European Commission

# Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles

Final Project Report


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Ricardo Energy & Environment


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Joint Research Centre

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# Executive Summary

Ricardo Energy & Environment was commissioned to provide technical support to the European Commission on *"Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles"* (hereafter, the 'project'). The project was commissioned by the European Commission's DG Joint Research Centre (hereafter 'the JRC'). This final report provides a summary of the final findings of the project, which were also presented in draft form and discussed with stakeholders at the final project workshop on 4th February 2019.

For electric vehicles, the production (and disposal) of the traction battery may constitute a significant share of the full lifecycle impacts. With the take-up of electric vehicles anticipated to accelerate in the coming years, minimisation of these impacts will be increasingly important.

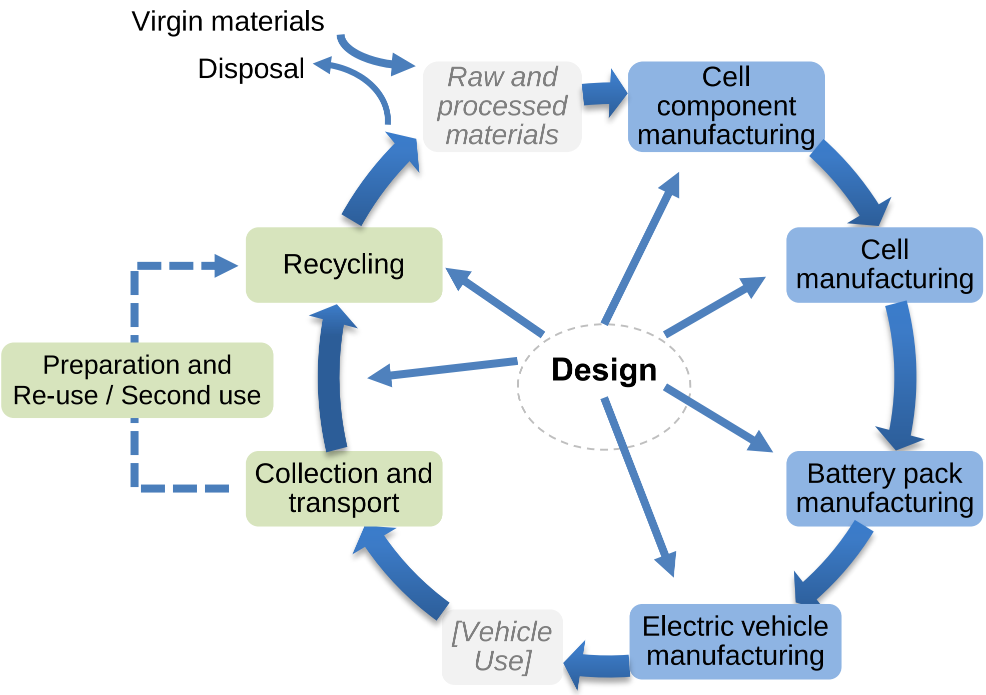
The objective of the project is to support the Joint Research Centre (JRC) in providing a strong factual base and techno-economic analysis to address the following six key research questions:

1. What are the current available and emerging techniques in the manufacturing, re-use and recycling of traction batteries for electric vehicles? How are end-of-life batteries currently processed and what are the emerging plans for the future?
2. What is the current environmental impact of traction batteries for electric vehicles across the whole life cycle? What are the current environmental hotspots and how are they addressed?
3. What will the potential environmental impacts and hotspots of traction batteries over their whole life cycle be if electric vehicles are deployed at large scale and/or in accordance with current trends, in the near, medium and long term?
4. What are the perspectives for developing a sustainable value chain for electric vehicle batteries in the EU?
5. What are the current strengths and weaknesses of the EU economy (industry, infrastructure, policy framework) for dealing with the lifecycle of traction batteries in the perspective of road transport electrification?
6. What public policies could be envisaged to ensure truly circular lifecycles for traction batteries, and to harness the opportunities for growth and jobs in the EU?

In order to investigate and provide robust answers to these key research questions, the Project team followed an analytical approach to build the evidence base supporting the analysis, identifying key challenges and finally developing potential policy solutions. The initial part of the analysis focusses on reviewing state-of-the-art techniques for the manufacturing, reuse/repurposing and recycling of batteries, to better understand the environmental lifecycle impacts and hotspots, and to feed into the analysis of implications of electric vehicle (EV) deployment, which were explored by scenario modelling. By establishing the characteristics of what a sustainable value chain could look like, the analysis could identify the strengths, weaknesses, opportunities and threats of the EU economy in reaching a circular economy model for EV batteries. The final part of the analysis then laid out concrete challenges facing the development of a sustainable value chain, and how to address these by identifying policy alternatives and prioritising these (according to better regulation criteria) to propose a shortlist of policy solutions to be considered.

A circular view of the EV battery value chain is summarised in Figure ES1.

**Figure ES1: Circular view of the EV battery value chain for Europe**




*Notes*: The 'Raw and processed materials' and Vehicle use' stages are not directly addressed in this study. Re-use or Second use / repurposing are optional additional steps that may be applied where feasible; whenever batteries become waste (e.g. where further reuse or repurposing is not feasible) they should be recycled.

## Techniques for the manufacturing, reuse/repurposing and recycling of batteries

A limited review and analysis were conducted on the ongoing activity for EV traction battery (1) manufacturing, (2) reuse and repurposing, and (3) recycling. This was further refined in consultation with stakeholders across the EV battery value chain.

Whilst historically there has been some EV battery pack production in Europe, most production of EV battery materials, components and battery cell manufacturing has occurred elsewhere (mainly in East Asia and increasingly in the USA). However, there is significant interest in further European battery production and there are several new facilities already being planned to increase EU manufacturing and capability in this area, to complement an already strong automotive manufacturing sector (cf. for instance the European Battery alliance initiative).

Previously hybrid electric vehicles batteries have also used Nickel Metal Hydride (NiMH) chemistries, now most new hybrid and other electric vehicles use Lithium ion (Li-ion) batteries of various chemistries. Li-ion batteries using NMC (Nickel Manganese Cobalt Oxide) and NCA (Nickel Cobalt Aluminium Oxide) cathodes are the most popular, though new formulations and new chemistries are under development (such as solid-state, lithium sulphur and sodium ion batteries). There are also a range of battery form factors – prismatic, pouch and cylindrical, with different advantages and disadvantages.

The manufacturing processes to produce current battery chemistries and form-factors are very similar. Therefore, many of the previous and in-development improvements to these processes have (or will have) similar benefits across these. However, whilst most new chemistries could be manufactured with minor changes to the production process, some – particularly solid-state batteries – would require more fundamental changes to several of the sub-stages of current manufacturing processes.

According to feedback from interviews with expert stakeholders, much of the cost reduction for battery manufacturing in the last 10 years has been due to increases in production efficiency through optimisation. Hence, current manufacturing produces significantly more kWh of batteries per annum for the same machinery than before.

A range of future potential improvements were identified for improving battery performance and battery manufacturing itself during the project. Such improvements are mainly driven by cost and battery performance considerations, though in many cases there will be benefits to other areas also. Cathode materials/component production (particularly Cobalt) contribute to a significant proportion of the costs. Battery cell manufacturing is highly complex and energy intensive (due to dry room and drying processes) – with energy consumption a significant component of costs and environmental impacts. Energy consumption costs as much as 20% (or more) of the total, so there are clear drivers to reduce this. Ongoing improvements in process efficiency, and technologies improving the energy density of batteries (i.e. in Wh/kg) lead to both significantly reduced costs and reduced impacts per kWh of battery capacity in the future.

The final fate for EV batteries in Europe should be recycling, however there is increasing interest in the potential for reuse or repurposing of the batteries prior to this stage due to potential economic, resource efficiency and other environmental benefits.

**Re-use** means the complete or partial re-use of the battery for the *original* purpose the battery was designed for (i.e. in the same type of EV), whilst **Re-purposing** (interchangeable with “second-use”) means the complete or partial re-use of the battery for a *different* purpose/application than the battery was originally designed for (e.g. for energy storage). Both may require an element of remanufacturing.

Batteries may be assessed for remanufacturing and/or reuse or repurposing when they are returned (or collected) from their original EV use due to fault or replacement when they reach the end of their useful life in a vehicle – typically assumed to be when they reach e.g. a 70-80% of the original capacity (or state-of-health , SOH). There are strong drivers for battery remanufacturing, since OEMs must ensure there will be an adequate supply of parts for their vehicles beyond their active production period.

Research and piloting activities into battery second life are still relatively new, with a range of technical, economic and other types of barriers and uncertainties still to be assessed and overcome. The lack of traceability and standardisation in EV battery packs, together with insufficient, inaccessible or unstandardized information on usage history/battery status from battery management systems (BMS) is a key barrier. There are also important legislative/regulatory uncertainties / inconsistencies that need to be addressed to help facilitate innovation and the market in this area. From a technical perspective, greater standardisation and information would facilitate more accurate assessment/grading and automated disassembly processes (where relevant) could also help improve safety.

Whilst the costs for remanufacturing and reuse/repurposing of batteries are reported as potentially very low (~10% of the cost of a new battery), a combination of reduced lifetime for second use (vs new batteries) and the rapid reduction in new battery costs creates uncertainties for the economic competitiveness for second life batteries in the future if they are leaving vehicle use after 10-15 years.

Europe has significant technical strengths and experience in battery recycling, driven in part by stronger legislative requirements in the region compared to the rest of the world. Collection and recycling rates for EV Li-ion batteries are currently very low, however. Theoretically, most materials in a Li-ion battery can be recycled, however the focus to date has been mainly on active materials (and current collectors). In most cases, recovery is limited to certain (high cost) materials, such as cobalt and nickel, with other lower cost components, such as the binders, lithium salts and separators not currently being recovered.

The economics of battery recycling is highly dependent on battery chemistry, commodities markets and the process / techniques applied. Most battery recycling plants use pyrometallurgical (smelting) processes, also in combination with other pre-treatment and hydrometallurgical processes. Current recycling recovery rates are around 50-60% of total weight (with 50% required by the Battery Directive). However, the potential for higher recovery rates of 70-80% (or even higher) have been proposed as feasible for the medium-term at least, principally using new purely hydrometallurgical treatment processes.

Feedback from the consultation for this project suggested that current (and proposed future) recycling processes would be able to cope with the majority of anticipated chemistry improvements and potential new battery types, although there could be some difficulties with possible lithium sulphur batteries.

The waste and recycling stakeholders interviewed also highlighted the significant (10-20 year) lead time that battery recyclers have before recycling technologies for new battery chemistries need to be deployed at scale. This leaves significant time for technology improvement and investment in capacity, although overall there is a need to design batteries better for recycling much sooner.

The main challenges appear to be economic, where reduction in valuable material content (in particular cobalt) is likely to reduce the value of recovered materials. However, increases in scale and the potential for greater automation and streamlining of battery pack disassembly could reduce costs significantly. Feedback suggests nevertheless that, in the near-term at least, net costs were unlikely to turn positive.

## Environmental lifecycle impacts and hotspots, and the implications of EV deployment

This project provided a high-level review of the evidence quantifying the environmental impacts associated with the batteries used in these vehicles from available lifecycle assessment (LCA) literature and consultation with stakeholder experts.

A range of information is available from the literature on (mainly GHG) lifecycle impacts from EV battery production, EV use (and, to a lesser extent, battery disposal). Fewer studies explore the wider environmental implications, such as air pollutant emissions, water consumption and other resource use. Most also focus Li-ion batteries for electrified/electric passenger cars (i.e. HEV, PHEV and BEV).

The results from different studies can vary significantly principally due to a range of key factors including: production energy demand (and location), the amount of cell materials and other components, use of primary versus secondary data (some use also quite old information and technical progress has been rapid), the details of production processes included in the analysis, treatment of recycling, and the LCI (life cycle inventory) impacts databases used. Results from the EV operational phase also vary significantly based on key assumptions for vehicle efficiency, lifetime mileage and electricity mix.

The review suggested that improvements in battery energy density, process optimisations and changes to battery chemistries may be expected to be reduced significantly per kWh battery. In addition, key hotspots due to use of materials like Cobalt, and manufacturing energy consumption can/are likely to be reduced through shifts in technology or manufacturing using cleaner energy mixes.

Currently ongoing vehicle LCA work (led by Ricardo) for DG CLIMA covering a range of road transport vehicle, powertrain and fuel/energy carrier types should also lead to further insights in the future.

In the present Project, a modelling exercise was carried out using the SULTAN transport model (previously developed for DG CLIMA by Ricardo experts) to assess the wider impacts on emissions and resources resulting from alternative scenarios for EV uptake in eBikes, motorcycles/mopeds, light- and heavy-duty vehicles in Europe. As part of this analysis a Base Case, with conservative assumptions for reuse / repurposing and recycling was compared with a Sustainable Value Chain (SVC) scenario with greater amounts of reuse/repurposing and enhanced recycling (and recycling recovery) rates.

The results showed significant potential for reduction in emissions, demand for primary raw materials, and increased economic value, for the SVC scenario, compared to the base case. The exercise also showed that the increased emissions due to EV battery manufacture (and disposal) are expected to be very significantly lower than the corresponding emissions improvements resulting from EV operation.

## Developing a sustainable value chain

A sustainable value chain for EV batteries can be defined as one which reduces environmental impacts and avoids the depletion of natural resources to maintain an environmental balance while promoting economic growth. In this context, key opportunities for improving the value chain include:

- Low recycling rates to extract key virgin materials (linked to low collection performance and high costs for recycling techniques – in particular lithium).
- High dependence on non-EU countries for cell component and cell manufacturing with limited influence on manufacturing processes and their environmental footprint.
- Resource intensive operational processes in cell manufacturing (energy, water and raw materials) with opportunities to reduce resource use (including waste generation).
- Emerging re-use market to use the energy storage capacity retained in discarded first use traction batteries. Fast evolving technologies require flexibility for re-use market to evolve.
- In line with re-use, emerging re-purposing market for use in energy storage systems. Fast evolving technologies require flexibility and cross-sector collaboration for the market to evolve.
- Emerging recycling market to extract raw materials from battery waste.

In addition, as the value chain matures there is a growing risk of negative externalities occurring with regards to waste disposal for end-of-life traction batteries as the ownership and liability for the subsequent electro chemical hazardous waste becomes unclear.

The current policy landscape in the EU provides a framework to regulate the EU EV battery value chain in a way that aims to minimise negative environmental impacts. The key policies regulating the market include the Batteries Directive (2006/66/EC), ELV Directive (2000/53/EC) and REACH (Regulation (EC) 1907/2006). Together these policies regulate:

- The use of hazardous substances
- The environmental performance of batteries throughout their lifecycle
- The collection, treatment and recycling of waste batteries, including targets for collection rates and for recycling efficiencies

Additional mechanisms are also in place to facilitate access to raw materials and foster growth in innovation through R&D needed by industry to manufacture EV batteries.

To better understand the development of a sustainable EU EV battery value chain, eight circular economy business models were reviewed with a viewing to better understanding the associated strengths, weaknesses, opportunities and threats. Alongside this, the consumption patterns and possible interaction with the EU EV battery value chain are taken into account – namely the generally low usage of vehicles and their traction batteries as well as the growing demand for electricity resulting in pressures on energy security and the need for better management of peak demand.

The business models reviewed include: Integrated value chain; Car sharing schemes; Battery leasing schemes; Battery swapping schemes; Vehicle to grid energy systems; Re-use for application as EV battery; Re-purposing for use in energy storage systems; Extraction of raw materials through recycling; and Safe handling and treatment of waste.

## Strengths, weaknesses, opportunities and threats

Limited access to raw materials has been identified as a key constraint for growth in the sector, although it is recognised that recycling is expected to play a role in alleviating this constraint through the return of extracted raw materials to the market. In addition, should there be more rapid developments / changes in battery chemistries (e.g. shift to sodium-ion, faster elimination of cobalt) this could reduce these constraints, though likely only in the medium-longer term.

Key areas of emerging growth for EU industry relate to battery cell (and cell component) manufacturing, re-use and re-purposing – from an industry perspective, securing access to skilled labour and expertise is essential. The need for a skilled workforce, and a predictable legal framework to support it, is expected to positively impact job creation with one estimate indicating 15 jobs are created for every 1,000 tonnes of EV battery waste. Growth is also envisaged in the EU for battery pack manufacturing and EV manufacturing, building on the established industries and optimising existing technical capabilities and capacities.

The current construction of installations in the EU indicates that significant capital has been used to facilitate growth in cell component manufacturing. The need for financial investments for infrastructures is ongoing in the light of continued planned growth. Investments are also required to establish software infrastructures to support the development of emerging circular economy business models.

The European Battery Alliance has established a stakeholder network to facilitate communication which is an important enabler for growth across the value chain.

Several weaknesses and threats have been identified in relation to the current policy framework across the complete value chain. Commonalties exist, and the following points are flagged:

- Lack of definitions for emerging markets (primarily with respect to re-use and re-purposing although other emerging circular economy business models would also benefit from clearer definitions).
- Lack of standards at EU level (standards are typically developed in-house and differ between producers).
- Transparency (producer responsibility but also financial transparency in the light of emerging circular economy business models such as V2G).

The figure below provides a visual overview of the strengths, weaknesses, opportunities and threats.

**Table ES1: Summary of SWOT analysis for the EV battery value chain in the EU**

| EV battery value chain | Industry | Infrastructure | Policy |
|---|---|---|---|
| Raw materials | Weak | Intermediate | Strong |
| Cell component manufacturing | Intermediate | Intermediate | Strong |
| Cell manufacturing | Intermediate | Intermediate | Intermediate |
| Battery pack manufacturing | Strong | Strong | Strong |
| EV manufacturing | Strong | Strong | Strong |
| Re-use | Intermediate | Intermediate | Weak |
| Re-purposing | Intermediate | Intermediate | Weak |
| Recycling | Strong | Strong | Strong |

*Note*: **Green** = key strengths that future policy should continue to reinforce and support; **Amber** = development areas that should be monitored; and **Red** = key barriers or constraints that future policy should look to ease.

## Policy alternatives

Based on the opportunities to optimise resource yields and reduced environmental impacts in the EV battery value chain, and the current policy landscape of the respective value chain components, a portfolio of policy alternatives to address the key challenges identified was assessed and discussed with expert stakeholders.

The outcome of this analysis set out priorities for current and near-future policy needs which include the following four areas (each covering detailed potential actions):

- Addressing legal uncertainties in existing standards and definitions:
  - the current regulatory landscape may either not be sufficient to cover a well-functioning market, or on the other hand may present overlaps or inconsistencies. Clarifying uncertainties (e.g. on product responsibility, waste definitions, etc.) is expected to facilitate the development of a robust market.
- Improving transparency across the different value chain components through extended regulation:
  - this could facilitate access to information throughout the supply chain to allow market actors to make more informed choice, e.g. on material sourcing or product performance.
- Establishing new and updating existing targets:
  - with respect to existing recycling targets and the option to establish new reuse and repurposing, where appropriate. This is expected to foster a more resource-efficient use of materials.
- Establishing a monitoring and reporting framework to facilitate evidence gathering:
  - this could help set a level playing field to better understand environmental impacts throughout the lifecycle of batteries.

The qualitative analysis undertaken for each of these policy options illustrates that there are associated regulatory costs as well as additional costs arising for economic operators to comply with changes to regulation (without further assessment it is not possible to ascertain the full extent of the associated costs).

However, the overall range of expected benefits outweighs the identified costs for the policy alternatives shortlisted; these positive impacts include industrial growth, job creation and enhanced environmental protection.

# Résumé

Ricardo Énergie et Environnement a été chargée de fournir un appui technique à la Commission européenne sur le projet « *Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles* » (Perspectives de l'économie circulaire pour la gestion des batteries utilisées dans les véhicules électriques) (ci-après dénommé le « projet »). Ce projet a été commandité par le Centre commun de recherche de la Commission européenne (ci-après dénommé « le JRC »). Le présent rapport final offre un résumé des conclusions finales du projet qui ont également été présentées sous forme d'avant-projet et examinées avec les parties prenantes lors de l'atelier final du projet qui s'est tenu le 4 février 2019.

Pour les véhicules électriques, la production (et l'élimination) des batteries de traction peut représenter une part importante des impacts sur le cycle de vie complet. L'augmentation du nombre de véhicules électriques devant s'accélérer au cours des prochaines années, la minimisation de ces impacts revêtira une importance croissante.

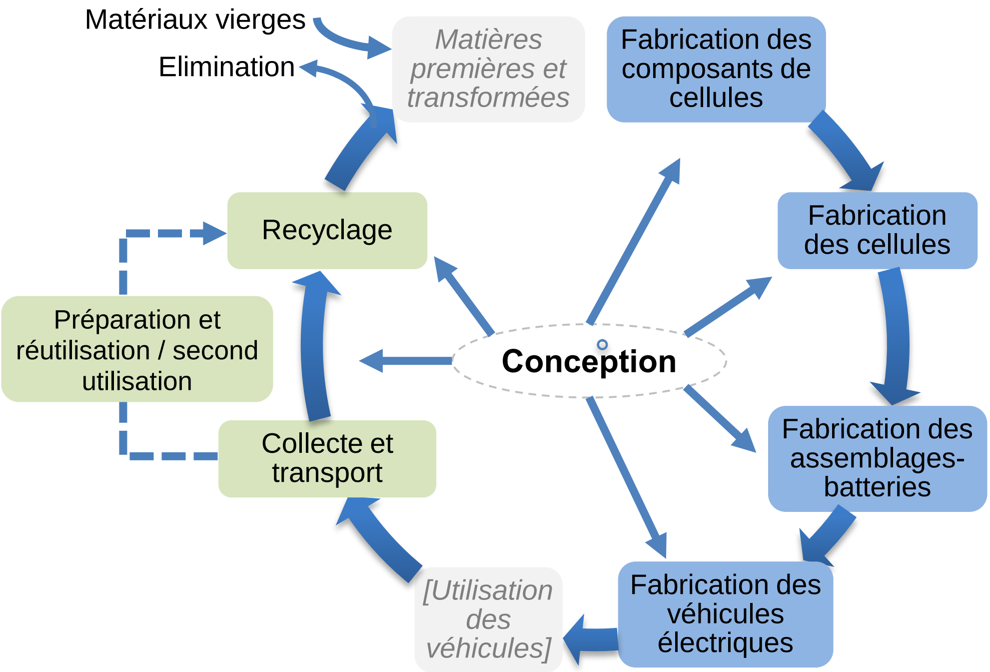
Le projet a donc pour objectif d'aider le Centre commun de recherche (JRC) à fournir une base factuelle solide et une analyse techno-économique afin de répondre aux six questions de recherche clés suivantes :

1. Quelles sont les techniques actuellement disponibles et émergentes pour la fabrication, la réutilisation et le recyclage des batteries de traction pour véhicules électriques ? Comment les batteries en fin de vie sont-elles actuellement traitées et quels sont les nouveaux plans pour l'avenir ?
2. Quel est l'impact environnemental actuel des batteries de traction pour véhicules électriques tout au long de leur cycle de vie ? Quels sont actuellement les points sensibles pour l'environnement et comment sont-ils traités ?
3. Quels seront les impacts et les points sensibles environnementaux potentiels des batteries de traction tout au long de leur cycle de vie si les véhicules électriques sont déployés à grande échelle et/ou conformément aux tendances actuelles, à court, moyen et long terme ?
4. Quelles sont les perspectives de développement d'une chaîne de valeur durable pour les batteries de véhicules électriques dans l'UE ?
5. Quels sont les points forts et les points faibles actuels de l'économie de l'UE (secteur industriel, infrastructure, cadre politique) pour faire face au cycle de vie des batteries de traction dans la perspective de l'électrification des transports routiers ?
6. Quelles politiques publiques pourraient être envisagées pour assurer des cycles de vie réellement circulaires aux batteries de traction et pour exploiter les opportunités de croissance et d'emploi dans l'UE ?

Afin d'examiner ces questions de recherche clés et de leur fournir des réponses solides, l'équipe du projet a suivi une approche analytique en vue de constituer une base de données factuelles à l'appui de l'analyse, en identifiant les principaux défis et en élaborant des solutions politiques potentielles. La première partie de l'analyse consiste à examiner les techniques les plus modernes de fabrication, de réutilisation/reconversion et de recyclage des batteries afin de mieux comprendre les points sensibles et les impacts environnementaux du cycle de vie, puis à intégrer l'analyse des conséquences du déploiement des véhicules électriques, qui ont été explorées par une modélisation de scénarios. En définissant les caractéristiques de ce à quoi une chaîne de valeur durable pourrait ressembler, l'analyse a permis d'identifier les points forts, les points faibles, les opportunités et les menaces pesant sur l'économie de l'UE dans la mise en place d'un modèle d'économie circulaire destiné aux batteries pour véhicules électriques. La dernière partie de l'analyse a ensuite exposé les difficultés concrètes rencontrées par le développement d'une chaîne de valeur durable et la manière de les résoudre en identifiant des alternatives politiques et en les hiérarchisant (selon des critères d'amélioration de la réglementation) afin de proposer une première sélection de solutions politiques à envisager.

Une vue circulaire de la chaîne de valeur des batteries pour véhicules électriques est présentée à la Figure ES2.

**Figure ES2 : vue circulaire de la chaîne de valeur des batteries de véhicules électriques pour l'Europe**




*Remarques* : Les étapes « Matières premières et transformées » et « Utilisation des véhicules » ne sont pas directement abordées dans cette étude. La réutilisation ou la seconde utilisation/reconversion sont des étapes supplémentaires facultatives qui peuvent être appliquées dans la mesure du possible ; chaque fois que les batteries deviennent des déchets (par exemple, lorsqu'elles ne peuvent plus être reconverties ou réutilisées), elles doivent être recyclées.

## Techniques de fabrication, de réutilisation/reconversion et de recyclage des batteries

Un examen et une analyse limités ont été menés sur l'activité en cours pour (1) la fabrication de batteries de traction pour véhicules électriques, (2) leur réutilisation et reconversion, et (3) leur recyclage. Cette démarche a été affinée en consultation avec des parties prenantes de la chaîne de valeur des batteries pour véhicules électriques.

Alors qu'il existe historiquement une production d'assemblages de batteries pour véhicules électriques en Europe, la majeure partie de la production de matériaux, de composants et de cellules de batteries pour véhicules électriques a été réalisée ailleurs (principalement en Asie de l'Est, et de plus en plus aux États-Unis). Cependant, il existe un intérêt significatif pour l'extension de la production de batteries en Europe, et plusieurs nouvelles installations sont déjà prévues afin d'accroître la production et les capacités de l'UE dans ce domaine et de compléter ainsi un secteur de la construction automobile déjà robuste (cf. l'initiative de l'Alliance européenne pour les batteries, par exemple).

Auparavant, les batteries de véhicules électriques hybrides utilisaient également des systèmes chimiques à base de nickel-métal-hydrure (NiMH). Aujourd'hui, la plupart des nouveaux véhicules hybrides et autres véhicules électriques utilisent des batteries au lithium ionique (Li-ion) basés sur divers systèmes chimiques. Les batteries Li-ion utilisant les cathodes NMC (oxyde de nickel-manganèse-cobalt) et NCA (oxyde de nickel-cobalt-aluminium) sont les plus répandues, bien que de nouvelles formulations et de nouvelles compositions chimiques soient en cours de développement (tels que des batteries à l'état solide, au lithium-soufre et au sodium ionique). Il existe également un éventail de facteurs de forme de batterie – prismatique, en poche et cylindrique, avec différents avantages et inconvénients.

Les processus de fabrication permettant de produire les composés chimiques et les facteurs de forme actuels des batteries sont très similaires. Par conséquent, bon nombre des améliorations antérieures et en cours de développement de ces processus ont (ou auront) des avantages similaires dans tous ces domaines. Cependant, alors que la plupart des nouveaux composés chimiques pourraient être fabriqués avec des modifications mineures du processus de production, certains – notamment les batteries à l'état solide – nécessiteraient d'apporter des modifications plus fondamentales à plusieurs sous-étapes des processus de fabrication actuels.

Selon les informations recueillies lors d'entretiens avec des intervenants experts, une grande partie de la réduction des coûts de fabrication des batteries au cours des 10 dernières années est due à l'amélioration de l'efficacité de la production grâce à l'optimisation. Par conséquent, la fabrication actuelle produit nettement plus de kWh de batteries par an pour le même appareillage qu'auparavant.

Une série de futures améliorations potentielles ont été identifiées en vue d'améliorer les performances des batteries ainsi que la fabrication des batteries elles-mêmes au cours du projet. Ces améliorations sont principalement motivées par des considérations de coût et de performances des batteries, même si, dans de nombreux cas, d'autres domaines en bénéficieront également. La production de matériaux/composants cathodiques (le cobalt en particulier) représente une part importante des coûts. La fabrication des cellules de batteries est extrêmement complexe et consomme beaucoup d'énergie (en raison des processus en salle sèche et de séchage), la consommation d'énergie représentant une composante importante des coûts et des impacts environnementaux. La consommation d'énergie coûte jusqu'à 20 % (ou plus) du total, de sorte qu'il existe des raisons évidentes de la réduire. L'amélioration constante de l'efficacité des processus et les technologies d'amélioration de la densité énergétique des batteries (c'est-à-dire en Wh/kg) entraînent à la fois une réduction significative des coûts et une réduction des impacts par kWh de la capacité des batteries à l'avenir.

Le destin final des batteries pour véhicules électriques en Europe devrait être le recyclage, mais il existe un intérêt croissant pour le potentiel de réutilisation ou de reconversion des batteries avant cette étape en raison des avantages potentiels en termes d'économie, d'efficacité d'utilisation des ressources et d'environnement.

La **réutilisation** désigne la réutilisation complète ou partielle de la batterie pour l'usage *initial* auquel elle était destinée (c'est-à-dire dans le même type de véhicule électrique), alors que la **reconversion** (interchangeable avec la « seconde utilisation ») désigne la réutilisation complète ou partielle de la batterie à une fin/application *différente* de celle pour laquelle la batterie avait été initialement conçue (par exemple : pour le stockage d'énergie). Les deux peuvent nécessiter un élément de réusinage.

Les batteries peuvent faire l'objet d'une évaluation en vue d'un réusinage et/ou d'une réutilisation ou reconversion lorsqu'elles sont restituées (ou collectées) à partir de leur utilisation initiale pour véhicules électriques pour cause de défaillance ou de remplacement lorsqu'elles atteignent la fin de leur vie utile dans un véhicule – généralement lorsqu'elles atteignent par exemple 70 à 80 % de leur capacité initiale (ou "état de santé"). Il existe de puissantes incitations en faveur du réusinage des batteries puisque les constructeurs doivent s'assurer que l'approvisionnement en pièces de rechange sera suffisant pour leurs véhicules au-delà de leur période de production active.

Les activités de recherche et de projets-pilote en matière de seconde vie des batteries sont encore relativement nouvelles, avec toute une série d'obstacles techniques, économiques et autres, ainsi que des incertitudes restant à évaluer et à surmonter. Le manque de traçabilité et de normalisation des batteries pour véhicules électriques, associé à des informations insuffisantes, inaccessibles ou non normalisées sur l'historique d'utilisation ou l'état de la batterie à partir des systèmes de gestion de la batterie (BMS), constitue un obstacle majeur. Il existe également d'importantes incertitudes et incohérences législatives ou réglementaires qui doivent être résolues afin de faciliter l'innovation et le marché dans ce domaine. D'un point de vue technique, un renforcement de la normalisation et des informations faciliterait une évaluation/un classement plus précis, et des processus de désassemblage automatisés (le cas échéant) pourraient également contribuer à améliorer la sécurité.

Alors que les coûts de réusinage et de réutilisation/reconversion des batteries sont considérés comme potentiellement très faibles (environ 10 % du coût d'une nouvelle batterie), une combinaison de durée de vie réduite pour la seconde utilisation (par rapport aux batteries neuves) et de réduction rapide du coût des nouvelles batteries génère des incertitudes quant à la future compétitivité économique des batteries réutilisées si elles ne servent plus à alimenter un véhicule après une période de 10-15 ans.

L'Europe possède des atouts techniques et une expérience considérables en matière de recyclage de batteries, en raison notamment des exigences législatives plus strictes dans la région par rapport au reste du monde. Toutefois, les taux de collecte et de recyclage des batteries Li-ion pour véhicules électriques sont actuellement très faibles. Théoriquement, la plupart des matériaux d'une batterie Li-ion peuvent être recyclés, mais à ce jour l'accent a été mis principalement sur les matériaux actifs (et les collecteurs de courant). Dans la plupart des cas, la récupération est limitée à certains matériaux (à coût élevé), tels que le cobalt et le nickel, avec d'autres composants moins coûteux, tels que les liants, les sels de lithium et les séparateurs, qui ne sont pas actuellement récupérés.

L'économie du recyclage des batteries dépend fortement de la composition chimique des batteries, des marchés des matières premières et des processus/techniques utilisés. La plupart des usines de recyclage de batteries utilisent des procédés pyrométallurgiques (fusion), également combinés à d'autres procédés de prétraitement et d'hydrométallurgie. Les taux actuels de récupération par recyclage se situent autour de 50 à 60 % du poids total (un pourcentage de 50 % étant requis par la directive européenne relative aux piles et accumulateurs). Toutefois, il a été proposé que des taux de récupération supérieurs de 70 à 80 % (voire plus) seraient réalisables au moins à moyen terme en utilisant principalement de nouveaux procédés de traitement purement hydrométallurgiques.

Les résultats de la consultation sur ce projet ont suggéré que les processus de recyclage actuels (et futurs proposés) seraient en mesure de prendre en charge la majorité des améliorations chimiques attendues et des nouveaux types de batteries potentiels, bien que les batteries au lithium-soufre puissent présenter certaines difficultés.

Les acteurs de la gestion des déchets et du recyclage interrogés ont également souligné le délai important (10 à 20 ans) dont disposent les recycleurs de batteries avant que les technologies de recyclage des nouveaux composés chimiques des batteries ne soient déployées à grande échelle. Cela laisse beaucoup de temps pour l'amélioration des technologies et pour l'investissement dans le renforcement des capacités, bien que dans l'ensemble il soit nécessaire beaucoup plus tôt de mieux concevoir les batteries afin de pouvoir les recycler.

Les principales difficultés semblent être de nature économique en ce sens qu'une réduction de la teneur en matériaux précieux (le cobalt, notamment) est susceptible de réduire la valeur des matériaux récupérés. Cependant, les augmentations d'échelle et le potentiel de renforcement de l'automatisation et de la rationalisation du démontage des assemblages de batteries pourraient réduire considérablement les coûts. Toutefois, les commentaires obtenus à cet égard suggèrent qu'au moins à court terme il est peu probable que les coûts nets deviennent positifs.

## Points sensibles et impacts environnementaux sur le cycle de vie, et implications du déploiement des véhicules électriques

Ce projet a fourni un examen approfondi des données quantifiant les impacts environnementaux associés aux batteries utilisées dans ces véhicules à partir de la documentation disponible sur l'analyse du cycle de vie (ACV) et de la consultation des intervenants experts.

Une série d'informations est disponible dans la documentation relative aux impacts sur le cycle de vie (principalement en ce qui concerne les GES) de la production de batteries de véhicules électriques et de leur utilisation (et, dans une moindre mesure, de leur élimination). Un nombre plus réduit d'études explorent les implications environnementales plus larges, telles que les émissions de polluants atmosphériques, la consommation d'eau et l'utilisation d'autres ressources. La plupart se concentrent également sur les batteries Li-ion pour les voitures particulières électrifiées/électriques (VEH, VHR et VEB).

Les résultats de différentes études peuvent varier de manière significative, principalement en raison de toute une série de facteurs clés, dont notamment : la demande en énergie de production (et son emplacement), la quantité de matériaux de cellules et d'autres composants, l'utilisation des données primaires par rapport aux données secondaires (certaines utilisent également des informations assez anciennes et les progrès techniques ont été rapides), les détails des processus de production inclus dans l'analyse, le traitement du recyclage et les bases de données sur les impacts de l'ICV (inventaire du cycle de vie) utilisées. Les résultats de la phase opérationnelle du véhicule électrique varient aussi considérablement en fonction des hypothèses clés relatives à l'efficacité du véhicule, au kilométrage à long terme, et au mix électrique.

L'examen a suggéré que les améliorations de la densité énergétique des batteries, l'optimisation des processus et les modifications de la composition chimique des batteries devraient être considérablement réduites par kWh de batterie. En outre, les principaux points sensibles dus à l'utilisation de matériaux tels que le cobalt et à la consommation d'énergie de fabrication peuvent être réduits grâce à des évolutions de la technologie ou de la fabrication en utilisant des sources d'énergie plus propre.

Les travaux en cours d'ACV des véhicules (menés par Ricardo) pour la DG CLIMA, qui couvrent un éventail de types de véhicules de transport routier, de groupes motopropulseurs et de carburants/ vecteurs énergétiques, devraient également permettre de se faire une idée plus précise de l'avenir.

Dans le cadre du présent projet, un exercice de modélisation a été réalisé à l'aide du modèle de transport SULTAN (précédemment mis au point par des experts de Ricardo pour la DG CLIMA) afin d'évaluer les impacts plus larges sur les émissions et les ressources résultant de scénarios alternatifs d'adoption des véhicules électriques tels que les vélos électriques, les motos/cyclomoteurs, ainsi que les véhicules utilitaires légers et lourds en Europe. Dans le cadre de cette analyse, un scénario de référence, avec des hypothèses prudentes concernant la réutilisation/reconversion et le recyclage, a été comparé à un scénario de chaîne de valeur durable (CVD) avec des quantités plus importantes de réutilisation/reconversion et des taux de recyclage (et de valorisation) améliorés.

Les résultats ont indiqué un potentiel significatif de réduction des émissions, de la demande de matières premières primaires, et d'augmentation de la valeur économique, dans le scénario de la CVD, par rapport au scénario de référence. L'exercice a également montré que les émissions accrues dues à la fabrication (et à l'élimination) des batteries de véhicules électriques devraient être très nettement inférieures aux améliorations des émissions correspondantes résultant du fonctionnement des véhicules électriques.

## Développement d'une filière durable

Une filière durable pour les batteries de véhicules électriques peut se définir comme une chaîne de valeur qui réduit les impacts environnementaux et évite l'épuisement des ressources naturelles afin de maintenir un équilibre environnemental tout en favorisant la croissance économique. Dans ce contexte, les principales possibilités d'amélioration de la filière incluent :

- de faibles taux de recyclage pour extraire les matières premières vierges essentielles (liés aux faibles taux de récupération et aux coûts élevés des techniques de recyclage – notamment le lithium).
- une forte dépendance vis-à-vis des pays non membres de l'UE pour la fabrication de cellules et de composants de cellules avec une influence limitée sur les processus de fabrication et leur empreinte environnementale.
- des processus opérationnels à forte consommation de ressources dans la fabrication des cellules (énergie, eau et matières premières) offrant des possibilités de réduction de l'utilisation des ressources (y compris en ce qui concerne la production de déchets).
- un marché émergent de la réutilisation pour utiliser la capacité de stockage d'énergie résiduelle dans les batteries de traction mises au rebut après la première utilisation. Les technologies mises en œuvre, qui évoluent rapidement, exigent de la flexibilité pour que le marché de la réutilisation se développe.
- comme pour la réutilisation, un marché émergent de la reconversion en vue d'une utilisation dans les systèmes de stockage d'énergie. Les technologies mises en œuvre, qui évoluent rapidement, exigent de la flexibilité et une collaboration intersectorielle pour que le marché se développe.
- un marché du recyclage émergent pour extraire les matières premières des déchets de batteries.

En outre, à mesure que la filière se développe, il existe un risque croissant d'externalités négatives concernant l'élimination des déchets de batteries de traction en fin de vie, car la propriété et la responsabilité des déchets électrochimiques dangereux ultérieurs deviennent floues.

Le paysage politique actuel de l'UE fournit un cadre permettant de réglementer la chaîne de valeur de l'UE pour les batteries de véhicules électriques de manière à minimiser les impacts négatifs sur l'environnement. Les principales politiques régulant le marché comprennent la directive relative aux piles et accumulateurs ainsi qu'aux déchets de piles et d'accumulateurs (2006/66/CE), la directive relative aux véhicules hors d'usage (2000/53/CE) et le règlement REACH ((CE) N° 1907/2006). Ensemble, ces politiques réglementent :

- L'utilisation des substances dangereuses
- La performance environnementale des piles et batteries tout au long de leur cycle de vie

- La collecte, le traitement et le recyclage des piles et batteries usagées, incluant des objectifs en matière de taux de collecte et d'efficacité de recyclage

Des mécanismes supplémentaires sont également en place afin de faciliter l'accès aux matières premières et de favoriser la croissance de l'innovation grâce à la R&D nécessaire à l'industrie pour fabriquer des batteries pour véhicules électriques.

Pour mieux comprendre le développement d'une filière européenne durable des batteries pour véhicules électriques, huit modèles fonctionnels d'économie circulaire ont été examinés en vue de mieux appréhender les points forts, les points faibles, les opportunités et les menaces associés. Parallèlement à cela, les modes de consommation et les interactions possibles avec la filière européenne des batteries pour véhicules électriques sont pris en compte, à savoir l'utilisation généralement faible des véhicules et de leurs batteries de traction, ainsi que la demande croissante en électricité entraînant des pressions sur la sécurité énergétique, et la nécessité d'une meilleure gestion des pics de demande.

Les modèles fonctionnels examinés comprennent : la chaîne de valeur intégrée ; les systèmes de covoiturage ; les systèmes de location de batteries ; les systèmes d'échange de batteries ; les systèmes d'énergie véhicule-réseau ; la réutilisation pour un emploi en tant que batterie de véhicule électrique ; la reconversion en vue d'une utilisation dans des systèmes de stockage d'énergie ; l'extraction des matières premières secondaires par le recyclage ; et la manipulation et le traitement sécurisés des déchets.

## Points forts, points faibles, opportunités et menaces

L'accès limité aux matières premières a été identifié comme une contrainte majeure à la croissance du secteur, bien qu'il soit reconnu que le recyclage devrait jouer un rôle dans l'atténuation de cette contrainte par le retour sur le marché des matières premières extraites. En outre, en cas d'évolutions/modifications plus rapides de la composition chimique des batteries (par exemple : passage au sodium-ion, élimination plus rapide du cobalt), ces contraintes pourraient également être atténuées, même s'il est probable que cela n'intervienne qu'à moyen et à long terme.

Les secteurs clés de cette croissance émergente pour l'industrie européenne concernent la fabrication, la réutilisation et la reconversion des cellules de batterie (et de leurs composants) – et du point de vue de l'industrie, il est essentiel de garantir l'accès à une main-d'œuvre qualifiée et à des personnels possédant l'expertise nécessaire. La nécessité d'une main-d'œuvre qualifiée, associée à un cadre juridique prévisible à l'appui, devrait avoir un impact positif sur la création d'emplois puisqu'une estimation indique que 15 emplois sont créés pour 1.000 tonnes de déchets de batteries de véhicules électriques. La fabrication des assemblages de batteries et des véhicules électriques devraient également croître dans l'UE, en s'appuyant sur les industries existantes et en optimisant les compétences et les capacités techniques existantes.

La construction actuelle d'installations dans l'UE indique que des capitaux importants ont été utilisés afin de favoriser la croissance de la fabrication des composants de cellules. Le besoin d'investissements financiers pour les infrastructures est permanent compte tenu de la poursuite de la croissance prévue. Des investissements sont également nécessaires à la mise en place d'infrastructures logicielles permettant de soutenir le développement de nouveaux modèles fonctionnels d'économie circulaire.

L'Alliance européenne pour les batteries a mis en place un réseau de parties prenantes en vue de faciliter la communication, laquelle constitue un facteur essentiel de croissance pour l'ensemble de la chaîne de valeur.

Plusieurs points faibles et menaces ont été identifiés par rapport au cadre politique actuel sur l'ensemble de la chaîne de valeur. Des points communs existent, et les points suivants sont signalés :

- Absence de définitions pour les marchés émergents (principalement en ce qui concerne la réutilisation et la reconversion, bien qu'il serait également bénéfique de définir plus clairement d'autres modèles fonctionnels émergents d'économie circulaire).
- Absence de normes au niveau de l'UE (les normes sont généralement élaborées en interne et diffèrent d'un producteur à l'autre).

- Transparence (responsabilité des producteurs mais aussi transparence financière à la lumière des modèles fonctionnels émergents d'économie circulaire tels que le modèle V2G – connexion véhicule-réseau).

La figure ci-dessous fournit un aperçu visuel des points forts, des points faibles, des opportunités et des menaces.

**Tableau ES2 : Résumé de l'analyse SWOT pour la chaîne de valeur des batteries de véhicules électriques dans l'Union européenne**

| Chaîne de valeur des batteries de véhicules électriques | Industrie | Infrastructure | Politique |
|---|---|---|---|
| Matières premières | Faible | Intermédiaire | Fort |
| Fabrication des composants de cellules | Intermédiaire | Intermédiaire | Fort |
| Fabrication des cellules | Intermédiaire | Intermédiaire | Intermédiaire |
| Fabrication des blocs de batterie | Fort | Fort | Fort |
| Fabrication des véhicules électriques | Fort | Fort | Fort |
| Réutilisation | Intermédiaire | Intermédiaire | Faible |
| Reconversion | Intermédiaire | Intermédiaire | Faible |
| Recyclage | Fort | Fort | Fort |

*Remarque :* **Vert** = principaux points forts que la future politique devrait continuer à renforcer et à soutenir ; **Orange** = zones de développement à surveiller ; et **Rouge** = principaux obstacles ou contraintes que la future politique devrait chercher à atténuer.

## Options politiques

Sur la base des opportunités d'optimisation du rendement des ressources et de la réduction des impacts environnementaux dans la filière des batteries pour véhicules électriques, ainsi que du paysage politique actuel des composantes de la filière, un ensemble d'options politiques permettant de répondre aux principaux défis identifiés ont été évaluées et examinées avec des intervenants experts.

Les résultats de cette analyse ont permis de définir des priorités pour les besoins politiques actuels et dans l'avenir proche, lesquels comprennent les quatre domaines suivants (chacun d'entre eux couvrant des actions potentielles détaillées) :

- Lever les incertitudes juridiques inhérentes aux normes et définitions existantes :
  - le paysage réglementaire actuel peut ne pas suffire à couvrir un marché opérationnel ou peut, au contraire, présenter des chevauchements ou des incohérences. La clarification des incertitudes (par exemple : concernant la responsabilité sur les produits, la définition des déchets, etc.) devrait faciliter le développement d'un marché robuste.
- Améliorer la transparence dans les différentes composantes de la filière grâce à une réglementation étendue :
  - cela pourrait faciliter l'accès à l'information tout au long de la chaîne d'approvisionnement afin de permettre aux acteurs du marché de faire des choix plus éclairés (par exemple : sur l'approvisionnement en matériaux ou sur la performance des produits).
- Établir de nouveaux objectifs et mettre à jour les objectifs existants :
  - pour les objectifs de recyclage existants et l'option d'en créer de nouveaux pour la réutilisation et la reconversion, le cas échéant. Cela devrait favoriser une utilisation des matériaux plus économe en ressources.
- Établir un cadre de surveillance et de déclaration des informations afin de faciliter la collecte des données :
  - cela pourrait contribuer à créer des conditions de concurrence équitables pour mieux comprendre les impacts environnementaux tout au long du cycle de vie des batteries.

L’analyse qualitative réalisée pour chacune de ces options politiques indique qu’il existe des coûts réglementaires associés ainsi que de nouveaux coûts supplémentaires pour que les opérateurs économiques puissent se conformer aux modifications apportées à la réglementation (sans nouvelle évaluation, il est impossible de déterminer l’ampleur réelle des coûts associés).

Cependant, l’ensemble des avantages escomptés l’emporte sur les coûts identifiés pour les alternatives politiques retenues ; ces impacts positifs incluent la croissance industrielle, la création d’emplois et une protection accrue de l’environnement.

# Kurzfassung

Ricardo Energy & Environment wurde im Rahmen des Projekts *„Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles“* (Perspektiven für den Umgang mit in Elektrofahrzeugen genutzten Batterien im Rahmen der Kreislaufwirtschaft) (nachfolgend das „Projekt“) mit der technischen Beratung der Europäischen Kommission beauftragt. Das Projekt wurde von der Europäischen Kommission GD Gemeinsame Forschungsstelle (nachfolgend „JRC“) in Auftrag gegeben. Dieser Abschlussbericht liefert eine Zusammenfassung der abschließenden Ergebnisse des Projektes, die im Rahmen des letzten Projektworkshops am 4. Februar 2019 auch betroffenen Branchenakteuren in der Entwurfsform vorgelegt und mit diesen diskutiert wurden.

Mit Blick auf Elektrofahrzeuge wirkt sich die Produktion (und Entsorgung) von Antriebsbatterien möglicherweise in erheblichem Umfang auf die Gesamt-Umweltbilanz dieser Technologie aus. Mit der in den kommenden Jahren zu erwartenden weiteren Verbreitung von Elektrofahrzeugen nimmt die Minimierung der Umweltbelastung der Batterietechnik einen immer wichtigeren Stellenwert ein.

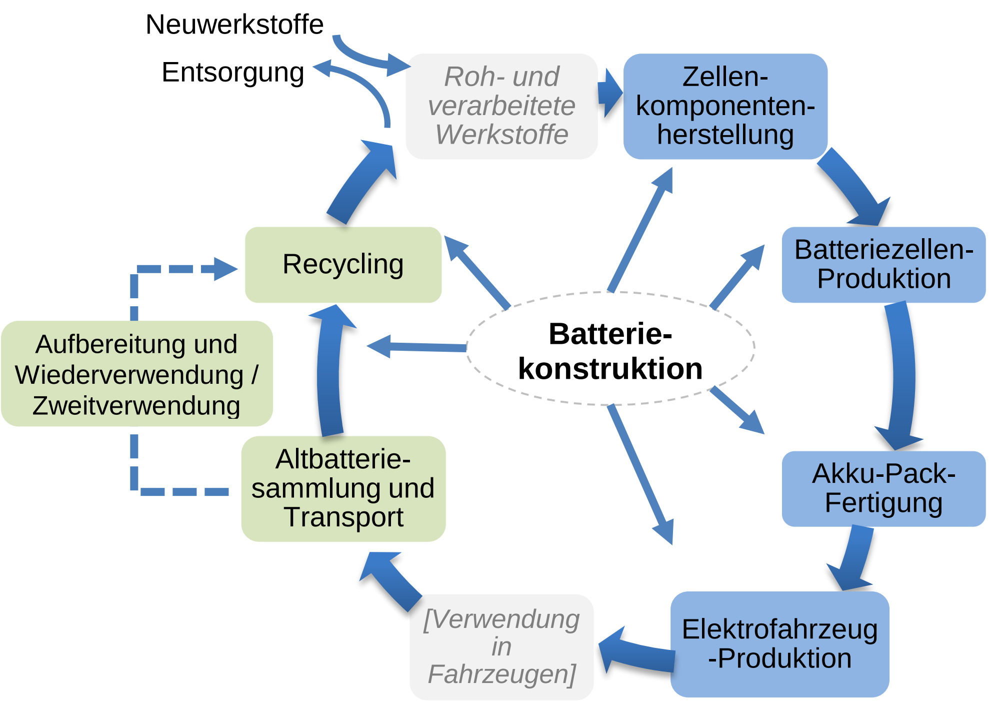
Ziel des Projektes war es, die Gemeinsame Forschungsstelle (JRC) bei der Erarbeitung einer soliden Faktenbasis und technisch-ökonomischen Analyse zu unterstützen, um die folgenden sechs zentralen Forschungsfragen zu beantworten:

7. Welches sind die derzeit verfügbaren und neu aufkommenden Technologien im Bereich der Produktion, Wiederverwendung und dem Recycling von Antriebsbatterien für Elektrofahrzeuge? Wie sieht der derzeitige Umgang mit Altbatterien aus, und welche neuen Pläne gibt es bezüglich der Weiterbehandlung von Altbatterien in naher Zukunft?
8. Welches sind gegenwärtig die Auswirkungen von in Elektrofahrzeugen genutzten Antriebsbatterien auf die Umwelt über deren gesamte Nutzungsdauer betrachtet? Welches sind die aktuellen kritischen Umweltaspekte und welche Lösungsansätze gibt es?
9. Welches sind über die gesamte Nutzungsdauer von Antriebsbatterien betrachtet deren potenziellen Auswirkungen auf die Umwelt und wie sehen mögliche Belastungsszenarien aus, wenn sich die Nutzung von Elektrofahrzeugen auf breiter Basis etabliert und/oder sich aktuelle Nutzungstrends kurz-, mittel- und langfristig fortsetzen?
10. Wie sehen die Perspektiven für die Entwicklung einer nachhaltigen Wertschöpfungskette für Elektrofahrzeug-Batterien in der EU aus?
11. Welches sind die aktuellen Stärken und Schwächen der EU-Wirtschaft (Industrie, Infrastruktur, Regelwerke) in Bezug auf die Handhabung des Nutzungszyklus von Antriebsbatterien und mit Blick auf die voraussichtliche umfassende Elektrifizierung des Straßenverkehrs?
12. Welche politischen und regulatorischen Rahmenbedingungen könnten geschaffen werden, damit Antriebsbatterien im Sinne einer wirklichen Kreislaufwirtschaft genutzt und damit verbundene Wachstums- und Beschäftigungschancen in der EU mobilisiert werden können?

Um diesen zentralen Forschungsfragen nachzugehen und belastbare Antworten darauf zu finden, verfolgte das Projektteam einen analytischen Ansatz. Auf einer die Analyse stützenden Evidenzbasis aufbauend wurden die wichtigsten Herausforderungen herausgearbeitet und daraus abgeleitet mögliche politische Lösungen entwickelt. Der erste Teil der Analyse konzentriert sich auf eine Begutachtung der neuesten Techniken für die Herstellung, Wiederverwendung/Umnutzung und das Recycling von Batterien, um deren Auswirkungen auf die Umwelt und sonstige umweltbelastende Faktoren über die gesamte Nutzungsdauer dieser Technik besser zu verstehen. Die dabei gewonnenen Erkenntnisse fanden Eingang in die Analyse der Implikationen einer breit ausgelegten Elektromobilität, die mithilfe verschiedener Modellszenarien erkundet wurden. Anhand einer Aufstellung von Eigenschaften, durch die sich eine nachhaltige Wertschöpfungskette auszeichnen könnte, ermittelte die Analyse mit Blick auf die EU-Wirtschaft Stärken und Schwächen sowie Chancen und Risiken eines Kreislaufwirtschaftsmodells für Elektrofahrzeug-Batterien. Im letzten Teil der Analyse werden schließlich die identifizierten Problembereiche dargelegt, die der Entwicklung einer nachhaltigen Wertschöpfungskette im Weg stehen. Gleichzeitig werden Herangehensweisen vorgestellt, wie diese Problembereiche mittels bestimmter umweltpolitischer Instrumentarien und Prioritätensetzungen (im Sinne verbesserter ordnungspolitischer Kriterien) angegangen werden können. Die Analyse mündet in einer Auflistung in Betracht zu ziehender bevorzugter Lösungsansätze.

Abbildung ESES3 zeigt die kreislaufartige Darstellung der Wertschöpfungskette für Elektrofahrzeugbatterien im Überblick.

**Abbildung ES3: Kreislaufartige Darstellung der europäischen Wertschöpfungskette für Elektrofahrzeugbatterien**




*Anmerkungen:* Die Stadien „Roh- und verarbeitete Werkstoffe" und „Verwendung in Fahrzeugen" werden in dieser Studie nicht unmittelbar behandelt. Die Stadien „Wiederverwendung / Zweitverwendung" bzw. Umnutzung sind optionale zusätzliche Schritte, die soweit möglich angewendet werden können. Wenn Altbatterien zu Abfall werden (z. B. dann, wenn eine weitere Wiederverwendung oder Umnutzung nicht möglich ist), sollten sie recycelt werden.

## Technologien für die Produktion, Wiederverwendung / Umnutzung und das Recycling von Batterien

Im Rahmen der Studie erfolgte eine begrenzte Sichtung und Analyse der derzeit laufenden Aktivitäten (1) zur Produktion, (2) zur Wiederverwendung und Umnutzung sowie (3) zum Recycling von Antriebsbatterien für Elektrofahrzeuge. Diese Fragestellung wurde mit Blick auf die Wertschöpfungskette der Antriebsbatterien für Elektrofahrzeuge in Abstimmung mit den Akteuren weiter verfeinert.

Bislang gab es zwar in gewissem Umfang eine europäische Akku-Pack-Produktion für Elektrofahrzeuge, aber der überwiegende Teil der Produktion von Grundstoffen, Komponenten und Batteriezellen für E-Fahrzeuge erfolgte außerhalb Europas (vor allem in Ostasien und zunehmend auch in den USA). Allerdings besteht durchaus großes Interesse daran, die europäische Batterieproduktionsindustrie voranzubringen. So existieren bereits Pläne zum Ausbau der Produktionskapazitäten und Produktionstechnologien in der EU in diesem Bereich in Ergänzung einer bereits starken Automobilindustrie (siehe beispielsweise die europäische Batterie-Allianz-Initiative).

Ältere Batterietypen für Hybrid-Elektrofahrzeuge funktionieren noch mit Nickel-Metallhydrid-(NiMH)-Verbindungen. Heute verwenden die meisten neueren Hybrid- und anderen Elektrofahrzeuge Lithium-Ionen-(Li-Ion)-Batterien unterschiedlicher chemischer Zusammensetzungen. Li-Ionen-Batterien mit NMC-Kathoden (Nickel-Mangan-Kobalt-Oxid) und NCA (Nickel-Kobalt Aluminiumoxid) werden am häufigsten verwendet. Allerdings werden aktuell neue chemische Formulierungen und Verbindungen entwickelt (beispielsweise Festkörper-, Lithium-Schwefel und Natrium-Ionen-Batterien). Darüber hinaus gibt es eine Reihe von unterschiedlichen Batterieblockformaten – prismatisch, Beutel-förmig und zylindrisch, mit unterschiedlichen Vor- und Nachteilen.

Die Produktionsverfahren zur Herstellung von Batterien mit den heute gängigen Arten der chemischen Zusammensetzung und Formaten sind sehr ähnlich. Daher haben viele der bisherigen und in Entwicklung befindlichen Verbesserungen dieser Produktionsverfahren überall vergleichbare Vorteile. Während allerdings die meisten neuen chemischen Zusammensetzungen bislang mit nur geringfügigen

Änderungen des Produktionsverfahrens ausgekommen sind, würden einige Batteriezusammensetzungen, insbesondere Festkörperbatterien, grundlegendere Veränderungen mehrerer der Teilstufen derzeitiger Herstellungsverfahren erfordern.

Laut dem Feedback angehörter Sachverständiger konnte ein großer Teil der in den letzten zehn Jahren erzielten Kostenreduzierungen bei der Batterieherstellung dank gesteigerter Produktionseffizienz durch Optimierungen erreicht werden. Daher produzieren aktuelle Fertigungsprozesse bezogen auf einen vergleichbaren Maschinenpark im Vergleich zu früher pro Jahr deutlich mehr Batteriespeicherkapazität in kWh.

In Bezug auf die Verbesserung der Batterieleistung und die Batterieproduktion selbst wurden im Verlauf des Projekts eine Reihe potenzieller zukünftiger Verbesserungen identifiziert. Solche Verbesserungen betreffen überwiegend die Kosten und die Batterieleistung, wobei in vielen Fällen auch Vorteile in Bezug auf andere Bereiche entstehen. Die Herstellung der Kathodenwerkstoffe bzw. Komponenten (insbesondere Kobalt) tragen zu einem erheblichen Teil der Kosten bei. Die Batteriezellenproduktion ist sehr aufwendig und energieintensiv (aufgrund der Trockenraum-Anforderungen und Trocknungsprozesse). Das bedeutet, der Energieverbrauch stellt einen wesentlichen Bestandteil der Kosten und Umweltbeeinträchtigung dar. Der Energieverbrauch macht 20 Prozent (oder mehr) der Gesamtproduktionskosten aus. Somit besteht hier ein klarer Anreiz zur Kosteneinsparung. Laufende Verbesserungen der Prozesseffizienz und Technologien zur Optimierung der Energiedichte von Batterien (ausgedrückt in W/kg) führen in der Zukunft sowohl zu deutlich reduzierten Kosten als auch zu weniger Umweltverschmutzung pro kWh Batteriekapazität.

Die Endbestimmung für Elektrofahrzeug-Batterien in Europa sollte in der Material-Wiederverwertung (Recycling) bestehen. Allerdings besteht zunehmendes Interesse an einer möglichen Wiederverwendung oder Umnutzung von Altbatterien vor deren endgültigen Recycling. Das Nutzenpotenzial in diesem Fall ist zum einen wirtschaftlicher Art und schlägt sich zum anderen in Form verbesserter Ressourceneffizienz sowie weiterer Vorteile für die Umwelt nieder.

Unter **Wiederverwendung** ist die vollständige oder teilweise Weiterverwendung von Altbatterien für deren *ursprünglichen* Zweck zu verstehen (also deren Weiternutzung in der gleichen Art von Elektrofahrzeug), während **Umnutzung** (synonym mit „Zweitverwendung“) die vollständige oder teilweise Wiederverwendung von Altbatterien für einen *anderen* Zweck bzw. eine andere Anwendung (z. B. Neuverwendung als Energiespeicher) beschreibt als deren ursprüngliche Zweckbestimmung war. Beide Nutzungsoptionen erfordern unter Umständen eine Wiederaufarbeitung in der einen oder anderen Form.

Nach Rücknahme aus ihrer ursprünglichen Zweckbestimmung als Antriebsbatterien in Elektrofahrzeugen nach dem Ende ihrer üblichen Verwendungsdauer oder nach sonstigem Defekt können Altbatterien auf potenzielle Möglichkeiten einer Wiederaufarbeitung und/oder Wiederverwendung bzw. Umnutzung beurteilt werden. Ein solches Ende der Nutzungsdauer ist in der Regel erreicht, wenn die Batteriekapazität nur noch 70-80% der ursprünglichen Kapazität (State-of-Health, SOH) erreicht. Es bestehen gute Gründe für Interesse an einer Wiederaufarbeitung von Altbatterien, da die Originalteilehersteller für eine ausreichende Versorgung mit Ersatzteilen für E-Fahrzeuge über deren aktive Produktionsperiode hinaus sorgen müssen.

Forschungs- und Pilotprojektaktivitäten im Bereich Zweitverwendung von gebrauchten Batterien sind bislang relatives Neuland, denn es bestehen noch eine Reihe zu untersuchender und zu überwindender technischer, wirtschaftlicher und anderer Hindernisse und Unwägbarkeiten. Wesentliche Hemmnisse bestehen in einer fehlenden Rückverfolgbarkeit und Standardisierung der Akku-Pack-Produktion für Elektrofahrzeuge sowie einer unzureichenden, nicht verfügbaren oder nicht standardisierten Informationslage bezüglich der Verwendungsgeschichte bzw. des Zustands von für eine Zweitverwendung vorgesehene Gebrauchtbatterien aus entsprechenden Batteriemanagementsystemen (BMS). Darüber hinaus bestehen nach wie vor erhebliche gesetzliche bzw. regulatorische Unsicherheiten bzw. uneinheitliche Herangehensweisen, die angegangen werden müssen, um Innovationen und einem entsprechenden Markt den Weg zu ebnen. Aus technischer Sicht würden ein höheres Maß an Standardisierung und bessere Produktinformationen eine genauere Beurteilung/Einstufung der Wiederverwertbarkeit von Batterien ermöglichen, und automatisierte Demontageverfahren (wo dies möglich ist) würden die Verbesserung der Sicherheit erleichtern.

Während die Kosten für die Wiederaufarbeitung und Wiederverwendung bzw. Umnutzung von Batterien von den Akteuren als potenziell sehr niedrig angegeben werden (rund 10% der Kosten einer neuen Batterie), schafft die Gemengelage aus einer (im Vergleich zu Neubatterien) reduzierten

Nutzungsdauer für eine Zweitverwendung und die derzeit schnell sinkenden Kosten für die Herstellung von Neubatterien in der Zukunft eine gewisse Unsicherheit mit Blick auf die wirtschaftliche Wettbewerbsfähigkeit umzunutzender Gebrauchtbatterien, wenn diese nach 10-15 Jahren aus der Nutzung in Fahrzeugen ausgemustert werden.

Europa verfügt über erhebliche technische Stärken und Erfahrung beim Batterie-Recycling. Dies liegt zum Teil auch an den im Vergleich zum Rest der Welt strengeren gesetzlichen Recycling-Anforderungen in Europa. Für in Elektrofahrzeugen genutzte Li-Ionen-Altbatterien sind die Rückgewinnungs- und Recyclingquoten derzeit allerdings noch sehr niedrig. Theoretisch können die meisten in einem Li-Ionen-Akku verbauten Werkstoffe recycelt werden, aber der Fokus lag bisher in erster Linie auf den aktiven Werkstoffen (und den Stromabnehmern). In den meisten Fällen beschränkt sich die Werkstoffrückgewinnung auf bestimmte (hochwertige) Materialien wie Kobalt und Nickel, wobei andere kostengünstigere Komponenten, wie Bindemittel, Lithiumsalze und Separatoren, momentan noch nicht zurückgewonnen werden.

Die Wirtschaftlichkeit des Batterie-Recycling ist stark abhängig von den in den Batterien verbauten chemischen Substanzen, den Preisen auf den einschlägigen Rohstoffmärkten und den angewendeten Verfahrenstechniken. Die meisten Batterie-Recycling-Anlagen verwenden pyrometallurgische Prozesse (Schmelzprozesse), auch in Kombination mit anderen Vorbehandlungs- und hydrometallurgischen Prozessen. Aktuell bewegen sich die Rückgewinnungs- bzw. Recyclingquoten um 50-60% des Gesamtbatteriegewichts (wobei die Batterie-Richtlinie 50% als Richtwert vorgibt). Allerdings werden nach aktuellem Stand auch höhere Rückgewinnungsquoten von potenziell 70-80% (oder sogar noch höher) zumindest mittelfristigen als machbar angesehen, wenn neue, rein hydrometallurgischen Behandlungsverfahren in Betracht gezogen werden.

Im Rahmen dieses Projekts eingeholte Einschätzungen von Branchenakteuren machen deutlich, dass die derzeitigen (und angedachten zukünftigen) Recyclingverfahren durchaus in der Lage wären, den größten Teil der zu erwartenden chemischen Werkstoffverbesserungen und möglichen neuen Batterietypen in Wiederverwertungsprozesse zu integrieren, mit der Einschränkung, dass es mit möglichen Lithium-Schwefel-Batterien einige Schwierigkeiten geben könnte.

Die befragten Akteure der Entsorgungs- und Recycling-Wirtschaft betonten mit Blick auf die zukünftigen Batteriegenerationen neuer chemischer Zusammensetzungen außerdem den Umstand der noch großzügigen Vorlaufzeiten von voraussichtlich 10-20 Jahren für notwendige entsprechende Recycling-Technologien größeren Stils. Demnach bliebe noch genügend Zeit für die Entwicklung technologischer Verbesserungen und für Investitionen in Recycling-Kapazitäten. Allerdings besteht insgesamt betrachtet eine Notwendigkeit zu einer möglichst frühzeitigen Einführung von Batterien, die für das Recycling besser geeignet sind.

Die größten Herausforderungen scheinen wirtschaftlicher Art zu sein, da ein geringerer Wertstoffgehalt der recycelten Batterien (insbesondere von Kobalt) die Werkstoff-Rückgewinnung weniger wirtschaftlich erscheinen lässt. Andererseits könnten höhere Produktionszahlen und das Potenzial für eine weitere Automatisierung und Rationalisierung der Zerlegung von Altbatterieblöcken die Kosten deutlich senken. Nach Einschätzung der befragten Branchenakteure werden die Nettorecyclingkosten auf absehbare Zeit allerdings noch nicht ins Positive drehen.

## Umweltbilanz und umweltbelastende Faktoren über die Gesamtnutzungsdauer von Batterien betrachtet und die Implikationen einer verbreiteten Elektromobilität

Dieses Projekt leistet eine fundierte Datenbestandsaufnahme bezüglich der Umweltauswirkungen in Verbindung mit der Verwendung von Antriebsbatterien in E-Fahrzeugen auf der Grundlage verfügbarer Literaturquellen zu einschlägigen Ökobilanzen sowie durchgeführter Konsultationen sachverständiger Akteure.

Der Literatur über die Umweltauswirkungen (vor allem Treibhausgasemissionen) der Batterie-Produktion für Elektrofahrzeuge, der Elektromobilität überhaupt (und in geringerem Umfang der Batterieentsorgung) lassen sich eine Reihe von Informationen entnehmen. In geringerem Umfang stehen Studien zur Verfügung, welche die weiterreichenden Auswirkungen der Elektromobilität auf die Umwelt, wie zum Beispiel Luftschadstoffemissionen, Wasserverbrauch und die Nutzung sonstiger Ressourcen untersuchen. Die meisten Untersuchungen beschäftigen sich auch mit Li-Ionen-Batterien für elektrifizierte bzw. vollständig elektrisch betriebene Personenkraftwagen (d. h. Hybridfahrzeuge, Plug-in-Hybridfahrzeuge und Batterieelektrische Fahrzeuge).

Die Ergebnisse der verschiedenen Studien können aufgrund einer Reihe von Schlüsselfaktoren deutlich voneinander abweichen; zu diesen zählen: der Energiebedarf für die Produktion (und wo dieser Bedarf anfällt), die benötigten Werkstoffmengen für die Batteriezellen und anderen Komponenten, die Verwendung von Primärdaten gegenüber Sekundärdaten (einigen Studien liegen auch eher veraltete Daten zugrunde, wohingegen der technische Fortschritt schnell voranschreitet), die in den jeweiligen Analysen entsprechend untersuchten Produktionsverfahrensdetails, die Vorgehensweise beim Recycling und schließlich die zugrundeliegenden Umweltbilanz-Datenbanken. Die mit Blick auf die Nutzungsphase von Elektrofahrzeugen verfügbare Datenlage weicht von Studie zu Studie je nach den entsprechend gewählten Schlüsselannahmen für die Fahrzeugeffizienz, die Gesamtkilometerleistung und den zur Anwendung gekommenen Strommix ebenfalls deutlich voneinander ab.

Die durchgeführte Datenbestandsaufnahme kommt zu dem Schluss, dass Verbesserungen in der Batterieenergiedichte, Verfahrensoptimierungen und Optimierungen in der chemischen Zusammensetzung zukünftiger Batteriegenerationen eine erhebliche Reduzierung der Umweltbelastungen pro produzierter kWh Batterieenergie erwarten lassen können. Hinzu kommt, dass umweltbelastende Faktoren infolge der Verwendung von Werkstoffen wie Kobalt und der Energieverbrauch im Produktionsprozess durch Technologie-Verbesserungen oder den Einsatz eines saubereren Energiemixes in der Produktion voraussichtlich abgemildert werden bzw. vermindert werden können.

Die derzeit (unter der Leitung von Ricardo) für die GD Klimapolitik durchgeführten Umweltverträglichkeitsstudien bezüglich der Nutzung verschiedener Straßenverkehrsfahrzeuge, Antriebsarten und Verbrennungsmotoren bzw. anderer Energieträgersysteme dürften in naher Zukunft weitere Erkenntnisse bringen.

Im Rahmen des vorliegenden Projekts wurde unter Verwendung des (zuvor von Ricardo-Experten für die GD Klimapolitik entwickelten) SULTAN-Verkehrsmodells eine Extrapolationsmethode angewendet, um auf der Grundlage alternativer Szenarien zur Verbreitung der Elektromobilität bei den unterschiedlichen Verkehrsmitteln E-Bikes, E-Motorräder, E-Mopeds, Elektro-PKW und Elektro-LKW in Europa die voraussichtlichen globaleren Effekte auf Emissionen und Ressourcen einzuschätzen. Weiterhin wurde im Rahmen dieser Analyse ein Basis-Szenario mit eher vorsichtigen Annahmen bezüglich der Wiederverwendung / Umnutzung und des Recycling von Antriebsbatterien einem eine nachhaltige Wertschöpfungskette beinhaltenden Szenario mit höheren Wiederverwendungs- / Umnutzungs- und Recyclingquoten gegenüber gestellt.

Die Ergebnisse offenbarten für das Nachhaltigkeitsszenario ein im Vergleich zu dem Basis-Szenario erhebliches Einsparpotenzial bei den Emissionen und bei der Nachfrage nach Primärrohstoffen sowie eine erhöhte wirtschaftliche Wertschöpfung. Die Extrapolationsübung ergab weiterhin, dass die durch die Produktion von Antriebsbatterien für Elektrofahrzeuge (und deren Entsorgung) verursachten Mehr-Emissionen voraussichtlich erheblich niedriger ausfallen werden als der entsprechende Emissionsrückgang durch die Elektromobilität selbst.

## Entwicklung einer nachhaltigen Wertschöpfungskette

Eine nachhaltige Wertschöpfungskette für Elektrofahrzeug-Batterien zeichnet sich dadurch aus, dass sie umweltschonend ist und die natürlichen Ressourcen nicht erschöpft. Sie zeichnet sich weiterhin durch die Bewahrung des ökologischen Gleichgewichts aus und generiert gleichzeitig wirtschaftliches Wachstum. In diesem Zusammenhang zeichnen sich interessante Perspektiven für eine Steigerung der Wertschöpfungskette in folgenden Bereichen ab:

- Steigerung der bislang noch niedrigen Recyclingraten bei der Rückgewinnung produktionswichtiger Neuwerkstoffe (aufgrund eines nach wie vor geringen Anteils an Altbatterie-Rückführungen und hohen Kosten für entsprechende Recyclingtechniken – dies gilt insbesondere in Bezug auf Lithium).
- Verringerung der aktuell noch hohen Abhängigkeit von Nicht-EU-Ländern als Zulieferer für Batteriezellen-Komponenten und für die Batteriezellen-Produktion und des derzeit begrenzten Einflusses auf die Herstellungsverfahren und deren Umweltbilanz.
- Ergreifen von Chancen zur Reduzierung des Ressourcenverbrauchs (einschließlich der anfallenden Abfallmengen) hinsichtlich der aktuell noch sehr ressourcenintensiven Betriebsabläufe bei der Batteriezellen-Produktion (Energie, Wasser und Rohstoffe).
- Weiterentwicklung des gerade entstehenden Marktes für eine Wiederverwendung der Energiespeicherkapazitäten erstmalig ausgemusterter Antriebsbatterien. Die momentan schnelle

technologische Entwicklung eröffnet flexible Lösungen für die Batterie-Wiederverwendung in der einen oder anderen Form.

- Analog zur Wiederverwendungsoption ist die Weiterentwicklung des gerade entstehenden Marktes für die Umnutzung ausgemusterter Antriebsbatterien mit dem Ziel der Verwendung in Energiespeichersystemen anzuvisieren. Die momentan schnelle technologische Entwicklung eröffnet flexible Lösungsperspektiven und erfordert Sektor-übergreifende Zusammenarbeit, damit sich dieser Markt entwickeln kann.
- Weiterentwicklung des gerade entstehenden Marktes für das Recycling von Rohstoffen/Werkstoffen aus Altbatterien.

