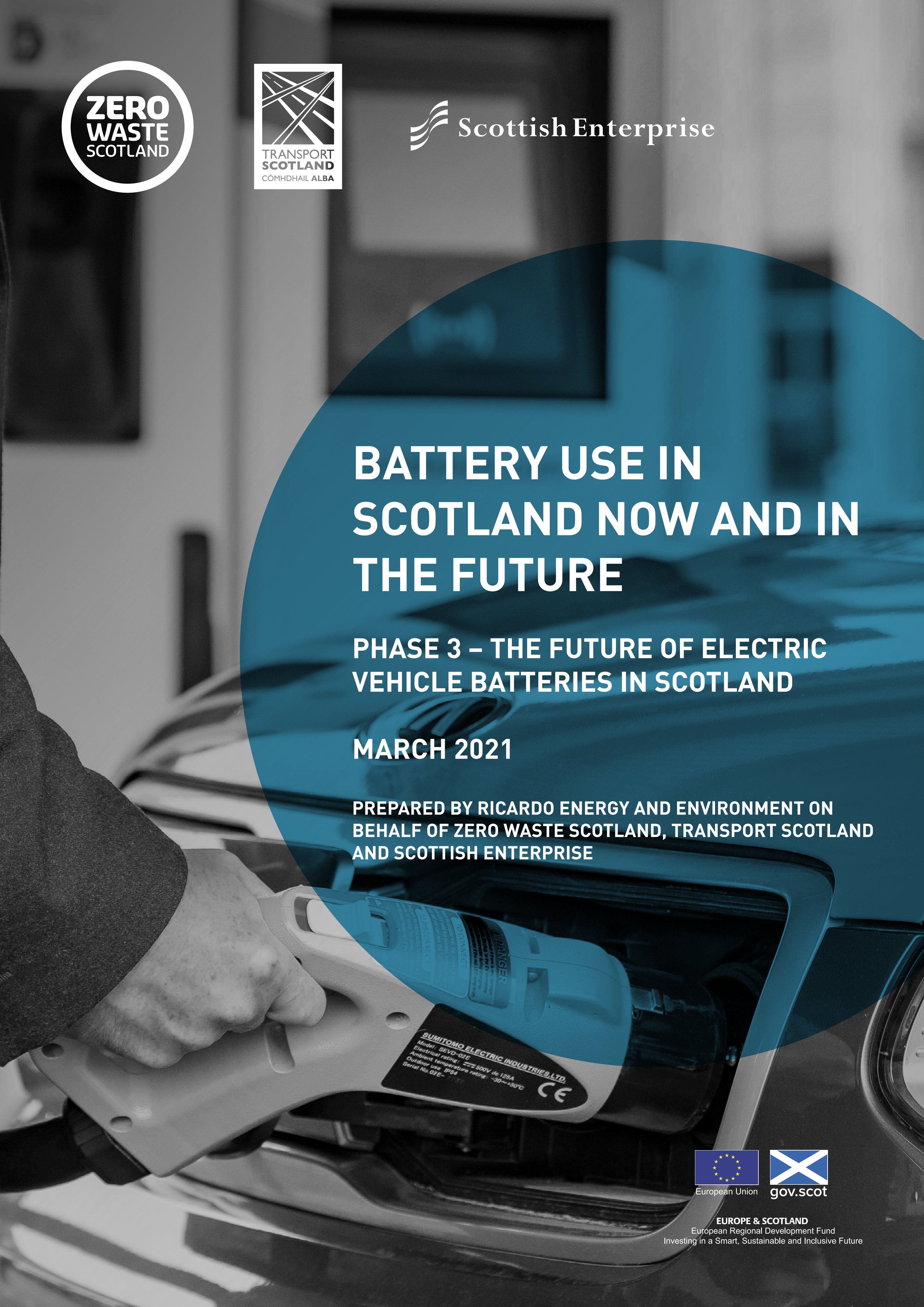

ZERO WASTE SCOTLAND

TRANSPORT SCOTLAND
CÒMHDHAIL ALBA

Scottish Enterprise

BATTERY USE IN SCOTLAND NOW AND IN THE FUTURE

PHASE 3 – THE FUTURE OF ELECTRIC VEHICLE BATTERIES IN SCOTLAND

MARCH 2021

PREPARED BY RICARDO ENERGY AND ENVIRONMENT ON BEHALF OF ZERO WASTE SCOTLAND, TRANSPORT SCOTLAND AND SCOTTISH ENTERPRISE

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Investing in a Smart, Sustainable and Inclusive Future

FOREWORD

Scotland's world-leading targets to help end the climate crisis include fuelling half of Scotland's heat, transport and electricity demand from renewable sources by 2030. Achieving this rapid transition from fossil fuel producer and consumer to global pioneer of green power will involve a huge transformation of our energy systems. To get there, we need to move from centralised to local energy supplies and establish abundant energy storage to ensure supply meets demand.

We will also need more options for zero emission transport, such as electric vehicles. The UK Government's decision to outlaw the sale of new petrol and diesel cars by 2030 is accelerating that with more people switching to electric cars.

This rising use of electric vehicles is increasing the number of batteries needed to power them. In parallel to this, the last decade has also seen an explosion in ownership of smart phones, laptops and other portable consumer electronics all powered by rechargeable batteries.

All batteries have a limited primary life span. But at their ultimate end-of-life they still contain valuable and potentially hazardous metals and other materials that should be collected and reprocessed. We need a system in place to keep batteries in use for as long as possible, and then to reuse the materials they contain in other ways. With no such system, the growth in demand will put unsustainable pressure on already vulnerable supply chains, depleting raw materials on a global scale. The single biggest cause of the climate crisis in Scotland is everything we produce, consume and too often waste. Keeping products like batteries in a loop of use through the circular economy is key to ending this waste and the damaging emissions it creates.

It is already possible to reuse, repurpose, and remanufacture batteries but this is not currently taking place in Scotland at any significant level. As a result, these precious resources are being exported to other countries for disposal and recycling – losing their value and increasing carbon emissions.

Embedding the circular economy in Scotland's transition to green energy to help end the climate crisis would retain these resources and their value within our borders as use of batteries grows. This would give Scotland a way to produce batteries which reduces carbon emissions and creates significant new job opportunities in the process. Future innovation should also focus on producing new batteries designed with end-of-life in mind, which are easy to disassemble to increase their value.

This research is the result of an important new collaboration between Zero Waste Scotland, Transport Scotland, and Scottish Enterprise. This joint work recognises that future policy decisions will affect the growth in battery use and production in Scotland, and their wider environmental and economic impact. Our key objectives were to assess the current battery sector in Scotland, in order to identify the potential for Scottish companies to improve sustainability and increase circularity within the supply and disposal chains.

This report builds on the findings from the first report in the series of three, to consider the future for electric vehicle batteries. The aim of this part of the research is to provide insight into how electric vehicle batteries may change in the future, making projections from the gathered data, and to determine what opportunities may be available to Scottish companies to engage in electric vehicle battery developments.

Analysis has been conducted with respect to different modes of transport, including, electric vehicles and e-bikes, rail, marine and aircraft. Additionally, the report provides an overview of end-of-life processes for batteries and opportunities to increase their circularity potential.

We now have a better understanding of the quantities and chemistries of electric vehicle batteries that will be coming to their end-of-life in the future, although with some degree of uncertainty. We are also more informed about which circular economy opportunities are most appropriate for electric vehicle batteries in Scotland. This will help to inform both policy and waste management investment decisions. This information and knowledge will help in efforts to ensure the Scottish Government achieves its aim of ending the nation's contribution to the climate crisis by 2045.

This is the first time that Zero Waste Scotland, Transport Scotland and Scottish Enterprise have worked together as a project team to take a joined-up approach to the material aspects of the increasingly decarbonised transportation system. This sector will undergo rapid and transformational change in the next decade and we firmly believe that embedding a circular economy approach will deliver a just and prosperous transition for Scotland.

Zero Waste Scotland exists to lead Scotland to use products and resources responsibly, focusing on where we can have the greatest impact on climate change. Using evidence and insight, our goal is to inform policy, and motivate individuals and businesses to embrace the environmental, economic, and social benefits of a circular economy. We are a not-for-profit environmental organisation, funded by the Scottish Government and European Regional Development Fund.

Transport Scotland is the national transport agency for Scotland, delivering the Scottish Government's vision for transport.

Scottish Enterprise is Scotland's national economic development agency committed to growing the Scottish economy for the benefit of all, helping create more quality jobs and a brighter future for every region.

CONTENTS

1 INTRODUCTION

Zero Waste Scotland, Transport Scotland and Scottish Enterprise (hereafter referred to collectively as the Project Group), have commissioned Ricardo Energy & Environment to:

- Provide a detailed picture of current battery use in Scotland
- Give short to medium-term projections for how that will develop, including specific electric vehicle battery projections
- Highlight future policy or regulation considerations to improve sustainability and support a greater level of circularity across the entire battery life cycle

This report covers Phase 3 of the project and, in parallel with Phase 2, follows on from the Phase 1 report which provided details and discussion of current battery use in Scotland. Phase 3 focuses in particular on the future of electric vehicle (EV) batteries in Scotland.

The aim of Phases 2 and 3 is to provide insight into how battery uses and chemistries may change in future, making projections from the data gathered in the previous phase. The project also aims to understand, through literature research and stakeholder engagement, what opportunities may be available to Scottish companies to engage in battery developments, and to improve the sustainability and increase the circularity of the battery value chain.

Analysis has been conducted with respect to different modes of transport, including, electric vehicles and e-bikes, rail, marine and aircraft. Additionally, the report aims to provide an overview of end-of-life processes for batteries and opportunities to increase their circularity potential.

The EV battery sector has grown steadily over the last decade, however, due to the regulatory phase out of all petrol and diesel powered vehicles, the expansion of this market is expected to be even more significant in the next decade to 2030. According to data published by the Society of Motor Manufacturers and Traders, pure EVs (i.e. those driven by battery power alone) account for 6.5% of all new cars registered in the UK in 2020, this is up from 1.5% in 2019.

Alongside the rapid growth of EV batteries, there is an expectation that the industry will see a large increase in EV battery waste. However, it is difficult to predict when these batteries will arise as waste, as producers claim different lifespans for their EV batteries. Also, lifespan estimates from manufacturers tend to be conservative compared to actual longevity of batteries, mainly for insurance risk purposes. The predictions of market growth and waste arisings are discussed in detail in Section 4 of this report.

[1] Society of Motor Manufacturers and Traders (2021). UK automotive looks to green recovery strategy after -29.4% fall in new car registrations in 2020

2 METHODOLOGY

This report details the results of Phase 3 of the research project, which focuses on developing a quantitative and qualitative understanding of the future of EV use in Scotland, and the associated regulatory and end-of-life processes for EV batteries.

The activities completed to develop this understanding were:

- Projection modelling of available battery supply and end-of-life data
- High-level policy and literature review
- Stakeholder engagement interviews

The methodology followed is described in the remainder of this section.

2.1 Projection modelling

Data accessed
In order to project levels for EV batteries placed on the market (POM) and EV battery waste in Scotland from 2025 to 2050, data was sourced from the 2020 Future Energy Scenarios (FES) report from the National Grid ESO2. This report provided steady and rapid transition projections of the number of electric cars expected to be on the road in the UK up to 2050.

Gaps, limitations and assumptions
Based on the data available for this study, the following gaps and limitations were identified:

- No Scotland specific data
- Includes only battery electric cars
- No projections in terms of EV battery weight

To support filling these gaps the following assumptions were made:

- An electric car lifetime of 15 years was applied to the cars on the road data to establish placed on the market figures across the period 2016-2050.
- To estimate the Scottish share of battery POM and waste, Ricardo used the share that the Scottish population represents in the UK. This approach is justified in that there are no deviations in policy or targets relating to batteries for Scotland. Data from the Office for National Statistics[3] was used to calculate a 10-year average from mid-2010 to mid- 2019. The result of this calculation is an average share of 8.28%.
- The source data was for battery electric cars, and therefore assumed to exclude hybrids from all years of projections.
- It is recognised that the POM data includes only BEV cars, and excludes other types of vehicles. However, cars are expected to dominate EV battery volumes up to 2050, representing approximately 70% of all electric vehicle capacity[6].
- To estimate the weight of EV batteries POM, Ricardo estimated the capacity in GWh of the EVs POM assuming an average capacity for pure electric at 45kWh, based on conservative internal expert opinion, and used DfT data to calculate the split between the two types. Results were used to evaluate the weight in tonnes of EV batteries POM, using battery pack energy density projections from Ricardo's 2020 report on conventional and alternatively fuelled vehicles Life Cycle Assessment (LCA)[5].
- It is assumed that EV batteries will retain 80% of their capacity at the end of their first life application.

[2] National Grid ESO (2020). Future Energy Scenarios
[3] Office for National Statistics (2021). Main figures
[4] Department for Transport (2020). Vehicles Statistics
[5] Ricardo Energy & Environment (2020). Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA
[6] *JRC Publications Repository* (2019). Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles

2.2 Literature review

Building on the foundation of knowledge from Phases 1 and 2, a further literature review was undertaken to gather information on current and future electric vehicle and battery-specific technologies, policies, and business models to improve the circularity of electric vehicle batteries in Scotland.

The literature review used the sources listed in **Table 1** as a starting point from which to better understand the available research, and to better identify any knowledge gaps which existed. These gaps were then specifically addressed through in-depth research of further sources as referred to throughout the body of this report, and via the stakeholder consultation activities.

The literature review also used a number of online articles to provide relevant up-to-date examples of research and development projects which are happening in the battery industry.

Year	Author	Document type	Report Title
2021	British Standards Institution	Report	PAS 7060: Electric vehicles – Safe and environmentally-conscious design and use of batteries – Guide
2014	Gaines	Article	The future of automotive Li-ion battery recycling: Charting a sustainable course
2018	Martinez-Laserna, et al.	Article	Battery second-life: Hype, hope or reality? A critical review of the state of the art
2021	The Climate Group	Report	Progress and Insights Report
2020	The Faraday Institution	Report	High-energy battery technologies
2020	The Faraday Institution	Report	The importance of coherent regulatory and policy strategies for the recycling of EV batteries
2019	World Economic Forum	White Paper	A Vision for a Sustainable Battery Value Chain in 2030

Table 1 **Key initial literature sources**

Gaps, limitations and assumptions

As with the Phase 2 literature review, there are a number of resources examining new battery technologies for EV but relatively few which specify end-of-life options for these batteries. As EVs have become widespread only relatively recently, the vast majority of EV batteries that have been produced thus far will not reach the end-of-life stage for several more years. Because of this, what articles and studies exist detailing end-of-life management options are typically very speculative and thus include several assumptions.

