle traction motors operate	15	9	34	58
At which threshold can AC current cause electrocution?	18	19	21	58

Table 14: Collated data from apprentice survey responses. Carried out in TU Dublin 21.10.2021.

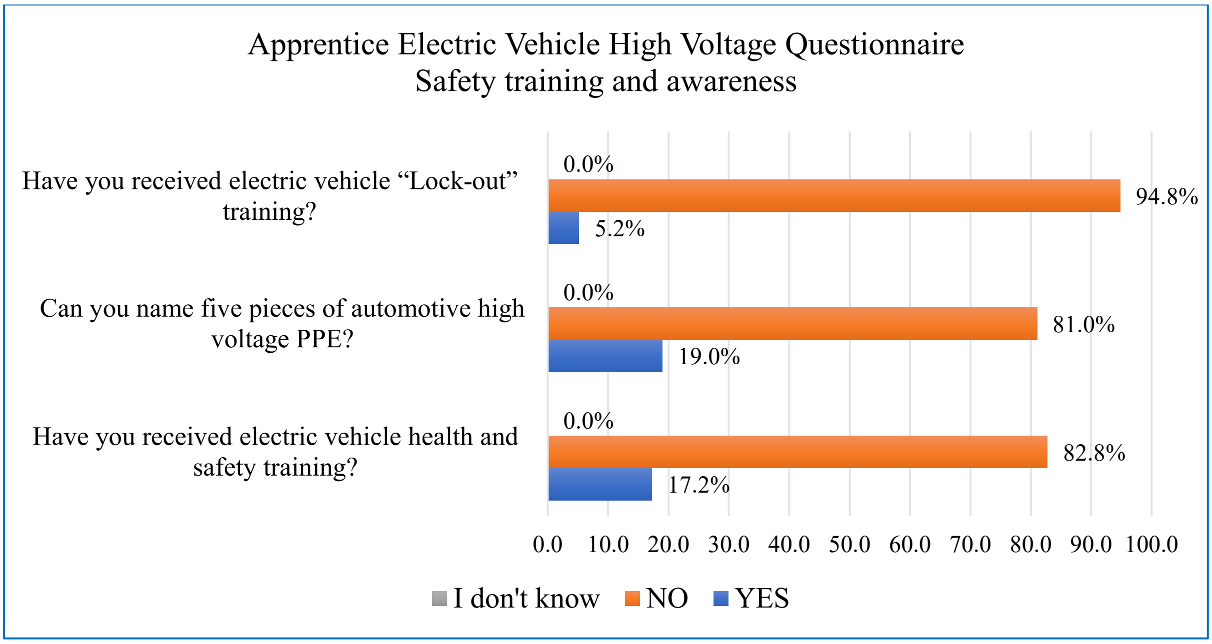


Figure 19: Electric vehicle high voltage safety training and awareness.

17% of apprentices surveyed say they have completed EV health and safety training, but only 5% received lock-out training and over 80% could not name five pieces of EV PPE.

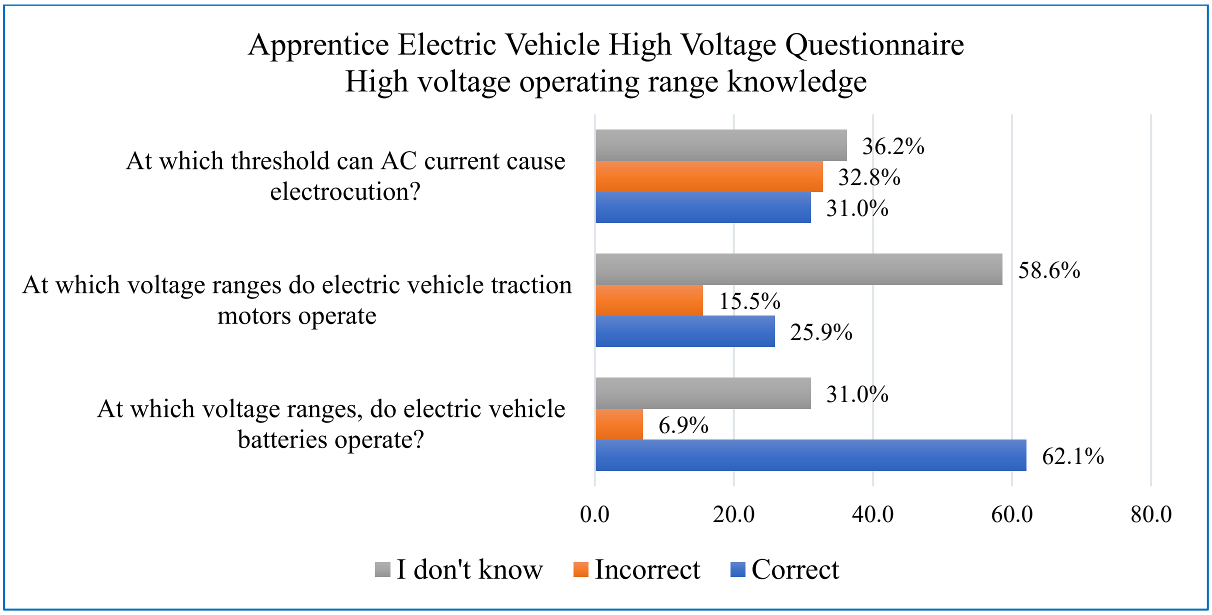


Figure 20: Basic knowledge of electric vehicle high voltage operating ranges.

62% of apprentices knew the voltage operating range of EV LIBs, but this dropped to 26% regards their understanding of the working range of an EV traction motor. The level of understanding regards the dangers of current was poor, with 69% answering incorrectly or not knowing the electrocution threshold in Amperes.

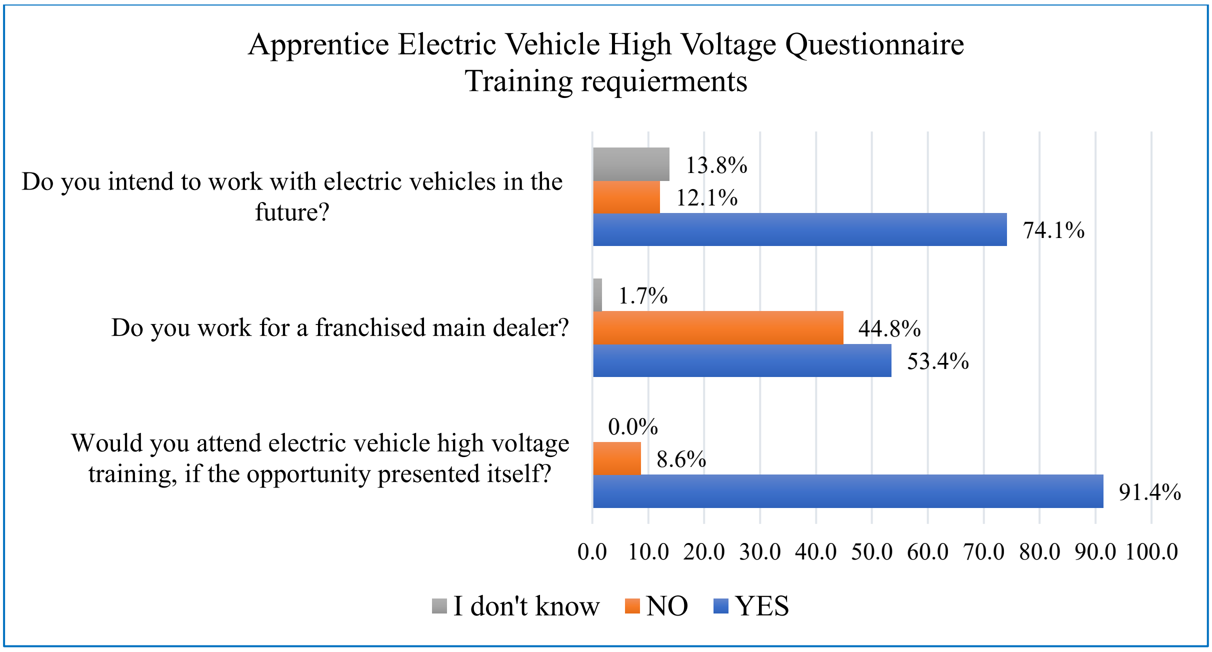


Figure 21: Electric vehicle training requirements.