Hinzu kommt, dass mit zunehmender Reife der Wertschöpfungskette das Risiko negativer Nebeneffekte hinsichtlich der Entsorgung von Altantriebsbatterien an Gewicht gewinnt, da Fragen nach der Verantwortung und Haftung für die im Zuge von Verwertungsprozessen anfallenden elektrochemischen Schadstoffe bis dato nicht geregelt sind.

Die aktuell bestehenden Regelwerke auf EU-Ebene stellen einen Rahmen dar für die Regulierung der Wertschöpfungskette für Elektrofahrzeugbatterien in der EU, die darauf abzielt, die umweltbelastenden Faktoren möglichst gering zu halten. Die wichtigsten diesen Markt regulierenden Regelwerke umfassen die Batterie-Richtlinie (2006/66/EG), die Altfahrzeuge-Richtlinie (2000/53/EG) und die REACH-Verordnung (EG) Nr. 1907/2006. Zusammen genommen regulieren diese EU-Gesetzeswerke:

- den Umgang mit Gefahrstoffen
- die Umweltverträglichkeit von Batterien über ihre gesamte Nutzungsdauer betrachtet
- die Rückgewinnung, Aufarbeitung und das Recycling von Altbatterien, einschließlich Vorgaben für Einsammelquoten und für die Recyclingeffizienz.

Darüber hinaus sind weitere Mechanismen vorhanden, um die Verfügbarkeit von Werkstoffen zu verbessern und um das Vorankommen von Innovationen durch F+E zu fördern, die von den Batterieproduzenten für die Herstellung von Elektrofahrzeug-Batterien benötigt werden.

Zum besseren Verständnis der Entwicklung einer nachhaltigen Wertschöpfungskette für Elektrofahrzeugbatterien in der EU wurden acht Kreislaufwirtschaftsmodelle einer näheren Betrachtung unterzogen, um ein besseres Verständnis der damit verbundenen Stärken, Schwächen, Chancen und Risiken zu erlangen. Daneben wurden die derzeit bestehenden Nutzungs- und Verbrauchsmuster betrachtet und deren mutmaßlichen Wechselwirkungen mit der Wertschöpfungskette für Elektrofahrzeugbatterien in der EU berücksichtigt. Dabei ist in erster Linie die derzeit noch geringe Verbreitung von E-Fahrzeugen und demnach noch allgemein geringe Nutzung von Antriebsbatterien festzustellen – dies vor dem Hintergrund einer wachsenden Nachfrage nach Strom und dem daraus resultierenden Druck auf die Energiesicherheit und die damit verbundene Notwendigkeit einer besseren Planung der Spitzenbedarfszeiten.

Die untersuchten Kreislaufwirtschaftsmodelle umfassen: Integrierte Wertschöpfungskette; Car-Sharing-Systeme; Batterie-Leasing-Systeme; Batteriewechsel-Systeme; Vehicle-to-Grid-Energiesysteme; Wiederverwendung für die Anwendung als Elektrofahrzeugbatterie; Umnutzung ausgemusterter Antriebsbatterien zur Verwendung in Energiespeichersystemen; Rückgewinnung der in Altbatterien enthaltenen Rohstoffe durch Recycling; sowie der sichere Umgang und die Aufarbeitung von Batterie-Müll.

## Stärken, Schwächen, Chancen und Risiken

Die begrenzte Verfügbarkeit von Rohstoffen ist als ein bedeutendes Wachstumshemmnis in diesem Sektor zu konstatieren. Wobei allerdings durchaus erkannt wird, dass durch Recycling zurückgewonnene und dem Markt somit wieder zur Verfügung stehende Rohstoffe/Werkstoffe voraussichtlich eine Rolle bei der Entschärfung dieses Hemmnisses spielen werden. Sollten darüber hinaus weitere baldige Entwicklungen bzw. Fortschritte in der chemischen Zusammensetzung zukünftiger Batteriegenerationen erreicht werden (z. B. vermehrte Verwendung von Natrium-Ionen, schnellerer Verzicht auf Kobalt) dann könnte dies, wenn auch wahrscheinlich nur mittel- bis langfristig, zur Verringerung der beschriebenen Hemmnisse beitragen.

Als wichtige Entwicklungsbereiche für das Gedeihen einer sich entwickelnden Kreislaufwirtschaft für Antriebsbatterien in der EU sind zu nennen: die Batteriezellenproduktion (und die Produktion von Zellenkomponenten), die Wiederverwendung und die Umnutzung ausgemusterter Antriebsbatterien.

Aus industriepolitischer Sicht ist die Sicherung eines Potenzials an qualifizierten Arbeitskräften und von Know-how von wesentlicher Bedeutung. Der Bedarf an qualifizierten Arbeitskräften in einer solchen Kreislaufwirtschaft, und ein darauf abgestimmter rechtlicher Rahmen zur Unterstützung einer solchen Entwicklung, wird sich voraussichtlich positiv auf die Schaffung von Arbeitsplätzen auswirken. Schätzungen gehen beispielsweise von 15 Arbeitsplätzen pro 1.000 Tonnen zu verarbeitenden Elektrofahrzeugaltbatterien-Mülls aus. Mit einem Wachstum ist auch für die Akku-Pack-Produktion und die Elektrofahrzeug-Fertigung in der EU zu rechnen. Eine solche Entwicklung kann auf dem etablierten Industrie-Know-how aufbauen und bestehende technische Fähigkeiten und Kapazitäten optimieren.

Die aktuelle Bautätigkeit im Bereich Neuerrichtung von Produktionskapazitäten in der EU deutet darauf hin, dass bereits in erheblichem Umfang Kapital für Investitionen in das Wachstum der Fertigung von Batteriezellenkomponenten aufgewendet wurde. Angesichts des geplanten weiteren Wachstums besteht allerdings eine fortdauernde Notwendigkeit nach weiteren Investitionen in die entsprechenden Infrastrukturen. Weiterhin besteht Investitionsbedarf für den Aufbau von Software-Infrastrukturen zur Unterstützung der Entwicklung von auf der Kreislaufwirtschaft aufbauenden Geschäftsmodellen.

Die Europäische Batterie-Allianz hat ein Netzwerk von Branchenakteuren etabliert, um die Kommunikation untereinander zu erleichtern. Dies ist ein wichtiger Schritt, um das Wachstum in der gesamten Wertschöpfungskette für Antriebsbatterien voranzubringen.

Mit Blick auf das aktuelle Regelwerk wurden über die gesamte Wertschöpfungskette hinweg mehrere Schwächen und Risiken identifiziert. Es bestehen Gemeinsamkeiten, wobei die folgenden Punkte hervorzuheben sind:

- Mangelnde Definitionen für auf der Kreislaufwirtschaft aufbauende Geschäftsmodelle (vor allem in Bezug auf die Aktivitäten Wiederverwendung und Umnutzung ausgemusterter Antriebsbatterien, wobei auch andere aufkommende Geschäftsmodelle der Kreislaufwirtschaft von klareren Definitionen profitieren würden).
- Fehlende gemeinsame Standards auf EU-Ebene (Standards werden in der Regel unternehmensintern entwickelt und unterscheiden sich von denjenigen anderer Hersteller).
- Transparenz (Herstellerverantwortung, aber auch finanzielle Transparenz angesichts aufkommender Geschäftsmodelle der Kreislaufwirtschaft wie Vehicle-to-Grid, V2G).

Die folgende Abbildung gibt eine visuelle Übersicht über die Stärken, Schwächen, Chancen und Risiken der Kreislaufwirtschaft für Antriebsbatterien.

**Tabelle ES3: Zusammenfassung der SWOT-Analyse für die Wertschöpfungskette für Elektrofahrzeugbatterien in der EU**

| Wertschöpfungskette für E-Fahrzeugbatterien | Industrie | Infrastruktur | Regelwerke |
|---|---|---|---|
| Rohstoffe | Schwach | Mittel | Stark |
| Zellenkomponentenherstellung | Mittel | Mittel | Stark |
| Batteriezellen-Produktion | Mittel | Mittel | Mittel |
| Akku-Pack-Fertigung | Stark | Stark | Stark |
| E-Fahrzeug-Produktion | Stark | Stark | Stark |
| Wiederverwendung | Mittel | Mittel | Schwach |
| Umnutzung | Mittel | Mittel | Schwach |
| Recycling | Stark | Stark | Stark |

*Anmerkung:* **Grün** = wichtige Stärken, die künftige Regelwerke weiter konsolidieren und unterstützen sollten; **Bernstein** = weiter zu beobachtende Entwicklungsbereiche; und **Rot** = bedeutende Hindernisse bzw. Einschränkungen, die künftige Regelwerke versuchen sollten abzubauen.

## Regulierungsansätze

Auf der Grundlage der ermittelten Chancen zur Optimierung der Ressourcenausnutzung und zur Reduzierung der Umweltbeeinträchtigungen im Rahmen der Wertschöpfungskette für E-Fahrzeugbatterien und unter Betrachtung der aktuellen Regelwerke bezüglich der verschiedenen Komponenten der Wertschöpfungskette wurden eine Reihe von Vorschlägen für die Ausgestaltung zukünftiger Regelwerke erarbeitet und unter Einbeziehung fachkundiger Interessensvertreter der Handlungsbedarf einer Bewertung unterzogen.

Im Ergebnis dieser Analyse wurden Prioritäten für unmittelbar und in naher Zukunft erforderliche Regelwerk-Ausgestaltungen formuliert, die folgende vier Bereiche (mit jeweils detaillierten Handlungsvorschlägen) umfassen:

- Beseitigen rechtlicher Unsicherheiten in bestehenden Normfestlegungen und Definitionen:
  - Die aktuellen regulatorischen Festlegungen sind möglicherweise entweder nicht ausreichend, um einem gut funktionierenden Markt gerecht zu werden, oder sie beinhalten unter Umständen gewisse Überschneidungen oder Widersprüchlichkeiten. Durch eine Präzisierung unklarer Festlegungen (z. B. mit Blick auf die Produktverantwortung, die Festlegung, was als Abfall anzusehen ist, usw.) kann die Ausbildung eines robusten Kreislaufwirtschaftsmarkts voraussichtlich unterstützt werden.
- Verbesserung der Transparenz zwischen den verschiedenen Komponenten der Wertschöpfungskette durch erweiterte Regulierung:
  - Diese Maßnahme könnte mit Blick auf die gesamte Lieferkette den Zugang zu wichtigen Produktinformationen erleichtern und es den Marktteilnehmern somit ermöglichen, eine gezieltere Auswahl beispielsweise bei ihrer Materialbeschaffung oder hinsichtlich Produkteigenschaften zu treffen.
- Aufstellen neuer und aktualisieren bestehender Zielvorgaben:
  - hinsichtlich bestehender Recycling-Zielvorgaben und der Möglichkeit, gegebenenfalls neue Wiederverwendungs- und Umnutzungsperspektiven für Altbatterien zu schaffen. Auf diese Weise soll eine ressourceneffizientere Verwendung von Materialien bzw. Werkstoffen erreicht werden.
- Etablierung eines Regelwerks für Kontrollmechanismen und Nachweispflichten zum Zweck der Nachvollziehbarkeit der Produktbeschaffenheit:
  - Dies könnte zur Schaffung gerechter Wettbewerbsbedingungen und mit Blick auf die gesamte Nutzungsdauer von Antriebsbatterien zu einer besseren Erfassung der Produkt-Umweltbilanzen beitragen.

Die für die einzelnen Regelwerk-Ausgestaltungen vorgenommenen qualitativen Analysen machen deutlich, dass die Einhaltung eines anspruchsvolleren Regelwerks durch die wirtschaftlichen Akteure mit zusätzlichen Kosten für diese sowie mit Kostenaufwand für die Regulierungsinfrastruktur selbst verbunden ist. Ohne eingehendere Analysebewertungen ist es allerdings nicht möglich, das volle Ausmaß der damit verbundenen Kosten zu quantifizieren.

Allerdings überwiegt der zu erwartende Gesamtnutzen die mit den vorgeschlagenen Regelwerk-Ausgestaltungen identifizierten Kosten. Diese positiven Effekte beinhalten in erster Linie Wachstumsimpulse für den Industriesektor, Schaffung von Arbeitsplätzen und ein Mehr an Umweltschutz.

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# Acknowledgements

Through the course of this study we have received contributions from a range of organisations and individuals through several different means (e.g. informal communications, interviews, questionnaire responses and workshops / meetings). We would like to formally acknowledge and thank all the contributors for their insights and for sharing their knowledge with us.

A full list of contributor organisations can be seen in the table below:

| Organisations | |
|---|---|
| ACEA - European Automobile Manufacturers' Association | National Physical Laboratory (NPL), UK |
| Argonne National Laboratory | Nissan |
| ARN - Auto Recycling Nederland | Peter Ursem |
| AVERE - The European Association for Electromobility | Piaggio |
| Bellona Europa | RECHARGE |
| Belmont Trading | Renault |
| Cummins Inc | Saft |
| EBRA ivzw - European Battery Recycling Association | Spiers New Technologies |
| EcarACCU bv | T&E |
| ECOS - European Environmental Citizens Organisation for Standardisation | Tesla |
| EEB - European Environmental Bureau | TNO |
| EGARA - European Group of Automotive Recycling Associations | Toyota Motor Europe |
| EMIRI | Umicore |
| Eucobat - European Compliance Organisations for Batteries | University of Birmingham |
| EUROBAT - Association of European Automotive and Industrial Battery Manufacturers | University of Leicester |
| F&R Cawley Ltd | Vito |
| Ford of Europe | Volvo Cars |
| Greenspire Advisors Ltd | Volvo Group |
| Imperial College London | Warwick Manufacturing Group (WMG), University of Warwick |
| Kompetenznetzwerk Lithium-Ionen Batterien (KLiB e.V.) | |

# Glossary

| Abbreviation | |
|---|---|
| AP | Acidification Potential |
| B7 | 7%vol biofuel blend in diesel |
| BAU | Business As Usual |
| BEV | Battery Electric Vehicle (fully electric) |
| CH4 | Methane |
| CNG | Compressed Natural Gas |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| $CO_2e$ | Carbon Dioxide equivalent |
| DB | Database |
| EC | European Commission |
| eLCAr | E-Mobility Life Cycle Assessment Recommendations |
| EoL | End-of-Life |
| EP | Eutrophication Potential |
| EPD | Environmental Product Declaration |
| ETS | Emission Trading System |
| EV | Electric Vehicle |
| FCEV | Fuel Cell Electric Vehicle (running on hydrogen) |
| FQD | Fuel Quality Directive (98/70/EC) |
| GHG | Greenhouse Gases |
| GWP | Global Warming Potential |
| $H_2$ | Hydrogen |
| HD | Heavy Duty |
| HDV | Heavy Duty Vehicle (lorries, buses and coaches) |
| HEV | Hybrid Electric Vehicle |
| ICE | Internal Combustion Engine |
| ICEV | Internal Combustion Engine Vehicle |
| ICEV-D | Diesel ICE Vehicle |
| ISO | International Organisation for Standardisation |
| kWh | kilo-Watt-Hour |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCV | Light Commercial Vehicle (van) |
| LDV | Light Duty Vehicle (Car or LCV) |
| LEV | Low Emission Vehicles (includes BEVs, PHEVs, REEVs and FCEVs) |

| Abbreviation | |
|---|---|
| Li-ion | Lithium Ion |
| LNG | Liquefied Natural Gas |
| MJ | Mega-Joule |
| MS | Member State |
| Mt | Mega ton (million tonnes) |
| $N_2O$ | Nitrous Oxide |
| NEDC | New European Drive Cycle |
| NGO | Non-Government Organisation |
| $NH_3$ | Ammonia |
| NOx | Nitrogen Oxides (includes nitrogen monoxide and nitrogen dioxide) |
| OEM | Original Equipment Manufacturer |
| PC | Passenger car |
| PCR | Product Category Rules |
| PEF | Product Environmental Footprint |
| PHEV | Plug-in Hybrid Electric Vehicle |
| PIV | Plug-in Vehicle * |
| $PO_4$ | Phosphate |
| $PO_4e$ | Phosphate equivalent |
| POCP | Photochemical Ozone Creation Potential |
| PtX | Power-to-X (where X can be a variety of hydrocarbon liquid fuels or gases) |
| RE | Renewable Energy |
| RES | Renewable Energy Sources |
| REEV | Range Extended Electric Vehicle |
| RW | Real world |
| SETAC | Society of Environmental Toxicology and Chemistry |
| $SO_2$ | Sulphur Dioxide |
| $SO_2e$ | Sulphur Dioxide equivalent |
| TC | Test cycle |
| TCO | Total Cost of Ownership |
| TTW | Tank-to-Wheel |
| VAT | Value Added Taxes |
| VOC | Volatile Organic Compound |
| WLTP | World harmonised Light duty vehicle Test Procedure |
| WTT | Well-to-Tank |
| WTW | Well-to-Wheel |
| xEV | Electric vehicles (includes BEVs, PHEVs, REEVs and FCEVs) |
| ZEV | Zero Emission Vehicle (includes BEV and FCEV) |

# 1 Introduction and overview

## 1.1 Introduction

Ricardo Energy & Environment has been commissioned to provide technical support to the European Commission on *"Circular Economy Perspectives for the Management of Batteries used in Electric Vehicles"* (hereafter, the 'project'). The project was commissioned by the European Commission's DG Joint Research Centre (hereafter 'the JRC').

This final report provides a summary of the project final findings, which were presented in draft form and discussed with stakeholders at the final project workshop on 4th February 2019.

Following this introductory chapter, the report is structured to include the main technical analysis in Chapters 2 to 5, and the sustainable value chain, SWOT ad policy analysis in Chapters 6 to 8.

## 1.2 Background and Context

At the general level, the EU has set itself targets for reducing its greenhouse gas (GHG) emissions under progressive targets for 2020 and 2030. All sectors need to contribute to the low-carbon transition according to their technological and economic potential, and the deployment of electric vehicles (EVs) is a promising approach for decarbonisation of road transport.

The 2016 Strategy for Low Emission Mobility has emphasised the need to speed up the deployment of zero- and low-emission vehicles and set out a range of measures to support this transition. As part of the subsequent Mobility Packages, the Commission proposed several legislative and non-legislative measures, including revisions to the rules on procurement of clean vehicles (Directive 2009/33/EC), new post-2020 $CO_2$ emission performance standards for light- and heavy-duty vehicles, and an action plan to enhance the implementation of the Directive on alternative fuel infrastructure (Directive 2014/94/EU), in particular as regards EV recharging infrastructure deployment.

For electric vehicles, the production (and disposal) of the traction battery may constitute a significant share of the full lifecycle impacts. With the take-up of electric vehicles anticipated to accelerate in the coming years, minimisation of these impacts will be increasingly important.

The EU has strong circular economy initiatives that tie in with the overarching objectives on climate and energy. The Communication on "*Next steps for a sustainable European future*" pledged to apply the principles of sustainable development to all EU policies and initiatives, including an emphasis on the circular economy. The Commission has also presented proposals to review two pieces of legislation that help to set the regulatory environment of vehicle batteries: the End-of-Life Vehicles (ELV) Directive (2000/53/EC) and the Batteries Directive (2006/66/EC)[1]. Finally, a recently launched initiative is underway to propose environmental criteria for batteries in the perspective of a potential Eco-design regulation. To help inform these processes, and to also address the broader EU circular economy objectives, there is a need for research to better understand the EV batteries from a techno-economic, market and policy perspective.

## 1.3 Scope and objectives

The objective of the project is to support the Joint Research Centre (JRC) in providing a strong factual base as well as well-documented techno-economic analysis to address the following six key research questions:

1. What are the current available and emerging techniques in the manufacturing, re-use and recycling of traction batteries for electric vehicles? How are end-of-life batteries currently processed and what are the emerging plans for the future?
2. What is the current environmental impact of traction batteries for electric vehicles across the whole life cycle? What are the current environmental hotspots and how are they addressed?

[1] Results of the evaluation of the Batteries Directive have were also published in 2018 - http://ec.europa.eu/environment/waste/pdf/Published%20Supporting%20Study%20Evaluation.pdf (Trionmics/Oeko Institute, 2018).

3. What will the potential environmental impacts and hotspots of traction batteries over their whole life cycle be if electric vehicles are deployed at large scale and/or in accordance with current trends, in the near, medium and long term?
4. What are the perspectives for developing a sustainable value chain for electric vehicle batteries in the EU?
5. What are the current strengths and weaknesses of the EU economy (industry, infrastructure, policy framework) for dealing with the lifecycle of traction batteries in the perspective of road transport electrification?
6. What public policies could be envisaged to ensure truly circular lifecycles for traction batteries, and to harness the opportunities for growth and jobs in the EU?

In addition to considering the institutional and policy perspectives, this study also aims to promote an understanding of how technological developments, industry business models and subsequent environmental impacts of industrial activity respond to this institutional environment and what further EU policies might be promoted to fill any identified gaps in reaching EU recycling and re-use targets for EV traction batteries.

## 1.4 Overall research approach and key issues

An overview of the methodological approach adopted to address the research questions is summarised in Figure 1.1 below. The first stage of the work involved a refining of the scope of the study approach, followed by conducting a comprehensive review of information on the sector and further development of understanding using stakeholder consultation and a variety of analytical tools – as presented in this final report. The analysis of these has been fed into conclusions and proposed policy alternatives, which was also presented and discussed at the project workshop held with expert stakeholders on 4th February 2019.

In Table 1.1 below, a summary is provided of the research questions posed by JRC, along with an explanation of the key issues within each area, which this project has sought to address.

**Figure 1.1: Overview of the project methodology**

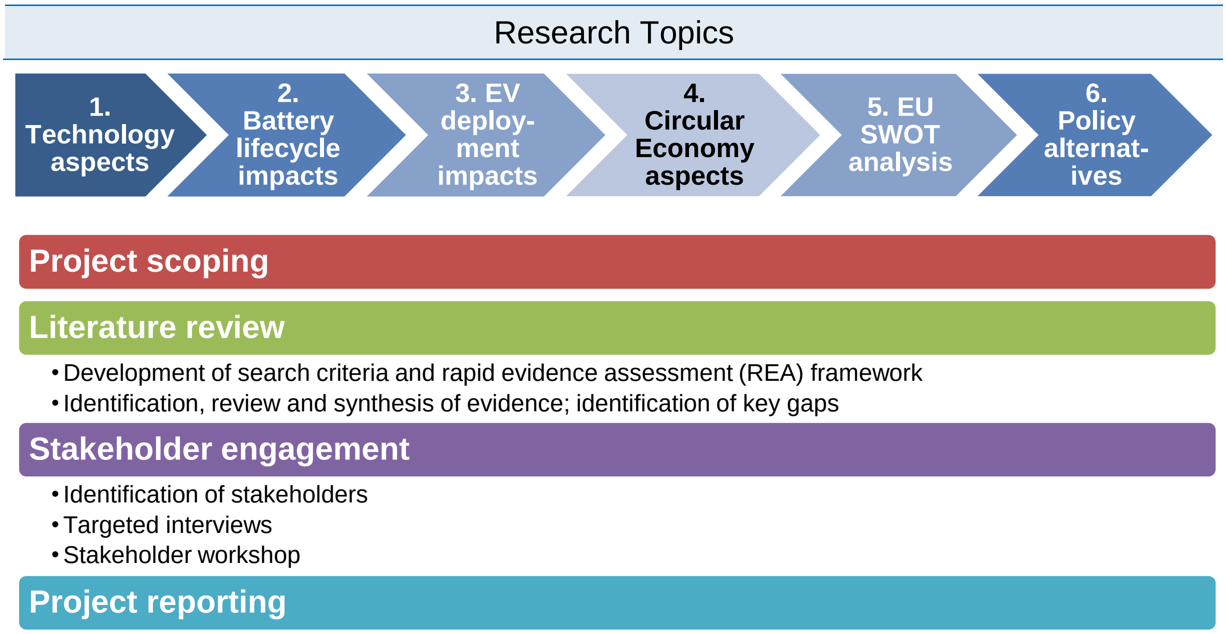


**Table 1.1: Summary of key issues to address by research topic**

| Research topic | Key issues | Expected Results |
|---|---|---|
| **Topic 1:**<br>What are the current available and emerging techniques in the manufacturing, re-use and recycling of traction batteries for electric vehicles?<br>How are end-of-life batteries currently processed and what are the emerging plans for the future? | Technological developments are very fast-moving and much of the literature is already out of date. It is important to understand the latest research so that we consider the most relevant techniques and technologies, with due regard to battery type.<br>There is a need to assess as far as feasible potential changes due to new battery chemistries proposed (i.e. from Li-ion to solid state, Li-S, Na-ion, or Li-Air).<br>To fully understand emerging future plans, consultation with stakeholders is necessary. | **General:** Understanding the state of the art and promising developments of the manufacturing and in particular the recycling, re-use (and other post-traction use) processes of batteries for electric mobility, considering current and emerging technologies, current market statistics and actors, business models, industrial capabilities and investments, repurposing schemes, and recycling capabilities.<br>**Specific:** Mapping of relevant technologies in terms of suitability (with respect to battery types) and assessing the likely future processes for manufacturing, recycling, and re-use. |
| **Topic 2:**<br>What is the current environmental impact of traction batteries for electric vehicles across the whole life cycle?<br>What are the current environmental hotspots and how are they addressed? | To make credible future forecasts, we must begin with a solid baseline assessment of the present. The LCA definition of scope can be complicated and not necessarily consistent between different studies.<br>Different assumptions on e.g. emission factors, sourcing of materials, energy, etc can dramatically change results. Of course, detailed results will vary by country, timeframe, supply chains etc but the main point is the “big picture”. There is much uncertainty due to assumptions about future developments. | **General:** Understanding the hot spots in the LCA for batteries and how to reduce environmental impacts at the hotspots.<br>**Specific:** Meta review of existing studies and data. Focusing on main conclusions / comparisons of LCA that give the overall picture, and highlighting differences in assumptions that drive large differences in conclusions, specific areas that stand out as having very large environmental impacts, and the mitigating actions presently addressing these hotspots. Develop an estimate of the per vehicle/battery level of environmental impacts. |

| Research topic | Key issues | Expected Results |
|---|---|---|
| **Topic 3:**<br>What will the potential environmental impacts and hotspots of traction batteries over their whole life cycle be if electric vehicles are deployed at large scale and/or in accordance with current trends, in the near, medium and long term? | This topic about the overall impacts due to the scale of potential fleet deployment. EV battery technology is rapidly improving and this means unit costs (€/kWh) are rapidly decreasing. In fact, costs are decreasing much faster than industry analysts predicted, which means a large scale of EV deployment may arrive sooner than previously predicted. Most projections of sales don't go beyond 2025, but having some longer-term predictions will be instrumental for making plans now to develop effective second-use and recycling capabilities throughout the EU. Furthermore, as the electric vehicle market develops, the installed battery energy capacity (in kWh) is likely to increase as the technology develops and costs reduce. This has implications for the future arisings of used automotive batteries that needs to be taken into account in the analysis. | **General:** Anticipating the evolution of electric mobility in the near, medium and long term, based on projections for 2025 and 2030 (and indications of general trends to 2050), with deployment scenarios displaying sensitivity to the main factors, specifically with a view to analysing its impact on the traction battery value chain and the environment in the EU.<br>**Specific:** In the context of other market predictions for the deployment of EVs across the EU, our latest forecasts and trends given the current state of evolution in battery and other related technology using our SULTAN policy scenario tool for sustainable transport. |
| **Topic 4:**<br>What are the perspectives for developing a sustainable value chain for electric vehicle batteries in the EU? | A sustainable EV battery value chain promotes environmental sustainability and cooperation between different members of the value chain. To close the loop on EV batteries, actors at the end of the chain for re-use and recycling must be able to coordinate well with battery manufacturers and OEMs to ensure the specifications of batteries produced are also suitable for the re-use and recycling purposes at the end of the chain. Consumer preferences and requirements are an important component. How do consumer preferences for EVs affect the batteries produced and subsequently the possibilities for recycling and re-use? | **General:** Proposing options for steering the anticipated evolution towards a more circular economic model, in particular from the perspective of actors in each part of the value chain, and options to align the incentives of different market actors.<br>**Specific:** Using circular economy models and value chain concepts, a descriptive assessment of the pathway required to aim to close the resource loop in the production of EV batteries and quantitative estimates of the gaps to be closed. Case studies used to illustrate key issues for battery manufacturing, recycling, and re-use/second life. |

| Research topic | Key issues | Expected Results |
|---|---|---|
| **Topic 5:**<br><br>What are the current strengths and weaknesses of the EU economy (industry, infrastructure, policy framework…) for dealing with the lifecycle of traction batteries in the perspective of road transport electrification? | Large scale EV deployment requires planning and preparation on the part of EU policymakers and industry actors. High volumes of batteries will need to be repurposed or recycled, and it is imperative to understand how prepared EU institutional and market structures are to respond to the challenge. | **General:** Anticipating the evolution of electric mobility in the near, medium and long term, based on projections for 2025 and 2030 (and indications of general trends to 2050), with deployment scenarios displaying sensitivity to the main factors, specifically with a view to analysing its impact on the traction battery value chain in the EU.<br><br>**Specific:** Up to date SWOT of the EU's institutional and industrial structures given updated forecasts of large-scale EV deployment and the areas that the EU is well-prepared for against the areas the EU needs to do more work to prepare for. |
| **Topic 6:**<br><br>What public policies could be envisaged to ensure truly circular lifecycles for traction batteries, and to harness the opportunities for growth and jobs in the EU? | To ensure a circular approach to EV batteries and minimise environmental impacts from EV battery waste, the role of public policy is to close the gap between the solutions that will be provided by the market without intervention and the EU goal for where the market should be to minimise environmental externalities. At the same time, these policies should aim to promote the competitiveness of EU industry for the EV battery value chain and increase employment opportunities in industry. A more competitive EU industry can also better compete with leading markets China, Japan, and the US. This will lead to more trade and export opportunities, which in turn leads to more jobs within the EU. | **General:** Proposing options for steering the anticipated evolution towards a more circular economic model, in particular from a public policy perspective but centred on the market evolutions driven by industrial actors, and broadening the outlook to the afterlife use of traction batteries outside electric mobility (e.g. energy storage).<br><br>**Specific:** Identification of possible policy alternatives and the development of a shot list of those suitable to address the challenges identified in the study, with an assessment of the advantages and disadvantages of each policy alternative. |

# 2 Overview of the technical review and the value chain

The main research, analysis, modelling, writing and other investigative activities that led to the production of the final outputs were carried out in Task 2. This task was divided into a series of subtasks to clearly answer all of the research questions and to conduct stakeholder interviews.

A mapping of the research tasks and tools against each of the key research questions is given below.

**Table 2.1: A mapping of research questions, inputs and analysis tools**

| Chapter (Task) | Key research question | Research inputs | Analysis tools |
|---|---|---|---|
| **Chapter 3 (Task 2.2)** | What are the current available and emerging techniques in the manufacturing, re-use and recycling of traction batteries for electric vehicles? What are emerging plans for the future? | Literature review<br>Stakeholder interviews with battery manufacturers, OEMs and suppliers, waste and energy firms, and academic researchers. | Technology roadmaps |
| **Chapter 4 (Task 2.3)** | What is the current environmental impact of traction batteries for electric vehicles across the whole life cycle? What are the current environmental hotspots and how are they addressed? | Literature review<br>Stakeholder interviews with policy stakeholders, waste firms, academic researchers. | Meta-analysis of LCA studies |
| **Chapter 5 (Task 2.4)** | What will the potential environmental impacts and hotspots of traction batteries over their whole life cycle be if electric vehicles are deployed at large scale and/or in accordance with current trends, in the near, medium and long term? | Literature review<br>Stakeholder interviews with automotive industry, waste and energy firms, academic researchers. | SULTAN policy scenarios to explore fleet-level impacts |
| **Chapter 6 (Task 2.6)** | What are the perspectives for developing a sustainable value chain for electric vehicle batteries in the EU? | Literature review<br>Stakeholder interviews with, battery manufacturers, OEMs and suppliers, waste and energy firms, academic researchers and policy stakeholders<br>Task 3 workshop | Value chain analysis<br>Circular Economy business model analysis<br>Case studies |
| **Chapter 7 (Task 2.5)** | What are the current strengths and weaknesses of the EU economy (industry, infrastructure, policy framework) for dealing with the lifecycle of traction batteries in the perspective of road transport electrification? | Literature review<br>Data review<br>Stakeholder interviews with policy stakeholders, battery manufacturers, and academic researchers. | SWOT analysis |
| **Chapter 8 (Task 2.7)** | What public policies could be envisaged to ensure truly circular lifecycles for traction batteries, and to harness the opportunities for growth and jobs in the EU? | Literature review<br>Stakeholder interviews with policy stakeholders, battery manufacturers, OEMs and suppliers, academic researchers, waste firms and energy firms.<br>Task 3 workshop | Circular Economy Model<br>Multi-criteria analysis |

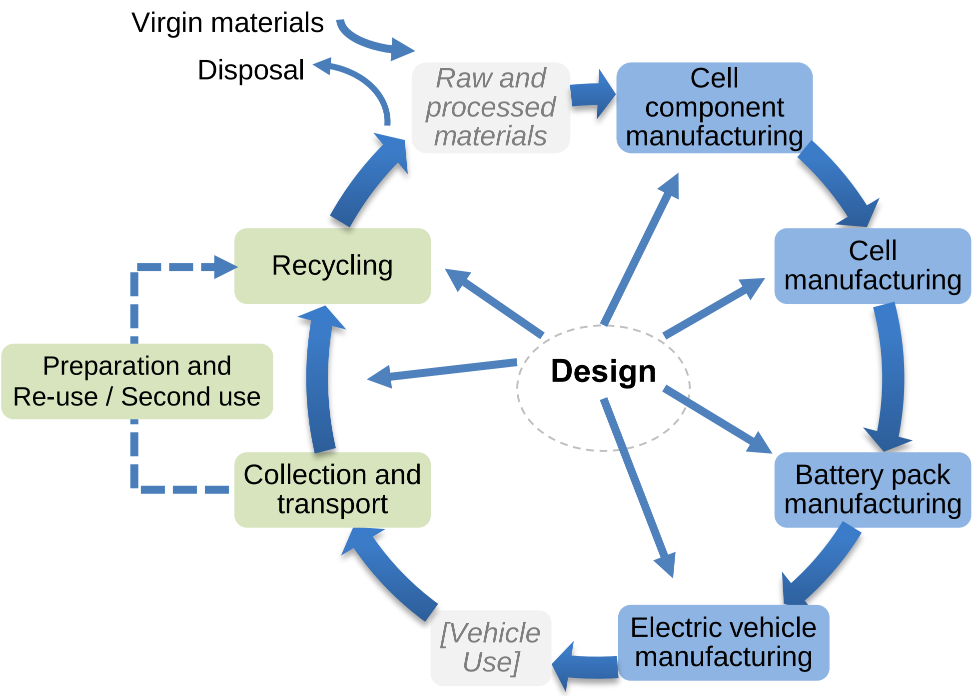
## 2.1 Developing a more detailed picture of the value chain

This section provides a more detailed picture of the EV battery value chain, building on information also already provided in a number of recent publications[2]. Figure 2.1 gives an illustration of the objective of a circular value chain (also acknowledging some inputs and outputs). The automotive LIB (lithium-ion battery) value chain has previously been described in detail in (JRC, 2017), with a summary of the key statistics and considerations from this report provided in Figure 2.2 below.

The following sections of this chapter provide a higher-level overview of the different stages of the value chain, with particular detail for the latter stages following the vehicle use phase (light green boxes in Figure 2.1), since these have not been explored in as much detail in earlier JRC publications and elsewhere. The raw materials and vehicle use stages of the value chain are not directly addressed in this study. Key European stakeholders from across the EV battery chain involved in the "European Battery Alliance" (EBA) are also presented in Figure 2.3 below.

To more fully understand the issues, opportunities and barriers across the value chain (and any differences between battery forms and types/chemistries), it is also helpful to further disaggregate the different value chain stages into further sub-steps: more detail is provided in the relevant sections below, and also for the key stages in Chapters 3 and 6 of this report.

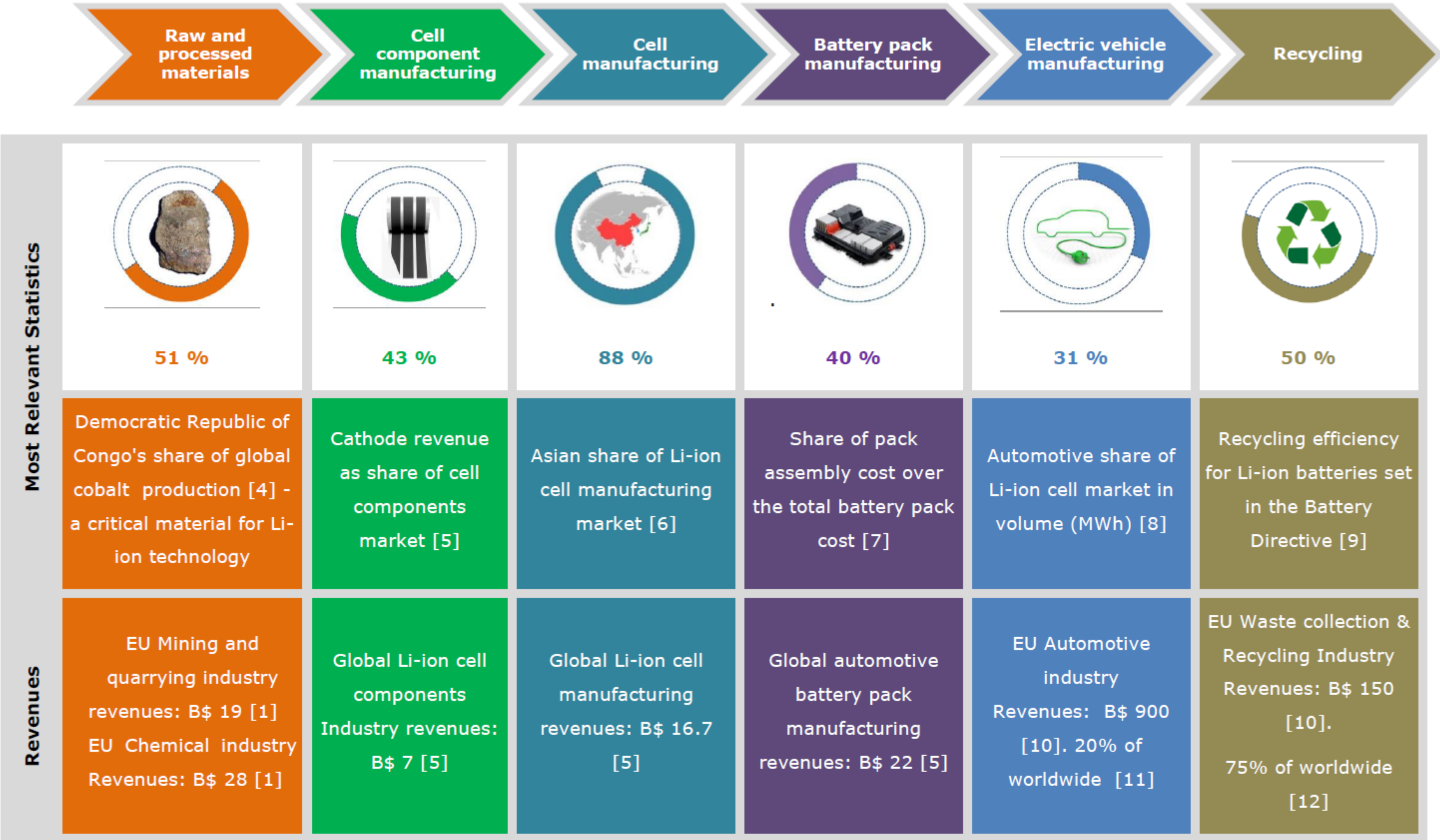
**Figure 2.1: Circular view of the EV battery value chain for Europe**




*Notes*: The 'Raw and processed materials' and Vehicle use' stages are not directly addressed in this study. Re-use or Second use / repurposing are optional additional steps that may be applied where feasible; whenever batteries become waste (e.g. where further reuse or repurposing is not feasible) they should be recycled.

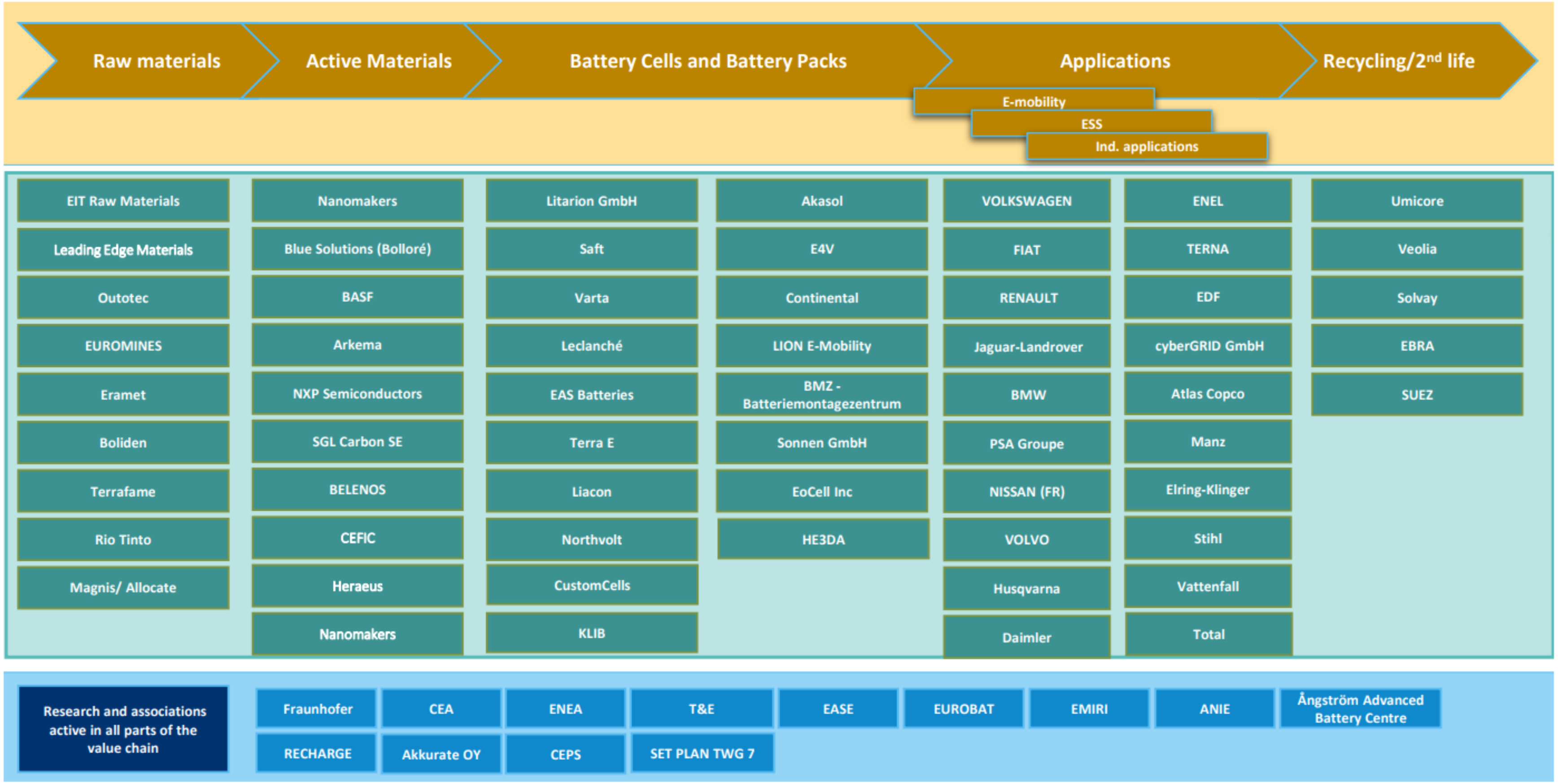
[2] For example, (JRC, 2017a), (JRC, 2017a), (JRC, 2017b), (European Commission, 2018), (European Commission, 2018a) and (European Commission, 2018b)

**Figure 2.2: Automotive lithium-ion battery value chain (data from 2015) (JRC, 2017)**



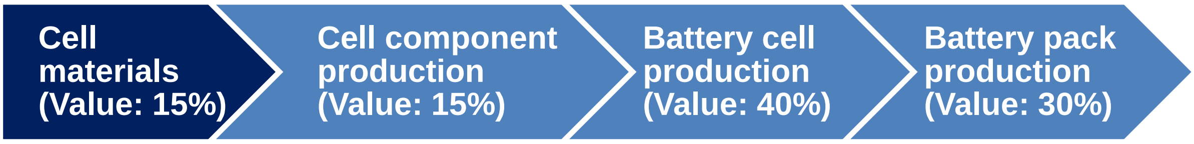

*Notes*: Sources cited in the JRC figure above include – [1] (European Commission, 2015a); [4] (European Commission, 2014); [5] (Pillot, 2016); [6] (CEMAC, 2016); [7] (CEMAC, 2015); [8] (Pillot, 2016a); [9] (EU, 2006); [10] (Eurostat, 2017); [11] (ACEA, 2017); [12] (BIR, 2017).

**Figure 2.3: European stakeholders from across the EV battery chain involved in the "European Battery Alliance" (EBA)**




Source: (Electrive, 2018)

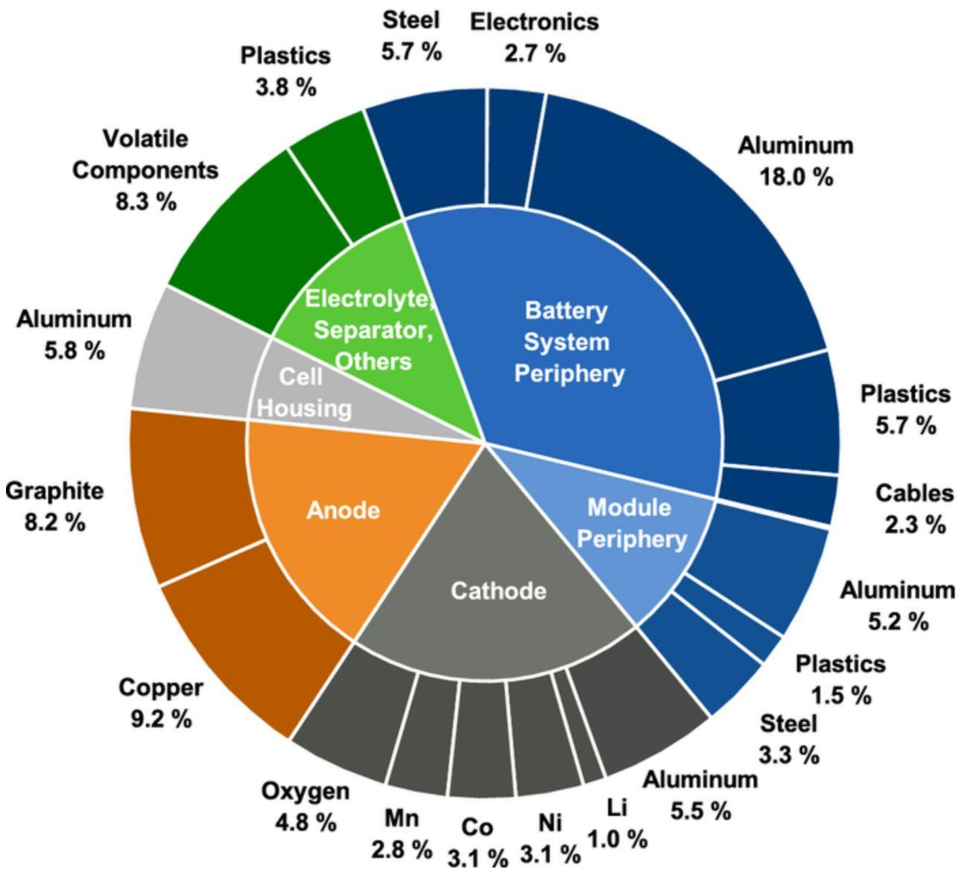
## 2.2 Raw and processed materials




Automotive traction batteries for electric vehicles come in a variety of chemistries and forms, which are discussed further in Section 3. These raw cell materials are responsible for ~15%[3] of the value of the battery pack (as indicated above), however few of the key materials are sourced in Europe.

Whilst there are some differences in content, the material composition of the various lithium ion battery (LIB) chemistries that currently dominate the marketplace are generally quite similar with the exception of the active materials for the cathode (i.e. Cobalt, Nickel and other active materials) – as shown in Figure 2.4 for a generic EV battery system (though there are also lithium salts in the electrolyte), and Figure 2.5 for different cathode chemistry types (see Section 3.1). These materials also comprise a significant cost of the cell (~42%). Mining and chemical industries provide the range of raw and processed materials used in the production of the various EV battery cell components including the anode, cathode, electrolyte and separator (JRC, 2017), as well as copper and aluminium current collectors. Additionally, inactive phases are also included within electrodes during battery manufacture for various reasons (binding, conductivity). These can also influence recycling process for that battery - the binder in particular is important as this defines what recycling process can be used (Wu, 2018).

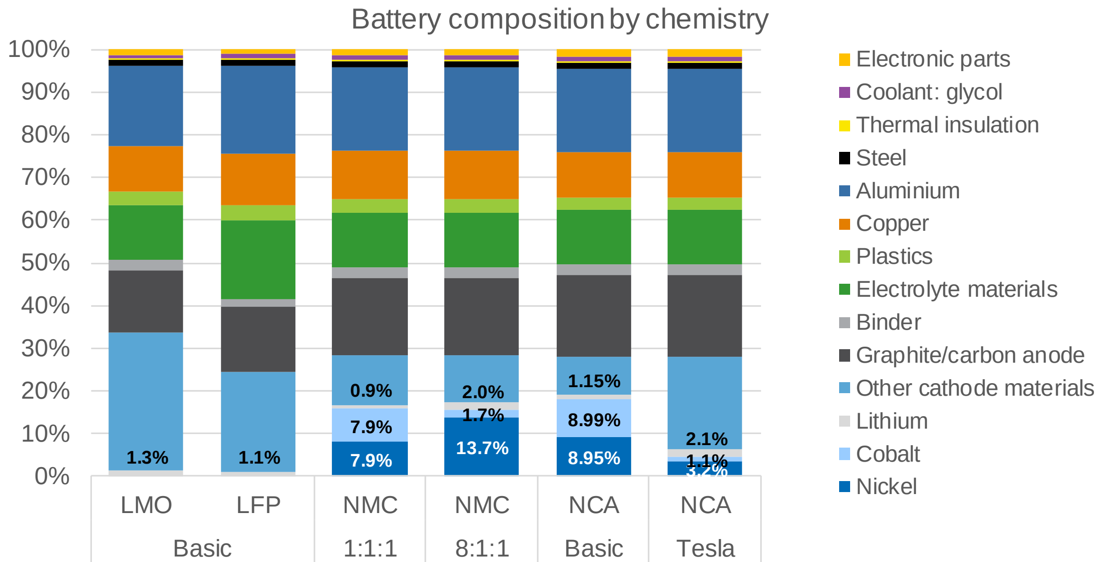
**Figure 2.4: Generic composition of EV battery system – average across the different chemistries by battery component area, as a % of total battery pack mass**




*Source*: (Jan Diekmann, 2017)

[3] Estimated breakdown based upon (Roland Berger, 2015), (Roland Berger, 2011) and (C. Pillot, 2017).

**Figure 2.5: Indicative battery composition for the main chemistries used in current and near-term xEV models – shares by battery chemistry based on the GREET model as a % of the total mass**




*Source*: Calculated based on GREET model (ANL, 2018) and other sources.

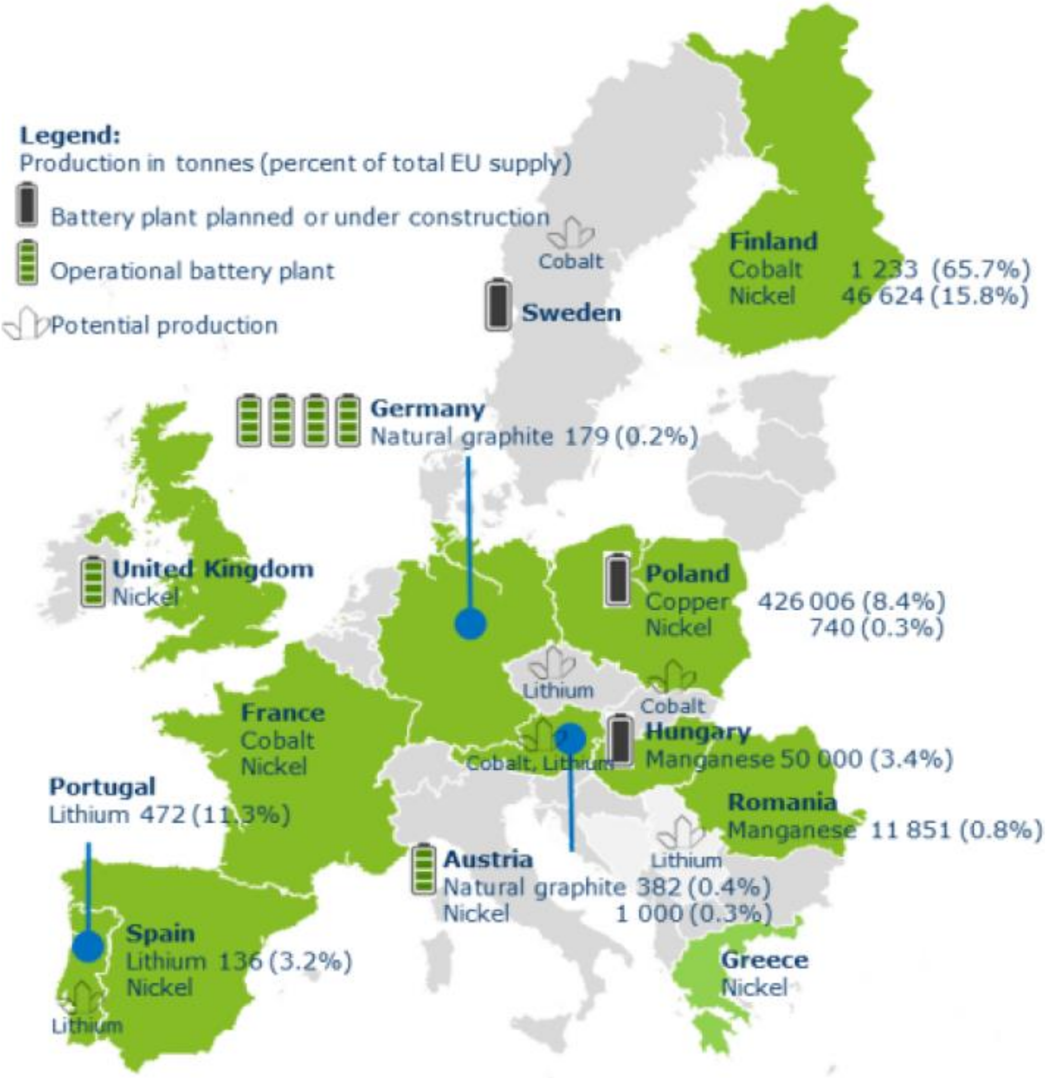
Notes: The overall % shares by mass for the key Lithium, Cobalt and Nickel components are highlighted.

There are a number of key materials that have a high economic importance, but also have a high supply-risk, and are termed "critical raw materials (CRMs)" (JRC, 2017) (though these CRMs currently do not have a particular legal status in the EU). These CRMs include: Cobalt (Co), Manganese (Mn), Nickel (Ni), and natural graphite[4]. Although Lithium (Li) is not currently on the CRM list, the anticipated rapid increase in demand for LIB for automotive and energy storage purposes appears likely to result in potential supply issues in the future. Lithium has a range of uses, with batteries accounting for almost half (46%) in 2017, followed by use in ceramics and glass (27%); lubricating greases (7%); polymer production (5%); continuous casting mold flux powders (4%); air treatment (2%) and other uses (9%) (USGS, 2018a). Other materials, such as aluminium and copper, are also significant in terms of their contribution to the lifecycle environmental impacts of EV batteries (discussed further in Chapter 4). The trend over recent years has been to reduce the thickness of current collectors (down to about 8 µm now). However, it's becoming harder to get lower and the current trend is now to make thicker electrodes to reduce the number of current collectors instead (Wu, 2018).

More details on the raw and processed materials value chain are provided in (JRC, 2017), (JRC, 2017a), and (European Commission, 2018c). The source raw materials for Co/Ni are sulphate precursors currently mainly produced from nickel/cobalt sulphides, and for Li they are based on lithium hydroxide precursors produced from lithium carbonates (usually produced from brines or from hard-rock deposits). An assessment was also provided of the potential sourcing for key materials (and batteries) in the EU in (European Commission, 2018), which is illustrated in Figure 2.6. This assessment has noted that, apart from cobalt (mainly in refined form), coverage of EU demand by domestic sourcing is very limited for the other materials such as nickel, natural graphite, manganese and lithium. Recycling input for cobalt production is currently around 16%, but negligible for other key materials like lithium and natural graphite (JRC, 2017).

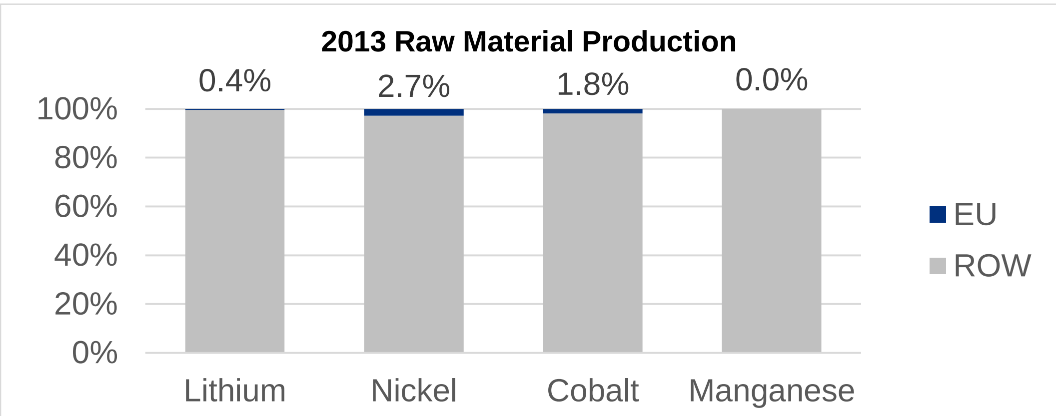
[4] Nickel is used for its capacity, Cobalt is to stabilise the material for long life and Manganese is used for safety.

**Figure 2.6: Mine production and potential of battery raw materials, and battery plants in the EU11**



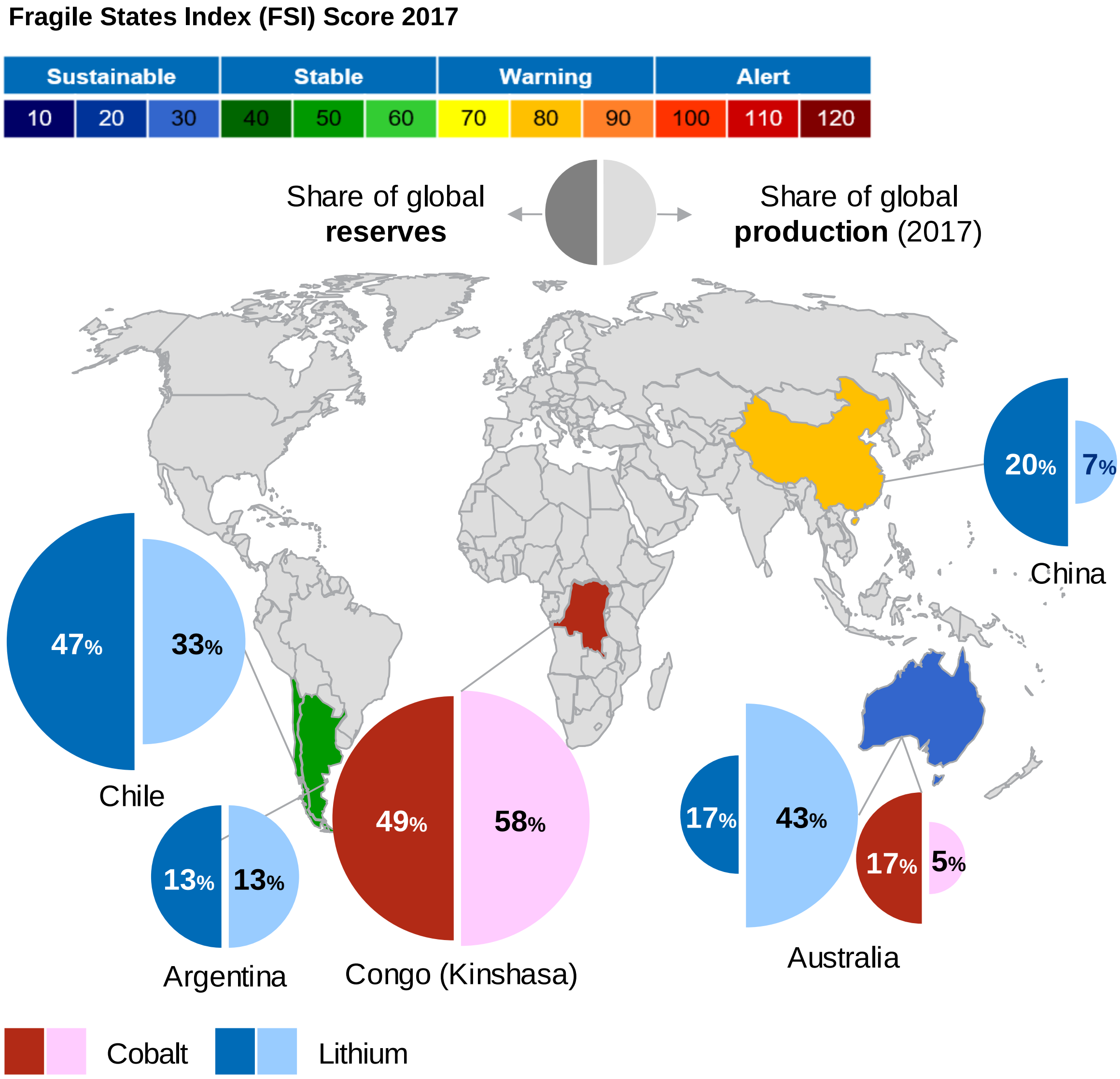

Source: (European Commission, 2018). Note: Most of the currently operational EV battery production facilities in Europe only assemble batteries (battery modules and packs) and do not manufacture the complete battery cells or cell components. The UK battery plant includes some cell assembly as well as battery module/pack production – the electrode rolls are imported.

**Figure 2.7: EU share raw material production in 2013 for key LIB materials**




*Source*: (USGS, 2018) for Nickel and Manganese. (European Commission, 2019) for Lithium and Cobalt.

**Figure 2.8: Shares of current production and reserves for Cobalt and Lithium in comparison with the Fragile States Index (FSI)**



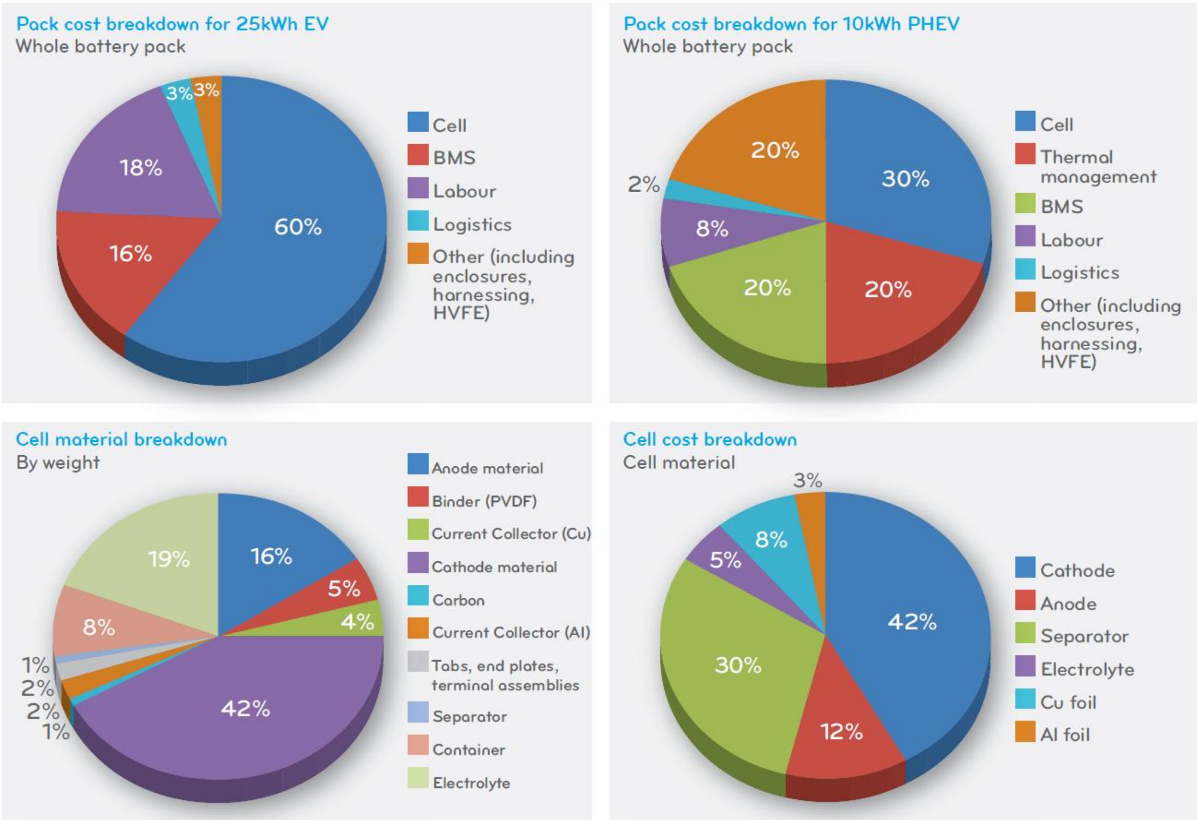

*Source*: Ricardo analysis based on (USGS, 2018).

## 2.3 Battery manufacturing

Battery manufacturing itself can be broadly split into three key steps, which are further described in the following sub-sections: manufacturing of cell components from raw materials, manufacturing of individual battery cells, and the final battery pack manufacturing stage. Additional details on the techniques used in battery manufacturing are also provided in later Section 3.2.

The contribution of the final stage to the overall cost of the battery pack will vary depending on the size (and purpose) of the battery – with it accounting for a higher share for PHEV, as illustrated in Figure 2.9, where the cell cost is only 30% of the total pack cost, compared to 60% for a 25kWh EV battery.

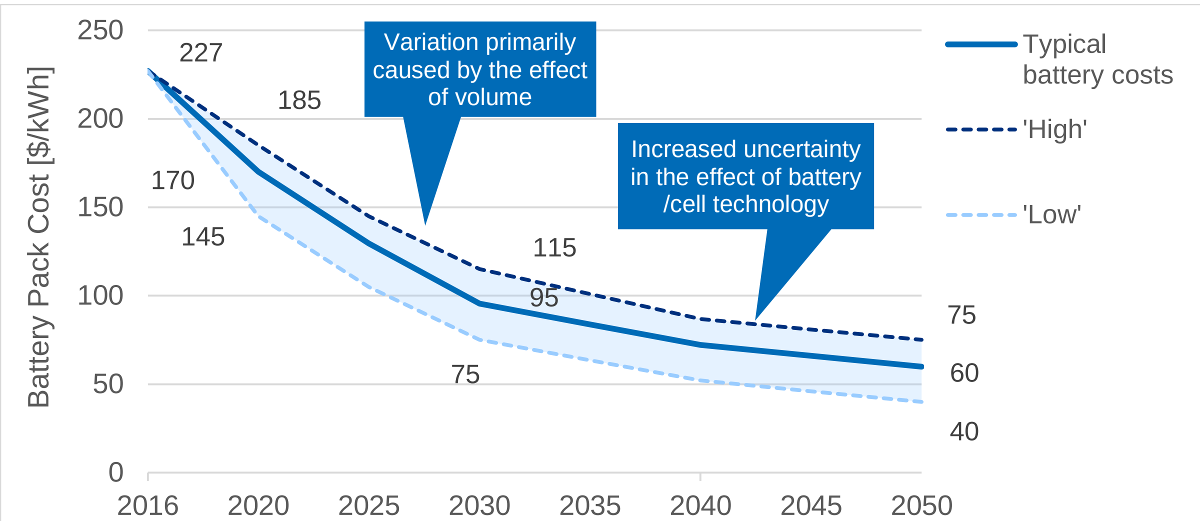
**Figure 2.9: Illustrative breakdown of the costs for EV and PHEV battery packs and cells**




*Source*: (Johnson Matthey, 2015)

The 2016 cost for EV battery packs reached ~$227/kWh in 2016 according to (McKinsey, 2017) and is projected to reduce to potentially below $100/kWh by 2030 (see Figure 2.10). Whilst the battery accounts for around half the overall cost of a BEV car currently, this share is expected to significantly reduce in the future (though to an extent offset by an increase in battery capacity / electric range).

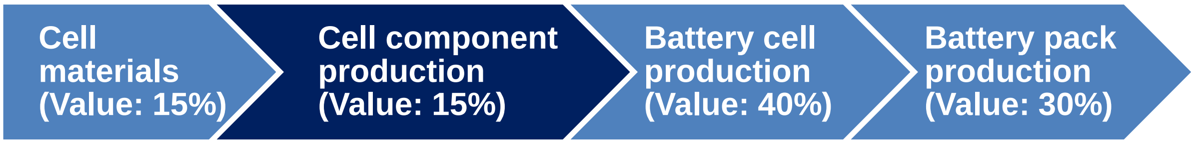
**Figure 2.10: Current and projected future costs of Li-ion battery packs for pure electric vehicles to 2030**




*Source*: 2016 cost from (McKinsey, 2017). Projections are Ricardo estimates based on a range of sources and client feedback.

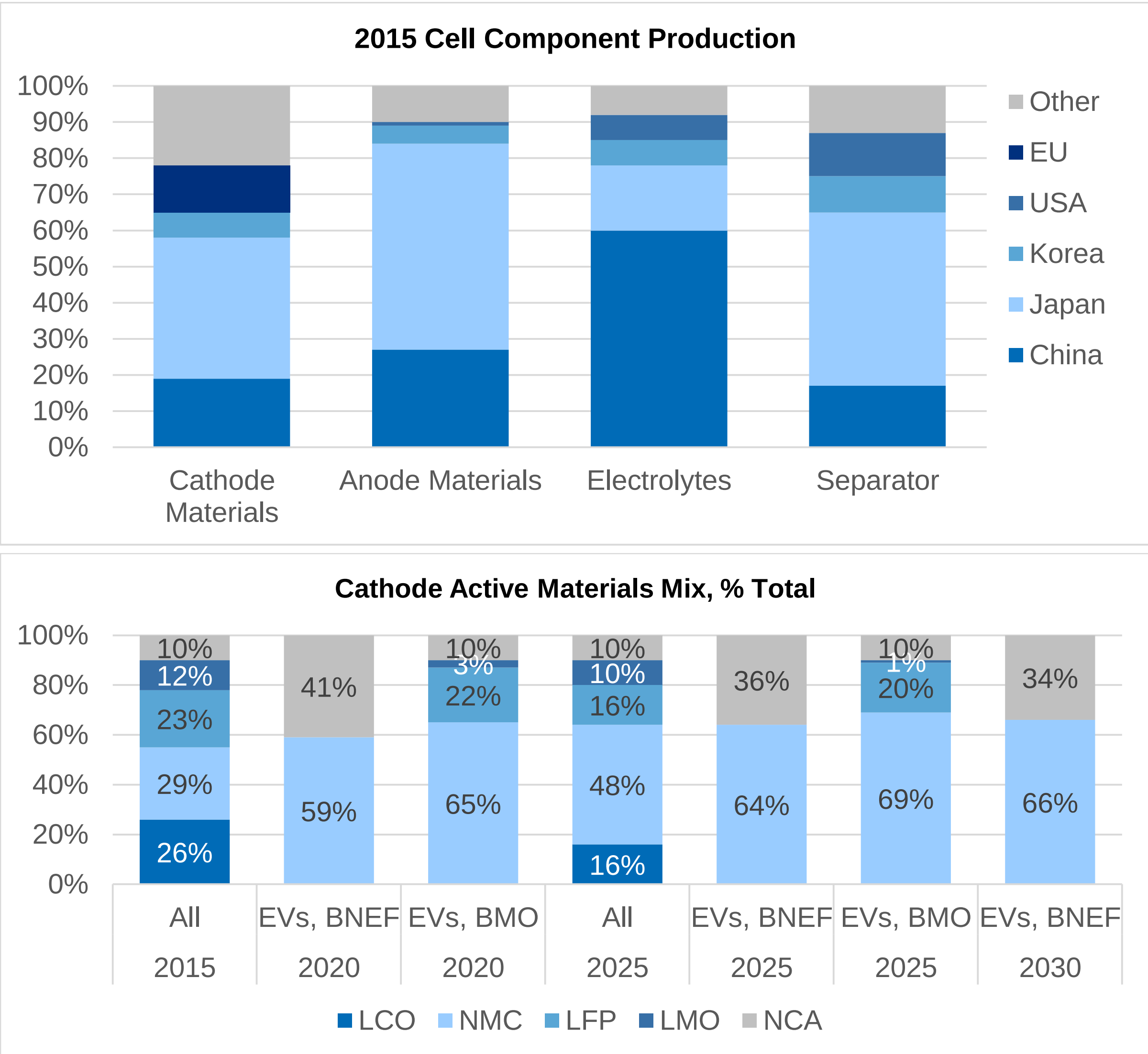
The following subsections provided an overview of the three battery manufacturing stages, with further details on the current and future technologies and processes provided in later Section 3.

### 2.3.1 Cell component production



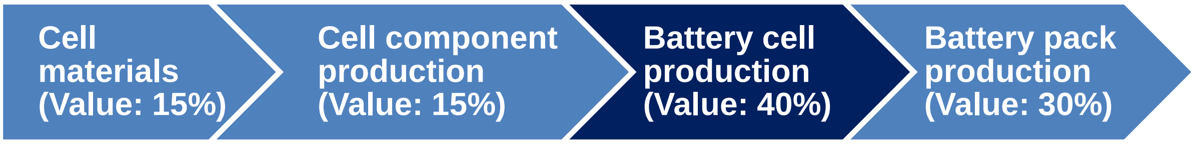

Revenues from Li-ion cell component industry were worth ~$7 billion globally in 2015 (JRC, 2017). The key/major cell components include the cathode (mentioned in the previous section), the anode (often a form of graphite), the separator, the electrolyte and current collectors (copper for the anode and aluminium for the cathode). Together, the anode and cathode account for around 54% of the cell cost (as indicated above in Figure 2.9). The separator is a critical component that represents a further 15-30% of the cell cost (versus <5% of the materials (TDDJ, 2016)); however, it is complex to manufacture. Cell component manufacturing is largely located outside of Europe, although Europe does perform some processing of the (likely imported) raw materials into cathode materials. There have also been recent announcements on the development of cell and cell component manufacturing in Europe, e.g. in Poland and Hungary and in Germany, Sweden (Electrive, 2018c) (European Commission, 2018). In addition, Europe does have electrolyte manufacturing capacity (around 15% of global capacity), although current utilisation of this is very low (1%) (JRC, 2017).