In addition, while there is ongoing research into emerging technologies and chemistries, many of these are also largely hypothetical as of yet, with tests either small-scale or not yet carried out. The general trends of EV batteries could change significantly with the refinement of these technologies.

2.3 Stakeholder engagement

To complement the knowledge gained from the desktop research and data analysis, stakeholder interviews were conducted to collect information, expert opinion and insight from a wide range of stakeholders.

During the interviews, contacts were also asked to identify any further stakeholders across the battery value chain in Scotland who may be able to provide further insights or additional data sources.

25 key organisations were chosen in collaboration with the Project Group, based on the collective knowledge of the Scottish battery value chains. These stakeholders included regulators, compliance schemes, trade associations, recyclers, manufacturers, and academic institutions. A total of 14 interviews were conducted. In addition to these external interviews, focussed discussions were held amongst our in-house battery technology experts, including representatives from Ricardo Energy & Environment's sustainable transport team and senior engineering team members from our Automotive & Industrial and Performance Products divisions.

It is worth noting that interviews which were conducted with stakeholders for Phase 1 & 2 and provided useful insights for Phase 3 have been included in these figures. An outline of each stakeholder group has been provided below in Table 2:

Stakeholder Type	Number invited to interview	Reason for selection	Number of interviews completed
Regulators	3	Insights on regulatory environment	2
Trade Associations	2	Trends and market growth, regulatory environment	1
Compliance Schemes	5	Insights on policy & market trends	4
Manufacturers	9	Information on current research and novel technologies. Trends and market growth	2
Academia	4	Information on current research and novel technologies	4
Recyclers	2	Insights on recycling & reuse of current and new technologies, Trends and market growth	1

Table 2 Stakeholder engagement tracking

Interviews were conducted during February and March of 2021 by members of Ricardo's project team. Interview questions were derived from the main project research questions, as outlined by the Project Group, and were then tailored to the type of stakeholder and specific business context.

It is worth noting that engagement with EV battery manufacturers was difficult for this project due to their protective nature over the technological developments and commercial sensitivity.

2.4 Identification and assessment of opportunities for Scotland

The insights gained from our modelling, stakeholder engagement and desk-based research into future developments in the battery sector were combined to develop a list of potential opportunities for Scotland. These opportunities, detailed in Section 7, were then analysed via a Multi Criteria Analysis process, which covered:

- Level of uncertainty / risk in the long-term benefit for Scotland
- Technical or legislative capability within Scotland to implement
- Potential scale of economic benefit
- Potential scale of environmental benefit

A red-amber-green rating was given for each criterion, based on stakeholder insight and our internal experts' judgement, and these scores were combined to give an overall viability rating of low, medium or high for Scotland.

3 THE CIRCULAR ECONOMY IN ELECTRIC VEHICLE BATTERIES

3.1 Design and manufacturing

Battery manufacturing has seen a dramatic increase in capacity, and this is forecast to continue over the next decade. In 2010, the global demand for lithium-ion (Li-ion) batteries was around 19GWh. It reached 160GWh in 2019 (from a capacity of 285GWh) and is set to reach over 2000GWh by 2028. At of the end of 2019, the major manufacturers are predominantly located in Asia, with the Korean LG Chem, the Chinese CATL and BYD and the Japanese Panasonic taking the top four spots. Tesla takes 5th position. LG Chem alone is set to increase its capacity from 50GWh in 2019 to 170GWh in 2024[6].

Europe, and the UK in particular, hold a very small share of battery manufacturing. The current UK battery manufacturing capacity is around 2GWh, which is forecast to need to increase dramatically to 140GWh domestic manufacturing in 2040 just to support its automotive industry[7].

The battery manufacturing supply chain
The battery manufacturing process is broadly made up of four steps:

- Material extraction and processing
- Cell manufacturing
- Module assembly
- Pack assembly

[6] Brian Wang (Energy Central) (2020). World Battery Production
[7] Jason Deign (Green Tech Media) (2020). UK Needs Battery Industry Boost in 'Next Year or Two'
[8] Advanced Propulsion Centre UK, Innovate UK (2019). Automotive Batteries Report Summary

Figure 1: The battery manufacture supply chain details the stages of battery production and the associated supply chain[8]:

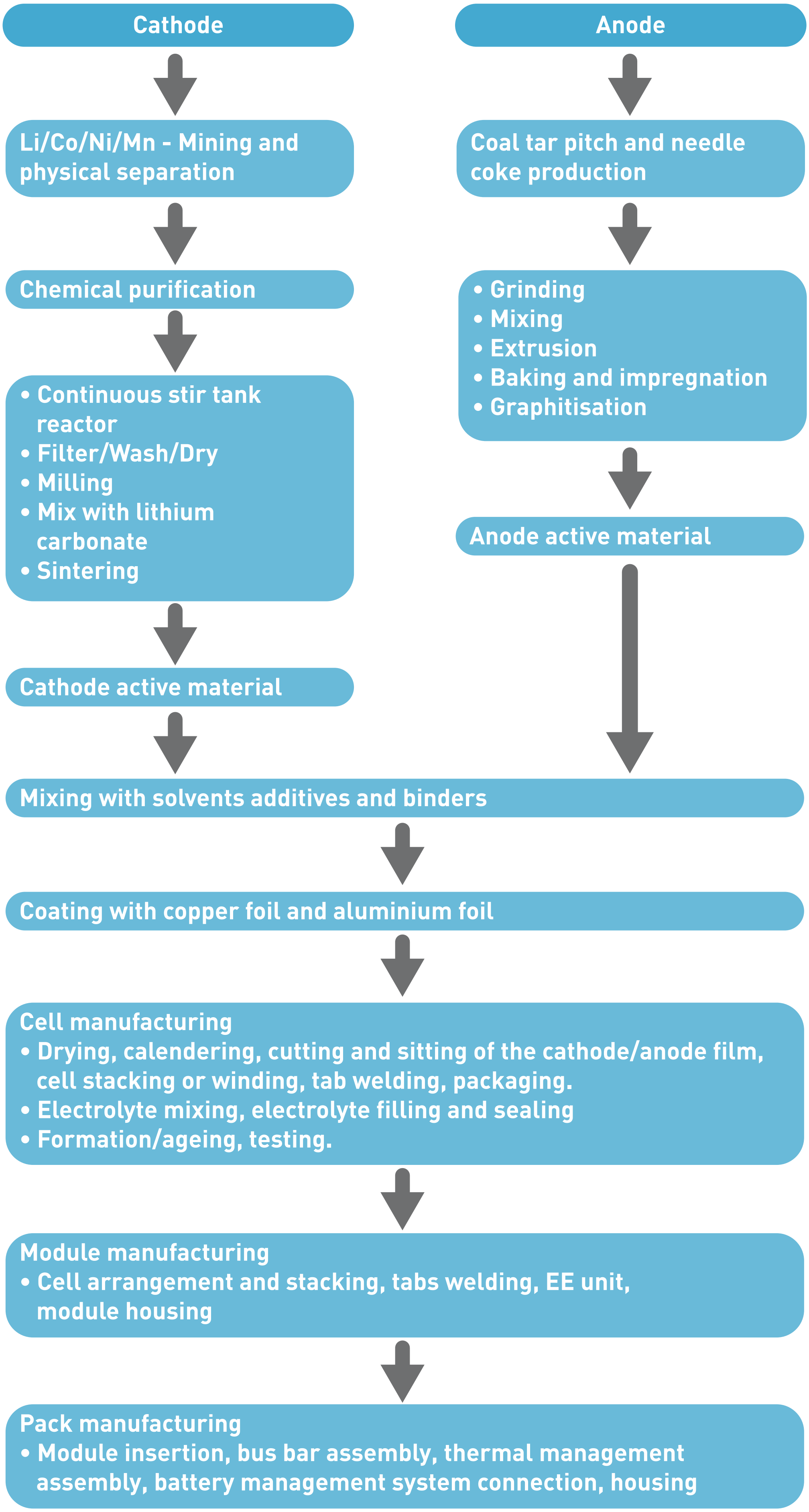


Figure 1 The battery manufacture supply chain

UK companies have indicated that they are willing to invest in the processes included in the anode and cathode active material manufacturing, excluding mining and chemical purification[9]. This presents a major opportunity for developing recycling capabilities that will supply these companies with the necessary cobalt/nickel/manganese (in the form of sulphates) and lithium (carbonate/hydroxide). The steps where the processing of the cathode and anode active materials begins (mixing and coating) to a manufactured cell are the processes that take place in cell production 'gigafactories'.

The UK will need to significantly increase its cell manufacturing capabilities: the World Economic Forum (WEF) predicts that in order for battery power to have the biggest possible impact on global emissions, the battery value chain (including mining, cell production and recycling) will need to increase by 19 times by 2030[10]. The projected need in terms of UK battery production is for at least seven 20GWh annual capacity Gigafactories by 2040. Two British companies, AMTE Power and Britishvolt, are planning to build the first UK Gigafactory which will have a combined capacity of up to 30GWh annually. There are currently several potential locations for the proposed facility[11], including the Michelin Scotland Innovation Park (MSIP) in Dundee.

The Scottish government is currently working to enable the upscaling of battery cell production[12]. This indicates Scotland's ambition to take a strong role in the expansion of battery production capacity. However, Scotland faces competition as a suitable location for a significant Gigafactory facility for EV batteries for road transport. The main UK manufacturing hub for EVs is the West Midlands, with Jaguar Land Rover playing a significant role in the local area. As such, it is initially most likely for significant EV battery manufacturing capacity to be relatively close to this region. In the medium to longer term however, given the stated need for a total UK capacity requirement equalling around seven Gigafactories, there is certainly potential for other areas, such as Scotland, to be considered.

3.2 End-of-life options

The operating conditions of batteries in EVs are often associated with rapid charge and discharge rates and high temperatures. Furthermore, the power and storage capacity requirement that are directly linked to the performance and range of the vehicle mean there is limited room for battery deterioration before the battery pack is deemed to have reached the end of its useful life. Typically, this happens when the battery has reached 80% of its original capacity. It is expected that EV batteries will typically last for 15 years, or the life of the vehicle (in the case of light-duty vehicles). At the end of this period, commonly termed End-of-Life (EoL) the owner of the battery is faced with three options[13]:

- Reuse in a second-life application
- Recycling
- Disposal

Disposal of EV batteries should be a last resort, as the toxicity of many different battery chemistries makes them difficult to dispose of safely and without damage to the surrounding environment. In 2017, worldwide sales of EVs exceeded 1 million for the first time, representing about 250 000 tonnes of battery waste at the end-of-life stage. Given that, by 2040, the number of EVs on the road in the UK could exceed 11 million[14], there is clearly a need for means by which to manage this future waste. The establishment of such means would likely see significant challenges but also potential economic, technological, and environmental opportunities.

[9] APC, Innovate UK (2019). Automotive Batteries Report Summary
[10] World Economic Forum (2019). A Vision For A Sustainable Battery Value Chain in 2030
[11] The Guardian (2020). UK's first car battery 'gigafactory' to be built by two startups
[12] Current News (2020). Government to 'pave the way' for a UK Gigafactory as it hands funding boost to Scottish battery facility
[13] Catapult Energy Systems (2020). Storage and Flexibility Net Zero Series: Second-life Batteries
[14] Accenture (2019). 11 million electric vehicles forecast to hit UK roads by 2040 creating a £150 billion opportunity for utilities, Accenture finds

Academics are currently considering an EV model of ownership that has been tested by some vehicle manufacturers, that could have several benefits for battery reuse and recycling. This model sees the consumer own every part of the EV except for the battery which is leased by the original manufacturer[15], facilitating more effective EoL options, encouraging circular battery design, and reducing the cost of EVs which will encourage uptake by consumers. Furthermore, if the manufacturer has more control over the battery over its lifespan, it can do more to ensure that battery capacity does not fall below 80%, allowing it to be more effectively reused or repurposed.

One example of this has been the development by the vehicle manufacturer Renault[16] who have established a rental model for the Li-ion batteries in its electric cars so that they can be reused and remanufactured when customers return them. However, stakeholders provided anecdotal evidence that this leasing model has yet to become mainstream because it doesn't seem to increase profitability. Car manufacturers are understood to be resistant to recycling their batteries with third parties for technology proprietary reasons and it is easier for them to focus on production rather than end-of-life waste management – still a very linear approach. However, there is potential that if batteries are designed with greater capacity and longevity, this could make this leasing model more profitable over time for car manufacturers, referred to as Original Equipment Manufacturers (OEMs). This satisfies one of the key tenets of the circular economy in deriving the maximum value possible for as long as possible from the materials used. It does, however, simply move the question of EoL options further into the future.

The key factor in the level of opportunity which will arise from EV battery EoL options is which business model is adopted by OEMs. Business model options include:

- OEMs operate a leasing model for batteries and retain ownership at EoL, either for in-house recycling, their own development of second-life applications or direct-to-consumer re-sale
- OEMs sell battery at EoL to a second-life third party, who would assess the remaining capacity within the battery pack and individual cells and match to suitable second-life application
- OEMs licence collection and recycling to a third party with recovered materials becoming available to loop back into the manufacturing supply chain

The first of these options would offer minimal opportunity to Scotland, where the latter two offer possible chances to develop the facilitating and operation infrastructure required. The difficulty in making decisions on investment potential lies in the fact that few OEMs have confirmed their position as yet. Ricardo is aware, through confidential conversations with the OEM market, that several are actively investigating options to retain battery ownership and develop second-life applications with less intensive energy requirements, but the scale of this remains to be confirmed. The market preferences are likely to become clearer over the next five years, and OEMs decisions will be influenced by developments in Extended Producer Responsibility (EPR) legislation for the regions in which they operate.