The results show that apprentices are ready and willing to engage with new EV technology. 91% of students surveyed expressed willingness to attend an EV training course.

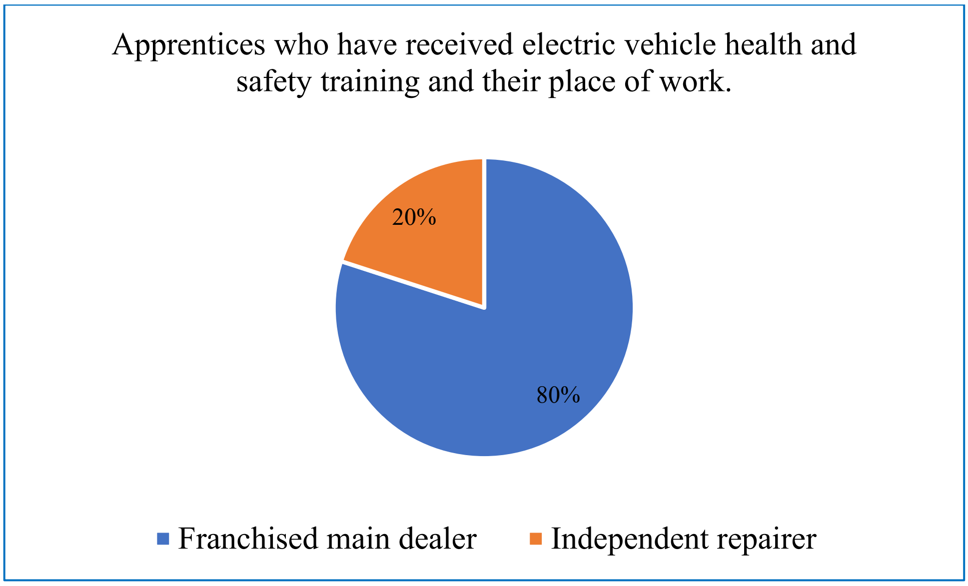


Figure 22: Apprentices who received electric vehicle health and safety training - broken down by place of work. Franchised main dealer versus independent repairer.

Apprentices who worked at a franchised dealer were four times more likely to receive EV training, compared to those working for an independent repairer. This highlights that apprentices employed by a branded franchise, have significantly more opportunity for continued professional development

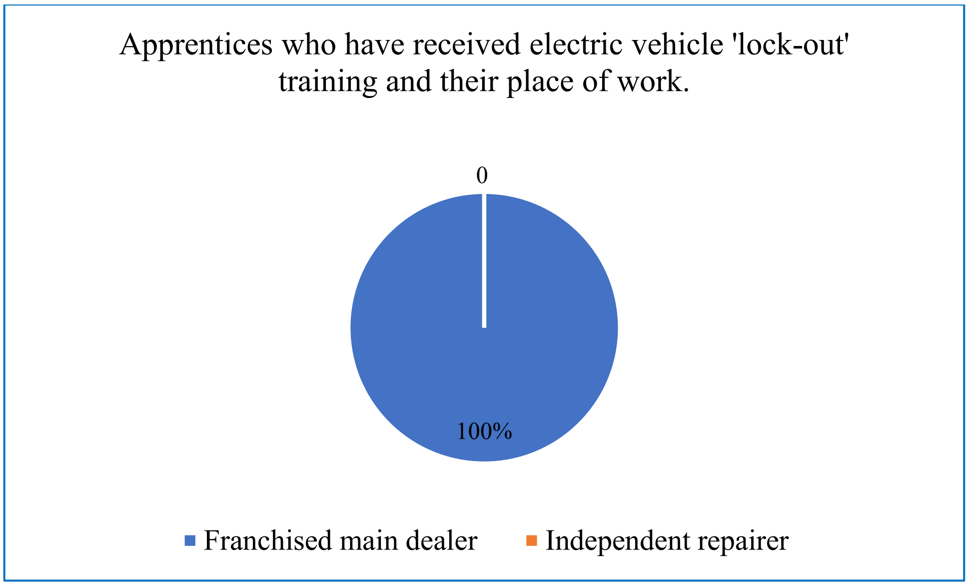


Figure 23: Apprentices who received electric vehicle ‘lock-out’ training - broken down by place of work. Franchised main dealer versus independent repairer.

Only apprentices who were employed by a franchised dealer received lock-out training. This highlights a skills gap within the independent repairer field and warrants further investigation.

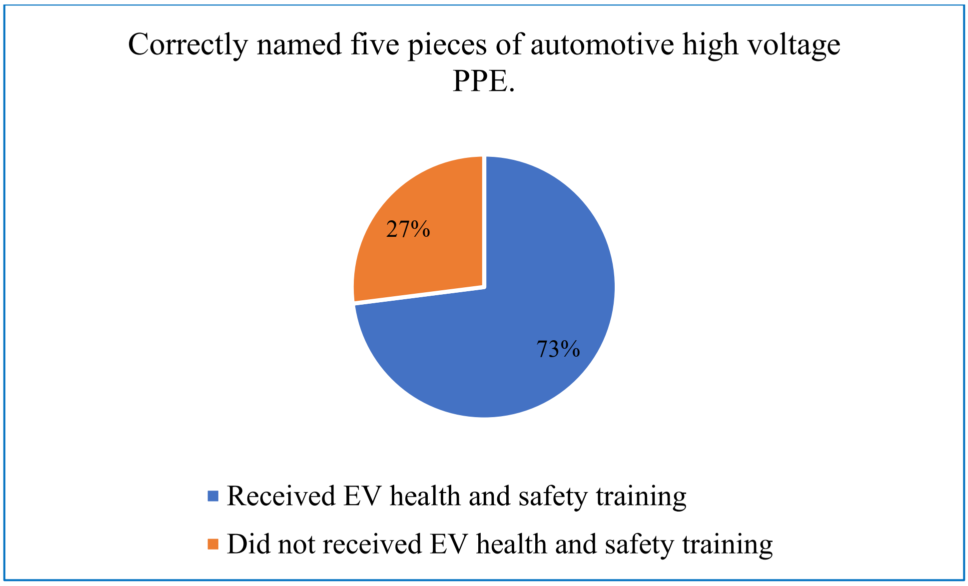


Figure 24: Apprentices who correctly named five pieces of EV PPE, broken down into attended EV training versus those who did not.

The apprentices who could correctly list five pieces of EV PPE, were all employed by a franchised main dealer. This suggests that although 27% have not completed EV training, they have been exposed to correct EV working methods.

4.6. Case study: Volkswagen Group Ireland

Volkswagen Group Ireland (VWG) have seen sales of EVs grow by over four-hundred percent within the last twelve months (SIMI, 2021c). Aftersales Director, Robert Guy stated that this is creating new challenges for the business. One of these challenges is ensuring that their dealer network is fully trained and equipped to deal with this new market.

Tadgh Cronin outlined the VWG EV technical training program to the author during a site visit to their National Learning Centre. He said there are three distinct levels of EV training:

Electrically Instructed Person: This is an employee who has received core online training that all dealer staff must complete. This course covers identification, handling and dangers of EVs.