**Figure 2.11: 2015 cell component production globally, and projected future mix for cathode materials**




*Sources*: (JRC, 2017), (Alves Dias, Blagoeva, Pavel, & Arvanitidis, 2018). *Notes:* Specific market share for the EU is unknown, but small, for many components.

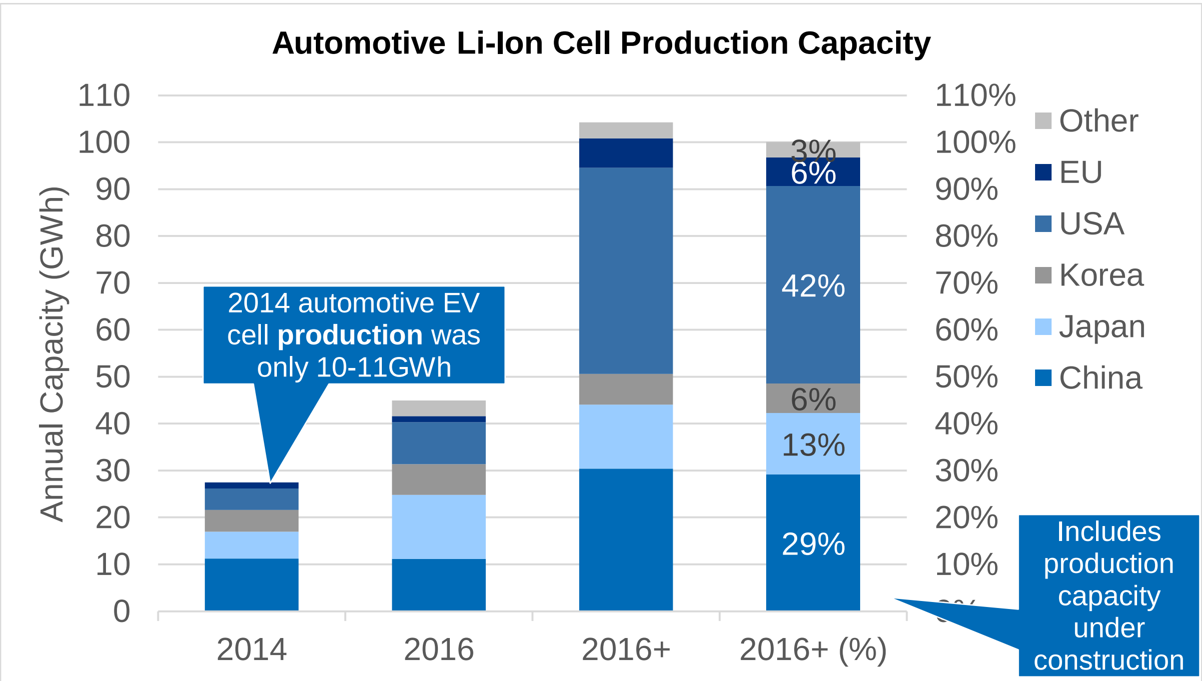
### 2.3.2 Battery cell manufacturing




Cell manufacturing accounts for the largest share of the battery pack value (Johnson Matthey, 2015) (JRC, 2017), at ~40% of the total (with Li-ion cell manufacturing revenues worth ~$16.7 billion globally in 2015, (JRC, 2017)). However, despite the high value, European cell manufacturing has been difficult: EV cell manufacturer Li-Tec (Daimler subsidiary and the only EV cell manufacturer in Germany) stopped production in 2015 due to high production costs. Currently there is global EV Li-Ion cell manufacturing over-capacity, with utilisation ranging from 10% (China) to 40% (Japan), which has discouraged investment in European EV Li-Ion cell manufacturing. Whilst other European companies, have investigated the potential to develop EV battery cell manufacturing capability, many such plans have either been abandoned (e.g. Bosch - (Reuters, 2018)), or re-focused on next generation battery chemistries. However, more recent forecasts suggest that additional global EV battery production capacity will be needed by 2020, and there are plans for new EU cell production facilities, such as CATL and BMZ in Germany, LG Chem in Poland, Samsung SDI in Hungary, and most recently Northvolt in Sweden (Electrive, 2018c). BYD is also reportedly considering setting up manufacturing facilities in Europe (Electrive, 2018b). The following Figure 2.12 summarises the current and near-term planned/under construction automotive Li-ion cell global production capacity by region (as of 2017); currently EU planned production capacity represents only 6% of the global total, though this could grow significantly if the most recent announcements on plans in the EU were to go ahead.

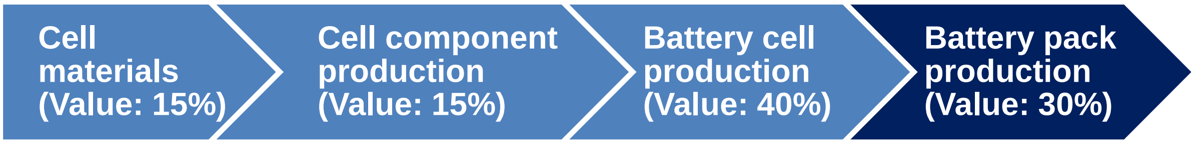
It should be noted that cell manufacturing is not always conducted at a single site. Due to difficulties transporting whole batteries, the manufacture of electrodes can be separated from the assembly of the cell (e.g. manufacturing of batteries for Nissan's EVs in Sunderland, UK). This allows for final cell manufacture at preferable locations which may not have substantial cell production capacity (Wu, 2018).

**Figure 2.12: Estimated automotive Li-ion cell production capacity by world region**




*Source*: (JRC, 2017)

### 2.3.3 Battery pack production

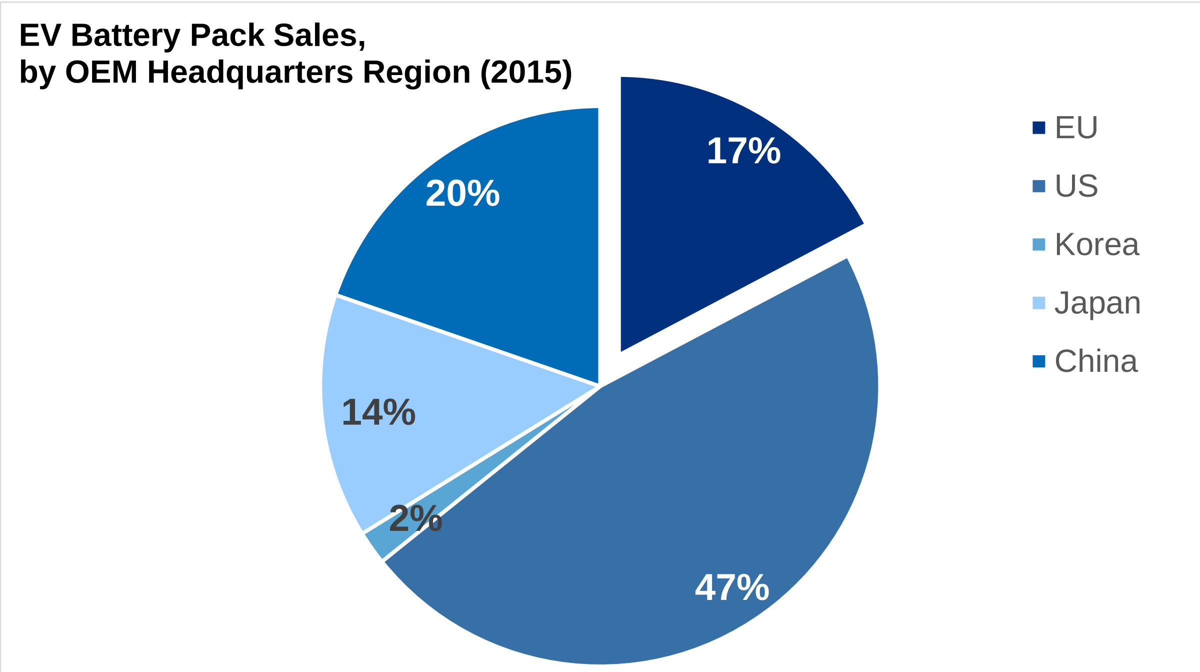



In this final stage of the battery manufacturing process, the battery management system (BMS, ~16% of the battery pack value) is assembled with the cells with the associated labour cost (~18% of pack value) – see earlier Figure 2.9 (Johnson Matthey, 2015).

After adding small additional costs (for logistics and other costs) this stage represents over 30% of the final battery value (Roland Berger, 2015) (with automotive battery pack manufacturing revenues worth ~$22 billion globally in 2015, (JRC, 2017)). To date, European OEMs have favoured outsourcing the cell manufacturing (possibly due to little European cell manufacturing activity), but have retained the battery pack design and manufacturing in-house. In contrast, Asian OEMs (and Tesla) have cell manufacturing either in-house or through joint ventures in addition to the battery pack assembly. General Motors in the US currently outsources all cell and battery pack manufacturing to LG Chem. However, according to the European Battery Directive (EU, 2006), responsibility for the battery at the end of the vehicle's life remains with the OEM as it is the one putting the battery on the market.

Figure 2.13 provides an overview of EV battery pack sales by OEM headquarters region.

**Figure 2.13: EV battery pack sales by OEM headquarters region for 2015**



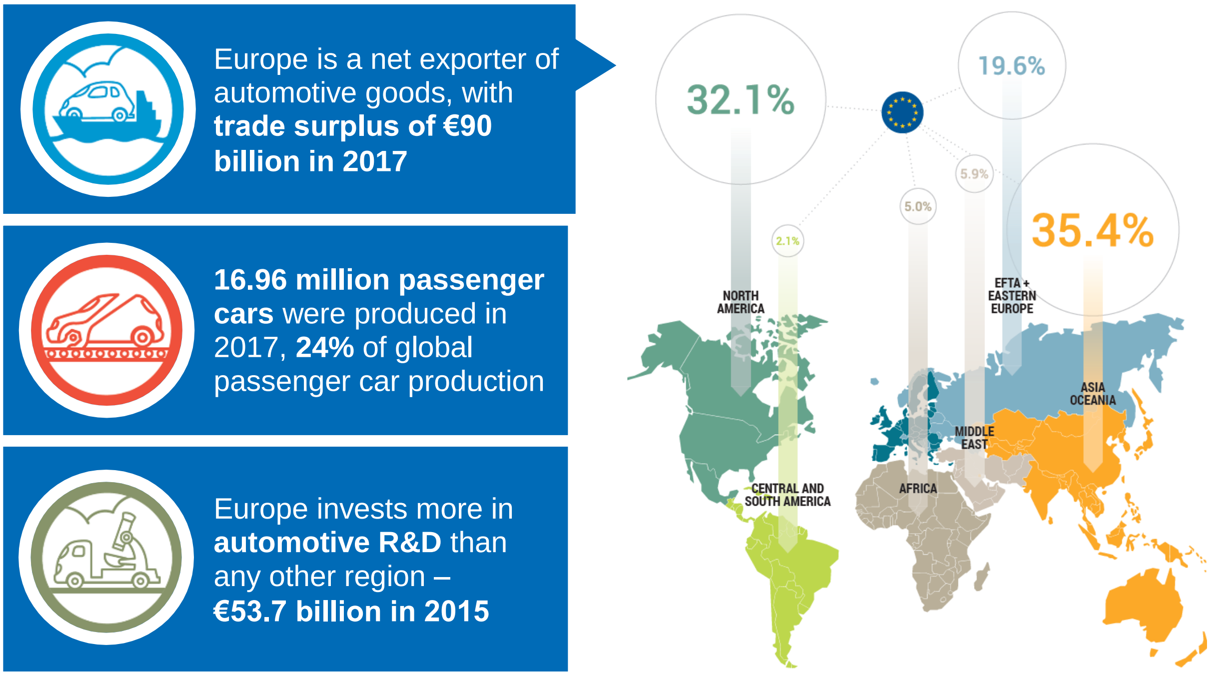

*Source*: (JRC, 2017)

## 2.4 EV manufacturing

Figure 2.14 shows some key statistics for the European automotive market, from (ACEA, 2018). The European automotive manufacturing industry employs around 2.5 million people in direct manufacturing and 0.8 million in indirect manufacturing, which overall represents 1.5% of all EU jobs. A third of the value of the automotive supply chain is related to the powertrain, and Europe produces approximately 25% of global light vehicle engines and gearboxes with an estimated value of €65-70bn. (ING, 2017) (ACEA, 2018).

The manufacturing capacity of OEMs Tier 1 and Tier 2 supply chain is generally globally distributed, since their production plants for parts are normally located in the proximity of OEM's vehicle assembling plants, which are also distributed around the globe.

**Figure 2.14: Key statistics on the European automotive market for 2017**



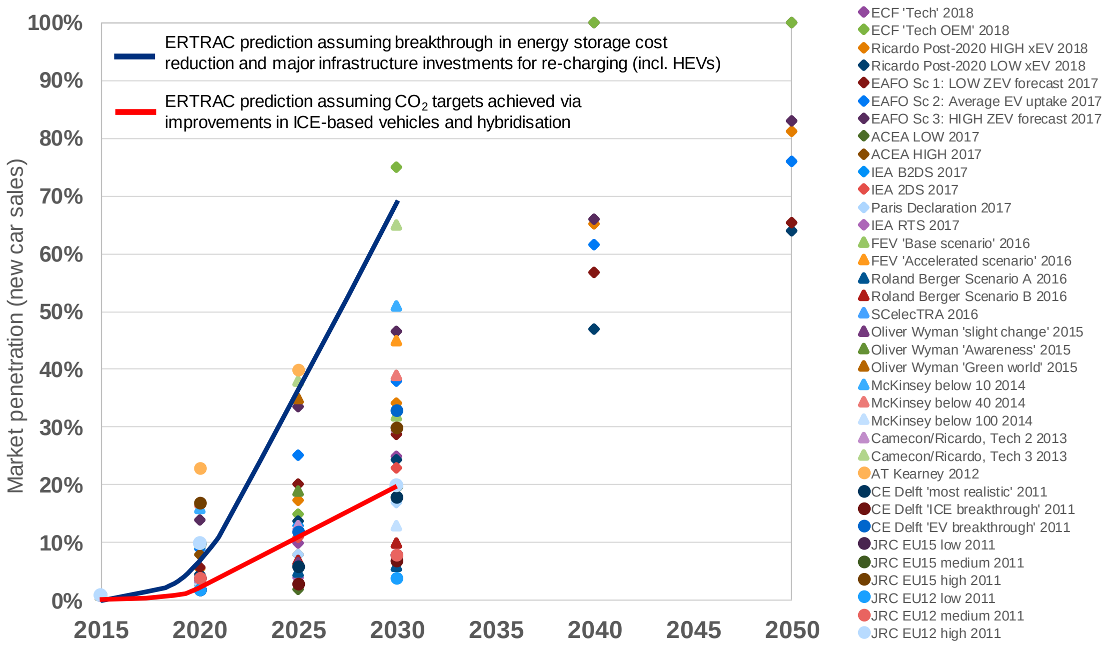

*Source*: (ACEA, 2018)

Moving towards EVs will affect the value chain significantly.  For example, the battery pack is a significant proportion of the value in an EV; however, the current European share of the automotive battery pack value chain relatively low – as summarised on the previous sections.

Currently the battery system for a pure electric (BEV) passenger car accounts for around half or more of the total cost of the vehicle; it is a significantly lower share for PHEVs. In future years this share is likely to reduce substantially for PHEVs, but to a lesser extent for BEVs, being offset by an increase in battery capacity (in kWh) to increase range/utility.

New vehicle sales projections from the literature for xEVs in the light duty vehicle sector (i.e. cars and vans) by 2030 and 2050 vary significantly depending on underlying assumptions, as illustrated in Figure 2.15.

**Figure 2.15: Projections, forecasts and scenarios for xEV new vehicles sales 2020 – 2050 form the literature**




*Source*: European Road Transport Research Advisory Council (ERTRAC), Ricardo analysis

Corresponding expectations for uptake of xEVs for heavy duty applications are generally much lower, with the exception of urban buses. New heavy truck models are only now being introduced into the market place, being focused mainly on smaller trucks for urban distribution applications. Even though the batteries used by these vehicles are several times the size of those used in LDVs, the number of new registrations are several orders of magnitude lower than those for passenger cars in the EU. Therefore, it seems likely they would only contribute to a relatively very small share of kWh battery demand by 2030. This will be further evaluated in the analysis for Task 2.4 (Chapter 5).

There is also a rapidly growing market for eBikes in Europe; however the battery pack capacities for typical eBikes (at ~300-500 Wh) (ebiketips, 2016) are over two orders of magnitude smaller than the sizes of the packs in the most recent passenger car models (e.g. 40 kWh in the new Nissan Leaf). In comparison, the relative sales of xEVs (including PHEVs) were already approaching 300,000 for EU+EFTA countries in 2017 (Car Sales Statistics, 2018), compared to sales of eBikes in Europe, which were ~1.67 million in 2016 (Pedelecs, 2017). However, the eBike market share of all bike sales is already very high in some countries (e.g. almost 20% in Germany in 2017), compared to only 1.4% for EU new car sales of xEVs.

## 2.5 Battery re-use (original purpose)

The definitions of reuse, remanufacturing, repurposing and second-use/life in literature and legislation are not always consistent (Ardente, Peiró, Mathieux, & Polverini, 2018). For the purposes of this report, the following definitions will apply:

**Re-use:** meaning the complete or partial re-use of the battery for the original purpose the battery was designed for, possibly after remanufacturing / refurbishment / reconditioning / repair (see below).

**Re-purposing**: (interchangeable with “second-use”) meaning the complete or partial re-use of the battery for a different purpose/application than the battery was originally designed for. This will require an element of remanufacture also.

**Re-manufacturing /refurbishment /reconditioning /repair:** this range of processes are all different stages of getting batteries ready for either re-use (in original purpose) or re-purposing for second use (i.e. a different application). Some or all of these different stages may be applied depending on the situation. Distinctions between these concepts relate mostly to the ownership change, level of performance, guarantees and services for the reprocessed product vs a new product.

### 2.5.1 Overview


Re-use of an electric vehicle battery is where a battery, which has been designed for electric vehicle use, and which has already been used for this purpose, is then used again as a battery for an electric vehicle. Re-use is an optional step that may occur after a simple inspection or after more intensive refurbishment / reconditioning / remanufacture / repair depending on the condition of the battery and the amount of work needed to make sure it is once again fit for its original purpose.

Theoretically, re-use is preferable to re-purposing as it should be less energy and resource intensive to make the battery fit again for the same purpose, compared with the effort and time required to remanufacture it for an alternative purpose. As a result, it should also be more economical to re-use rather than repurpose. Re-use should also be preferable to occur before recycling for the same reasons (the final end-of-life fate should always ideally be recycling), as well as being higher up the waste hierarchy. There are however, a number of challenges associated with re-use which impact on its feasibility in general, and in comparison to recycling. These issues will be covered in more detail in section 2.5.3.

Additional details on the techniques used in battery reuse, repurposing/second life and recycling are also provided in later Section 3.3.

### 2.5.2 Re-use opportunity and costs

#### 2.5.2.1 Scale of the opportunity

Several different studies have estimated the scale of the opportunity in relation to the numbers of post-consumer electric vehicle EV batteries expected, their expected residual capacity and their monetary value. Some are summarised below.

**Table 2.2: Information from the literature on the potential availability and value of used EV batteries**

| Source | Number | Capacity | Monetary value |
|---|---|---|---|
| (Elkind, 2014) | 50% of 2014 “on the road” can be repurposed. | 75% of original capacity.<br>Up to 850 MWh could be stored and dispatched.<br>Aggregated capacity: 425 MW | Used 24 kWh Nissan LEAF battery resale value: up to $2,400 resale value<br>Used 85 kWh Tesla Model S battery resale value: up to $8,500.<br>Research by Society of Automotive Engineers (SAE) International estimated battery resale value at $20-$100/kWh |
| (Foster, Isely, Standridge, & Hasan, 2014) | >3,000,000 Li-ion batteries expected annually for remanufacturing, recycling and repurposing 2029-2032.<br>50% of new vehicle demand between 2020-2033. | | Re-use (remanufacturing): feasible and saves 40% over new battery cost<br>Re-purposing, feasible if:<br>R&D <$82.65/kWh - (for upper bound sales) price of $150.00 per kWh.<br>R&D $50/kWh -<br>lowest economic sale price - $114.05/kWh |
| (Reid & Julve, 2016) | | 1M new EVs = 25G Wh of storage | |
| (Kampker, et | | 70-80% residual | A battery for re-use can be produced |

| Source | Number | Capacity | Monetary value |
|---|---|---|---|
| al., 2016) | | value | for around 60% of the initial cost of a new battery.<br>Total benefit of 60,26 €/kWh can be achieved by remanufacturing. |

#### 2.5.2.2 Process

The process for re-use of EV batteries includes several distinct stages, each of which will have its own associated costs and challenges. More detail will be provided in Section 3.3.1 on specific techniques and more complex technical approaches; however, at a high-level, re-use will involve:

- Collection / return to reconditioning facility
- Storage
- Measuring and grading
- Repairing/refurbishing/reconditioning/remanufacturing [where required]
- Inspection
- Re-packaging and delivery

The research conducted has not revealed the costs of these individual steps or indeed the overall costs involved; however, from the table above, it can be reasonably concluded that re-use could be an economically feasible solution. According to (Bobba, et al., 2018) and (Bobba, Mathieux, & Blengini, 2019), the size of the available flows of EV batteries will be an important aspect for the development of a business case related to reuse of batteries. Several challenges are still to be faced and, despite there is an increasing interest in reusing batteries and stakeholders have highlighted the *"potential relevance of governmental incentives on battery reuse"*. The economic viability does also depend on the level of repairing / refurbishing / reconditioning / remanufacturing (if any) which may be required, and this will vary from battery pack to battery pack depending on the specific state of health. This highlights the importance of the measuring and grading step to determine whether or not it is economically (or practically) feasible to prepare the battery for re-use, prepare it for re-purposing or to move it straight to recycling. Sorting cells based on chemistries is becoming an increasing challenge with the diversity of chemistries.

Feedback from the stakeholder interviews suggested that the costs for reuse or repurposing were well below 25% of the cost for production of a new battery. However, this is highly dependent on work flows and other aspects, such as cell capacities: it may not be economical with smaller cells that each require grading but gets more economical with larger capacity cells. For battery reuse the costs are mainly related to the battery collection, and sorting/grading steps; there are additional costs for repurposing as further remanufacturing and packaging steps are necessary. Currently battery pack producers' have to pay a waste treatment plant operator a cost of disposal per kg of battery.

### 2.5.3 Potential benefits, barriers and uncertainties

#### 2.5.3.1 Benefits

Re-using EV batteries offers potential environmental and economic benefits, however even though some studies proved that there are environmental and economic benefits, the sustainability of reusing batteries should still be proved (European Commission, 2017c). For manufacturers, re-use could allow for the residual capacity of EV batteries to be harnessed at a relatively low cost (compared with the manufacturing cost associated with a new battery). By extending the life of components such as cells, housing, cables and electronics (Kampker, et al., 2016), manufacturers reduce the need for new inputs. Not only does this lower the costs of manufacturing, it also improves resource efficiency, reducing the need for primary resources with also a corresponding environmental benefit from pollution reduction (Ramoni & Zhang, 2013). This is also particularly relevant that CRMs (critical raw materials) are embedded in traction battery chemistries (Bobba, Mathieux, & Blengini, 2019). A recent scientific paper confirms and quantifies, through an adapted Life Cycle Assessment method, the environmental benefits of extending an EV battery's lifetime through repurposing and implementing it in a second-use application (Bobba, 2018). These benefits of course are highly dependent on the cases (e.g. chemistry, scenario of re-purposing, life cycle impact category considered). Moreover, although large scale development of re-purposing of EV batteries might intuitively increase the resource efficiency of the use of raw materials, it should not be forgotten that it will also imply a delay in the availability of secondary raw materials: a recent scientific paper (Bobba, Mathieux, & Blengini, 2019) quantifies this delay for various deployment scenarios for raw materials such as Lithium and Cobalt.

For consumers, there are also potential economic benefits. Widespread re-use offers the opportunity for EV owners to recoup some of the initial investment in their vehicle by selling the battery back to the car manufacturer. It could also reduce the potential battery replacement costs (in cases where this is needed) by allowing owners to purchase re-used batteries rather than new ones, at a lower price.

> *"Lower upfront prices from…future revenue mean[s] greater adoption of these vehicle technologies that can dramatically reduce air pollution and save consumers money over the life of the vehicles".* (Elkind, 2014)

Kamper et al. note that "*demand for remanufacturing is likely to increase given the expected rise in the number of EV batteries and high resource prices coupled with limited availability of key resources such as lithium, cobalt and other rare earth metals*." (Kampker, et al., 2016). The potential increase in European demand for EV batteries and materials used in them is explored further in Section 5.

#### 2.5.3.2 Issues and barriers

While there are clearly a number of potential benefits to re-using electric vehicle EV batteries, there are also a number of barriers that need to be addressed in order for this to become a more widely accepted practice. In fact, Kampker et al. concluded that the economic success of re-manufacturing hinges on successfully overcoming the challenges however "*entry barriers and regulatory boundaries exceed the achievable profits thus far*" (Kampker, et al., 2016).

Key barriers cover health & safety concerns, regulation, technical challenges and perceptions of re-used products. For example, due to the potential for reputational damage, there is a risk that there may be reluctance from EV manufacturers to let others use their batteries for 2$^{nd}$ life applications. A summary of the other principle barriers identified in the literature review and stakeholder interviews are below.

<u>Health & Safety barriers</u>

In terms of health and safety, there are several risks associated with refurbishing (and therefore both re-use and re-purposing). The Commission for Environmental Cooperation notes that refurbishment is "not considered practical" and "is too dangerous" due to the flammable and explosive nature of the active material as well as the toxicity of the gaseous emissions in such an event, and because the batteries are capable of discharging in excess of 200 volts – "*sufficient to seriously injure or kill a worker who is not trained on proper procedures*" (CEC, 2015). (Kampker, et al., 2016) also concur with this, indicating that high voltage, explosion risks and electrolyte fumes are only a few hazards in disassembling a battery pack.

It is possible that some health & safety issues could be overcome through improvements in the initial battery design and manufacturing process. An example of where this is currently happening is provided by Wuttke: "*batteries [for the electrified Mercedes models] are also designed such that they can be opened easily in an expert manner and the components can be replaced easily and without any risks… When a battery cannot be repaired because a certain element is not replaceable, this leads to unnecessary and above all costly waste… In this way, costs are reduced for customers while at the same time helping to protect the environment*" (Wuttke, n.d.). In addition, moving and storing a used battery also becomes a major issue where repair is not possible locally. According to (Bobba, et al., 2018) implementation of solutions are starting to be developed, e.g. Van Peperzeel (Lelystad - The Netherlands). However, there is also currently no standardisation on battery packs at the moment making it even more difficult to do this.

<u>Regulatory barriers</u>

The lack of a clear regulatory position regarding re-used electric vehicle batteries, also presents a challenge. This lack of regulation was highlighted by RECHARGE: "*There are no standards or regulations pertaining to battery re-use currently in place world-wide"* (Tytgat & Tomboy, 2017)*; and both* (Chmura, 2016) *and* (Gattiglio, 2017) *both note that there are currently no standards specific to used automotive Li-ion cells in existence. Industry however recognises need for standardization*"

RECHARGE go further, noting that in order for re-use to be successful regulations will be essential to deliver reliable and durable re-used batteries. However, they also state that this is likely to prove challenging given that so many factors can impact on state of health (which in turn affects consistency of performance) and that these can only be controlled by the user (Tytgat & Tomboy, 2017).

As a result of the health & safety, technical and regulatory challenges, RECHARGE prepared a set of recommendations with regards to the minimum requirements for consideration of re-use and second life of batteries. A slightly updated set of recommendations has also been provided more recently by RECHARGE, as summarised below in Table 2.3. The accompanying text from RECHARGE states:

"*When the minimum requirements listed are fulfilled, RECHARGE supports the re-use of batteries for their original applications. This requires that quality, performances and safety standards are observed before placing the battery for a second time on the market*" (Tytgat & Tomboy, 2017).

In the same report, RECHARGE also set out the re-use concepts and recommendations from the Battery Association of Japan. The associated table of recommendations from the Battery Association of Japan (BAJ) is also shown in Table 2.4 below, which limits re-use to a specific set of circumstances and does not allow for any re-purposing. The concepts are as follows (Tytgat & Tomboy, 2017):

1) Ensuring the personal safety,
2) Recycling and effectively using resources,
3) Reducing business risks of the entities related to lithium-ion secondary batteries and developing their businesses.

Some manufacturers also show caution, with Ford having indicated in a 2014 presentation that their approach is to 'de-energize' (i.e. discharge) used batteries with no re-use then allowed (according to their internal processes). Instead these units are then sent for recycling (Tytgat & Tomboy, 2017).

**Table 2.3: Non-exhaustive list of minimum requirements to be considered for allowing re-use or second life of batteries (RECHARGE)**

| | | **Re-use: Same purpose in same application** | **Second life: Different purpose or different application** |
|---|---|---|---|
| **Safety and performance** | **Product** | Refurbishment /remanufacturing by qualified professional | Re-purposing/ remanufacturing by qualified professional |
| | | Quality control of the product for similar quality, safety and performance as the new product. | Quality control of the product for minimum quality, safety and performance |
| | | | Validation of the safety and performance compatibility between first use and second life (particularly through access to the data of the Battery management System of the first use). |
| | | | Qualification as a new product according the applicable legislation, particularly UN transport tests. |
| **Producer responsibility** | **Market operations** | In case of operation by a new producer, identification of endorsement of the producer responsibilities and liabilities (including warranty) | Placing on the market declaration of the producer for the second purpose and endorsement of the producer responsibilities and liabilities (including warranty) |
| **Extended producer responsibility** | **After market operations** | First EPR applicable | New EPR applicable, endorsed by the new producer |

*Source*: (RECHARGE, 2018a)

**Table 2.4: Battery Association of Japan recommended concepts of reuse**

| | **Consumer or Industrial use** | |
|---|---|---|
| | **Authorized use** *(A battery can have more than one application from the beginning.)* | **Unauthorized use** *(Application not intended initially)* |
| Battery system or assembly (e.g. battery pack or module with a special protective function) | **Permitted (Case 1)** | **Prohibited (Case 3)** |
| Single battery (e.g. cell with a special protective function removed) | **Prohibited (Case 2)** | **Prohibited (Case 4)** |

*Source*: (RECHARGE, 2014), (RECHARGE, 2018a).

In the stakeholder consultation, regulatory uncertainties regarding the classification of batteries at the end of first life in EU and national legislation were also highlighted - in particular, the unclear definitions of '*re-use'* and '*same purpose'*. It was suggested that these need to be more clearly specified in order to promote the re-use of first life batteries. Additionally, if the battery pack is classified as '*waste'* at the end of the first life, then this has implications on its handling and treatment and may prevent re-use.

A further regulatory concern raised in the stakeholder consultation was the differences in member state interpretations of the EU Waste Framework Directive. In this, it is stated that for the waste status to be removed for a battery it should meet '*all current standards and regulations',* however, the understanding and implementation of this varies between member states.

#### 2.5.3.3 Uncertainties

In addition to benefits and barriers, there are two main uncertainties in relation to the feasibility of re-use: obsolescence and quality & quantity of batteries available for re-use.

<u>Obsolescence</u>

New battery chemistries are being developed which may well overtake lithium-ion as the primary choice of battery for electric vehicles in the future - particularly if they prove to be less hazardous and with greater capacity. This could result in the current generation of lithium-ion batteries being unfit for re-use simply because technology has moved on. However, there are potential opportunities as a result of new research and development in this area: *"due to an elaborate design for remanufacturing, which takes all requirements into consideration, for example by modular interfaces and replaceable components, the barrier of a disruptive character of the technology can be overcome"* (Kampker, et al., 2016). In addition, it may take a long time for new advanced chemistries to fully enter the market; this typically takes at least 10 years for a new chemistry (Wu, 2018). What will be important will be to develop flexible battery management systems that can handle different cell chemistries (Podias, et al., 2018).

<u>Quality & quantity</u>

As briefly noted during the discussion of regulatory barriers, battery *"state of health" (*SOH*)* has a considerable impact on the reusability. The SOH is impacted by a great number of factors however, this is ultimately in the control of the user and is therefore not something that the manufacturer can influence or understand before the used battery is returned to them. As noted by Ford: *"It is…quite important in the decision-making process for possible further re-use or second use to know the exact history of the battery. Only with professional diagnostic equipment used by experts who have the knowledge on how the get the history out of the battery management system BMS can that advice or decision be taken"* (Ford analytics, 2017). RECHARGE raised a similar concern, stating *"Battery re-use post-mobility represents a wide gap that will be challenging to govern given the highly variable nature of battery wear and inherent differences in chemistry, construction, and power management".*

Feedback from the stakeholder interviews indicated that information from grading needs to consider aging / stress in the first life influencing in some respect failure rate and safety; the currently available SOH metric (i.e. state of health = remaining capacity versus original capacity when new) is insufficient to provide an accurate assessment, and further information from battery usage/charging history is needed to make a better assessment. However, the differences between warranties and life cycles across EV batteries used for different vehicles will add to the complexities in trying to establish a standardised approach.

Accordingly, as well as concerns about general state of health, it is also possible that initial owners of these batteries may use them well below the 80-70% capacity which is widely recommended as being the time when an EV should have its battery replaced (Tytgat & Tomboy, 2017). This may reduce the number of batteries that become available, and may also mean that a higher number will need to be recycled rather than re-used or indeed, repurposed. However, this is dependent on the intended use case of the second life batteries – some use cases may still find value in a battery with substantial capacity loss.

(Kampker, et al., 2016) summarise: *"The uncertainties in quality, time and quantity of the returns are a great challenge for a successful remanufacturing business model"*.

A key enabler for reuse and repurposing would be sharing of (standardised) battery management system (BMS) data, to improve economics in the assessment/grading step.

### 2.5.4 Activity

At present, there are a limited number of post-consumer EV batteries available. If it is assumed that the first-life period lasts for 7-10 years, we can expect the number of post-consumer batteries to become increasingly significant from around 2020 (Tytgat & Tomboy, 2017). (Foster, Isely, Standridge, & Hasan, 2014) state that *"The number of lithium-ion batteries becoming available annually for remanufacturing, recycling and repurposing is likely to exceed 3,000,000 between 2029 and 2032 as well as reaching 50% of new vehicle demand between 2020 and 2033. Thus, a sufficient number of batteries will be available."*

Given the number of batteries which are likely to become available and the fact that around 70-80% of capacity remains, re-use has significant potential: depending on the previous use of the battery, some cells/modules from these batteries may be replaced to bring them up to acceptable performance again, or others may be remanufactured also for reuse in an EV. As a result, a number of car manufacturers, academics and governmental organisations have been carrying out research into re-use and trialling potential re-use schemes with some of these now having been commercialised on a large scale.

**Renault**

Renault offer a battery leasing scheme for their ZOE models to customers: the *"Z. E. flex battery hire agreement"* (Renault, 2018). Under this arrangement, customers purchase the vehicle but lease the battery, with the price per month linked to annual mileage. RECHARGE (Tytgat & Tomboy, 2017) explains that the system allows the manufacturer to retain ownership of the battery and therefore control the value chain, including decisions about whether to repair or replace the batteries and, if replaced, whether a used battery should then be re-used, re-purposed or recycled.

**Nissan**

In 2018, Nissan and 4R Energy Corp (a joint venture with Sumitomo Corporation), launched a battery re-use programme for its LEAF models in Japan whereby old batteries can be replaced either by new or re-used battery packs (available at a discounted price compared to new ones). Once removed, the old packs are sent to a remanufacturing facility in Namie where they are disassembled. The state of health of all 48 modules is assessed, with any that have lost 20% or more of their capacity then replaced (Clean Technica, 2018). The packs are then re-combined (as necessary), re-packaged and then sold for re-use (Yoshida, 2018).

(Electrek, 2018) reported that a reused battery pack will cost $2,850 (USD) compared with $6,200 (USD) for 24 kWh, $7,600 (USD) for 30kWh, and $7,800 (USD) for 40kWh for new packs

**ACCUmotive (subsidiary of Daimler)**

Daimler have been designing their EV batteries with a view to remanufacturing which is carried out through their subsidiary ACCUmotive. Their website states that: *"decommissioned energy accumulators can…remain in use after being duly examined. With so-called remanufacturing, the battery continues to be used after replacing defective components."* (Wuttke, n.d.).

# 2.6 Battery re-purposing and second use

## 2.6.1 Overview


Re-purposing is another potential option for used EV batteries, particularly where re-use may not be feasible but where enough residual capacity (and value) remains for a second-use to be appropriate. This will also depend on the State-of-Health (SOH) of the battery which, if it is too poor, it may mean that the only suitable option is to recycle. (Reid & Julve, 2016) note that *"As batteries from the first electric cars reach their useful life automotive companies will be confronted with the decision to recycle or find them another use. One alternative to recycling those batteries is to recondition them and reuse them in less strenuous applications such as stationary applications"*.

Additional details on the techniques used in battery reuse, repurposing/second life and recycling are also provided in later Section 3.3. In addition, EC JRC has also recently published its own sustainability assessment of second life application of automotive batteries (SASLAB) (Bobba, et al., 2018).

## 2.6.2 Possible applications, market size and costs for repurposed EV batteries

There are a significant number of current and potential future applications / use cases for batteries that have been identified in the literature. Figure 2.16 provides a useful illustration of these, with further information provided in Table 2.5.

In terms of the scale of the opportunity for repurposing of EV batteries, much of the information provided in section 2.5.2.1 is applicable to re-purposing as well as re-use.

It is anticipated that energy storage will significantly increase over the next ten years as highlighted in Figure 2.17. Bloomberg has also concluded that the global energy storage market will rise to 125 GW / 304 GWh by 2030, essentially doubling 6 times between 2016-2030, with around 35 GWh of this in the UK and Germany (the two largest European markets) (BNEF, 2017), see Figure 2.18. Scenarios from (IRENA, 2017) suggested a potentially even larger potential for battery energy storage by 2030, as high as 421 GWh.

In addition, the following economic figures in Table 2.6, have been identified for the potential market capacity and value for repurposed battery energy storage from a range of sources. The potential cost/price of such repurposed batteries should also be compared with future projections in new battery costs (see earlier Figure 2.10), which illustrates the potential risk that repurposed batteries may struggle to compete on a purely economic basis with new batteries should the costs of the latter continue to decline rapidly.

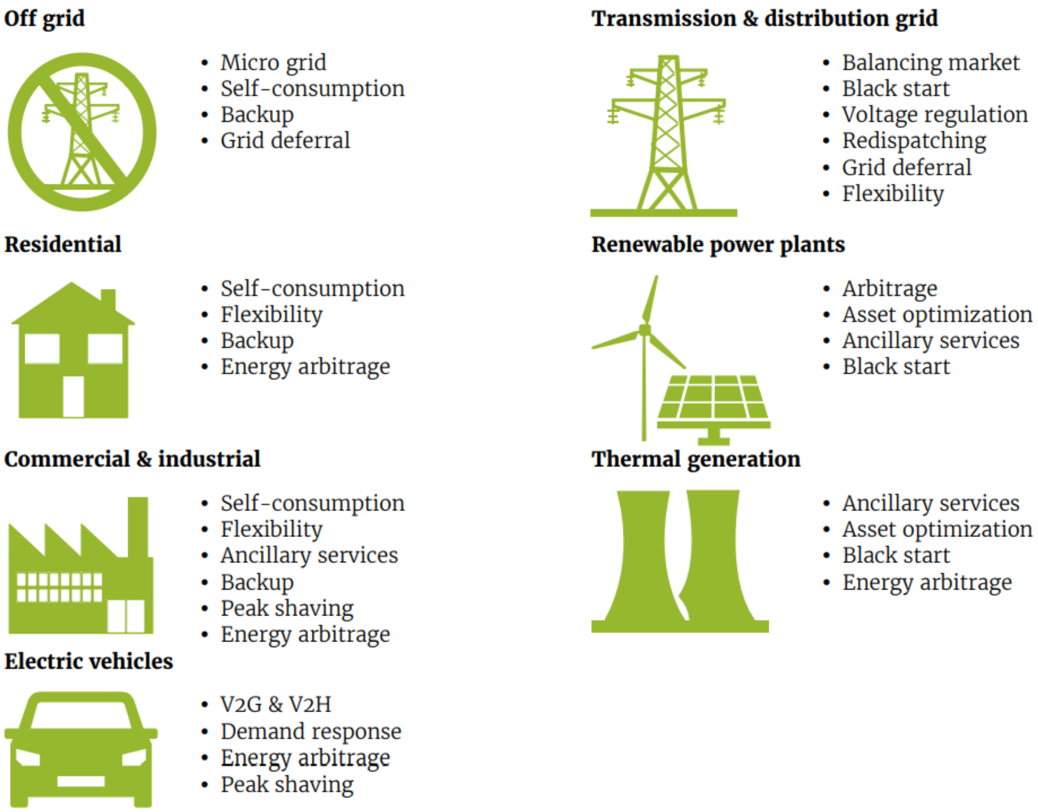
It is possible that much of this demand for energy storage may be met by second life batteries from the EV market. One stakeholder consulted during the project suggested that *'a significant share'* of the batteries reaching end of life within a vehicle would be suitable and could be used for repurposing. However, it was highlighted that the proportion of batteries which may be available for this use at end of life depends to a great extent on the ownership and usage case during first life. For example, if an EV owners owns their battery and uses it until it has reached an unacceptable SOH, it may not be suitable for re-purposing. However, if the battery is leased, and will be replaced at 80-90% SOH, then this could much more easily be re-purposed.

This feedback also appears to be supported by analysis from NREL (National Renewable Energy Laboratory – USA): they expect most batteries to become available for second use at the end of the expected EV service life of ~15 years:

*"NREL studies show that these batteries can retain as much as 70% of their initial capacity and potentially continue to operate for another 10 years in second use as energy storage for utilities—translating into a total service life of up to 25 years."* (RECHARGE, 2018a).

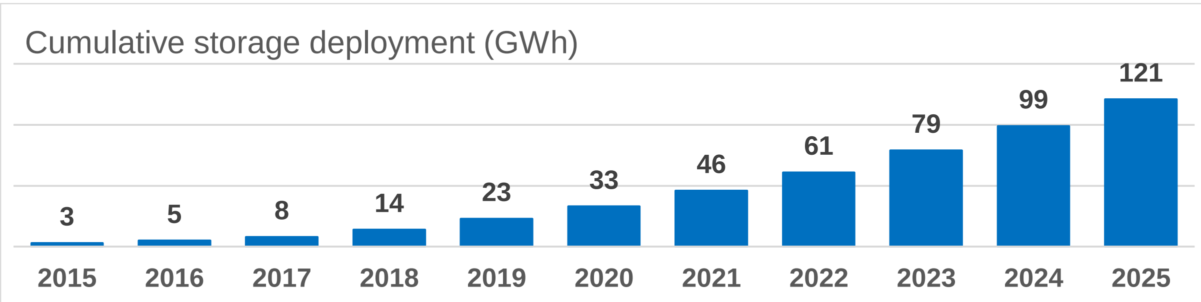
Analysis by NREL also showed that regional repurposing facilities specializing in a single model of BEV could potentially harvest and retrofit Li-ion batteries for second use at less than $500 for today's typical BEV battery, while avoiding transportation expenses associated with nationwide battery collection.

**Figure 2.16: Overview of potential battery use cases**




*Source*: (Reid & Julve, 2016)

**Figure 2.17: Projected increase in global energy storage up to 2025 according to Ørsted**




*Source*: (Ørsted, 2018). Notes: Cumulative deployment includes batteries, flywheels and compressed air solutions, with Li-ion batteries comprising 82% of the total global deployment.

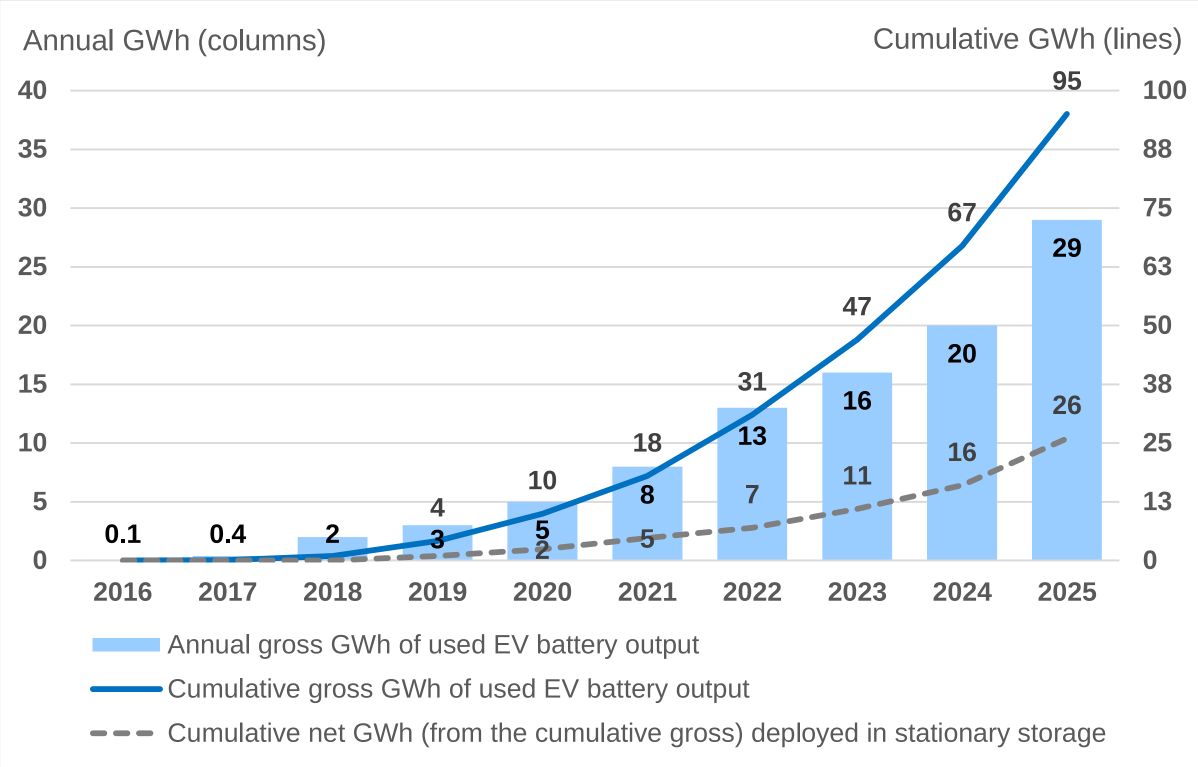
**Table 2.5: Possible second life battery use cases identified in the literature**

| Area | Use | Commentary |
|---|---|---|
| Off grid | Micro grid<br>Self-consumption<br>Back-up<br>Grid deferral | There is potential for post-consumer EVs to be used to provide a solar and battery (PVS) energy solution for areas currently “off-grid” without the need for extensive infrastructure (Reid & Julve, 2016). |

| Area | Use | Commentary |
|---|---|---|
| Residential | Self-consumption<br>Flexibility<br>Back-up<br>Energy arbitrage | • Used EV batteries could be put to use in combination with solar panels, providing a back-up solution if required (Elkind, 2014)<br>• They also provide an opportunity to store excess energy produced by PV for later use. This has the benefit of "increasing self-consumption rate up to 60-70% with payback today of 10 years in Southern Germany" (Reid & Julve, 2016).<br>• These could be installed by home-owners retrospectively or during development for a fully integrated home renewable energy system (Elkind, 2014). |
| Commercial & industrial | Self-consumption<br>Flexibility<br>Ancillary services<br>Back-up<br>Peak shaving<br>Energy arbitrage | According to (Reid & Julve, 2016), one in six industrial users in Germany has already onsite power generation. Therefore, adoption of batteries should help German companies to reduce their energy costs through peak shaving, price arbitrage as well as providing backup power. |
| Electric vehicles | V2G & V2H<br>Demand response<br>Energy arbitrage<br>Peak shaving | • One area where EV batteries could "revolutionize the energy sector" is through smart grid technology whereby electric vehicles charge at night (using excess renewable energy) thereby turning them into mobile energy storage units (Reid & Julve, 2016).<br>• Another area for development is vehicle to grid. As RECHARGE state: "infrastructure is not yet ready for the power feed-in of a large number of electric vehicles – the grid's limited transmission capacity would be overstretched." (Tytgat & Tomboy, 2017).<br>• There are current barriers however which will need to be addressed in order for V2G to be introduced (Tytgat & Tomboy, 2017):<br>  o Distribution systems will require two-way inverters to be installed.<br>  o Clear regulatory framework is also necessary. |
| Transmission & distribution grid | Balancing market<br>Black start<br>Voltage regulation<br>Re-dispatching<br>Grid referral<br>Flexibility | (Reid & Julve, 2016) note that "The first major commercial application for batteries is in providing ancillary services and in particular fast response power to the primary reserve market for frequency regulation.". They also that future applications in this area are likely to relate to reducing the stresses caused by renewables and peak demand. |
| Renewable power plants | Arbitrage<br>Asset optimisation<br>Ancillary services<br>Black start | The opportunities for EV batteries in relation to renewable energy power plants are similar to the others outlined above in that they can help to store excess energy for use at a later time, when required thereby helping to make these power stations more efficient. |
| Thermal generation | Ancillary services<br>Asset optimisation<br>Black start<br>Energy arbitrage | (Reid & Julve, 2016) note that: "Batteries will allow conventional power plants to generate more revenues on the balancing market while increasing their flexibility. In addition, batteries give conventional power plants the ability to restart the grid in case of a feared blackout. A combination of traditional power plants and batteries increases the overall efficiency of the system, by allowing the power plants to run more efficiently and by increasing the provisioning of ancillary services." |

*Source*: Columns 1 and 2 from (Reid & Julve, 2016)

**Figure 2.18: BNEF forecast of used battery availability, and estimated volumes for a second life in stationary energy storage**




*Source*: Reproduced from BNEF (Bloomberg New Energy Finance)

**Table 2.6: Summary of information identified on the potential market and price for repurposed batteries**

| Source | Capacity/market size | Value or Price of repurposed batteries |
|---|---|---|
| (Elkind, 2014) | N/A | Price of re-purposed batteries estimated at $38-132/kWh (may vary depending on application). |
| (Reid & Julve, 2016) | 25 GWh of second-life batteries entering the German market by 2025 | Estimated at €150/kWh ($175/kWh). |
| (BNEF, 2016) | N/A | $49/kWh to repurpose [by 2018], compared to the current new stationary battery price [in 2016] of around $300/kWh. |
| (BNEF, 2018) | N/A | Chinese refurbishers will pay $4/kg for batteries with reuse potential; a battery more suited for recycling will go for as little as $1.50/kg. |

## 2.6.3 Potential benefits, barriers and uncertainties

### 2.6.3.1 Benefits

Although Li-ion batteries in vehicles should be replaced once capacity has reduced to around 80%, they retain around 70-75% of their initial value (Kampker, et al., 2016). As a result, there is a strong economic case to consider and develop re-purposing.

There are several specific economic benefits:

1) They offer the same services but at reduced cost compared to new batteries (Reid & Julve, 2016).
2) It may help to reduce the cost of electric vehicles:

a. if the repurposing value is taken into consideration by customers at initial purchase or by retailers in pricing their vehicles (Elkind, 2014).
b. by extending the total life of the battery (Reid & Julve, 2016).

As (Foster, Isely, Standridge, & Hasan, 2014) explain: *"Lithium-ion batteries are a major cost component of an electric vehicle and a plug-in electric hybrid vehicle. One way of reducing this cost is to develop additional uses for such batteries at the end of vehicle application."*

These economic benefits could help to drive demand for EV thereby bringing about a number of environmental benefits associated with EV adoption (Tytgat & Tomboy, 2017).

#### 2.6.3.2 Barriers

However, while re-purposing is preferable to occur *prior* to recycling (i.e. which should continue to follow later) in terms of the waste hierarchy, and while there is considerable potential in giving used EV batteries a second-use, there are a number of barriers: health & safety, regulatory, economic and technical.

<u>Health & safety</u>

Many of the concerns highlighted in section 2.5.3 in relation to re-use are also applicable to re-purposing. The possibility of reusing the whole battery pack without dismantling it is the preferable option according (Bobba, et al., 2018). However, re-purposed batteries will in many cases likely require an element of remanufacture in order to make them fit for their second-use, meaning they will need to be dismantled which brings with it concerns over the volatility of the active material and electrolyte, and the potential discharge of voltage (at least from EVs involved in crashes) as previously discussed.

There are also concerns from permitting authorities over the use of re-purposed EV batteries due to concerns about fire safety, and / or environmental impacts (Elkind, 2014)

<u>Regulatory</u>

Again, the concerns outlined in section 2.5.3, primarily the lack of regulation, are also applicable to re-purposing however the issue is compounded by the fact that the batteries will be used for a different purpose that the one originally intended.

Some of the key challenges have been outlined by Elkind: *"Second-life battery usage involves the complicated worlds of utilities, hazardous and toxic wastes, and local permitting, among others…additional challenges, such as regulations regarding the transportation of used electric vehicle batteries (currently classified as hazardous waste) and disposal and recycling."* (Elkind, 2014).

In addition, RECHARGE note that *"The UN Model Regulation for the transport of Dangerous Goods applies to Lithium batteries. For safety reasons, it requires specific testing requirements in accordance with defined technical specifications. This needs to be secured before the second use of the battery"* (Tytgat & Tomboy, 2017). These requirements differ based on the mode of transport being used and can add extra stages of complexity to the process. For example, there are different requirements for air freight or sea transport, i.e. for air transport, batteries must additionally be discharged to a certain level.

Finally, the lack of regulation also raises liability concerns. The battery manufacturer designs and manufacturers them for a specific purpose and may not anticipate the battery then being remanufactured for a different purpose in the future. If the re-purposed battery then malfunctions in its new environment, it is unclear at present where liability would lie. As a result, EV battery manufacturers may wish to discourage re-purposing (Elkind, 2014).

<u>Economic</u>

As a result of these health and safety issues, and technical challenges, as well as the uncertainties surrounding quality and quantity of batteries available for re-purposing, there are a number of economic barriers. For example, re-purposing a battery safely and to the required standard results in high remanufacturing costs, while at the same time there are low-cost alternatives to re-purposed EV batteries which are suitable for energy storage solutions (CEC, 2015). As (Foster, Isely, Standridge, & Hasan, 2014) note: *"The costs of refurbishing and connecting them into a grid are likely to be high and will be more than building new dedicated batteries for those applications."*

In addition, the waste treatment operator and cell transport costs are also likely to be a major hurdle for 2nd life batteries (Wu, 2018).

Elkind also draws attention to the potential, unintended negative impact on re-purposing of incentive schemes aimed at benefiting energy storage more generally (Elkind, 2014).

A number of stakeholders illuminated another economic barrier to the effective re-purposing of batteries as transport costs can be up to or greater than 50% of the overall recycling cost. Another stakeholder suggested that these high costs may be due to the UN Dangerous Good Regulation meaning that expensive packaging is needed in some cases. Additionally, the costs associated with recovery of batteries exceeds the raw material value, adding further difficulties to the economic case.

Technical

Related to health and safety issues, are some technical concerns and reduced lifetimes remain a major barrier to the technical deployment of second life batteries. For example, there are concerns as to whether or not it is possible to effectively re-purpose a battery so that it meets the required standard for its second-use – this appears to be an area of contention. While there are a number of commercial, pilot and research projects looking at this (as covered in section 2.6.4), both RECHARGE and the Battery Association of Japan have outlined their opposition to re-purposing as discussed in section 2.5.3.

The Commission for Environmental Cooperation also highlight the following technical barrier: “sensitivity to uncertain degradation rates in second use” (CEC, 2015).

#### 2.6.3.3 Uncertainties

Feasibility

There are some contradictions between sources on the desirability and feasibility of using EV batteries as energy storage. The examples of RECHARGE and the Battery Association of Japan have been previously outlined, and these are in contrast to the wide range of example projects set out. In addition, Elkind states that *“Because second-life batteries will retain significant capacity, they may be well-suited for various customer and grid applications, particularly if aggregated for bulk energy storage.”* (Elkind, 2014), while Kampker et al state *“Second-life concepts like a reuse as a stationary energy storage...due to very different requirements and conditions dissimilar application might not be the optimum solution [for LIB]”*

This highlights a need for increased research and a need to overcome other barriers and uncertainties.

Economic uncertainties

While the potential for economic benefit is considerable, as outlined earlier in this section, there are also a number of barriers which result in an uncertain economic case for re-purposing at present. In addition, the *“viability will depend on the resale value of the batteries and on the implemented storage strategy.”* (Faria, et al., 2014).

Very little information exists on the cost of repurposing. Additionally, despite the relevance at end of life, the majority of technoeconomic studies on the subject do not account for degradation – which is hard to assess even by experts without more detailed information on the battery charging history. Thus, there is significant uncertainty over the economic case for re-purposing (Wu, 2018).

Feedback from the stakeholder consultation interviews for this project have also suggested that the lack of certainty over the costs of remanufacturing arise because it is rarely done in practice and the trend is for battery packs to be reused as a whole.

However, feedback from the consultation also suggested that - providing that the legal barriers are removed and logistics costs remain reasonable - the cost of remanufacturing would be significantly lower than the price of a new pack. This is because the cost of diagnostic operations on a whole battery pack are likely to be no more than 10% of the cost of the battery pack, and even if the pack is disassembled into modules and then diagnosed these costs are likely to be around 50% of the new battery pack cost. This leads to an overall estimate of remanufacturing costs of well below 25% of a new battery pack. The main current barrier to second use is the logistics cost to transport the batteries, due to the classification of end-of-life batteries as waste, which can be considerable.

Obsolescence

As with re-use, obsolescence could present a challenge for re-purposing. With new emerging chemistries, potentially fewer than anticipated used batteries might enter the market due to an extended first life, while remanufacturing processes and regulation may also have to evolve to suit new chemistries. As (Kampker, et al., 2016) state:

> *"The electric mobility as a comparatively new market also faces a high cost pressure to produce the single components especially the battery more efficiently, to effectively increase the attractiveness of EVs. Fast innovation cycles and the disruptive character of electric cars offer a high degree of freedom regarding innovative design for remanufacturing. This freedom allows functional updates to prolong the life time by improving the utility additionally to conventional reparation. Less power train components combined with an improved wear and a high efficiency form the basis for a prolonged life cycle of electric cars."*

An alternative perspective could be that if EV owners find it more attractive to upgrade their battery early, for a better performing one, this might help develop the market for repurposing. However, this would also depend on the degree to which this replacement market is served by battery remanufacturing and reuse (see also Figure 3.17 together with further discussion in later Section 3.3.2).

Quality, quantity and demand

The uncertainties surrounding quality and quantity of post-consumer batteries outlined under the re-use section, are also applicable here. (Foster, Isely, Standridge, & Hasan, 2014) also note that negative perceptions of re-purposed batteries could impact on their use and this highlights the need for a robust regulatory environment.

There are also uncertainties about the level of demand. As (Faria, et al., 2014) state: *"The demand for lithium-ion batteries for vehicle applications through 2050 has a high degree of uncertainty. Repurposing applications are currently not fully developed and recycling processes are still evolving. There is a high degree of uncertainty associated with the cost-benefit analysis."*

Technical

There are technical uncertainties in the suitability of end of life EV batteries for second life applications in energy storage. In particular, Tesla have voiced doubts that their remaining service life and performance after 10-15 years will not be adequate to provide sufficient reliability and predictably and won't provide a convincing economic case to provide grid services (Clean Technica, 2016).

The challenge here is that already even first life battery providers rarely provide warrantees for cells for their use, and it seems less likely that a 2nd life battery operator would be able to issue a warrantee for their product in this context (Wu, 2018).

The differences between warranties and life cycles across EV batteries used for different vehicles will therefore add to the complexities in trying to establish a standardised approach.

### 2.6.4 Activity

Given the expected number of post-consumer EV batteries that are likely to become available and their residual capacity and value, there is a considerable amount of work being undertaken to research, develop, trial and launch re-use/re-purposing schemes. Table 2.7 below provides an overview of examples uncovered through this research.

**Table 2.7: Examples of potential case studies for battery repurposing and second life**

| Organisation(s) | Project | Location(s) | Overview |
|---|---|---|---|
| Renault | Battery leasing, re-use and re-purposing | UK | Renault’s leasing model has been outlined in section 2.5.4. Through this model, they not only seek to re-use batteries but also to re-purpose them where more appropriate. |
| ACCUmotive (subsidiary of Daimler) | Re-purposing | Germany | As outlined in section 2.5.4, Daimler’s subsidiary ACCUmotive re-uses and repurposes used EV batteries while Daimler seek to address the challenges by incorporating better design and manufacturing techniques. |
| Daimler, The Mobility House, GETEC and REMONDIS | 2nd Life batteries | Germany, Westphalia | A 13 MWh battery storage project, has been set up by these organisations in Germany. As Daimler state on their website:<br>“Because the lifecycle of a plug-in or electric vehicle battery does not end after the vehicle's operating life. If used in stationary power storage, the systems are fully operational even after the service life guaranteed by the manufacturer – with slight capacity losses only of secondary importance. Cost-effective use in stationary operation is possible for at least an estimated ten years longer. Reusing the modules from electric cars in a battery storage doubles their economic value and also demonstrably improves their eco-balance.”<br>(Daimler, 2016) |
| Mercedes-Benz Energy (subsidiary of Daimler) and enercity | EV battery storage | Germany, Herrenhausen | “The lithium-ion batteries earmarked for automotive use provide a system service on the German market for primary control power (PCP) before they are used in electric vehicles from Daimler AG. Through "live storage" of the replacement batteries the partners are creating an attractive business case which can only be realised jointly by an automotive manufacturer and an energy supply company in this form. The partners thus benefit from their respective expertise in the areas of the energy industry, system services, battery development and production plus marketing.”<br>(Daimler, 2017) |
| UPS (with UK Power Networks and Cross River partnership) | EV charging solution | UK, London | Funding secured from UK government Office for Low Emission Vehicles.<br>“deployed a radical new charging technology in London that overcomes the challenge of simultaneously recharging an entire fleet of electric vehicles (EVs) without the need for the expensive upgrade to the power supply grid… allowing UPS to increase the number of EVs operating from its central London site from the current limit of 65 to all 170 trucks based there… A key part of this initiative is the use of onsite energy storage batteries. Although new batteries have been deployed at this stage, it is envisaged that in the future these could be second-life batteries that have already been used in a UPS EV. Together with the smart-grid, this will pave the way toward a UPS EV infrastructure strategy that can dynamically make use of a |

| Organisation(s) | Project | Location(s) | Overview |
|---|---|---|---|
| | | | conventional power upgrade, a smart grid, onsite storage, and in many cases, local power generation including solar and other alternative sources." (UPS, 2018) |
| 2BCycled | Residential renewable energy storage | EU, Netherlands | "A research project with the aim to determine the business case for second life for discarded EV-batteries, evaluating the economic potential of the local household/PV system…The aim of the dismantling project is to investigate whether batteries from hybrid or fully electrically-powered cars can be given a second life, at the end of the useful life of the vehicle." (Tytgat & Tomboy, 2017) |
| The California Energy Commission and the California Public Utilities Commission | Energy storage pilots | USA, California | "Both supported energy storage pilot projects to meet the 1,325 megawatt target. Among the current initiatives, the California Energy Commission issued in April 2014 a request for energy storage projects with grant awards up to $6 million." (Elkind, 2014). |
| Nissan & Sumitomo Corporation | Renewable energy storage | Japan, Osaka | "Starting the world's first used electric vehicle battery energy storage system. The system will use Nissan Leaf lithium-ion batteries to regulate energy from a solar plant in Osaka, Japan. The system (600kW/400kWh) includes 16 used lithium-ion EV batteries and aims to provide energy fluctuations from a nearby solar farm. Sumitomo launched the system through a joint venture "4R Energy Corporation" with Nissan Motor Co. founded back in September 2010 to find new business models for used lithium-ion EV batteries." (Tytgat & Tomboy, 2017). |
| General Motors | Micro-grid back-up | | "Using second-life batteries to develop a microgrid backup system". (Elkind, 2014) |
| Pacific Gas & Electric | Demand response | USA | Began a pilot program to study plug-in electric vehicle batteries as demand response resources. (Elkind, 2014) |
| EUROBAT (Association of European Automotive and Industrial Batteries manufacturers) | Battery performance improvement | EU | "Batteries 2020 - The project aims to improve performance, lifetime and total cost of ownership of batteries for EVs by the simultaneous development of high-performing and durable cells, reliable lifetime prediction, understanding ageing phenomena and assessment of second life in renewable energy applications." (Gattiglio, 2017) |
| Toyota Motor Corporation and Chubu Electric | EV battery reuse for storage | Japan, Nagoya City | "the two companies have concluded a basic agreement with the aim of commencing a verification project that entails construction of a large-capacity storage battery system (Storage Battery System) that reuses electrified vehicle batteries (batteries), as well as examination of |

| Organisation(s) | Project | Location(s) | Overview |
|---|---|---|---|
| Power | | | the recycling of used batteries…<br>“1) reuse: aim to reuse batteries collected from electrified vehicles manufactured by Toyota as a storage battery system for utilization in meeting various challenges posed by the electric power system. When combined in large numbers, used batteries, even with reduced performance levels, can be repurposed for energy supply-demand adjustments, frequency fluctuation management, and voltage fluctuation management in distribution systems, all factors that accompany the widespread introduction of renewable energy. Not only can these efforts serve as a solution to address the challenges within the electric power system, Chubu Electric Power and Toyota expect these efforts to have positive effects in the operation of thermal power plants…<br>“2) recycling: The two companies will consider establishing a mechanism to recycle reused batteries by collecting materials such as rare-earth metals and re-utilizing them.”<br>(Toyota, 2018) |
| Solar City (a subsidiary of Tesla since Nov 2016) | Renewables energy storage | | “detailed its ambitions to build the world’s largest battery manufacturing facility costing $2 billion. Besides aiming to bring down costs for Tesla’s large batteries (85 kWh), the value proposition ties in nicely with its sister company, SolarCity, who is already using Tesla’s energy storage systems to store solar energy for both residential and commercial purposes.” (Tytgat & Tomboy, 2017). |
| University of Delaware | V2G | Delaware, USA | “In a Delaware pilot project, the ‘Cash Back Car’ concept electricity is stored in and retrieved from the batteries of idle vehicles. Car owners would be paid. The retrofitted Mini Coopers and other vehicles plugged into sockets where a Chrysler plant once stood do more than suck energy out of the multi-state electricity grid. They also send power back into it. The pilot project at the University of Delaware has had enough success to set off a frenzy of activity in the auto and electricity industries. Entrepreneurs and government agencies see the technology as a possible solution to a vexing dilemma: how to affordably store renewable energy so it can be available when it is needed, not only when the wind blows or the sun shines. The idea is that utilities would pay vehicle owners to store electricity in the batteries of electric vehicles when the power grid has a surplus and drain electricity back out of them when demand rises. The plan takes advantage of a key fact about cars: They spend most of their time parked. The technology makes idle vehicles a source of storage for utilities and cash for car owners. Of course, nothing with electricity is simple. (Tytgat & Tomboy, 2017). |
| The Faraday Institution (University | various | UK | “The Faraday Institution is the research vehicle for the ISCF Faraday Battery Challenge, which comprises a £246m commitment over the next 4 years to develop, design and manufacture world-leading batteries in the UK. The programme is split into three separate elements, |

| Organisation(s) | Project | Location(s) | Overview |
|---|---|---|---|
| founders: Cambridge, Imperial, Oxford, Southampton, UCL, Warwick) | | | delivered in parallel, to provide connectivity across research and innovation strands" (The Faraday Institution, 2018). |
| EVEREST energy storage | Grid support | | "The EVEREST consortium is led by EValu8 Transport Innovations Limited...The EVEREST system is a modular energy storage device, using second life battery packs from electric and hybrid vehicles, to act as aggregated grid support." (Future Transport Systems, n.d.) |
| Jaguar Land Rover, Connected Energy, the University of Warwick and Videre Global | Residential applications | UK | collaboration on "a second-life battery research project in the UK...The £1.3 million project is co-funded by an Innovate UK grant awarded last month and will see second-life batteries from Jaguar Land Rover electric vehicles trialled in domestic applications." (Current, 2017) |
| Renault / Powervault | Residential renewable energy storage | | collaboration "to turn batteries that have reached the end of their on-road life into an energy storage system for the home. Powervault already produces "smart battery" units to store electricity generated by household solar panels. As part of the new system it will integrate the spent batteries from Renault's electric vehicles...and use them for energy storage" (iNews, 2017) |
| Vattenfall, BMW Bosch | Energy storage – grid stabilisation | Germany, Hamburg | "Test electricity storage in Hamburg. 2,600 used battery modules from over 100 electric vehicles are being merged to form a large electricity storage facility in Hamburg. The stored energy is available within seconds and can help to keep the electricity grid stable." (Bosch, 2016) |
| Hyundai, Wärtsilä | Energy storage | Korea | Hyundai Motor Group (HMG) has selected Wärtsilä – a major player in the world's energy business – for a technology and commercial partnership designed to utilize second-life electric vehicle (EV) batteries for the growing energy storage market.<br>Hyundai is also currently developing a 1MWh-level ESS (Energy Storage System) that utilizes Hyundai IONIQ Electric's and Kia Soul EV's second-life battery. Using its proprietary technology, the company has already implemented a demonstration project in Hyundai Steel's factory. (Inside EVs, 2018) |

## 2.7 Battery recycling

### 2.7.1 Overview


Where a battery's state of health is too poor to reasonably allow for re-use or re-purposing, it should go through a recycling process. In some cases, even if the battery is in a good state of health, recycling may be viewed as the most practical option. This may be due to some of the health and safety issues raised earlier in relation to re-use and re-purposing.

Recycling batteries allows for some of the economically valuable materials to be recovered, which can then be used to manufacture new products. It does not allow the remaining battery capacity to be made use of; however, it does prevent potentially valuable materials from being disposed of.

Under the Batteries Directive, there are minimum collection and recycling targets for each Member State, however, the collection rates only apply to portable batteries and therefore do not apply to traction batteries (EU, 2006). Regardless, according to (Bobba, et al., 2018), the current collection rate of automotive and industrial batteries in Europe far exceeds these requirements, at nearly 100% for vehicle batteries becoming waste and recycled in the EU. However, but there is also a significant export stream of used vehicles to countries leading to about 45% of complementary flows (Oeko Institut, 2016). According to (Urban Mine Platform, 2019), for portable Li-ion batteries the current collection percentage is much lower (less than 10% percent on average across the EU).

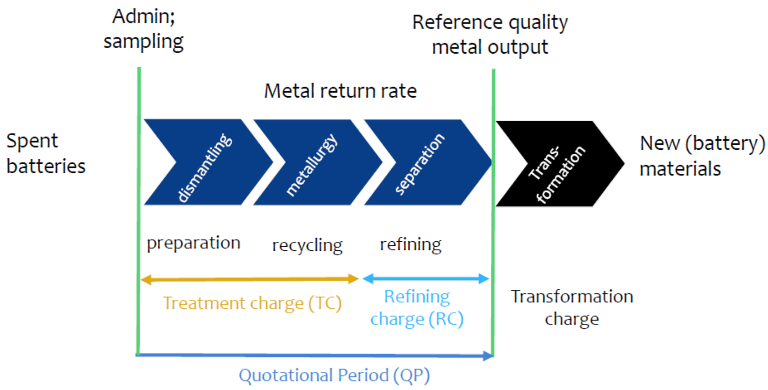
Figure 2.19 provides a high-level overview of a battery recycling process. The Commission for Environmental Cooperation (CEC) notes that the supply chain for used EV batteries tends to be controlled by car manufacturers and dismantlers rather than battery manufacturers themselves and that car manufacturers, such as Toyota, are looking to develop and secure a "reverse supply chain" (CEC, 2015).

While the Figure 2.19 provides an overview of a typical, high-level recycling process, there are a number of different recycling methods being used and further developed around the world, which can be broadly categorised as follows:

- Physical processes:
    - Mechanical
    - Pyrometallurgy
- Hydrometallurgy: chemical and biological processes
- Hybrid processes (i.e. pyrometallurgy and hydrometallurgy, mechano-chemical processes)
- Intermediate, and
- Direct

Some organisations have developed their own hybrid techniques, and these are often referred to by the name of the company that uses them. More detail is provided in section 3.3 on the different techniques used to recycle EV batteries.

**Figure 2.19: Generic overview of the battery recycling process**




*Source*: (Gattiglio, 2017)

## 2.7.2 Recycling costs and material recovery

Theoretically, most materials in a lithium-ion battery can be recycled (Elkind, 2014) however the focus been mainly on active materials (and current collectors) and, in most cases, recovery is limited to certain (high cost) materials, with other lower cost components, such as the binders, lithium salts and separators not currently being recovered (Wu, 2018). (Ramoni & Zhang, 2013) note that *"Li-ion batteries recycling processes as at this moment mainly aim at metal recovery, there is no indication yet that organic battery component such as the electrolyte is taken into consideration in the recovery process"*. Cobalt, Nickel and Copper are almost always recovered, with several processes also recovering aluminium (Gaines, 2014).

Cobalt is generally seen as the most important material to recover (Ramoni & Zhang, 2013) due to its considerable value (Lebedeva, Di Persio, & Boon-Brett, 2016), and is also one of the primary reasons that battery recycling is a profitable activity. However, battery manufacturers are working to reduce the amount of cobalt required (Wang, Gaustad, Babbitt, & Richa, 2014) in order to reduce costs, but this will also make recycling less economically viable (CEC, 2015). Corroborating this, information gathered in the stakeholder consultation and peer review process (Wu, 2018) has revealed that the trend in the industry is to move from a cathode composition of Nickel, Manganese and Cobalt in a 1:1:1 ratio to an 8:1:1 ratio (and beyond) and eventually to a cathode analogous to enhanced nickel oxide. Further barriers and uncertainties will be discussed in section 2.7.3.

Recovery of lithium is more variable between process primarily due to economic rather than purely practical reasons, for example:

> *"Interviews with industry members indicate that lithium is currently plentiful and not expensive; at current prices, therefore, it is not worth recovering in a pure form through the recycling operation."* (CEC, 2015)

However, it should be noted that there is also a natural lag time in the response time to increase lithium production due to the method of production which is often with brine pools (Wu, 2018). There is actually very little lithium in a lithium-ion battery (i.e. only 1-2% in the cathode and electrolyte- see Figure 2.4), and:

> *"Recycling becomes economically feasible only if the price of lithium salts increases to $98.60 per kg due to a shortage of new lithium, which is possible but perhaps not likely, with increasing demand for lithium-ion batteries… Recycling will likely not be economically feasible in isolation but will eventually be necessary for all batteries. Thus, the costs of recycling must be assigned to original vehicle use, remanufacturing and repurposing applications."* (Foster, Isely, Standridge, & Hasan, 2014)

However, research carried out at Queens University in Australia into the development of an economically viable lithium recovery process has found that *"when applied to recycling automotive LIBs, [current industrial processes] are needlessly energy intensive and complicated…Instead of such extreme measures, LIBs can be disassembled by automated processes."* (Sonoc, 2015).