Recycling

By virtue of their complex structure and various designs, recycling of Li-ion batteries is significantly more difficult and, thus, more expensive than traditional lead-acid batteries. Current rates of recycling Li-ion batteries in Europe are around 5%, with no operating plants in the UK. The cost of recycling Li-ion batteries at present is around 3 times the value of the reclaimed materials. Additionally, future chemistries are likely to stop using some critical metals, such as cobalt, which will further reduce the incentive for recycling as the value of recovered materials will drop while operating costs remain relatively fixed.

[15] Jyoti Ahuja, Louis Dawson and Robert Lee (2020). A circular economy for electric vehicle batteries: driving the change

[16] Groupe Renault (2017). Renault Optimizes the Lifecycle of its Electric Vehicle Batteries

The Faraday Institution is carrying out work to improve the recycling process as part of the ReLiB project, and while the process is still difficult and cost-intensive, efforts are being made to address the roadblocks to Li-ion battery recycling before larger numbers of EV batteries reach their end-of-life.

Globally, the EV battery recycling industry has not yet developed into a fixed business model type. Active recyclers are placed at varying levels of the battery supply chain:

- Automotive OEMs
- Cell manufacturers
- Component refiners and manufacturers (cathode materials, metals etc.)
- Independent recyclers

All of these players have strong claims to be best placed to deliver the recycling stage of the lifecycle of an EV battery, either through access to feedstock, scale of operations, chemical expertise and capability or ready-made use or access to market for the recovered materials. Learning from the Chinese market, which is most developed and scaled thus far, the largest market shares have been captured by recyclers who also operate as material suppliers, separate to the various levels of manufacture.

Despite the challenges and uncertainty over the global future of the shape of the recycling market, there will nevertheless be significant volumes of batteries reaching EoL in the coming years, both EV and other batteries. Now is the right time to consider investment in recycling infrastructure to be a lead player in the domestic industry. Scotland has the academic, chemical and technological innovation expertise to capitalise on this opportunity.

Second-life

Upon reaching the end of its useful life, an EV battery still retains around 80% of its original capacity. While no longer suitable for their initial transport application where power, capacity and weight are all critical, these batteries can still provide required energy supply to less demanding applications such as:

- Stationary energy storage
  - o Grid balancing and off-grid supply to support renewables infrastructure
  - o Uninterrupted power supply
  - o Telecommunications
- Spare EV battery back-up
- Less intensive vehicle applications (forklifts, warehouse tuggers etc.)

Depending on factors like dispatch strategy, depth of discharge and appropriate sizing, second-life batteries could serve for an additional 7-12 years[20]. One source assumes a 16-year lifetime under specific operating conditions[21]. However, second-life battery applications come with a specific set of challenges, namely the lack of standardisation between different battery manufacturers, which increases the complexity of refurbishment, and the continuous reductions of costs of new batteries. The current lack of standardisation leans towards OEM take-back and internal second-life reuse or remanufacture being the most viable way forward for the industry, as does their obvious access to high volume of supply.

[17] The Faraday Institution. Reuse and Recycling of Lithium Ion Batteries
[18] Linda Gaines (2014). The future of automotive lithium-ion battery recycling: Charting a sustainable course
[19] Boston Consulting Group (2020). The Case for a Circular Economy in Electric Vehicle Batteries
[20] E. Martinez-Laserna, I. Gandiaga, E. Sarasketa-Zabala, et al. (2018). Battery second-life: Hype, hope or reality? A critical review of the state of the art
[21] Ian Mathews, Bolun Xu, Wei He, et al. (2020). Technoeconomic model of second-life batteries for utility-scale solar considering calendar and cycle aging

However, as discussed above, there are very few firm decisions made on how this will develop in the EV market, and there are viable potential markets in the providers and end users of stationary energy storage equipment. It may develop that the dominant business model is one of automotive OEMs partnering directly with stationary storage producers, but as EV battery design and manufacture develops towards longer life and greater reliability, the dynamic may shift towards OEMs themselves being more willing to invest in their own second-life applications[22].

One of the key steps in facilitating second-life reuse of EV batteries is in the testing and grading of cells, and subsequent matching to suitable second-life applications. This is an area where Scotland has a burgeoning technical and academic experience base, and combined with the environmental and logistical benefits of a potential localised reuse collection and processing sector could offer a strong opportunity for future development.

[22] BCG (2020). The Case for a Circular Economy in Electric Vehicle Batteries

Case study: eVoyager (Nissan Leaf second-life batteries)

The UK's first seafaring electric ferry completed its first journey in October 2020 and, provided it completes a set of quality and safety tests, will be passenger-ready in 2021. The 12 person capacity e-Voyager is a collaboration between Plymouth Boat Trips and Voyager Marine and was funded by MarRi-UK and the Department for Transport. The boat was designed and developed by the University of Plymouth and the University of Exeter, with propellers from Teignbridge Propellers and motor from EV Parts, who also designed a battery storage system using end-of-first-life Nissan Leaf batteries that can provide the boat with 400 volts of electricity. Three 22kWh charging points have been installed by Plymouth City Council that are capable of charging the e-Voyager in around three hours overnight, which can be topped up as needed throughout the day, and a charging infrastructure for marine vessels across Plymouth is currently being developed.

The use of repurposed Nissan Leaf batteries presents some commercial benefits: they require less maintenance than a typical diesel engine, and tests are being run regarding the vessel's fuel consumption. Plymouth Boat Trips is currently converting other vessels in its fleet as well as building new similar boats. Notably, Voyager Boatyard recently won funding from Innovate UK to develop an e-Ferry that will be capable of carrying 150 passengers for up to 14 hours on a single charge. Details of battery and motor specifications have not yet been announced, but the design will include other renewable energy sources like photovoltaic panels. The battery and motor system designed by EV Parts for the e-Voyager is directly transferrable to a large number of the 24 million commercial vessels in the UK, meaning that this is an excellent opportunity for the circular economy of EV batteries.

Sources:
Plymouth Boat Trips (2020). Plymouth Boat Trips and Voyager Marine launch UK's first sea-going electric ferry
Plymouth Boat Tips (2021). Cremyll Ferry Goes Electric
University of Plymouth. Creating the UK's first electric sea-going passenger boat

4 PROJECTIONS & SCENARIOS FOR FUTURE ELECTRIC VEHICLE BATTERIES

4.1 Electric vehicles batteries placed on the market

The current trend and expectations suggest that road transport will experience the biggest transition to battery power, first passenger cars, and then followed by HGVs. Rail, marine and aviation will also increase their use of batteries, but the share of battery powered vehicles will be marginal in comparison to road and haulage. The majority of electric vehicle capacity on the road up to 2050 will be cars and so the modelling work on projecting future numbers and battery capacities has focused on cars.

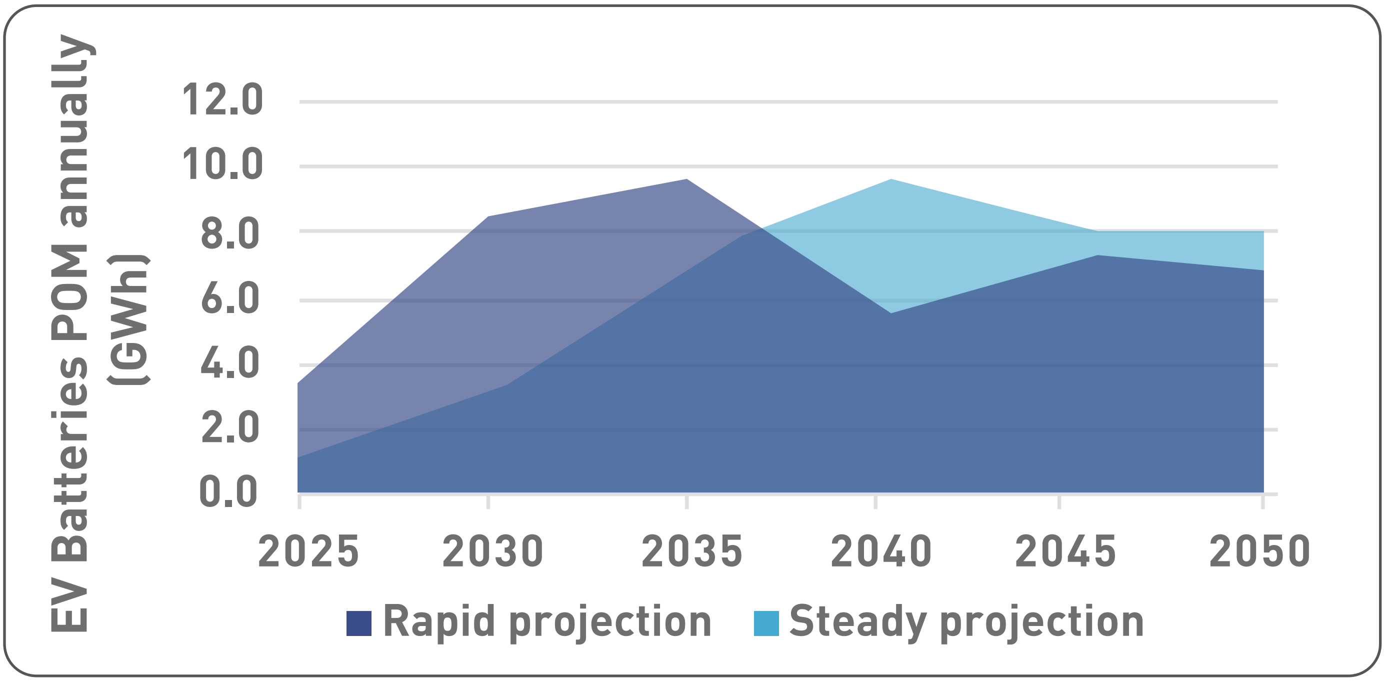
Using the methodology outlined in **Section 2.1**, **Table 3** and **Figure 2** show the estimated projection of the amount of EV batteries POM annually in Scotland from 2025 to 2050 in GWh and tonnes.

It is estimated that the capacity of the EV batteries POM per annum would be between 1.0 and 3.2 GWh in 2025 and that the weight of EV batteries POM per annum between 5,000 and 16,000 tonnes in 2025. In the rapid projection, battery tonnages POM will peak in 2030 at 28,000 tonnes per annum before dropping away to 12,000 by 2050, and in the slow projection tonnages POM will peak in 2040 before dropping away to 13,000 in 2050. This future decrease in battery tonnage POM is due to both changes in modes of transportation (less EV's being added to the road) and the energy density of batteries improving (future batteries weigh less).

In total, between 263,000 and 325,000 tonnes of electric car batteries will have been placed on the Scottish market by 2050.

Year	Low projection		High projection	
	Capacity (GWh)	Weight (tonnes)	Capacity (GWh)	Weight (tonnes)
2025	1.0	5,000	3.2	16,000
2030	2.8	10,000	8.1	28,000
2035	6.0	16,000	9.6	25,000
2040	9.9	20,000	5.6	11,000
2045	8.0	15,000	7.1	13,000
2050	8.0	13,000	6.9	12,000

Table 3 Projection of the amount of EV batteries POM annually in Scotland by capacity in GWh and weight in tonnes