High Voltage Technician: This covers the general technician employees and this hands-on course teaches the risks of working on EVs, classification of batteries and LIB lock-out procedures.

High Voltage Expert: This training allows a technician to diagnose and repair an EV LIB, and allows technicians to work on a faulty EV, for which the LIB cannot be successfully de-energised to make the vehicle safe.

The author found the VWG training centre extremely impressive. It was clear that a large capital investment had been made by the company to ensure the instructors were expertly schooled and the latest equipment was available to them for training their network. The author deems this type of training necessary for any person intending to remove an EV LIB at EoL for recycling.

The high standards being implemented by VWG may not be attainable for all businesses within the EV domain however. The author sees the costs associated with conducting highly technical, hands-on and equipment-intensive training, as a potential barrier, as not all organisations will be able to implement the same standards due to cost. This may lead to untrained operators attempting to remove LIBs, which will heighten the potential for accidents to occur.

4.7. Case study: Watt4Ever

Watt4Ever is a Belgian company who provide a second life for EV batteries that have reached their automotive EoL. The organisation process decommissioned EV LIBs and disassemble them, then rebuild them into stationary storage energy systems. Their mission statement says, "*We strive to provide affordable, sustainable and local storage solutions driven by a circular* *economy… by …recycling high-voltage batteries…this helps to reduce the ecological footprint of EVs. Watt4Ever's mission supports the objectives of the EU Green Dea*l" (Watt4Ever, 2021).

Fredericq Peigneux, a Business Intelligence Officer in Watt4Ever, outlined his company's framework to the author. The company has contracts with clients, mainly manufacturers who were early to the EV market, then commandeer their EoL LIBs and dismantle the battery packs to module level. Due to the inherent LIB hazards, their technicians use a multitude of high voltage PPE and tooling during this process. Fredericq noted that the disassembling is a manual process and automation is difficult because of the lack of standardisation in LIB design. This was an issue highlighted in the literature review. The battery modules that cannot be repurposed are recycled using Hydro or Pyro-metallurgical processes depending on suitability. The good battery modules are then re-assembled into stationary storage systems, as displayed in Figure 25 (researched in section 2.7).

When asked about any potential barriers for the business, Fredericq said that not all LIBs can be repurposed. Batteries with cathode chemistries of NMC, NCA and LFP are preferable, in line with section 2.4.1.

Watt4Ever provide a solid business and environmental case, demonstrating how the EV battery circular economy value chain, with regards to reuse and second life, could be implemented in Ireland.

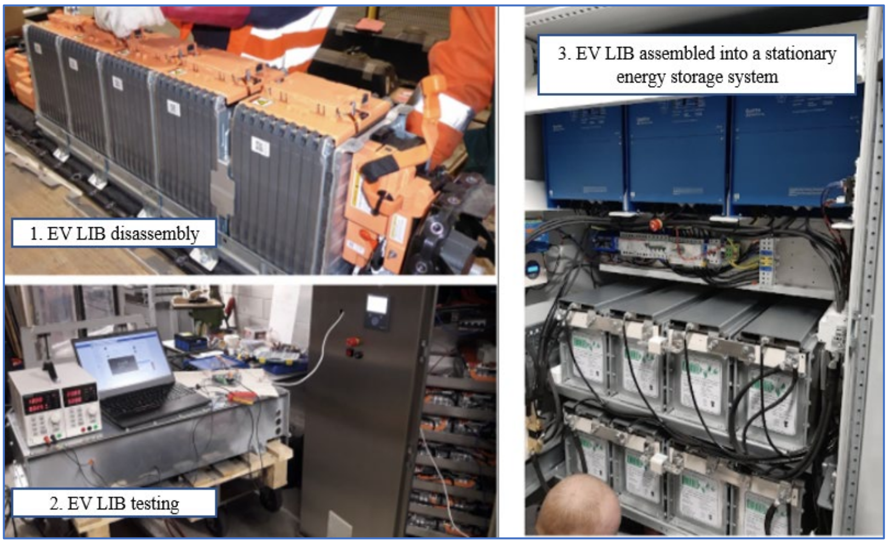


Figure 25: Watt4Ever reusing an EoL EV battery for a stationary storage system (Watt4Ever, 2021)

4.8. Data Analysis and Discussions Conclusion

Important themes and findings emerged during the primary research of this study. The EoL waste management of EV batteries and their transport is regulated by legislation, that although is proving adequate in mitigating the safety and environmental hazards, requires comprehensive modernising. This agrees with the literature review.

Storage is currently not an issue for the Irish EV market, as all actors stated they do not store LIBs onsite. If a LIB is replaced on an EV, the removed unit is generally returned to Europe for recycling the same day, by the same transport company delivering the new unit. The transport of the LIBs is carried out by specialist companies who must adhere to ADR and IMDG legislation.

Organisations are working hard to train their networks and fill any knowledge gaps surrounding EVs, with a particular focus on high voltage health and safety. Site visits were made to Hyundai, Nissan and Volkswagen training centres, while the author also attended EV level 3 high voltage training run by Bosch and the SIMI to witness the knowledge transfer first-hand. It was apparent that this type of training must be hands-on and requires a large capital investment, as the photos displayed in Figures 26 and 27 allude to. The associated costs involved in running safe EV training courses may lead to different standards being delivered by different actors, which may increase the risk of an accident.

The survey of light-vehicle automotive apprentices exposed a training gap between manufacturer networks and independent repairers. Apprentice employees of franchised main dealers were found to have a better general knowledge of EV high voltage hazards and more opportunity to upskill, when compared to apprentices who work for independent repairers.

A barrier to safe LIB working practises that also emerged from the study was access to relevant information for actors outside of a manufacturer network. This was highlighted as a serious issue in particularly for ATFs, who will be charged with carrying out the pre-recycling phases of EoL EVs in the future, but rely on generic information rather than specific product disassembly training.

Other concerns were uncovered from the study that were not considered beforehand. The lack of regulation of second-hand LIBs in the private online sectors like eBay, along with the EoL recycling costs for imported vehicles in particular were examples of this.

Various enablers around Irish EoL EV LIBs were also discovered. Many organisations are currently training their network on the correct and safe working practices of EVs. State-of-the-art training facilities run by Volkswagen, demonstrate best practices from an Irish perspective, and could be as used as a benchmark for the industry. While Watt4Ever presented the possibility for a new business model repurposing LIBs, that poses future opportunity for the Irish market.

Figure 26: MKW Bosch electric vehicle high voltage training. The equipment displayed highlights the large capital investment required to run EV training (McGuinness, 2021).

Figure 27 Hyundai Ireland, electric vehicle technical training centre. Lithium-ion batteries, electric vehicles, diagnostic tooling and equipment, create significant costs for educating actors in this new technology (MMcGuinness, 2021).

5. CONCLUSION AND RECOMMENDATIONS

5.1. Introduction

Chapter 5 denotes the conclusions based on the findings from this research. A summary of the research objectives and relevant recommendations will be put forward based on developed conceptions from the research.

5.2. Research Objectives Conclusions

5.2.1. Identify and analyse, electric vehicle lithium-ion battery recycling methods

Recycling EV LIBs is a technically complex process which requires large scale capital investment. Pyro and Hydro-metallurgical methods are currently used by battery recyclers to achieve this. At the time of writing, the cathode chemistry largely denotes the economic value in recycling the LIB, and the type of recycling process it will undergo.

The recycling efficiency of Pyro and Hydro-metallurgical methods varies greatly. Northvolt, recently stated they can now recycle ninety-seven percent of material from an EoL LIB using the Hydro-metallurgical method. Direct recycling, although not yet commercialised, promises to be a more environmentally friendly form of recycling. This is because the recovered materials may be used directly for new cathode production without the further processing required by recycling technologies.