However, although automated dismantling processes are also being researched, clearly this would require a level of standardisation and scale to be practically useful.

The economics of battery recycling is highly dependent on battery chemistry, commodities markets and the process / techniques applied and there is considerable variation in the figures presented by different researchers and organisations. The following Table 2.8 from Ford Analytics demonstrates this issue.

**Table 2.8: Ford Assumptions and literature values for battery recycling**

| | Ford assumption | Min. literature value* | Max. literature value* |
|---|---|---|---|
| Recycling cost | 2.4 €/kg battery | 0.34 €/kg battery | 4 €/kg battery |
| Consideration of transport cost to recycling plant (at the end of first life) | No | No | No |
| Primary source (recycling process) | Ford | GRS-Battery (largest common battery collection scheme in Europe) | LithoRec (Research project to develop a recycling technology – 2011) |
| Has the recycling technology/process been implemented | Yes | Yes | No |
| Reference unit | Electric vehicle battery | 2-4 kg lithium ion battery | Electric vehicle battery |
| Reference year | Today (2017) | Today (2016) | Today (2011) |

*Source*: Reproduced from (Ford analytics, 2017). Notes: Min literature value refers to portable batteries, recycling cost may increase for heavier BEV batteries. Max literature value refers to development of specific recycling processes for xEV batteries.

Based on the Litho-Rec project, (Ford analytics, 2017) that it is possible to reach a positive revenue (i.e. recycling from batteries gets positive), based on the sale of extracted raw materials with the largest cost component by far being the investment and fixed costs. However, it is important to note that this was a development project and not delivered on a commercial scale at the time.

Susteco suggests that recycling, and indeed re-purposing, will only become economically viable around 2030 with the break-even point being around 2020 (Meeus, 2018). In addition, according to (IVL, 2017), currently: *"In general the cells are removed from the rest of the pack, and the structural material and electronics in the packs are sent to separate recycling. If the cells contain cobalt and/or nickel they are sent to recycling facilities in Europe. If the cells are LFP, however, they have no material value and are sent to be burned for energy recovery"*. This is also the case for LMO battery chemistries and reduction in content of high-value materials (i.e. cobalt) / changes to new chemistries under development (e.g. lithium sulphur) with materials with no intrinsic value (e.g. sulphur) could also undermine future economics.

However, to counterbalance this effect it is expected that the costs for recycling will also significantly reduce as plants/operations are scaled up, according to the waste and recycling stakeholders consulted during the project. In general, it is expected that for every increase in facility size by a factor of ten, the costs are only four times bigger. For example, 5 plants of 100,000 tonnes p.a. capacity would be a lot more inefficient than one plant for 500,000 tonnes. Nevertheless, feedback from EUCOBAT suggests that (given the high dismantling cost and the lack of intrinsic value) waste lithium batteries are not expected to have a positive value in the near future at least.

Based on the literature review and confirmed with the consultation with stakeholders, currently as much as half of the cost of disposal of end-of-life batteries is due to the cost for logistics (i.e. transporting the batteries) to recycling (or repurposing/remanufacturing) facilities due to their waste classification and potential safety issues. Such costs could potentially be addressed through a combination of more localised dismantling facilities, greater availability of regional recycling facilities closer to key markets and addressing waste classifications for batteries send for reuse/repurposing, rather than recycling/disposal. The first two items are more likely to follow naturally as the EV market expands and the need for more battery recycling capacity increases.

A summary of the on the quantity and types of materials that different recycling techniques recover is provided below in Table 2.9.

**Table 2.9: Efficiency of recycling for various elements in selected processes for NMC and LFP chemistries**

| Material | Hybrid: combination of pyrometallurgical & hydrometallurgical processes - NMC and LFP [%] | Purely hydrometallurgical process - NMC only [%] | Purely hydrometallurgical process - LFP only [%] |
|---|---|---|---|
| Lithium | 57% | 94% | 81% |
| Nickel | 95% | 97% | NA |
| Manganese | 0% | ~100% | NA |
| Cobalt | 94% | ~100% | NA |
| Iron | 0% | NA | 0% |
| Phosphate | 0% | NA | 0% |
| Natural graphite | 0% | 0% | 0% |
| Aluminium* | 63% | ? | ? |
| Copper | 41% | ? | ? |

Source: Based on (JRC, 2017), and assumptions based on analysis of lifecycle inventory data from (RECHARGE, 2018) for aluminium and copper. Notes: * mainly through battery dismantling / mechanical pre-treatment processes before the main hydro-/pyro-metallurgical steps.

## 2.7.3 Opportunities, barriers and uncertainties

### 2.7.3.1 Opportunities and benefits

As outlined in section 2.7.1 there are potential economic benefits to recycling used EV batteries. While there are many factors influencing the technical and economic feasibility of doing so, recycling does provide an opportunity to recover materials, particularly valuable metals such as cobalt, nickel, copper and aluminium, which can then be sold and used to make new products. It is estimated that *"recovering materials from LIBs can generate $240 per ton on average overall"* (Wang, Gaustad, Babbitt, & Richa, 2014) and with the number of used EV batteries coming onto the market set to increase substantially over the next 5, 10, 15 years, the economic opportunity will grow. To retain the maximum possible value, it is best if recycling can be "closed loop" where by the materials recovered are then used to manufacture new EV batteries (CEC, 2015). This is also particularly important in regions where local availability of key mineral resources needed to support manufacturing in the region might be low.

### 2.7.3.2 Barriers and challenges

There are a number of challenges to EV battery recycling however, despite the scale of the opportunity. These are primarily technical and economic issues.

<u>Technical</u>

Ramoni & Zhang highlight a potential issue with cathode recycling, whereby *"the reduction temperature…may exceed the operating temperature…causing metal oxide to enter slag for smelting process without being converted into metallic form"* (Ramoni & Zhang, 2013). This can lead to an increase in production costs and environmental impact than would be the case with primary production.

While closed-loop recycling for the recovered materials from EV batteries may be the most economically beneficial, there are some concerns about the purity and performance of the recovered materials in comparison to virgin products. Gaines for example, states that *"There is some question, however, about whether the recovered material will perform as well as virgin material, which could have implications for battery power and lifetime, so manufacturers may be reluctant to purchase recycled compounds"* (Gaines, 2014). Ramoni & Zhang note that *"there are no well-known comparisons or analyses of the processes in terms of purity of the material recovered.''* (Ramoni & Zhang, 2013). However, feedback from Umicore (a battery raw materials provider *and* battery recycler) during the stakeholder consultation suggested that this was not an issue for the materials currently recovered in recycling processes.

In terms of infrastructure and capabilities in this area, the Commission for Environmental Cooperation noted that *"The recycling of EOL NiMH and Li-ion batteries from EDVs is in its infancy, with many players currently vying for positions in the market. It is anticipated that other market entrants will appear in the next two to five years, but at the moment, industry contacts report that there are but a few market players (which all do business with each other) that have commercial arrangements to ship batteries of particular chemistries to the facility with the expertise to recycle the particular battery chemistry". Wang et al also conclude that "a more proactive approach must be taken to develop a robust LIB recycling infrastructure."*

EUROBAT notes that in the case of Li-ion, *"a high recovery rate of materials is challenging in comparison with lead-based and nickel-based batteries. This is primarily due to the wide varieties of chemical components and system complexity"* (EUROBAT, 2014). Gaines also draws attention to the complexity involved in Li-ion recycling in comparison to these other two battery chemistries, highlighting the wider variety and number of cells, the powder-based active materials, and the fact that there are different specifications between manufacturers (Gaines, 2014). In addition, (Wu, 2018) has also indicated that binders are a big problem as electrodes are designed to stick together well, so removing them is an issue. Binders are often very stable in most solvents, and if solvents are used these also need to be recycled. The burning of binders (e.g. in pyrometallurgical processes) can release hydrofluoric acid which is very corrosive and dangerous. Finally, according to (Lebedeva, Di Persio, & Boon-Brett, 2016) *"Recycling of lithium-ion batteries is a complex and costly process…additional complexities arise from the need for dismantling and pre-treatment of large electric vehicle batteries to reach sizes compatible with recycling process"*. Such considerations are, however, likely to be overcome for collection and treatment in Europe, as facilities are expanded to handle larger flows of EV batteries, and it seems likely dedicated facilities will be developed once uptake reaches a certain point.

However, the situation is somewhat more complicated when considering the potential for safe dismantling and recovery of cells/ materials in developing countries with very high logistic costs, safety and transport constraints and lack of recycling capacity and smelters in particular.

<u>Economic</u>

While the potential economic benefits have been set out, it is important to note that there are a number of concerns regarding economic feasibility. There are several reasons for this, one of the most substantial being the moves being made by manufacturers to reduce the quantity of cobalt used. As Ramoni & Zhang highlight, *"recovery of cobalt has been indicated as the main economic driver for recycling Li-ion batteries...Therefore, recycling EV batteries without cobalt cathodes casts further doubts on the cost effectiveness of EV batteries recycling"* (Ramoni & Zhang, 2013). This point is also highlighted by the Center for Energy Economics (Center for Energy Economics, 2016).

Ramoni & Zhang are concerned about the ability of markets to absorb the material recovered through recycling. They recognise that this will vary between materials but "for material like lithium, price collapse or possibly an inability to sell the reclaimed lithium at all could be the result if its market is inundated with recycled material." (Ramoni & Zhang, 2013).

While technically feasible, the economic viability of recovering lithium is questioned by much of the literature. EUROBAT states that: *"The recycling of lithium is technically and industrially feasible, but as only a small quantity is used in each battery (between 1 to 2% of their total weight), and because only a small number of large-format lithium-ion batteries have reached end of life, this has not yet become economically viable"* (EUROBAT, 2014). However, it has also been noted that *"Without recycling, lithium demand is predicted to outstrip supply in 2023*" (Sonoc, 2015)

#### 2.7.3.3 Uncertainties

Many of the uncertainties over improved recycling are linked to the issues outlined under the barriers section. For example, it is not known if or when cobalt might be completely removed from EV batteries or the impact that might have.

Similarly, given the ongoing research and development of new battery chemistries, there are uncertainties about potential obsolescence of recycling techniques, equipment and infrastructure. As Gaines states *"battery technology is still evolving. Recycling processes designed for a specific design or chemistry could become irrelevant quickly."* (Gaines, 2014). As (Foster, Isely, Standridge, & Hasan, 2014) state: "*recycling processes are still evolving. There is a high degree of uncertainty associated with the cost-benefit analysis."*

In addition to uncertainties over battery chemistries, and the use of cobalt, the quantity of batteries which will become available is also unclear and is likely to change as re-use and re-purposing opportunities develop. In particular, the storage and shipment of battery waste is a major issue. The JRC has also recently published a report further exploring the issues around Cobalt for electromobility in more detail (Alves Dias, Blagoeva, Pavel, & Arvanitidis, 2018).

### 2.7.4 Activity

At the moment industrial LIB recycling is mainly limited to portable batteries, as the volumes of waste EV batteries from end-of-life vehicles is still very small (though there are larger volumes of NiMH batteries from hybrid vehicles) (JRC, 2017). Industrial recycling of spent Li-ion batteries occurs in many regions of the world. Table 2.11 below provides an overview of companies around the world that carry out recycling, their location(s) and the type of process used.

In addition to these companies, a range of research has also been undertaken to try and develop simpler processes in the EU and globally; this has also included the assessment of how methods might be improved with greater scale. Further information on this is provided in later Section 3.3.

The potential volumes and market values for recovered materials from EV battery recycling have been estimated previously in a range of recent studies, including those in Table 2.10. Similar estimates have been developed as part of Task 2.4 of this project (see Chapter 5), and in other recently published work by the JRC (Alves Dias, Blagoeva, Pavel, & Arvanitidis, 2018).

As reported by Reuters, China has also seen recent activity in EV battery recycling, with plans to start new trial schemes in greater Beijing Hebei Tianjin region, the Yangtze River, Pearl Delta River and Central China areas (Meng & Mason, 2018). A recent producer responsibility scheme requires EV manufacturers to set up facilities for collection and recycling of used batteries with local government also providing support through policy and an "industrial fund" (Meng & Mason, 2018).

Similar policies with regards to producer (i.e. OEM) responsibilities for EV batteries are also reportedly being introduced in Norway.

**Table 2.10: Estimates for the potential amount and value of materials recovered from EU LIB recycling**

| | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 | Scenario 1 | Scenario 2 |
|---|---|---|---|---|---|---|
| | 2030 | | 2035 | | 2040 | |
| **Amount of recovered material (tonnes)*** | | | | | | |
| Cobalt | 2,922 | 4,058 | 6,519 | 9,054 | 13,509 | 18,763 |
| Nickel | 10,604 | 13,535 | 23,662 | 30,200 | 49,035 | 62,584 |
| Aluminium | 31,826 | 39,783 | 71,013 | 88,766 | 147,163 | 183,954 |
| Lithium | 1,162 | 2,421 | 2,593 | 5,401 | 5,373 | 11,193 |
| **Value of recovered material (million €)*** | | | | | | |
| Cobalt | 189 | 263 | 422 | 587 | 875 | 1,216 |
| Nickel | 116 | 148 | 258 | 329 | 534 | 682 |
| Aluminium | 54 | 68 | 121 | 152 | 252 | 315 |
| Lithium | 15 | 32 | 34 | 71 | 71 | 148 |

*Source*: (CEPS, 2018). *Notes*: Scenario 2 assumes higher EU recycling rates and efficiencies.

**Table 2.11: Overview of key global automotive battery recycling operations and recycling processes based on a review of available literature**

| Company | HQ location | Facility location | Battery types | Recycling process | Materials recovered today | Recycling volume, tonnes of batteries per year |
|---|---|---|---|---|---|---|
| Accurec | Germany | Germany (x2) | NiCd, NiMH, Li-ion | Pyrolysis and hydrometallurgy. | Aluminium, copper, iron scrap, iron/magnesium, and nickel/cobalt. Potential also for $Li_2CO_3$ | 1500-2000 |
| AkkuSer | Finland | Finland | NiCd, NiMH, Li-ion, Zn alkaline | Crushing, chemical treatment | Nickel, cobalt, manganese, iron, copper, aluminium | 1000 (li-ion)<br>4000 |
| AERC Recycling Solutions | USA | USA (x3) | All types including Li-ion and Li metal | Pyrometallurgy | | |
| Batrec | Switzerland | Switzerland | Li | Pyrolysis, pyrometallurgy. | Ferromanganese, zinc. | 200 |
| Chemetall Lithium | Germany | Germany | Li-ion | | Electrode materials only | |
| Dowa Eco-system | Japan | | Various (incl. Li-ion) | Pyrometallurgy | | 1000 |
| Eurodieuze | France | France | Li-ion | Hydrometallurgy | Nickel, steel | 200 |
| G&P Batteries | UK | UK | Various (incl. Li-ion) | Pyrometallurgical or hydrometallurgical. | | |
| Glencore (formerly Xstrata) | Switzerland | Canada (x2) Norway | Li-ion | Pyrometallurgical with hydrometallurgical treatment of slag and electrowinning | | 7000 |
| GRS Batterien | | Germany | | Pyrometallurgy | Cobalt, nickel, copper | |
| Hunan BRUNP | China | China | Various (incl. NiMH, Li-ion) | Hydrometallurgy | | 3600-1000<br>>6000 |
| JX Nippon Mining and Metals | Japan | | Various (incl. Li-ion) | Pyrometallurgy | | 5000 |
| Nippon Recycle Center corp | Japan | Japan (x3) | NiCd, NiMH, Li-ion, alkaline | Pyrometallurgy | | |

| Company | HQ location | Facility location | Battery types | Recycling process | Materials recovered today | Recycling volume, tonnes of batteries per year |
|---|---|---|---|---|---|---|
| Pilagest | | Spain | | Mechanical separation, chemical treatment. | Plastic, paper, ferro-compounds, ferric components, metals, zinc sulphate, manganese salts/dioxide/graphite. | |
| Recupyl | France | France Singapore | Li-ion | Mechanical separation, hydrometallurgical leaching and refining. | Aluminium, cobalt, stainless steel, lithium products. | 110 |
| Retriev Technologies | Canada | Canada USA (x2) | Li metal, Li-ion | Crushing, mechanical separation, solids and liquid solution sent off site for further processing/purification. | | 4500 |
| Shenzhen Green | China | China | NiMH, Li-ion | Hydrometallurgy | | 2000-3000 |
| SNAM | France | France | NiCd, NiMH, Li-ion | Crushing, pyrolysis, distillation, pyro-metallurgy. | Cadmium, ferronickel alloys, ferro-cobalt alloys | 300 |
| Sony Electronics Inc - Sumitomo Metals and Mining Co | Japan | | Li-ion | Pyrometallurgy | | 120-150 |
| Umicore | Belgium | Belgium | Li-ion, NiMH | Pyrometallurgical smelting followed by hydrometallurgical refining. | Cobalt, nickel | 7000 |
| Valdi (ERMET) | France | France | Various (incl. Li-ion) | Pyrometallurgical | | 20000 |

*Source*: (IVL, 2017), (Lebedeva, Di Persio, & Boon-Brett, 2016)

*Notes:* In many cases, the companies listed in the table state their treatment capacity only (which differs from actual volume). In addition, several state their capacities for all batteries, with Li-ion being a limited share.

## 2.8 Outstanding uncertainties and data gaps

We have identified a number of key gaps or uncertainties, mainly for the end-of-first life aspects, that could not be fully addressed in the consultation exercise with stakeholders, which include the following:

**Battery reuse**

There are a number of gaps in information, particularly in relation to the cost of re-use and the various steps that this requires. There also appear to be some inconsistencies in relation to the feasibility of re-use, though some manufacturers are undertaking reuse on a commercial scale as part of their warranty and repair activities.

At present, there appear to be few examples available in the public literature of where re-use is being undertaken, and manufacturers are in general reluctant to discuss reuse models in detail: for example, what challenges they have encountered, and whether or not they intend to commercialise this, and if so, their expected timescale for delivery. The exceptions are Nissan/Renault and Tesla, which have previously provided public information on the role of battery remanufacturing and the reuse of battery cells (or other components) in their overall operation (i.e. either to serve the second-hand market or provide warranty / other repairs).

**Battery repurposing and second life:**

The key outstanding uncertainties / gaps in available information for second life include:

- What are the associated costs to remanufacture to different specifications (for different uses), and will these costs also come down sufficiently that remanufactured batteries are economically attractive compared to new batteries given the further reduction in costs expected for these?
- To what extent will emerging chemistries and changes to other energy technology impact on the viability of repurposing and the market for such batteries?
- What is the feasibility and desirability of different potential second-use applications? How might potential warranty and insurance issues be addressed?
- To what extent can reuse and repurposing on one hand reduce the demand for battery raw materials and on the other hand delay the availability of secondary raw materials in the future?

**Battery recycling:**

The key outstanding uncertainties / gaps in available information for battery recycling include:

- How could recycling be made more cost effective without cobalt to recover?
- Could simpler, less expensive techniques be more widely adopted? What are the issues with these?
- What are the costs associated with the different stages of recycling?
- What is the value to and global position of the EU recycling industry, and how might this change as battery technology evolves and new chemistries are introduced?
- What are the actual quantities placed on the market, generated as waste, reused, exported outside the EU and finally becoming available for recycling?
- To what extent can secondary raw materials fulfil future demand for battery raw materials?
- How do the economics of battery recycling and in particular the costs of logistics and safe handling (and reporting) versus other less desired routes?

# 3 Techniques for the manufacturing, re-use and recycling of EV batteries (Subtask 2.2)

*"What are the current available and emerging techniques in the manufacturing, re-use and recycling of traction batteries for electric vehicles? What are emerging plans for the future?"*

**Key outputs:**

- A high-level assessment of global technological development / status, and the pros- and cons- of different techniques/options.
- A roadmap summarising and visualising the direction of technological development.

This chapter provides a summary of the findings from available academic and industry literature on the ongoing activity for (1) manufacturing, (2) reuse and repurposing, and (3) recycling of traction batteries. This information has been updated and enhanced with additional insights from stakeholder interviews, and feedback from/after the project workshop, particularly in relation to future development plans and likely impacts of introduction of advanced battery chemistries in the medium-long term.

A summary is provided at the ends of the key sections with identified future development/improvements from the above stages. A high-level technology roadmap is also provided for battery production, providing a combined summary of advances in processes with predictions for technological trends and barriers to progress to show in which direction the technology is moving.

## 3.1 Overview of traction batteries for electric vehicles

Most electrified vehicle batteries in use today use either Lithium ion (Li-ion) or Nickel Metal Hydride (NiMH) chemistries, though these are being phased out. However, there are a range of different battery chemistries being utilised and under development. In the past, some sodium-based chemistries (i.e. the sodium-nickel chloride (Zebra) battery) have been used for commercial and heavy-duty vehicles, though the current and recently announced heavy duty buses and lorries are using Li-ion chemistries, e.g. (Green Car Congress, 2018); nevertheless, new sodium chemistries are under active research for the future due to the lower cost and greater abundance of sodium as well as the ability to use aluminium current collectors, eliminating the use of copper (Wu, 2018). Modern electric motorcycles, scooters and eBikes also use mainly lithium-based battery types (Li-ion and Li-Polymer) (Zero, 2018), (BMW, 2018) (Cycling Weekly, 2016).

Current hybrid electric vehicles (HEVs) use both lithium- and nickel- based batteries (in addition to their lead-acid automotive battery), however there is a shift towards Li-ion (e.g. 4$^{th}$ generation Toyota Prius). Plug-in HEVs (i.e. PHEV), however, only use lithium-based batteries, as do full battery electric vehicles (BEVs). Even within lithium ion battery types, there different chemistries available that have different benefits, particularly in terms of power density (particularly important for PHEVs), energy density, as well as other parameters (e.g. cost, cycle life, etc.). High power and high energy Li-ion batteries are often combined for better performance. For example, combinations of different battery types can be used to achieve both fast vehicle acceleration and long travelling range, but this approach generates additional complexity (e.g. also in battery management systems and for end of life processing) and extra costs.

The main Li-ion battery (LIB) chemistries used currently as traction batteries for vehicles are summarised in the following Table 3.1 and Figure 3.1, and include:

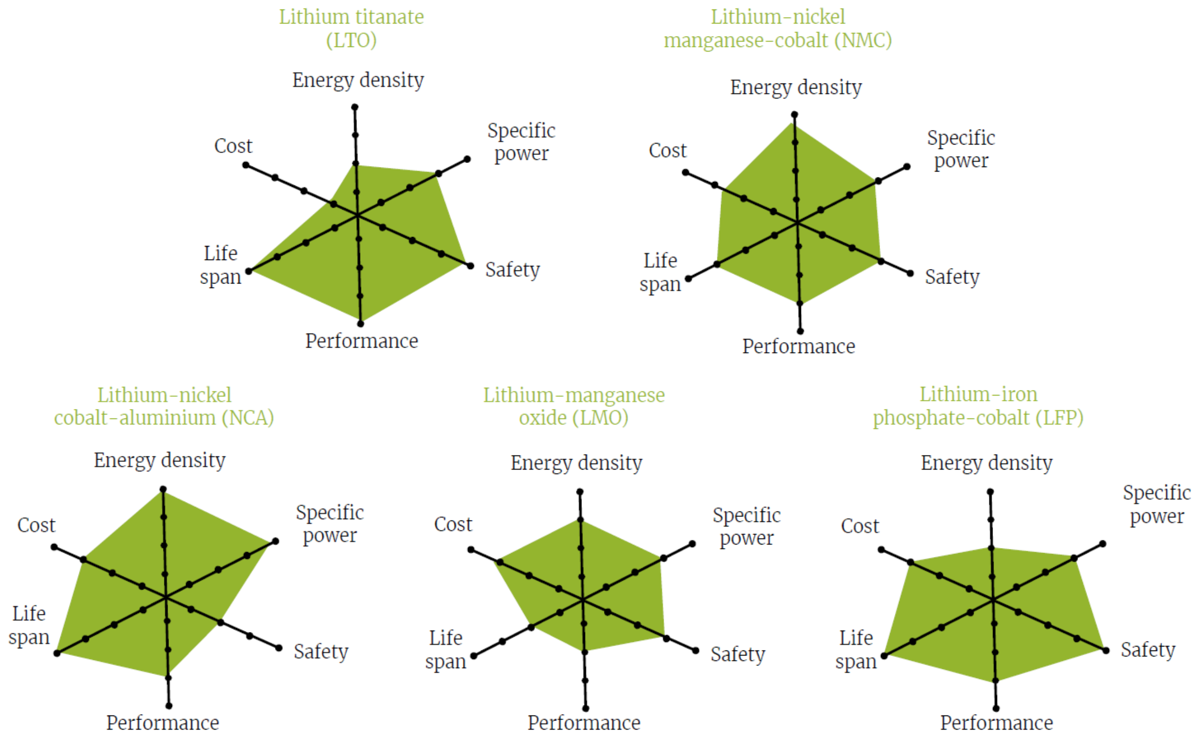
**Table 3.1: Overview of the main Li-ion battery chemistries currently used in electric vehicles**

| Abbrev. | Cathode | Anode* | 2016 EV share |
|---|---|---|---|
| LFP-C | Lithium Iron Phosphate ($LiFePO_4$) | Graphite | 35% |
| LMO-C | Lithium Manganese Oxide ($LiMn_2O_4$) | Graphite | 7% |

| Abbrev. | Cathode | Anode* | 2016 EV share |
|---|---|---|---|
| NMC-C | Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) | Graphite | 44% |
| NCA-C | Lithium Nickel Cobalt Aluminium Oxide ($LiNiCoAlO_2$) | Graphite | 14% |
| LTO | LMO or NMC | $Li_4Ti_5O_{12}$ (Lithium Titanate) | Share not available. |

*Sources*: (Battery University, 2017), (BYD, 2018). *Notes*: * Graphite is a form of carbon (C)

**Figure 3.1: Overview of trade-offs for different lithium-ion battery chemistries**




Source: (Battery University, 2017), (Reid & Julve, 2016).

Batteries also come in a number of form factors, which are also an important consideration, i.e.:

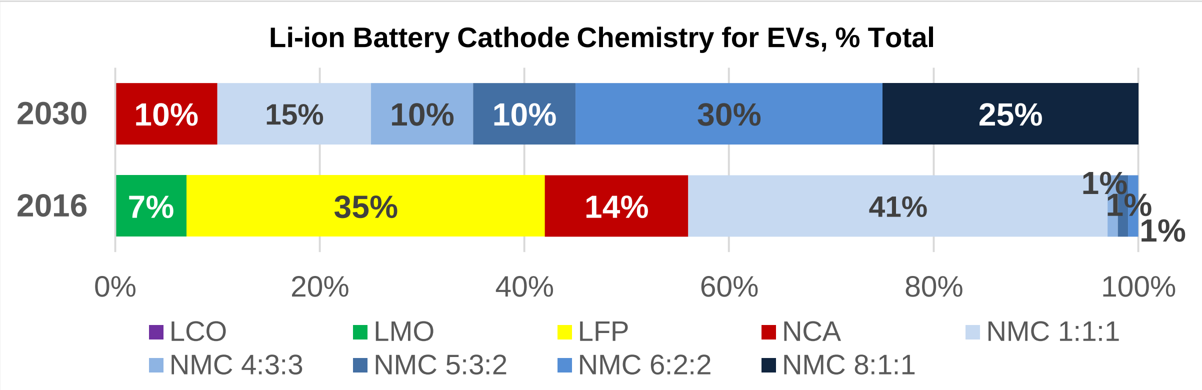
- **Cylindrical batteries**: The common form for domestic batteries with a hard case of steel /aluminium; these are used predominantly by Tesla in vehicle applications, offer a long calendar life and are low cost, but it has less ideal packaging density. They are harder to recycle /recover – they are designed to be more durable, being formed somewhat like a 'swiss roll', and require fewer mechanical confinements. Cell design also allows added safety features that are not possible with other formats (Battery University, 2017).
- **Prismatic cells:** This type is used in mobile phones, and a number of EVs, e.g. BMW i3, and are encased in aluminium or steel for stability and are generally more space-efficient than cylindrical cells. The manufacturing process also uses a jelly roll electrode, though mechanical stress on the container is higher and thermal management becomes more complex than in a pack of cylindrical cells. They are generally more expensive to manufacture, but can be easier to recycle.
- **Pouch cell:** highest energy density; used mainly for lithium-polymer batteries in EV applications (e.g. as found in the Kia Soul EV). This form uses a laminated architecture (i.e. cut electrode sheets, which is harder to manufacture compared to winding a jelly roll), in a soft case/bag, which is easier to manufacture but can be harder to recycle. Pouch cells sit in a mechanical confinement, and these fixtures and fittings are easier to recover.

Consumer requirements motivate developments in battery technology with demands for improved range, faster recharging speeds, performance, and weight (and obviously also reduced costs). Ongoing technological development work to improve the lifecycle capacity of traction batteries will not only maximise primary use for electric vehicles, but it may also lead to better options for secondary use of these batteries.

Analysis by (McKinsey, 2017a) found that there was no obvious winner in Li-ion chemistry and form factor in terms of overall performance for mass-market EVs, as their benchmarking also revealed similar energy density increases (of more than 30 percent) in the period from 2011 to 2018 across all designs. Currently LFP and LTO battery chemistries are favoured for heavy duty vehicle applications due to higher cycle life (LFP) and the ability to sustain higher charging loads (LTO) (IEA, 2018). However, most projections suggest a shift to predominantly NMC across all vehicle types between 2020-2030, e.g. Figure 3.2.

There are also a range of future battery technologies under development (covering anode, cathode and electrolyte materials) that could outperform current Li-ion batteries in the future. In the nearer-term these include Lithium Sulphur (Li-S) chemistries and solid-state (electrolyte) battery chemistries (potentially with lithium metal anodes), which are anticipated to be introduced into the marketplace by 2025[5]. There are also a number of longer-term alternative chemistries being researched, including Zinc-air and Lithium-air (Li-air), as well as sodium-ion (Na-ion) and magnesium-ion (Mg-ion) based chemistries[6]. There is also ongoing research into advanced supercapacitors with potential for EV applications[7]. With an estimated 10-15 year vehicle/battery life in their primary use, these new batteries are unlikely to be available for second-use and recycling until the 2030-2050 period.

**Figure 3.2: Current and projected Li-ion battery chemistry mix for electric vehicles**




*Source*: (BYD, 2018). *Notes*: NMC 1:1:1 = ratio of Nickel : Manganese : Cobalt in the cathode; similarly for others.

The focus for the discussion in this chapter (and in the later chapters of this report) will therefore be on Li-ion batteries, but with a higher-level analysis on the potential differences resulting from new battery chemistries in the future. For example, not many operators currently recover the graphite from battery anodes when recycling and the main shift/interest is for more conventional Li-ion battery chemistries is in utilising silicon (e.g. via dosing) in the anode to improve energy density. However, solid state batteries could use different materials and remove the need for graphite anodes completely (i.e. moving to lithium metal instead – which is also more easily recoverable). In addition, copper could potentially be removed for a solid state or sodium-ion battery (i.e. using aluminium instead).

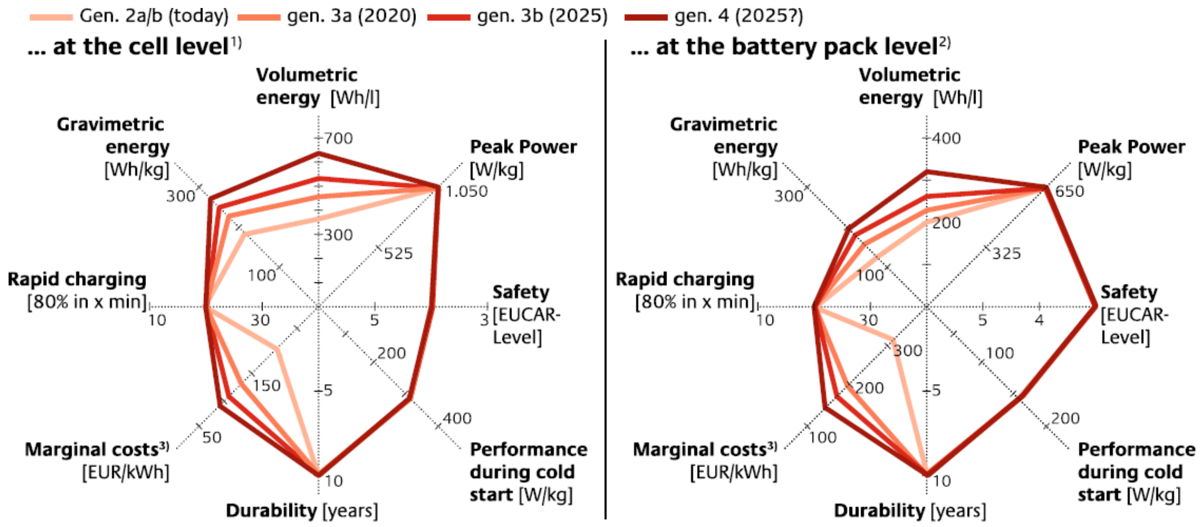
[5] The Boston Consulting Group "BCG Focus: Batteries for electric cars – challenges, opportunities and the outlook to 2020."
[6] http://www.faradion.co.uk/technology/sodium-ion-technology/
[7] https://www.autocar.co.uk/car-news/new-cars/evs-could-be-fully-charged-seconds-following-supercapacitor-revolution

### 3.1.1 High-level technology roadmap for battery chemistries

A high-level roadmap for the main different battery chemistries is presented in Figure 3.4. This is based upon a review of various sources and roadmaps on battery technology development, and was also reviewed with stakeholders as part of the consultation activities.

A further assessment of how key performance indicators for EV batteries could evolve between now and 2025 was also developed by the German electromobility platform (NPE, 2016) and is presented in Figure 3.3.

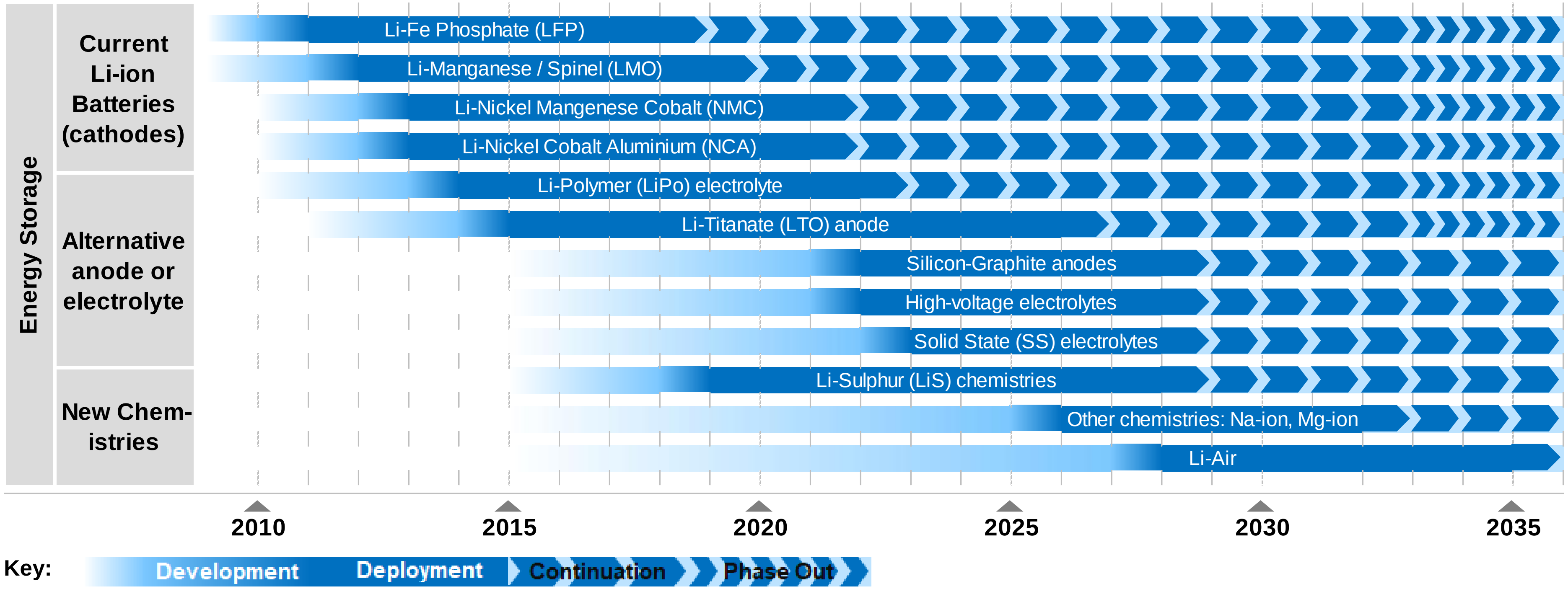
**Figure 3.3: Expectations for key performance of EV batteries today and in the future**




1) Battery cell for EV 2) Battery pack for EV with 80 kWh 3) Assuming 15 million cells over the life cycle of a vehicle or a vehicle family (currently equates to about 70.000 Gen. 2a vehicles with 20 kWh energy content respectively)
Source: NPE SWG2.2 M. Weiss, A. Lamm, P. Lamp (2015)

*Source*: (NPE, 2016). Notes: gen. 3a and 3b are further optimised developments of the current Li-ion chemistries (e.g. NMC with also anode improvements), and gen. 4 are new chemistries (e.g. solid-state, Li-S).

**Figure 3.4: High-level technology roadmap for xEV battery chemistries**




| EV Battery type | Chemistry | Manuf. using chemistry in their vehicles currently on the market | Current xEV applications |
|---|---|---|---|
| Li-ion | LFP | BYD, SAIC, Cherry | Light and heavy-duty vehicles: BEV, PHEV |
| Li-ion | LMO | Nissan, General Motors, Mitsubishi, Honda, VW | Light duty vehicles: BEV, PHEV and HEV. |
| Li-ion | NMC | Toyota, BMW, GM, Mercedes, Renault, Proterra, VW | Light and heavy-duty vehicles: BEV, PHEV |
| Li-ion | NCA | Tesla | Light duty vehicles: BEV |
| Li-ion | LTO anode | Mitsubishi, Honda | |
| Li-Polymer (LiPo) | NMC | Kia, Hyundai | Light duty vehicles: BEV, PHEV; eBikes. |
| Others | Others | None currently, research stage. | N/A |

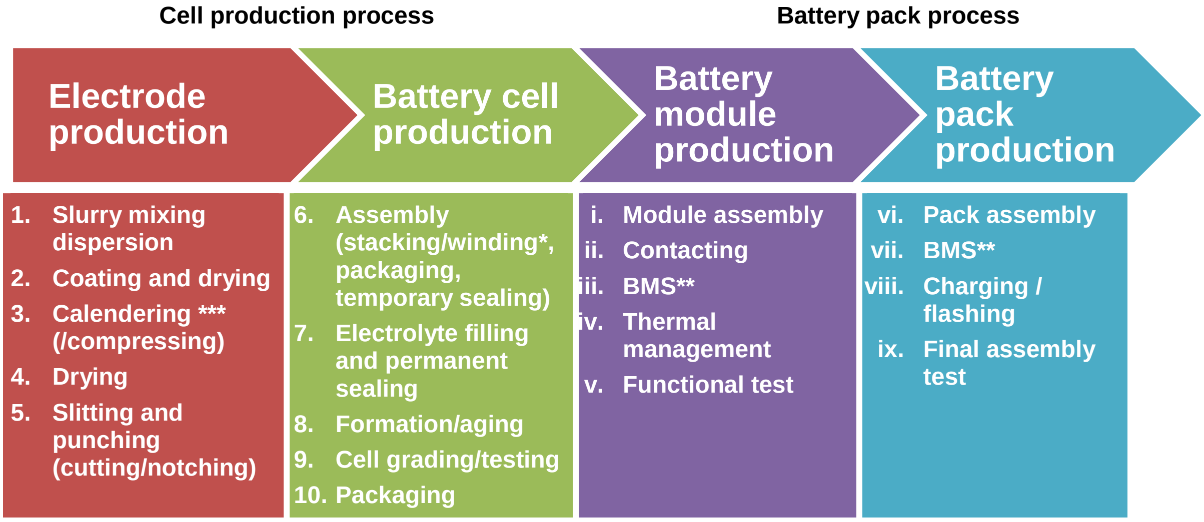
*Source*: Ricardo internal battery experts and a review of other sources, principally (NPE, 2016), (APCUK, 2017), (JRC, 2017), (JRC, 2017b), (European Commission, 2018).

# 3.2 Battery manufacturing

## 3.2.1 Overview of the manufacturing process for Li-ion batteries

Figure 3.5 provides an illustration of the key stages and sub-stages/steps involved in the manufacturing of current Li-ion batteries. The stages and processes involved are very similar for different battery chemistries, and also for different form factors (i.e. cylindrical, prismatic and pouch), though there will be greater differences within each of the steps indicated. For example, Figure 3.6 provides a high-level illustration of the cell assembly process and the small differences between cylindrical and prismatic cell manufacture. The overall processes used to manufacture cell electrodes are also similar for the anode and cathode.

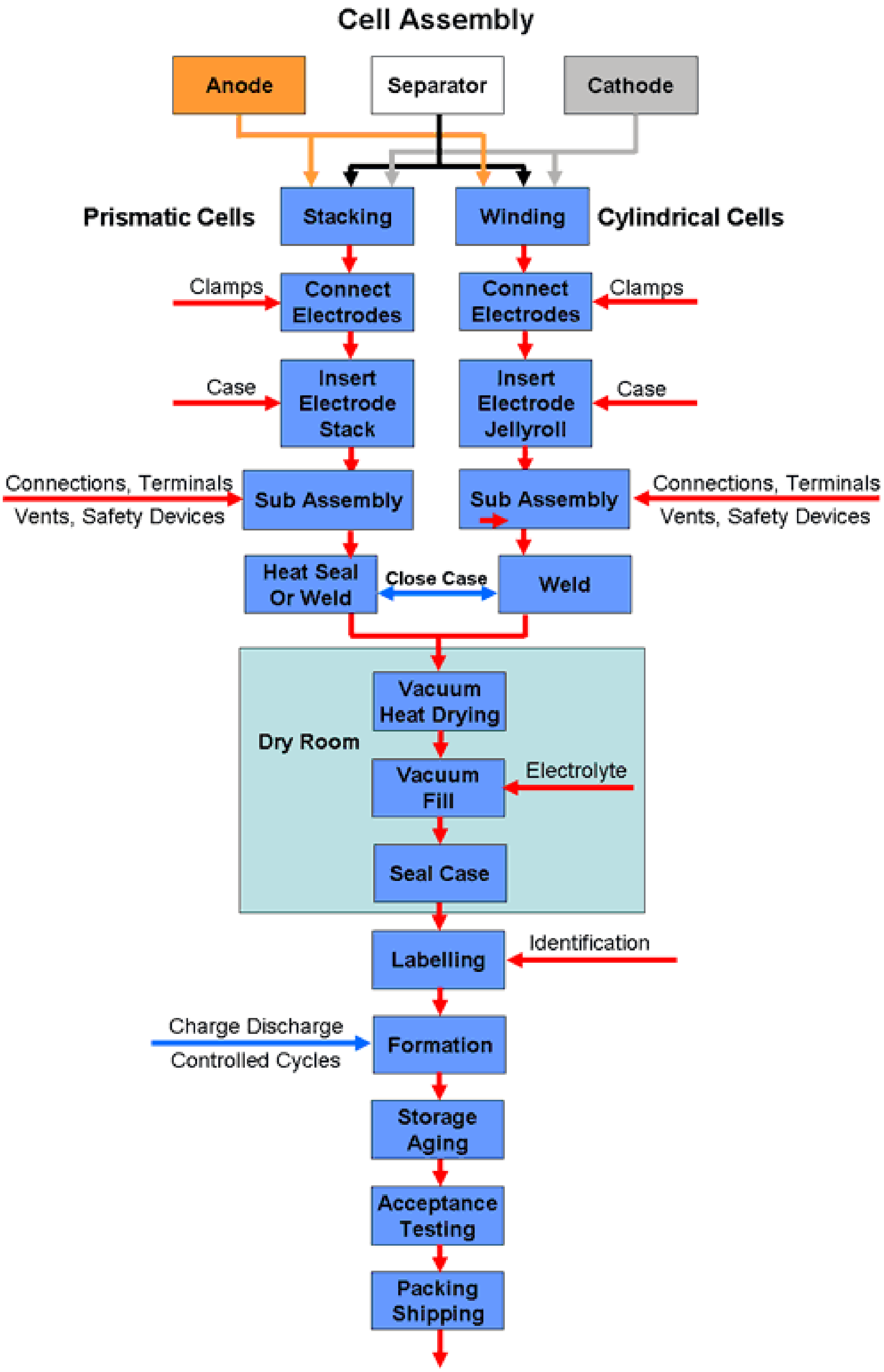
**Figure 3.5: High-level overview of the battery manufacturing process and stages**




*Source*: (Siemens, 2018), (Electropaedia, 2018), (ANL, 2018), (Gert Berckmans, 2017).

*Notes*: * Stacking for pouch cells, winding for cylindrical and prismatic cells; ** BMS = Battery Management System. *** The calendering process uses series of hard pressure rollers for compaction, to achieve uniform thickness of electrode material coatings on current collector foils.

**Figure 3.6: Overview of the cell assembly process for cylindrical and prismatic battery cells**




*Source*: (Electropaedia, 2018).

### 3.2.2 Future improvements to battery manufacturing

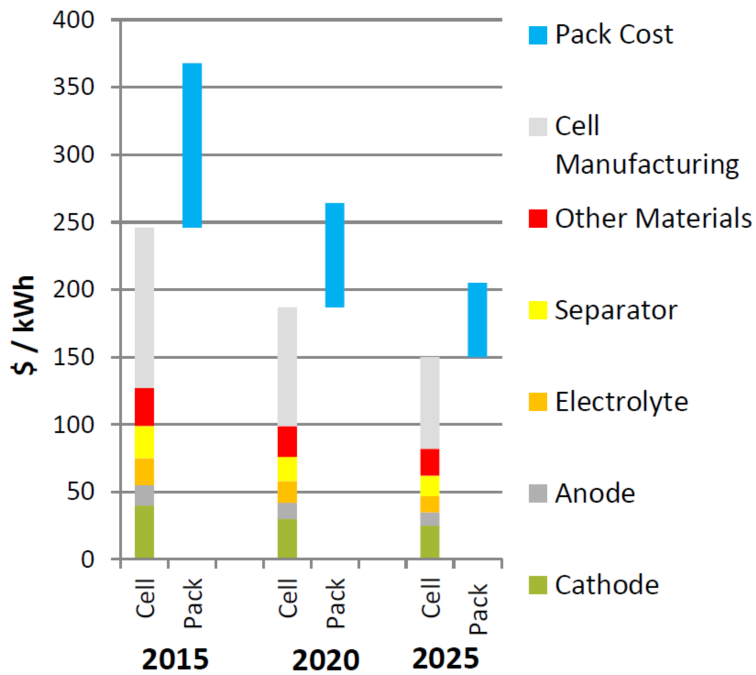
According to feedback from interviews with expert stakeholders, much of the cost reduction for battery manufacturing in the last 10 years has been due to increases in production efficiency through optimisation. Hence, current manufacturing produces significantly more kWh of batteries per annum for the same machinery than before. Energy consumption costs as much 20% (or more) of the total, so there are clear drivers to reduce this.

A range of improvements have been identified for improving battery performance and battery manufacturing itself. Such improvements are mainly driven by cost and battery performance considerations, though in many cases there will be benefits to other areas also (e.g. also discussed in later Chapter 4). For example, earlier Figure 2.9 and Figure 3.7 provide an illustration of the relative costs of different battery/manufacturing components in the overall cost of the battery cell/pack, and how these could evolve over the next decade. These highlight that the cathode is responsible for a significant component of overall costs, but that the greatest future cost reductions are anticipated through improvements in cell and pack manufacturing. These anticipated cost reductions have been assessed by experts as due to a combination of economies of scale/learning by doing, automation and technical improvements to manufacturing, see Figure 3.8 from (Sheridan Few, 2018). However, material costs are likely to be variable due to the wide range of chemistries in use, whereas cell and pack manufacturing are more uniform across the industry and therefore subject to incremental reduction.

The publicly available research is into this area is often highly detailed, but there also a lot of work that is carried out by industry that is not readily available due to its confidentiality. However, we have summarised the available information on potential future improvements to battery manufacturing in the following Table 3.2. This table includes our assessment of the likely primary impacts of the improvements. Energy consumption is an important component responsible for a significant share of the environmental impacts (see also Chapter 4) and costs of battery manufacture. The improvements that seem likely to result in the greatest cost savings (and environmental benefits) are therefore likely to be those that have an impact on particularly energy intensive materials / manufacturing stages – namely the cathode materials and drying processes, see Figure 3.9.

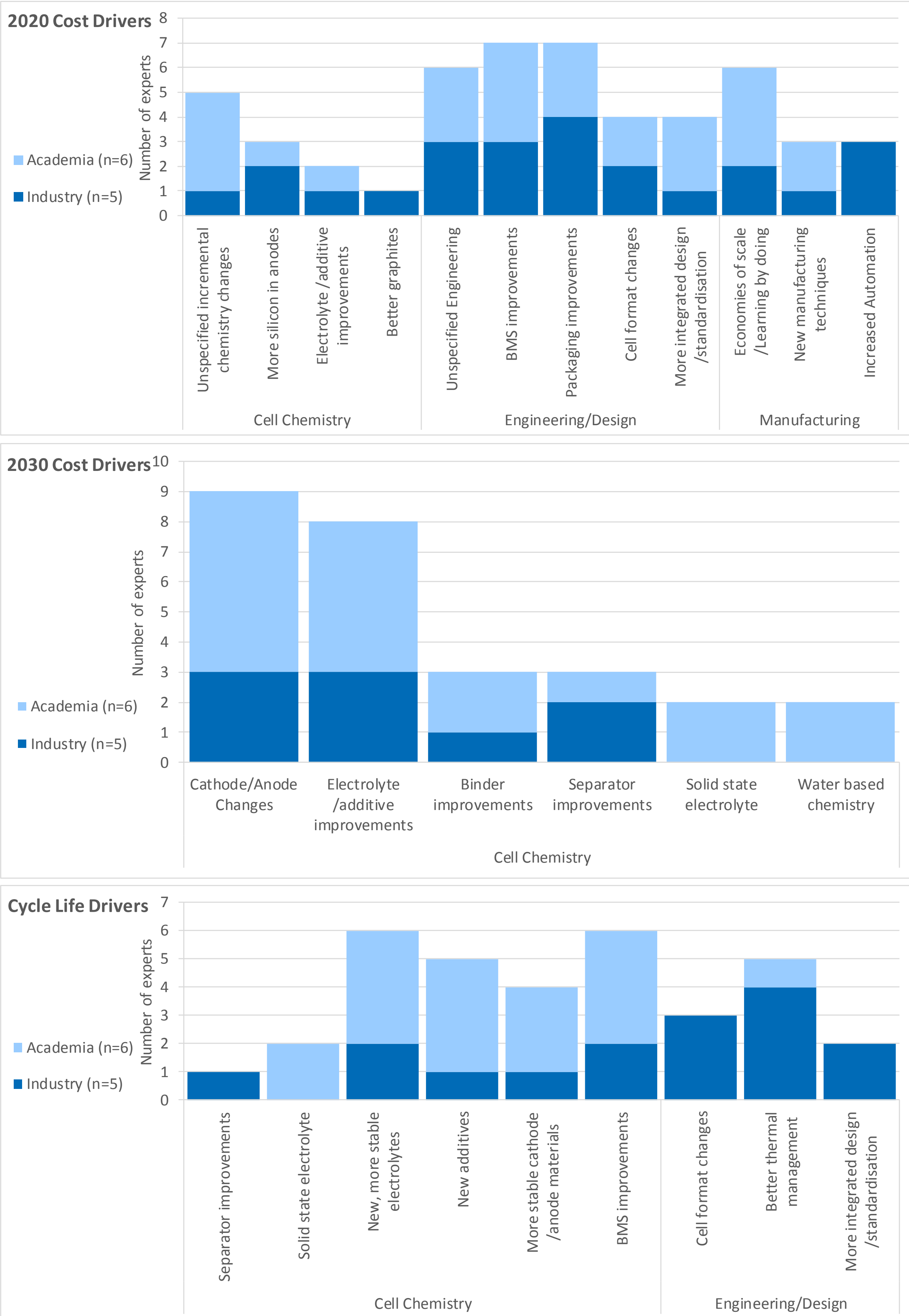
One of the big challenges is also solvent (i.e. NMP, N-Acetyl-P) recycling and reuse during the manufacturing process (Wu, 2018), hence there is significant interest in exploring alternatives.

**Figure 3.7: Evolution of LIB component, cell and pack costs for EV applications**



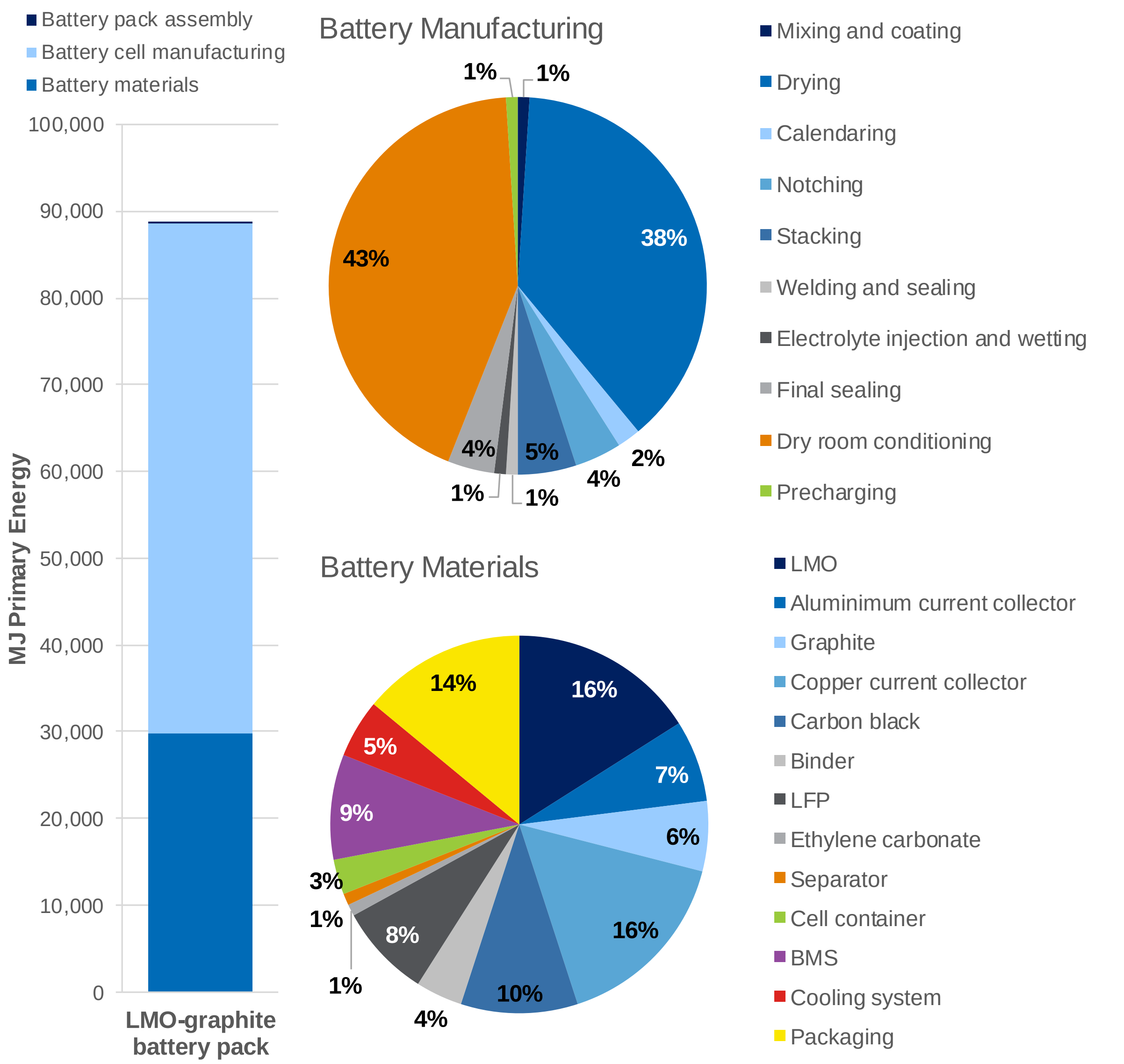

*Source*: (C. Pillot, 2017), (JRC, 2017b).

**Figure 3.8: Expert views on drivers of cost reduction and cycle life for 2020-2030 period**




*Source*: Ricardo analysis of (Sheridan Few, 2018)

**Figure 3.9: Energy intensity (total MJ primary energy and % total energy) of Li-ion battery manufacturing by material and manufacturing stage**




*Source*: Ricardo analysis of data from (Chris Yuana, 2017)

**Table 3.2: Summary of battery manufacturing process, material flow (in/out) and future developments and improvements ('+' = benefit, '-' = disbenefit, '?' = uncertain)**

| Manufacturing | Process | Materials | Future developments / improvements | Primary impacts: Cost/QA | Energy /GHG | Resource | Bat. Perf.* | Others |
|---|---|---|---|---|---|---|---|---|
| **Cell components** | Slurry mixing | + Active material<br>+ Conductive agent<br>+ Solvents<br>+ Binder | • Anode: optimised Li-ion anode materials and structures (e.g. Silicon, LTO, hard carbon – for sodium batteries) | + | | | + | |
| | | | • Anode: Next generation materials (transition metal oxides, metallic anodes and novel additives) | + | ? | ? | + | ? |
| | | | • Cathode: optimised Li-ion cathode materials and structures (e.g. LFP, NMC, NCA, LMO, etc.) | + | + | + | + | + |
| | | | • Cathode: Cathode materials for new chemistries (e.g. Na-ion, Mg-ion, Li-S) | + | + | + | + | + |
| | | | • Solvent: Solvent replacements for NMP*** (e.g. N-Acetyl-P, water) | + | + | | + | + |
| | | | • Solvent/Binder: Solvent-free/dry powder painting processes | + | + | | | |
| | | | • Solvent/Binder: Next generation binders (e.g. hybrid, self-healing) | + | | | | |
| | | | • Solvent/Binder: Binderless systems | + | + | | + | |
| | Coating | + Al/Cu foil | • Binderless systems using alternative electrode materials, removing need for metallic current collector | + | | + | | + |
| | | | • Improvements to battery collector foils through a reduction in thickness. | + | | + | | |
| | | | • Improvements to coating process/methods (e.g. dry blend/powder coating process, spray coating, other alternatives to NMP) producing thicker/graded electrodes leading to reduction in Al/Cu content. | + | | + | | |
| | | | • Changes to coating methods to respond to new chemistries not suited to current methods. | + | | | + | |

| Manufacturing | Process | Materials | Future developments / improvements | Primary impacts | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | Cost/QA | Energy /GHG | Resource | Bat. Perf.* | Others |
| | Drying | - Solvents (recaptured) | • Solvent: Solvent replacements for NMP<br>• Solvent/Binder: Solvent-free/dry powder painting process<br>• Energy reduction through reducing size of the drying rooms and optimizing process steps | +<br>+ | +<br>+ | <br>? | ?<br>? | +<br>+ |
| | Calendaring | N/A | • Further optimisation of the calendaring process/equipment | + | | | + | |
| | Slitting and punching | + Remaining Al/Cu foil | • No specific improvements identified, other than process optimisation. | + | | | | |
| | General/all | | • General process improvements and better quality control in all steps / processes – greater automation and monitoring through advanced process control (APC)<br>• Sourcing/synthesis of the raw materials with more uniformity | + | | | | |
| **Cell production** | Assembly: Stacking / Winding | + Separator<br>+ Adhesive tape<br>+ Al/Cu tabs | • New stacking processes and packaging principles to maximise energy- and power density and durability, and reduce costs<br>• Separators with reduced thickness and cost, oxidation resistance, heat dissipation and ceramic coatings.<br>• Next generation separators (e.g. phase change, auxetic structures)<br>• General improvements to stacking and welding, alt. joining methods<br>• Use of lasers for electrode cutting | +<br>+<br>+<br>+<br>+ | | | +<br>+<br>+<br>+ | |
| | Assembly: Packaging (Case / Pouch) | + Pouch Foil / Casing | • No specific improvements identified, other than process optimisation. | + | | | | |
| | Assembly: Temp. seal | + Solvents | • Inclusion of thermal protection circuits within cylindrical cells. | + | | | + | |
| | Electrolyte filling and permanent seal | + Electrolyte<br>- Remaining Al/Cu foil | • Optimised liquid electrolytes for Li-ion (e.g. high-voltage electrolytes)<br>• Liquid electrolytes for new chemistries<br>• Room temperature solid state electrolytes | + | | | +<br>+<br>+ | |

| Manufacturing | Process | Materials | Future developments / improvements | Primary impacts: Cost/QA | Energy /GHG | Resource | Bat. Perf.* | Others |
|---|---|---|---|---|---|---|---|---|
| | Formation/aging | N/A | • Reducing process time for battery formation and testing | + | | | | |
| | Cell grading/testing | N/A | • Development of rapid, non-invasive/destructive techniques (NDT) for testing Li-ion batteries | + | | | | |
| | Packaging | N/A | | | | | | |
| | General/all | | • Embedded sensors in cells | | | | + | |
| | | | • Cells that eliminate thermal runaway | | | | + | |
| | | | • Cross-OEM standardisation of cell formats | + | | | + | |
| | | | • Further process optimisation, automation, improved quality control | + | | | + | |
| **Module production** | Module assembly | + Steel / Al / plastic enclosure parts, wiring, etc | • Advanced pack design for performance and manufacturing | + | ? | ? | + | ? |
| | | | • Mixed cell packs (high energy and power) | | | | + | |
| | | | • New cell-module-pack concepts | | | | + | |
| | Contacting | | • Including components better capable of withstanding higher voltages. | + | | | + | |
| | BMS** | Various /electrical | • Smart and connected BMS enabling accurate SOC and SOH monitoring and life prediction | -/+ | | | + | |
| | | | • Distributed BMS enabling individual cell monitoring | -/+ | | | + | |
| | Thermal management | Various: electrical systems, coolant, etc. | • Advanced thermal management strategies (e.g. integrated with vehicle cooling) | ? | | | + | |
| | | | • Passive thermal management (e.g. phase change materials) | ? | | | + | |
| | Functional test | N/A | • No specific improvements identified, other than process optimisation. | + | | | | |
| | General/all | | • Further process optimisation, automation, improved quality control | + | | | | |
| **Pack production** | Pack assembly | + Steel / Al / plastic enclosure parts, wiring, etc | • Alternative automated assembly methods using screws/fixings or other means for easier disassembly | ? | ? | | | + |
| | BMS** | Various /electrical | • Similar to module production | -/+ | | | + | |

| Manufacturing | Process | Materials | Future developments / improvements | Primary impacts: Cost/QA | Energy /GHG | Resource | Bat. Perf.* | Others |
|---|---|---|---|---|---|---|---|---|
| | Charging / flashing | N/A | • No specific improvements identified, other than process optimisation. | + | | | | |
| | Final assembly test | N/A | • No specific improvements identified, other than process optimisation. | + | | | | |
| | General/all | | • Further process optimisation, automation, improved quality control | + | | | | |

*Sources*: (Gert Berckmans, 2017), (APCUK, 2017), (Brandon Ludwig, 2016), (Zachary Favors, 2015), (Fraunhofer IPA et al., 2014), (Amir A. Asif, 2017), (Siemens, 2018), (EUROBAT, 2014a), (NPE, 2016). Assessment of likely primary impacts based on Ricardo's assessment of reviewed material, to be tested with stakeholder experts.

*Notes*: Aluminium foil = cathode, Copper foil = anode. * Improvement to battery operational performance/life. **BMA = Battery Management System; ***NMP = N-Methyl-2-pyrrolidone

### 3.2.3 Implications of advanced battery chemistries

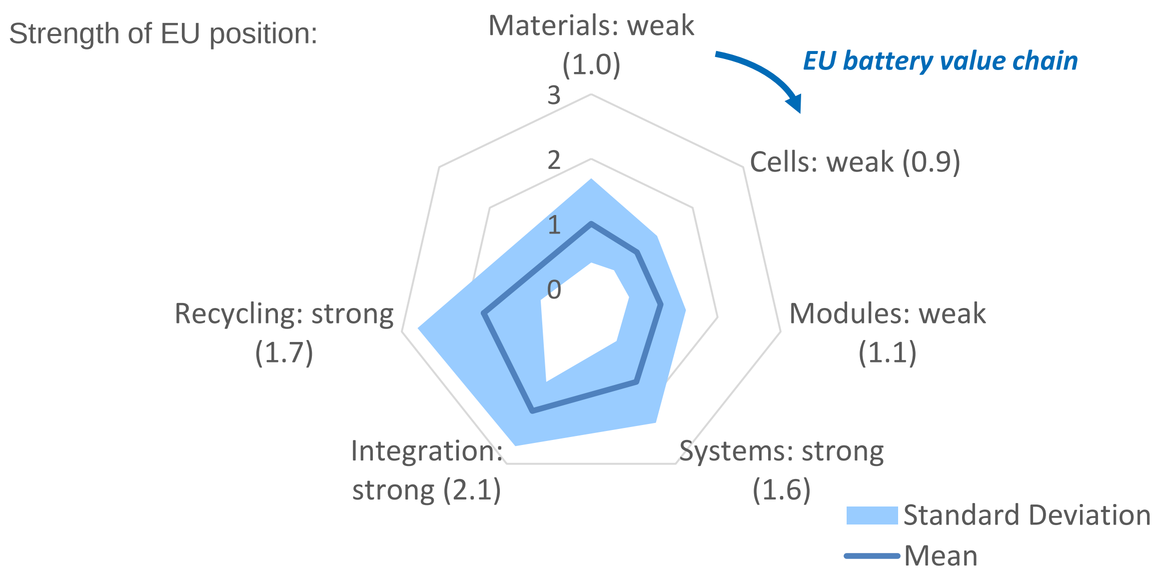
A range of advanced battery chemistries are currently under research and development, with commercial deployment expected for some of these before 2025 (e.g. Li-S and solid-state batteries), and for others (e.g. Li-air) sometime after 2030. As a result, there is currently little available information in the literature on how such new technologies might change the manufacturing processes for current LIB chemistries, and the degree to which some of the process/material improvements listed in Table 3.2 are compatible, or directly linked, to these new chemistries. The main changes indicated in the available life cycle assessments (LCA) of new chemistries for Li-S, Li-SS (solid-state) batteries and Na-ion appear to be changes to the electrolyte filling processes (mainly for solid-state and metal-air systems), and the materials/production of the anode (e.g. to lithium metal for Li-S and Li-SS) and cathodes themselves (Deng, 2017), (Peters, 2016) and (Lastoskie, 2015). It could therefore be concluded that most (with the exception of those which use metallic lithium) of the technical improvements listed in the previous section would equally apply / benefit advanced battery chemistries. This was also largely confirmed during the stakeholder consultation exercise with battery experts.

However, one stakeholder particularly emphasised that there was considerable remaining potential for improving conventional chemistries. In particular, high voltage electrolytes and silicone anodes could be disruptive, and it was suggested that with these it could be possible to reach more than 550 Wh/kg (at a pack level). In addition, the RECHARGE stakeholder interviewed pointed out that it is expected that cell manufacturing for solid state will require significant new investments and there are difficulties in scaling up ceramic- or glass-based solid-state electrolytes. Nevertheless, sodium-ion (Na-ion) batteries at least would be expected to work with similar cathodes to Li-based materials. Manufacturing processes will be similar. For the maturity of other future chemistries is not sufficient to determine what their industrial manufacturing process will be, though Li-air (which is more like a fuel cell) would require completely different manufacturing processes, so would be very disruptive. It seems likely that the current Li-ion equipment would not be re-usable to a significant extent, and the new processes may not benefit from past optimisation.

### 3.2.4 European activity

There is a range of information in the public literature on the production and sourcing of Li-ion batteries for electric vehicles, and on the options being research for improvements to these. However, it was not possible to develop a clear picture of the relative levels of research and industry activity in the three main stages of battery manufacturing in Europe versus other regions. The only sources identified that have provided an assessment are presented in Figure 3.10 and Figure 3.11 below. No significant further information/detail was identified in the interviews with stakeholders.

**Figure 3.10: Rating of EU position in the global LIB value chain**



*Source*: (JRC, 2017b), (Ecofys, 2017)

**Figure 3.11: Rating of the relative merits of different countries for battery manufacturing by NPE (2016)**

| | Weighting [%] | DE[4] "normal case" | DE-NB[5] "best case" | South Korea | Japan | Czech Republic | Hungary | Poland | Slovakia | China | USA | France |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Staff** | **30%** | **2.8** | **3.6** | **2.7** | **3.3** | **3.7** | **2.2** | **4.0** | **3.4** | **3.8** | **3.6** | **2.6** |
| Labour costs 2015 | 10% | 1 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 3 | 2 |
| Lab. c. prognosis 2019 | 30% | 1 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 3 | 2 |
| Staff availability | 30% | 3 | 3 | 4 | 2 | 4 | 1 | 5 | 4 | 3 | 4 | 4 |
| Staff motivation | 30% | 5 | 5 | 1 | 5 | 3 | 1 | 3 | 2 | 3 | 4 | 2 |
| **Energy** | **25%** | **2.2** | **4.0** | **4.6** | **1.0** | **3.4** | **3.0** | **4.0** | **3.2** | **2.0** | **2.6** | **4.2** |
| Electricity | 80% | 2 | 4 | 5 | 1 | 3 | 3 | 4 | 3 | 2 | 2 | 4 |
| Natural gas | 20% | 3 | 4 | 3 | 1 | 5 | 3 | 4 | 4 | 2 | 5 | 5 |
| **Logistics[3]** | 5% | 5 | 5 | 3 | 4 | 2 | 2 | 2 | 1 | 2 | 4 | 4 |
| **Subsidies** | 15% | 1 | 1 | 5 | 1 | 2 | 4 | 4 | 3 | 4 | 4 | 1 |
| **Exchange rate risks** | 5% | 3 | 3 | 4 | 4 | 1 | 2 | 2 | 3 | 5 | 5 | 3 |
| **Economic and financial stability** | 5% | 5 | 5 | 4 | 3 | 3 | 1 | 3 | 3 | 3 | 5 | 4 |
| **Transparency** | 3% | 5 | 5 | 2 | 4 | 2 | 2 | 3 | 2 | 1 | 4 | 4 |
| **Corporate tax rates** | 5% | 2 | 2 | 3 | 2 | 5 | 5 | 5 | 4 | 3 | 1 | 2 |
| **Innovation ecosystem** | 7% | 5 | 5 | 1 | 3 | 1 | 1 | 1 | 1 | 3 | 5 | 3 |
| **Total** | **100%** | **2.8** | **3.5** | **3.5** | **2.4** | **2.9** | **2.6** | **3.5** | **2.9** | **3.1** | **3.5** | **2.9** |

1) 5 = best rating; 1 = worst rating 2) assessment of the members of SWG 2.2 3) Reliability of logistics according to the Logistics Performance Index (LPI) of the World Bank 4) DE = average labour costs in Germany, no exemption from the EEG levy 5) DE-NB = labour costs in the new German Länder, exemption from the EEG levy
Source: Roland Berger based on own analyses and (Baehr Verpackung, 2015) (Busan Agency Co. Ltd., 2015) (CEIC, 2015) (City of Yokohama, 2015) (Countryeconomy.com, 2015) (OECD.stat, 2015) (Department of Energy & Climate Change, 2015) (Elkind, 2014) (EUI, 2015) (European Commission, 2014) (eurostat, 2015) (GTAI, 2014) (IMD, 2015) (KEPCO, 2015) (KOGAS, 2015) (State Administration of Taxation, 2013) (Transparency International Deutschland e.V., 2014) (MOL, 2014) (MOL, 2015) (paper.people.com.cn, 2013) (pk Elektronik, 2015) (U.S. Energy Information Administration, 2015) (Wesoff, 2015) (Worldfreightrates.com, 2015) (Worldbank, 2015)

*Source*: (NPE, 2016)

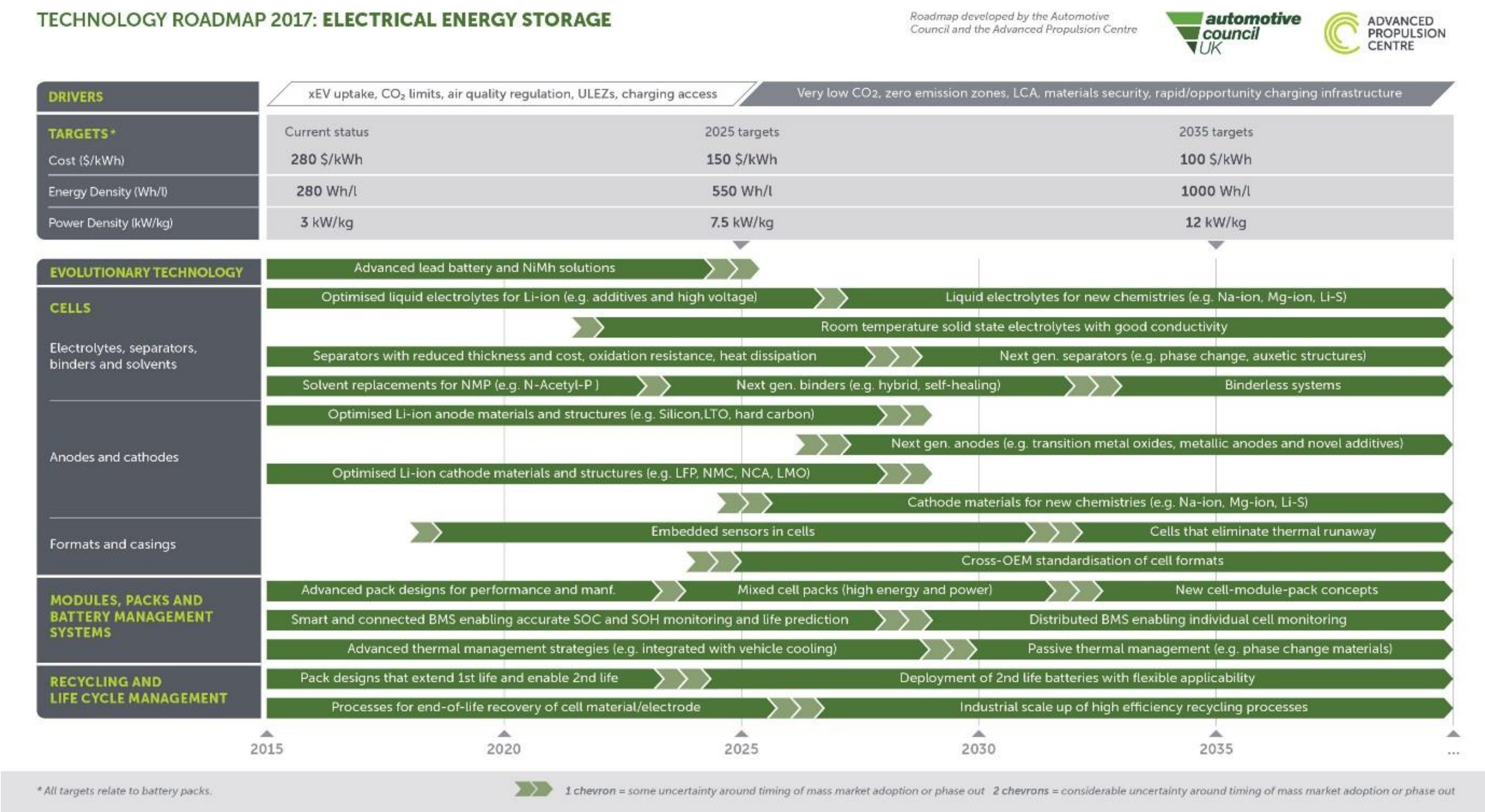
## 3.2.5 Technology roadmap for battery manufacturing

Figure 3.12 shows a roadmap for battery energy storage that visualises the direction of technological development. This roadmap is the most detailed one identified in the literature review (with others mainly covering higher-level battery chemistry changes only) and was developed already in close consultation with stakeholders. The roadmap complements the areas for improvement identified already in in the earlier Table 3.2, and was also tested/reconfirmed with stakeholders in this project.