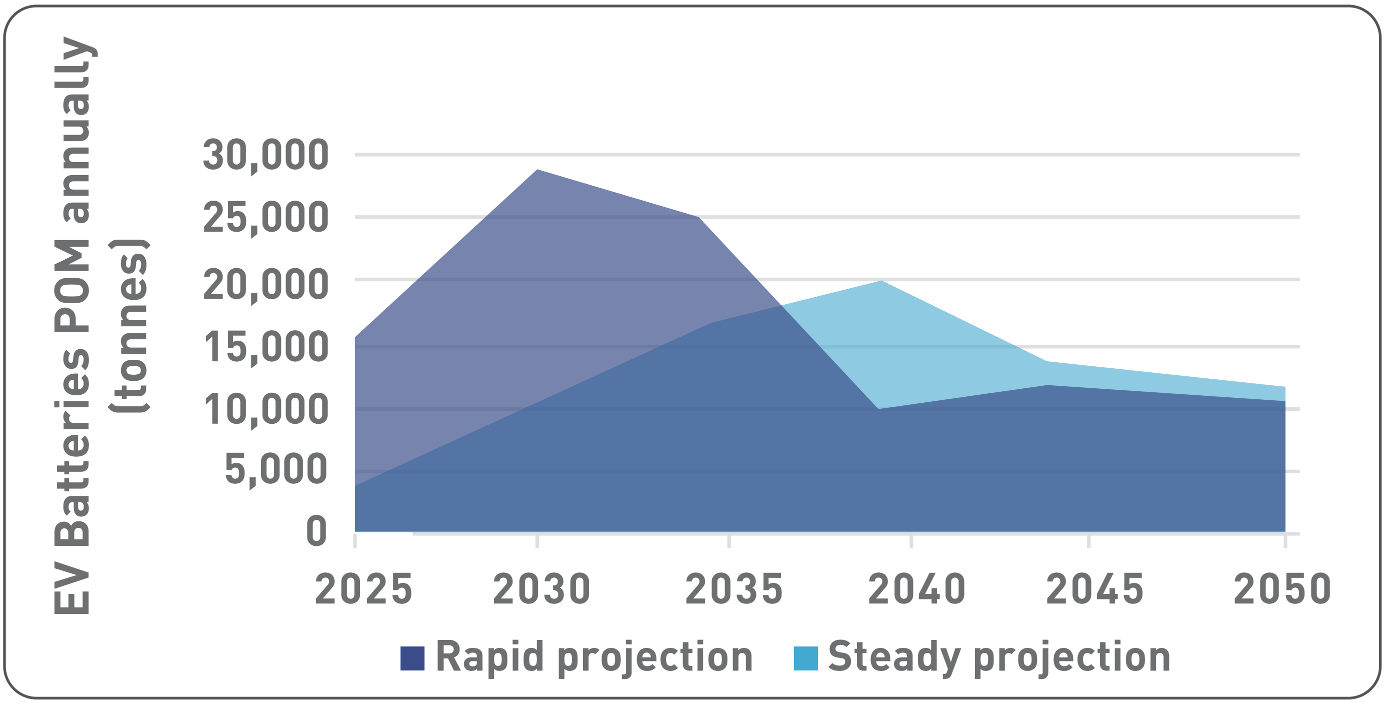


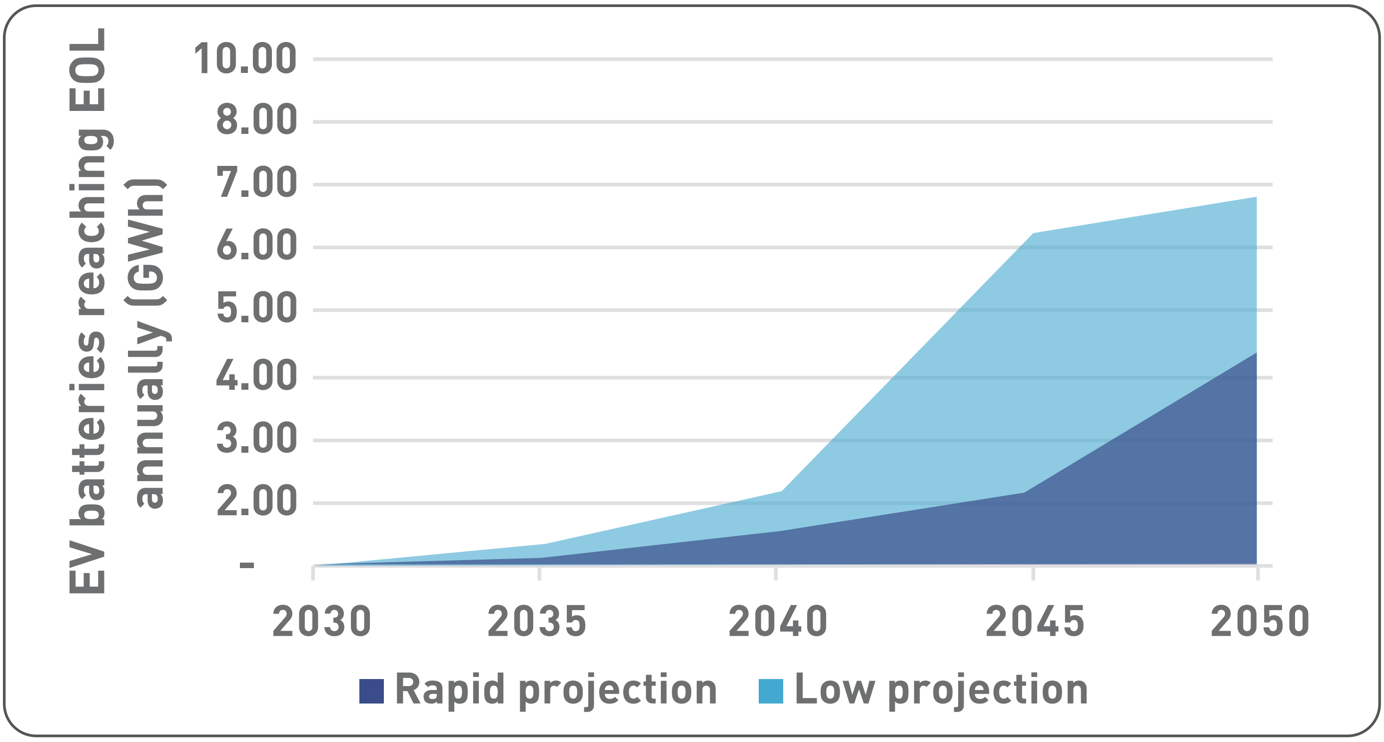
Figure 2 Projection of the amount of EV batteries POM annually in Scotland by capacity in GWh and weight in tonnes

4.2 EV battery waste

Using the methodology outlined in the **Section 2.1**, **Table 4** and **Figure 3** show the estimated projection of the amount of EV batteries becoming available for second-life purposes in Scotland from 2035 to 2050 with a 15 year expected first life applied.

Year	Low projection		High projection	
	Capacity (GWh)	Weight (tonnes)	Capacity (GWh)	Weight (tonnes)
2035	0.17	2,000	0.47	5,000
2040	0.77	5,000	2.60	16,000
2045	2.21	10,000	6.46	28,000
2050	4.83	16,000	7.71	25,000

Table 4 Projection of the amount of EV batteries reaching end of first life annually in Scotland by capacity in GWh and weight in tonnes



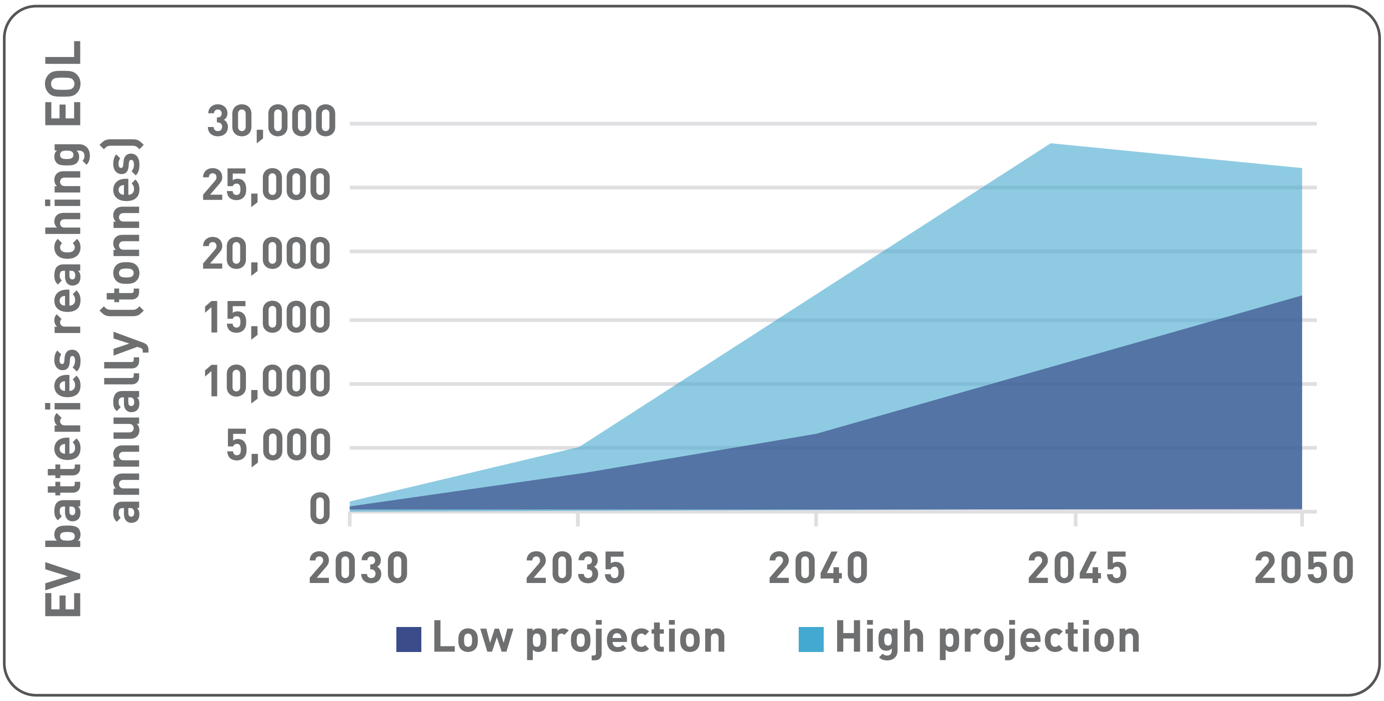


Figure 3 Projection of the amount of EV batteries reaching end of first life annually in Scotland by capacity in GWh and weight in tonnes

It is estimated that EV battery waste will start to become significant from 2035 and that the capacity of the EV batteries reaching end-of-life in 2050 would be between 4.83 and 7.71 GWh. The weight of EV batteries reaching EoL is to reach between 16,000 and 25,000 tonnes per annum in 2050. In total, by 2050, it is estimated that between 94 and 234 thousand tonnes of batteries will have reached the end of their first life.

As discussed in Section 2, the 15 year first- life estimate is dependant on a range of factors and batteries may last between ten and twenty years in the future.

5 FUTURE CHANGES IN ELECTRIC VEHICLE BATTERY USE

The market for batteries will undergo a significant expansion between now and 2050. In the transport sector, the major driver for this will be road transport. Under all but the most pessimistic scenarios, personal road transportation will shift almost entirely to battery power. Batteries will also find some applications in other modes of transport like HGVs, trains that operate on lines with discrete electrification, and potentially limited use in the marine and aviation sectors.

The supply of batteries currently comes predominantly from south-east Asia, with China in a leading position, but there is also a significant manufacturing base in Europe and the United States.

A summary by transport mode of the demand for electric vehicle batteries has been provided below, with each of these being discussed further in the following sections of the report.

Road transport
The National Grid's FES report[23] has developed four scenarios that project the number of EVs on the road in Britain. Under three of the scenarios, the number of total vehicles on the road remains similar to present numbers, with a gradual transition to battery powered vehicles. Under the fourth scenario, the total number of vehicles falls by a third and, again, experiences a gradual transition to battery powered vehicles. The scenario analysis does not consider the recent acceleration to 2030 of the ban on sales of new petrol or diesel vehicles, and as such the transition to EV is likely to be even more rapid. With HGVs battery power electrification has a much more modest share. Distances covered by lorries as well as the necessary capacity of batteries poses a challenge to electrification of HGVs. Under one of the FES scenarios, battery powered lorries reach 25% of the total number of HGVs, however, in two of the remaining ones the share is 10% and is negligible in the last one. Larger vehicles such as HGVs are understood to be more likely to undergo a transition to hydrogen fuel cell propulsion systems than battery-driven. Other road-based vehicles which may undergo increased electrification in future include scooters, motorcycles and 'off highways' vehicles such as agricultural equipment.

Bicycles
E-bicycle (EB) demand is still relatively small in the UK, but current predictions demonstrate a potential exponential growth in sales, with many consumers purchasing an EB in place of a car or other personal vehicle.

[23] National Grid ESO (2020). Future Energy Scenarios

Rail
Rail transport is headed towards electrification. The preferred method is the use of overhead lines, but in some cases where the line poses challenges to full electrification, discrete electrification and battery powered trains could present a viable alternative. The share of batteries in rail transport is likely to be negligible compared with road transport.

Marine
Marine transport is projected to transition towards hydrogen/ammonia as means of decarbonisation. Batteries could have a limited application for small vessels and short journeys, but the battery capacity is likely to be negligible.

Aviation
Air travel is unlikely to experience a significant shift towards electrification in the short-medium term. The projections suggest it will remain reliant on fossil fuels, with partial decarbonisation coming from efficiency gains and use of biofuels.

5.1 Road

Scotland has announced that it will accelerate the procurement of ultra-low emission vehicles in the public and private sector car and van fleets by the mid-2020s and into the commercial bus fleet by the early 2030s. The plan includes an expansion of electric charging infrastructure, including charging hubs. The Scottish Government has announced a plan to create an 'electric highway' on the A9, including charging points along the route[24].

Government policies have been one of the main driving forces behind the electrification of road vehicles. However, market competition amongst OEMs has also pushed forward the development of EV batteries with many of them publicly committing to fully electrifying their fleets in the coming years[25].

The predicted growth of the EV battery market has led to the introduction and development of voluntary schemes being set up across various industry sectors to help make zero-emission transport the standard by 2030. One such scheme is the EV100, launched by The Climate Group, whose business signatories have committed to delivering fully electric fleets by 2030[26].

Collectively, companies (such as Unilever, Sky, Coca-Cola European Partners, BT, Severn Trent, Dixons Carphone and Ikea) which have committed to fully electrifying their fleet by 2030 as part of the EV100 scheme, and have deployed 169,000 EVs to date, with more than half of vehicle deployments having taken place during 2020[27].

However, members of the scheme have faced challenges regarding EV procurement (especially for heavy-duty EVs) and charging infrastructure, which could affect progress without targeted support from policymakers and the private sector. According to a new policy briefing (Entitled 'Charging Up') from Policy Exchange[28], developed to help the DfT and the Department for Business, Energy and Industrial Strategy (BEIS), 35,000 charging points a year will need to be installed to support the UK's 2030 ban on new petrol and diesel cars. An average of 7,000 EV charging points have been installed annually across the UK in recent years, so significant increase in the pace of infrastructure provision is vital.

The Climate Group has forecasted that more than 4.8 million EVs could be on the road by the end of the decade if all members fulfil their commitments. In addition to the commitments to electrify their fleets, member companies have collectively pledged to install 6,500 new charging locations by 2030. According to The Climate Group's head of transport Sandra Rolling, most EV100 members have either continued with their fleet electrification plans as usual or have accelerated delivery timelines during the global Covid-19 pandemic[29]

[28] Edie (2021). Report: UK needs to install five times as many EV charging points to meet climate goals
[29] Edie (2021). EV100: Businesses doubled electric vehicle roll-outs in 2020

Typical battery chemistries

The vast majority of literature and analysis available to-date has focused on Li-ion batteries for passenger cars; such analysis can be readily read-across to light commercial vehicle applications (i.e. vans). However, there is also growing interest in applications for heavy duty vehicles as well as e-bicycles (further detail provided in section 4.2), mopeds and motorbikes. Heavy-duty vehicle applications such as buses, trucks and vans with required energy over 20kWh have historically used (and still currently use) "Zebra" battery chemistries - NaNiCl (Sodium Nickel Chloride)[30]. For example, vans with gross vehicle weights of 7.5 and 9 tonnes were electrified using these Zebra batteries[31]. However, many heavy-duty vehicles now use Li-ion based chemistries. Examples include most notably electric buses produced by BYD[32], as well as new models recently announced by Daimler[33], Renault[34], and Tesla[35].

Previous heavy-duty vehicle applications using Li-ion chemistries have predominantly adopted Lithium Iron Phosphate (LFP) chemistries (i.e. in BYD vehicles), due to their higher cycle life and improved safety versus other chemistries. However, the batteries that are to be used in many recently announced heavy duty vehicles use Li-ion cathode chemistries that are Nickel Manganese Cobalt (NMC)-based (e.g. Daimler, (AVID Technology, 2016)) or Nickel Cobalt Aluminium (NCA)-based (e.g. Tesla), which are similar to those in light duty vehicles.

The use of battery electric vehicles is most applicable to light-medium duty urban vehicles such as delivery vans or refuse collection vehicles whose drive cycles involve frequent stops and starts and do not need a long range.