LIB recycling is currently at capacity within the EU, but plans for up to twenty Gigafactories, many with in-house recycling facilities, will come on stream over the coming years (Ortiz and Careaga, 2021).

The EU commission has acknowledged that batteries are of ‘strategic importance’ for the emergence of EV technology and aim to future-proof all aspects of the market. They also note the elemental materials of LIBs are finite and the supply of these raw materials is not guaranteed. To reduce the EUs supply-chain risks, a new Batteries Directive has been proposed, which will ensure the LIB life-cycle moves away from linear supply and becomes circular. This will reduce the environmental and social impacts of LIBs, while also assisting the bloc to reach net-zero emissions by 2050.

5.2.2. Appraise the current domain for end-of-life electric vehicle lithium-ion batteries in Ireland

Legislation ensures that EoL LIBs in Ireland are correctly recycled, but currently only a small number of EV LIBs are reaching EoL in the state. WEEE Ireland approximated that four batteries per annum are returned for recycling to the EU, however this does not include LIBs replaced under manufacturer warranty, or due to technical incidents and recalls.

All Irish organisations interviewed for this study are in the process of training their networks to meet the emerging technical and safety concerns surrounding EVs. These training undertakings are extremely important to ensure that front-line operators understand the dangers associated with LIBs and can apply correct methodologies when working on the vehicles. The cost of training and equipping staff with PPE and tooling is significant, and this has led to different standards being employed by different organisations. This is a potential area for concern, as the hazards present for all LIBs are largely the same.

This research highlighted an anomaly within the Irish market in relation to UK imported vehicles. A scheme known as Blackbox operated by WEEE, compels EV distributors in Ireland to contribute to a fund during EV registration that is directed to the correct and sustainable waste management of LIBs at EoL. Used vehicle imports escape this fee, which presents an impending financial constraint for future recycling efforts, as over the last five years an (SIMI, 2021b).

5.2.3. Evaluate and assess, national and international end-of-life electric vehicle lithium-ion battery pre-recycling practices.

The literature review presented a knowledge gap with respect to the pre-recycling phases of safety, disassembly, storage, and transport. Although limited knowledge was gained from international stakeholders about pre-recycling practices, the Irish stakeholders discussed the topic at length.

Storage is currently not an issue from an Irish perspective, while ADR and IMDG legislation is ensuring only specialist transportation companies move LIBs overseas for processing. It was noted by Ken Byng of CarTakeBack.com, that because of the high shipping costs associated with LIB transportation, some companies are not adhering to the regulations and moving them illegally, which has resulted in accidental fires.

Lack of access to specific technical documentation was highlighted as a major issue for organisations outside of a manufacturer network, in particularly ATFs, who are charged with dismantling EoL EVs to remove the LIB. This issue was an area of concern for companies in Ireland and also the UK.

Safety during LIB removal was a reoccurring theme to emerge from all stakeholders interviewed. As discussed section 5.2.2, organisations are currently investing much time and resource into training their networks to manage the emerging EV market.

5.2.4. Identify and discover, Irelands electric vehicle lithium-ion battery recycling barriers and enablers, if any.

Most manufacturers interviewed fully understood the complete life-cycle of an EV, but several barriers emerged in relation to Ireland's LIB recycling field. Knowledge gaps were identified, both at organisational and operator level.

The author uncovered specific technical barriers faced by ATFs, who do not have access to model-specific EV documentation on LIB removal. One stakeholder had not considered EV EoL an issue for third parties, due to an incorrect but understandable assumption that EoL EVs could never end up outside the manufacturer's network.

A clear knowledge divide also emerged between apprentices employed within a franchised network, compared to those from independent repairers, suggesting a skills shortfall in the independent sector. It was unclear whether this shortfall in the independent sector was due to under investment or an unwillingness to get involved with new technologies.

A lack of public knowledge surfaced too when the second-hand LIB market was discussed. When numerous used EV LIBs can be found for sale on the internet with little or no technical knowledge required to purchase and handle, it was mentioned by one stakeholder that "*it is just a matter of time before a serious accident occurs*".

EoL EVs fall under three separate regulations: ELVs, EPR and the EU Battery Directive. All of which were drafted before the rapid growth of EVs. Multiple stakeholders cited the conflicts within the different regulatory framework and the crossover in rules as barriers to a correctly functioning EoL EV recycling market.

The main enabler that emerged from the study from an Irish perspective, is the vast upskilling currently being carried out by all organisations within the Irish EV field, and the willingness of Irish technicians to want to be trained. All Irish stakeholders demonstrated, and stressed, the importance of training staff in the safe working practices of EVs and their batteries. As more actors within the Irish automotive industry become proficient in working with EVs, the associated knowledge and understanding will proliferate and the risks of an accident will be reduced. This can only help the process of LIB pre-recycling in Ireland.

5.2.5. Formulate a health and safety best practice methodology for pre-recycling operations of end-of-life electric vehicle lithium-ion batteries.

The contextual understanding gained during the site visits for this research in particular helped form the authors concept, that an industry wide standard for technicians working on new or EoL EVs should be adopted, followed by regulations.

The National Standards Authority of Ireland (NSAI) state that a standard is an agreed way of managing a process. This means that a standard is repeatable, harmonised, agreed and a documented way of doing something (Mullen, 2021).

Countless standards exist within the EV production field, for example ISO-6469 is a wide-ranging standard regarding design of safety specifications and protection against electrical hazards for EVs (BSI, 2020). Yet no standard framework exists for technicians or operators working directly on or around the high voltage LIB which encompasses EoL pre-recycling phases.

The author believes that a certified industry standard complying to EU Regulation 1025/2012 on standardisation, is necessary to ensure all actors working with EV LIBs are expert and fully aware of the associated risks to mitigate potential accidents.

As this theme developed during the study, a follow-up question was asked of the Irish interviewees: Do you think legislation, should be introduced for technicians who work on high voltage components of EVs? All respondents answered yes.

Alan McDermott of Nissan said "*absolutely, this is something that we would be fully behind*". While Volkswagens Tadgh Cronin was also in favour of regulatory standards, he stated that "*the risks when working on four to eight hundred-volt batteries presents a new level of danger not previously seen in the motor industry. And there are no second chances with this technology if the correct standards and procedures are not set and implemented…and High Voltage technicians should have their skill and qualifications recognised in a poorly represented industry"*.

Research proved that there is a clear lack of standardisation regarding the manual process technicians follow across the EV field. Differences between battery packs, voltage ranges, PPE, tooling, manufacturer processes, documentation and training curriculums, hamper the formulation of a standard health and safety best practice methodology for the per-recycling phases as proposed in research objective five.

The core idea around an industry standard is that the methodology is developed and agreed by all the relevant experts and actors, not a single person. However, the author's concept is proposed in Figure 28. Central to this idea is that an individual must be certified to an industry standard before working on EVs. This will guarantee awareness of personal health and safety hazards and correct working principles are understood.