According to (NPE, 2016) major changes in battery cell technology affect the production stages of electrodes and cells to different degrees, and according to (Wu, 2018), current battery pilot lines can't handle some advanced battery types (e.g. metal-air systems); the manufacturing equipment currently doesn't exist for mass production yet. It is recommended that future development efforts therefore focus on the implementation of modular manufacturing systems that would allow for flexibility in adjusting the processes or expansion depending on developments in this area (although this would come at a higher up-front cost). This would make transitions to new cell generations simpler, faster and more cost-effective, requiring more minor modifications to machines and systems.

It is estimated that around 50 % of the current battery production plants can remain in use once the transition from optimised conventional Li-ion chemistries (i.e. based on NCA, NMC, etc) to new solid-state, Li-S or other advanced chemistries occurs. This was confirmed by stakeholders who suggested that the majority of new chemistries could be achieved with minor changes to the production process. This is not, however, the case for Li-air, which would need a completely different process.

**Figure 3.12: ACUK/APCUK Electrical energy storage technology roadmap**



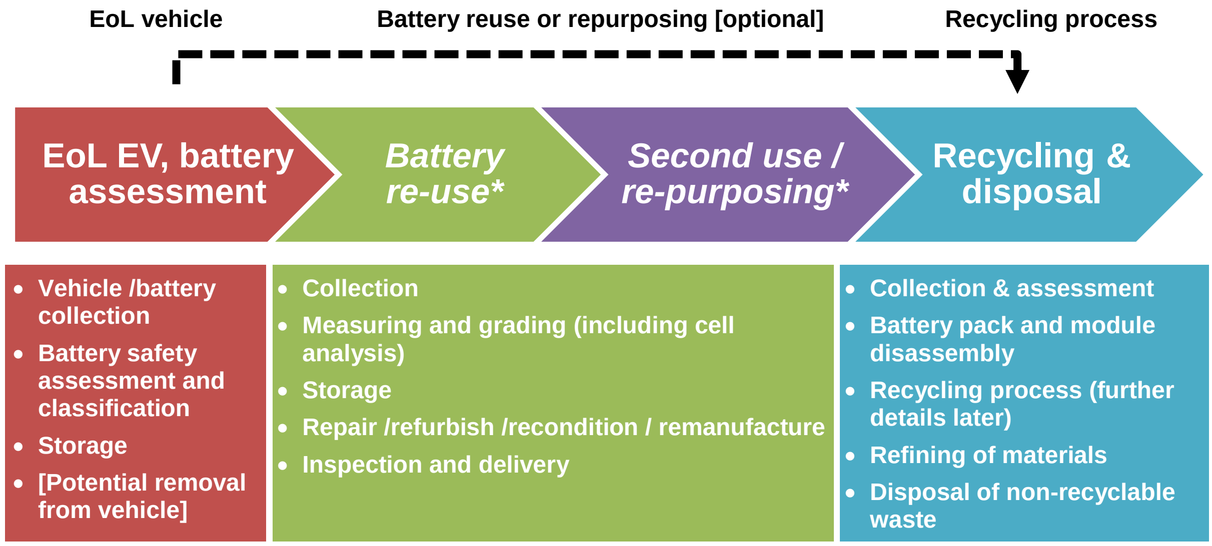

*Source*: (APCUK, 2018)

## 3.3 Battery re-use, re-purposing for second life and recycling

### 3.3.1 Overview of re-use, re-purposing and recycling

The following Figure 3.13 provides an illustration of the key stages and sub-stages/steps involved in the end-of-life vehicle/battery processes for Li-ion batteries for a circular economy, including the optional battery reuse/repurposing stages. Re-use or Second use / repurposing are *optional* additional steps in the value chain that may be applied where feasible. The principle approach adopted in the EU is that whenever batteries become waste (e.g. where further reuse or repurposing is not feasible) they should be recycled. The stages and processes involved are similar for different battery chemistries, and also for different form factors (i.e. cylindrical, prismatic and pouch), though there will be some differences within each of the steps indicated to account for variations in these. RECHARGE has also previously outlined a high-level summary of the options for the fate of rechargeable batteries at the end of their first-life application, illustrated in Figure 3.14.

**Figure 3.13: High-level overview of the battery manufacturing process and stages**




*Sources*: (RECHARGE, 2014), (Tytgat & Tomboy, 2017), (Gattiglio, 2017).

Notes: * Reuse and second use / repurposing are *optional* additional steps.

The main parameter influencing the processes adopted is the batteries' economic value at their ultimate end of life. According to (RECHARGE, 2014), when this value is positive, recycling is an alternative to second life. However, the value of recovered products (metals, chemicals) may be lower than the cost of recycling, in which case the final stage of recycling is a net cost and cannot have a positive impact on the value chain of batteries, reducing the initial cost. It is unclear, currently, how the economics of recycling are likely to evolve depending on technological and economy-of scale improvements.

Once a battery has reached the end of its first or second use and is deemed no longer suitable for further reuse or repurposing, it will need to move to recycling (and/or disposal). There are a small number of techniques used in battery recycling, which also include pre-treatment steps (including deactivation of the battery), which can be summarised in the following categories:

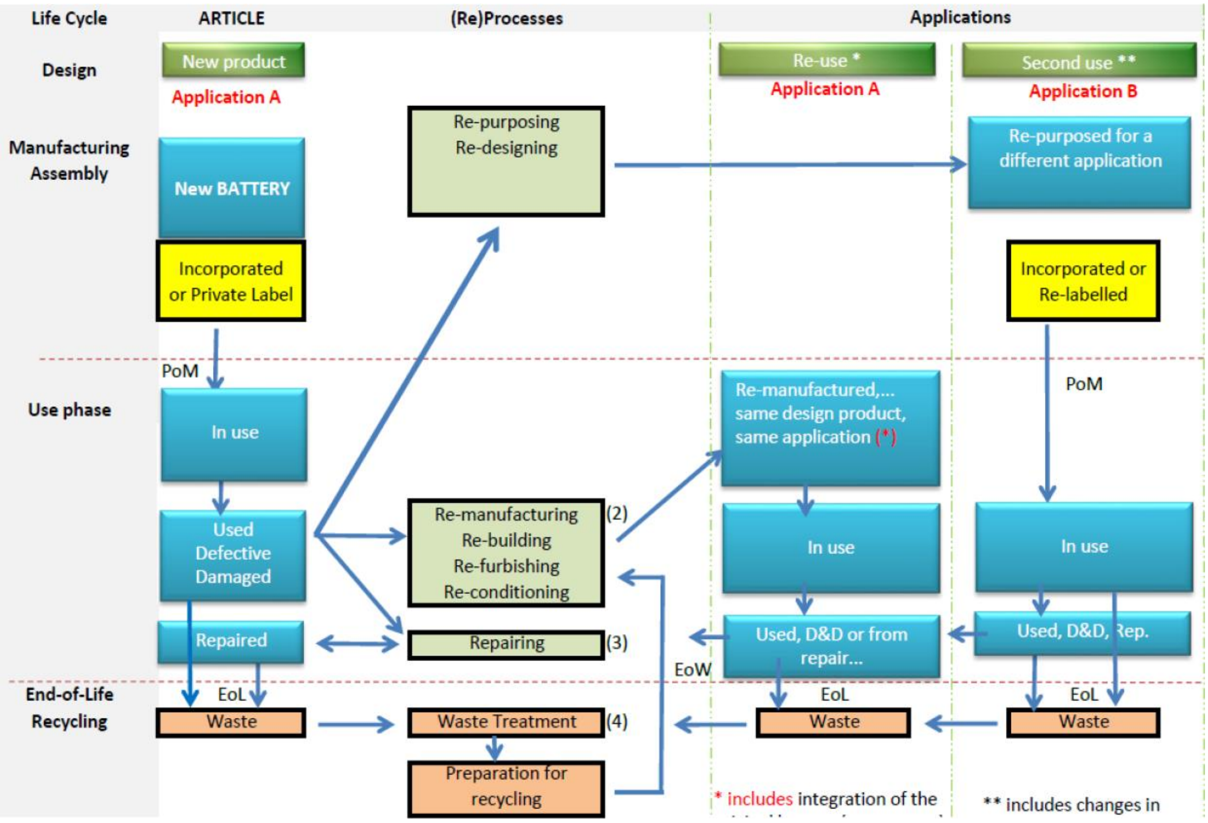
- Physical processes:
  - Mechanical
  - Pyrometallurgy (smelting)
- Hydrometallurgy: chemical and biological processes
- Hybrid processes (i.e. pyrometallurgy and hydrometallurgy, mechano-chemical processes)
- Intermediate, and
- Direct.

Some organisations have also developed their own hybrid techniques which are sometimes referred to by the name of the organisation that uses or developed it (e.g. the Umicore process, or the Retriev process). (B. Friedrich L. P., 2017) provides a useful categorisation for the different elements involved in such processes according to the following general steps in Table 3.3, with an overview of how the processes are interlinked provided in Figure 3.15. In addition, a qualitative assessment is provided of a number of industrialised recycling processes in Table 3.4.

In some cases, depending on the (a) recycling process, (b) battery type and (c) material, not only recovery of component elements is possible, but also the engineered morphology (i.e. the specific materials used in battery production – sometimes called direct recycling).

The following subsections provide further details on battery re-use and repurposing, and recycling.

**Figure 3.14: Schematic from the RECHARGE association showing the various service life options for a rechargeable battery**



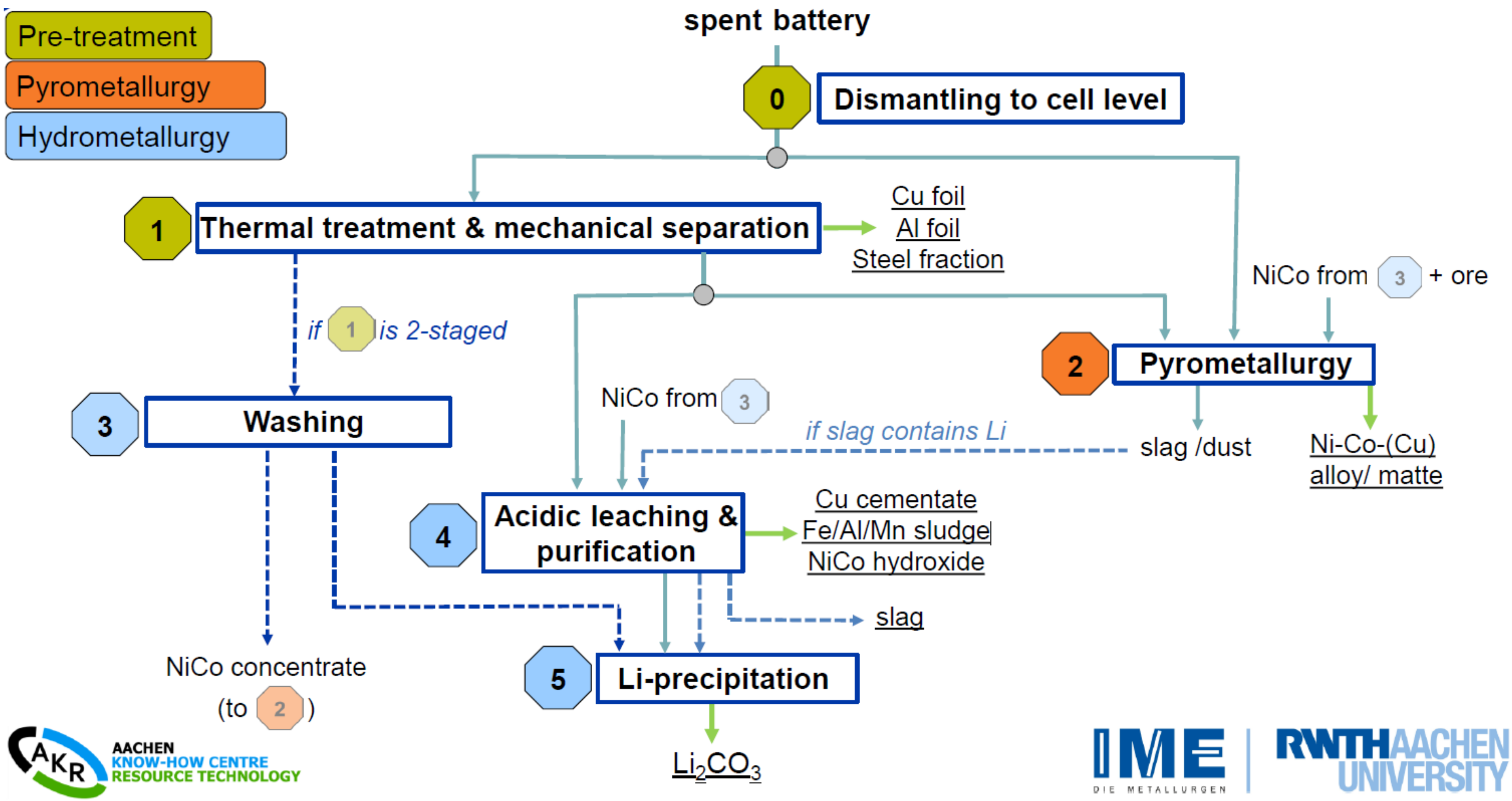

*Source*: (RECHARGE, 2014)

**Table 3.3: General categorisation of the recycling process steps following collection and assessment**

| Type | # | General process |
|---|---|---|
| Pre-treatment | 0 | Cell discharging and dismantling to cell level |
| Pre-treatment | 1 | Thermal treatment & mechanical separation |
| Pyrometallurgy | 2 | Pyrometallurgy |
| Hydrometallurgy | 3 | Washing |
| Hydrometallurgy | 4 | Acidic leaching & purification |
| Hydrometallurgy | 5 | Li-precipitation |

*Source*: (B. Friedrich L. P., 2017).

**Figure 3.15: Overview of various recycling treatment options / stages**




*Source*: (B. Friedrich L. P., 2017).

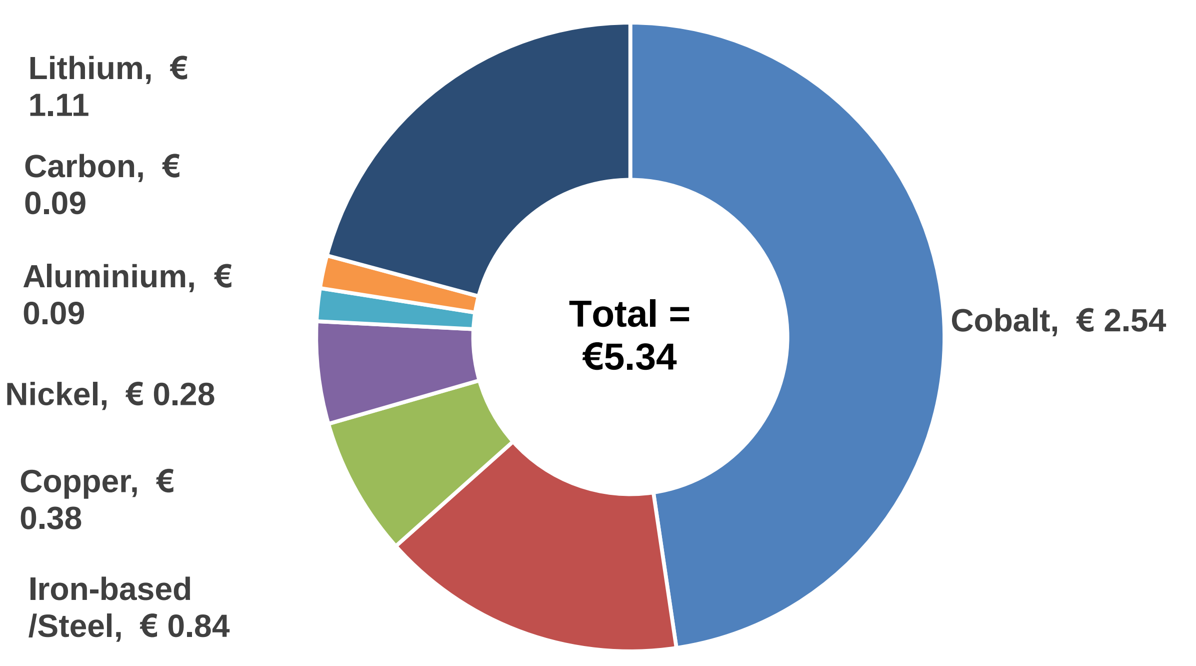
**Table 3.4: Qualitative comparison of different industrialised recycling paths /processes**

| Path | Recycling steps | | | | | | Keywords | Recovered Metals | Energy | Chemicals/ Additives | By-product generation | Safety Risk | Accessibility for EU | Basket value per kg | % Max |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 | | | | | | | | | |
| 1 | ✓ | (✓) | ✓ | | | | Pyrolysis in rotary kiln, EAF & converter | Ni, Co, Cu, (Fe) | High | Low | High | Low | No | €4.03 | 75% |
| 2 | ✓ | | ✓ | | | | Smelting in shaft furnace | Ni, Co, Cu, (Fe) | Medium | Low | High | Medium | Yes | €4.03 | 75% |
| 3 | ✓ | ✓ | ✓ | | | | Thermal treatment + Mechanical separation, Pyrometallurgy | Ni, Co, Cu | High | Low | Medium | Low | Yes | €4.52 | 85% |
| 4 | | | ✓ | | | | Direct smelting in EAF | Ni, Co, Cu | High | Low | High | High | Yes | €3.21 | 60% |
| 5 | ✓ | ✓ | | | ✓ | ✓ | Pyrolysis, Mechanical + Hydrometallurgy | Ni, Co, Cu, Fe, Mn, Li | High | High | Low | Low | Yes | €5.34 | 100% |
| 6 | ✓ | (✓) | | | ✓ | | Mechanical (inert gas) + Hydrometallurgy | Ni, Co, Cu, | Medium | High | Low | Medium | Yes | €4.32 | 81% |

*Source*: (B. Friedrich L. P., 2017).

*Notes*: Recycling steps according to Table 3.3, breakdown in value of materials per kg of battery from Figure 3.16. EAF = Electric Arc Furnace.

**Figure 3.16: Breakdown of the recycled materials value in the average Li-ion battery, € per kg of battery scrap**




*Source*: (B. Friedrich L. P., 2017). *Notes*: Based on average for the battery types LCO, NMC, LMO, LFP and NCA.

### 3.3.2 Battery reuse and repurposing

From both an economic and technical point of view, the possibility of reusing the whole battery pack without dismantling it is the preferable option according to (Bobba, et al., 2018), and interviews with stakeholders. However, there are also important economic and social conditions needed to make this happen. An assessment of the battery is first performed to assess the pack as a whole (and sometimes also individual modules, cells where the BMS/information allows this). The costs for reuse/repurposing of the whole pack are estimated as no more than 10% of the cost of manufacturing new batteries, according to feedback from the stakeholder interviews.

If it is not possible to reuse the pack as a whole, the battery pack can be remanufactured. Remanufacturing for reuse (or repurposing) has to do with replacing cells within a battery that can no longer hold sufficient charge to meet the standards for use in a vehicle (or alternative second life). Remanufacturing involves partial disassembly of the battery, removal of substandard cells, replacement of these cells, and reassembly of the battery (Foster, Isely, Standridge, & Hasan, 2014). As outlined in section 2.5.1, the key stages in battery re-use and for repurposing for second use are similar, though there will be different technical/performance and cost requirements for reuse (typically >80% of original capacity) and second life application (<80% of original capacity, with the cut-off point for EoL recycling being less clear):

- Collection/ return to reconditioning facility
- Measuring and grading
- Storage
- Repair/refurbish/recondition/remanufacture
- Inspection and delivery

(Ramoni & Zhang, 2013) highlight the importance of all of these stages in remanufacturing, emphasising that "*proper handling throughout storage and transportation of EV batteries are required to minimize possibility of damages*".

The repair / refurbish / recondition step can be carried out in a number of different ways, depending on the level of technical difficulty the remanufacturer wishes to go into. A key challenge in refurbishment is that cells of difference performance will be in the same pack - this needs innovations in the power electronics, such as in cell-by-cell control. For Nissan's re-use programme outlined in section 2.5.4, all 48 modules are assessed and those with <80% capacity are replaced (Clean Technica, 2018), however it does not appear that the replaced modules undergo any repair or refurbishment, they seem to simply be replaced. (Kampker, et al., 2016) estimate that 0% to 15% of the cells need to be replaced for remanufacturing. This is also consistent with (Foster, Isely, Standridge, & Hasan, 2014), which considers 85% of the batteries are reusable at end of vehicle application life, and that the remaining 15% being are damaged beyond repair (also discussed further below). It should be noted though, that this is dependent on the ownership model for the battery and the warranty it was sold/leased under. For example, if an OEM guarantees a certain level of performance through a battery lease, this may lead to high numbers of batteries coming to be repurposed due to relatively high SOH at the end of first life. Conversely, if the battery is privately owned, this may lead to a significantly lower SOH at the end of first life due to the high cost of replacement which the owner may not deem to be necessary.

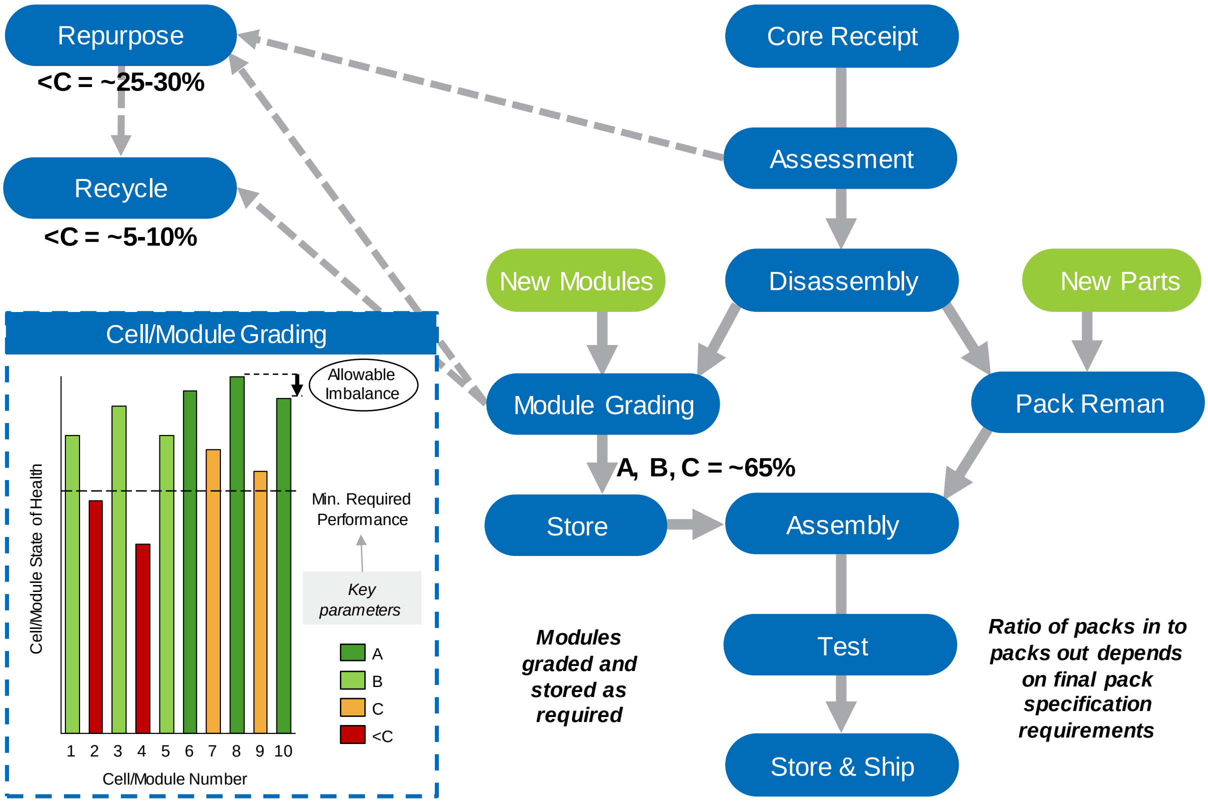
There are strong drivers for battery remanufacturing, since OEMs have to ensure there will be an adequate supply of parts for their vehicles beyond their active production period, for up to 15 years or more. Typically, other parts will also be remanufactured or sourced from low-volume manufacturers to cover such repairs/replacements. However, high-volume battery manufacturers are unlikely to be able/willing to produce the low volumes of batteries required to service remaining vehicles towards the end of their life (except at extremely high cost), and there are limits as to how long battery packs could be stored in advance (even in ideal conditions). Therefore, remanufacturing offers a route to provide lower cost replacements past the end of the production of the vehicle model. The following Figure 3.17 provides an illustration of the relationship between remanufacturing (for reuse), repurposing (for second use) and recycling. This strategy is already applied by some processors of used HEV battery packs. The module (or cell, if the module is designed with disassembly in mind) grading process dictates whether the module or cell goes to remanufacturing, repurposing or recycling, i.e. the best cells are grouped together to produce higher overall average quality packs, lower quality cells are repurposed, and the too far degraded/damaged cells are recycled. The grading process may assess a range of parameters on the battery characteristics and state-of-health, also depending on what information is available from the battery management system.

More detailed technical processes would require the battery to be completely disassembled and then all components undergoing cleaning, examination and repair if necessary / possible (Ramoni & Zhang, 2013). During the disassembly stage, planning, safety and power management are crucial. However, there are a number of difficulties in planning disassembly, particularly in determining the optimum sequence to carry it out and level of disassembly required (Ramoni & Zhang, 2013). In terms of safety, "disassembly might require the absence of atmospheric air to prevent oxidation of the cathode". Disassembly was highlighted as a key area for improvement in the stakeholder interviews. It was suggested that the use of AI and advanced robotics will lead to substantial changes in safety, reliability and efficiency of the process. However, stakeholders feel that there is still considerable uncertainty in the final economics for battery reuse/repurposing. Therefore, if the overall environmental benefits were greater than simply recycling, a mechanism to ensure second life use happens would be needed, where feasible from a performance perspective. It may also be desirable to adopt policies that would ensure that the key resources locked up in EV batteries don't 'leak out' of the EU after their first life use. Warrantee is a big issue that needs to be addressed for second life. Generally, it was felt more research was needed to understand the potential for reuse and repurposing, and the complex issues involved.

Repair could include SEI removal from electrodes, something which (Ramoni & Zhang, 2013) highlight as being important to *"rejuvenate the electrodes and enable high ions transfer, replacing the worn-out electrolyte, the cells will be ready for reassembly for EV reuse or lower performance applications use"*. However, in practice this is likely to be extremely difficult to do according to (Wu, 2018).

The shares of cells/modules going to recycling following grading processes will increase for older vehicles, or those used intensively or in adverse environmental or usage conditions.

**Figure 3.17: Illustrative process / decision-tree for warranty or other return, or end-of-life batteries determining suitability for remanufacture for reuse, repurposing for second use, or recycling**




*Source*: Ricardo research, feedback from stakeholder interviews.

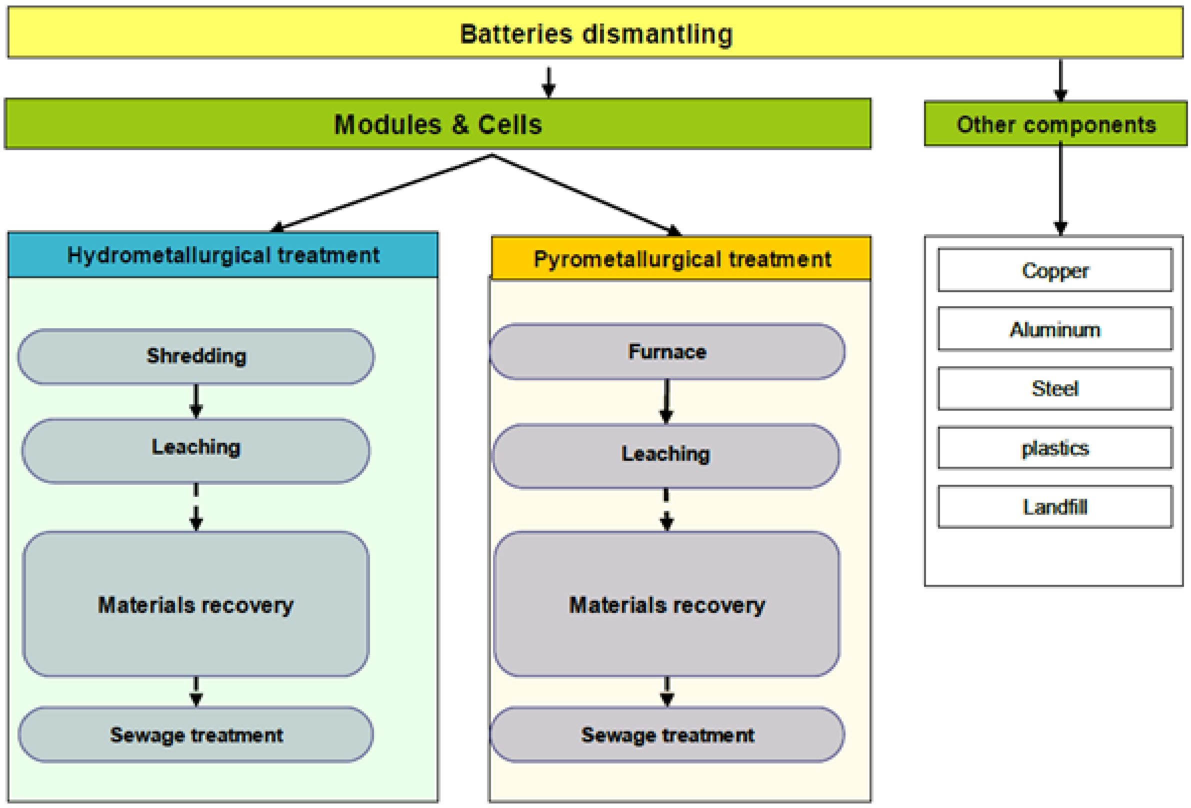
### 3.3.3 Recycling: Pyrometallurgy (smelting)

Pyrometallurgy, also sometimes referred to as "smelting" (Gaines, 2014), use high temperatures to transform, separate and purify metals (CEC, 2015),.

According to (Gaines, 2014), there are no standard pyrometallurgical processes and each company that uses this technique has developed its own bespoke method, however the following are presented as example pyrometallurgical steps, also illustrated in Figure 3.18:

- Dismantle to module level;
- Feed into a high-temperature shaft furnace (combined with a slag forming agent);
- Electrolyte and plastics burn to supply some of the energy for the smelting, and the valuable metals are reduced to an alloy of copper, cobalt, nickel, and iron.
- The metals are recovered from the alloy by leaching.

**Figure 3.18: Generic schematic of treatment processes for EV drivetrain batteries at their end of life**




*Source*: (Renault, 2011)

The process is currently operational and economical for batteries with cathode materials containing cobalt and nickel, it is not for designs with manganese spinel or LFP cathodes (Gaines, 2014).

Fundamentally this technique for recycling can be applied equally for new or advanced battery chemistries also, however recovered materials / benefits will be variable based on the specific chemistry / battery type, and newer chemistries are likely to yield reduced product value (e.g. with lower content of high value materials, such as cobalt in particular).

By itself, this technique is unable to recover lithium in a form that can be reused for battery applications: the slag contains lithium, aluminium, silicon, calcium, iron, and any manganese that was present in the cathode material. Recycling of aluminium or lithium from the slag is neither economical nor energy efficient (Gaines, 2014). The following table, from (Naberezhnykh, et al., 2013), provides a summary of the advantages and disadvantages.

**Table 3.5: Summary of the advantages and disadvantages of pyrometallurgical recycling processes**

| Advantages | Disadvantages |
|---|---|
| Allows rough separation of more and less valuable materials. Only more valuable materials are further refined, and low value elements are recycled as slag. | Profitability is dependent on scale. Costs are lowered by building large multifunctional installations. |
| Relatively cheap – doesn't consume chemicals or energy maintain. Battery contains enough energy sustain pyrometallurgical process. | Often intensive requirement of energy to get process started. |
| All solvents are destroyed in process and the off-gas is cleaned. | Emissions control needed. For example, care is needed not to form highly corrosive HF when burning binders since they have fluorine in them. |

| Advantages | Disadvantages |
|---|---|
| Very little waste. Only waste fraction produced is fluorine containing residue, however research into the recovery fluorine is currently being undertaken. | Slag is obtained as a recycling product; it has a commercial risk as it can only be used for construction products and it is low value. |
| Process is very robust – all types of Li batteries can be treated together. | Further treatment required to separate and refine the products. |
| Direct recovery of metals. | Relatively low extraction of valuable metals? |
| Low space requirement. | Greenhouse gas emissions from combustion. |

*Source*: (Naberezhnykh, et al., 2013)

### 3.3.4 Recycling: Hydrometallurgy

In this process, there are two main steps, one mechanical and one chemical. The mechanical phase involves separation of materials (metals, paper, plastic and black mass) by shredding. The chemical process is then applied to the black mass resulting in a solution which is then treated (for example, by electrolysis) to separate out the dissolved metals (CEC, 2015). Overall the steps followed are somewhat similar to pyrometallurgy, as summarised in Figure 3.18, and can also be used in a complimentary way in combination with pyrometallurgy in hybrid recycling processes. For example, Umicore developed a hydrometallurgical process to leach lithium from the slag fraction with the resulting lithium carbonate then usable for manufacture of new Li-ion batteries. However, this is only feasible economically if it is carried out on a large scale according to (Naberezhnykh, et al., 2013).

A summary of the advantages and disadvantages is provided in Table 3.6, from (Naberezhnykh, et al., 2013).

**Table 3.6: Summary of the advantages and disadvantages of hydrometallurgical recycling processes**

| Advantages | Disadvantages |
|---|---|
| Low set up costs – not only capital investment but also competences i.e. hydrometallurgy is easier | All metals/materials have to be refined even if it doesn't pay off – no 'low value' solution such as slag. |
| Can be built on smaller scale than pyro plants. | Requires input of chemicals and energy. Large consumption of acids/bases required to dissolve low value elements. |
| Allows for maximum extraction of metals. | Contaminated plastics often sent to landfill. |
| Easy to adjust for changes in product requirements. | Problem with what to do with solvents – sometimes released into nature, other option is energy recovery which is costly. |
| High selectivity. | High amount of water required. |
| Low off-gas volumes. | Low productivity. |
| Extraction of ignoble metals possible. | There is currently no requirement to label cells – makes separation of chemistries difficult. |

*Source*: (Naberezhnykh, et al., 2013)

### 3.3.5 Recycling: Direct (Li-ion)

Direct recycling allows for the recovery of the majority of battery components (i.e. cathode, anode, electrolyte, metals) for reinsertion into the battery supply chain with little or no additional processing. The steps involved are outlined by (Gaines, 2014):

- Breached, discharged cells are placed in a container.
- $CO_2$ is added, and the temperature and pressure are raised to bring $CO_2$ above its critical point.

- The supercritical carbon dioxide extracts the electrolyte (ethyl methyl carbonate, diethyl carbonate, and $LiPF_6$) from the cells, and is removed.
- The electrolyte separates from the gaseous $CO_2$, and after further processing, can be recycled for use in batteries if it is determined to be economic.
- The cells, devoid of electrolyte, undergo pulverization or other size-reduction steps, possibly in the absence of water or oxygen to avoid contamination of materials.
- Subsequently, the cell components are separated through techniques that exploit differences in electronic conductivity, density, solubility, or other properties.
- Cathode materials may need to undergo re-lithiation prior to reuse in batteries.

Previously a single chemistry has been required for such processes, however newer processes are being developed that offer the potential to be more flexible to different chemistries and electrodes (OnTo Technology LLC, 2016). There is some uncertainty as to whether the recovered components and materials would be of a high enough quality for their original applications, however they could potentially be used in applications with less stringent requirements. Furthermore, given the pace of development of battery technology, it may be that some of the recovered materials and components would no longer be directly applicable in the manufacture of new EV batteries once recovered at the end of their first life (in 10-15 years), and this is likely to be exacerbated following a further delay due to second-life applications.

### 3.3.6 Recycling: Intermediate process (Li-ion)

(Gaines, 2014) also outlines the steps involved in intermediate recycling processes, which is only economical if cobalt and/or nickel are contained in the cathodes of the feed batteries:

- A hammer-mill is used to reduce size and plastics and metals are separated using a shaker table
- The aqueous stream from the hammer mill is filtered yielding mixed metal oxides, carbon, and a liquid stream
- The liquid stream is then “dewatered to some extent”. It can be mixed with “soda ash to precipitate $Li_2CO_3$, which is subsequently filtered from the solution and sold”.
- “The metals (including the Al) can be separated and sent for recycling.”

### 3.3.7 Future improvements to battery reuse, repurposing and recycling

The potential for battery reuse and repurposing is currently being explored through a number of real-world applications and test-projects, for example as identified in earlier Table 2.7.

For recycling, a range of processes have already been developed in the EU and other countries, some of which are already being applied at existing recycling facilities. Key challenges for the future revolve around a combination of improving the economics of recycling, scaling up processes ahead of larger volumes of EV batteries becoming available and refining or developing new processes (or sub-processes) to handle changes in future battery chemistries. In particular, (Sonoc, 2015) and identifies significant potential to reduce the energy intensity and cost of LIB recycling through the application of automated processes. (Gaines, 2014) also highlights simplification of the process as an area for improvement (which would then lead to increase cost-effectiveness) as well as suggesting improvements to battery (and component) labelling and battery design decisions that facilitate end of life recycling.

New chemistries and changes to battery manufacture which result in lower quantities of cobalt or other valuable materials, will prove challenging to recyclers. Since this is the direction of travel in battery technology, some recyclers are starting to develop new processes or are working to adapt their existing processes so that future changes can be handled. For example, Umicore’s facility is able to handle a range of EV battery chemistries currently being researched and / or developed (Naberezhnykh, et al., 2013), including solid-state batteries and silicon-doped anodes (according to feedback from Umicore for this current project). However, it is currently unclear as to their relative recycling efficiency and cost-effectiveness vs current chemistries; through the increased scale of recycling facilities as more xEV batteries reach their end of life would be expected to reduce overall costs. Others are also developing new processes that are theoretically more flexible to different battery forms and chemistries and recover a broader range of battery materials (including lithium). For example, Canadian recycling start-up Li-Cycle claims that the (hydrometallurgical) process it has developed can recycle all types of lithium-ion (Li-ion) batteries recovering over 90% of materials including lithium, cobalt, copper, and graphite. They claim that recycling all of the battery materials is necessary to make LIB (lithium-ion battery) recycling profitable (Li-Cycle, 2017).

The potential introduction of advanced chemistries such as lithium-sulphur and sodium-ion batteries, that use much less expensive materials, could potentially cause difficulties in the longer term for the economics of recycling processes (particularly at the smaller scales/volumes these new technologies will start at). However, in theory, sodium-ion batteries could use similar electrode materials, with the main difference being the replacement of lithium. However, sulphur is regarded as a poison to recover the metals in recycling processes, so could generate issues in the future if this chemistry was to be utilised. No specific information has been identified on the potential implications of solid-state battery chemistries, though it seems likely the impacts would be more favourable in some respect due to, for example, easier separation and recycling of the (most likely) lithium metal anodes. The waste and recycling stakeholders interviewed also highlighted the significant (10-20 year) lead time that battery recyclers have before recycling technologies for new battery chemistries need to be deployed at scale. This leaves significant time for technology improvement and investment in capacity.

However, overall there is a need to design batteries better for recycling - if a battery is designed to be recycled then the need to come up with new chemical solutions will be less pressing. Such considerations also need to be balanced with other design considerations, such as maximising the useful life of the battery (e.g. also for potential second life applications). New binders could also play a key role here, if they can be designed to make it easier to separate components at the end-of-life.

Feedback from the waste and recycling stakeholders consulted in this project generally suggested that there would be only incremental improvements to the recycling technology and efficiency. However, a number of stakeholders suggested that large improvements could be made in this field through the introduction of automation and streamlining pack disassembly. This would need to use advanced AI and robotics technology to deal with the wide variety of pack designs which would need to be handled.

The potential for improvements to battery recycling that were identified in the literature review and stakeholder interviews, are summarised in Table 3.7, with our assessment as to the likely primary impacts of the improvements. No amendments to this were proposed in the discussions with stakeholders.

**Table 3.7: Summary of the identified future development/improvements in EV battery recycling processes**

| Recycling Process | Future developments / improvements | Primary impacts | | | |
|---|---|---|---|---|---|
| | | Cost/QA | Energy /GHG | Resource | Others |
| Battery design | • Inclusion of labels or other distinguishing features | + | + | + | + |
| | • Use of a minimum number of different materials | + | ? | ? | + |
| | • Standardisation of formats and materials | + | + | + | + |
| | • Avoidance of toxic materials | + | | | |
| | • Designs that allow easy separation of parts (e.g. a separable cooling system, reversible joining - nuts and bolts instead of welds, and avoidance of potting or adhesive compounds to hold cells in place). | + | | | |
| | • New binders which allow easier separation of active components with the cell. | + | + | + | + |
| General process | • Further process optimisation, automation, improved quality control through scaling up for high volumes | + | + | ? | ? |
| | • Increased use of automated pack disassembly through AI and advanced robotics | + | ? | ? | + |

| Recycling Process | Future developments / improvements | Primary impacts | | | |
|---|---|---|---|---|---|
| | | Cost/QA | Energy /GHG | Resource | Others |
| Pre-treatment | • Disassembly by automated processes, which recovers valuable electronics for reuse | + | + | + | + |
| | • Discharge of cells to recover residual energy | ? | (+) | (+) | ? |
| | • Other less-destructive alternatives to pyrolysis pre-treatment, such as microwave-based processes | ? | ? | + | + |
| | • Recovery of the electrolyte | ? | ? | + | + |
| | • Development /adaptation of processes for new battery types (i.e. Li-S, solid-state, Na-ion, etc.) | + | + | | |
| Pyrometallurgy | • No specific improvements identified other than process optimisation and complementary use with additional hydrometallurgical steps | + | | | |
| Hydrometallurgy | • Recovery of Li from shaft furnace slags and leaching of Li by $H_2SO_4$ (LiBri) | + | + | + | + |
| | • Electrolyte (Li-salt, e.g. $LiPF_6$, LiTFSI) recovery based on liquid phase extraction (ELIBAMA project) | ? | + | + | + |
| | • Further development of unconventional hydrometallurgical concepts, such as direct re-synthesis, electrochemical processes and bio-leaching | ? | + | + | + |
| | • Development (and scaling up) of processes for new battery types (i.e. Li-S, solid-state, Na-ion, etc.) | + | + | + | + |
| Direct recycling | • Development of direct recycling methods and scaled up application to new battery types | + | + | + | + |

Source: (Gaines, 2014), (Sonoc, 2015), (Naberezhnykh, et al., 2013), (B. Friedrich L. P., 2017a).

### 3.3.8 Technology roadmap for battery re-use, repurposing and recycling

No technology roadmaps for battery re-use, repurposing and recycling have been identified in the literature. The stakeholders interviewed as part of the consultation were also unable to further clarify likely potential timing for the improvements identified in Table 3.7 for recycling, reuse and repurposing.

# 4 Environmental lifecycle impacts and hotspots for EV batteries (Subtask 2.3)

*"What is the current environmental impact of traction batteries for electric vehicles across the whole life cycle? What are the current environmental hotspots and how are they addressed?"*

**Key outputs:**

- An analysis of the environmental impacts and hotspots and hotspots associated with the EU electric vehicle batteries market as it is today, with, with a higher level (mainly qualitative) analysis of how this is also likely to change based on future market developments (particularly battery chemistry changes).

This chapter provides an assessment of the current state of play in the electric vehicle batteries market and a review of the evidence quantifying the environmental impacts associated with the batteries used in these vehicles (i.e. at the vehicle battery-pack level). This review also shows how different stages of the lifecycle contribute to the overall environmental impacts, and which are the most significant in different impact categories. Further work is also ongoing in a new study (also led by Ricardo) for the European Commission, DG Climate Action which is developing and will be applying an LCA methodology for a range of road transport vehicle, powertrain and fuel/energy carrier types[8].

## 4.1 Overview

### 4.1.1 How well are the impacts of EV traction batteries characterised in the literature?

There is a range of information available from the literature on the lifecycle impacts from EV battery production (and, to a lesser extent, disposal), and although much of this is focused on GHG emissions (and secondarily on primary energy use), there are also studies available that explore the wider environmental implications, such as air pollutant emissions, water consumption and other resource use (such as key potentially resource constrained materials used in batteries like Li, Ni, Co for cathodes, and graphite for anodes). The majority of studies focus on batteries based on current Li-ion battery chemistries for electrified/electric passenger cars (i.e. HEV, PHEV and BEV), though there are also some studies that consider applications in other modes and for new chemistries (such as Li-S, solid-state and Na-ion batteries).

Whilst some studies have provided more detailed information on the breakdown of impacts between different components or manufacturing stages, and sometimes also for different chemistries, it is difficult to find a consistent approach. There is significant variability in some of the estimates for impacts from battery manufacturing, due in part to differences in key assumptions, and some studies have explored these in more detail and attempted to develop normalised comparisons also for different LIB cathode chemistries, for example (Peters, J. F., and Weil, M., 2017). LCA that include an assessment of the whole lifetime of EVs in comparison with conventional or other alternative powertrains are even more variable, due to the additional degrees of freedom available for assumptions for operational impacts (in particular the source of electricity and lifetime km) and on the treatment of end-of-life impacts (e.g. assuming a recycled content or avoided burden approach to account for recycling).

The following sections of this chapter provide a summary of the available evidence and attempts to answer key questions regarding the impacts, and hotspots, from EV batteries' lifecycle and how these might change in the future.

[8] "Determining the environmental impacts of conventional and alternatively fuelled vehicles through Life Cycle Assessment", led by Ricardo in partnership also with E4tech and ifeu. The project will be completed towards the end of 2019.

In addition, voluntary Product Environmental Footprint (PEF) Category Rules (CR) have also recently been developed for mobile batteries, which may help improve comparability of future results in the European context (RECHARGE, 2018).

### 4.1.2 Variability in estimates for (GHG emissions) impacts from batteries

Figure 4.1 provides an illustration of the (unnormalized) distribution of estimates for the GHG emissions impacts from the manufacturing of batteries of different chemistries for electric vehicles in terms of metrics per kWh of energy storage and per kg of battery. Distinguishing these elements is important as different battery chemistries have a range of different energy densities (in Wh/kg) and the mass of the battery has important impacts on EV performance (i.e. either in terms of the capacity of the battery that can be included in the EV, and/or the energy consumption per km of the vehicle). It can be seen that whilst a range of chemistries have been assessed in earlier estimates, most of the more recent analyses have focused on NMC Li-ion batteries, which have become dominant in the marketplace.

It is important to note that most of the LCA information available in the literature appears to be based upon analyses of now older battery chemistries /formulations that were introduced 5-10 years ago. In the last few years, significant improvements have been made to these chemistries to increase the energy density (in Wh/kg) of EV batteries, which would be expected to result in significant reductions in impacts per kWh of battery (although the kWh capacities of the battery packs in BEVs has also increased as a result). This is also further discussed in later section 4.5.2.

Even so, a gradual decline in the apparent emissions over time in the literature both on a per kWh basis and a per kg basis in Figure 4.1. The reasons for this are not readily apparent in the source material but it seems likely it could be a combination of improved data sources / understanding, some improvements to battery energy density, reductions in impacts from battery materials (e.g. reduced use of higher impact materials, reduction in waste, etc.) and manufacturing energy.

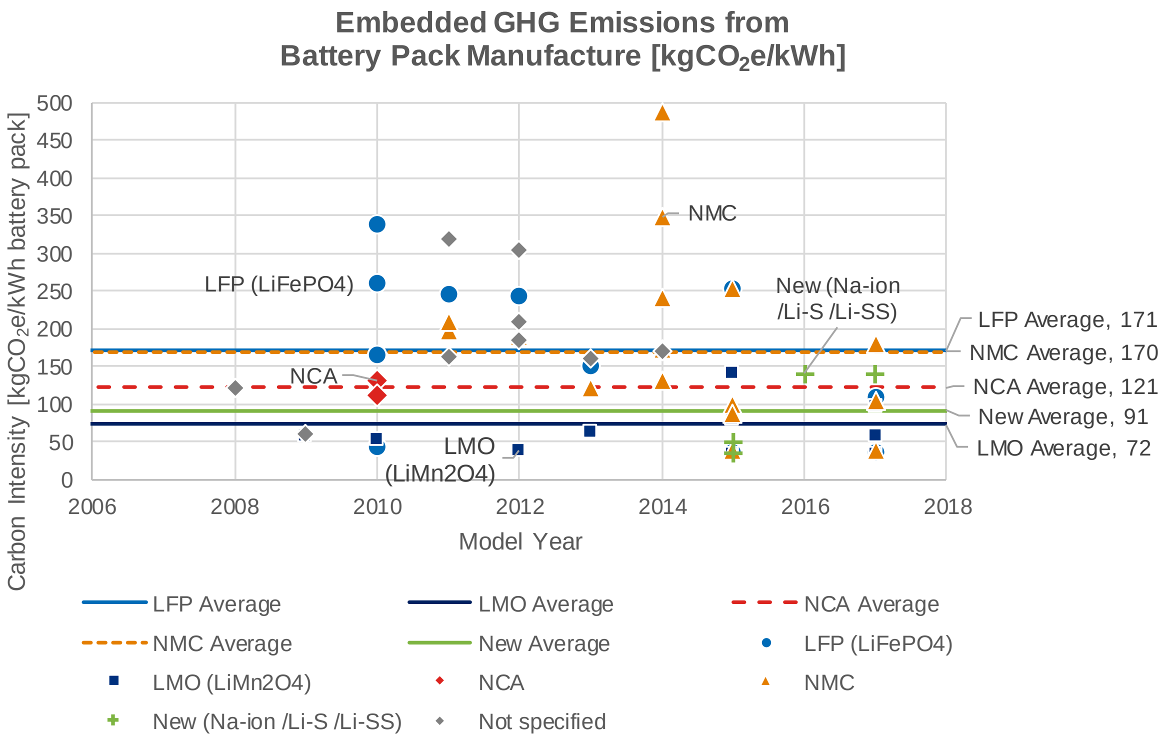
It is also worth noting that the only available analyses in the literature identified for the NCA chemistry are now rather old, which is important as Panasonic/Tesla have reportedly made significant improvements to the NCA batteries (both in terms of chemistry and form factor) used in Tesla's vehicles, and significant volumes of such batteries are now being manufactured in Tesla's Gigafactory in Nevada (USA). No information has been identified on LCA analyses of these new batteries, and how the change in form factor from 18650 (used in the Model S) to 21700 (Model 3) will affect the rest of the value chain.

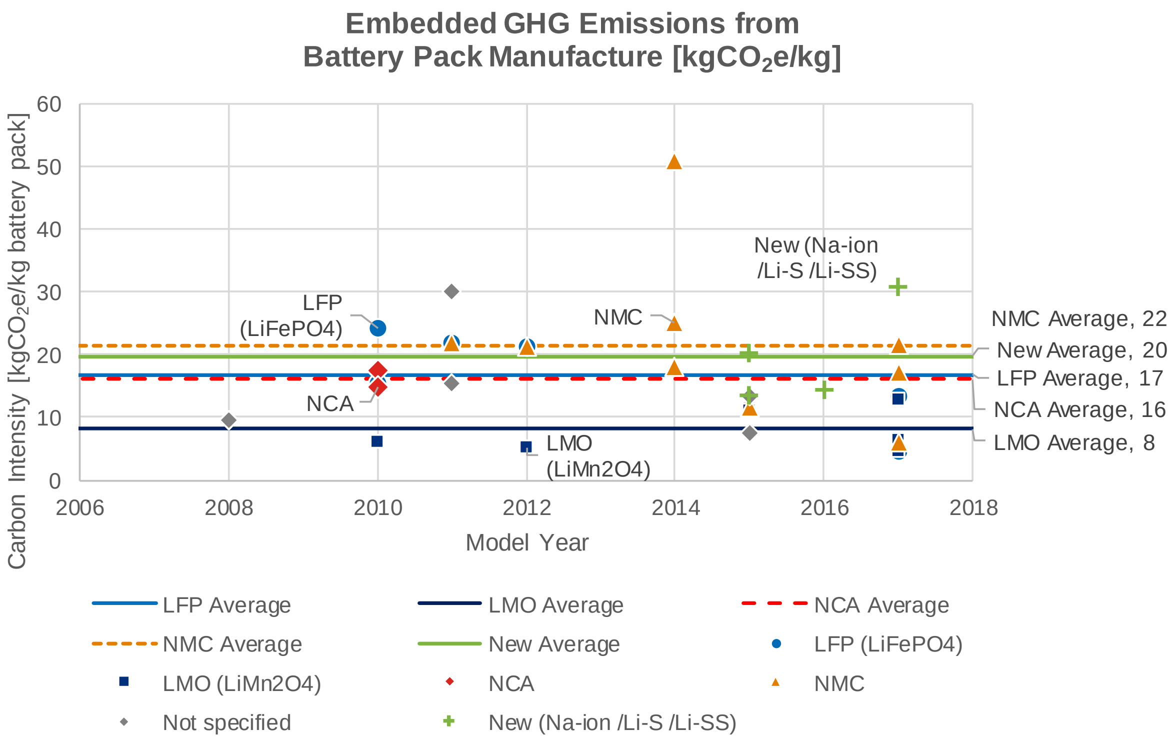
The key reasons for the variations seen in the results for embedded GHG emissions from battery pack production stem from differing assumptions regarding:

- Direct energy demand associated with cell manufacture and pack assembly (and assumptions regarding carbon intensity of this energy).
- The amount of cell materials and other battery components.
- The use of primary versus secondary data, and age of data (some studies use now quite old data).
- The details of the production processes included in analysis.
- LCI (life cycle inventory) impact databases used.

The importance of geographical considerations for battery manufacture is also key, relating in particular to the GHG intensity of the energy source used in manufacturing and in the production of key materials, which can have a particularly large impact. This is illustrated in Figure 4.2, which compares estimated impacts of EV batteries of different chemistries in China versus the US.

**Figure 4.1: GHG impacts from battery production for different battery chemistries from the literature**

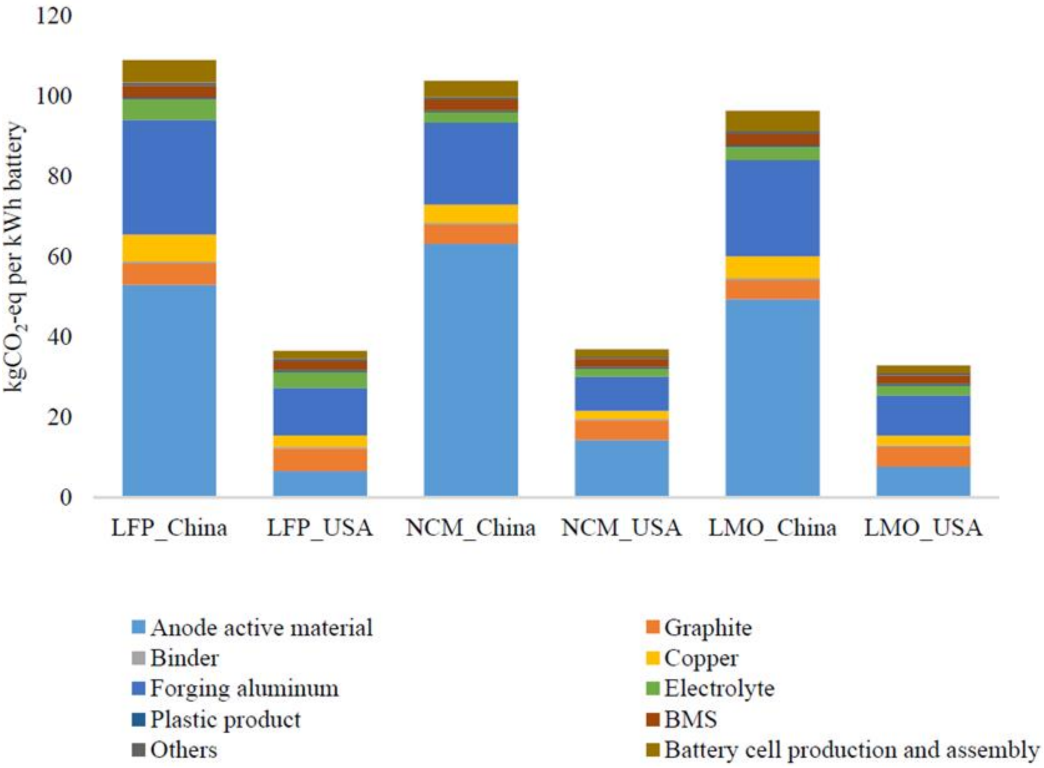



*Source*: Ricardo, compiled from the literature. New chemistries include Li-SS = Lithium solid-state, Li-S = Lithium Sulphur, and Na-ion = Sodium-ion chemistries.

*Notes*: Results presented above are unnormalized, and use a variety of different assumptions e.g. on production location, battery energy density, composition, manufacturing energy consumption, etc. This helps to explain the variability seen in some of the results.

**Figure 4.2: A comparison of the estimated relative breakdown of different impacts from the production of a BEV battery in the US versus China**




Source: (Han, Zhexuan, Shuhua, Zongwei, & Fuquan, 2017)

### 4.1.3 Are the batteries for different powertrains or vehicle types significantly different?

Whilst historically the batteries used in hybrid electric vehicles, such as the Toyota Prius, have used NiMH (Nickel Metal Hydride) battery chemistries (which have significantly lower energy density in Wh/kg), new hybrid models being introduced to the market are now generally utilising Li-ion chemistries similar to those used in PHEV (and BEVs). There are also some differences in the smaller Li-ion batteries used in HEVs and PHEVs, compared to those in BEVs. Since the packs in BEVs are much larger, these use chemistries that are more optimised to improving energy density; however, the smaller packs in PHEVs and HEVs need to have much greater power density. In addition, the battery packaging, BMS, etc., comprise a larger overall share of the total pack mass relative to the battery cells in PHEVs and HEVs. Overall impacts per kWh of energy storage for these batteries are therefore likely to be somewhat higher than for BEVs; however, we have not identified specific analysis of the significance of this differential in the available literature. The overall absolute impacts from the batteries are much smaller than for BEVs. In recent years there has also been increasing interest in possible applications of super-/ultra-capacitors integrated with batteries (i.e. a Li-ion capacitor, LiC[9]) as a way of potentially improving overall vehicle efficiency and reducing the size of the battery pack needed/allowing for optimising this further towards energy density (versus power density) (EE Times, 2012), (InsideEVs, 2018). Capacitors have much higher power density and round-trip cycle efficiency compared to batteries, but much lower energy density; however recent research has suggested potential breakthroughs that could bring energy densities close to batteries (Wired, 2018). Although the environmental impacts of capacitors are reportedly lower than for batteries, due to using less exotic materials, there are currently no available LCA studies on the potential impacts of these in EV applications (as LiCs are not a very mature technology). The main potential benefit of the application of LiC in EVs is likely to be the potential to optimise and down-size the battery packs, with particular benefits to PHEV applications.

[9] Lithium-ion capacitor (LiC) is a hybrid energy storage device which compounds the energy storage mechanisms of lithium-ion batteries (LIBs) and electric double-layer capacitors (EDLCs) (BIC, 2017).

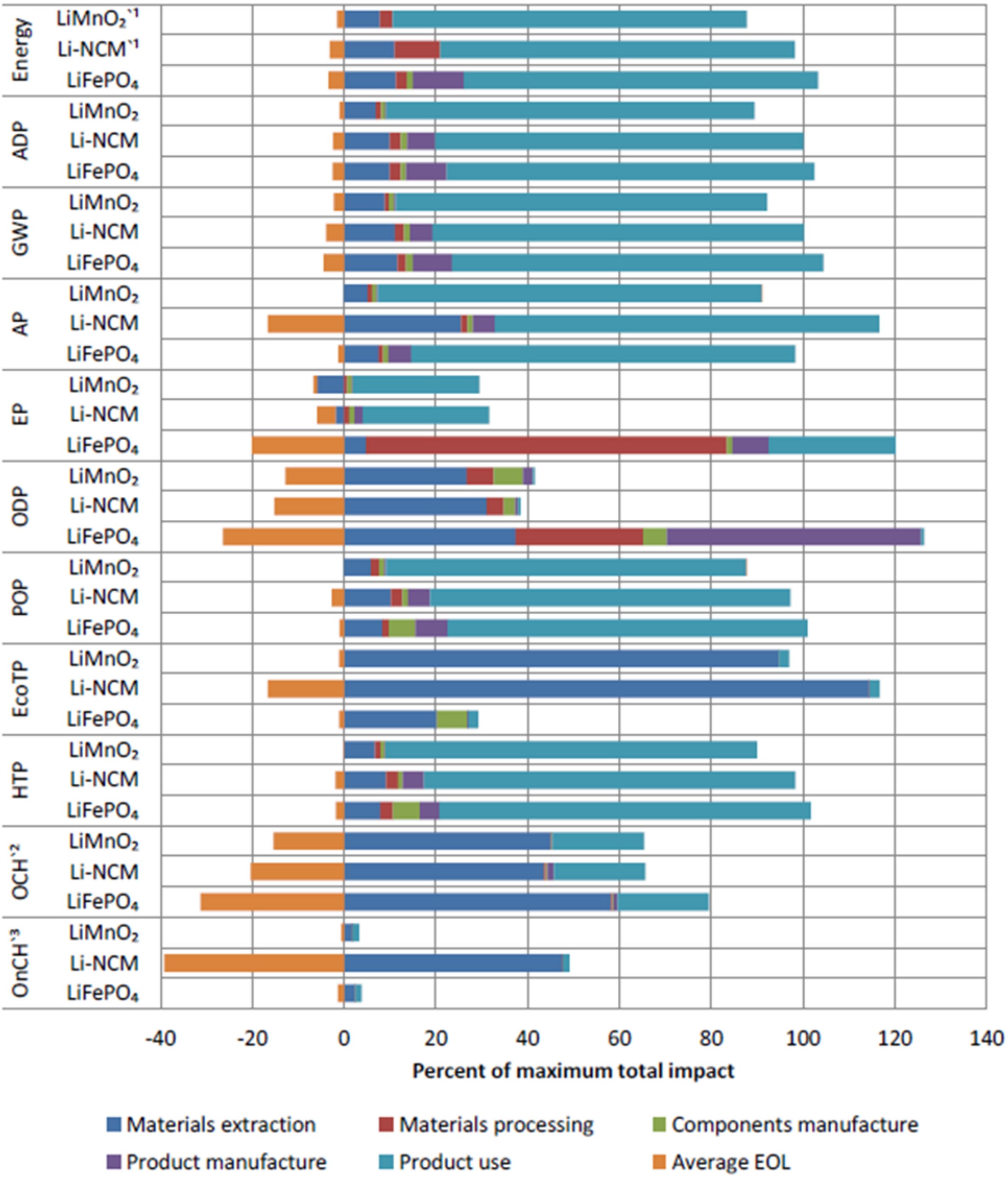
The vast majority of literature and analysis available to-date has focused on (lithium ion) batteries for passenger cars; such analysis can be readily read-across to applications light commercial vehicles (i.e. vans). Since these vehicle types account for the vast majority of vehicles in Europe, and are also likely to take up electric powertrains fastest, it is appropriate that such applications in light duty vehicles will be the primary focus for the analysis. However, there is also growing interest in applications for heavy duty vehicles (and e-bikes/motorcycles/mopeds). Whilst there was some previous experience in NaNiCl (Sodium Nickel Chloride) “Zebra” battery chemistries in heavy-duty vehicle applications, most of the vehicles on the market currently (e.g. most notably the electric buses produced by BYD), and those for new models recently announced (e.g. by Daimler, Renault, and Tesla), use lithium ion chemistries. Previous heavy-duty vehicle applications using Li-ion chemistries have predominantly adopted 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 NMC-based (e.g. Daimler, (AVID Technology, 2016)) or NCA-based (e.g. Tesla), similar to those in light duty vehicles.

## 4.2 Breakdown of environmental impacts over the battery lifecycle

### 4.2.1 How do different impacts vary over the battery lifecycle?

Figure 4.3 (from (US EPA, 2013)) and Figure 4.4 (from (Ford/LG Chem, 2016)) illustrate how the significance of different environmental impacts can vary by battery manufacturing stage (or component) as well as over the whole lifecycle for BEV passenger car applications. Although the results from (US EPA, 2013) are now slightly dated (e.g. LIB technologies have evolved significantly in the last 6 years), they nevertheless provide a comprehensive illustrative assessment of the range of impacts and their significance, which is also broadly consistent with results seen in other more recent literature. Europe has a larger share lower carbon generation including renewables, so the relative share of impacts of the product use would be expected be lower. The disaggregated breakdowns available from a range of key studies also clearly show the significance of the cell manufacturing process in the overall energy and GHG impacts for Li-ion batteries (Ford/LG Chem, 2016), (NTNU, 2011), (Peters, J. F., and Weil, M., 2017), (US EPA, 2013).

**Figure 4.3: A comparison of the relative breakdown share of different lifecycle impacts for BEV batteries by chemistry based on the US electricity mix**




Notes: ADP = abiotic depletion potential; AP = acidification potential; EcoTP = ecological toxicity potential; EP = eutrophication potential; GWP = global warming potential; HTP = human toxicity potential; OCH = occupational cancer hazard; ODP = ozone depletion potential; OnCH = occupational non-cancer hazard; POP = photochemical oxidation potential.

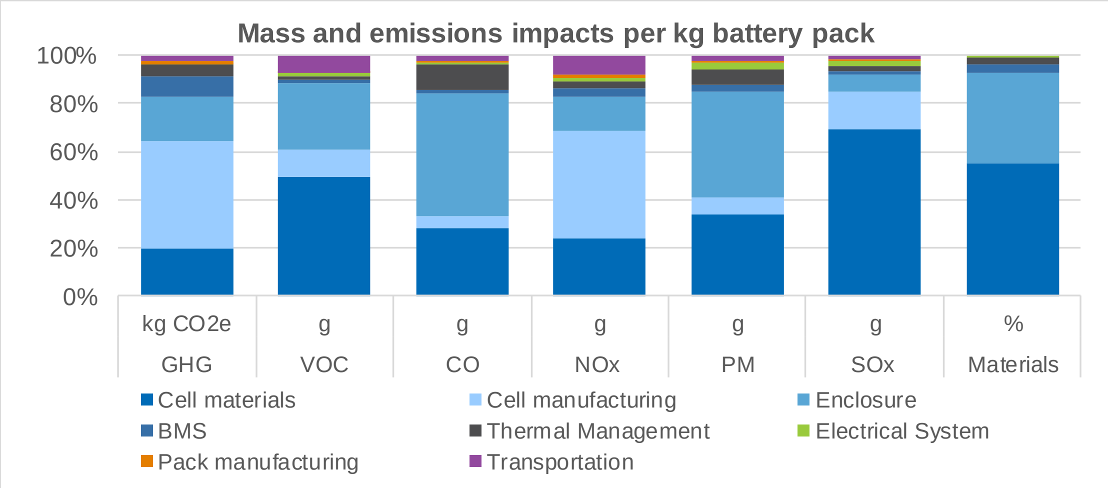
\1 Primary energy consumed during the materials processing, component, and product manufacture was combined to protect proprietary data submitted by manufacturer.

\2 Occupational cancer hazard impact was scaled to 50% in this figure because of the wide range across stages.

\3 Occupational non-cancer hazard impact was scaled to 10% in this figure because of the wide range across stages.

*Source*: (US EPA, 2013). *Notes*: Assumes a lifetime mileage of 193,120 km for the vehicle.

**Figure 4.4: A comparison of the relative breakdown of different impacts from the production of a Ford EV battery (% share of emissions and materials by component, per kg of battery pack)**




*Source*: Based on (Ford/LG Chem, 2016). *Notes*: Cells are LMO/NCM mix produced by LG Chem in South Korea.

The impact of materials and manufacturing for the cathode also represent a significant share of GHG and energy consumption impacts. For most impact categories, the energy consumption from the operational phase currently dominates the overall lifecycle impacts for BEVs (and even more so for PHEVs), though this will depend on the source of the electricity (important as this mix is also changing in many countries). This confirms that reducing impacts from manufacturing and operational energy consumption are likely to lead to significant benefits in the battery manufacturing and overall EV lifecycle, respectively. The trend towards higher battery energy densities and improved manufacturing efficiency, driven by performance and cost considerations, will also result in reduced impacts per kWh.

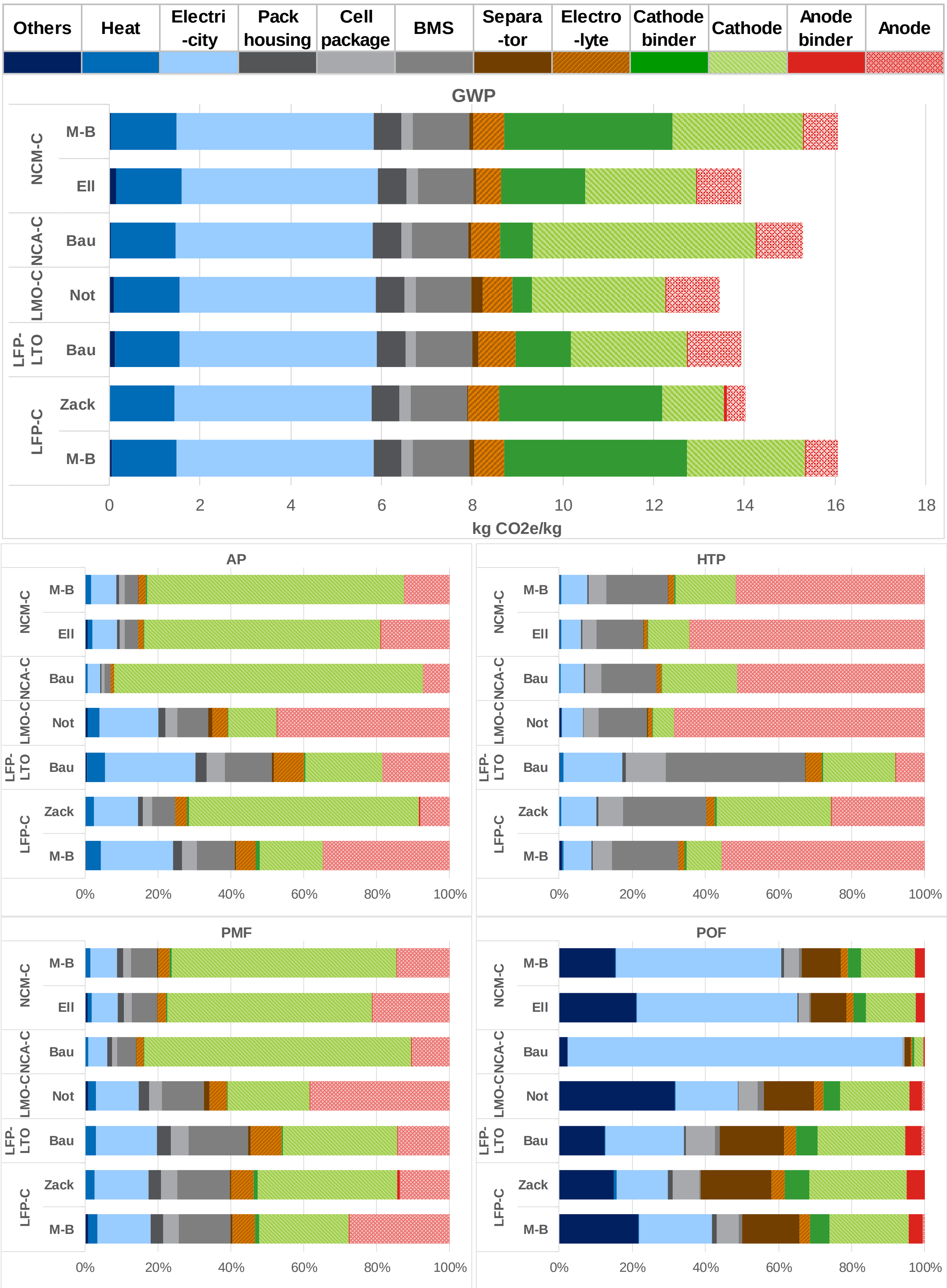
The literature highlights that for some environmental impact categories, the contribution from the battery manufacturing stage is much more significant. For example, Figure 4.3 and Figure 4.4 above and also (Gaines, 2014) show that SOx emissions (which contribute to overall Acidification Potential) from battery manufacturing are particularly large for the manufacture of batteries with cathode chemistries containing cobalt and nickel (i.e. NCM and NCA). The gradual reduction in the cobalt content in such chemistries (and potential elimination of its use in EV batteries in the future), that is currently being driven by a combination of cost and resource scarcity concerns, would be expected to significantly reduce such impacts in the future, as will recycling EoL batteries to recover these materials.

Other environmental impacts from battery production from impact categories such as Eutrophication Potential (EP), Ozone Depletion Potential (ODP), Eco-Toxicity Potential (EcoTP) and Occupational Cancer/non-Cancer Hazards (OCH/OnCH) are also very significant compared to the operational phase for certain battery chemistries according to (US EPA, 2013), illustrated in Figure 4.3. In most of these cases it is the cathode materials and manufacturing, and in particular the use of cobalt, that contributes to these impacts – which also account for the larger 'credits' from recycling at the EoL stage in most cases. Again, increased battery recycling and the drivers/trend in reduction in cobalt use in batteries would be expected to reduce these impacts in the future.

### 4.2.2 How do battery impacts vary by battery type / current chemistry?

The analysis presented in the previous section, from (US EPA, 2013), has highlighted some differences between different LIB chemistries for different environmental impact categories when they are evaluated on a consistent basis. When comparing the relative impacts of different chemistries between different literature sources, this is more challenging, as there are a multitude of factors / assumptions that can impact the overall analysis. Nevertheless, (Peters, J. F., and Weil, M., 2017) conducted an analysis of a range of sources in an attempt to provide comparable results, normalising for key assumptions/factors in the analysis. Figure 4.5 and Table 4.1 present an overview of the unified (and original) results of this analysis for GHG emissions (in GWP), as well as the relative importance of different battery manufacturing components / stages in four of the other key impact categories.