Structural batteries

One type of battery use which is being developed within the car industry is that of structural batteries[36]. Structural batteries essentially eliminate the boundary between the battery and the object it's powering, for example making the structure of the car itself the battery (e.g. the floor, rather than using the floor to support the battery pack).

Approximately one third of an EV's weight is the battery pack, therefore integrating the battery into the structure of the car will not only reduce the weight but also improve its mileage efficiency. Tesla have confirmed that they are working on integrating the battery pack into the chassis of their vehicles. Researchers at Imperial College London[37] are looking to create "invisible" batteries, where the material itself is the energy storage device. The electrical storage happens in the thin layers of composite materials that make up the car's frame. These "invisible" structural batteries will help to improve the safety of vehicles as there will be no need for thousands of energy-dense, flammable cells packed into the car. The movement towards structural batteries will make recycling more challenging as, by definition, the battery raw materials will be integrated with other structural materials and therefore subject to end-of-life and recycling requirements for the vehicle as a whole. It also introduces significant challenges to identifying suitable second-life applications for the battery cells, introducing added complexity into the dismantling and assessment process.

[30] Association of European Automotive and Industrial Battery Manufacturers (EUROBAT), The European Automobile Manufacturers Association (ACEA), Japan Automobile Manufacturers Association (JAMA), Korea Automobile Manufacturers Asssociation (KAMA), International Lead Association (ILA) (2014). A review of battery technologies for automotive industries

[31] Green Car Guide (2007). Commercial Vehicles Go Green

[32] BYD, Alexander Dennis Ltd.. BYD ADL Enviro200EV

[33] Daimler (2019). Fully battery-electric driven truck for heavy-duty distribution: Mercedes-Benz eActros starts in the Murg valley: emission-free and quiet transportation

[34] Renault Trucks (2019). Renault Trucks Showcases Master Red Edition, 100% Electric Z.E. Line-Up and Reinvigorated Municipal Focus at Freight in the City

[35] Trucking Info (2021). Elon Musk: Tesla Semi Ready for Production – But There's a Snag

[36] Wired (2020). The Batteries of the Future are Weightless and Invisible

[37] Emile Greenhalgh is the Royal Academy of Engineering Chair in Emerging Technologies.

In addition to road vehicles, the use of structural batteries has been explored in the aviation industry over the last three years. A group of European researchers (Sorcerer project[38]) have worked on developing a structural Li-ion battery which could be used to build parts of an aeroplane's cabin or wings. However, the research team believe that since commercial aeroplanes require so much energy it is unlikely that they will be adopted into vehicle design within the next decade.

5.2 Electric bicycles

The first commercial electric bicycles (EBs), went on sale in the 1990s, and rapidly grew in popularity throughout the 2000s and 2010s: sales of electronically power-assisted cycles in Europe grew from 98,000 in 2006 to 1,667,000 ten years later[39], although China overwhelmingly remains the main global market and has pioneered research into EBs, making it a potentially useful case study. Of the 2016 total, the United Kingdom was responsible for 75,000 of these sales, so the market is still relatively small, but the UK and Scottish governments are championing a number of schemes to increase the usage of EBs by both consumers and businesses.

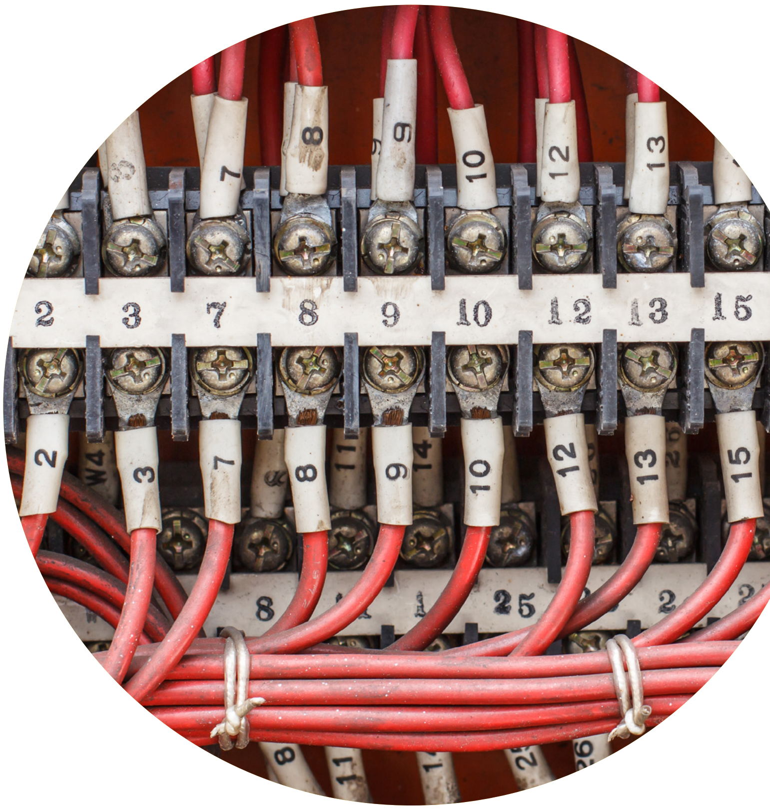
There are three main types of EB:

- Pure – the driving power of the electric motor is controlled through a handlebar throttle
- Power-assisted (pedelec) – the motor is designed to assist the rider while pedalling
- Hybrid – the motor can either be controlled through a throttle or assist while pedalling

In 2020, there were 17,208 shared bicycles (bicycles available for multiple users, such as self-service rental schemes, public bike share, and peer-to-peer sharing) available in the UK, of which 1544 were located in Scotland[40]. This figure includes both electric and conventional bicycles, so it is reasonable to assume, given the still relatively small market for EBs, that the vast majority of the total 17,208 shared bicycles are not electric. When compared to the 75,000 UK sales of EBs in 2016, it is clear that EBs are overwhelmingly privately owned by consumers.

However, shared EB schemes are increasing in size and number, having received significant interest due to the increased reduction in car use compared to conventional bikeshare schemes as well as increased accessibility for elderly people and those with health difficulties[41].

Currently in Scotland, there is not much utilisation of EBs by businesses, however the Scottish government has created a scheme in which businesses can obtain interest free loans with which to purchase EBs and cargo EBs[42]. In particular, it is hoped that cargo EBs will replace cars and vans in local deliveries and small-scale hauling.



[38] Sorcerer Group
[39] Confederation of the European Bicycle Industry (2017). European Bicycle Markets: 2017 Edition
[40] CoMoUK. (2020). Scotland Bike Share Users Survey 2019/20
[41] CoMoUK. (2020). Shared Bikes: Bike share map
[42] Energy Saving Trust. E-Bike Loan

Typical EB battery chemistries

Modern EB batteries are generally one of five types as outlined in **Table 5**.

Type of battery	Advantages	Disadvantages
Lead-acid (Pb-Acid)	Very cheap Easy to recycle Low internal impedance Tolerant of overcharging Can deliver high currents Widely available	Heavier than other battery types with low energy-to-weight/ volume ratio High environmental impact
Nickel-cadmium (NiCd)	Higher capacity, faster charge rate and fewer maintenance requirements than lead-acid Operates within wide temperature range Long life	Cadmium hard to recycle More expensive than lead-acid Gradually loses charge capacity (memory effect)
Nickel-metal hydride (NMH)	Less toxic and susceptible to memory effect than NiCd Good energy-to-weight/volume ratio	More expensive than NiCd High self-discharge, affected by ambient temperatures
Lithium-ion (Li-ion)	Lighter than other comparable capacity batteries High energy density, low memory effect Low self-discharge rate	More expensive than other comparable batteries Susceptible to damage from overheating, overcharging and over discharging
Lithium-ion polymer	Lightweight High energy density Longer life span than Li-ion	More expensive than Li-ion Less energy-dense than Li-ion Requires special case during storage, charging and discharging

Table 5 List of main types of EB batteries

The most popular type of battery used in EBs is currently (Pb-Acid) (over 80% of EBs produced in 2016 used Pb-Acid) due to its comparatively lower price. However, the market for Li-ion battery-powered EBs is growing and it is predicted that by 2023, 60% of the EBs produced will use Li-ion batteries. While Pb-Acid batteries are significantly less expensive, and easier to recycle, **Table 6** shows the mass of battery required from an Pb-Acid and Li-ion battery to achieve the same range (20mi/32km)[44]:

Battery Chemistry	Capacity (ah)	Mass (kg)
Lead-Acid	15	13.6
Lithium Ion	9	2.7

Table 6 Mass of equivalent range Pb-Acid and Li-ion batteries

The lighter weight of Li-ion batteries makes them appealing to consumers for improved functionality reasons.

[43] eBicycles. E-Bike Facts & Statistics for 2021
[44] eBikeKit. Electric Bike Batteries Explained

Case Study: Chinese E-Bike Market

The world's biggest market for e-bikes is China, with estimates of up to 200 million on the road in the country and 35 million sold each year. China has high levels of traffic and air pollution, leading to the widespread adoption of e-bikes which are significantly cheaper in China due to their use of lead acid batteries as opposed to the lithium-ion batteries that are more common in Europe (though Li-ion batteries are increasing in popularity in China).

E-bike usage has seen a number of benefits in China: increased levels of mobility amongst the middle and working class can be attributed to the low cost of e-bikes; e-bikes are also cheaper to run than cars which is effective at discouraging existing car owners from using their cars, particularly for short journeys. In Scotland, e-bikes could be a helpful mobility tool as the centres of larger cities begin to be pedestrianised (such as Edinburgh).

However, there has been pushback in several Chinese cities due to safety concerns related to e-bikes with many restricting their use and some banning them outright. E-bikes in China are not subject to any stricter regulation than conventional bicycles, meaning that no license, training or safety equipment is required to use one. In Beijing in 2015, e-bikes were involved in 21,423 road injuries, 37% of the total, and 113 deaths, 12% of the total. Furthermore, there is concern that an increase in e-bike usage with well-established public transit systems could result in a decreased use of that system, resulting in lower revenues.

For Scotland's commuters, e-bikes can be a cost-effective and environmentally friendly means of travel, but in order to reduce the potential friction Scotland could face between e-bikes and other modes of transportation, great care should be taken to ensure that regulation is comprehensive and fair to mitigate as far as possible any safety issues.

Sources:
Forbes (2016). As China Chokes on Smog, the Biggest Adoption of Green Transportation in History is Being Banned
The New York Times (2016). Beijing's Electric Bikes, the Wheels of E-Commerce, Face Traffic Backlash
Christopher R. Cherry, Hongtai Yang, Luke R. Jones, Min He (2016). Dynamics of electric bike ownership and use in Kunming, China

End-of-life options
As the chemistries of EB batteries is largely the same as other EV batteries, with only the performance specifications differing, the end-of-life options are also similar. In China, where the EB market is most advanced, nearly all Pb-Acid batteries are recycled using pyrometallurgy methods, with the current recycling rate reaching 96%[45]. In addition, some Li-ion batteries can be reused through echelon utilisation, i.e. using a battery that is no longer suitable for use in an EB for other energy storage uses or in equipment with a lower battery capacity requirement.

5.3 Rail

Scotland's ambition is to decarbonise Scottish passenger rail services by 2035, ahead of the UK's target of 2040. The Scottish Government plans to invest in battery-powered trains and work with developers of hydrogen fuel cell trains (hydrail) to accelerate their development and deployment through practical trials in Scotland.

As of early 2020 around 40.7% of Scotland's railway track is electrified[46]. In terms of the proportion of total vehicle kilometres under electric traction, however, the figure is far greater and constitutes 76% of all passenger journeys. The routes to all main rail freight terminals in Scotland's central belt are electrified, and around 45% of Scottish rail freight journeys are electrically hauled from origin to destination.

Scotland has considered the anticipated end-of-life dates for the current leased ScotRail fleet and when decision points should occur. At the end of 2020 there were 148 diesel-only trains, with 394 carriages, and 203 electric units, with 649 carriages leased by ScotRail[47]. The diesel units have a range of anticipated end-of-life dates (depending on class type) between 2025 and 2035. The volume of passenger rolling stock replacement is to 2035 is therefore significant, and offers an opportunity to consider investment in battery applications.

Changes in rail transport are not possible without the support of an adequate highly planned network. This is particularly important for hydrail, since no mass production of hydrogen for transport applications (and associated infrastructure) is yet in place. Key infrastructure considerations for both battery electric and hydrail technology include cost effectiveness, shareability with other types of vehicle and sustainability. The latter is a particularly key issue since the energy source and technology used to produce the electricity and hydrogen will heavily influence the overall (lifecycle) greenhouse gas reduction potential. Renewable energy sources, possibly in combination with carbon capture, are therefore required.

Hydrail can offer a large range and can be better adapted for long-distance and high energy-requiring freight trains, whilst battery trains may be used for shorter stretches of non-electrified rail (such as those partially electrified with catenary systems). Therefore, fuel cell trains may also be more relevant for cross-border freight transport, although this would depend on the possibility to refill hydrogen across the rest of the UK.

Battery electric trains
Battery electric trains replace the diesel generator with a rechargeable battery and utilise the batteries for traction power on non-electrified lines. Batteries may also be installed for traction power to allow a catenary based train to pass non-electrified sections of a rail network, such as narrow tunnels.

Currently, most projects relate to passenger trains, with limited or no dedicated battery electric solutions for freight trains being tested yet. Freight trains are heavier and typically need 10 times the power (5-6 MW) of passenger trains; this means that load (capacity) and range are issues where recharging batteries at regular intervals is impractical[48]. Nevertheless, battery electric

[45] Wenqiu Liu, He Liu, Wei Liu, Zhaojie Cui (2021). Life cycle assessment of power batteries used in electric bicycles in China
[46] Scottish Engineering (2020). Electrification paper: Introduction to the Rail Cluster Project
[47] Ibid.
[48] Institute of Transport Economics (TOI) (2020). Battery Electric and Fuel Cell Trains: Maturity of Technology and Market Status

technology is soon to be extended to freight trains, with a battery electric freight train planned to be tested by Burlington Northern Santa Fe Corporation and General Electric from 2020 in the U.S.