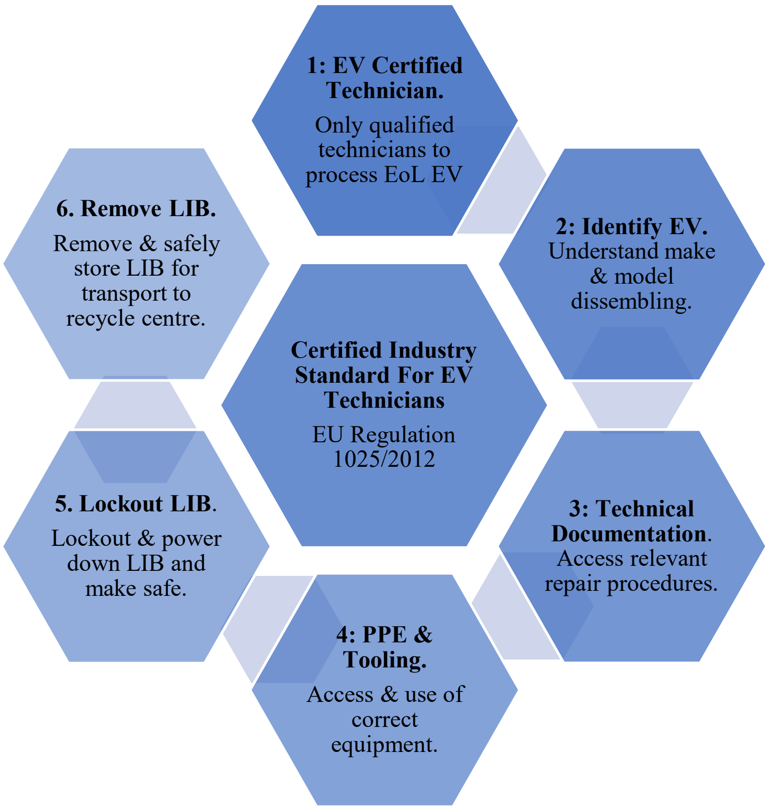


Figure 28: The authors concept for a health and safety best practice methodology for the per-recycling phases of EoL EV LIBs in Ireland. Steps 1 to 6 should be followed when removing an EV LIB, however only by qualified personal.

5.3. Recommendations

The author recommends that all stakeholders within the Irish EV field develop an industry standard for EV Certified Technicians in conjunction with the NASI for operatives working directly on EVs. This standard should then become compulsory through a statutory regulatory scheme or legislation.

The author suggests following the Safe Electric framework already in existence Ireland. Safe Electric is a statutory regulatory scheme for electrical contractors operated by the Register of Electrical Contractors of Ireland on behalf of the Commission for Regulation of Utilities (SafeElectric.ie, 2021). The scheme stipulates that before carrying out electrical work in a domestic setting the person is required by law to register with Safe Electric.

Such a scheme for the automotive sector would ensure only competent operatives would be eligible to work on EVs, which will lessen the possibility of serious accidents occurring.

5.4. Further Discussion

Three topics that emerged during the primary research that may be worthy of further study are UK imported vehicles, the sale of second-hand LIB and repurposing automotive LIBs.

Second-hand EVs being imported from the UK are not contributing to WEEE Ireland's Blackbox scheme. Outstanding fees for recycling will exist when these vehicles reach EoL, this will cause considerable financial burden for the sustainable waste management of the LIBs for the country. This topic should be considered by relevant stakeholders without delay.

The unregulated market of second-hand LIBs has the potential to cause a serious accident. The transportation and storage of LIBs is highly regulated. Private individuals buying and selling LIBs may not be aware of the personal and environmental hazards associated with these products, this warrants further investigation.

Finally, the subject around repurposing automotive LIBs into stationary storage systems from an Irish perspective also merits further discussion. The author understands this area is already being research by some parties. Nevertheless, after speaking with Watt4Ever, it was clear that this part of the recycling value chain could be implemented in Ireland and a new industry with economic and environmental potential developed.

5.5. Conclusion

The batteryfication of transport is evolving at an unprecedented rate. Many states in the EU will ban ICE vehicles in the near future, while COP26 affirmed that EVs will form the cornerstone of global plans to decarbonise transport. The emergence of this new technology will present unprecedented challenges for the automotive sector EoL waste management.

The LIB is a key enabler for the EU in achieving net-zero emissions by 2050 while also allowing a sustainable circular economy. To underpin this, the European Green Deal and new Batteries Directive will provide a legislative framework to meet these objectives.

The technical complexity of recycling, economic barriers due to the current lack of economies of scale because of the small number of LIBs reaching EoL, regulation gaps, high transport costs and the associated environmental and personal hazards present many hurdles for recyclers

Yet, EV LIBs provide potential for repurposing at the end of their automotive life before recycling. And while LIB recycling within the EU has reached capacity, plans for twenty Gigafactories some with inhouse recycling facilities have been approved with Northvolt already operating.

Ideally from an Irish perspective the proximity principal would apply to EoL LIBs so they could be recycled locally, however due to the large capital investment needed this is unlikely to happen in the near term. The recycling value chain steps that will occur in Ireland involve removal, storage and transport of the LIB. These pre-recycling phases each present inherent health and safety implications for the individual who conduct them.

To lessen the associated hazards of the pre-recycling phases, a statutory regulatory scheme is recommended which would permit only certified technicians to perform operations on EVs.

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Appendix

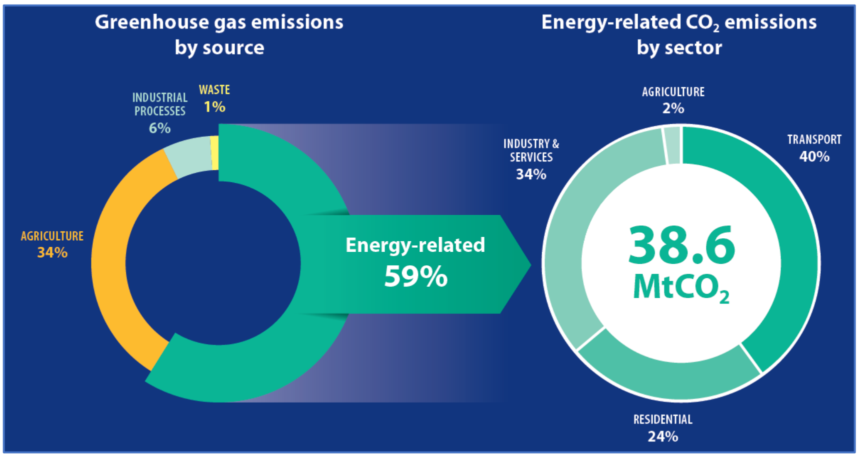

Figure 29: Ireland's 2018 carbon dioxide Emissions (SEAI, 2020b).

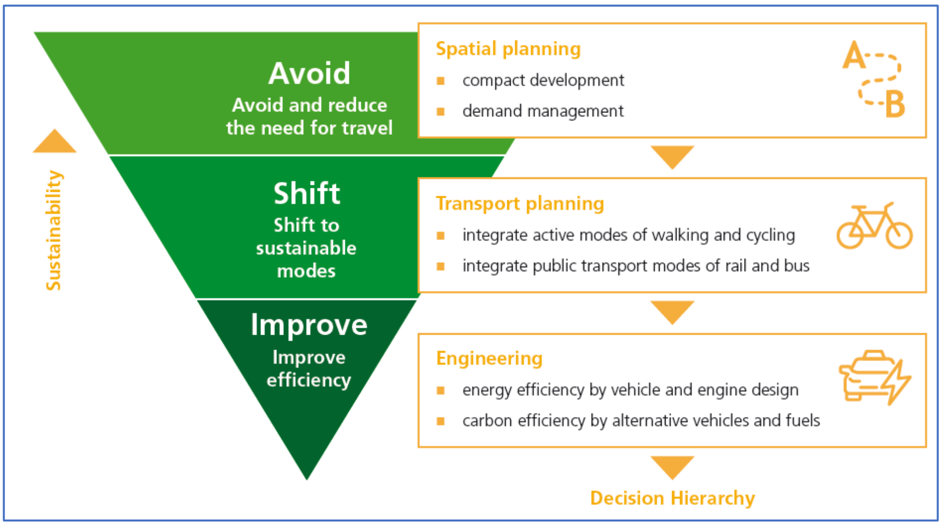

Figure 30: The hierarchy of transport sustainability in the avoid-shift-improve framework (EPA, 2020 adapted from EEA, 2016).