**Figure 4.5: Estimated GHG breakdown of impacts (per kg battery) from the production of Li-ion batteries of different types: normalised estimates based on unified LCI datasets**




*Source*: (Peters, J. F., and Weil, M., 2017). *Notes*: GWP = Global Warming Potential, AP = Acidification Potential, HTP = Human Toxicity Potential, PMF = Particulate Matter Formation, POF = Photochemical Ozone Formation. NMC-C = NMC Cathode – Carbon (Graphite) Anode; similarly also for the other battery chemistries.

**Table 4.1: Comparison of Climate Change Impact results (ILCD 2011)**

| Study | $kgCO_2e$ | M-B (2011) | Zack (2010) | Bau (2010) | Not (2010) | Bau (2010) | Ell (2014) | M-B (2011) |
|---|---|---|---|---|---|---|---|---|
| Chemistry | Unit | LFP-C | LFP-C | LTP-LTO | LMO-C | NCA-C | NCM-C | NCM-C |
| Original LCI | /kg | 23.9 | 21.2 | 18 | 8.08 | 17.5 | 17.4 | 23.8 |
| | /kWh | 271 | 228 | 348 | 70.9 | 132 | 156 | 227 |
| Unified LCI | /kg | 16 | 14 | 13.9 | 13.5 | 15.3 | 14.4 | 16.1 |
| | /kWh | 147 | 169 | 266 | 116 | 115 | 104 | 124 |
| | Wh/kg | 88 | 93 | 52 | 114 | 133 | 112 | 105 |

*Source*: (Peters, J. F., and Weil, M., 2017).

Notes: NMC-C = NMC Cathode – Carbon (Graphite) Anode; similarly also for the other battery chemistries.

The analysis from (Peters, J. F., and Weil, M., 2017) also shows that the differences between different chemistries per kg of battery are anticipated to be relatively small from a GHG and energy perspective, but more significant for other impact categories. The results suggest that the energy required for battery production (particularly from drying processes – see earlier Section 3.2) contributes around 35-45% of the embedded GWP of an automotive Li-ion battery pack. (Though analysis with the latest GREET model shows a lower 19-25% share according to (Dai, Dunn, Kelly, & Elgowainy, 2017)). This suggests such impacts could be reduced by a similar proportion if low carbon energy is used during component production and battery assembly. In terms of the battery components, the Cathode and Cathode Binder contribute the most to the embedded GWP of a Li-ion battery pack. Therefore, improving these aspects of battery chemistry/manufacturing could also lead to significant benefits.

Other recent analysis by (J.B. Dunn, 2015) has also explored the potential impacts of an expected shift towards silicon-dosed graphite anodes, which are of interest due to their potential to improve battery energy density (in Wh/kg) and overall performance. This work highlighted the significant contribution of cobalt (in the cathode) and silicon (in the anode) as the most energy-intensive materials to include in the supply chain. However, improvements in the overall energy density of the batteries due to silicon dosed-anodes resulted in a lower absolute manufacturing energy consumption for a similar kWh capacity battery.

No information has been identified from the LCA literature on potential differences in battery manufacturing (or broader EV lifecycle) impacts between different battery form factors. However, the available evidence on the similarity in battery manufacturing processes for different form factors (i.e. as discussed in Chapter 3) suggests these should be small / not significant compared to other considerations. The potential differences due to impacts from end-of-life (EoL) disposal are explored in the next report section.

## 4.3 Environmental impacts and credits from end-of-life disposal and recycling

### 4.3.1 What are the impacts from end-of-life disposal and recycling?

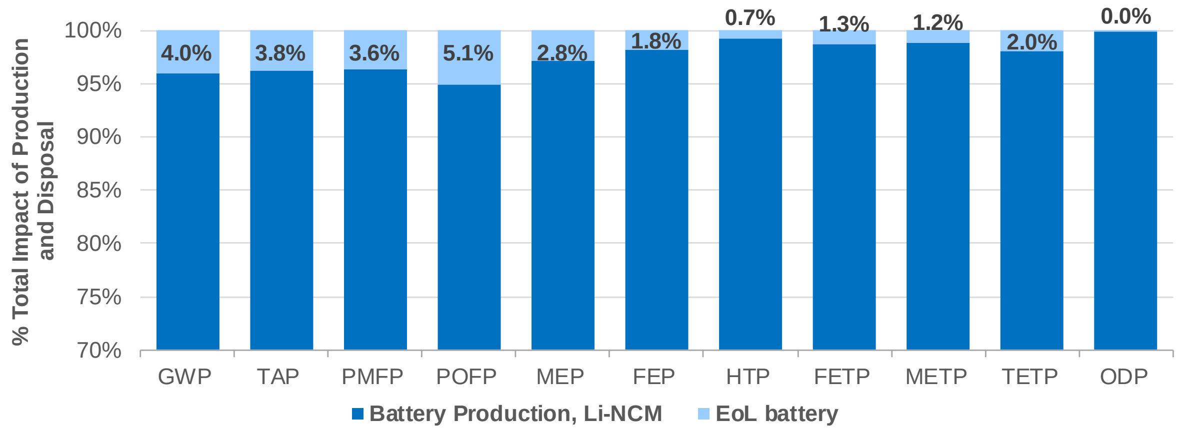
Overall, very few of the LCA studies identified consider the end-of-life phase as part of the analysis, as was also found by a recent review in (Ellingsen, Hung, & Strømman, 2017). There are also different approaches for how to consider battery end-of-life in a vehicle LCA study.

Some studies only consider collection, dismantling and separating within the LCA analysis boundary. The environmental impacts of the treatment are assigned to the recycled materials to be included in the future product using these recycled (secondary) materials (so called 'Recycled Content' approach). These studies therefore assign an additional impact for end-of-life disposal with recycling associated with the processing emissions, for example:

- (Hawkins, Singh, Majeau-Bettez, & Strømman, 2013) and (Ellingsen, Singh, & Strømman, 2016) reported 3.6-8.0 $kgCO_2e$/kWh for battery recycling.
- (Li, Gao, Li, & Yuan, 2014) reported 27 $kgCO_2e$/kWh for battery recycling.

The relative significance, for different environmental impact categories, of the end-of-life recycling stage in relation to the battery manufacturing stage is illustrated in Figure 4.6 below for an NMC battery, assuming the 'Recycled Content' LCA methodology based upon (Hawkins, Singh, Majeau-Bettez, & Strømman, 2013).

**Figure 4.6: The relative impact of end-of-life recycling versus battery production for NMC battery using the 'Recycled Content' LCA accounting methodology for different impact categories**




*Source*: Based on (Hawkins, Singh, Majeau-Bettez, & Strømman, 2013). *Notes*: TAP = Total Acidification Potential, PMFP = Particulate Matter Formation Potential, POFP = Photochemical Ozone Formation Potential, MEP = Marine Eutrophication Potential, FEP = Freshwater Eutrophication Potential, HTP = Human Toxicity Potential, F/M/T-ETP = Freshwater/Marine/Terrestrial Ecotoxicity Potential, ODP = Ozone Depletion Potential

Other LCA studies apply a recycling credit, since the future use of recycled material will offset use of primary material (also known as the 'Avoided Burden' or 'End of Life' approach). For example, (US EPA, 2013) reported emissions reduction of 16-23 kg$CO_2$e/kWh due to recycling credit.

Figure 4.8 and Figure 4.7 also provide an illustration of the relative size of the potential credit for different types of end of life recycling of LMO batteries based on the 'Avoided Burden' approach, for overall energy consumption (Figure 4.7) and for different environmental impact categories (Figure 4.8).

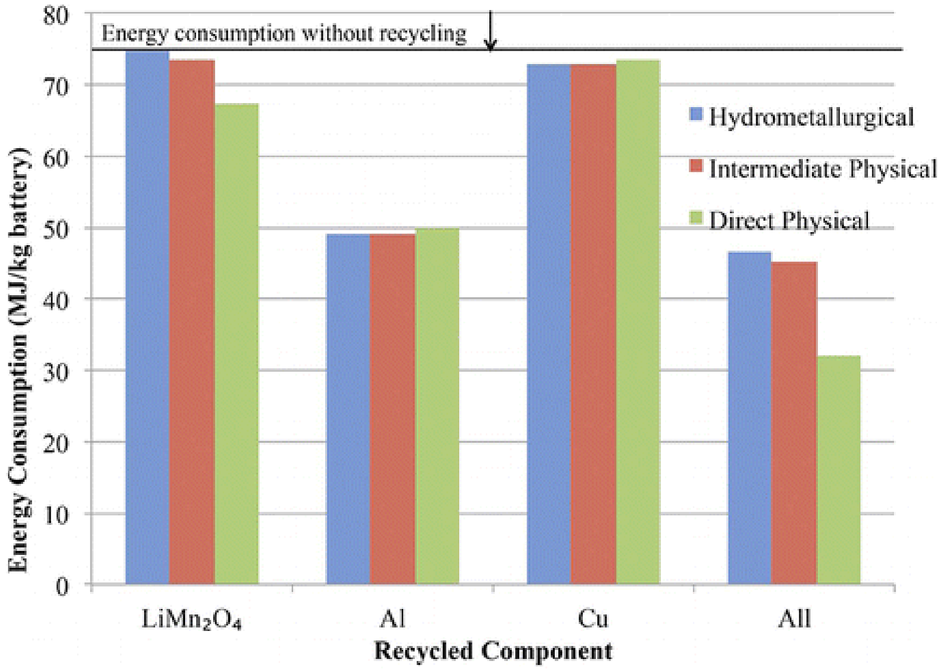
The analyses suggest reductions in net GHG emissions of up to 50% based on hydrometallurgical recycling processes, with some other impacts resulting in even greater savings, whilst others far fewer, particularly for pyrometallurgical recycling options[10]. In particular, (Dunn L. G., 2015) has also highlighted that recycling metals made from sulphide ores (i.e. such as Ni, Co) can significantly reduce the environmental burden from the battery cathode materials. The main point to bear in mind is that whilst these processes generate GHGs, EVs are displacing ICEs and thus off set a significantly greater amount of GHGs from the whole system perspective (as illustrated in Section 4.4). In addition, with recycling there is an offset for the next life for the materials, i.e. reducing the impact from mining.

(IVL, 2017) also provided a comparison of the potential recycling GHG savings per kg of battery from a range of different studies, including those from the LithoRec project, which are summarised in Table 4.2. In addition, the results in Table 4.3, also from (IVL, 2017), are taken from the LithoRec project and are for a pilot scale plant. These figures give an indication of what stages of the recycling process are the most energy demanding, and what materials holds most potential for reduction in GHG emissions.

Whilst the findings for GHG emissions are important, other impacts are also significant – including criterial air pollutants, water consumption and air toxic emissions; stakeholders consulted in this project emphasised that it was important that these should also ideally be quantified in LCA.

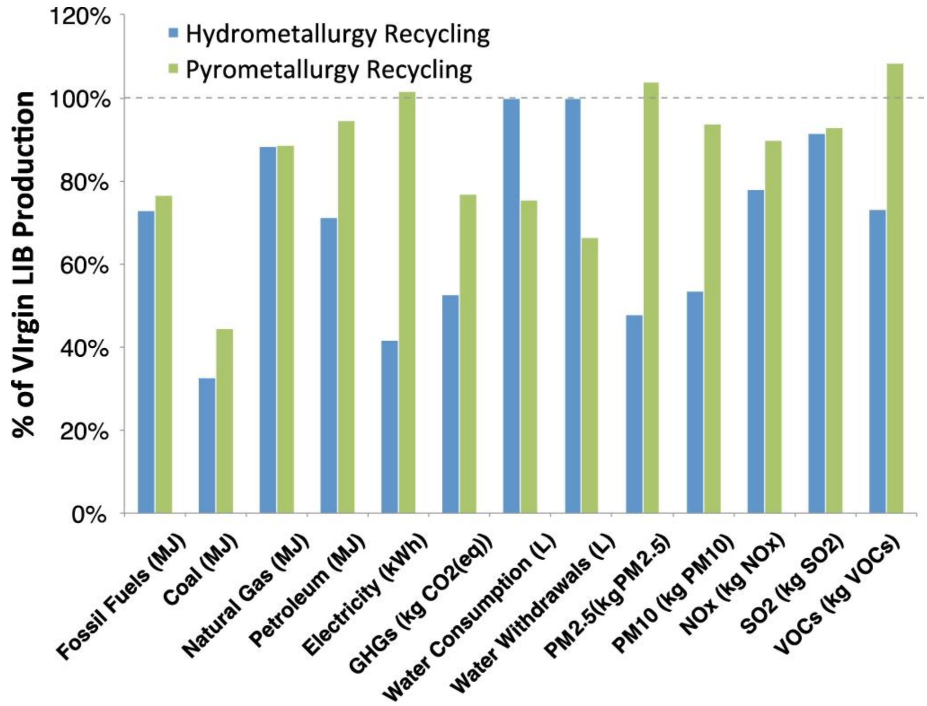
[10] Argonne National Laboratory (ANL) has indicated that their 'EverBatt' model (ANL, 2018a) has recently also been updated to provide quantification of the effects of different types of recycling on battery LCA results, according to feedback received after the final project workshop.

**Figure 4.7: The impact of different recycling types on the net energy consumption for an LMO Li-ion battery**




*Source*: (Dunn, Gaines, Sullivan, & Wang, 2012)

**Figure 4.8: Resource use and environmental emissions of battery production and recycling (using hydrometallurgy and pyrometallurgy), compared to virgin battery production, for the LMO battery design**




*Source*: (Hendrickson, 2015)

**Table 4.2: Overview of LCA results for the recycling stage**

| Method | GHG emissions, $gCO_2e$/kg battery | Chemistry |
|---|---|---|
| LithoRec [1] (Prototype scale) | -1035 (hydrometallurgy, see details in Table 4.3) | 35% NMC, 35% NCA and 30% LFP |

| Method | GHG emissions, $gCO_2e$/kg battery | Chemistry |
|---|---|---|
| Libri [1] (Prototype scale) | 1244 (pyrometallurgy) | 35% NMC, 35% NCA and 30% LFP |
| Umicore [2] (Industrial scale) | -70% = -1500 gCO2/kg Co (Pyro + hydro leaching) | LCO |
| Hydrometallurgical [3] | -2000, mainly from removing need for primary aluminium | LMO |
| Intermediate physical recycling [3] | -2000, mainly from removing need for primary aluminium | LMO |
| Direct physical recycling [3] | -2500 | LMO |

*Source*: (IVL, 2017); [1] (Buchert, 2011), [2] (Dunn, James, Gaines, & Gallagher, 2015a), [3]. (Dunn, Gaines, Sullivan, & Wang, 2012)

**Table 4.3: Details from the LCA study of a pilot stage recycling technology based on hydrometallurgy from the LithoRec project**

| /kg battery | Dismantling | Cell separation | Cathode separation | Hydro-processing | Total |
|---|---|---|---|---|---|
| $gCO_2e$ | 234 | 586 | 213 | 1,461 | 2,494 |
| Main impact from: | Transport, Steel and Al recycling. | Cu recycling, washing, burning of separator. | Electricity | Supporting materials and electricity. | |
| $gCO_2e$ credit | -1,966 | -325 | -269 | -970 | -3,530 |
| Materials recovered: | Stainless steel and plastics | Copper and Aluminium | Aluminium | Cobalt, Nickel | |
| **Net $gCO_2e$** | **-1,732** | **261** | **-55** | **491** | **-1,035** |
| **Energy, MJ** | | | | | **-(16-28)** |

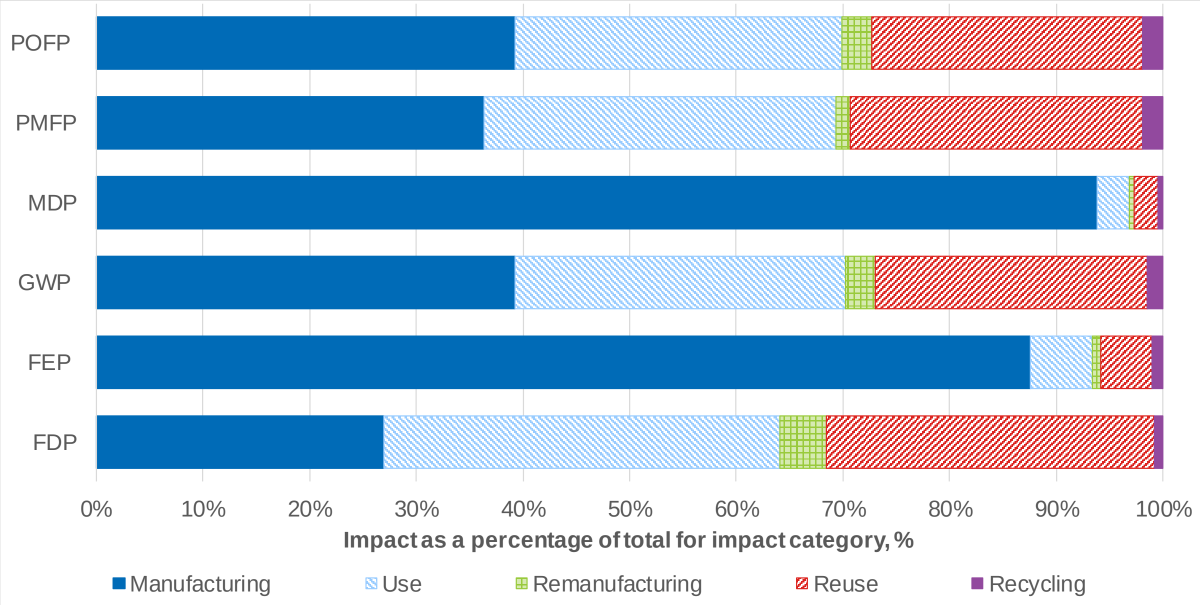
*Source*: (IVL, 2017)

### 4.3.2 How might EV battery reuse / second-life applications affect the analysis?

As discussed in earlier Chapters 2 and 3 of this report, the potential for EV battery reuse / second-life is currently at a relatively early stage of investigation. As a result, there are relatively few studies available on the potential environmental impacts at the end of the life of the battery in the EV due to battery remanufacturing/repurposing for reuse.

However, (Ahmadi, Young, Fowler, Fraser, & Achachlouei, 2015) conducted a cascaded analysis of an EV battery second use scenario where the battery is replacing natural gas generation by providing energy storage services. Figure 4.9 and Figure 4.10 provides a summary of the cascaded impacts for the different stages of battery use for different impact categories; the remanufacturing stage is <10% of the new battery production in all cases. Overall the study found that the cascaded use system appears significantly beneficial compared to the conventional system. However, the study also found that battery energy efficiency fade is a considerable determinant of potential performance for second use.

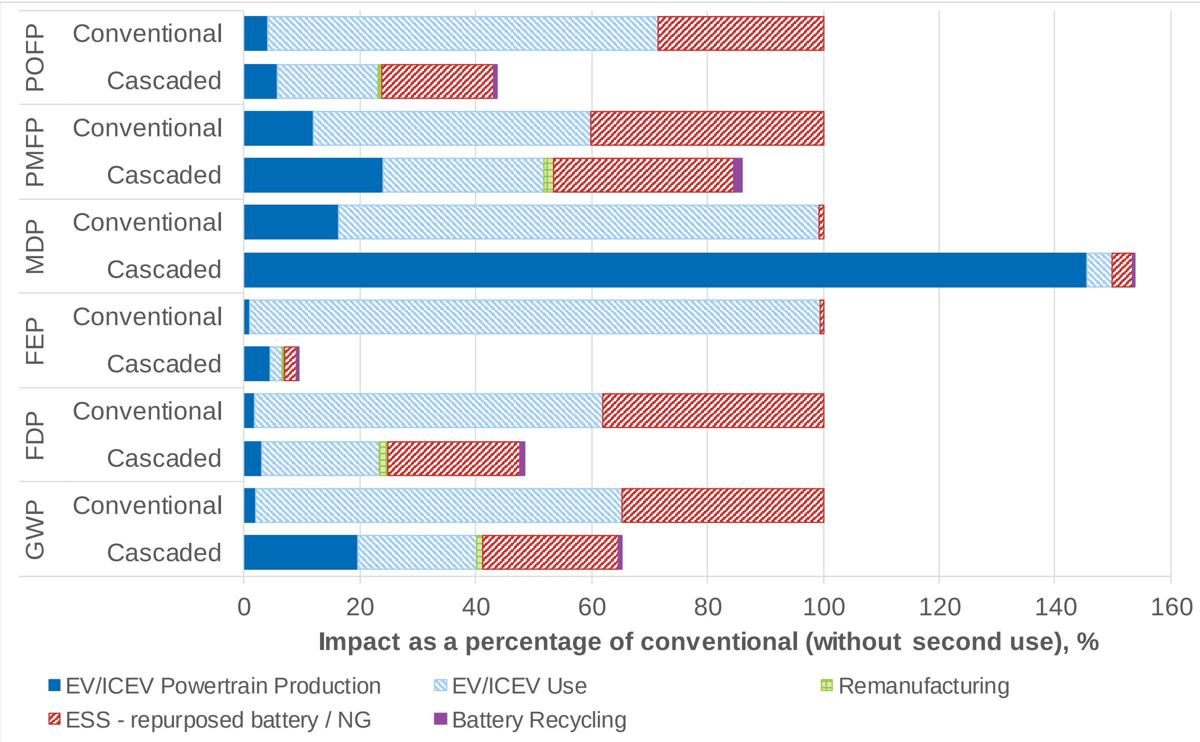
**Figure 4.9: Life cycle impact assessment indicator results for 1 kWh of power delivered by the Li-ion battery pack cascaded use for six indicators**




*Source*: Ricardo analysis of data from (Ahmadi, Young, Fowler, Fraser, & Achachlouei, 2015).

*Notes*: No additional credits are included for end-of-life recycled materials, only impacts from recycling processes. GWP = global warming potential, POFP = photochemical oxidation formation potential, PMFP = particulate matter formation potential, FEP = freshwater eutrophication potential, MDP = metal depletion potential, and FDP = fossil-resource depletion potential.

**Figure 4.10: Life cycle impact indicator results for cascaded use of Li-ion battery pack versus conventional ICEV system, for six life cycle impact assessment indicators. Cascaded values are shown as a percentage of conventional values.**




*Source*: Ricardo Analysis of data from (Ahmadi, Young, Fowler, Fraser, & Achachlouei, 2015).

*Notes*: (a) global warming potential (GWP), (b) photochemical oxidation formation potential (POFP), (c) particulate matter formation potential (PMFP), (d) freshwater eutrophication potential (FEP), (e) metal depletion potential (MDP), and (f) fossil-resource depletion potential (FDP)

(Casals, AmanteGarcía, Aguesse, & Iturrondobeitia, 2015) also considered the total GHG emissions resulting from the first and second life uses of an EV battery, for a range of different second life applications: (i) household energy arbitrage (with grid electricity), (ii) household renewable energy storage (RES) with grid support, and (iii) island RES. The study concluded that: *"from an environmental point of view, the use of batteries is only advisable in association with renewable energy sources. If that is not the case, the environmental impact caused by the losses derived from the energy storage should be added to the emissions coming from the pollutant energy source acting as a multiplier factor"*.

A recently published study by JRC for the SASLAB project (Bobba, et al., 2018) has also conducted an experimental evaluation and lifecycle assessment of the potential for xEV battery second life applications versus peak shaving and increase of PV self-consumption applications. This study also found that (for the LMO/NMC battery and the two applications assessed) a repurposed battery is environmentally beneficial only if it replaces a fresh battery (either a LMO/NMC or a PbA battery). The addition of a repurposed battery in a building in which no batteries were previously used did not entail benefits according to the analysis.

Should a battery be repurposed/remanufactured for reuse/second-life application, an alternative way to treat the impacts of this, in terms of the EV battery value chain, could therefore be as follows:

- *Where the EV itself has come to the end of its life also:* to apply a credit based on the displacement of production impacts of a new battery, reduced to take into account the likely shorter useable life of the repurposed/remanufactured battery compared to a new one (e.g. this could be 50% of the useable life of a new battery).
- *Where the EV itself has not come to the end of its life also:* as above, except that accounting for any mid-life replacement batteries for the EV should also be included (whether these are new or repurposed/remanufactured).

The utilisation of this proposed simplified approach would also have benefits for the high-level assessment of potential fleet-level environmental impacts from EV deployment, which is discussed further in Chapter 5. The main limitation of the approach is that it requires an assumption on the potential (limit on) demand for energy storage batteries and the share of these that might be substituted by second life batteries, which is uncertain.

## 4.4 Overall lifecycle impacts from EV batteries and whole vehicles

### 4.4.1 How significant are lifecycle impacts from batteries versus the whole vehicle?

Earlier Figure 4.3, in Section 4.2.1, has already illustrated that environmental impacts of batteries vs impacts from the whole electric vehicle use can be significant for certain impacts and battery chemistries. In addition, it is important to understand whether this is the case also in contrast with conventional powertrains. This will help highlight environmental hotspots, for example where emissions from the battery lifecycle might contribute to higher impacts than conventional vehicles. These impacts are also expected to be different in significance for different vehicle types due to differences in their characteristics and operational profiles.

A review of the available LCA literature has shown that there are considerable variations also in the relative impacts of EVs (and the importance of battery production impacts) compared to conventional vehicle comparators, mainly as result of the following key considerations:

- The assumed conversion losses in battery.
- (Additional) energy required to transport weight of battery.
- Carbon intensity of electricity.
- Assumed vehicle lifetime mileage.
- Assumed drive cycle (e.g. NEDC or 'real-world' conditions).

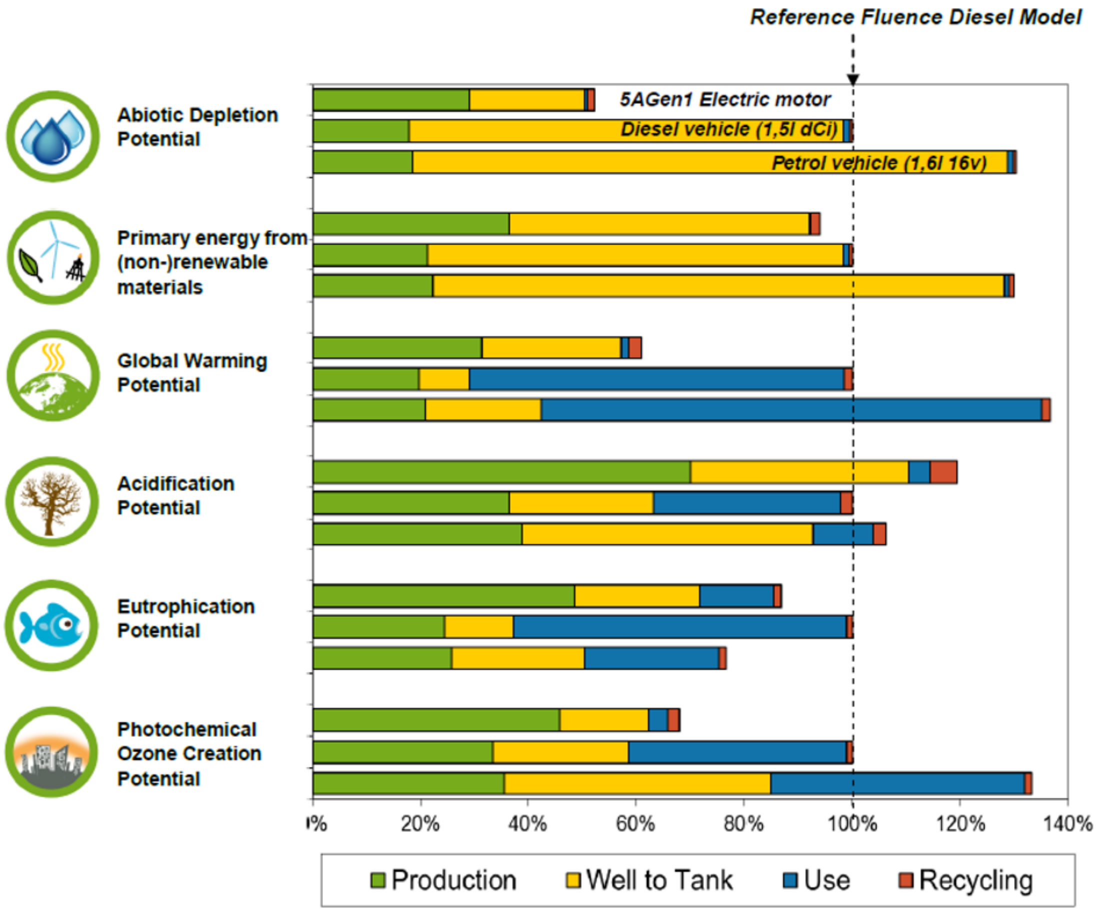
The following subsections present findings from key sources for different vehicle types.

As noted at the start of this chapter, an additional piece of work is ongoing for EC DG CLIMA (also led by Ricardo), which will develop consistent results for a range of different vehicle types, powertrains and energy carriers for the EU situation. This project will be completed towards the end of 2019, and will also provide estimates for the outlook for comparisons in the longer term (to 2050).

### 4.4.2 Passenger cars

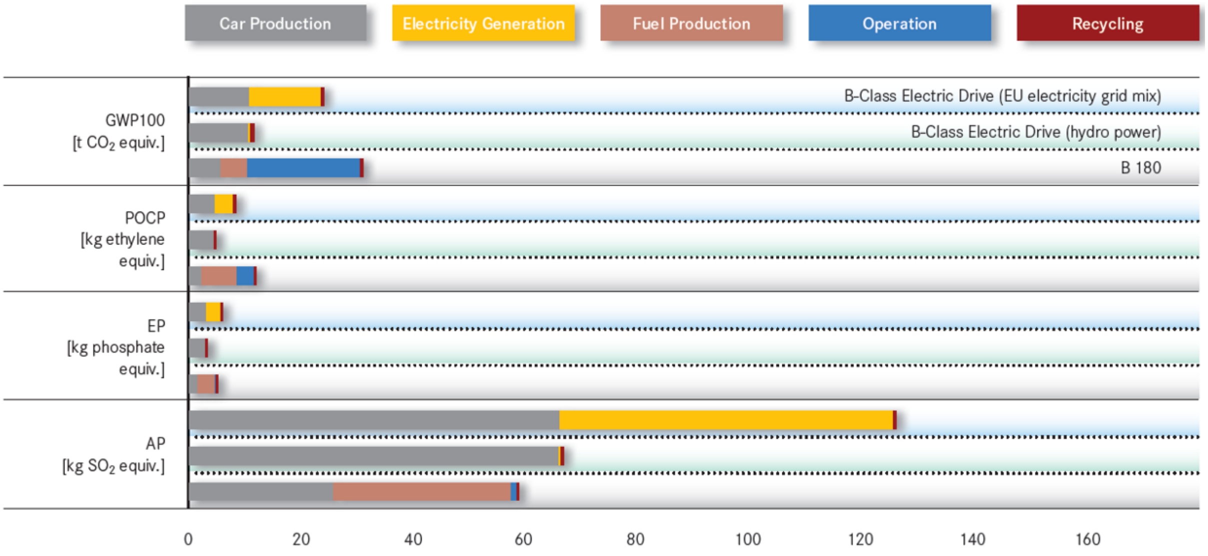
For passenger cars, many manufacturers are now reporting environmental impacts of their vehicles in environmental product declarations (EPD). These product declarations uniformly use the 'Recycled Content' approach for lifecycle analysis, so do not account for the significant differences between the recycled content of materials used in vehicle manufacturing and the much higher overall recycling rates of the vehicles, and in particular key materials such as steel and aluminium, at the end of their lives. Figure 4.11, Figure 4.12 and Figure 4.13 below illustrate the lifecycle impacts of fully electric models from Renault and Mercedes-Benz in comparison with equivalent petrol or diesel equivalents for a variety of environmental impact categories. Whilst for the most part the impacts of the electric models are significantly lower than those of conventional equivalents, this is not the case for the acidification metric mainly due to higher emissions of SOx (also highlighted earlier) in the manufacturing phase and due to operational electricity use.

**Figure 4.11: Lifecycle environmental impacts of Fluence for diesel, petrol and battery electric models (EU fuel and electricity production mix)**



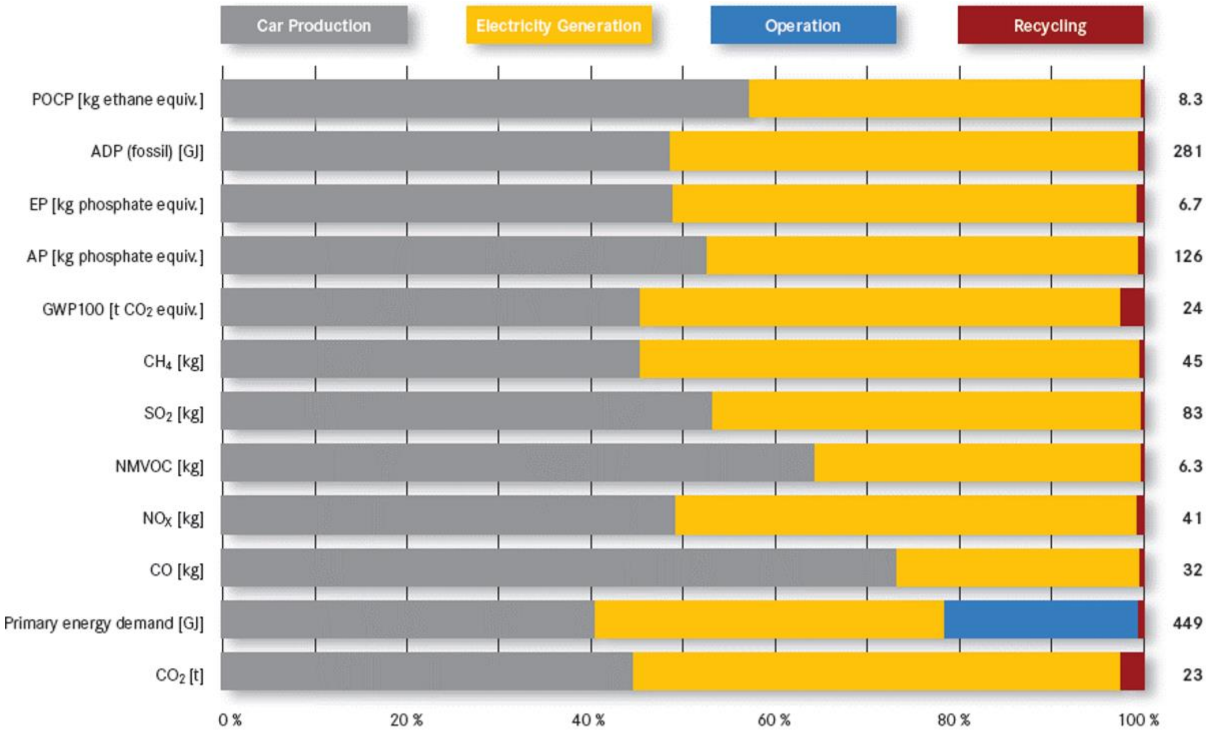

*Source*: (Renault, 2011). *Notes*: 'Well to Tank' = emissions resulting from the production of the fuels / electricity used in the vehicle, 'Use' = mainly direct operational emissions (also known as 'Tank to Wheel') emissions (i.e. primarily exhaust emissions) emitted during the operation of the vehicle; also includes other emissions e.g. from vehicle maintenance. Recycling = emissions associated with recycling processes – no additional credits are provided for recovered materials.

**Figure 4.12: Lifecycle environmental impacts from the Mercedes B-Class Electric Drive in comparison with the regular B 180 petrol-engine variant**




*Source*: (Daimler AG, 2014)

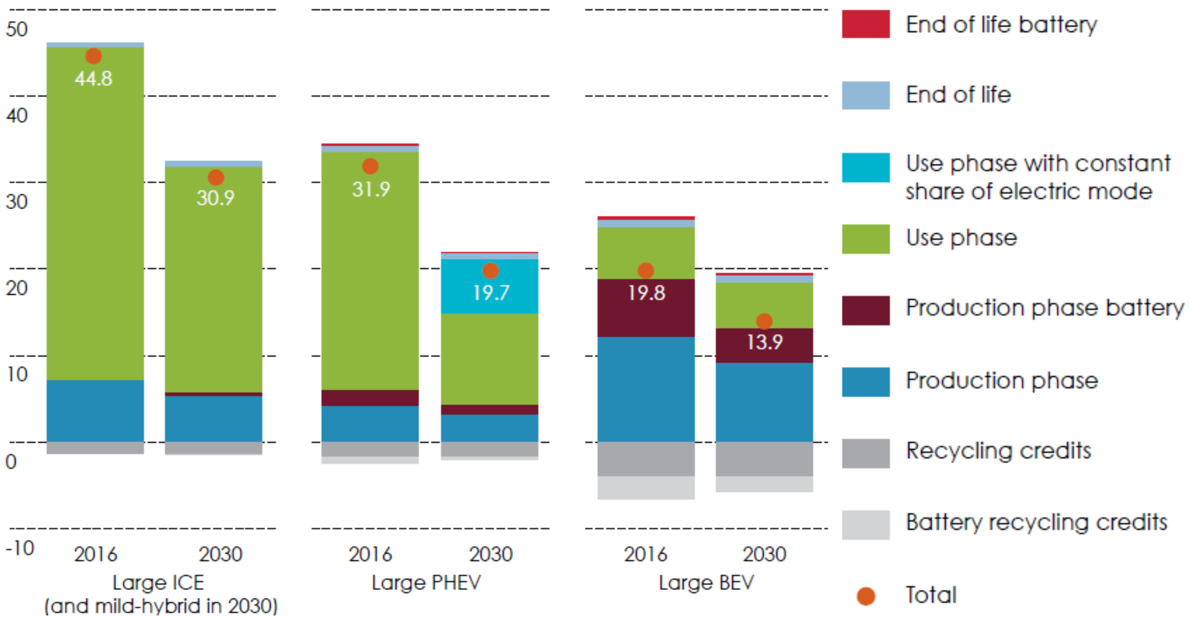
**Figure 4.13: Share of lifecycle phases for different impacts for the Mercedes B-Class Electric Drive (EU electricity Mix)**




*Source*: (Daimler AG, 2014). *Notes*: Operation = mainly direct exhaust emissions emitted during the operation of the vehicle; Recycling = emissions associated with recycling processes – no additional credits are provided for recovered materials.

Figure 4.14 provides an analysis from the alternative 'Avoided Burden' LCA approach for GHG emissions from large passenger cars. This analysis from (ECF, 2017) also shows the importance of recycling in further reinforcing lifecycle emissions savings from electric vehicles in the current and medium-term (2030) perspective.

**Figure 4.14: Global warming potential: 2016-2030 results compared for the large car sector (t CO2e)**

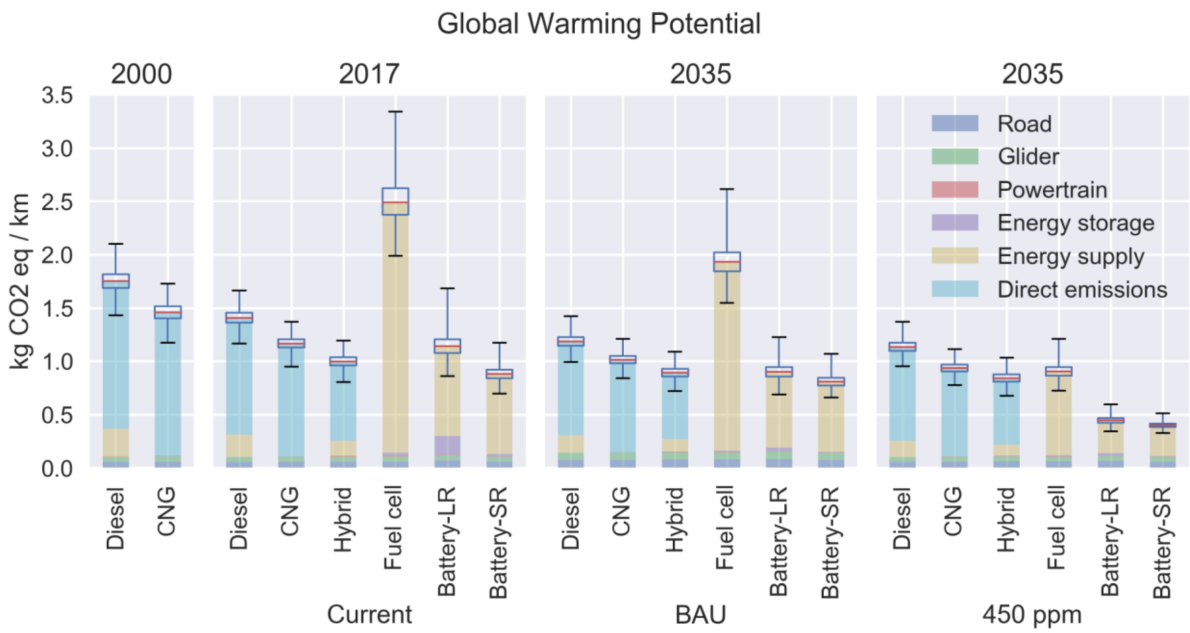



*Source*: (ECF, 2017). *Notes*: The use phase includes emissions from the production of fuel / electricity used in the vehicle as well as direct exhaust emissions from vehicle operation.

### 4.4.3 Heavy duty vehicles

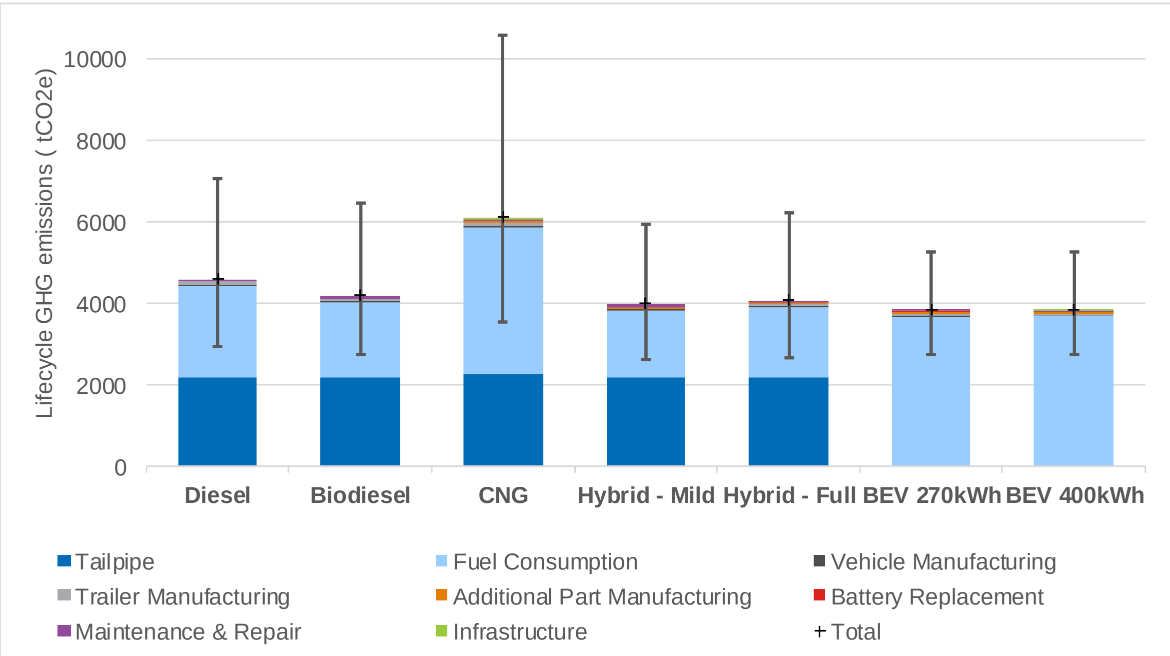
There are very few LCA studies available that consider the environmental impacts of electric (or even conventional) heavy duty vehicles. However, according to information available at (Volvo Trucks, 2018), tailpipe GHG emissions from high-mileage conventional trucks are responsible for around 99% of total lifecycle emissions. This was also a finding from previous work we conducted for DG CLIMA (AEA et al., 2012). As a result, despite the batteries being much bigger, the overall share of impacts from battery manufacture for electric heavy-duty trucks, and busses, are not expected to be significant in the overall context of emissions resulting from the operational phase due to their much higher lifetime activity compared to passenger cars and vans. This is also demonstrated in the findings of two studies that have been identified that have looked at electric urban buses – see Figure 4.15 – and electric heavy trucks – see Figure 4.16.

**Figure 4.15: Comparative analysis of estimated GHG impacts from different urban bus powertrain types at different time horizons**




Source: (Cox, Castillo, & Mutel, 2017)

**Figure 4.16: Lifecycle greenhouse gas emissions of heavy-duty trucks in the United States**




Source: Ricardo analysis of (Sen, B., Ercan, T. and Tatari, O., 2017)

### 4.4.4 Motorcycles

Only one source was identified in the literature that compared the lifecycle impacts of EV motorcycles with conventional (and other) powertrain types (Cox & Mutel, 2018). The results of this study show similar trends to those for passenger cars – i.e. that although the GHG impacts of battery production significantly increase overall manufacturing emissions, there are considerable overall net GHG savings versus conventional powertrains.

# 4.5 Potential effects of future changes on the lifecycle impacts of EV batteries

## 4.5.1 How might future changes in materials and energy sources affect different impacts?

### 4.5.1.1 Materials used in battery manufacture

In addition to changes in the actual materials used in EV batteries (some of which have been discussed already), a reduction in the impacts resulting from the production of raw materials for battery production is anticipated in the future due to broad decarbonisation of industry, transport and energy. Within Europe, industrial $CO_2$ emissions are capped under the EU ETS and with economy-wide decarbonisation targets of 80-95% reduction on 1990 levels by 2050 (or even climate neutrality as set out in the recent long-term strategy), the impacts from key battery materials that could be produced in Europe, such as steel and aluminium (with the latter being particularly strongly linked to energy decarbonisation), are likely to significantly reduce. Decarbonisation of materials is likely to occur at different rates in different regions, which creates an element of uncertainty in the overall trends for battery manufacture depending on the region of manufacture and the sourcing of these materials. In addition, future improvements in the efficiency of the production of key materials can also be expected.

In previous work for DG CLIMA (AEA et al., 2012) and for the UK Committee on Climate Change (Ricardo-AEA, 2013) our analysis showed that the carbon intensity of steel, aluminium and plastics produced could reduce by ~37%, 51% and 31% respectively by 2050, when compared to current levels even in conservative scenarios (i.e. sourcing from non-EU regions). More recent analysis presented in (ECF, 2018) also indicates that the emissions intensity of EU steel and plastics production could halve by 2050, and that aluminium manufacturing emissions could be much greater through the use of zero emission electricity generation.

The effects of such a transition would be two-fold, first they would act to reduce the impacts from the materials used in battery manufacturing (which account for around 35% of the GHG impact currently, according to Figure 4.4). However, this would also potentially reduce the net benefits gained from recycling at the end of the batteries' life, since the carbon intensity of the virgin material being displaced would be lower.

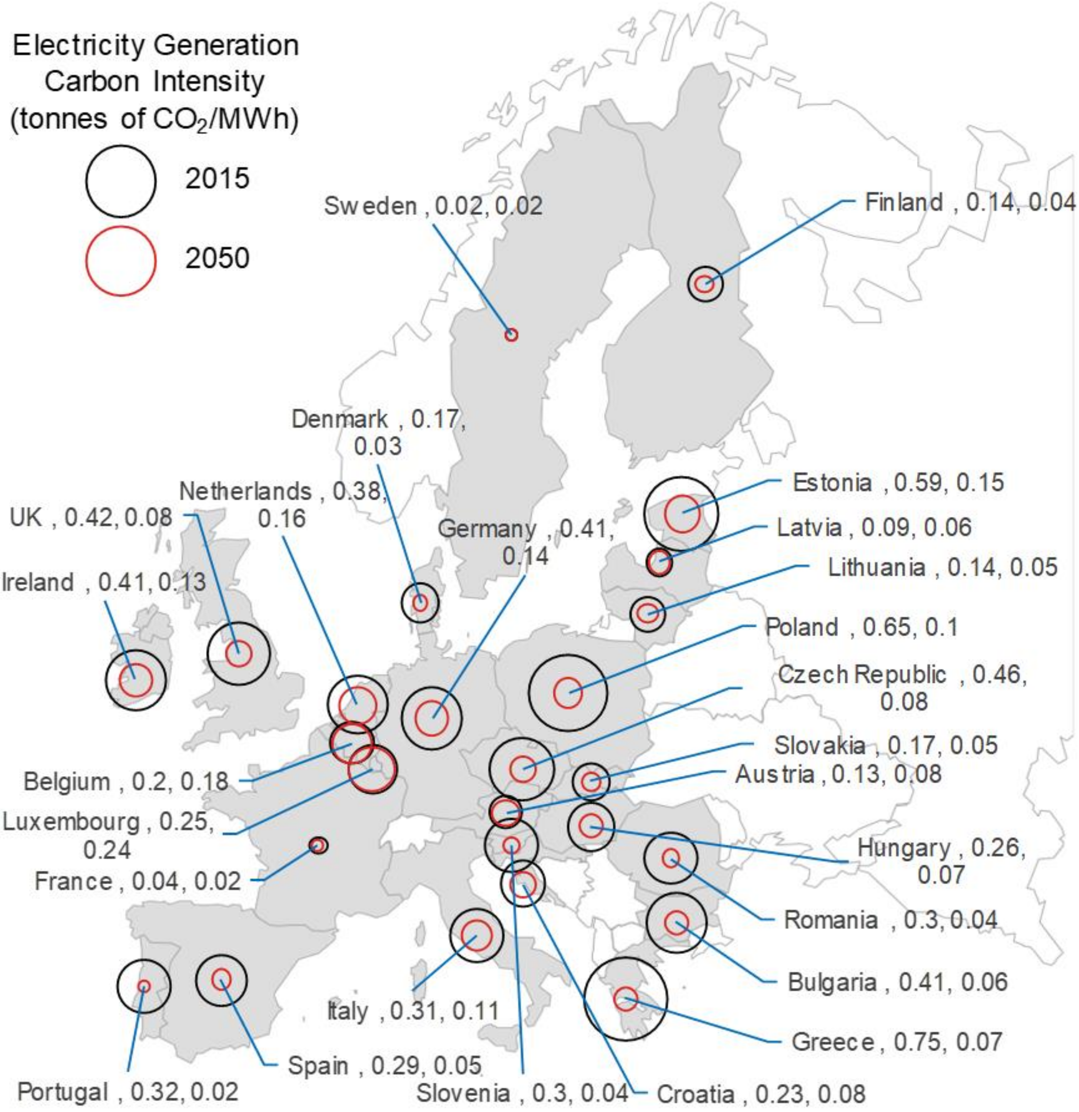
Besides changes to the energy mix and material processing/production techniques, there are also potential impacts resulting from changes in supply chain, for example, the UK are currently investigating Cornish lithium as opposed to importing from Chile (Energy Voice, 2018). However, such potential developments are difficult to take into account in practice.

### 4.5.1.2 Energy sources used in battery manufacture

In a similar way, the other major factor affecting the environmental impacts of battery production (and also recycling) is the GHG intensity of the energy used in battery manufacturing processes - accounting for 35-40% of the impact according to the following Figure 4.5. This has two dimensions – improvements in local electricity mixes and shifts in EV battery manufacturing locations impacting this.

The earlier analysis has already demonstrated that this has an important influence, and is a major contributor to geographical variations in the production impacts of EV batteries. This makes the location of battery manufacturing (and sourcing of energy) a particularly important consideration. However, in Europe, and also in other global regions, there is a transition to renewable and other low carbon generation technologies that is anticipated. Figure 4.17 provides an illustration of the current and future GHG intensity of electricity generation in different European countries. The average EU electricity mix is anticipated to reduce by almost 80% in the EU's reference case, and by over 90% versus 1990 in low carbon economy scenarios. This will have a significant impact on the emissions intensity of battery manufacture in Europe, though lower in other regions.

**Figure 4.17: Current and projected future carbon intensity of grid electricity in different EU countries**




*Source*: Ricardo analysis based on the on European Commission: European Reference Scenario 2016 (European Commission, 2016e), comparing 2015 with 2050

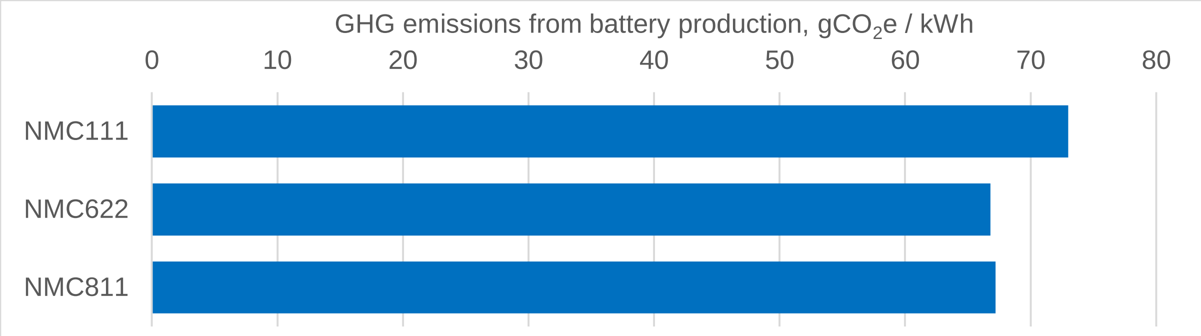
## 4.5.2 How might changes in manufacturing or use of advanced battery chemistries affect the analysis?

### 4.5.2.1 Effects of improvements in the performance and energy density of current Li-ion chemistries

Whilst there is potential for reduction in the environmental impacts of battery production through the use of cleaner energy sources in their manufacture, improvements in the impacts associated with the raw materials, further gains can also be made through refinements to current chemistries to increase the energy storage density (in Wh/kg) of batteries. Such improvements have been a significant contributor to the rapid reduction in battery costs in recent years, and increases in BEV battery pack kWh capacities. The impact of improvements in energy density on different impact categories is illustrated in Figure 4.19 below for an 8.3-16.7% increase in energy density. The effects change for each impact category, due to differences in the importance of the manufacturing stages / materials. Such evolutionary improvements are mainly related to changes in the NCM cathode materials, which only account for a smaller share of overall impacts for certain categories – notably for GWP. Production GHG emission results for three NMC cathode chemistries, calculated by the GREET model, are also presented in Figure 4.18. Similar effects would also be expected for other Li-ion battery types, though the benefits could be further amplified when looking at the whole system, since a lighter and more energy dense battery would be mean less tractive power is required. This finding was also confirmed in the findings of analysis by (Baumann, Peters, Weil, & Grunwald, 2016) - high energy density batteries require fewer cells to be produced for the same storage capacity and therefore show generally lower impacts per kWh of capacity (as long a similar operational lifetimes are achieved).

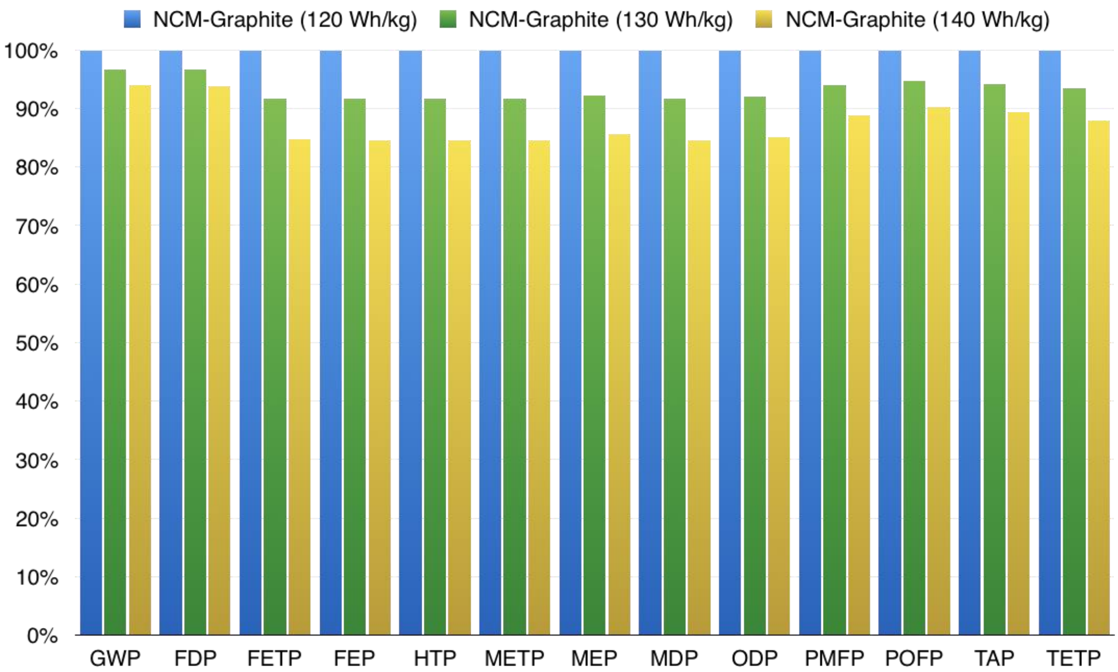
Such considerations have in recent years been counteracted by increases in battery size/capacity, due to the need to improve EV utility. However, with EV ranges now reaching more acceptable / manageable levels for a wider proportion of potential users, it seems likely such benefits may be harnessed to a greater extent in future years.

**Figure 4.18: Li-ion battery production GHG emissions for different NMC cathode chemistries from GREET**




*Source*: Data provided by Argonne National Laboratory during the stakeholder consultation for this project. *Notes*: Battery energy density (Wh/kg) assumptions: NMC111 = 164, NMC622 = 182, NMC811 = 178.

**Figure 4.19: Environmental impact comparison for NCM-graphite battery with higher energy density (NCM-Graphite (120 Wh/kg = 100%)**



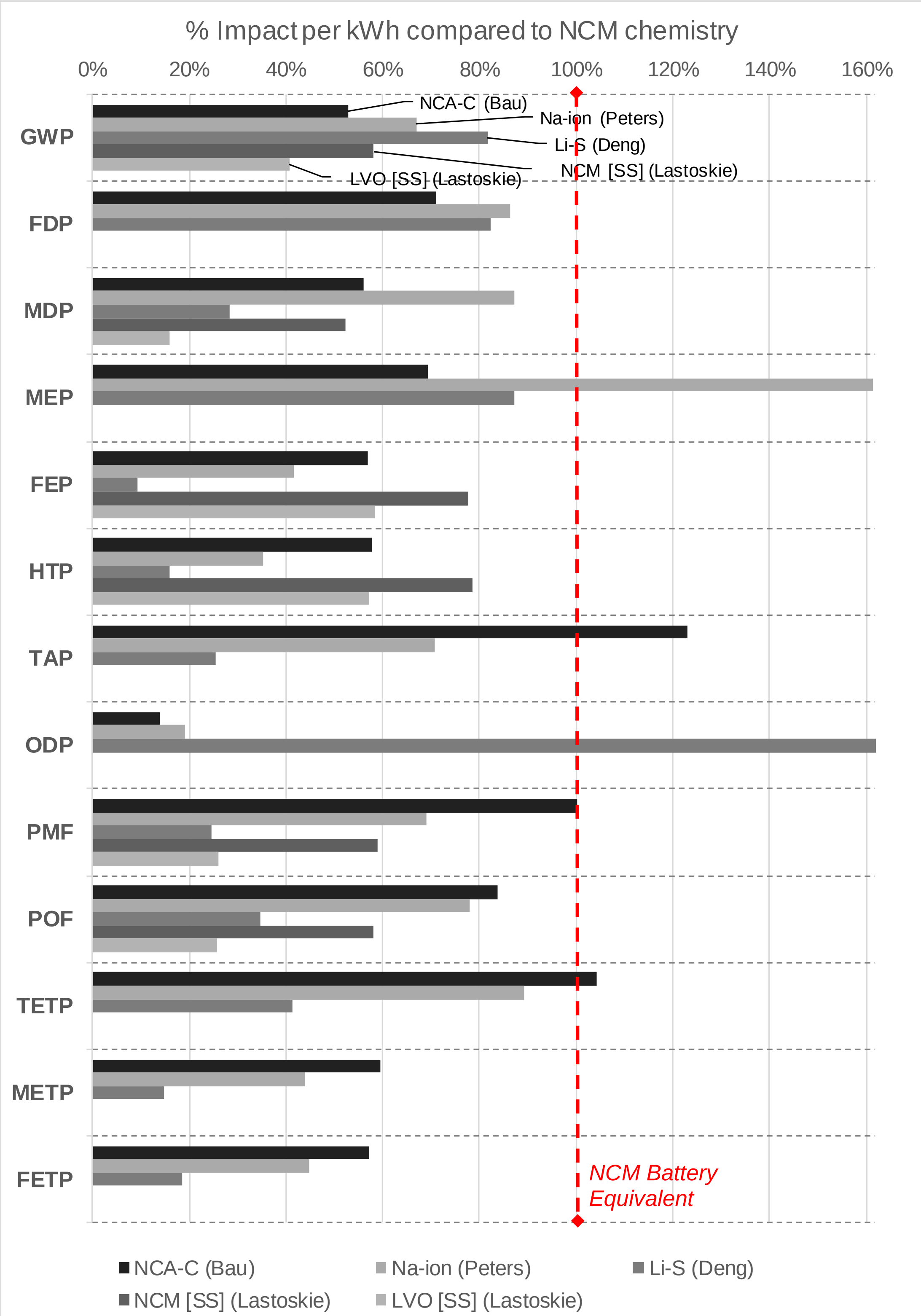

Source: (Deng, 2017)

*Notes*: FDP = Fossil Depletion Potential, F/M/T-ETP = Freshwater/Marine/Terrestrial Ecotoxicity Potential, FEP = Freshwater Eutrophication Potential, HTP = Human Toxicity Potential, MEP = Marine Eutrophication Potential, MDP = Metal Depletion Potential, ODP = Ozone Depletion Potential, PMFP = Particulate Matter Formation Potential, POFP = Photochemical Ozone Formation Potential, TAP = Total Acidification Potential

#### 4.5.2.2 Potential effects due to shifts to new EV battery chemistries/technologies

As discussed in earlier chapters of this report, there are a number of new battery technologies / chemistries being researched and developed, which are anticipated to be introduced into the EV market in the next 5-10 years (e.g. Li-S, solid-state, Na-ion batteries) and beyond (e.g. Li-air). Since these newer technologies are still being developed for mass deployment, there is little available information on their potential environmental impacts. A small number of LCA studies have been identified and a comparison of the potential environmental impacts per kWh battery of these chemistries, relative to a typical NCM battery, is provided in Figure 4.20 below.

**Figure 4.20: Characterisation values for the compared batteries (per kWh of storage capacity)**




*Source*: Based on analysis of supplementary material from (Peters, J. F., and Weil, M., 2017), (Peters, 2016), (Deng, 2017) and (Lastoskie, 2015) (for LVO = Lithium Vanadium Oxide, and other solid state [SS] chemistries).

*Notes*: GWP = global warming potential, FDP = fossil depletion potential, MDP = metal depletion potential, MEP = marine eutrophication potential, FEP = freshwater eutrophication potential, HTP = human toxicity potential, TAP

= terrestrial acidification potential, ODP = ozone depletion potential, PMP = particulate matter formation, POF = photochemical oxidant formation, TETP = terrestrial ecotoxicity potential, METP = marine ecotoxicity potential, FETP = freshwater ecotoxicity potential. [SS] = solid-state electrolyte battery chemistry.

Comparisons are also provided, in Figure 4.20, with current NCA battery chemistry, from the same source (Peters, J. F., and Weil, M., 2017). As the chart shows, new chemistries are anticipated to significantly reduce impacts across almost all impact categories: for GWP the reductions are reduced by 18-59%, depending on the technology, and for certain impact categories (e.g. FETP, METP, HTP and TETP) impacts are reduced by as much as 80-90%. According to the literature sources, these improvements are due to a combination of higher energy density (in the case of Li-S and solid-state (SS) chemistries), and changes in key materials/composition (particularly for the Na-ion and Li-S chemistries). For example, according to (Deng, 2017), the Li-S battery does not use heavy metals such as Nickel, Cobalt, and Manganese, and it uses much less copper than a conventional NCM-Graphite battery. Since these new battery types are also at a lower stage of development when compared to current Li-ion chemistries it is expected that further improvements could also be anticipated in the future.

## 4.6 Summary and conclusions for the environmental impacts of EV batteries

The following Table 4.4 provides a summary of the overall findings and conclusions for the environmental impacts of batteries, based on the questions posed in the previous subsections of this report chapter.

**Table 4.4: High-level summary of the findings and conclusions on lifecycle impacts of EV batteries**

| # | Question | Summary of findings |
|---|---|---|
| 1 | How well are the impacts of EV traction batteries characterised in the literature? | The impacts of current EV Li-ion battery manufacture are relatively well characterised (but most focus on GHG and energy), allowing an understanding of the scale of impacts across the lifecycle and which are the key stages in terms of impact hotspots. However, differences in assumptions and the basis of the LCA make comparability difficult in some cases, and there is less information available / greater uncertainty on advanced chemistries and on impacts end-of-life treatment and potential reuse/second use. |
| 2 | What is the variability in estimates for (GHG emissions) impacts from batteries? | There is significant variability in estimates for GHG impacts from battery manufacture (and disposal when covered also), due to different sources and assumptions – key factors include the electricity mix for manufacturing, battery energy density and treatment/inclusion of end-of-life recycling. Results from more recent studies tend to have lower impacts, and the region of production has been shown to be a key factor (through the strong link to manufacturing energy GHG intensity in particular).<br><br>Variations between conventional chemistries tend to be smaller (as also demonstrated in studies that have attempted to produce normalised results for different studies), with stronger links between impacts to the specific energy densities of batteries. Most studies appear to be based on older battery chemistries, so also seem likely to overstate impacts compared to newer formulations (e.g. NMC 8:1:1) and better optimised manufacturing. |
| 3 | Are the batteries for different powertrains or vehicle types significantly different? | Hybrid cars have typically used NiMH batteries in the past, but are now moving to Li-ion batteries similar to those used in PHEVs. These batteries tend to be optimised more for power (i.e. due to fewer cells / smaller pack size) compared to fully electric vehicles (i.e. BEVs). However, no significant difference in their environmental impacts has been otherwise identified in the LCA literature. The main impact will be a lower pack-level energy density (as the share of non-cell components is greater) and therefore higher impacts per kWh of battery, also because the |

| # | Question | Summary of findings |
|---|---|---|
| | | module and pack assembly components and processes are a significant contributor to most of the overall environmental impacts. There appear to be no significant differences in the types/chemistries of batteries used in other vehicle types currently, except for relative packaging and capacity considerations. |
| 4 | How do different impacts vary over the battery lifecycle? | With current EU grid electricity mixes, the EV use phase dominates the lifecycle impacts for the majority of impact categories and battery chemistries. Exceptions (where the production phase dominates) are in most cases due to impacts from Li-ion battery (LIB) cathode components (materials extraction and processing), and include eutrophication potential (for LFP cathode chemistry), ozone depletion potential, eco-toxicity potential and occupational cancer/non-cancer hazard (for all LIB chemistries).<br><br>Impacts from cobalt (Co) use are particularly significant, though are expected to decline as this is phased out (due to cost and resourcing concerns).<br><br>Impacts/credits from end-of-life recycling are discussed below. |
| 5 | How do battery impacts vary by battery type / chemistry? | As indicated above, there are some variations in certain impacts between different Li-ion battery cathode chemistries. However, analyses of normalised results from the literature show that in most cases the differences are relatively small (or driven by the content of certain materials like cobalt). Impacts of energy consumption in battery manufacturing account for 35-45% of the total GHG, and does not appear to vary significantly for the battery current chemistries per kg of battery. The cathode and cathode binder contribute the most to the embedded GWP of a Li-ion battery pack. Therefore, improving these aspects of battery chemistry /manufacturing could also lead to the most significant benefits. Based on the available evidence, options being investigated to improve battery energy densities (i.e. in Wh/kg), such as silicon dosing of the battery anodes, will lead to also in net reductions in impacts per kWh of battery storage. |
| 6 | What is the impact of battery recycling on the overall result? | Impacts/credits from end-of-life recycling are less clear, with much of the evidence base coming out of Argonne National Laboratory / the US GREET vehicle lifecycle model.<br><br>Two different methodologies for handling recycling predominate: ‘recycled content’ approaches are used in manufacturer product declarations and essentially give fewer net credits than alternative ‘avoided burden’ approaches, which account for generally much higher automotive recycling rates (vs content).<br><br>There still appears to be significant uncertainty on the net gains due to (currently energy intensive) recycling, and on how these might evolve in the future for new recycling processes and scaling up and optimisation of recycling for EV batteries specifically. |
| 7 | How might EV battery reuse / second-life applications affect the analysis? | Possible second life applications of EV batteries are still at relatively early stages of investigation, with few studies available considering environmental impacts. One study conducted a cascaded analysis of an EV battery second use scenario in comparison with fossil generation reference systems. This study found that remanufacturing impacts were <10% of a new battery and that there were significant overall benefits compared to a conventional system, but that battery efficiency fade was a significant determining factor in potential second use performance. |

| # | Question | Summary of findings |
|---|---|---|
| | | Another study found that second use was only beneficial from an environmental point of view when used in conjunction with renewable energy sources. More information/research is therefore needed to establish more clearly the potential benefits. |
| 8 | How significant are lifecycle impacts from batteries versus the whole vehicle use? | There are significant variations in the findings from the literature due to the use of a range of different assumptions for key parameters (like lifetime mileage, electricity mix, driving cycles, recycling, etc). Most available analysis focuses on passenger cars, where production emissions for BEVs currently account for around double those for conventional vehicles (i.e. around half the total production burden for BEVs), but net emissions (including operation) are significantly lower for most environmental impacts (except acidification where both production and operational impacts are higher than for conventional vehicles) with the EU electricity mix. A key assumption is the methodological treatment of recycling, i.e. ‘recycled content’ vs ‘avoided burden’ discussed above. |
| 9 | Are the impacts of batteries versus the whole vehicle use for different vehicle types significantly different? | The situation appears similar for passenger cars and motorcycles, in terms of the relative balance of production and disposal impacts versus operational energy consumption.<br><br>For heavy duty vehicles (lorries and buses), that have much higher lifetime mileages, manufacturing emissions are uniformly dwarfed by those from operational energy consumption (accounting for up to 99% of all emissions for some vehicles) for all powertrains. |
| 10 | How might future changes in materials and energy sources affect different impacts? | Decarbonisation of the sourcing and production of materials (i.e. through economy-wide pressures to reduce emissions), and of the energy sources used in battery manufacturing could have a very significant effect on overall impacts. Carbon emissions from EU electricity generation are anticipated to reduce by 89-90% versus 1990 by 2050. The manufacture of materials and batteries will therefore have an increasing importance in the future. |
| 11 | How might changes in manufacturing or use of advanced battery chemistries affect the analysis? | Information from the literature shows that improvements in the battery chemistries to produce higher energy density batteries, also lead to reduced impacts per kWh of battery capacity (though this is not uniform for all impact types). However, increases in battery pack capacities would be expected to counter-act such improvements.<br><br>There are only a few sources that consider potential impacts of advanced chemistries (including Li-S, solid-state batteries, and Na-ion). These all showed substantial reductions, compared to the currently dominant NMC chemistry, in most or all environmental impact categories could be expected:18-59% reduction in GHG, and as much as 80-90% reduction in some others. Improvements are due to a combination of energy density improvements and changes to materials and processes.<br><br>No studies were identified that specifically looked at other improvements to manufacturing techniques and their impacts, though inferences have been drawn for these in Chapter 3. |

## 4.7 Outstanding questions, gaps and uncertainties for battery LCA

We have identified a number of key gaps or uncertainties and questions relating to lifecycle impacts of EV batteries for discussion with stakeholders during the project, however many of these questions remain open and more research is needed to answer many of them. Those outstanding included:

**Production**

- *Lifecycle impacts*: How much might the most significant impacts from production change over time as a result of:
  - Advanced battery chemistries?
  - Improved manufacturing techniques?
  - Supply chain optimisation?

  Which advances are likely to provide the greatest benefits (per kWh)?
- *There is uncertainty in estimating future impacts of battery production based on changes in energy intensity, chemistry and types:*
  - How might future impacts from production be reduced by more simple chemistry /performance improvements?
  - Is the correlation to improvements in energy density (Wh/kg) benefiting impacts clear?
- *Lifecycle impacts by production stage and lifecycle component:* What are the most significant environmental impacts per production stage or lifecycle component?

**End-of-Life**

- *Contribution of optimised recycling processes to overall impacts:* What level of key materials recovery and impact reduction (% savings on production) might future optimised recycling achieve in the 2020-2030 period?
- *Treatment of battery second life in LCA of batteries / vehicles:* How should battery second life be credited in lifecycle analysis?
- *To what extent could changes to new/advanced battery chemistries affect recycling benefits:* Are advanced battery types (i.e. Li-S, solid-state, Na-ion, etc.) likely lead to relatively greater, or fewer benefits (credits) from recycling?
- *Quantified LCA impacts per type of recycling process and battery type are highly variable or uncertain in the literature:* additional information is needed on material recovery rates, the impact of battery recycling on the overall LCA result (e.g. % credits on production emissions) and how this varies by process and battery type.
- *Materials and energy:* How might future changes in materials and energy sources (e.g. used also for battery manufacturing) affect different impacts/credits for recycling? Has this been quantified/explored?

# 5 Assessment of the potential environmental impacts of traction batteries in the context of future EV deployment (Subtask 2.4)

*What will the potential environmental impacts and hotspots of traction batteries over their whole life cycle be if electric vehicles are deployed at large scale and/or in accordance with current trends, in the near, medium and long term?*

**Key outputs:**

- EU-level projections for overall potential environmental impacts from xEV deployment over the whole lifecycle and potential implication for key resources such as lithium, cobalt and nickel.
- Annual results provided for 2020 (current stage), 2025 (near-term), 2030 (medium-term) and 2050 (long-term).

This subtask builds on the findings from Subtask 2.3 (environmental lifecycle impacts and hotspots for EV batteries), to assess the fleet-level impacts if electric vehicles are deployed at a large scale in Europe. The objective is to show the overall impacts (e.g. on emissions) in the years they actually occur. The environmental impacts (and resource requirements for key materials) related to traction batteries have been assessed via scenario modelling, as described in more detail in the sections below.