ScotRail and Hitachi

The British Rail Class 385 AT200 is a type of electric multiple unit built by Hitachi Rail for Abellio ScotRail. A total of 70 units have been built, divided into 46 three-car and 24 four-car sets. Hitachi has proposed developing a battery electric multiple unit variant of the Class 385, allowing such a trainset to traverse lines that aren't electrified at present. Hitachi Rail is one of the global leaders in battery train technology. They introduced their first battery train on Japan's railways back in 2016. Hitachi is collaborating with UK's leading battery manufacturer – Hyperdrive Innovation – to develop a market-leading battery to power trains in Scotland[49]. Hitachi anticipate that electric trains can be a major contributor to the UK government's target of net zero emissions by 2050[50].

Flirt Akku

Stadler unveiled and trialled in October 2018 a prototype version of its electric multiple-unit trains, equipped with a battery and approved for passenger operation[51]. The design is production ready, with 55 Flirt Akku commissioned by the Schleswig-Holstein public transport association to replace diesel trains in North Germany[52]. Stadler has also estimated that the units could be used to operate on 80% of non-electrified routes in Germany, as well as in the United Kingdom (UK), the Netherlands and Italy[53].

Case study: Vivarail

The manufacturer Vivarail launched a two-car battery electric production train approved for passenger service in October 2018. These Class 230 D-Train 230002 variants have been converted from 1980s London Underground carriages, using the aluminium bodyshells while installing new current-system and purpose-built machinery. They have four Li-ion battery packs each with a capacity of 106kWh and a requirement of 750V to operate.

The D-train has a maximum range of 64km with a capacity of up to 297 passengers, and the battery is expected to last for 7 years, with the train body expected to have a service lifespan of 25 years. The D-train was trial operated in Scotland over three days in an event supported by Transport Scotland and ScotRail, travelling for 40 miles on battery alone after charging for 8 minutes. Three Class 230 D-trains are currently operated by West Midland Trains, and Transport for Wales has commissioned five to be built. Vivarail has confirmed a long-term supply of batteries with Hoppecke, ensuring sustained production.

The estimated cost of production for a converted Class 230 is around £800,000, making it roughly half the price of a new diesel multiple unit train, and an expected 4000L of fuel can be saved each year compared to a Class 150 DMU. Vivarail also provides a cost comparison of their Class 230, a new regional DMU and a Class 150 DMU:

[49] The Engineer (2020). Hyperdrive Innovation and Hitachi Rail to develop battery tech for trains
[51] Ibid.
[52] Railcolor (2018). [DE] Stadler presents: the FLIRT Akku battery train
[53] Stadler Rail (2019). Stadler Supplies 55 Battery-Operated Flirt Trains for the Schleswig-Holstein Local Transport
[54] Vehicular Technology Society (2019). Stadler's New Battery-Operated Train

	New regional DMU	Class 150	Class 230
Lease rental per car per month (£)	15,000	7,500	7,000
Non-capital lease rental per car per month (£)	6,000	3,000	0
Depot maintenance per car per mile (p)	60	70	40
Fuel consumption per car per mile (litres)	0.8	0.75	0.5

Due to the modular power system of the Class 230, any Vivarail train can convert to battery power. Furthermore, the charging point of the Class 230 can draw power from any existing infrastructure with a supply of 11kV or 33kV, but if the supply is not strong enough then the train is also fitted with a static battery bank, comprised of packaged second-use batteries, presenting an opportunity for battery reuse. This bank charges overnight at a lower cost and acts as an energy reserve during the day to power the train as needed.

Sources:
Railway Technology. Class 230 D-Train
Vivarail (2018). Battery Train Update
Vivarail (2019). Vivarail launches fast charge system for the Class 230 battery trains – the UK's only battery train with a range of 60 miles between charges

5.4 Marine

The maritime sector in Scotland makes a significant contribution to Scotland's economy. Consequently, Scotland's ambition of net zero emissions cannot be achieved without decarbonising the marine transport modes. There are over 1,400 vessels fishing in Scotland's inshore waters, making up two-thirds of the Scottish fleet[54]. Inshore vessels are typically smaller boats under 10m in length and have a one or two-person crew. These vessels fish within inshore waters that extend from the coast out to 12 nautical miles (nm), with the majority of fishing activity taking place within 6 nm.

The UK's Clean Maritime Plan[55] estimates that alternative fuels will play the most significant role in reducing emissions from UK shipping, with a relatively small role for electric propulsion. In particular, this research suggests that electric propulsion options may be focused predominantly on smaller vessels that operate on shorter routes, such as ferry crossings.

Electrification in the maritime sector may take the form of:

- Shore-side power (powering vessels' auxiliary systems for vessels at berth, also referred to as cold-ironing)
- Hybrid electric vessels (the use of electric motors & batteries to complement other energy sources such as diesel engines)
- Fully electric vessels (the use of electric motors & batteries)
- Electric charging for port operations (e.g. powering non-road mobile machinery such as cranes)

[54] Scottish Parliament (2019). Inshore Fisheries
[55] Department for Transport (2019). Clean Maritime Plan

CalMac Ferries Ltd have electrified three of their Scottish ferries[56] over the last decade using hybrid technology and Li-ion batteries:

- MV Hallaig, 2012
- MV Lochinvar, 2013
- MV Catriona, 2016

Each ferry has the capacity to hold 150 passengers, 23 cars and uses a 700 kWh battery.

In general, due to cost-effectiveness, Li-ion batteries are widely used in the energy storage systems of electric and hybrid ferries. Compared to lead acid batteries that have low cost but heavy weight, Li-ion batteries are more costly but are light enough to be used in electric ferries.

Case study: Ærø EnergyLab electric ferry

The UK government projects that maritime electric propulsion will likely be concentrated in short ferry voyages. Scotland, which typically sees over ten million ferry passengers per year, could benefit from further deployment of this technology – as noted above, there have already been advancements in the UK, with Scotland's three operational hybrid ferries, and a fully electrified passenger ferry capable of carrying 12 people expected to begin commercial journeys in Plymouth in April 2021.

Ellen, the world's largest fully electrified ferry commissioned by Ærø EnergyLab, illustrates the further potential for electrification of ferries in Scotland. The ferry is capable of carrying 200 passengers and 30 cars for up to 22 nautical miles (40km) on a single charge and is recharged in under 25 minutes with energy from local wind turbines. Ellen is powered by 840 lithium-ion batteries totalling 4.3MWh, supplied by Leclanché, an energy storage company based in Switzerland. According to them, the ferry prevents the release of 2,520 tons of CO2 into the atmosphere each year.

The ferry cost a total of Đ21.3m (£18.3m) with around 70% of the cost being funded by the European Union. This figure is around 40% higher than a conventional diesel ferry but does not take into account the significant investment required to develop the required electrical infrastructure including wind turbines. However, the E-Ferry project coordinator, Trine Heinemann, estimates that the running costs of the ferry are 25% that of an equivalent diesel ferry due to the use of lightweight materials and decreased maintenance costs thanks to the relative simplicity of the electric engine in comparison to diesel. In a press release, the ferry's operators state that the ferry is estimated to break even after four to eight years, and to have a lifespan of around 30 years. Ellen is not yet fully operational, and they have run into some difficulties, with a number of batteries needing to be replaced. In addition, the high-capacity requirement means that the batteries are very heavy, and unless energy density improves, it is unlikely that vehicles like Ellen will be able to make longer journeys or carry any more substantial cargo. However, for island hopping ferries that are prevalent in the Scottish isles, this project could present an exciting opportunity for electric ferries in Scotland.

Sources:
BBC News (2020). Plug-in and sail: Meet the electric ferry pioneers
Ærø Kommune (2020). E-ferry Ellen crosses the finish line, and delivers great results
Leclanché (2020). E-ferry Ellen, Powered by a Leclanché Battery Storage System, Wins European Solar Prize 2020 Award for Demonstrating the Potential of Green Electric Mobility
Department for Transport (2019). Clean Maritime Plan

[56] Caledonian MacBrayne (2015). Third Hybrid Ferry Launches on the Clyde

5.5 Aircraft for short routes

For Scotland's islands, air travel is a fast and convenient method of travel. As a result, there is an ambition to decarbonise scheduled flights within Scotland by 2040. Scotland aims to make the Highlands and Islands the world's first net-zero aviation region by 2040, as such Scotland is "actively considering" the use of electric aircraft on short flights between the islands and mainland.

Electrification of air travel is still a very new concept, and the majority of developments are still in the speculative / theoretical stage.

Scottish regional airline LoganAir has partnered with Cranfield Aerospace Solutions to retrofit one of their existing planes for electric propulsion. The initiative is called Project Fresson, and if all goes to plan, Cranfield and its partners, including Rolls Royce, will fit electric batteries and motors into one of LoganAir's Britten-Norman Islander aircraft. This nine passenger plane will be tested as a demonstration platform for electric flight, potentially entering service commercially in 2021 or 2022. Currently, no details have been made publicly available about the battery they are planning to use, but most probably it will be lithium ion.

There is a similar island-hopping service planned in Canada, with the airline Harbour Air, North America's largest seaplane fleet, who are aiming to fully electrify their fleet. After the successful flight of a DHC-2 de Havilland Beaver which was retrofitted with a 750hp electric motor in 2019 , the airline is currently undergoing certification and approval. The battery was developed by MagniX in partnership with Eviation, they are also currently working with Li-ion batteries but are also considering next -generation technologies including lithium-sulfur.

Larger commercial aircraft are also in development: Easyjet and Wright Electric are developing a 186-capacity fully electric plane capable of flying 300 nautical miles (560 km) that could enter into service from 2030. Ground testing of the 1.5MW electric motor and 3KV inverter is planned for 2021 followed by flight testing in 2023. They have built a 2-seat aircraft as proof-of-concept with 600lbs (272kgs), and though current battery energy densities mean that any further scaling up will make the batteries too heavy, Wright Electric hope that battery technology and efficiency will improve sufficiently by their planned 2030 flight date. They believe that new battery technologies could emerge, but in case there is not enough advancement, they are also ready to switch to a hybrid model instead.

[57] The Press and Journal (2019). Nicola Sturgeon unveils plan to create emission-free airways over the Highlands and islands
[58] Royal Aeronautical Society. Electric Pioneer
[59] Harbour Air Seaplanes. Going Electric
[60] Geekwire (2019). Harbour Air's all-electric seaplane makes its first flight
[61] Wright Electric (2020) Wright Electric Begins Engine Development Program for 186 Seat Electric Aircraft
[62] The Manufacturer (2017). Startup Wright Electric plans for electric passenger planes

Case study: Eviation

A fully electric commercial plane is also being developed by Eviation. Alice, the plane, will be capable of transporting up to nine passengers and two flight crew 44nmi (815km) at a top speed of 220 knots. The aircraft will be powered by a 920kWh lithium ion battery with a mass of 3.6 tonnes (around 60% of the maximum take-off weight of the plane). The battery recharges at a ratio of 2:1, or for half the time it flies. The electric propulsion engine, developed by MagniX, is also being utilised by Harbour Air and a number of other companies developing electric aviation technologies. The first test flight is planned for 2021, with certification for commercial journeys planned for 2023.

The final price for the aircraft is expected to be $4 million, claims that the direct operating cost will range from $230-250 for the prototype, in comparison to existing aircraft of similar sizes which the company expects to be 30-50% more expensive to run. Because no test flights have yet been completed, these figures are still speculative.

There is some scepticism surrounding the plane's potential performance: many conventional short haul planes operate for up to 12 hours a day with one refuelling, compared to the Alice's substantial charging requirements. This would limit the plane's activity and therefore potential revenue. It should also be noted that the cost of charging infrastructure will likely be high which could limit the plane's deployment in Scotland. Furthermore, there have also been some safety concerns: during testing in January 2020, a fire caused by the Li-ion batteries caused severe damage to the Alice prototype, requiring it to be rebuilt. It is likely that the certification phase will be very lengthy given this fire risk, as well as charging degradation and other issues. Nevertheless, if successful, the Alice aircraft shows that commercial electric air travel may soon be a reality for short distance flights such as those to Scotland's islands, and could present an interesting opportunity for the decarbonisation of transport.

Sources:
Simple Flying (2019). Who is Alice? – An Introduction To The Bizarre Eviation Electric Aircraft
Flight Global (2020). Eviation Alice fire involved lithium-ion batteries which ignited after hours of powerplant tests
Forbes (2019). Billionaire Richard Chandler Takes Control Of Eviation, Giving It Funds To Make Electric Passenger Plane Take Flight
Future Flight (2019). Eviation Uses Dassault Software to Fast-Track Alice's Service Entry

6 FUTURE CHANGES IN ELECTRIC VEHICLE BATTERY CHEMISTRIES

The new technologies that will be commercialised over the next 10 years are still largely based on Li-ion but seek to improve performance and reduce the use of rare metals, with the exception of aluminium-air and sodium-ion batteries. **Figure 4** shows a prediction of how EV battery chemistry will evolve to 2050, as developed in a previous Ricardo project for the European Commission. The remainder of this section outlines the characteristics of the main categories of batteries expected to be used in EV applications.

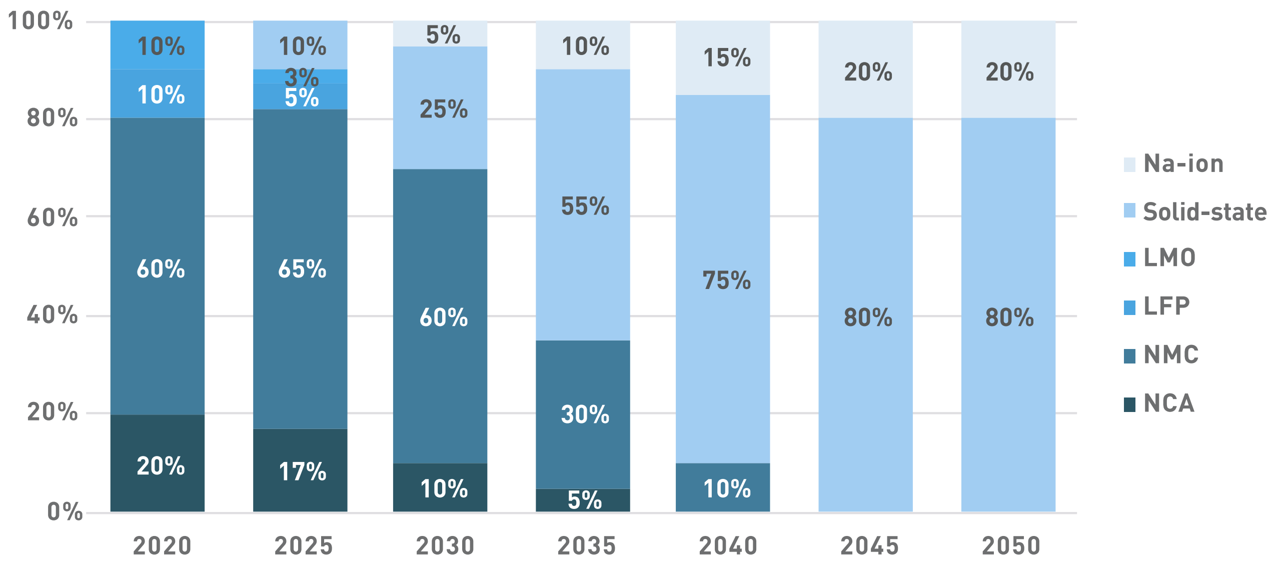


Figure 4 **Projection of EV battery technology mix by chemistry**
(Na-ion = sodium-ion; LMO = lithium-manganese-oxide; LFP = lithium iron phosphate; NMC = nickel-manganese-cobalt; NCA = nickel-cobalt-aluminium oxide)

6.1 Current state-of-the-art Li-ion batteries

Li-ion based battery technologies remain the dominant chemistry for high power applications that are suitable for EVs, and are predicted to do so for the next decade. There have been several technological advances within Li-ion based batteries.