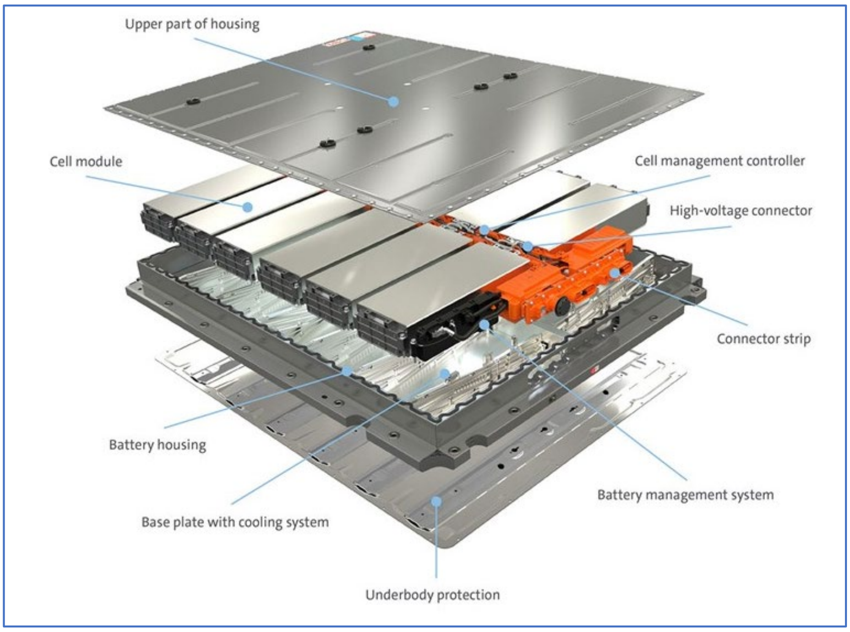

Figure 31: Overview of an electric vehicle battery pack (Pollard, 2020).

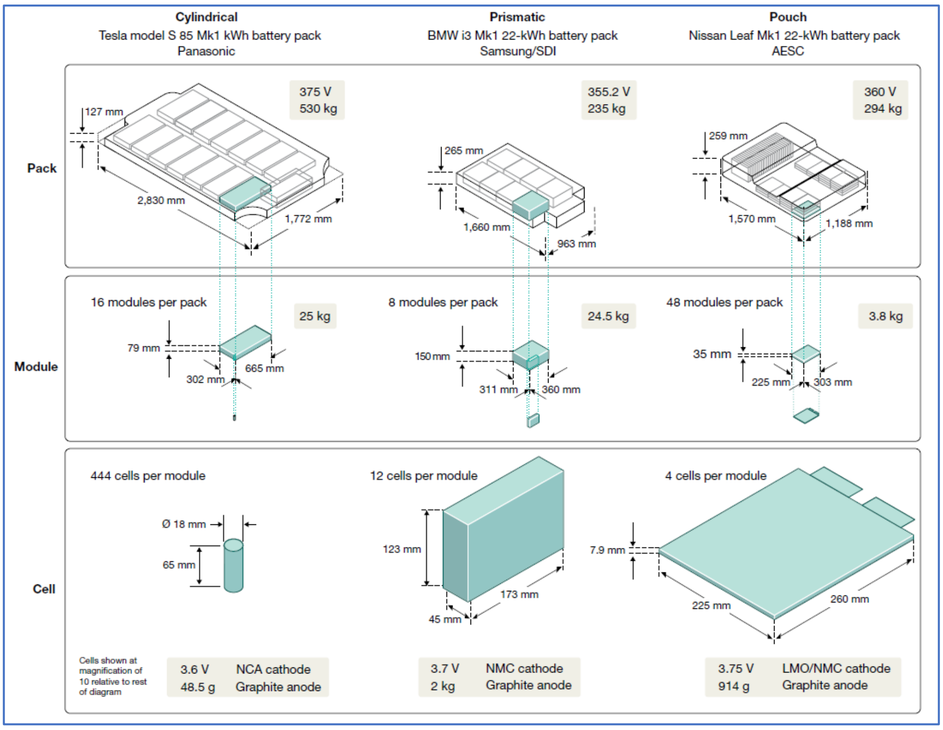

Figure 32: Examples of three different battery packs and modules (cylindrical, Prismatic and Pouch) used in electric vehicles. Each cell has particular recycling challenges. (Harper *et al.*, 2019).

EPR & circular economy

1. Can you provide a brief overview of WEEE Irelands role, specifically in relation to extended producer responsibility (EPR) and industrial batteries?
2. How is EPR managed in relation to dealers, importers & distributors of EV batteries. For example, if a new company is placing industrial batteries on the Irish market, how are they made aware that they must register and report to WEEE / is this monitored?
3. Can you explain WEEE IRL Blackbox?
4. From WEEE IRL perspective, do you consider the current EU battery regulation 2006/66/EC fit for purpose?
5. What do you consider are the current enablers, to ensure EV batteries placed on the market today, will end up correctly recycled and complement the Irish & EU circular economy?
6. From Irelands viewpoint. What future barriers (current or future), if any, do you envision with regards to end-of-life EV batteries recycling and the circular economy?

Lithium-ion battery

7. Can you provide a brief overview of the current WEEE process followed, when a dealers / importer contacts you and request an EV battery collection?
8. Does the EV battery cathode chemistries (NMC / NCA etc.) determine where WEEE send battery for recycling?
9. From Irelands viewpoint. What barriers (current or future), if any, do you envision with regards to recycling large numbers of end-of-life EV batteries?

Figure 33: Sample of a set of questions sent to a stakeholder (WEEE Ireland).

Technological University Dublin City Campus

MSc in Sustainable Transport and Mobility - TU226.
questionnaire.

Recycling end-of-life electric vehicle lithium-ion batteries: Analysis of pre-recycling phases from an Irish perspective.

Student Name: Matt McGuinness
Student Number: D19128353

Declaration:

The author is a second-year master's student at TU Dublin in Sustainable Transport and Mobility[1].

The aim of this dissertation, is to study current best practices of electric vehicle lithium-ion battery recycling methods. A specific focus will be on the primary steps of the recycling process; including safety in the working environment when handling lithium-ion batteries, removal of the batteries from a vehicle and disassembly of the battery to module level.

All information provided for this study will be treated with confidentiality and only used for the purpose of completing the authors MSc dissertation.

Please feel free to contact the author to seek further clarification: matthew.mcguinness@tudublin.ie

Figure 34: Author's Questionnaire cover sheet with a stated declaration.

Interview with Elena Wrelton, from ELVES. 07-09-2021.

Audio file New Recording.m4a Microsoft word – textural coding – Macro-enabled

Matt:

Can you give me an overview of Electric ELVES

ELVES:

OK, right? So electrical Elves, So we started it. In 2018. And it is the program for electric vehicle batteries. Well, at the moment it's called industrial batteries, but that's because the definitions under the battery regulations and so we're modifying it to say electric vehicle batteries, which obviously makes more sense to Joe Bloggs anyway.

And so it started in 2018. Its primary role, I suppose, is to make sure that we are delivering on behalf of the producers on the battery regulations in terms of take back and recycling. So basic collection and recycling.

Matt:

So that's you delivering on behalf of the producers, that refers to extended producer responsibility is also you.