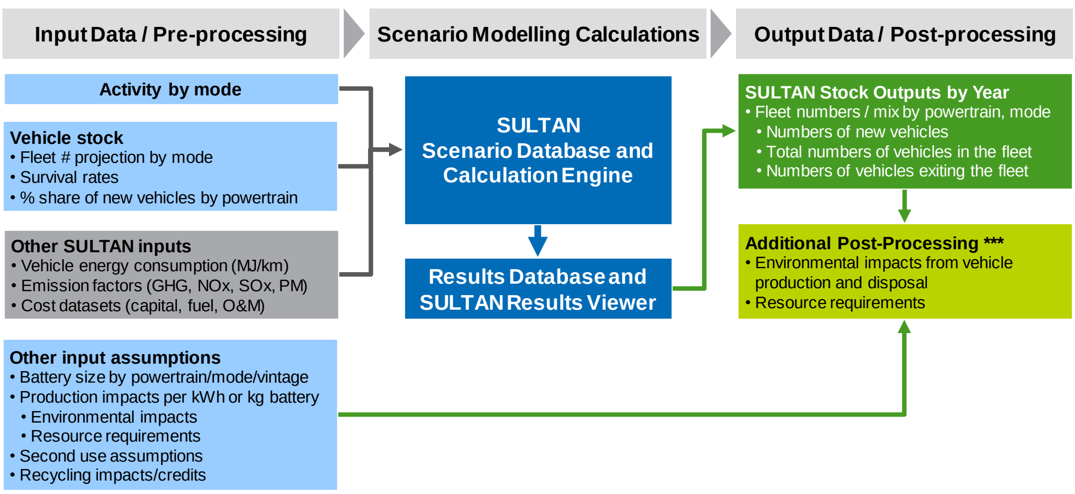
## 5.1 Summary of the methodological approach

The overall approach developed for this project was to carry out post-processing of outputs from the SULTAN illustrative transport scenarios tool, that Ricardo originally developed for DG CLIMA, to assess the implications on the vehicle fleet for different levels of uptake. SULTAN utilises stock modelling to calculate the impacts of different policy choices on GHG emissions, energy, air quality pollutants and costs for a range of different vehicle types including: cars, vans, buses, trucks, motorcycles and e-bikes.

The post-processing of outputs from the model has been used to determine the wider implications for the EV battery value chain in terms of battery volumes, lifecycle emissions/impacts and the demand for key resources. Non-battery vehicle production and disposal impacts have not been assessed.

An outline of the approach developed for the estimation of aggregate impacts (and their timing) is provided in Figure 5.1 below.

**Figure 5.1: Outline of the methodological approach developed to estimate impacts based on post-processing of SULTAN stock model outputs for different xEV uptake scenarios**



### 5.1.1 Lifecycle, value-chain and resource input assumptions

The literature review carried out in Chapter 4 provided an overview of the state of play concerning the environmental impacts of traction batteries. In this work, the lifecycle impacts were analysed at the individual vehicle level and presented for numerous environmental impacts, including energy consumption, GHG emissions, air pollutant emissions and other categories such as ecotoxicity potential. The aim of this chapter is to use this data in combination with SULTAN modelling outputs (which covers new vehicle numbers and batteries entering and exiting the fleet) to estimate the impacts at a fleet-level and identify the main factors that most influence the results. The SULTAN model already calculates the emissions from vehicle operation for GHGs, NOx, PM and SOx for both direct (i.e. TTW) and indirect (i.e. WTT) emission components (as well as fuel/energy consumption). Therefore, these impacts were also selected for the overall battery fleet impacts analysis, so their relative scale/significance could be compared.

The meta-analysis in the LCA literature review has provided detailed results/projections for a variety of battery sizes, cell chemistries, manufacturing regions and other variables, for each stage of the lifecycle. The first part of this subtask was therefore to convert the results into a suitable set of inputs to the fleet analysis. Based on this review, previous analysis by Ricardo for the European Commission and other clients, and the discussions with stakeholders for the project, indicative projections of the average battery composition, energy density and capacity were developed for each modelling year.

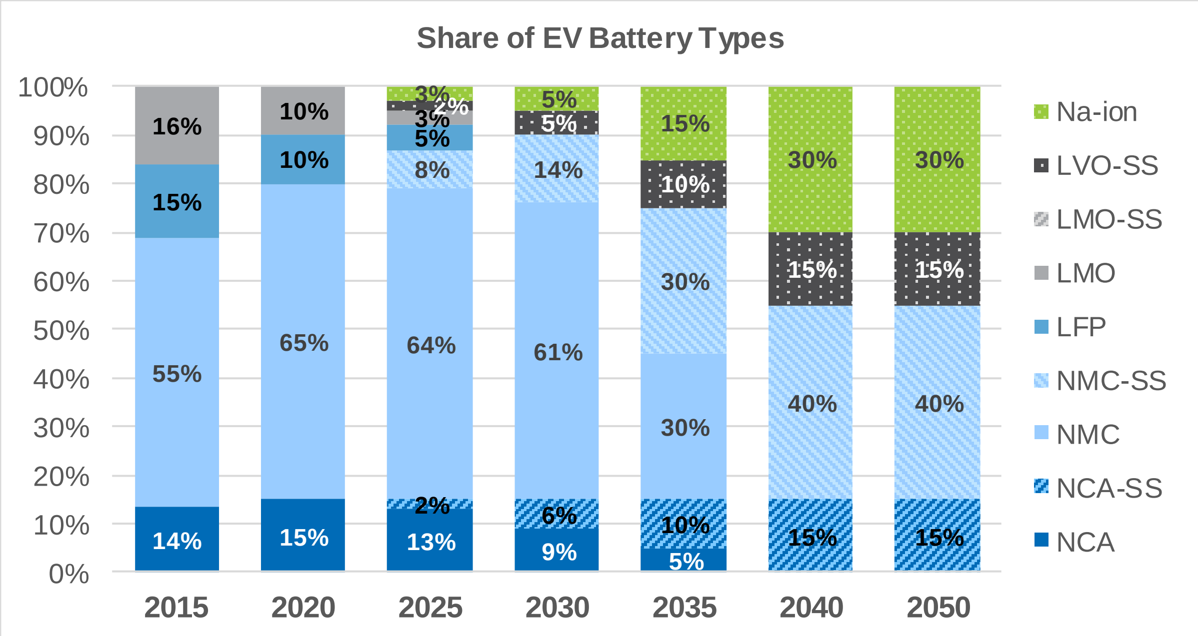
The set of battery lifecycle related inputs used in the analysis are shown in Table 5.1, together with a summary of some of the key assumptions. A summary of the assumptions on the shift in battery chemistries is also provided in Figure 5.2, which includes a gradual transition to solid-state electrolytes (with Li-metal anodes) and Na-ion chemistries from 2025. Feedback from the stakeholder interviews suggested that Li-S chemistries were less likely in transport applications, due to lower volumetric density versus other advanced chemistries. Furthermore, it was assumed that Cobalt use is entirely eliminated from EV batteries by 2040 (based on current technological trends/developments and stakeholder feedback). Further information on these is provided in the Appendices, and the fleet level inputs are described in the following Section 5.1.2.

**Table 5.1: List of battery lifecycle related inputs**

| Input | Summary description/assumptions |
|---|---|
| **Battery production** | **By mode and powertrain type** |
| Average battery composition (%) | Projections of average battery composition (with particular attention to changes in lithium, cobalt and nickel based on future shifts in battery cathode chemistries) for each modelling year. These were used to develop estimates for resource requirements, as well as emissions impacts. |
| Average battery capacity (kWh) | Projections of average battery capacity for each vehicle type and powertrain: used to calculate the volume of batteries exiting the vehicle fleet in each modelling year. |
| Average battery energy density (Wh/kg) | Projections of average battery energy density: used to calculate the mass of batteries (and the breakdown of this into different materials/components). The default assumption is that average EV battery cell energy density will increase to ~500 Wh/kg by 2030, and then to ~800 Wh/kg by 2050. |
| Battery production environmental impacts (GHG, NOx, PM, SOx) | Projections of the environmental impacts for this lifecycle stage over time, taking into consideration potential decarbonisation of manufacturing processes and that of the production of key materials.<br>A simplified LCA calculation methodology was developed, based on data from the GREET model (ANL, 2018) for battery material composition (and emissions factor) data for the main battery types, assumptions on future reduction in Cobalt from battery cathodes, and information on process energy from the PEFCR for rechargeable batteries (RECHARGE, 2018), as well as other literature such as (Ford/LG Chem, 2016). Assumptions for battery composition for solid-state and sodium-ion batteries was based mainly on data from (Lastoskie, 2015) and (Peters, 2016). |

| Input | Summary description/assumptions |
| --- | --- |
| **Battery use** | **By mode and powertrain type** |
| Battery lifetime / replacement | SULTAN has been modified to produce these outputs.<br>By default, LDVs batteries are assumed to last the life of the vehicle, with a sensitivity case developed assuming a single replacement. HEV batteries are assumed to last the life of the vehicle in all cases. HDVs are assumed to have at least one battery replacement in all cases. |
| End of lifecycle stage destination (%) | Percentage of batteries (by capacity) to re-use/repurposing, recycling, and disposal/loss (e.g. outside of the EU via exports, etc). |
| **Reuse/second life** | **For all batteries exiting the vehicle fleet combined** |
| Re-use/re-purposing environmental impacts (GHG, NOx, PM, SOx) | Estimated environmental impacts for this lifecycle stage over time, taking into consideration potential decarbonisation of manufacturing processes.<br>Simple assumptions, based on % share of new battery production (taken as 5% for reuse, and 10% for repurposing). |
| Credits for recycling and reuse/repurposing (GHG, NOx, PM, SOx) | Projections for the credits that could be gained by recycling/recovery of key materials, or from displacing a new battery that would have been used instead of a reused/repurposed battery. This has been estimated as a fraction of the impact of producing a new battery based on the assumption that a repurposed battery will last half as long as a brand new one. |
| Second-use lifetime (years) | Assumption concerning the average length of time a battery will be used in its second life application – taken to be 10 years. This is used to calculate the delay in the transfer of these batteries to recycling, and hence the recovery of materials. |
| End of lifecycle stage destination | Percentage of batteries (by capacity) to recycling or disposal/loss. |
| **Battery recycling** | **For all batteries at their end-of-life combined** |
| Recycling environmental impacts (GHG, NOx, PM, SOx) | Projections of the environmental impacts, based on key aspects such as the energy consumption (i.e. gas and electricity) for recycling processes. |
| Credits for recycling (GHG, NOx, PM, SOx) | Projections for the credits that could be gained by recycling a battery, also factoring in future decarbonisation of material production (i.e. reduced recycling credits in the future). |
| Materials recovery (%) | Projections of the effectiveness of the recycling process in terms of the quantity of materials that can be recovered in each modelling year (varied between the base case, and the sustainable value chain case). |
| **Battery disposal** | **For all batteries at their end-of-life combined** |
| Disposal impacts | Projections of the environmental impacts for this lifecycle stage over time. |

**Figure 5.2: Projected share of different battery types/chemistries used in the modelling analysis**




*Source*: Ricardo assumptions based on literature and stakeholder discussions. *Notes*: SS = solid state electrolyte, LVO-SS = Lithium Vanadium Oxide Solid State battery chemistry from (Lastoskie, 2015).

Using the input assumptions above, two alternative cases were developed so that the circular economy aspects of xEV batteries could be assessed in relation to the environmental impacts and resource availability. These included: (1) a base case consisting of no significant action to develop a sustainable value chain for xEV batteries in the EU and (2) an alternative case where a sustainable value chain is developed. These cases were developed and informed based on the literature review and stakeholder interviews. A summary of the cases is provided in Table 5.2.

**Table 5.2: Overview of EV value chain scenarios**

| # | Scenario name | Summary of scenario definition |
|---|---|---|
| 1 | **Base case (Base/BC)** | This scenario assumes that no significant action will be taken to develop a sustainable value chain for EV batteries in the EU. It has been used as a baseline for comparison with scenario 2 – the sustainable value chain (SVC) option. Conservative estimates have been adopted for the percentage of EV batteries to be reused or repurposed (for second life use) and recycled in this scenario, as well as more conservative recycling rates for key materials.<br>xEV battery cell manufacturing in the EU increases from essentially zero up to 2020, to around 40% of demand by 2040. |
| 2 | **Sustainable value chain (SVC)** | This scenario assumes that work is carried out to develop a more sustainable value chain for EV batteries. Compared to the base case, enhanced numbers of batteries will be manufactured for a second life, while recycling will also be higher. Assumptions concerning the effectiveness of recycling processes have also been increased in this scenario for key materials, such as lithium.<br>xEV battery cell manufacturing in the EU increases from essentially zero up to 2020, to around 80% of demand by 2040. |

### 5.1.2 xEV deployment scenario development

Two xEV deployment scenarios were developed (and run using the SULTAN model) to explore the potential range of impacts from EV deployment in the EU – representing a minimum and a maximum uptake scenario. The SULTAN model was modified to provide additional outputs for the total number of new batteries produced (and the capacity), as well as those exiting the vehicle fleet in each modelling year, which were required for the lifecycle impact calculations.

The analytical approach has been used to determine (for both of the EV uptake scenarios) what the most likely high-level impacts could be under two EV battery value chain cases (a base case and a sustainable value chain option), plus two simple sensitivities on key assumptions (i.e. where there is greater uncertainty). These two sensitivities included:

(a) **High xEV battery production impacts:** a sensitivity on the impacts from battery production – i.e. through higher impacts from the production of materials used in batteries (i.e. fewer future improvements to process efficiency and sourcing of renewable electricity) and lower energy density improvements for batteries (resulting in heavier batteries using more material resources); and

(b) **LDV battery replacement:** a mid-life battery replacement assumed for all light duty vehicles (versus default case = no battery replacement). For HDVs (i.e. buses and trucks) it is assumed at least one battery replacement is needed during the life of the vehicle in all cases.

A description of the two xEV deployment scenarios that we have developed is provided in Table 5.3 below, plus additional information in Figure 5.3 and a comparison with scenarios from the literature in Figure 5.4 for passenger cars. These are broadly consistent with work that we have recently performed for the European Commission and for other clients. For powered two-wheelers (including e-bikes), only one uptake profile has been developed as these account for a small share of overall battery capacity. For eBikes, uptake was based upon our recent project work for DG CLIMA (Ricardo Energy & Environment, 2016 (publication pending)). More detailed information on the xEV powertrain uptake scenarios is provided in the Appendices to this report.

**Table 5.3: Overview of EV deployment scenarios for light duty vehicles**

| # | Scenario name | Summary of scenario definition |
|---|---|---|
| 1 | **Minimum EV deployment scenario (LOxEV)** | This scenario follows a trajectory consistent with reaching the low-end of projections for xEV deployment for 2030 and 2050 (see Figure 5.4), whilst still achieving an average new vehicle $gCO_2$/km consistent with the European Commission's post-2020 $CO_2$ Regulation proposals (in October 2018, when the analysis was completed) for light duty vehicles (LDVs) and heavy-duty vehicles (HDVs), extrapolated through to 2050.<br>For buses/coaches an increasing share of PHEVs and BEVs (for buses) or FCEVs (for coaches) are assumed to be deployed through to 2050, alongside non-plug-in HEVs.<br>For medium trucks, shares increase for HEVs, PHEVs, BEVs and FCEVs to account for ¾ of sales by 2050. For heavy trucks, deployment is mainly of HEVs through to 2050, with small shares also of FCEVs. |
| 2 | **Maximum EV deployment scenario (HIxEV)** | This scenario follows a trajectory consistent with medium-high projections for xEV deployment for 2030 and 2050 for LDVs, reaching 100% xEV deployment by 2050. Improvement to conventional and hybrid vehicle efficiency is frozen after 2025 for LDVs. Even so, the rate of improvement in average vehicle $gCO_2$/km would be slightly higher than the minimum EV scenarios after 2030.<br>For HDVs, buses are assumed to shift mainly to BEVs by 2050, with coaches transitioning mainly to PHEVs and FCEVs. For medium and large trucks, smaller shares of PHEVs, BEVs and FCEVs are assumed to be introduced into the fleet in future periods (with greater shares in medium trucks). |

**Figure 5.3: Assumed shares of xEVs (PHEVs, BEVs and FCEVs) in the new fleet and vehicle parc for different deployment scenarios**

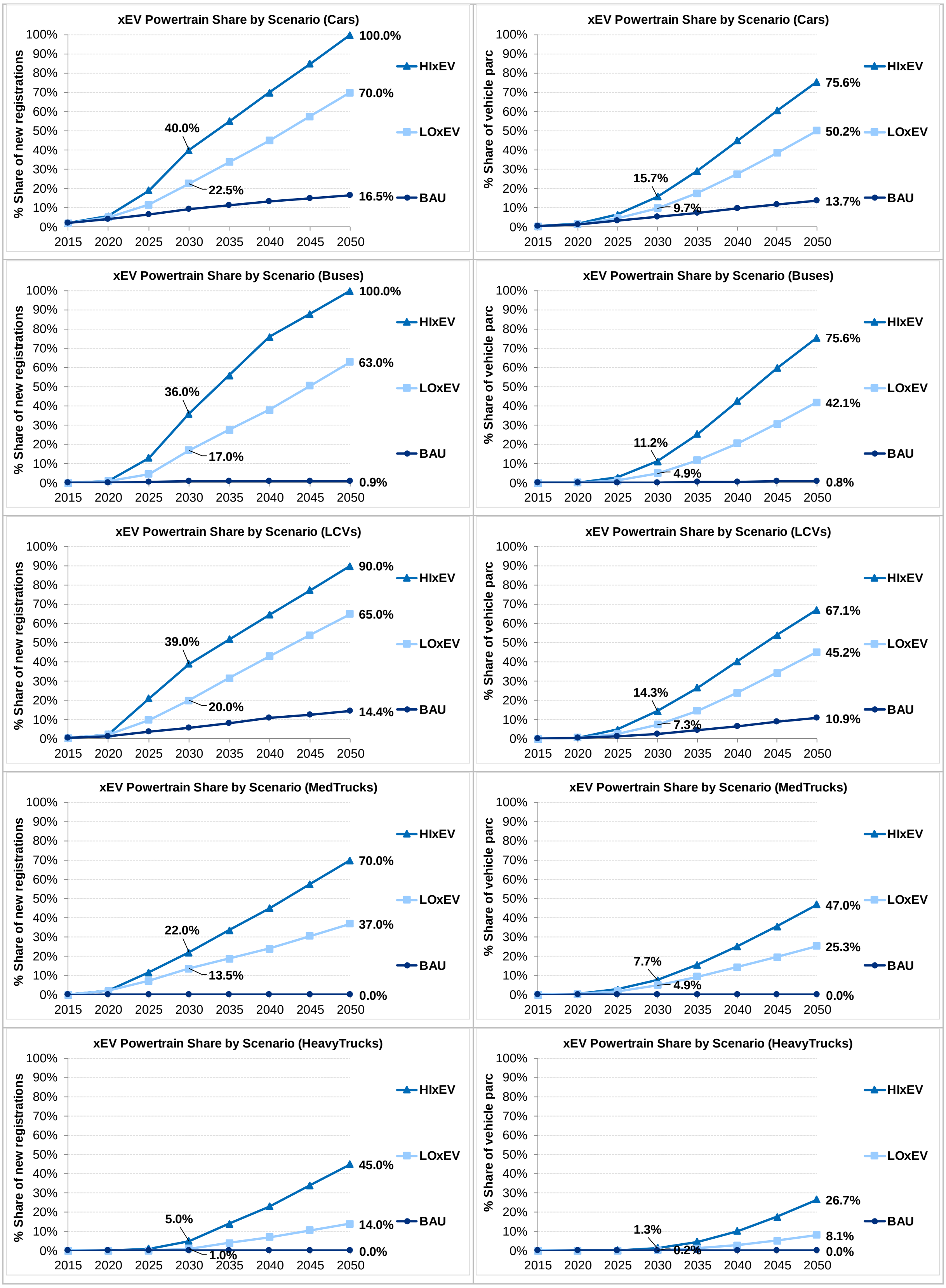
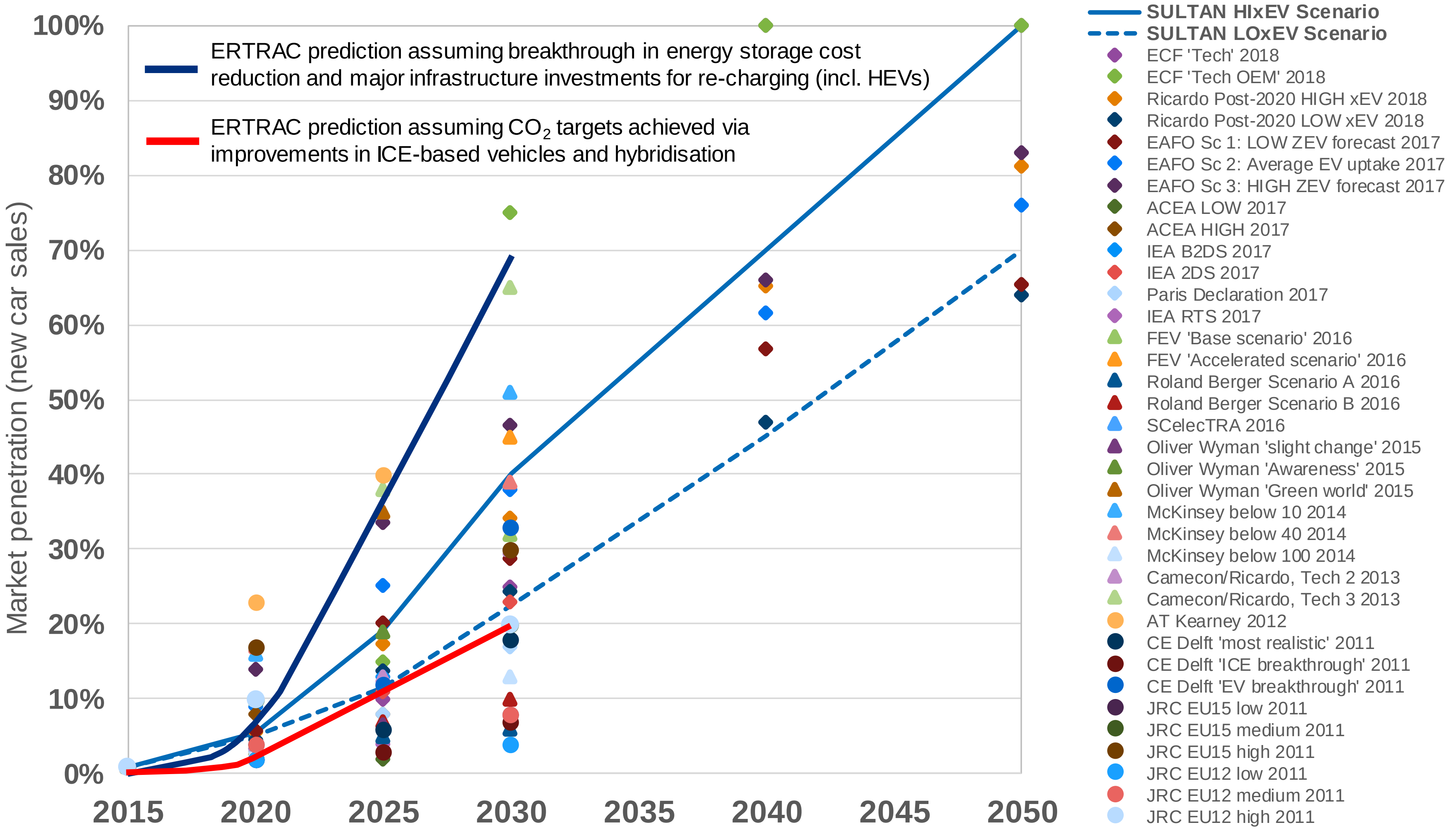


**Figure 5.4: The developed low/minimum and high/maximum xEV uptake scenarios for passenger cars in comparison with forecasts from the literature**



## 5.2 Results and discussion

As with Subtask 2.3, the environmental and key resource impacts (e.g. lithium, cobalt, nickel, etc.) have been assessed quantitatively as far as possible, with post-processing of the SULTAN model outputs.

A summary of the results from the analysis is presented in the following subsections, covering:

1. Impacts on the demand for EV battery production and end-of-life processing (Section 5.2.1);
2. Impacts on GHG emissions (Section 5.2.2);
3. Impacts on other pollutant emissions (i.e. NOx, PM and SOx) (Section 5.2.3);
4. Impacts on resource consumption (Section 5.2.4).

### 5.2.1 Impacts on the demand for EV battery production and end-of-life processing

Table 5.4 provides a summary of the potential future GWh demand for xEV batteries for different scenarios; a breakdown of the demand by road transport mode is also provided in Figure 5.5 for the high xEV deployment scenario. The results show that annual battery production demand, using the default assumptions, could reach 173–262 GWh by 2030 (equivalent to around 4.5-6.7 times the current Tesla Gigafactory capacity[11]), and up to 995 GWh (~16 Gigafactories) by 2050.

Table 5.5 provides the resulting tonnes of batteries requiring end-of-life treatment for the scenarios. To put the figures in this table in context, Umicore's dedicated battery recycling plant in Hoboken (Belgium) has an annual capacity of 7000 tonnes (Umicore, 2018a), which would mean EU xEV battery recycling capacity by 2050 would need to be two orders of magnitude higher than this for the low/high xEV deployment scenarios.

Figure 5.6 also provides a breakdown in the *numbers* of end-of-life batteries by road transport mode; this illustrates that although eBike batteries may be vastly smaller than those in the other modes, they could be expected to continue to account for the majority of the overall numbers of recycled batteries in the future.

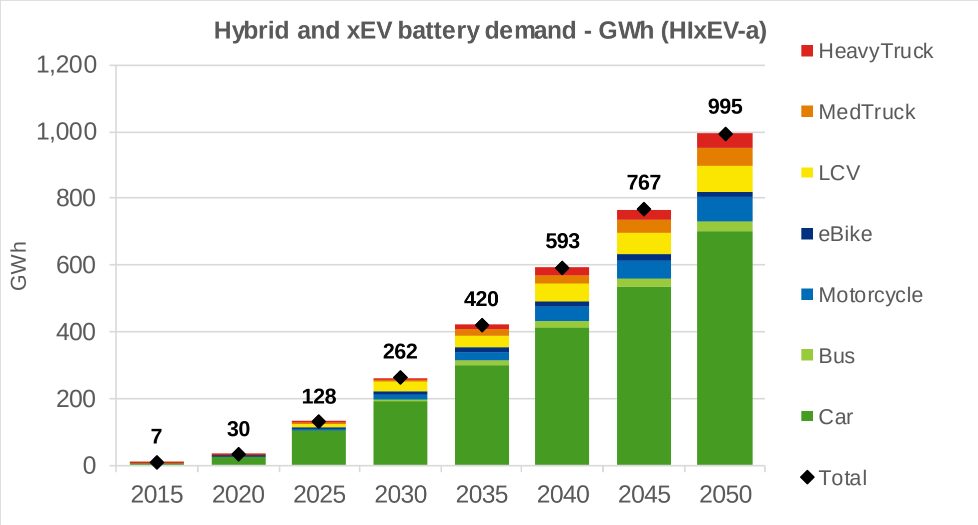
**Table 5.4: Projected future EU HEV and xEV battery demand for road transport, by scenario (GWh)**

| GWh | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| **Default case** | | | | | | | | |
| BAU | 7 | 20 | 42 | 60 | 84 | 107 | 123 | 145 |
| LOxEV | 7 | 30 | 85 | 173 | 299 | 440 | 593 | 792 |
| HIxEV | 7 | 30 | 128 | 262 | 420 | 593 | 767 | 995 |
| **Sensitivity (b) mid-life LDV battery replacement for BEVs** | | | | | | | | |
| BAU-BAT | 7 | 20 | 44 | 71 | 107 | 143 | 161 | 177 |
| LOxEV-BAT | 7 | 30 | 89 | 198 | 365 | 574 | 766 | 957 |
| HIxEV-BAT | 7 | 30 | 131 | 292 | 523 | 787 | 992 | 1,196 |

*Source*: Ricardo modelling analysis

[11] Based on the current 20 GWh annual capacity (Tesla, 2018a), and accounting also for projected future increase in battery cell energy density.

**Figure 5.5: Breakdown of projected future EU HEV and xEV battery demand for the HIxEV scenario (GWh)**



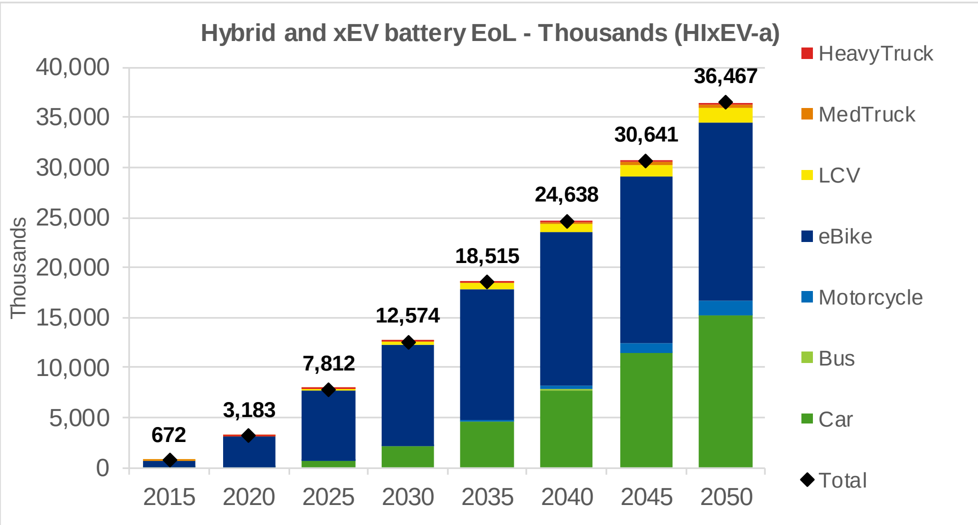

*Source*: Ricardo modelling analysis

**Table 5.5: Projected future EU HEV and xEV end-of-life batteries for road transport, by scenario (ktonnes)**

| ktonnes | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| **Default case** | | | | | | | | |
| BAU | 2 | 9 | 35 | 86 | 134 | 155 | 162 | 170 |
| LOxEV | 2 | 9 | 44 | 129 | 253 | 371 | 486 | 615 |
| HIxEV | 2 | 9 | 46 | 157 | 351 | 549 | 718 | 878 |
| **Sensitivity (b) mid-life LDV battery replacement for BEVs** | | | | | | | | |
| BAU-BAT | 2 | 9 | 45 | 106 | 156 | 186 | 192 | 195 |
| LOxEV-BAT | 2 | 9 | 58 | 195 | 367 | 564 | 690 | 793 |
| HIxEV-BAT | 2 | 9 | 60 | 237 | 549 | 837 | 976 | 1,089 |

*Source*: Ricardo modelling analysis.

**Figure 5.6: Projected future EU HEV and xEV end-of-life batteries for the HIxEV scenario (thousands)**

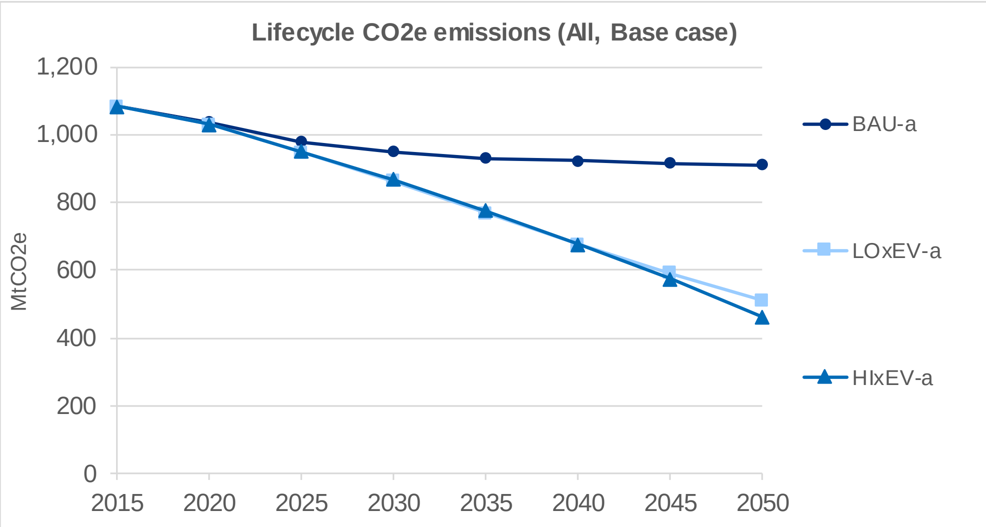



*Source*: Ricardo modelling analysis.

### 5.2.2 Impacts on GHG emissions

Figure 5.7 provides a summary of the projection in total emissions resulting from vehicle operational energy use and xEV (including also hybrid) battery production (also including those for remanufacturing for reuse and repurposing) and disposal, for different xEV deployment scenarios in the base case. Table 5.6 provides a summary of the breakdown in these emissions between different lifecycle stages for the high xEV scenario. This shows that the annual emissions resulting from operational energy consumption from the EU vehicle fleet (new and existing vehicles, including all vehicle, fuel and powertrain types) vastly outweigh i.e. being 1-2 orders of magnitude higher than the corresponding annual emissions resulting from xEV battery production and disposal across the time series. The credits from recycling / reuse / repurposing correspond to effects due to batteries produced 8-15 years previously (depending on the transport mode).

**Figure 5.7: Projected GHG emissions from road transport for different xEV deployment scenarios – including TTW emissions, WTT emissions, and emissions, plus emissions from xEV battery production and disposal**




*Source*: Ricardo modelling analysis. *Notes*: BAU = baseline, LOxEV / HIxEV = low / high xEV deployment.

**Table 5.6: Annual (in-year) fleet GHG emissions by lifecycle stage for the HIxEV scenario (Base case)**

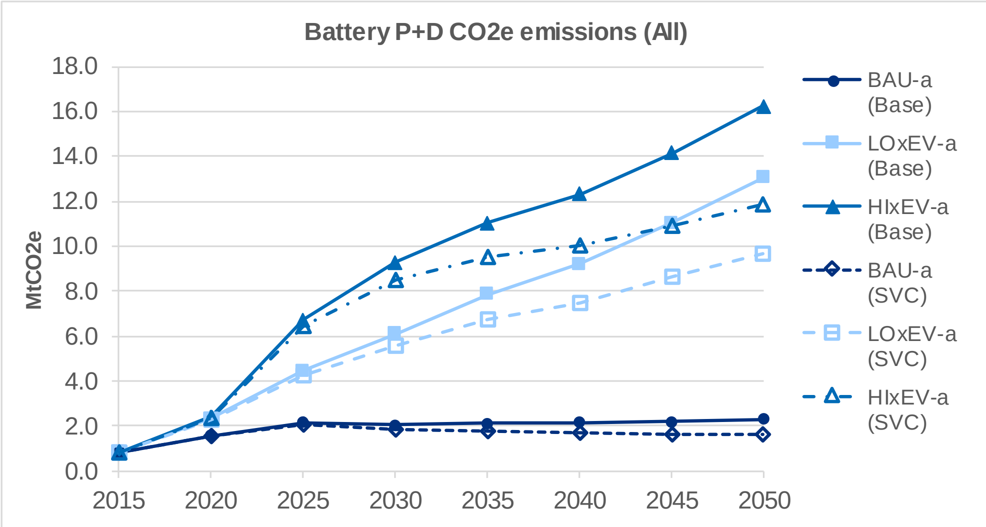
| GHG, $MtCO_2e$ | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Battery production | 0.8 | 2.4 | 6.8 | 9.5 | 11.6 | 13.1 | 15.1 | 17.3 |
| Fuel production | 238.9 | 216.8 | 200.0 | 191.9 | 186.4 | 176.9 | 160.0 | 132.7 |
| Fuel use | 841.9 | 810.7 | 743.5 | 666.3 | 576.6 | 487.0 | 398.9 | 313.0 |
| Battery reuse /repurposing | 0.00 | 0.00 | 0.01 | 0.01 | 0.03 | 0.05 | 0.07 | 0.09 |
| Battery disposal | 0.00 | 0.00 | 0.00 | 0.01 | 0.02 | 0.03 | 0.04 | 0.04 |
| Credit reuse /repurposing | 0.00 | -0.01 | -0.03 | -0.11 | -0.23 | -0.34 | -0.41 | -0.45 |
| Credit recycling | 0.00 | -0.01 | -0.05 | -0.16 | -0.33 | -0.52 | -0.66 | -0.80 |
| **Total emissions (Net)** | **1,081.6** | **1,029.9** | **950.3** | **867.5** | **774.1** | **676.2** | **573.1** | **462.0** |

*Source*: Ricardo modelling analysis.

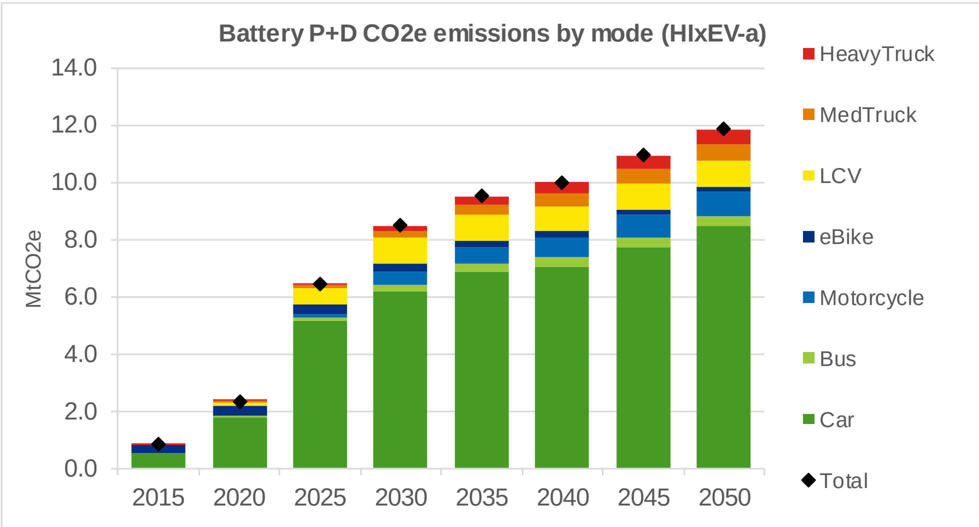
When considering the impacts directly attributable to battery production (also including those for remanufacturing for reuse and repurposing) and disposal, Figure 5.8 provides a summary overview of the effects of the different xEV deployment and circular economy scenarios. This shows that the combination of sustainable value chain improvements (i.e. increased recycling, reuse/repurposing and greater share of local battery cell manufacturing) results in a significant reduction in the GHG impacts across all xEV deployment scenarios – around 25% by 2050. The figure also provides an illustration of the breakdown in net emissions from xEV batteries by road transport mode, and between the different lifecycle stages (including credits) for high xEV deployment scenario (sustainable value chain (SVC) case).

**Figure 5.8: Projected GHG emissions from xEV battery production and disposal for road transport (Base)**

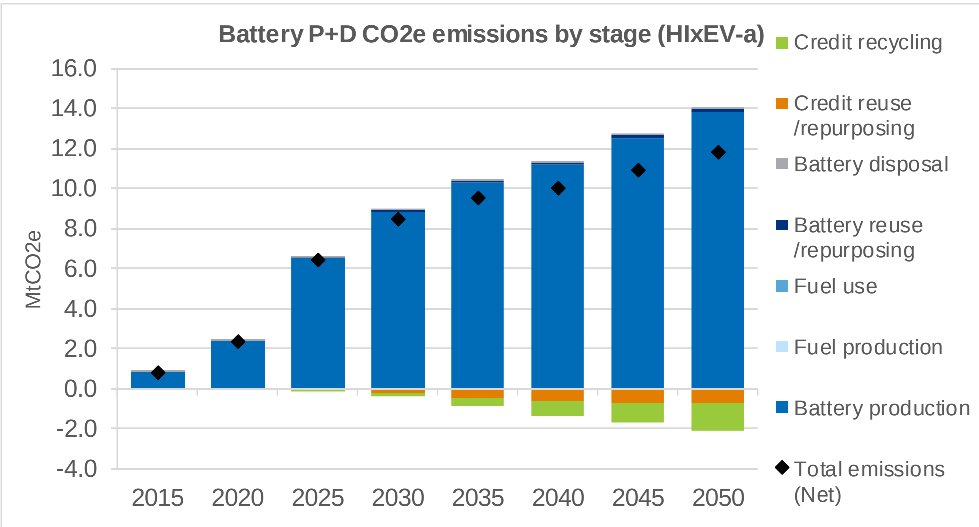
**Total GHG, by xEV and value chain scenario**




**Breakdown by mode for HIxEV Sustainable Value Chain (SVC) scenario**




**Breakdown by lifecycle stage for HIxEV Sustainable Value Chain (SVC) scenario (excluding operational fuel consumption)**




*Source*: Ricardo modelling analysis.

#### 5.2.2.1 Sensitivities on production impacts and LDV battery replacement

Table 5.7 provides a summary of the GHG results for two sensitivities conducted on the different scenarios, for the base case circular economy scenario assumptions. The sensitivity (a) on the higher impacts from battery production results in an increase of up to 30% in net GHG emissions from battery production and disposal by 2050 due to lower battery energy density and higher emissions from battery material production. (*Note*: As an alternative sensitivity on production impacts, more conservative assumptions on the level of improvement in battery energy density, i.e. to 400 Wh/kg by 2030 and 650 Wh/kg by 2050, results in a similar increase, of ~25%). For the sensitivity (b) on LDV battery replacement, the GHG results show that the net increase in demand peaks at around 23%-25% in 2040 (for LOxEV, HIxEV respectively) in the SVC case, which reduces to ~14% by 2050.

For the circularly economy base case scenario, GHG emissions increases for Sensitivity (a) are similar, and Sensitivity (b) they are a few percentage points higher.

**Table 5.7: Net GHG emissions from xEV batteries for different scenarios and sensitivities (SVC case)**

| $MtCO_2e$ | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| **Default case, Sustainable Value Chain (SVC)** | | | | | | | | |
| BAU-a | 0.82 | 1.55 | 2.06 | 1.83 | 1.75 | 1.67 | 1.63 | 1.62 |
| LOxEV-a | 0.82 | 2.29 | 4.27 | 5.54 | 6.77 | 7.50 | 8.63 | 9.66 |
| HIxEV-a | 0.82 | 2.35 | 6.46 | 8.47 | 9.50 | 10.00 | 10.94 | 11.85 |
| **Sensitivity (a) – High xEV battery production impacts** | | | | | | | | |
| BAU-PRO | 0.83 | 1.72 | 2.48 | 2.35 | 2.26 | 2.16 | 2.09 | 2.10 |
| LOxEV-PRO | 0.83 | 2.54 | 5.11 | 7.05 | 8.65 | 9.63 | 11.12 | 12.60 |
| HIxEV-PRO | 0.83 | 2.61 | 7.72 | 10.76 | 12.14 | 12.84 | 14.09 | 15.43 |
| **% Change for Sensitivity (a) – High xEV battery production impacts** | | | | | | | | |
| BAU-PRO | 0.4% | 11.1% | 19.9% | 28.7% | 29.0% | 29.0% | 28.5% | 29.7% |
| LOxEV-PRO | 0.4% | 11.1% | 19.6% | 27.3% | 27.8% | 28.4% | 28.9% | 30.4% |
| HIxEV-PRO | 0.4% | 11.1% | 19.5% | 27.0% | 27.7% | 28.4% | 28.8% | 30.3% |
| **Sensitivity (b) – mid-life LDV battery replacement for BEVs** | | | | | | | | |
| BAU-BAT | 0.82 | 1.55 | 2.12 | 2.09 | 2.16 | 2.15 | 2.04 | 1.87 |
| LOxEV-BAT | 0.82 | 2.28 | 4.36 | 6.08 | 7.89 | 9.23 | 10.51 | 11.05 |
| HIxEV-BAT | 0.82 | 2.34 | 6.55 | 9.12 | 11.22 | 12.51 | 13.35 | 13.50 |
| **% Change for Sensitivity (b) – mid-life LDV battery replacement for BEVs** | | | | | | | | |
| BAU-BAT | 0.0% | -0.2% | 2.8% | 14.3% | 23.6% | 28.2% | 25.1% | 16.0% |
| LOxEV-BAT | 0.0% | -0.1% | 2.0% | 9.9% | 16.6% | 23.1% | 21.8% | 14.3% |
| HIxEV-BAT | 0.0% | -0.1% | 1.3% | 7.6% | 18.0% | 25.1% | 22.1% | 13.9% |

*Source*: Ricardo modelling analysis.

### 5.2.3 Other environmental/emissions impacts

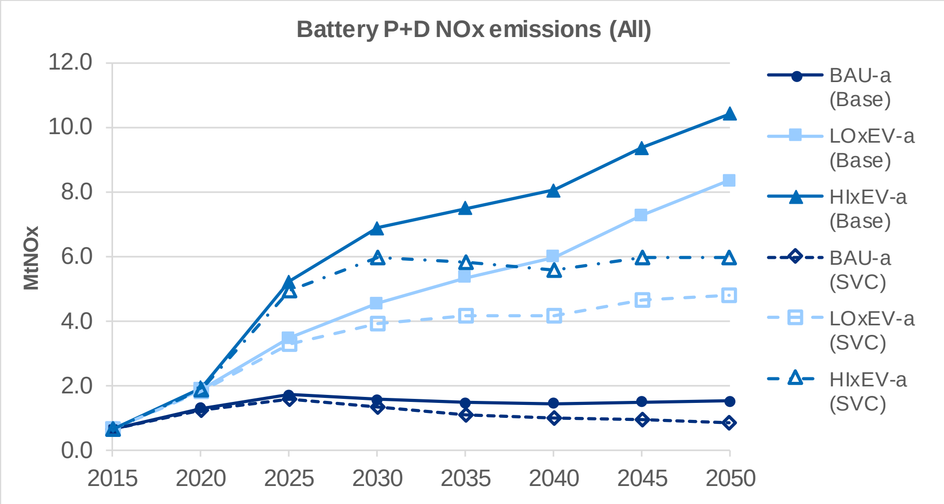
Figure 5.9 shows the change in total emissions of NOx, PM and SOx resulting from xEV battery production and disposal in the EU for different xEV deployment and circular economy scenarios. This also shows that these impacts could be substantially reduced through the adoption of the sustainable value chain scenario – by over 40% by 2050.

In terms of overall lifecycle emissions, the situation for emissions of $NO_x$, PM and $SO_x$ is similar to that for GHG, in that total emissions resulting from energy consumption of the vehicle fleet (i.e. including all vehicle/powertrain types) are vastly greater than the emissions resulting from battery production.

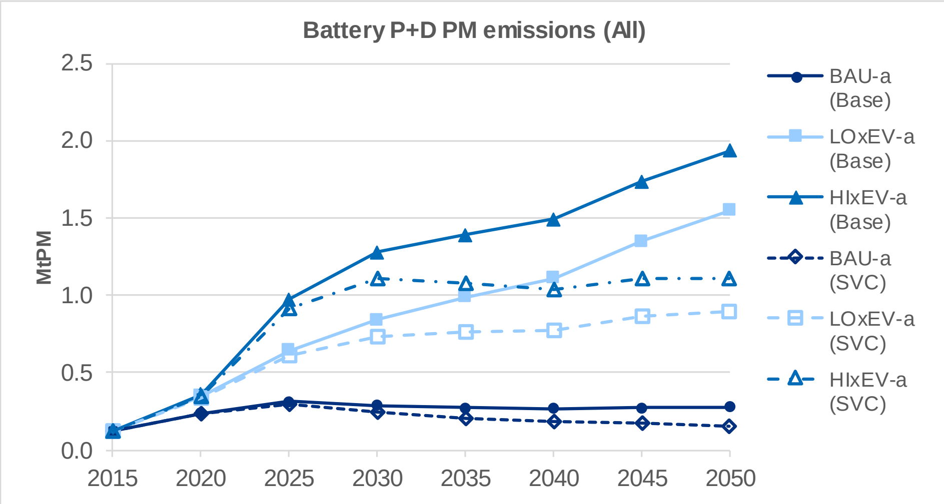
The result for NOx and PM (most important for human health impact indicators) is a net reduction in lifecycle emissions from higher xEV deployment (i.e. fuel/energy-related emissions reductions outweigh increases in emissions from xEV batteries). However, increasing the share of xEVs from the low to high deployment case results in small increases in SOx emissions (which are particularly important for the acidification LCA mid-point impact indicator) – see Table 5.8.

**Figure 5.9: Annual (in-year) air quality pollutant emissions from xEV battery production/disposal for different xEV deployment levels and circular economy scenarios**

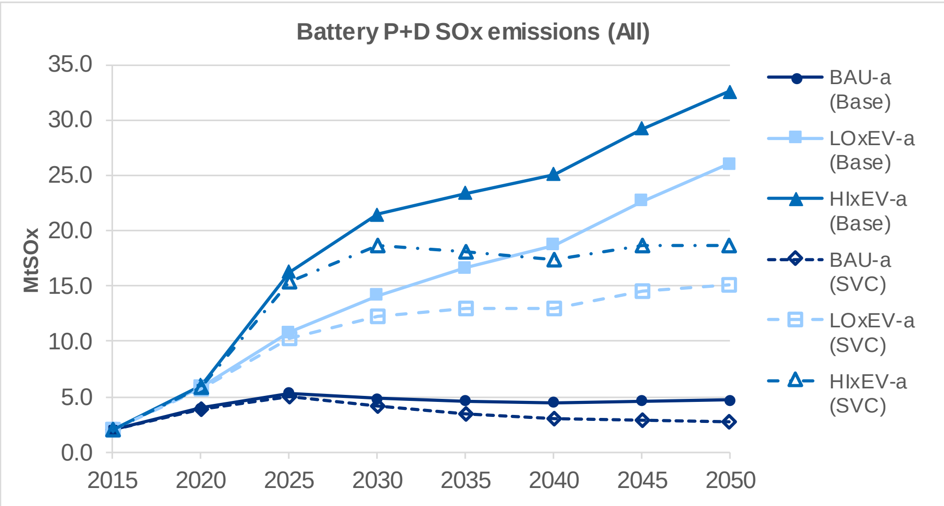
**NOx emissions**




**PM emissions**




**SOx emissions**




*Source*: Ricardo modelling analysis.

**Table 5.8: Annual (in-year) air quality pollutant emissions from vehicle operation (WTW) and xEV battery production/disposal for different xEV deployment and circular economy scenarios**

| Mtonnes | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| **NOx Base case (Base)** | | | | | | | | |
| BAU | 2,535 | 1,785 | 1,449 | 1,278 | 1,240 | 1,221 | 1,194 | 1,161 |
| LOxEV | 2,535 | 1,755 | 1,351 | 1,090 | 937 | 807 | 694 | 592 |
| HIxEV | 2,535 | 1,754 | 1,349 | 1,085 | 921 | 775 | 637 | 499 |
| **NOx Sustainable Value Chain (SVC)** | | | | | | | | |
| BAU | 2,535 | 1,785 | 1,449 | 1,277 | 1,239 | 1,221 | 1,194 | 1,161 |
| LOxEV | 2,535 | 1,755 | 1,351 | 1,090 | 936 | 805 | 691 | 588 |
| HIxEV | 2,535 | 1,754 | 1,349 | 1,084 | 919 | 772 | 634 | 494 |
| **PM Base case (Base)** | | | | | | | | |
| BAU | 221 | 179 | 155 | 144 | 139 | 136 | 133 | 130 |
| LOxEV | 221 | 178 | 151 | 132 | 116 | 101 | 87 | 73 |
| HIxEV | 221 | 178 | 153 | 135 | 120 | 104 | 87 | 68 |
| **PM Sustainable Value Chain (SVC)** | | | | | | | | |
| BAU | 221 | 179 | 155 | 144 | 139 | 136 | 133 | 130 |
| LOxEV | 221 | 178 | 151 | 132 | 116 | 100 | 87 | 73 |
| HIxEV | 221 | 178 | 153 | 135 | 119 | 103 | 86 | 67 |
| **NOx Base case (Base)** | | | | | | | | |
| BAU | 1,366 | 1,218 | 1,093 | 1,033 | 1,003 | 982 | 959 | 937 |
| LOxEV | 1,366 | 1,218 | 1,085 | 988 | 902 | 820 | 734 | 632 |
| HIxEV | 1,366 | 1,219 | 1,116 | 1,059 | 1,002 | 921 | 806 | 650 |
| **SOx Sustainable Value Chain (SVC)** | | | | | | | | |
| BAU | 1,366 | 1,218 | 1,092 | 1,033 | 1,002 | 980 | 958 | 935 |
| LOxEV | 1,366 | 1,217 | 1,084 | 986 | 899 | 815 | 726 | 621 |
| HIxEV | 1,366 | 1,218 | 1,115 | 1,057 | 997 | 913 | 796 | 636 |

*Source*: Ricardo modelling analysis.

#### 5.2.3.1 Sensitivities on production impacts and LDV battery replacement

*Sensitivity on higher impacts from battery production*

For NOx, PM emissions, overall lifecycle emissions increase to a relatively small degree and there is still a net improvement in lifecycle emissions resulting from increased xEV deployment. For SOx emissions, overall lifecycle emissions also increase, but the differential between low and high xEV deployment doesn't change significantly in absolute terms. Effects on battery production emissions are similar in percentage terms to those for GHG emissions.

*Sensitivity on LDV battery replacement*

Again, for NOx, PM emissions, overall lifecycle emissions increase to a relatively small degree, with net lifecycle emissions resulting from increased xEV deployment still being improved/reduced. For SOx emissions, overall lifecycle emissions also increase, with the differential between low and high xEV deployment increasing in absolute terms to a small degree (relative to lifecycle emissions). Effects on battery production emissions are similar in percentage terms to those for GHG emissions.

### 5.2.4 Impacts on resources

Under the study, assumptions for battery composition and changes in the mix of battery chemistries in the future, the resource requirements for Lithium, Cobalt and Nickel would still be projected to increase very substantially over the period to 2050, which would pose a potential availability risk.

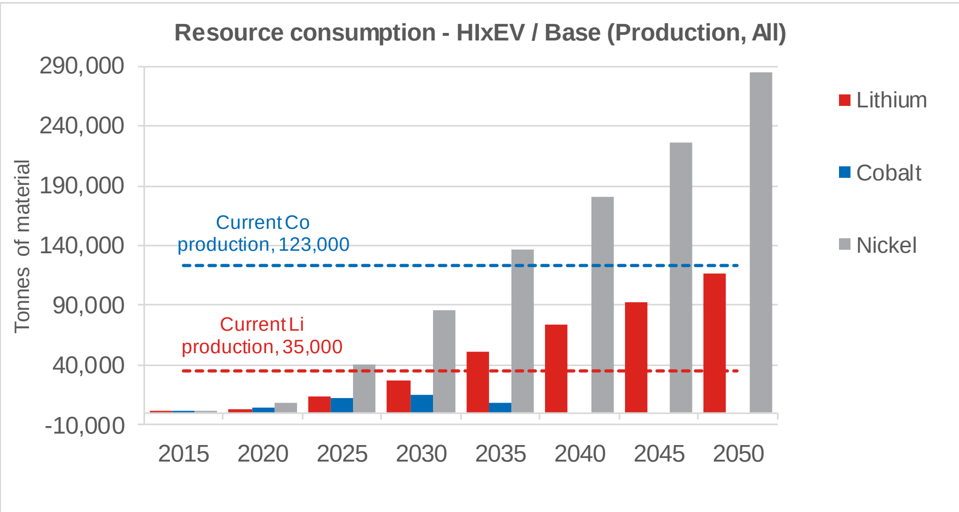
The following Figure 5.10 shows the projected future demand for these materials for EU hybrid and xEV battery production for vehicle production for the high xEV deployment case, plus the net impacts of developing a more effective circular economy for batteries though the sustainable value chain (SVC) scenario case, accounting for credits for materials recovered through recycling, and avoided new battery production through the reuse and repurposing of xEV batteries. The current global total production p.a. of key materials, according to information from (USGS, 2018), is as follows:

- Lithium (Li): 35 ktonne (with 14 Mtonne of reserves)
- Cobalt (Co): 123 ktonne (with 7 Mtonne of reserves)
- Nickel (Ni): 2.25 Mtonne (78 Mtonne of reserves)

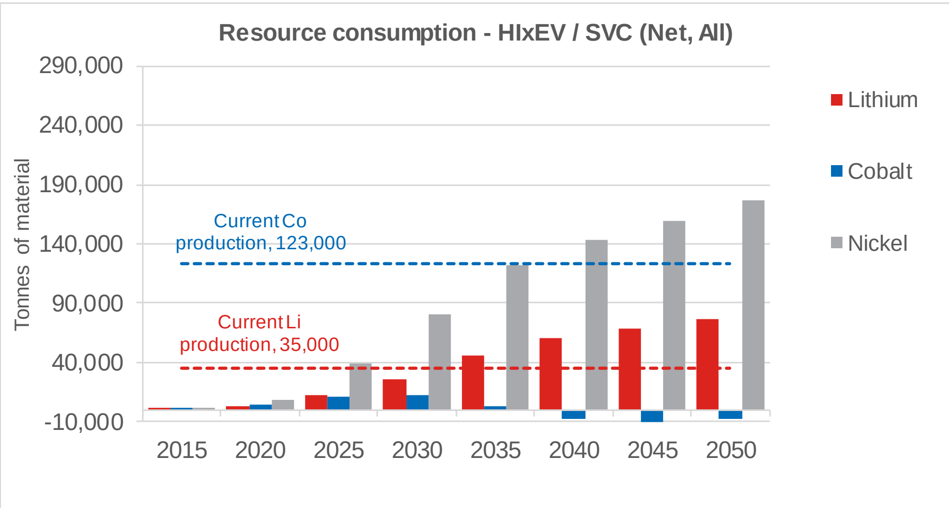
The figure illustrates the significant potential impact of recycling / reuse / repurposing on the demand for key materials for xEV batteries in the future; overall net demand with accounting for recycling/reuse/repurposing is 25% lower in the SVC scenario (as shown in the figure), versus the Base case. Since Cobalt is anticipated to be phased out from xEV batteries over the next 10-15 years, xEV battery recycling could become a net supplier of Cobalt for other uses in the period after 2035.

**Figure 5.10: Summary of the projected annual demand for key battery materials for the high xEV scenario**

**Material demand for xEV battery production**




**Net demand including material recovery (from recycling) and avoided burden credits (for reuse and repurposing)**

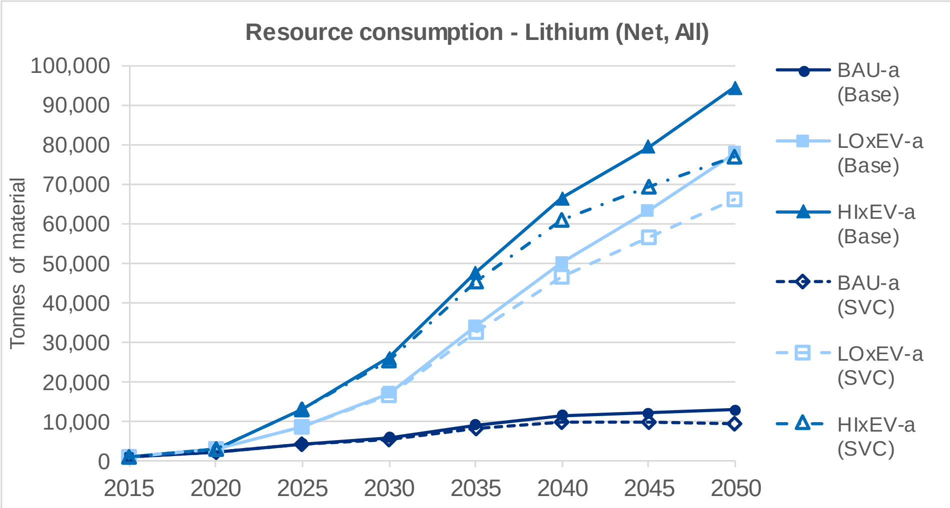



*Source*: Ricardo modelling analysis. Circular economy assumptions are provided in Appendix 1, subsection A1.2.

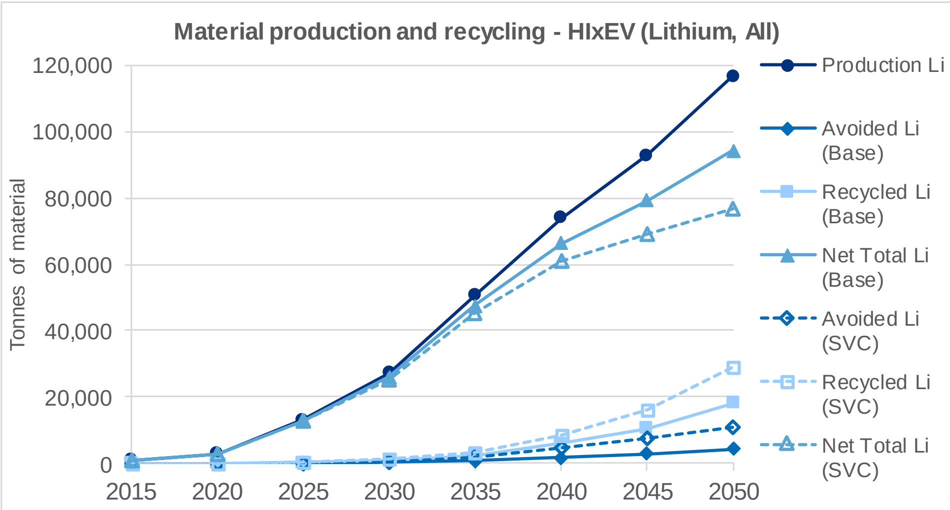
The following Figure 5.11 separately provides a comparison of the impacts of creating a more sustainable value chain for xEV batteries on the net resource consumption for Lithium. The figure also the contributions to the net demand for lithium *and* nickel from recycling and reuse/repurposing (e.g. through the avoided burden of battery production for new xEV batteries/energy storage batteries). Since nickel is already recovered in battery recycling plants, the benefits are lower for this component.

**Figure 5.11: Estimated Li and Ni annual resource consumption impacts for various scenarios**

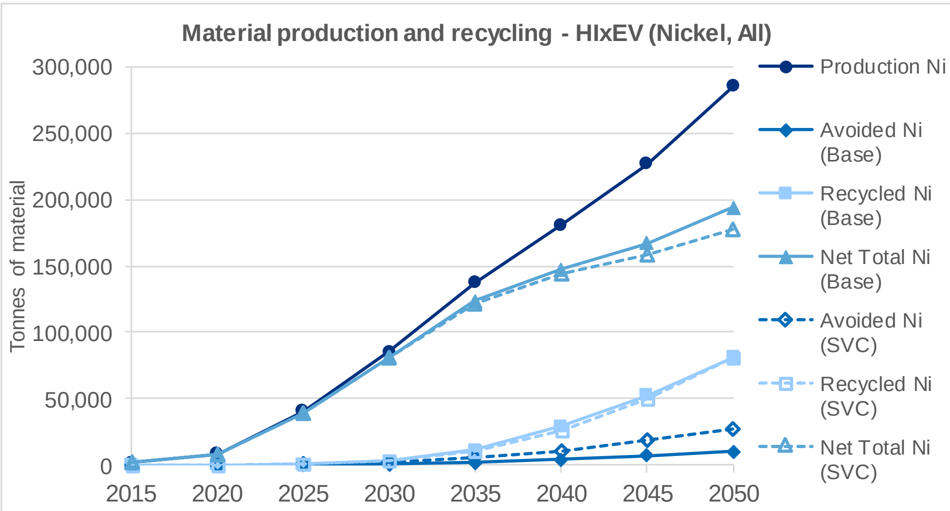
**Net Li resource consumption for base case and SVC, by scenario**




**Breakdown of Li material demand (production for xEVs and avoided demand for energy storage batteries) and recovery (recycling) for high xEV deployment**




**Breakdown of Ni material demand (production for xEVs and avoided demand for energy storage batteries) and recovery (recycling) for high xEV deployment**



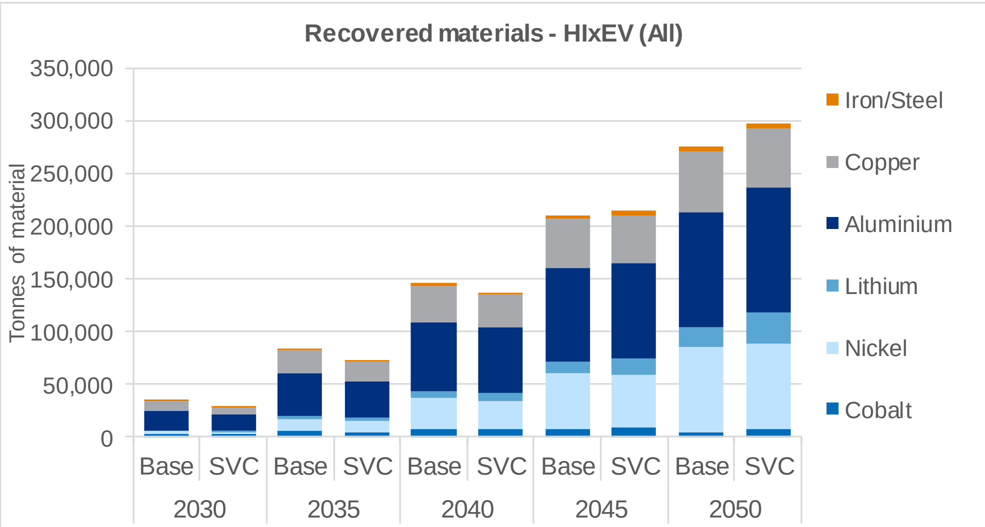

*Source*: Ricardo modelling analysis. Circular economy assumptions are provided in Appendix 1, subsection A1.2.

Figure 5.12 below shows the results of the scenario analysis with regards to the overall amount (in tonnes) and value of materials that would be recovered in the years 2030 to 2050 for the HIxEV scenario, under the Base Case and Sustainable Value Chain circular economy scenario assumptions. The amount (and value) of recovered material is lower for the SVC case in earlier periods, due to an increase in battery reuse/repurposing, which results in a delay in batteries being sent to recycling, offsetting the higher material recovery rates in this case. However, this reduction in recovered material can also be viewed from the wider perspective as being offset by a reduction in the materials required for production of new batteries resulting from the reuse/repurposing of xEV batteries. In later periods (after 2040) the overall volume (and value) of material recovered is higher.

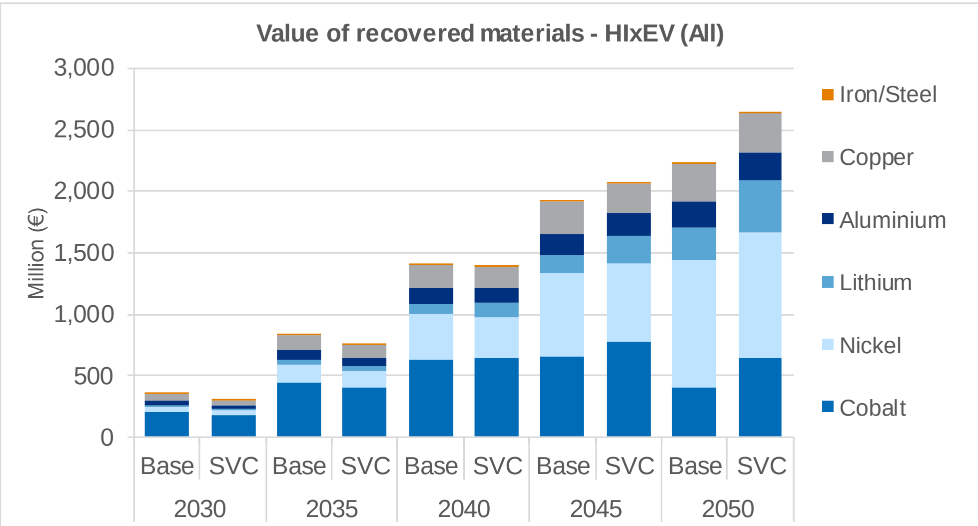
Since there is great uncertainty in future material prices, and no reliable forecasts are available, current prices have been used to calculate the value of raw materials in the scenario analysis.

**Figure 5.12: Estimated future annual volume and value of recovered materials from battery recycling for the high xEV uptake scenario and the two circular economy scenario cases**

**Quantity of recovered materials through battery recycling**




**Economic value of recovered materials through battery recycling (current material prices)**




*Source*: Ricardo modelling analysis. *Notes*: current metal prices based on (CEPS, 2018) and (LME, 2018). Assumed recycling rates are provided in Appendix 1, subsection A1.2.2.

#### 5.2.4.1 Sensitivities on production impacts and LDV battery replacement

The following Table 5.9 provides a summary of the two sensitivities conducted on the different scenarios, for the base case circular economy scenario assumptions. The sensitivity (a) on the higher impacts from battery production results in greater demand of materials (around 25%) for batteries as a lower energy density is assumed. The effects are similar also for nickel and cobalt (though by 2040 there is assumed to be no cobalt in xEV batteries, so there is a net supply from battery recycling).

For the sensitivity (b) on LDV battery replacement, the results show that the net increase in demand peaks at around 19%-21% in 2040 (for LOxEV, HIxEV respectively) for lithium in the base case, which reduces to ~11.5% by 2050. The effects on nickel demand are lower, at around 8-12% in the period 2030-2040 in the base case. For the sustainable value chain (SVC) scenarios, the net increase in material is roughly halved going from the base case to SVC for both materials – i.e. mitigating for the uncertainty modelled in this area.

**Table 5.9: Net material demand for Li for different scenarios and sensitivities (Base case)**

| ktonnes | 2015 | 2020 | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|---|---|
| **Default case, Base Case (Base)** | | | | | | | | |
| BAU-a | 904 | 1,921 | 4,072 | 5,630 | 8,999 | 11,424 | 11,993 | 12,761 |
| LOxEV-a | 904 | 2,828 | 8,490 | 17,017 | 33,901 | 49,948 | 63,044 | 77,678 |
| HIxEV-a | 904 | 2,903 | 12,895 | 26,012 | 47,465 | 66,361 | 79,290 | 94,305 |
| **Sensitivity (a) – High xEV battery production impacts** | | | | | | | | |
| BAU-PRO | 904 | 2,113 | 4,820 | 7,061 | 11,220 | 14,208 | 14,834 | 15,785 |
| LOxEV-PRO | 904 | 3,111 | 10,018 | 21,157 | 42,034 | 61,878 | 77,896 | 96,008 |
| HIxEV-PRO | 904 | 3,193 | 15,197 | 32,283 | 58,831 | 82,217 | 97,973 | 116,568 |
| **% Change for Sensitivity (a) – High xEV battery production impacts** | | | | | | | | |
| BAU-PRO | 0.0% | 10.0% | 18.4% | 25.4% | 24.7% | 24.4% | 23.7% | 23.7% |
| LOxEV-PRO | 0.0% | 10.0% | 18.0% | 24.3% | 24.0% | 23.9% | 23.6% | 23.6% |
| HIxEV-PRO | 0.0% | 10.0% | 17.8% | 24.1% | 23.9% | 23.9% | 23.6% | 23.6% |
| **Sensitivity (b) – mid-life LDV battery replacement for BEVs** | | | | | | | | |
| BAU-BAT | 904 | 1,920 | 4,212 | 6,387 | 10,629 | 13,888 | 13,971 | 14,357 |
| LOxEV-BAT | 904 | 2,827 | 8,687 | 18,629 | 38,655 | 59,610 | 73,148 | 86,678 |
| HIxEV-BAT | 904 | 2,902 | 13,093 | 27,925 | 54,888 | 80,395 | 92,259 | 105,064 |
| **% Change for Sensitivity (b) – mid-life LDV battery replacement for BEVs** | | | | | | | | |
| BAU-BAT | 0.0% | -0.1% | 3.5% | 13.4% | 18.1% | 21.6% | 16.5% | 12.5% |
| LOxEV-BAT | 0.0% | 0.0% | 2.3% | 9.5% | 14.0% | 19.3% | 16.0% | 11.6% |
| HIxEV-BAT | 0.0% | 0.0% | 1.5% | 7.4% | 15.6% | 21.1% | 16.4% | 11.4% |

*Source*: Ricardo modelling analysis.

# 6 Developing a sustainable EU value chain (Subtask 2.6)

*What are the perspectives for developing a sustainable value chain for electric vehicle batteries in the EU?*

**Key outputs:**

- Value chain analysis for EV batteries
- Circular economy business model analysis, illustrated with appropriate case studies
- A tabular summary of options, opportunities and barriers

The purpose of this chapter is to identify options for developing a sustainable value chain for EV batteries in the EU. The options discussed are in line with the measures included in the European Commission's Strategic Action Plan on Batteries 'to make Europe a global leader in sustainable battery production in the context of the circular economy' (COM(2018) 293 final, 2018). In general terms, the action plan notes the need for an integrated approach to the battery value chain, referring to R&I and a skilled workforce as relevant mechanisms to strengthen and develop Europe's existing role. The need for a skilled workforce, and 'the provision of a predictable legal framework' to facilitate it, is expected to positively impact job creation with one estimate indicating 15 jobs are created for every 1,000 tonnes of EV battery waste (European Commission, 2018).

With reference to sustainability, the action plan highlights the need to secure access to raw materials extracted through recycling, to ensure sustainability throughout the battery value chain and to achieve the lowest environmental footprint possible.

Developing a sustainable value chain is aligned with the aims of achieving a circular economy, which include:

1. Optimise resource yields by circulating the various constituents of the value chain at the highest utility and minimising waste.
2. Identify and remove negative externalities, whereby the cost to society is greater than the cost the consumer is paying for it.

Thus, a sustainable value chain for EV batteries can be defined as one which reduces environmental impacts and avoids the depletion of natural resources, in order to maintain an environmental balance while promoting economic growth.

In the context of a circular economy, the main ways in which resource yields can be optimised are through product use intensification, extended product lifetimes, product reuse and product recycling. Options for minimising waste along the EV battery value chain can be aligned with the waste hierarchy framework, distinguishing between prevention, reuse, recycle and waste disposal.

To identify sustainable options, an analysis of the EV battery chain has been undertaken. This reviewed the state of play for manufacturing techniques and capacities, as well as setting out the policy landscape for each of the value chain components. The analysis establishes where resource yields are not operating to their full potential and identifies negative externalities.

The extent to which resource yields can be optimised and the negative externalities can be removed is then analysed in the context of achieving a European circular economy in the EV battery value chain, considering the impacts on the value chain and barriers to adoption based on existing and planned developments in the EU.

The findings of this two-step analysis have been summarised in the Section 6.3, which forms the basis for the identification of policy alternatives in Section 8.

## 6.1 Analysis of the EV battery value chain

Whereas the technical review focusses on each component of the EV battery value chain individually, this analysis also takes a holistic approach to the value chain to facilitate closer integration across the chain in Europe and deployment of emerging industrial techniques and technologies, in line with the aims of the EU Strategic Action Plan on Batteries.

### 6.1.1 Cell component manufacturing

At the time of reporting, the EU plays a minor role in cell component manufacturing – accounting for 5% of global manufacturing for passenger EVs according to one estimate (CEPS, 2018). Although the EU has established infrastructure for electrolyte manufacturing, the installations have low utilisation rates, which indicates that infrastructure needs do not pose an immediate barrier to the EU for cell component manufacturing. Rather, barriers include low margins owing to high competition from third countries, complex manufacturing processes, the small scale of operation in the EU and limited access to raw materials.

EU plans for growth in cell component manufacturing are aligned with the development of a sustainable value chain through optimising resource yield and minimising the environmental footprint. In the immediate term, priorities to promote competitive cell component manufacturing in the EU include reaching economies of scale and achieving cost savings through engineering design. By focussing on next generation technologies to simplify manufacturing processes the EU is expected to become more competitive. In particular, improving energy intensity in cell component manufacturing processes is expected to achieve cost savings as well as reduce environmental impacts. For example, improvements are considered feasible by 2025 in relation to cathode materials and the drying processes – both of which are highly energy intensive processes (Yuana, 2017) with significant environmental impacts – e.g. drying processes account for 35-45% of the embedded GWP of an automotive Li-ion battery pack (Friedrich et al., 2017).