[63] RE&E(2020). Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA

The different chemistries that make up this category exhibit different sets of advantages and disadvantages, but overall, it could be said that Li-ion batteries are:

- Small
- Energy dense
- Long lasting
- Versatile
- Affordable

However, they suffer from:

- Safety issues
- Improvement slowing down – incremental advances of about 1-2% performance improvement annually over the last 5 years.

Development of Li-ion based batteries is directed towards alternative anode and cathode structures and use of new materials for the electrolyte. Some chemistries exclude some raw earth metals due to their scarcity. There is an expectation that producers of EV batteries will continue to lightweight individual batteries alongside the developments to enhance performance and lifespan, providing users with greater cost and performance efficiency. **Table 7** presents the different Li-ion chemistries and their characteristics in more detail.

Chemistry	Specific energy density of cells	Notes
Nickel Manganese Cobalt (NMC)	209 Wh/kg	• Mature and durable batteries with high power ratings • No major drawbacks, but safety, specific energy and affordability could be better • Some rare metals used
Nickel Cobalt Aluminium (NCA)	250 Wh/kg	• Energy dense, affordable and mature chemistry with good performance • Power density, safety and durability could be improved • Some rare metals used
Lithium Manganese Oxide (LMO)	166 Wh/kg	• Good power density and safety. The mix of materials for the cathode has few rare metals, compared to other chemistries • Energy density and affordability are the main drawbacks
Lithium Iron Phosphate (LFP)	165 Wh/kg	• Power dense, safe and durable. These batteries also have good performance and the mix of materials for the cathode has few rare metals, compared to other chemistries • Energy density and affordability are the main drawbacks
Lithium-sulfur cells	~600 Wh/kg	• High theoretical specific energy and energy density (2500Wh/kg and 2800Wh/l) • Abundance of sulfur – a cheap and widely available substitute to rare earth metals • Low lifespan – 100 cycles (some reports of up to 1000 cycles) • Expands during discharge so not suitable for space constrained applications
Lithium metal rechargeable cells	500 Wh/kg	• High performance • Low life cycle – currently 375 cycles because of dendrites growing on the anode (lithium deposits growing like needles) • Uses standard cathodes which does not resolve the issue around rare materials

Table 7 Current state-of-the-art in Li-ion batteries

Whilst Li-ion based batteries are predicted to remain dominant in the EV market in future, there are also examples of Sodium-ion and Aluminium-air batteries that move past the Li-ion chemistry altogether.

6.2 Li-ion future developments

Developments in Li-ion batteries have focused on changing the materials used in battery cathodes and anodes to improve performance. Examples of these developments have been provided in the **Table 8** below.

Chemistry	Characteristics
	Disadvantages • Low cycle life
High-voltage cathodes	An increase in the operating cell voltage with new materials could lead to increased specific energy and energy density. One prototype ($LiCoMnO_4$) offers 720Wh/kg for 1000 cycles at 5.3V (typically it is 3.7V-3.8V). Advantages • Higher voltage > fewer cells needed leading to fewer interconnections and reduced resistance • Decreased mass and volume Disadvantages • Lack of a suitable electrolyte for the higher voltage
Silicon anodes	Silicon is used alongside graphite in anodes in varying proportions and it could greatly improve performance. Silicon only anodes could theoretically provide great performance benefits but suffer from deterioration due to the expansion of silicon during operation. Research is carried out in alleviating this through manufacturing different structures like nanowires. Advantages • Theoretically, silicon has a ten times higher capacity than graphite • Hence, higher specific energy and energy density Disadvantages • Silicon increases in size by more than three times leading to degradation
Tin based anodes	Advantages • Higher capacity than graphite. Disadvantages • Increases in size by more than three times leading to degradation

Table 8 **Expected Li-ion battery chemistry developments**

[64] The Faraday Institution (2020). High-energy battery technologies

6.3 Lithium-air batteries

Lithium-air batteries use a lithium anode and air as the cathode. This composition within a cell allows it to potentially achieve a much higher capacity than current technologies – theoretically up to five times higher. Since the cathode uses air, this is a cheap and abundant material, helping to reduce the environmental impact of the battery overall[65].

On the other hand, lithium-air batteries have low power outputs and aren't very efficient. The batteries can also degrade rapidly if there are contaminants in the air which is used within the cathode[66].

6.4 Solid state batteries

There is currently significant research being undertaken on solid state battery technology. These batteries use ceramic, glass or sulphide for the electrolytes and are compatible with current lithium-based chemistries. There are reports of batteries lasting more than 1000 cycles in combination with excellent specific energy and energy density[67].

Solid state batteries have several advantages over Li-ion batteries:

- Safer
- Potentially higher energy densities
- Potentially easier to manufacture

However, some doubt has been cast on the belief that solid-state batteries will be a superior option to other battery types. It was believed until recently that solid state batteries could enable the use of lithium metal anodes by prohibiting dendrite penetration, but due to the solid electrolyte's high-conductivity it has been found that dendrite formation is actually easier in solid state batteries[68]. If further research corroborates this, the direction of solid state battery development will likely need to change.

[65] The Faraday Institution (2020). High-energy battery technologies
[66] Battery University. Future Batteries
[67] E.A. Wu, S. Banerjee, H. Tang, et al (2020) A stable cathode-solid electrolyte composite for high-voltage, long-cycle-life solid-state sodium-ion batteries
[68] The Faraday Institution (2020). High-energy battery technologies

6.5 Non-lithium-based batteries

The two main non-lithium-based batteries which are being developed for use in the EV sector are aluminium-air and sodium-ion. **Table 9** provides a summary of their advantages and disadvantages[69]:

Chemistry	Characteristics
Aluminium-air	Operate on a similar principle to Lithium-air batteries. The difference is that aluminium is consumed during the reaction, so they are not electrochemically rechargeable. Oxidised aluminium is easily recyclable and needs to be replaced instead of recharged. Advantages • Very high specific energy • Common recyclable materials used Disadvantages • Oxidation on the aluminium surface hinders performance. The solution is to either use specialised alloys (expensive) or use corrosive electrolyte (unsafe)
Sodium-ion batteries	Na-ion batteries are emerging as a potential alternative to Li-ion for some applications mainly because the materials used in them are more common and cheaper. Advantages • Lower cost than Li-ion • Abundance of sodium • No necessity for using rare earth metals in the cathode. Disadvantages • Large volumetric expansion when fully charged • Low cycle life as a result • Need for an alternative to graphite as an anode material [70 71]

Table 9 Key non-Lithium based battery chemistry future developments

6.6 Summary

Batteries for high power applications are (and are likely to remain) largely Li-ion based. This means that recycling approaches that are applicable to current technologies are likely to remain useful for the next generation of EV batteries.

It is worth noting that components such as the peripheral system, housing and conductors form more than half of the mass of the battery. That means that materials such as aluminium, steel and plastic polymers are likely to remain a large part of the battery pack.

Any adjustments in the recycling process will need to be focused on changes in the cathode, anode and electrolyte. Most likely, recycling will need to focus on the cathode as it is the component which is likely to undergo changes the most. The anode is likely to change too, with silicon becoming more widely used. The electrolyte could become solid state (glass, ceramic or sulphide).

Two chemistries that diverge significantly from current technology are aluminium-air and sodium-ion. In the case of aluminium-air, the aluminium in the battery undergoes oxidation, and the resulting oxide needs to be removed from the battery and is widely recyclable. Na-ion has a comparable structure to Li-ion, so the recycling process could remain similar. The recycling of the cathode would need to change due to the entirely different composition.

[69] The Faraday Institution (2020). High-energy battery technologies
[70] Battery University. Future Batteries
[71] Science Direct. Sodium Ion Battery

7 OPPORTUNITIES AND CHALLENGES IN ELECTRIC VEHICLE BATTERIES FOR SCOTLAND

This section discusses the key opportunities for Scotland to derive maximum benefit from the expected future development of the EV battery sector, and specific challenges to those. The overarching challenge, and note of caution, relevant to all of the opportunities mentioned, is the fact that every automotive OEM has made clear commitments to their planned business models for EV batteries as the industry continues to progress. As discussed in Section 3, there are three broad options for EV battery business models for OEMs:

- OEMs operate a leasing model for batteries and retain ownership at EoL, either for in-house recycling, their own development of second-life applications or direct-to-consumer resale
- OEMs sell battery at EoL to a second-life third party, who would assess the remaining capacity within the battery pack and individual cells and match to suitable second-life applications
- OEMs licence collection and recycling to a third party with recovered materials becoming available to loop back into the manufacturing supply chain

Which of these routes the majority of the market decides to follow will have a significant impact on both the levels of EoL batteries available for recycling or reuse, and the demand for materials or cell components for new manufacturing. If the first option is widely adopted then there will be very little opportunity for external organisations to benefit, as the materials will effectively be circulating within internal closed loop systems. Planning and decision making on this front from the OEMs is likely to take place over the next five or so years, and therefore it is difficult to definitively recommend the long-term investments in any of the opportunities mentioned below. Engagement with OEMs will be important to understand their plans, investigate the possibility for the location of any planned processes in Scotland, and identify likely potential gaps in the lifecycle value chain which Scottish parties may fill.

7.1 Technology design and manufacture

Despite the small battery manufacturing capacity, the UK, and Scotland in particular, is well positioned in the chemical sector with strong capabilities and good ties with battery manufacturers. Currently, the UK is engaged in production of speciality graphite cokes, it has Europe's second largest nickel refinery and Europe's largest electrolyte plant and is also engaged in R&D for cathode manufacturing[72].

Scotland already has some small-scale manufacturing of cells, modules and pack combined with capabilities in battery management solutions and excellent academic credentials in the future of battery chemistry and design. A separate set of appendices is available on request from Zero Waste Scotland detailing companies related to the battery industry based in Scotland and current relevant research at Scottish universities, as well as detail about international battery recycling operations.

[72] Science Direct. Sodium Ion Battery

The presence of this manufacturing capacity may create significant synergies with recycling or second-life battery applications. There are also potential synergies to benefit from if suggestions of a Scotland-based lithium refinery come to fruition. Scotland has a ready-made refining infrastructure and chemical industry expertise, providing a strong opportunity to locate the refined raw materials close to a potential manufacturing base.

Opportunity 1: Support development of battery design research and manufacturing capability

Opportunity 2: Support development of materials refinery capability to supply UK demand

Challenges

As mentioned in Section 3.1, the major challenge to the feasibility of Scotland's potential to develop a large-scale refining and manufacturing capability is competition from other areas of the UK. The UK's automotive manufacturing hub is in the West Midlands and as such the battery manufacturing industry may well gravitate to that region also. That being said, with an estimated seven gigafactories required to meet future UK EV demand, there is a strong case for at least one to be Scotland based. Also, the chemical and materials refinery experience within the country could serve UK wide.

7.2 Recycling

Our projections estimate that the level of end of first life EV batteries in Scotland could reach as high as 28,000 tonnes per annum by 2045. Scotland, and indeed the UK, currently has no recycling plants for Li-ion or processing plants for second-life batteries. In practice, this means that all end-of-life EV Li-ion batteries, other than those returned to the producer, are transported to the EU for recycling. Prices for this export are already very high and the overall cost to the economy is likely to increase as EV adoption becomes more widespread and as the EU is expected to introduce regulations limiting the import and disposal of Li-ion batteries to keep up with its own demand. With this export option for Li-ion battery disposal likely to become quickly unsustainable, there is an opportunity for Scottish policy to facilitate the establishment of Li-ion battery recycling in the UK in order to circumvent the current high price of waste management.

Not only would a domestic recycling infrastructure be beneficial from a waste management perspective, but with manufacturing projected to increase massively in the short-medium term future there will be a demand for materials recovered. The concept of urban mining, deriving valuable materials from products already in circulation, is growing. Input from our stakeholder interviews suggest that around 30 tonnes of recycled Li-ion could provide the same amount of usable materials as 250 tonnes of Lithium ore, or 900 tonnes of cobalt ore. As the global economy in general seeks to move away from the carbon-intensive extraction of raw materials, this attractive benefit to any recycling operation cannot be ignored.

Opportunity 3: Support development of recycling infrastructure for Li-ion batteries, and eventual replacement chemistries

Challenges

Though the development of EV battery recycling and processing plants in Scotland would present many opportunities, such a plan would also face substantial challenges. Not least is the fact that there would likely be considerable lead times and up-front costs involved in developing these plants, as well as the relatively high costs currently associated with Li-ion battery recycling, due to the as-of-yet limited volumes of end-of-life EV batteries. Whilst our projections estimate that there will be significant volumes of end-of-life batteries in Scotland in the medium- to long-term, there remains uncertainty of the level of availability of these batteries. If automotive OEMs opt for a business model which sees them retain ownership of the battery and bring it back 'in-house' for reprocessing or recycling, there would be very little scope for an independent domestic recycling sector.