ELVES:

Not the battery. Yes, that element yeah. So basically the the batteries. The EV batteries, batteries in EV cars like the the lithium ion nickel hydride batteries. They come into two sets of end of life vehicle or end of sort of EPR regulations. The ELV directive 'cause they're part of the car. And then they also come

Figure 35: Extract from transcribed interview with Elena Wrelton of ELVES

3. In general, would the Peugeot network be trained to remove an EV high voltage battery?
   Yes they are all trained to lock out the vehicle and remove a battery. — matt mcguinn... Knowledge enabler; matt mcguinn... Safety hazard
4. Are there specific protocols for a Peugeot dealer to follow, if they are required to store EV batteries on their premises?
   Leave it in the container it arrived in until the old one is removed and switch it with the old unit. — matt mcguinn... storage; matt mcguinn... safety hazard
5. Outside of standard high voltage EV PPE and tooling, is there specific special tooling Peugeot recommend for working with EV LIB?
   A vacuum tool to vacuum the cooling system and our diagnostic tool. — matt mcguinn... special tooling; matt mcguinn... knowledge gap
6. Do Peugeot repair EV batteries (replace modules / battery management systems etc.)?
   No not at the moment but we expect next year to train them. — matt mcguinn... training requirement; matt mcguinn... skills gap
   Have HQ received training yet? No
   Do you know if it is law in France to work on HV LIB?
7. Do Peugeot used different LIB chemistries, for example NMC (lithium nickel manganese cobalt oxide or NCA (lithium nickel cobalt aluminium oxide) etc.?
   Not sure at the moment. Will follow up. — matt mcguinn... knowledge gap
8. Do Peugeot use a pan-European transport company for returning EV batteries for recycling / refurbishing?
   Yes they have contracted a company in France and they make arrangements with a local transport company. — matt mcguinn... transport
   Who transports in Irl? Dhl

Figure 36: Example of how the data was coded. Martin Dunne of Peugeot IRL responses and the author's coding.

Comments extracted from: https://tudublin-my.sharepoint.com/personal/matthew_mcguinness_tudublin_ie/Documents/DT920_MSc Transport & Mobility/Disseration_MMcG/MMcG_Disseration assignments/ELVES interview transcribed Macro encoded text V2.docx
Created by: Matt McGuinness
Creation date: October 3, 2021

Page	Line	Comment scope	Comment text	Author	Date
2	11	a collection and recycling service for the electric vehicles batteries when they arise. And we also increasingly is being used by aftersales as well for things like warranty returns as well. And when they need to go for a recycling, they'll come through the electric ELVEs program	transport	matt mcguinness	03-Oct-2021
2	21	Collection and recycling	Transport	matt mcguinness	03-Oct-2021
2	24	. IT is a developing program because of the nature of the you know the industry and you know what we're actually dealing with and the fact that it is a change in technology and an increase in technology	Safety	matt mcguinness	03-Oct-2021
2	27	And So what one of the things we do is making sure that the ATF have access to the right information, so that is using the IDIS (International Dismantling Information System). Database and we need to do that before	Safety	matt mcguinness	03-Oct-2021
2	36	the ELV Directive for manufacturers to supply ATF with dismantling	Regulation - enabler	matt mcguinness	03-Oct-2021
3	36	the ELV Directive for manufacturers to supply ATF with dismantling information, so it's set up to do that. But it is an area where I think it's really coming into its own. For the EV's. Because basically for every maker model there is a dismantling guide on there. And when I say dismantling, it's about removing the apps, shutting it down. Yeah yeah	Safety	matt mcguinness	03-Oct-2021
3	6	It was set up under the ELV directive. And so there's a requirement there for manufacturers to supply information, and this was basically the joint. It's been going a long time.	Safety	matt mcguinness	03-Oct-2021
3	6	It was set up under the ELV directive. And so there's a requirement there for manufacturers to supply information, and this was basically the joint. It's been going a long time.	Regulation – enabler	matt mcguinness	03-Oct-2021
3	11	I think so. Like the I think one of the challenges with it is that for ATF they're not. They don't. You know, they know what they're doing. With a lot of cars. Yeah, they know it's the same process for each one. They're not going to go to a special online database for each and every car, but obviously when it comes to electric vehicle they need to.	Safety	matt mcguinness	03-Oct-2021

Figure 37: Coded thematic analysis from ELVES / Elena Wrelton, transcribed interview – extraction data sample 1.

Comments extracted from: D:\DT920_MSc Sustainable Transport & Mobility\CIVL9016 Disseration_MMcG\MMcG_Disseration assignments\MSc interviews - primary research\VW IRL_Robert Guy.docx
Created by: Matt McGuinness
Creation date: October 15, 2021

Page	Line	Comment scope	Comment text	Author	Date
1	17	costs involved because of the nature	Cost	matt mcguinness	15-Oct-2021
1	17	costs involved because of the nature. Of the repair	Safety Hazard	matt mcguinness	15-Oct-2021
1	17	costs involved because of the nature. Of the repair.	Barrier	matt mcguinness	15-Oct-2021
1	19	The dealers are qualified to do it	Knowledge enabler	matt mcguinness	15-Oct-2021
1	19	And but the factory would expect us as the OEM. To be involved with that repair.	Challenges	matt mcguinness	15-Oct-2021
1	26	So in the last 12 months we've replaced four batteries. And and on each occasion, I think two of them were done in our training center and the two that were done in the network. One of our people was there with the dealer	Safety hazard	matt mcguinness	15-Oct-2021
1	26	So in the last 12 months we've replaced four batteries. And and on each occasion, I think two of them were done in our training center and the two that were done in the network. One of our people was there with the dealer	Challenges	matt mcguinness	15-Oct-2021
1	32	Perfect close, it's an expensive warranty claim course	Cost	matt mcguinness	15-Oct-2021
2	4	quarantine process for the battery	Safety hazard	matt mcguinness	15-Oct-2021
2	4	quarantine process for the battery	challenges	matt mcguinness	15-Oct-2021
2	4	quarantine process for the battery	storage	matt mcguinness	15-Oct-2021
2	5	shipping process for the battery and the only people allowed work on it are people who are authorized, qualified, wearing the right gear	ADR legislation enabler	matt mcguinness	15-Oct-2021
2	5	hipping process for the battery and the only people allowed work on it are people who are authorized, qualified, wearing the right gear	Transport	matt mcguinness	15-Oct-2021

Figure 38: Coded thematic analysis from Volkswagen / Robert Guy, transcribed interview – extraction data sample 2.

1	Page	Line	Comment scope	Comment text	Author	Date	Company	Interviewee
104	5	15	it's moving so quickly, even the last 12 months.	technology evolution	matt mcgu	15-Oct-21	VW Ireland	Robert Guy
105	5	15	Yeah, and ask PSA in a years time.	technology evolution	matt mcgu	16-Oct-21	VW Ireland	Robert Guy
106	1	17	costs involved because of the nature	Cost	matt mcgu	15-Oct-21	VW Ireland	Robert Guy
107	1	32	Perfect close, it's an expensive warranty claim (	Cost	matt mcgu	15-Oct-21	VW Ireland	Robert Guy
108	2	14	Orphaned or imported vehicles. This is a huge i	legislation outdated	matt mcgu	15-Oct-21	WEE Ireland	Conor Leonard
109	10	24	idea between the electric ELVES program is to p	Enabler	Matthew I	03-Oct-21	ELVES	Elena Wrelton
110	2	9	Such high costs may encourage OEM's, dealers	Environmental hazards	matt mcgu	15-Oct-21	WEE Ireland	Conor Leonard
111	1	9	That's a total loss in their yards, so we have star	EOL EV	matt mcgu	08-Oct-21	WeTakeCaeBack	Ken Byng
112	1	15	role, I suppose, is to make sure that we are deli	Extended Producer Responsib	matt mcgu	03-Oct-21	ELVES	Elena Wrelton
113	17	4	You know who is the producer?	Extended Producer Responsib	Matthew I	03-Oct-21	ELVES	Elena Wrelton
114	7	14	How do you make sure that producer is register	Extended Producer Responsib	matt mcgu	03-Oct-21	ELVES	Elena Wrelton
115	7	14	And that's before we get into the technical test	Extended Producer Responsib	matt mcgu	03-Oct-21	ELVES	Elena Wrelton
116	2	31	Current models use Lithium Ion	Extended Producer Responsib	matt mcgu	09-Oct-21	Citroen Ireland	Joe Greene
117	3	16	And every time we sell an EV vehicle we uploa	Extended Producer Responsib	matt mcgu	15-Oct-21	VW Ireland	Robert Guy
118	3	20	. Extended producer responsibility	Extended Producer Responsib	matt mcgu	15-Oct-21	VW Ireland	Robert Guy
119	6	16	legislators will come to the OEM and say this is	Extended Producer Responsib	matt mcgu	15-Oct-21	VW Ireland	Robert Guy
120	6	25	I could see legislation the legislature is saying g	Extended Producer Responsib	matt mcgu	15-Oct-21	VW Ireland	Robert Guy
121	6	29	So that could be a future barrier, I think. You'd I	Extended Producer Responsib	matt mcgu	15-Oct-21	VW Ireland	Robert Guy
122	7	1	Register black box.	Extended Producer Responsib	matt mcgu	15-Oct-21	VW Ireland	Robert Guy
123	3	13	If the vehicles continue to be reliable, it may be	Future barrier	matt mcgu	09-Oct-21	Citroen Ireland	Joe Greene
124	6	15	They'll be people will look for a certificate of de	future issue	matt mcgu	15-Oct-21	VW Ireland	Robert Guy
125	7	8	Is that the people? The name of people who ru	future issue	matt mcgu	15-Oct-21	VW Ireland	Robert Guy
126	7	5	Is that the people? The name of people who ru	future issue	matt mcgu	16-Oct-21	VW Ireland	Robert Guy
127	6	3	Yeah, but unfortunately I think what's going to I	future issue	matt mcgu	08-Oct-21	WeTakeCaeBack	Ken Byng
128	14	13	Sea transport, you know. I used to work in the	IMDG legislation	matt mcgu	07-Oct-21	TU Dublin	Maurice Bardy
129	13	26	Now the ADR but, but remember if it's going to	IMDG legislation	matt mcgu	07-Oct-21	TU Dublin	Maurice Bardy
130	14	23	No, again, it doesn't really happen. And remem	IMDG legislation	matt mcgu	07-Oct-21	TU Dublin	Maurice Bardy
131	14	28	So whatever IMDG wants to do, then ADR follov	IMDG legislation	matt mcgu	07-Oct-21	TU Dublin	Maurice Bardy
132	13	26	There's there's very little difference between u	IMDG legislation	matt mcgu	06/10/2021	TU Dublin	Maurice Bardy
133	2	14	Orphaned or imported vehicles. This is a huge i	Imported vehicles	matt mcgu	15-Oct-21	WEE Ireland	Conor Leonard
134	9	5	Uh, rather would it be like from in it as an econ	Initial idea the start of the MS	matt mcgu	06-Oct-21	TU Dublin	Maurice Bardy
135	4	32	The key risks in terms of things like high voltage	Knowledge enabler	Matthew I	03-Oct-21	ELVES	Elena Wrelton
136	4	9	So yeah, it's it's the first step and the intention	Knowledge enabler	Matthew I	03-Oct-21	ELVES	Elena Wrelton
137	4	20	Yeah, late 2019 we ran. The first course, so we c	Knowledge enabler	Matthew I	03-Oct-21	ELVES	Elena Wrelton
138	4	25	did another one to start at 2020. This year we'v	Knowledge enabler	Matthew I	03-Oct-21	ELVES	Elena Wrelton
139	4	32	Good yeah, it has been good. We've done 109 p	Knowledge enabler	Matthew I	03-Oct-21	ELVES	Elena Wrelton

Figure 39: Coded thematic analysis Excel compiled data sample.

MSc in Sustainable Transport and Mobility - TU226. Technological University Dublin City Campus.
The author is researching the recycling value chain for end-of-life electric vehicle batteries. The specific area of study will focus on the pre-recycling phases of; safety, disassembly, storage, and transportation of EV LIBs within the recycling process.

Apprentice closed-ended questionnaire.

1. Do you work for a franchised main dealer?	YES	NO	I don't know
2. Have you received electric vehicle **health and safety** training?	YES	NO	I don't know
3. Have you received electric vehicle "**Lock-out**" training?	YES	NO	I don't know
4. At which **voltage ranges,** do electric vehicle **batteries** operate?	50 – 200v DC	50 – 400v DC	I don't know
5. At which **voltage ranges** do electric vehicle **traction motors** operate?	50 – 200v AC	50 – 800v AC	I don't know
6. At which threshold can **AC current** cause **electrocution**?	0.5 Amps	5 Amps	I don't know
7. Can you name **five** pieces of **automotive high voltage PPE**?			
8. Would you attend electric vehicle high voltage training, if the opportunity presented itself?	YES	NO	I don't know
9. Do you intend to work with electric vehicles in the future?	YES	NO	I don't know

Student Name: Matt McGuinness.
All information provided for this study will be treated with confidentiality, and only used for the purpose of completing the authors MSc dissertation.

Figure 40: Apprentice closed-ended questionnaire – survey carried out in TU Dublin, 21.10.2021.

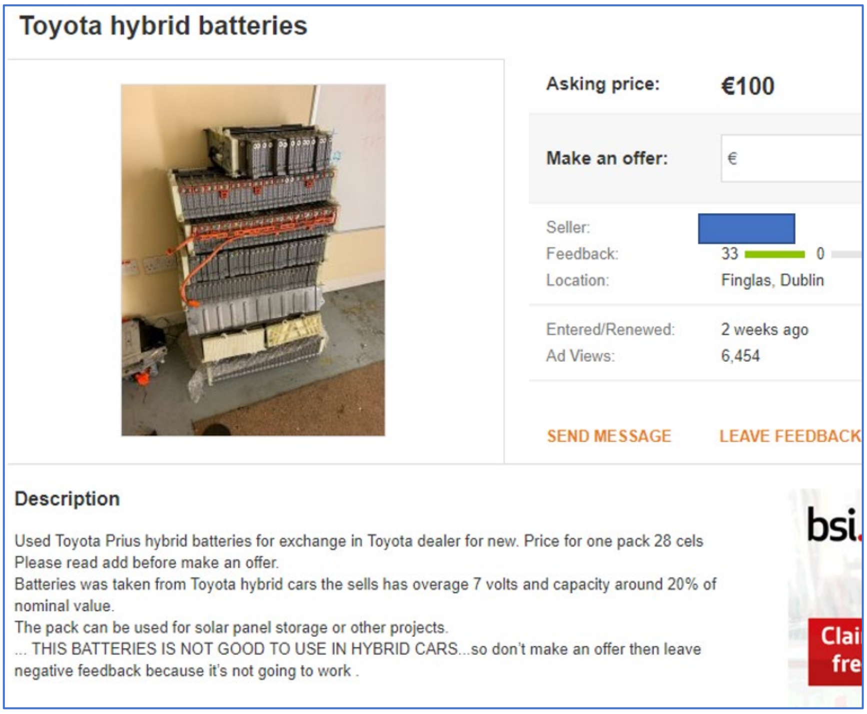

Figure 41: Second-hand high voltage battery for sale in Dublin. This unregulated market has the potential to causes a serious accident (adverts.ie, 2021).