[73] The Faraday Institution (2020). The importance of coherent regulatory and policy strategies for the recycling of EV batteries

This unknown factor could develop in either way over the next few years, as OEMs make their business model decisions for the different regions they operate in, and close watch should be kept on such developments.

Li-ion battery recycling methods are currently neither cost-effective nor energy efficient. Furthermore, when using methods such as pyrometallurgy, precautions must be taken to prevent the release of toxic by-products. However, there are a number of ways in which the process could be made more viable:

- "Separation technology for recovered cells that enables processing different chemistries, recycling processes for each cell chemistry, or technology that produces valuable products from a mixed stream
- Methods for separation of cathode materials after initial processing
- Greater recycling process flexibility or standardisation of battery materials and design; and
- Assurance that regulations will not impede recycling[74]"

In an ideal recycling scenario, the battery would be designed as simply as possible, with limited glues and sealants used, in order to maximise the amount of materials that can be easily recovered. However, EV batteries must be nearly indestructible so as to ensure the safety of the driver and passengers[75]. Balancing safety and ease of material recovery is a difficult task for battery manufacturers and so safety should be considered the priority. In the event of a crash, significant testing would have to be carried out to determine if the battery is suitable for further use.

7.3 Second-life

After approximately 10–15 years in use for EV applications, batteries are likely to be decommissioned. Batteries and even individual modules within the same battery pack suffer different rates of degradation. As a result, not all the modules taken out of EVs will be suitable for second-life applications, and for those material recycling may be the best value option. Of the batteries that come to the end of their useful life in EVs, about three quarters are expected to be used for second-life applications by 2025[76].

[74] Gaines (2014). The future of automotive lithium-ion battery recycling
[75] Interview with stakeholder
[76] Bloomberg (2018). Electric-Car Batteries Find Second-life

The environmental impact of second-life batteries is undoubtedly positive, since it defers recycling or disposal in favour of retaining materials at a high value use, and displaces manufacturing of a new battery.

From a technical standpoint, second-life batteries are characterised by lower power, lower capacity and varying cell-to-cell performance. While cell-to-cell performance should be largely balanced by the battery management system over its lifetime, the former factors can be compensated for by a robust testing and reassembly process and appropriate sizing of the second-life battery. Potential differences in performance can also be mitigated by focusing on a small range of unique pack configurations using batteries from a limited number of original manufacturers. Though this would allow for a higher level of standardisation, however, a thorough analysis of the expected lifetime of the battery depending on its state of health and the expected dispatch strategy would still need to be carried out.

From an economic perspective, second-life batteries show promise. One study suggests that second-life batteries can have a 60% lower cost than new batteries[77]. However, general conclusions cannot be drawn as these figures mean that a second-life battery is currently only marginally more economical than a new battery, given that they typically have a usable life of 50% of that of equivalent new batteries. The viability of the second-life batteries will hinge on their decreasing cost, increasing expected lifetime and continuous access to predictable and reliable market demand[78]. The UK has a well-functioning wholesale electricity market and a market for grid services which currently offers revenues that prove attractive for storage operators investing in new batteries. With further proliferation of renewable energy, the spread in prices and need for certain services like arbitrage, capacity provision and, to an extent, provide another potential market for second-life batteries[79].

Scotland already has high levels of renewable energy penetration. To facilitate further expansion of the renewable capacity, a low carbon solution to balance supply and demand would be necessary. Energy storage is a suitable solution, and a potentially significant supply of second-life batteries that retain most of their capabilities, are economically viable and offer excellent environmental benefits could meet a considerable proportion of the future demand for storage capacity. The potential demand for second-life applications in stationary storage markets should be investigated through a full engagement exercise with the key stakeholders, such as renewable energy developers, grid management operators, communications infrastructure operators and those requiring access to uninterrupted power supply services such as the healthcare sector.

To be able to capitalise on this opportunity, the capacity to reclaim, test, and reassemble battery packs (or even battery modules from individual cells) would need to be built up. There are still significant challenges associated with this process that remain, but Scotland already has academic and technical expertise in the field.

Opportunity 4: Support further development of battery pack and cell testing and grading capability

Opportunity 5: Engage further with stakeholders in potential stationary energy storage second-life markets

Opportunity 6: Assess feasibility of battery collection and sorting 'hubs', to home grading and matching services for second-life markets

Challenges

EV batteries come in different configurations and designs. Battery manufacturers use different designs for their cells, which can be cylindrical, prismatic or pouch. The battery modules and packs do not use standardised connections and packaging. Additionally, there are different chemistries currently in use.

77 Mathews, et al. (2020). Technoeconomic model of second-life batteries

78 Martinez-Laserna, et al. (2018). Battery second-life

79 Lane Clark & Peacock LLP (2021). Is battery storage a good investment opportunity?

These factors present a significant obstacle to automating the process of disassembly, testing, sorting and reassembly. The complexity created by the diversity of designs is likely to necessitate either a process that is heavily reliant on labour input, or separate automated lines to deal with the most common designs.

The British Standards Institution recommends that regulation be developed to ensure the "maximum commonality of components, systems, tools, fixtures, jigs, facilities and processes with other battery electric vehicles

being manufactured alongside the vehicle". However, as discussed in Section 5.1, the trend in EV manufacturing is towards batteries being built into the floor of the vehicle, necessitating an individual battery design for each vehicle.

As batteries degrade, they develop a degree of heterogeneity in the performance of the different modules or even individual cells. To achieve a good performance in a second-life battery, modules that exhibit similar rates of degradation must be graded and grouped together to restore relatively homogenous performance. This is a time-consuming step.

A new grading process could reduce the time from a few hours to a few minutes, which could be a major step in overcoming this obstacle.

7.4 Regulatory considerations

In line with the corresponding EU Directive requirements, the End-of-life Vehicle (ELV) regulations in the UK stipulate that minimum 95% of the weight of the vehicle must be reused and recovered at end-of-life and minimum 85% needs to be recycled. The regulations for batteries, however, lag behind – currently Li-ion is not explicitly mentioned and is covered under "Other batteries" for which a 50% recycling target is in place.

There are currently no regulations that deal with second-life applications, and a lack of standards on the performance, safety and testing of second-life batteries which further complicates the effective proliferation of battery reuse programs in the UK.

Part of the reason for this lack of regulation is due to the relative newness of EV technology. In 10 years' time, however, Scotland and the UK as a whole may face a glut of batteries with few options for dealing with them. While Scotland would likely not be a suitable location for EV battery manufacturing, as the main UK hub for EV production is in the West Midlands, it would be useful to develop a nation-wide strategy for battery reuse and recycling. However, there are some difficulties in determining what this strategy should entail:

- It is difficult to accurately predict the numbers of end-of-life batteries that Scotland may face in the future due to different reuse scenarios and varying lifespans depending on the different conditions batteries may face; this makes it problematic to ascertain what capacity any recycling/reuse plant should have
- Some stakeholders have raised concerns that Scotland-specific initiatives could be counterproductive to a UK-wide effort, and that time and money could be better utilised on development at a UK level

[80] British Standards Institute (2021). PAS 7060: Electric vehicles. Safe and environmentally-conscious design and use of batteries
[81] Smart Energy International (2020). University breakthrough in second-life use for Nissan EV batteries

Despite this concern, it is necessary to consider the risks of transporting end-of-life batteries, particularly as industry circularity increases and battery lifespans extend beyond the current 10-15 years. Even new batteries require a number of safety precautions before they are transported, lending weight to Scotland-specific initiatives: local recycling/reuse centres would reduce the risk and cost of transporting end-of-life batteries[82].

Extended Producer Responsibility is another regulation that is not currently well suited to second-life applications. It puts the responsibility for collection, recycling and disposal to the entity that put the battery on the market for the first time. Either a shift in responsibility or extended responsibility for the original producer needs to be enshrined in regulation. The UK-wide producer responsibility systems for batteries and accumulators and EoL vehicles is currently under review[83]. This review is being led by Defra, with input from the Devolved Administrations of Scotland, Wales and Northern Ireland.

The Faraday Institution has recommended a regulatory framework to increase the numbers of Li-ion batteries that are recycled or reused, including:

- A coherent waste hierarchy strategy that will allow the UK battery reuse/recycling industry to flourish
- Transparent battery reuse and recycling regulations
- Market and design regulations to facilitate the adoption of a circular economy model, incentivising recycling and reuse programs[84]

The adoption of such a framework would drive engagement and innovation within the EV industry and would enable the full potential of batteries to be unlocked. How far any Scottish-based framework could differ from the wider UK, and European context is a matter for consideration, as is the extent to which such deviations could really influence the market.

Opportunity 7: Investigate feasibility of Scottish-based regulatory interventions to encourage greater circularity

[82] Interview with stakeholder
[83] HM Government (2018). Our Waste, Our Resources: A Strategy for England
[84] The Faraday Institution (2020). The importance of coherent regulatory and policy strategies

8 CONCLUSIONS

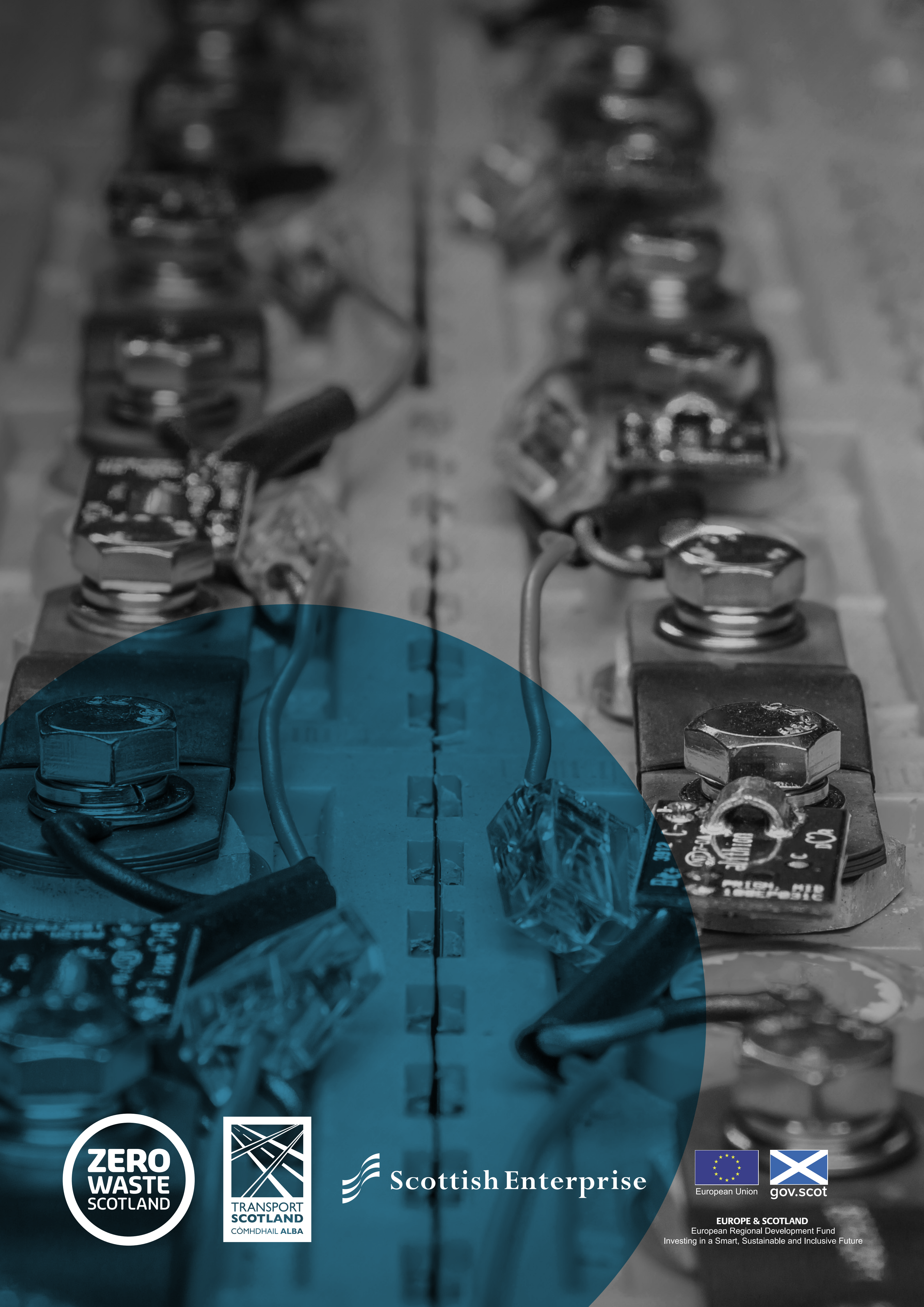
With the demand for EVs undoubtedly set to surge, Scotland faces an increasing battery capacity demand and eventual supply of end of (first) life materials. There are opportunities to develop existing capability in technology design and manufacturing, invest in recycling infrastructure, and develop logistical and regulatory frameworks to encourage reuse. However, all of these opportunities need to be considered in the context of significant uncertainty in the market surrounding the long-term plans of automotive OEMs for their batteries' EoL options.

The potential opportunities for Scotland identified through this project, and our initial assessment of likely feasibility as estimated following the procedure laid out in **Section 2.4**, are laid out in **Table 11**:

Opportunity	Likely feasibility for Scotland
Opportunity 1: Support development of battery design research and manufacturing capability	Medium
Opportunity 2: Support development of materials refinery capability to supply UK demand	Medium
Opportunity 3: Support development of recycling infrastructure for Li-ion batteries, and eventual replacement chemistries	Low
Opportunity 4: Support further development of battery pack and cell testing and grading capability	Medium
Opportunity 5: Engage further with stakeholders in potential stationary energy storage second-life markets	High
Opportunity 6: Assess feasibility of battery collection and sorting 'hubs', to home grading and matching services for second-life markets	Medium
Opportunity 7: Investigate possibility feasibility of Scottish-based regulatory interventions to encourage greater circularity	Low

Table 11 **List of opportunities and their likely feasibility**

It will be vital to directly collaborate with OEMs to assess their intentions with regard to production scaling, as well as their batteries' recyclability and reusability, and the planned business models for EoL. This collaboration would bring a degree of certainty, ideally encouraging investment into the infrastructure and informing future policy. With the insight from this engagement in development, the opportunities raised in this report can be considered in more detail for their comparative merits and weaknesses.



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