In the longer term (up to 2030), EU plans for growth are expected to involve improvements to cathode and anode technologies, electrolyte and additives. Such improvements are expected to bring about further environmental benefits associated with the production phase of EV batteries by further minimising the environmental footprint. An example is focussing on emerging battery chemistries which do not require cobalt. The use of cobalt is linked with $SO_x$ emissions and many of the negative environmental impacts including eutrophication, ozone depletion, eco-toxicity, and occupational cancer (see Section 4.2).

As highlighted in the Strategic Action Plan, the EU also needs to secure access to raw materials. At the time of reporting, the EU plays a minor role in this area. Domestic supply and production are negligible for many of the raw materials required, including lithium, cobalt, nickel, manganese and natural graphite. Domestic supply and production of cobalt has increased more recently through secondary extraction with recycling input for cobalt production in the EU, accounting for 16% of supply (Section 2.2). Improving access to recycled raw materials will also strengthen the sustainability of the overall value chain by reducing waste. Recycling is an important part of achieving a circular economy and waste management; however, where relevant, waste prevention and re-use options should be prioritised, in accordance with the waste hierarchy framework.

Current EV batteries rely on Li-ion chemistries. The various existing EV battery chemistries have different strengths and weaknesses that make it difficult to identify a future leading chemistry according to the vehicle needs (McKinsey, 2017a). Despite these uncertainties, forecasts indicate that Li-ion chemistries will continue to dominate the market up to 2030s across all vehicle types. Lithium-nickel-manganese-cobalt (NMC) is expected to remain the dominant type for passenger EVs (expected to account for 40% of EV batteries by 2025) (CEPS, 2018), while lithium-iron-phosphate is expected to remain the preferred chemical composition for e-buses. The use of lithium-based chemistries is expected to grow further with the emergence of lithium-sulphur and solid-state lithium EV batteries and potentially lithium-air in the longer term. However, there is also research ongoing into sodium (Na), magnesium (Mg) and zinc (Zn) battery chemistries. Thus, although a significant uncertainty is the fast-changing technical landscape which may render certain raw materials obsolete, the need for lithium, cobalt, nickel and manganese is expected to continue up to 2030. For example, Tesla has also announced plans to phase out the use of cobalt (from 3% to 0%) (Fortuna, 2018).

Options to facilitate access to virgin raw materials are dependent on imports, as few natural sources located in the EU. However, access to raw materials from treated recycled batteries could help to mitigate this dependency as well as contribute to the development of a sustainable value chain, as evidenced in the case of cobalt (see section 6.1.6).

**Box 1: Policy landscape for cell component manufacturing and sourcing of raw materials**

The placing on the market of traction batteries in the EU is regulated by the Batteries Directive (2006/66/EC). Of relevance to cell component manufacturing, Member States with battery manufacturers on their territory, are required to promote improvements to the environmental performance of batteries throughout their lifecycle (Article 5), and the use of mercury and cadmium are restricted (Article 4), without prejudice to additional provisions stipulated by the End-of-Life Vehicles (ELV) Directive (under which an exemption is permitted for spare parts of EVs manufactured before 2008) (2000/53/EC). The differences between the ELV and Battery Directives are potentially confusing and there is an argument for streamlining provisions.

Additional requirements apply to cell component manufacturers under the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation (to ensure that all substances used are registered and authorised) (Regulation (EC) 1907/2006). These requirements also apply to recycling operators later in the EV battery value chain, and as such there is potential to streamline the process across operators.

Requirements under the Restriction of the use of certain Hazardous Substances in electrical and electronic equipment (RoHS) Directive (2011/65/EU) do not apply to cell component manufacturing as the use of mercury and cadmium are regulated under the Batteries and ELV Directives.

To support growth in cell component manufacturing, grants through subsidies are available at EU level with Member State co-financing, together local and national subsidy programmes. For example, to attract foreign direct investment in Poland (from LG, South Korean battery producer), exemptions from tax income and real estate taxes are provided to economic operators in certain areas as well as investment grants and employment subsidies from local and state authorities. Local and national actions in Poland have also been coupled with EU development funds to meet infrastructure needs. In Hungary, EU grants were also accessed together with a local subsidy granted by the municipality, a regional development tax allowance and targeted funding to support employee training (ICCT, 2018). It recognised that ongoing financial support through EU budget programmes will provide further support to enable growth.

With regard to securing access to raw materials, the EU has established a Raw Materials Initiative under which a strategy on raw materials was adopted setting out a framework with the following aims (COM(2008)699):

- Ensure a sustainable supply of raw materials from global and European sources to support competitive industrial growth
- Promote recycling and resource efficiency to reduce EU dependency on primary raw materials

To achieve these aims, the Commission carries out regular assessments to establish a list of critical raw materials based of their economic importance and supply risk. In addition to meeting the aims above, the list of critical raw materials (CRM) is intended to help increase awareness of supply risks and opportunities as well as inform negotiations for trade agreements. Among the raw materials required for cell component manufacturing, cobalt and natural graphite are included in the list (whereas lithium is not) (COM(2017)490). One option to strengthen the EU role in cell component manufacturing could therefore be to extend the current CRM list to include lithium.

Access to raw materials for battery applications is an important consideration, as reflected in the EU raw materials strategy and the EU industrial policy strategy. The role of recycling and resource efficiency is also an ongoing priority as highlighted in a recent report on Critical Raw Materials and the Circular Economy (SWD(2018)36) and the accompanying report on raw materials for battery applications (SWD(2018)245)

### 6.1.2 Cell manufacturing

At the time of reporting, EV Li-ion cell manufacturing is largely located in China, South Korea, North America (Tesla/Panasonic) and Japan (ICCT, 2018), (JRC, 2017) (see also Chapter 2). Comparatively, the EU is not active in Li-ion cell manufacturing owing to limited infrastructure to support manufacturing and an already saturated market. In 2017, production capacity exceeded manufacturing rates, with global overproduction forecast to continue until 2020. The most recent evidence suggests there is now a surplus of demand versus supply for EV batteries, which is leading to delays in EV supply.

Despite evidence of previous overproduction, cell manufacturing in the EU is a growing industry with planned infrastructure underway following decisions by leading cell manufacturers to establish installations in the EU (ICCT, 2018). The existing EU legislative framework will facilitate sustainable growth by ensuring environmental impacts are regulated and minimised.

The announced planned infrastructures include investments for two gigafactories which will cover all aspects of the EV battery value chain, including but not exclusively cell manufacturing. The gigafactories will be located in Germany, led by Terra Holding GmbH (total planned production capability will be 34 GWh/ year by 2028) (Portfolio, 2017); and in Sweden, led by Siemens and Northvolt (planned capacity will be 32 GWh/ year by 2023) (Deign, 2018). Planned growth also includes an investment by South Korean SK Innovation to establish a €313 million cell manufacturing plant in Hungary with a capacity of 7.5 GWh per year, creating 410 jobs. Production is expected to commence in 2020 with EU OEMs including Mercedes-Benz already lined up to purchase the batteries (Higgs, 2018). At the same time, other South Korean cell manufacturing companies have invested in the region with LG Chem's recently completed plant in Poland (involving €1.4 billion investment with planned capacity to supply batteries for 100,000 EVs per annum) (Goettig, 2017); and Samsung SDI completing the construction of a cell manufacturing plant in 2018 in Hungary (€320 million investment expected to create 600 new jobs with planned capacity to supply batteries for 50,000 EVs per annum) (Portfolio, 2017).

EU growth in cell manufacturing is expected to benefit from existing EU R&D projects in this sector as well as the EU's leading role in manufacturing the technologies and equipment required to manufacture battery cells. For instance, much of the technology and equipment required to manufacture battery cells is developed in Germany[12]. The German economy minister also announced €1 billion in in subsidies until 2021 for setting up battery production, and the objective for Germany and Europe, more broadly, of producing 30% of the global market for battery cells by 2030 (Electrive, 2018e).

EU access to clean energy and compliance with rigorous industrial emission standards is expected to help ensure that EU cell manufacturing has a limited environmental footprint, particularly in comparison to its leading competitors e.g. China. The surge in cell manufacturing in China has led to sustainability concerns, owing to the large scale of the manufacturing plants and their dependence on coal energy which has an adverse effect on climate change mitigation and air quality (Clover, 2018). Moreover, announcements have been made in China to phase out the government subsidies and beneficial corporate tax rates following the uncovering of five vehicle manufacturers defrauding the government of ~€136 million in 2015 (EESI, 2018). With China becoming a less attractive option for cell manufacturing investors, there is opportunity for the EU to expand into this market.

There are also arguments that planned growth to involve the EU in EV Li-ion cell component manufacturing will further strengthen the development of a sustainable value chain through enhanced clarity over producer liability. This may help to reduce the number of stakeholders involved and avoid outsourcing production to third countries (removing the risk of environmental leakage and negative externalities from the value chain in relation to end-of-life management).

[12] Based on feedback from project consultation with EV manufacturers.

**Box 2: Policy landscape for cell manufacturing**

The placing on the market of traction batteries in the EU is regulated by the Batteries Directive (2006/66/EC). Although the EU is not industrially active in cell manufacturing, it is important to note that under the Batteries Directive, the vehicle manufacturer is regarded as a battery producer if the vehicle manufacturer places the battery on the market (i.e. within its vehicles). However, there is no mechanism in place to facilitate transparency across the value chain, namely between the battery producer and vehicle manufacturer, and as a net importer of EV battery cells, it is difficult for EU vehicle manufacturers to ensure that the most sustainable approach in cell manufacturing has been adopted. The use of international voluntary standards could help to address this challenge.

### 6.1.3 Battery pack manufacturing

EU battery (module and) pack manufacturing is generally carried out independently of cell manufacturing. This has allowed EU OEMs to retain control over battery pack design despite having a limited role in cell manufacturing – accounting for 22% of global manufacturing for passenger EVs (CEPS, 2018). In contrast, where cell manufacturing is well established, OEMs have typically set up integrated processes to allow in-house production of both cell and battery pack manufacturing (Hodges, 2018). This integrated approach is recognised as a key enabler allowing industry to reach economies of scale in battery pack manufacturing; thus, strengthening the EU role in cell component and cell manufacturing is also expected to strengthen the EU role in battery pack manufacturing. This approach will facilitate the development of a sustainable value chain primarily by minimising the environmental footprint across the full spectrum of the chain.

In the EU, there have been considerable improvements to cell energy density as a result of changes to cell design. For example, greater range (from 210km to 400km) for the Renault ZOE EV was achieved primarily through changes to the battery cell design. Other factors contributing to this improved range relate to the cell chemistry, accounting for circa 20% of the reported improvements. Further opportunities in battery cell design to improve cell energy density have been identified with respect to space optimisation, thinner foils, high loading and the use of separators (Delobel, 2017). The new 21700 cylindrical cell design used by Tesla/Panasonic has been developed to maximise energy density, performance/longevity (a critical component to minimising lifecycle impacts) and costs. Although EU OEMs have typically taken ownership of battery pack manufacturing, the extent of EU influence over battery pack design is limited for non-EU EVs.

In addition, battery pack manufacturing has consequences for later phases in the value chain and can affect stakeholder capacity to respond to economic opportunities in a sustainable way. Namely, battery pack design has important implications for options to minimise waste and optimise resource yield through re-use and recycling. As outlined previously (Section 3.1), the prismatic battery design may better for recycling at least. In the EU, the significance of the battery pack design in relation to re-use, re-manufacturing and recycling is recognised as a research priority, particularly the need for designs that are directly reusable for re-use and second life applications and that can be easily dismantled in a cost-efficient way (EBA, 2018).

Preferences concerning battery pack design might also vary by the type of vehicle – e.g. pouch cells have been cited previously as being better suited to e-buses owing to the fact they require fewer connections (Bloomberg, 2018). The extent to which recycling needs are considered in the battery pack design for e-buses (as with other modes of vehicles) is limited in comparison to performance/longevity and cost[13].

**Box 3: Policy landscape for battery pack manufacturing**

Under the Batteries Directive (2006/66/EC), the EV manufacturer is regarded as a battery producer if the EV manufacturer places the battery on the market (i.e. within its vehicles), even where cell components are imported from third countries. As flagged previously, there is no mechanism in place to facilitate transparency across the value chain and it is difficult for EU EV manufacturers to

[13] Based on feedback from project consultation with Argonne National Laboratory, EV manufacturers.

ensure that the most sustainable approach in cell manufacturing has been adopted.

However, where EU OEMs have adopted battery pack manufacturing in-house, there is a requirement on Member States to promote improvements to the environmental performance of batteries throughout their lifecycle (Article 5).

The eco-design (2009/125/EC) and energy labelling (Regulation (EU) 2017/1369) framework aims to support the integration of environmental aspects into product design to improve environmental performance throughout the life cycle of a product with the use of product-specific eco-design and energy labelling regulations and voluntary agreements. Thus far, traction batteries are not covered by the framework; however, the framework could be used to strengthen communication across the value chain in the same way that a lifecycle assessment might.

Another option could be to incorporate traction batteries under the waste electrical and electronic equipment (WEEE) Directive (2012/19/EU) and its provisions relating to suitable design for disassembly of products so that the battery can be easily removed (SWD(2018)36). The WEEE Directive does not apply to batteries, since it requires that all batteries should be removed and collected separately to WEEE. The traction battery could also be incorporated within the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability Directive so that it is subject to provisions ensuring that during the vehicle design, parts and materials are considered for re-use, recycling and recovery (2005/64/EC).

### 6.1.4 EV manufacturing

EV manufacturing is a growing market in the EU, driven by primarily by regulation to minimise environmental impacts (e.g. national emission ceilings to reduce vehicle emissions, zero carbon mobility strategies, etc.). There is also a growing consumer demand for passenger vehicles with a reduced environmental impact. EV manufacturing is well regulated and monitored in the EU to ensure that the environmental impact of the sector is minimised. However, the disconnect between EV manufacturing and EV battery manufacturing can present a challenge for ensuring the environmental impact is minimised across the value chain.

As discussed in section 5.4.2, the overall environmental footprint of an EV is significantly lower compared to conventional vehicles, with the exception of the acidification metric - mainly due to higher emissions of SOx (also highlighted earlier) from key materials (particularly Ni and Co) and energy used in the battery manufacturing phase and due to operational electricity use (i.e. impacts associated with EV battery cell component and cell manufacturing). The currently limited EU role in manufacturing EV batteries thus presents a challenge for minimising and monitoring these environmental impacts. Furthermore, the growing EV market presents a challenge to the EU automotive industry owing to the significance of the battery pack to the overall value of the EV and the EU's limited role in manufacturing it (~40% of the overall value - ICCT, 2018). However, steps are being taken to address this, with new battery (cell) manufacturing plants being planned, according to recent announcements by the EU Battery Alliance (EBA) (European Commission, 2018a).

Another consideration is the growing demand for EVs in the EU, particularly with respect to passenger EVs. Passenger vehicles are the leading type of EV in the EU and worldwide. Approximately 23% of global EV sales are manufactured in the EU (amounting to 770,000 of the 3,200,000 globally produced EVs) (CEPS, 2018). However, EV manufacturing in the EU has not grown at the same pace as demand, leading to a manufacturing deficit in the EU, making the EU a net importer of EVs (in 2017 there was a deficit of 160,000 EVs). Importing EVs presents the same challenges for minimising and monitoring environmental impacts as importing EV battery cells. In terms of numbers on the road, other modes of EVs are currently marginal in comparison to passenger vehicles, including vans, HGVs, buses, motorbikes, bikes among others. Nonetheless, demand is growing, particularly in the context of sustainable urban mobility planning – see below in relation to the e-bus. The main enabler for this market growth is the development of fast charging and high-power battery technologies – thus, the risk of environmental leakage to third countries remains a challenge regardless of the mode of vehicle.

The e-bus is an example of growing demand in the EU with 1,000 e-buses ordered in 2017 across the EU. Compared to global demand, the scale of operation remains low with demand driven largely by local initiatives at city level rather than at Member State level (leading countries include Austria, Belgium, Germany, the Netherlands and the UK). For example, the largest scale e-bus operation in the EU is in the Netherlands (Eindhoven), comprising a fleet of 43 e-buses (Gonzalez, 2018). Whereas the scale of operation in China is nationwide. Whilst most e-buses are aimed at urban operation, longer distance bus (i.e. coach) models are starting to become available, with operations introduced in China and recently also in Germany (Electrive, 2018d). Global demand for e-buses accounted for 12.5GWh in 2017 compared to 30.7GWh for passenger EVs and 99% of this demand originated from China where public subsidies have led to greatly reduced costs to spur sales with the estimated cost of an e-bus in China at ~€230,000 (e.g. compared to ~€650,000 in the US (Blanco, 2018)) (Bloomberg, 2018). The growing EU demand for EU e-buses has largely been met by Chinese manufacturing (with BYD the largest supplier); production has been brought over to the EU with a new plant in Hungary and planned expansion in France and the UK (Gonzalez, 2018). Establishing production of e-buses in the EU will help to ensure the development of a sustainable value chain owing to regulations managing the environmental impact of industrial manufacturing.

The growing popularity of differing modes of electric transport has implications for the extent to which industry can respond to reuse and recycle opportunities later in the value chain (whereby preferences in battery chemistries and battery design vary according to the mode of vehicle and affect industry capacity to carry out re-use or recycling options). To respond to emerging EV demand, flexibility in battery cell manufacturing is needed to meet the preferred chemical compositions and battery pack designs for the various modes of transport.

**Box 4: Policy landscape for EV manufacturing**

The placing on the market of traction batteries in the EU is regulated by the Batteries Directive (2006/66/EC). Under the Batteries Directive, the vehicle manufacturer is regarded as a battery producer if the vehicle manufacturer places the battery on the market (i.e. within its vehicles), even where traction batteries are imported from third countries.

Under the End-of-Life Vehicles (ELV) Directive, EV manufacturers are also required to make the dismantling and recycling of ELVs more environmentally friendly and are subject to targets for reuse, recycling and recovery of the ELVs and their components (excluding traction batteries but including spare parts of EVs manufactured before 2008) (2000/53/EC).

As flagged previously, there is no mechanism in place to facilitate transparency across the value chain and it is difficult for EU EV manufacturers to ensure that the most sustainable approach in cell manufacturing has been adopted, although the use of voluntary international standards could help to address this challenge. Another option could be to establish a reporting requirement for EV manufacturers that considers the complete lifecycle of the battery and its environmental impacts.

The latest texts agreed by the European Parliament and the Council on the Regulation setting emission performance standards for new passenger cars and light commercial vehicles stipulates that the European Commission shall no later than 2023 evaluate the possibility of developing an EU methodology for the assessment and the consistent data reporting of the full life-cycle $CO_2$ emissions of passenger cars and light commercial vehicles that are placed on the Union market (European Council, 2019). Although not explicitly stated, a complete lifecycle approach would include emissions related to the EV battery and its manufacturing.

### 6.1.5 Re-use and re-purposing (second life) applications

Re-use (whereby the battery is processed for further use as a traction battery) and re-purposing (whereby the battery is processed to serve a new use, typically as a unit within energy storage systems), also known as second life, are ways to extend the usage period of EV batteries/components. Re-use and repurposing will generally involve an assessment/grading process at the end of the batteries' first life in a vehicle, and then potentially also a remanufacturing stage.

Such markets for EV batteries are at an early stage of development, yet are fundamental to achieving a sustainable EV battery value chain, forming an integral part of the waste management hierarchy by minimising waste through extended product lifetime. As emerging markets, there is less competition (compared to earlier components of the value chain) and no evidence to date of market saturation. As yet, the extent of used EV batteries available for re-use or re-purposing is limited because insufficient EV batteries have reached their end-of-first-life, although the growing number of EVs on the road provides an indication of the size for this emerging market. Typically, an EV battery is on the road for

7-15 years (with a much shorter calendar lifetime, due to much higher mileage, for e-buses compared to other passenger vehicles); until the energy capacity falls below 70-80% its original capacity.

As the market evolves, there remain many uncertainties, not least the associated costs, health and safety risks and logistical issues. The greatest costs identified are linked with collection and transport of used EV batteries (as well as the administration and cost burden of transporting hazardous waste). Health and safety risks occur as a result of the substances used in the EV battery and inadequate labelling and documentation (in part due to commercially sensitive battery formulations) can lead to increased risk in the safe handling of the collected batteries. Logistical issues are wide-ranging and often stem from the disconnect in the value chain. Both re-use and re-purposing applications are inherently linked to earlier components of the EV battery value chain and establishing an integrated approach across the value chain would arguably facilitate growth in both areas. From cell component manufacturing, to battery pack design: e.g. the use of substances in cell component manufacturing should factor in later battery uses to avoid unnecessary complications (e.g. owing to the use of hazardous substances); and cell manufacturing should use reversible techniques and battery pack design should allow access to cell components to allow quick assessment of the battery energy capacity and quality.

#### 6.1.5.1 Re-use

Thus far, the approach to re-use is to assess the individual modules within the battery cell and replace on an individual basis. On average, between 0 and 15% of cells require replacement. Direct costs for re-use can save up to 40% compared to the costs associated with manufacturing a new battery (e.g. re-used traction batteries for Tesla have a resale value of up to €7,300). However, without any clear indication of the number of used batteries available for re-use or their quality, it is difficult to estimate the full scale of the opportunity or the infrastructure required to facilitate market growth.

While the associated cost data for re-use options are not publicly available (and it is not possible to identify the individual costs of collection, transport, storage, measuring, repairing, inspection, repackaging and delivery), the process for grading the battery modules is recognised as being costly and resource intensive (not least handling of used batteries which pose risks for health and safety and requires skilled labour). The extent to which this labour requirement can be met based on the number of EV batteries on the road. It is identified as an area where cost savings may be feasible, through finding an optimum sequence for this process, one which likely involves automation. To date, re-use processes are in-house and information concerning standards and logistics are not publicly available. Thus, in addition to information gaps, there are no standards for measuring end-of-life batteries or for repairing the battery and ensuring consistent quality across the market. Moreover, the differences between warranties and life cycles across EV batteries used for different vehicles will add to the complexities in trying to establish a standardised approach. Battery leasing may provide a useful option for addressing these challenges.

The removed battery modules are disposed of in the re-use process; thus, there is potential to improve re-use through treating the removed battery modules to allow for their re-use, or ensuring that they are dismantled appropriately for recycling.

One final consideration is the fast-changing technical landscape of EV batteries which may render re-use obsolete. With the advent of new battery chemistries and designs, it is important to ascertain a complete lifecycle overview to ensure that the most sustainable options are promoted.

**Box 5: Policy landscape for re-use**

Under the Batteries Directive (2006/66/EC) there are no provisions to define, regulate or facilitate the re-use of traction batteries.

Under the Batteries Directive, Member States shall ensure that EV manufacturers or third parties establish collection schemes for batteries removed from the vehicle. However, there is no stipulation relating to collection schemes for battery re-use. Additional detail could be added to existing provisions on collection schemes, as stipulated by the Batteries Directive, to provide clarity and ensure adequate handling of collected batteries that will better cater for re-use.

Targets under the Batteries Directive relate to recycling only; while under the ELV Directive (2000/53/EC), economic operators are required to meet re-use targets (95% for re-use and recovery; 85% for re-use and recycling by an average weight per vehicle per year), the targets relate to the vehicle as a whole and do not distinguish between re-use or recycling. Re-use targets could facilitate greater re-use of traction batteries.

The provision of information on re-use options to the end EV battery user could enable users to take appropriate action. Currently, under the Batteries Directive, requirements to provide information to the end EV battery user relate only to the substances used and waste management (with the onus on the Member State). Similarly, under the ELV Directive (2000/53/EC), there are no requirements relating to re-use options; however, it is noted that while under the Batteries Directive the Member State is responsible for providing the information, under the ELV Directive, the economic operator is responsible. The differences between the ELV and Battery Directives are potentially confusing for OEMs and there is an argument for streamlining provisions. Furthermore, there are examples of best practices concerning the dissemination of information under the ELV which could be adapted for re-use of traction batteries under the Batteries Directive, including:

- International Dismantling Information System (IDIS): Information for treatment operators to facilitate the environmental and economic dismantling and treatment of end-of-life vehicles to help meet ELV targets.
- Guidelines for Waste Vehicles: Includes criteria to distinguish between second-hand and waste in vehicles.

#### 6.1.5.2 Re-purposing

Re-purposed EV batteries are generally used in energy storage systems, regulating frequency and facilitating the integration of renewable energy into national grids, a range of other potential battery use cases were also highlighted in earlier Chapter 3. The process for re-purposing used EV batteries is similar to the process for re-use: each battery pack/cell component is assessed individually to determine the energy capacity and quality without need for dismantling. The dismantling process developed thus far requires skilled labour and it is unclear at this stage the extent to which this labour requirement can be met based on the number of EV batteries on the road. Automated dismantling processes are also being researched, but clearly would require a level of standardisation and scale to be practically useful. Currently in the EU there are no standards, provisions or legislation in place to define or regulate the re-purposing market.

Re-purposing requires no changes to the design of the battery; thus, re-purposing costs are low, and below that of manufacturing a new stationary battery. Estimates indicate that the value of re-purposed batteries entering the German market by 2025 at €150/kWh. Comparatively, the estimated value of re-purposed batteries is greater than the value of extracted raw materials from recycling processes (e.g. batteries with re-purposing potential have a market value of ~€3.50/kg whereas a battery for recycling has a market value of ~€1.30/kg) (BNEF, 2018). More generally, re-purposing is favoured over recycling according to the waste management hierarchy. In addition to generating less waste, the manufacturing process for re-purposing has a smaller environmental impact compared to the manufacturing of new batteries (Ahmadi, L. et al., 2015).

The fast-changing technical landscape of EV batteries may also render re-purposing obsolete and with the advent of new battery chemistries and designs it is important to ascertain a complete lifecycle overview to ensure that the most sustainable options are promoted.

**Box 6: Policy landscape for re-purposing**

Under the Batteries Directive (2006/66/EC) there are no provisions to define, regulate or facilitate the re-purposing of traction batteries.

In particular, challenges may occur in relation to establishing and overseeing collection schemes for re-purposing, ensuring that there is sufficient incentive for re-purposing, and determining producer responsibilities (namely with respect to the existing definition of when a product ceases to be waste and to which stakeholders extended producer responsibility should apply, in accordance with the Waste Directive (Directive (EU) 2018/851)). The following options are proposed to address these challenges:

- Additional detail could be added to existing provisions on collection schemes, as stipulated by the Batteries Directive, to provide clarity and ensure adequate handling of collected batteries that will allow re-purposing.

- Options to facilitate re-purposing could include the extension of targets established by the Batteries Directive or the inclusion of the traction battery under the associated ELV Directive with established re-use targets (2000/53/EU). Furthermore, a host of research initiatives are funded at EU level under the Horizon 2020 budget programme to facilitate EV battery re-purposing (e.g. Batteries2020, Energy Local Storage Advanced system; ABattReLife; Netfficient). EU funding to support ongoing research initiatives is needed.
- The re-purposing of traction batteries establishes a new purpose for the traction battery and therefore it needs to be clarified the extent of extended producer responsibility between the relevant stakeholders. One option to facilitate improved producer responsibility could be better control of registered vehicles to manage end-of-life and second-hand use (SWD(2018)36).

The provision of information on re-purposing options to the end EV battery user could enable users to take appropriate action. Currently, under the Batteries Directive, requirements to provide information to the end EV battery user relate only to the substances used and waste management (with the onus on the Member State). Similarly, under the ELV Directive (2000/53/EC), there are no requirements relating to re-purposing options; however, it is noted that while under the Batteries Directive the Member State is responsible for providing the information, under the ELV Directive, the economic operator is responsible. The differences between the ELV and Battery Directives are potentially confusing for OEMs and there is an argument for streamlining provisions. Furthermore, there are examples of best practices concerning the dissemination of information under the ELV which could be adapted for re-use of traction batteries under the Batteries Directive, including:

- International Dismantling Information System: Information for treatment operators to facilitate the environmental and economic dismantling and treatment of end-of-life vehicles to help meet ELV targets.
- Guidelines for Waste Vehicles: Includes criteria to distinguish between second-hand and waste in vehicles.

The re-purposing of traction batteries also relates to EU energy policies, although currently there are no provisions to regulate the entry into market or facilitate the uptake and use of re-purposed traction batteries. Furthermore, there is no policy to regulate the vehicle to grid (V2G) technologies. However both the need for greater energy storage systems and improved consumer integration in the supply of electricity are aligned with the Commission proposal to amend the common rules for the internal market in electricity which highlights the need to respond to storage opportunities and to integrate the consumer within the electricity market (COM(2016)864).

### 6.1.6 Recycling

Recycling battery waste is key to the development of a sustainable EV value chain, minimising waste and the environmental footprint. Product recycling is also a key concept for achieving a circular economy, although in line with the waste hierarchy, product recycling relates to end-of-life management, once options for waste prevention and re-use have been exhausted.

In addition to reducing waste generation, recycling can offer an economic incentive through raw material recovery (for example, the average value for selected raw materials per kg of average Li-ion battery scrap include €1.1 for lithium; €0.28 for nickel; and €2.54 for cobalt) (Friedrich et al., 2017), although using current technologies at current scales, costs to extract raw materials exceed financial returns for most raw materials concerned in the EU, and some materials (e.g. lithium) currently cost lot more to extract than others (e.g. cobalt). As the number of used EV batteries reaching their end-of-life increases, recycling is expected to return a profit from extracted raw materials as the scale increases; however, the scale of used EV batteries required to return a profit is uncertain. One industry stakeholder consulted during the study observed that one plant processing 500,000 tonnes of waste is more efficient than five plants processing 100,000 tonnes each; however, no indication as to the tipping point needed was provided[14]. This will be particularly important in the future, as the share of valuable materials, particularly Cobalt, in EV batteries is expected to reduce significantly. This will

[14] Based on feedback from project consultation with recyclers.

also help to improve the potential economics for a greater share of material recovery for LIB (i.e. beyond the ~50% currently).

Typically, it is expected that an EV battery will be in use for between 10 to 30 years (including re-use and re-purposing options). In the EU, current recycling processes are designed for much smaller quantities of battery waste than is anticipated in the wake of EV batteries reaching their end-of-life. It is likely that economies of scale will support a more competitive market for recycling, although the evidence to support this is lacking. Based on current chemical compositions and scales, recycling is only financially positive for EV batteries containing cobalt. Thus, recycling EV batteries used in e-buses, which mainly comprise lithium-iron-phosphate (LFP), is not financially viable without higher recycling fees, for example. In the EU, this is mitigated with a legal obligation to recycle battery waste. To ensure this legal obligation can be effectively met, clarity over producer liability is needed in the light of the extended value chain of EV batteries (concerning re-use and re-purposing in particular).

Referring back to the battery pack design, it is noted that certain EV batteries are easier to dismantle for recycling than others. The dismantling process requires skilled labour and it is unclear at this stage the extent to which this labour requirement can be met based on the number of EV batteries on the road. Consistency in battery pack design and more careful consideration of recycling needs would facilitate growth in this component of the value chain. Furthermore, EV battery producers are often reluctant to make details public concerning the cell composition and battery pack design for competitive reasons; while material safety data sheets are supplied, manufacturers are only required to indicate the range of substance content[15]. As such, recyclers can be provided with information that is more limited than desired to help with safe and effective dismantling and management of end-of-life EV batteries[16].

In the light of the EU's limited role in cell component and cell manufacturing, either a more standardised approach across the market and the use of labelling and transparency in these processes is needed, or an EU integrated approach is needed (whereby recycling is undertaken in-house by cell component and cell manufacturers established in the EU). However, this also needs to be handled carefully, as battery design decisions also impact on the durability/longevity of the battery – and therefore also the potential to get greater / intensified and/or longer period of use out of it (i.e. reducing/delaying the need for new batteries). For example, Tesla's battery design which uses bonding techniques to secure cells within individual modules (rather than screws/other fixings) was reportedly developed to maximise battery performance and lifetime in this way – which is higher up in the waste hierarchy.

An additional concern relates to the fast-changing EV battery value chain, particularly in relation to battery chemistries and cell manufacturing. Recycling techniques thus require flexibility to adapt to changes. Currently, recycling techniques in the EU are well positioned to adapt to the different chemistries and electrodes in use and the lag time between battery production and when they reach their end-of-life is generally considered sufficient to allow the recycling industry to respond to any changes[17].

**Box 7: Policy landscape for recycling**

Under the Batteries Directive (2006/66/EC) there is a legal requirement for Member States and industrial operators to collect, treat and recycle waste batteries, including targets for collection rates and for recycling efficiencies. However, the collection rates only apply to portable batteries and therefore do not apply to traction batteries.

Under the ELV Directive (2000/53/EC), a vehicle manufacturer is also responsible for collecting the battery, if contained within the vehicle. While EV manufacturers are not responsible twice for the collection of the battery, there is a risk of overlap between the policies, presenting an opportunity for simplification.

Recycling targets are set under the Batteries Directive without prejudice to the Waste Directive which are established by weight up to 2035 (Article 11 (2)) (Directive (EU) 2018/851). Additional

[15] Based on feedback from project consultation with EV manufacturers.
[16] Based on feedback from project consultation with recyclers.
[17] Based on feedback from project consultation with recyclers.

recycling targets are established by the ELV Directive (2000/53/EC); and with respect to the traction battery, there is a minimum requirement that the battery is removed from the vehicle at the time of vehicle scrappage. The fact that there are relevant targets across three separate policy instruments could lead to unnecessary reporting complexities and administrative burden.

Aims to reduce dependency on imported raw materials through greater raw material recovery from recycling operations (and the focus on making recycling profitable particularly with respect to CRM, e.g. (SWD(2018)36)) may create an unfair market in which EV manufacturers are responsible for recycling waste batteries but recycling operators benefit financially from the re-entry into the market of extracted raw materials. Currently, end-of-waste criteria are applied to determine when waste ceases to be waste following recovery processes and criteria are developed nationally in line with overarching principles stipulated by the Waste Directive. One option could be for the Commission to develop a uniform application-specific end-of-waste criteria at EU level (Article 6(2)) (Directive (EU) 2018/851) to ensure a fair playing field across Member States and between value chain stakeholders.

In addition, recycling economic operators are subject to requirements under the Industrial Emissions Directive, whereby recovery activities concerning the treatment of metal waste (including end-of-life vehicles and their components) are regulated (meaning that economic operators with a capacity over 75 tonnes per day in this activity are subject to environmental permitting requirements stipulating emission limit values and compliance with best available techniques, among other requirements) (Activity 5.3 (b) (iv)) (Directive 2010/75/EU). To improve traceability across the value chain and to minimise the environmental impact of manufacturing, one option could be to extend the remit of economic activities under the IED to include traction battery manufacturing.

Furthermore, recycling economic operators are subject to requirements under REACH (Regulation (EC) 1907/2006), whereby as soon as a material ceases to be waste according to the Waste Directive, REACH requirements apply. Recovery is considered a form of manufacturing/ mechanical processing in which the recovered substances cease to be waste. This process could be streamlined for recycling operators through labelling requirements earlier in the value chain.

### 6.1.7 Integrated value chain analysis

An integrated approach across the value chain is essential to developing a sustainable value chain for the EV battery. Coherence across the value chain can prevent the occurrence of negative externalities and facilitate faster deployment of emerging industrial techniques and technologies. This is particularly relevant to the EV battery value chain where technologies are fast evolving.

In the context of developing a sustainable value chain, key opportunities for optimised resource yields and reduced environmental impacts in the EV battery value chain are summarised as follows:

- High dependence on key virgin materials with low recycling rates to extract certain raw materials (linked to low collection performance and high costs for recycling techniques – in particular lithium, where it is generally currently uneconomic to recover this).
- High dependence on non-EU countries for cell component and cell manufacturing with limited influence on manufacturing processes and their environmental footprint. Risk of environmental leakage to third countries where there is a dependence on imports.
- Resource intensive operational processes in cell manufacturing (energy, water and raw materials) with opportunities to reduce resource use (including waste generation).
- Emerging re-use market to use the 70-80% energy capacity retained in discarded first use traction batteries. Fast evolving technologies require flexibility for re-use market to evolve with the market. Opportunity to enhance re-use options where cell components are currently discarded.
- In line with re-use, emerging re-purposing market for use in energy storage systems (between 70-80% of energy capacity available in used EV batteries). Fast evolving technologies require flexibility for re-use market to evolve with the market. Requires cross-sector collaboration.
- Emerging recycling market to extract raw materials from battery waste.

In addition, as the value chain matures there is a growing risk of negative externalities occurring with regards to waste disposal for end-of-life traction batteries as the ownership and liability for the subsequent electro chemical hazardous waste becomes unclear. Based on the current number of EVs, it is expected that between 2029 and 2032 over 3,000,000 Li-ion batteries will become available each year either for reuse, recycle or for disposal (Foster, Isely, Standridge, & Hasan, 2014).

Overall, the environmental impact of EV batteries, including their end-of-life, is very small compared to the impact of EVs (e.g. Figure 5.14). Thus, in order to develop a sustainable EV battery value chain, it is important to consider the EV value chain more widely, and the displacement potential for EVs versus alternatives that is tied to battery performance/size. In particular, further consideration should be given to consumption patterns and possible interaction with the EU EV battery value chain – namely:

- Low usage intensity of vehicles (in general) and their traction batteries once purchased (the average passenger car in Europe spends 92% of the time parked up).
- Growing (total and peak) demand for electricity resulting in pressures on national grids and energy security, and critically the need for better for management of peak demand.

A series of circular economy business models have been identified to address the issues identified in the value chain based on current and emerging practices in the EV battery chain taking an integrated approach. The options are presented in the table below structured according to the waste hierarchy framework.

Each of the options is described in more detail in the following circular economy business model analysis which assesses the economic impacts and barriers to implementation.

**Table 6.1: Options for developing a sustainable European EV battery value chain**

| Waste hierarchy / EV battery value chain | Prevention | Reuse | Recycle | Waste disposal |
|---|---|---|---|---|
| **High dependence on key virgin materials with low recycling rates to extract certain raw materials, in particular lithium, cobalt and nickel** | Reduce demand through intensified use (car sharing schemes)<br>Reduce demand through development of improved batteries robust for longer / more intensive usage | Reduce demand through re-use (as EV battery – battery leasing options to potentially facilitate optimal re-use and re-purposing) | Collect and extract raw materials from used batteries<br>(R&D to develop more efficient and cost-effective recycling options; cost savings related to transportation; improving economy of scale) | Ensure safe handling and management of electro chemical waste |
| **High dependence on non-EU countries for cell component and cell manufacturing** | Establish integrated value chain in the EU (to minimise environmental footprint of cell manufacturing) | Extended product life through re-use (as EV battery – battery leasing options to facilitate optimal re-use and re-purposing) | Effective capture /retention of key materials within EU, though collection and recycling to help feed materials to local cell component and cell production. | |
| **Resource intensive operational processes in cell manufacturing** | Establish integrated value chain in the EU (to minimise environmental footprint of cell manufacturing)<br>(R&D to develop more efficient and cost-effective options) | - | Collect and extract raw materials from used batteries | |

| Waste hierarchy / EV battery value chain | Prevention | Reuse | Recycle | Waste disposal |
|---|---|---|---|---|
| **Up to 70-80% energy capacity retained in discarded first use traction batteries** | - | Extended product life through re-use (as EV battery - leasing options to facilitate re-use) or re-purposing (e.g. in energy storage system)<br>Extend product use through optimum charging patterns (e.g. battery swapping schemes) | *Ensure recycling is only considered once remaining energy capacity is optimised* | |
| **Emerging recycling markets** | - | - | Collect and extract raw materials from used batteries | |
| **Low usage of vehicles and their traction batteries once purchased** | Reduce demand through intensified use (car sharing schemes). Intensify use through multi-purpose batteries (vehicle to grid schemes) | - | - | |
| **Growing demand for electricity (total and peak)** | Reduce on-peak electricity consumption (battery swapping schemes) | Intensify use by accessing energy stored in EV battery (V2G - vehicle to grid schemes) to help manage demand peaks / provide local network services. | - | |

## 6.2 Circular economy business model analysis

Based on the analysis of the EV battery value chain, the circular economy business model analysis will focus on the following models:

1. Integrated value chain
2. Car sharing schemes
3. Battery leasing schemes
4. Battery swapping schemes
5. Vehicle to grid (V2G) energy systems
6. Re-use (complete or partial re-use for the same application)
7. Re-purposing (complete or partial re-use for a different application)
8. Extraction of raw materials through recycling (for use in cell manufacturing)
9. Safe handling and treatment of waste

### 6.2.1 Integrated value chain

To date, the EU is a net importer of battery cell components and battery cells. As discussed in section 6.1.2, this has implications for developing a sustainable value chain, impeding the extent to which the EU can minimise environmental impacts occurring during manufacturing phases of the EV battery and potentially impeding EU capacity to respond to re-use, re-purposing and recycling opportunities. Lifecycle analysis indicates that energy consumption during cell component manufacturing is significant and that the use of hazardous substances both in cell chemistries and manufacturing can have wide-ranging environmental impacts (and associated costs).

Establishing an integrated value chain in the EU would allow EV manufacturers to take a complete lifecycle approach in production, avoiding uncertainties over liability, responsibility and mitigating risks of unintentional adverse environmental effects. Such an approach would require significant investment in the EU where cell manufacturing infrastructures are limited; however, rather than focussing on one component of the value chain, future investments could take an integrated approach across the complete value chain, streamlining processes to capture an adequate economy of scale and ensure that there is sufficient flexibility to respond technical changes - as demonstrated by Tesla's Gigafactory initiative in the US where recycling facilities are planned to be undertaken in-house and onsite with cell manufacturing (Box 8). Plans to launch a gigafactory in Germany are underway, led by TerraE-Holding GmbH. Production of the plant is currently projected to start in late 2019 and is planned to grow incrementally up to 2028 (total planned production capability is 34 GWh/ year) (Portfolio, 2017). In addition to infrastructure needs, it noted that there is a need for greater skilled labour in the EU[18]. Siemens and Northvolt have also announced plans to develop a gigafactory in Sweden (Siemens and Northvolt, 2018). The plant is expected to begin operations in 2020 with an initial capacity to produce 8 GWh/ year which is expected to increase to 32 GWh/ year by 2023 (Deign, 2018).

In terms of the policy infrastructure in place to support an integrated value chain, in the EU, Product Environmental Footprint Category Rules have been developed for e-mobility (including traction batteries used by e-bikes, EV, PHEV, cars, bus/trucks) (RECHARGE, 2018). These rules provide a framework for conducting a lifecycle assessment.

**Box 8: Closed loop battery recycling at Tesla Gigafactory**

The Tesla Gigafactory in Nevada US incorporates all components of the EV battery value chain allowing for a flexible production line that can change with the fast-changing technical landscape of the value chain. On completion it will be a net-zero energy factory with no consumption of fossil fuels. Renewable energy sources and energy storage systems are integrated as backup. A closed

[18] Based on feedback from project consultation with Professor Dave Greenwood, Warwick Manufacturing Group, University of Warwick.

loop water supply system allows water to be recirculated for use at the Gigafactory.

Battery cells were first produced in 2016 with mass production launched in 2017.

At peak production, 6,500 persons are directly employed – on completion of the Gigafactory up to 10,000 jobs will be created. An additional 20,000 to 30,000 jobs are indirectly linked to the Gigafactory. Tesla has committed to recycling all its own batteries in-house and construction for recycling facilities with the Nevada Gigafactory are underway which are designed to process all types of Tesla battery cells, modules and packs for reuse and recycling. (Tesla, 2018)

Integrating recycling facilities within the Gigafactory is expected to reduce transportation costs associated with shipping processed raw materials from one location to another. (Field, Yes, Tesla recycles all of its spent batteries and wants to do more in the future, 2018a)

Strengthening the EU role in the earlier phases of the EV battery value chain provides greater transparency in the production processes which will facilitate more comprehensive labelling needed to facilitate reuse and recycling later in the value chain – both being key to the development of a sustainable value chain. Potential impacts associated with this approach are set out below:

- Reduced environmental footprint of EV batteries expected, considering the complete lifecycle (not least as the EU has a well-established policy framework to control industrial emissions, provide access to clean energy, regulate substance use, manage waste, etc.)
- Opportunity for cost savings (achieved through reduced resource inputs in cell manufacturing, e.g. reduced energy input, reduced demand for raw materials, etc.)
- Greater flexibility across the value chain to adapt to emerging technologies
- Business opportunity whereby environmental footprint can be used as a selling point – e.g. green procurement contracts (public and private)
- Greater efficiency in managing end-of-first-life options where manufacturers are already aware of the techniques required to efficiently repair or dismantle first-used batteries

To facilitate an integrated value chain in the EU the following barriers would need to be overcome:

- Skilled labour force based outside the EU (where cell component and cell manufacturing industries have developed thus far)
- High capital investment required to develop new infrastructures
- Closed-loop installations are not economically viable yet (first use EV batteries still on the road)
- Administrative burden associated with recalling first-used EV batteries from third countries

### 6.2.2 Car sharing schemes

The average car in the EU spends 92% of the time parked and only 8% driving and the average number of passengers in a car per trip is 1.5. Through car sharing schemes, the average time spent parked can be reduced and the average number of passengers per trip can be increased, thus battery usage during the lifetime of the vehicle can be intensified (Ellen MacArthur, 2015). Car sharing schemes are already operational in the EU and include models, such as: shared occupancy of a hired car (e.g. Uber Pool); vehicle-sharing through fleet operators (where the vehicles are owned and managed by a fleet operator, e.g. Autolib, Car2Go and Flinkster); peer-to-peer car-sharing (either through informal agreements or established networks, e.g. Drivy); car-pooling (either through informal agreements or established networks, e.g. BlaBlaCar which links non-professional driver with passengers) (Ellen MacArthur, 2015).

Car sharing schemes have become increasingly popular in the EU, growing by 40% between 2010 and 2013. Some forecasts anticipate that up to 30% of passenger-kilometres travelled by car will be within car sharing schemes by 2050 (Ellen MacArthur, 2015). It is also estimated that their impact on car ownership could see between 5 and 15 cars replaced for every 1 car added to a car sharing fleet (T&E, 2017) . Such growth is expected to target areas outside towns and urban areas and would unlikely be uniform across Member States. The emerging trend of long-distance car sharing services has been found to compete with rail and coach services although the overall impact on emissions per kilometre is positive (T&E, 2017). The extent of EVs participating in car-sharing schemes in the EU is relatively limited (although there are examples elsewhere, e.g. E-Card in China[19]). Barriers limiting their use are illustrated in the example provided in the box below.

**Box 9: Barriers limiting EV use in car sharing schemes**

Within the French Autolib car sharing scheme, there was a trial in 2011 for members to hire a battery powered EV (BBC News, 2011). The scheme offered members use of EVs with a range of 250 km for a cost of EUR 4 to 8 / 30 minutes in addition to membership fees (EUR 10/ day or EUR 144/ year). Although the scheme mitigated 15,000 tons of $CO_2$ emissions between 2011 and 2016 (T&E, 2017), it has failed to operate with a profit and in 2017 it was announced that it had accumulated a loss of EUR 210 million, following which it was decided to end the scheme. Reasons for the scheme's financial failure include competition with other modes of transport, problems with the vehicle cleanliness, parking and booking (Modijefsky, 2018).

The issue of competition with other modes of transport is considered part of a wider issue associated with ingrained consumer preferences whereby members of car sharing schemes prefer to use fuel driven vehicles over EVs. In this way, there are a number of information and awareness raising campaigns to facilitate a shift in consumer patterns.

ICT4EVEU is an example of an EU pilot project establishing an ICT network to facilitate the use of EVs within car sharing schemes across three Member States, including the UK (Bristol), Spain (Vitoria and Pamplona) and Slovenia (Ljubljana and Maribor) (ICT4EVEU, n.d.). With respect to EVs, the ICT network was used to inform members in car sharing schemes about EV availability, EV power and charging stations. Among other things, the project was designed to address consumer concerns about the range of EVs.

The future impact of intensified use on the traction battery is uncertain and further research is needed to mitigate any undue stress on battery use (e.g. with smart driving and vehicle design) and ensure that intensified use does not have adverse effects on the lifetime of the battery. With current battery chemistry cycle lives, it is highly likely that increased cycling would reduce the EV range over a shorter period, prompting earlier replacement. However, batteries also degrade over time, so it is feasible that a greater number of usable km could be achieved over a shorter period before the battery reaches the end of its useful live in an EV. Future technology improvements may also favour more intensive use.

Based on current trends and experiences, the impact of increased car-sharing schemes on the EV battery chain is likely to be:

- Intensified car use could reduce the number of cars on the road (for every one EV added to a car-sharing fleet, between 5 and 15 EVs could be removed from the road) and reduce carbon emissions (15,000 tons associated emission savings from EV car sharing scheme in Paris between 2011 and 2015).
- Financial incentives to the individual user whereby maintenance and travel costs can be shared, and removes the financial burden of initial investment for the individual participating in car-sharing schemes run by fleet operators.
- Central ownership and management of EV fleet facilitates end-of-life battery management whereby it is easier for one organisation to manage rather than at the individual level

Overall, the evidence indicates that car sharing schemes could facilitate intensified traction battery use in EVs. However, the financial impacts are ambiguous with risks identified for EV manufacturers and car sharing operators. At the individual level, EV sharing schemes are financially attractive.

In addition to the uncertainties concerning economic viability, several barriers exist for the integration of EVs in car sharing schemes, as follows:

- Car sharing schemes are not designed to cope with on-peak demand and therefore are not suited for commuter use in urban areas

[19] See: https://www.evcard.com/

- Public concerns associated with the reliability of EVs and power supply are exacerbated with car-sharing schemes as user has less control over charging
- Risk of having an adverse impact on wider zero carbon mobility strategies with the rise in car sharing schemes outside towns and urban areas providing direct competition with train and coach services.
- Peer-to-peer car-sharing will have implications for insurance policies in Member States where vehicle insurance policies apply to the driver rather than the vehicle
- High capital cost for car sharing schemes wanting to invest in EVs
- R&D/pilot schemes needed to better assess the impact on battery lifetime from intensified use.

The shared use model could also be extended to intensify traction battery use for e-bikes however more data is needed to understand user patterns and establish demand.

### 6.2.3 Battery leasing schemes

Under a battery leasing scheme, the consumer owns the EV but not the battery. The battery is leased according to a separate contract so that ownership and responsibility is not transferred to the consumer. For passenger vehicles, battery leasing schemes can offer a financially viable business model and generally accepted by consumers (B. Hildebrandt, et al., 2016). However, very few schemes are operational – Renault are one of the few operators that offer a battery leasing scheme, as discussed below. Battery leasing can also be extended to other vehicle modes although costs and consumer acceptability are expected to vary according to the vehicle type. E.g. with respect to heavy duty EVs leasing contracts are commercially more viable when limited to a three-year period and the leasing costs are greater (~€155/ month) (NREL, 2015).

Renault offer battery hire for the ZOE model. The finance scheme allows the vehicle owner to hire a battery on a monthly basis according their requirements and under the scheme battery performance is guaranteed (minimum 75% of its original capacity) (Renault, 2018). The scheme is reported to provide peace of mind to EV owners and bring down the initial cost of the vehicle (the scheme is one contributing factor to reducing the vehicle capital cost to approximately half the cost of other EV models such as the Nissan LEAF) (though ongoing annual costs are higher due to the battery lease). The cost of leasing the battery is between €50-100 a month, depending on the annual mileage; and without ownership of the battery, there are no additional costs associated with battery maintenance and replacement (Wirgman, 2014). Indicative of the scheme's success, in 2017, Renault announced it had signed its 100,000$^{th}$ EV battery leasing contract and the Renault ZOE was the leading EV model sold in Europe according to January 2017 sales (followed by the BMW i3 and the Nissan LEAF) (Pontes, 2017). Despite the success of the battery leasing model for the Renault ZOE model, the ZOE model was made available for purchase complete with ownership of the battery in 2018 (at €8,900) (Zart, 2018). It is unclear at this stage how the two purchase options will compare.

In addition to the reported peace of mind and cost savings, a further incentive cited is that consumers do not want to be stuck with old technologies when new technologies are available (Zart, 2018). There is a risk that battery leasing will facilitate faster deployment of new technologies, rendering functioning batteries obsolete before the EV reaches its end-of-life. In such cases, the EV battery could be put forward for re-purposing in an energy storage system, thus mitigating the risk of creating unnecessary EV battery waste (see section 6.2.7).

By retaining ownership of the EV battery, EV manufacturers are able to monitor EV battery quality (ensuring that batteries are removed from the road once they fall below a specified threshold) and are well positioned to collect used batteries for re-use, re-purposing, and recycling.

While battery leasing schemes could contribute to the development of a sustainable value chain, based on their limited uptake thus far, any impacts are expected to be marginal. Nonetheless, the likely impacts include:

- Mitigated risk of having batteries on the road beyond the recommended performance threshold, likely to facilitate a standardised level of quality among the batteries recalled for re-use

- By removing the responsibility and liability of battery ownership on the consumer, the collection process for used batteries at the end of their first life can be streamlined, facilitating efficiency for later components of the value chain

The main barriers concerning battery leasing schemes are low uptake and high capital investment needs, in sum:

- Low uptake, preventing any meaningful impacts on the wider market
- High capital investment required for leasing companies to invest in EV batteries
- Financial risk where the leasing contract extends over many years – potential risk to both parties if the contract cannot be met (e.g. where the vehicle owner defaults or where the leasing company goes bankrupt)
- Risk of adverse effect where functioning batteries are replaced by new technologies
- Additional administrative complexity concerning product ownership and liability for end-of-life options – risk of negative externalities where EV battery user is not responsible for end-of-life management

### 6.2.4 Battery swapping schemes

In principle, battery swapping schemes involve the exchange of a depleted EV battery with a fully charged one. The depleted battery is then charged for a subsequent swap.

Under a battery swapping scheme, EV owners do not own the battery, bringing down the cost of the EV and household infrastructure required to charge the EV at home. Further, it allows fast recharging and extends the travel range of an EV as well as the lifetime of the battery itself owing to advanced control strategies for charging. From an energy perspective, depleted batteries can be charged during off-peak periods and charging practices can be overseen in a consistent way to optimise battery usage (M. Mahoor, et al., 2017).

However, EV batteries vary in chemical composition and design which means that battery swapping stations would either need to be model specific or require a range of batteries. Consistent standards would therefore be necessary to facilitate battery swapping schemes (M. Mahoor, et al., 2017). There is also a high financial risk to battery swapping station owners owing to the fast-evolving nature of EV batteries meaning that technologies could fast become obsolete.

Battery swapping does not appear to be a commercially viable business model for light duty vehicles, with evidence of a few failed initiatives and emerging concepts – as outlined below:

- The Better Place network was launched in 2008 in Israel and Denmark to facilitate battery swapping for EV owners and offer a distance revenue contract to subsidise the initial vehicle cost. The infrastructure to support the network was established with ~€860 million in funding and was intended to support growth in EV sales. However, less than 1,000 contracts were signed and the company went bankrupt by 2013. The main barriers identified were lack of public and private sector support coupled with high infrastructure investment needs. (Diwan, 2018)
- In 2013 Tesla launched a battery swapping station between LA and San Francisco targeting one model of vehicle. The swap takes 90 seconds to complete. Overall there was low interest in the scheme with only five participants in attendance (of the 200 Tesla owners invited). Tesla observed after that there was low consumer awareness and interest in the concept of battery swapping. (Diwan, 2018)
- In Sweden, Power Swap has recently been launched in a bid to establish a battery swapping network in Sweden. Reports on progress have not been identified at the time of writing this report (Power Swap, 2018).

The market for battery swapping schemes may be better suited to services where long charging stops present a problem, such as buses or taxi companies, or where there might be better opportunities for a standardised battery approach (e.g. for smaller batteries for 2-wheelers, or possibly for certain heavy-duty vehicles). For example, Aleees, a German electric bus manufacturer, highlights battery swapping as selling point for its next generation e-bus design (Aleees, 2018). However, commercial prospects for establishing a battery scheme for e-buses are limited as demand for e-buses in the EU is currently too small, with successful adoption of e-buses occurring at city level rather Member State level (Gonzalez, 2018).

In contrast to the above examples, battery swapping has been successful when combined with a vehicle sharing scheme for smaller battery packs. The Gogoro Energy Network was launched in Taiwan in 2015 to facilitate battery swapping for scooters, taking 6 seconds to swap batteries. Whereas the other battery swapping schemes discussed separate ownership of the vehicle and battery, Gogoro leases both vehicle and battery. By 2018, the network comprises 761 GoStations which are open 24 hours with a swapping station every kilometre in dense urban areas. On average there are 55,692 battery exchanges every day and since 2015, scooters have ridden a collective ~385 million km, avoiding 16.5 million litres of gasoline and offsetting 35,000 tonnes of CO2 eq. (Gogoro, 2018). Gogoro has successfully launched networks in Germany, deploying approximately 1,000 scooters in Berlin (Gonzalez, 2018).

In the light of limited commercial viability, the impact of battery swapping schemes on the EV battery value chain is uncertain. Nonetheless, the likely impacts include:

- Charging patterns can be regulated to ensure optimum lifetime for EV batteries
- Improved electricity usage flows as batteries can be charged during off-peak periods
- Mitigated risk of having batteries on the road beyond the recommended performance threshold, likely to facilitate a standardised level of quality among the batteries recalled for re-use
- By removing the responsibility and liability of battery ownership on the consumer, the collection process for used batteries at the end of their first life can be streamlined, facilitating efficiency for later components of the value chain
- When used in conjunction with vehicle sharing schemes (particularly for smaller vehicles such as scooters), avoided vehicle and battery costs; likely to have a positive impact on EV sales and increase the number of EVs on the road

The main barriers concerning battery swapping schemes include:

- Battery swapping stations almost certainly limited to certain vehicles according to battery type and therefore could potentially hinder innovation and competition in battery development/application, and ability for OEMs to provide more distinct/bespoke offerings
- Requires high capital investment (for infrastructure and battery fleet); existing business models indicate economically unviable/ high risk of failure
- Risk of battery technologies becoming obsolete before they reach end-of-first-life
- Requires multi-stakeholder collaboration between vehicle manufacturers and battery swapping stations
- Low consumer awareness of the benefits

### 6.2.5 Vehicle to grid energy systems

Vehicle to grid (V2G) systems are an emerging market that allow energy stored in EV batteries to be returned to the grid. V2G systems require bi-directional charging technologies. Incorporating these technologies with the EV battery is not a complex process although establishing an infrastructure to support a bi-directional energy system is. For the main part, V2G systems are being still being trialled although it has been commercially deployed by Nissan in Denmark and BMW in the US (Box 10).

V2G systems can facilitate intensified product use of EV batteries (as well as helping manage peaks in electricity demand, providing network and generation capacity benefits) whereby when the vehicle is out of use (i.e. when it is parked up), the energy stored in the battery can be returned to the grid. Similarly, the energy can be used to power a house or building rather than returned to the grid. For example, the battery of a Nissan LEAF vehicle stores the equivalent energy as consumed by 100 homes. Such systems can be used in conjunction with energy storage systems using re-purposed EV batteries to regulate the energy supply (section 6.2.7) (Morris, 2017).

**Box 10: Operational vehicle to grid system in the US**

In the US, a vehicle to grid system was made operational in 2013 following the completion of the eV2g feasibility study and pilot project (2008 – 2011) (Kempton, 2011), and a demonstration project in 2012 (University of Delaware et al., 2012).

The initial feasibility studies first examined vehicle user patterns in the US and the potential energy capacity of EV batteries. The findings showed that the average EV in the US is driven for one hour a day, travelling 30 miles despite having a range of about 100 miles with a drive train output of 100 kW (assuming a 15 kW grid connection with a storage capacity of 30kWh). Based on EV battery design and typical use, it was concluded that EV batteries could be used to provide short discharges, suited to energy capacity markets rather than energy power markets. The project considered the technical feasibility for technology to manufacture a grid integrated vehicle (GIV), software that allows the EV to interact with the electric grid and a GIV with vehicle to grid capability (V2G) whereby the EV battery can provide energy back to the grid. It also examined manufacturer and end-user costs and consumer acceptability. (Kempton et al., 2011)

The fleet used for the demonstration project comprised several dozen BMW MINI E, on offer to participants for a two-year lease to test the viability of the technology. Participants were required to purchase bi-directional charging stations to facilitate V2G technology. The software developed as part of the study enables the energy company to access EVs across different locations and combine their energy as one energy storage plant, thus allowing the EV batteries to be used for energy frequency regulation (University of Delaware et al., 2012).

Following the success of the demonstration project, the software and technology has been accepted by an energy power company (PJM Interconnection), allowing EVs across 13 states in the US to sell energy to the grid. From a governance perspective, the power company reduced its threshold concerning minimum input power levels and made changes to its payment schemes to facilitate faster and more accurate compensation for EV power suppliers (Electric Vehicles Research, 2013).

As illustrated in Box 10, V2G systems require bi-directional charging technologies. (Uddin et al., 2018) highlight the need to facilitate a standardised market for these technologies to avoid adverse effects on batteries (depending on the current frequencies) and to ensure a fair market for emerging business models.

An additional consideration in light of forecast EV sales in the EU, is that V2G energy systems could be used to avoid pressures on energy security. Forecasts indicate that EV sales could comprise 35% of global new car sales by 2040 which will result in a significant increase in demand for electricity (though not necessarily linearly correlated with generation capacity). In the UK, it is estimated that this trend will increase peak electricity demand by 3.5 GW by 2030 (Uddin et al., 2018). Arguably, use of this technology could provide an alternative solution for use during grid outages, strengthening energy security (Ustun, 2015).

The impact of intensified use on the quality and lifetime of the traction battery is uncertain (Deign, 2018). Both negative and positive impacts on Li-ion battery degradation have been reported (the additional cycling to discharge the battery reduces battery performance and can reduce battery lifetime by 5 years (M. Dubarry, 2018); while others found that the additional cycling can extend the lifetime of Li-ion batteries by 1.5 – 2.6 years (K. Uddin, et al., 2017)). The discrepancy between the findings is linked to charging patterns. Control algorithms can be used to help maximise V2G profits and minimise battery degradation; however, this would require additional infrastructure and work on batteries (Uddin et al., 2018).

The success described in Box 10 relies on the use of EV batteries to provide a low energy supply to regulate frequency rather than act as a source of power. Furthermore, the payment by the energy company acts as a financial incentive to compensate EV users for the additional stress on the battery. (Uddin et al., 2018) argue that the value of V2G storage to regulate energy supply is dependent on establishing an effective management system to distribute the stored energy as well as reaching an adequate scale of operation.

As EV numbers on the road grow, the extent of potentially available energy stored in EV batteries will be significant. In the UK, EV batteries held the equivalent of 2.2 gigawatt-hours (from 110,000 EVs on the road in 2018) and this is forecast to 1 terawatt-hour by 2030. Once commercially operational, such a system could have considerable financial benefits for individual EV owners, in the UK, is estimated that the benefits are in the range of £600 to £8,000 per year for vehicle owners (Irish, 2017).

Although the use of vehicle to grid energy systems is technically feasible, the infrastructure (relating to both physical and governance) is not in place for wide scale use. A plethora of V2G projects are underway in the EU (in Denmark, Finland, France, Greece, Italy, the Netherlands, Spain and the UK). The projects include a variation of demonstration studies, pilots and commercial trialling (see overview provided by SEEV4-City, (SEEV4-City, 2018)). In the UK, for example, a total budget of £30 million was allocated to 21 projects nationwide to support feasibility studies, research and development studies and trials for 2,700 vehicles. E4Future is led by a consortium of UK government departments in partnership with Innovate UK and a team of 50 stakeholders across industry and research bodies. Nissan is among the industry stakeholders trialling a V2G project (awarded £6 million from e4Future towards the £9.8 million project). The Nissan trial includes 1,000 vehicles. (NISSAN GB, 2018)

Overall, the evidence indicates that vehicle to grid energy systems could facilitate intensified traction battery use in EVs and provide a financial reward for consumers. The following barriers are considered to have slowed commercial uptake:

- Cooperation between EV manufacturers, energy power companies and EV users
- Interoperable EV charging stations which are compatible with electrical connection ports
- Software infrastructures are needed to manage the energy systems and ensure optimum charging patterns are adhered to avoid adverse effects on the performance of the battery
- Data required to facilitate optimum charging requires access to in-vehicle data and resources, which in turn requires a legal framework to ensure data protection and privacy etc.
- Governance is needed to manage peak holiday periods, network upgrades and installation costs
- Governance to manage multiple small power suppliers and ensure accurate and fast payment
- There is a risk of negative externalities as the financial incentive benefits the vehicle user and it is unclear how this would affect responsibility for end-of-life battery management.

### 6.2.6 Re-use for application as EV battery

As set out in the technical review, re-use options can extend battery life by 10 to 30 years. End-of-life traction batteries retain between 70-80% of their initial energy capacity and on average, between 0 and 15% of cells require replacement. Re-use allows this energy capacity to be better harnessed. Re-use offers considerable financial incentive for battery cell manufacturers with the main cost occurring from grading the cell components[20]. Reported costs suggest that battery re-use can reduce battery manufacturing costs by between 60 and 90% compared to the cost of manufacturing a new EV battery. The cost savings are primarily achieved through avoided material costs (with raw materials comprising a significant share of total cell manufacturing costs)[21].

Not all end-of-life traction batteries are eligible for reuse with 50% of traction batteries on the road in 2014 considered appropriate for reuse (Elkind E. , 2014). The extent of waste generated from end-of-life traction batteries not eligible for reuse is discussed in section 6.2.9. Among other factors, the viability of used traction batteries being put forward for reuse varies by battery pack depending on the specific state of health, the chemical composition of the battery cell and the design of the battery pack. The collection, handling and storage of used batteries must also be carried out in a certain way to avoid irreparable damage. These factors are determined internally by operators and there are no public standards in place to ensure a certain level of quality is adhered to. The lack of standards presents a risk to the safe transportation of EV battery waste transported for recycling and disposal purposes. Appropriate safety precautions are needed to ensure that all risks associated with the

[20] Based on feedback from project consultation with EV manufacturers.
[21] Based on feedback from project consultation with the European Battery Recycling Organisation, trade association and other feedback from EV manufacturers.

transportation of EV batteries for reuse are met. Furthermore, checks would be needed to ensure that transportation cannot be mis-used for transportation of EV batteries for recycling or waste disposal[22].

There is further ambiguity in this process as to battery ownership and liability whereby current legislation stipulates that the car manufacturer is responsible for end-of-life EV battery management with no legal obligation on the re-use manufacturers[23]. It is also unclear where the onus falls for measuring and grading used batteries to determine their suitability for reuse and there is no standardised process in place. It is also unclear where the onus falls for safe collection, handling and storage of used batteries before reuse treatment. Furthermore, there is a lack of transboundary mechanisms to facilitate cross-country collaboration across the various components in the value chain[24].

However, the associated capital costs to establish an installation capable of treating the re-used batteries are significant with an estimated 30-year payback period. Furthermore, supply is limited meaning that the market would still depend on newly manufactured batteries[25]. Current supply of used traction batteries is estimated to meet demand for between 55 and 60% of new EVs and is forecast to increase, meeting between 70 and 85% by 2050 (Mineta National Transit Research, 2014).

The re-use market is emerging and fast establishing itself. Examples of successful business models are apparent (e.g. Box 11) and the EU should take precautions to ensure it is well positioned to exploit such opportunities.

**Box 11: 4R Energy Cooperation**

4R Energy Corp (a joint venture between Nissan and Sumitomo Corporation) launched a battery re-use programme for first generation Nissan LEAF models in Japan (Reuters, 2018a). The programme collects and restores used batteries with less than 80% their original energy capacity (typically after 8-10 years of use on the road). Once restored, the re-used batteries have up to 90% their original energy capacity[26].

The programme has developed a new way to assess and grade used battery cells, reducing the time needed to assess all 48 battery cells from 16 days to 4 hours. The plant has capacity to process 2,250 battery packs a year. The re-used batteries are returned to the market at approximately half their original price (~€2,500).

To date, this programme is only operational in Japan[27].

A final consideration is the opportunity to enhance re-use options where cell components are currently discarded and treated for recycling.

Based on current trends and experiences, the impact of reuse options on the EV battery chain is likely to be:

- Savings of between 70-80% energy capacity from first-used battery cells
- Cost savings in battery cell manufacturing by up to 60% which could bring down EV maintenance costs making EVs more accessible to consumers (whereby EV batteries reaching 70-80% of energy capacity can be re-used, following remanufacturing, rather than requiring a new battery replacement).

Despite financial incentives, there are several barriers affecting the viability of re-use options in the EV battery value chain, as follows:

- Significant capital needs to establish re-manufacturing installations; established cell manufacturers will have a competitive edge

[22] Based on feedback from project consultation with the European Battery Recycling Organisation, trade association.
[23] Based on feedback from project consultation with the European Battery Recycling Organisation, trade association.
[24] Based on feedback from project consultation with recyclers.
[25] Based on feedback from project consultation with recyclers.
[26] Based on feedback from project consultation with EV manufacturers.
[27] Based on feedback from project consultation with EV manufacturers.

- Uncertainties concerning battery ownership and liability, increasing the risk of negative externalities occurring in relation to collection, transport, storage, measurement and grading, as well as at the end-of-life phase
- Low consumer awareness regarding the quality of reused batteries, coupled with a lack of transparency in the reuse processes and no standardised quality assurance process

### 6.2.7 Re-purposing for use in energy storage systems

Re-purposed EV batteries is an emerging market with limited used EV batteries available for re-purposing owing to insufficient EV batteries having reached their end-of-first-life (either through warranty replacement or end-of-life of the vehicle). However, the growing number of EVs on the road provides an indication of the size for this emerging market. By 2025, one estimate indicates that 27% of EV batteries on the road will be available for re-purposing (CEPS, 2018). The extent of waste generated from end-of-life traction batteries not eligible for re-purposing is discussed in section 6.2.9.

As discussed previously, re-purposed EV batteries for use in energy storage systems have a significantly lower environmental impact compared to newly made equivalents (re-purposed EV batteries have less than 10% the impact of newly made equivalents). In terms of design, EV batteries and batteries used in energy storage systems are the same and therefore manufacturing needs relate to dismantling and grading rather than technical changes. Health and safety risks occur primarily because of the disconnect between the earlier and later phases of the value chain whereby substance use may not be labelled or documentation for safe handling may be missing. Despite risks, it is generally considered that EU health and safety precautions facilitate a safe work environment for re-purposing[28], however discussion with recyclers indicates that in some cases it is not possible to get adequate documentation for battery handling/dismantling owing to confidentiality clauses in battery pack design[29].

The use of lithium batteries in such systems is well established with largest example in the EU based in the UK where a 6 MW/ 10 MWh Li-ion battery has been integrated to manage renewable wind energy into the national grid with a reported saving of ~€7.8 million compared to previous system upgrades (Luo et al., 2015). Thus, re-purposing offers considerable financial incentive for manufacturers of energy storage systems and can reduce running costs by approximately tenfold (Natkunarajah, et al., 2015) (Natkunarajah, et al., 2015) and manufacturing costs by between 80-90% (BNEF, 2016). It is unclear if this economic advantage will continue in coming years in the light of ongoing cost savings which are expected to continue bringing down the cost of newly manufactured batteries.

The associated capital costs to establish an installation capable of treating the reused batteries are significant with an estimated 30-year payback period (Mineta National Transit Research, 2014). Furthermore, secondary reuse of EV batteries requires cross-sectoral cooperation between transport and energy sectors.

The main cost of re-purposing occurs from collection and transportation of used EV batteries; this process also has a considerable administrative burden. One option to reduce the cost and administrative burden proposed by industry could be to establish an EU zone for transporting used EV batteries between Member States; there is also discussion as to the extent to which used EV batteries should be classified as waste if they are intended for re-purposing[30]. Such a system would require appropriate safety precautions to ensure that all risks associated with the transportation of EV batteries for re-purposing are met. Furthermore, checks would be needed to ensure that the system cannot be mis-used for transportation of EV batteries for recycling or waste disposal[31].

Despite the growing number of used EV batteries which are expected to become available by 2025, the supply of used EV batteries is not expected to meet demand (as outlined previously, energy storage systems are well-established and growing with the use of renewable energy). To address this, Nissan and Renault have launched energy storage systems which combine both used and new EV

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[28] Based on feedback from project consultation with EV manufacturers.
[29] Based on feedback from project consultation with recyclers.
[30] Based on feedback from project consultation with EV manufacturers.
[31] Based on feedback from project consultation with the European Battery Recycling Organisation, trade association.

batteries intended for aftersales operations. The system allows new EV batteries to be stored in a safe environment until they are placed on the market – e.g. for warranty repair/replacement.

**Box 12: Re-purposed EV batteries combined with new EV batteries**

Advanced Battery Storage: Groupe Renault has launched an advanced battery storage programme in the EU. The system will have a total capacity of 70 MW (equivalent to 60 MWh or the daily consumption of 5,000 households) (Groupe Renault, 2018).

xStorage Home: The system will use a combination of used EV batteries and new ones (intended for aftersales operations only) as part of a 6kWh battery storage system for home energy management in UK homes (Green Car Congress, 2018). The system provides greater independence from electricity provides with the ability to generate and manage renewable energy. The system boasts capacity to reduce household electricity bills by up to 66%. Users have the option to select either new or used EV batteries. Pricing starts at £3,881 (Nissan GB, 2018a)

Amsterdam Energy ArenA BV: 3 MW storage system (2.8 MWh) was implemented using re-purposed and new EV batteries (equivalent to 148 Nissan LEAF batteries). The system allows the energy produced by the 4,200 solar panels on the roof of the arena to be stored and used as back-up. (Nissan Europe, 2018)

In the EU, the lack of provisions to regulate re-purposing has led to increasing uncertainties over definitions and liabilities. Provisions are also required to support a fair and transparent market (mindful of prices and taxes) – not least to ensure that re-purposing market opportunities are not lost to third countries/regions[32]. It is argued by some OEMs that re-purposing (and re-use) should not be classified as an end-of-life solution; and that there should be flexibility to shift producer responsibility from the initial producer to the second-life operator as the battery enters its second-life[33].

Based on current trends and experiences, the impact of re-purposing options on the EV battery chain is likely to be:

- Extending the battery useable lifetime by replacing degraded battery cells so that the remaining 70-80% energy capacity can be accessed
- Cost savings in energy system upgrades by up to 80%, strengthening energy security and facilitating national grid access to renewable energy sources
- Strengthen EV battery supply chain in the EU by offering safe storage option for newly manufactured EV batteries before use in EVs

Despite financial incentives, there are several barriers affecting the viability of re-purposing options in the EV battery value chain, as follows:

- Significant capital needs to establish manufacturing installations
- Uncertainties concerning battery ownership and liability, increasing the risk of negative externalities occurring in relation to collection, transport, storage, measurement and grading, as well as at the end-of-life phase
- Low consumer confidence and awareness - concerns associated with reused batteries, coupled with a lack of transparency in the reuse processes and no standardised quality assurance process
- Administrative barriers, e.g. access to the grid (Jiao and Evans, 2016)
- Disconnect between the transport and energy sectors (Jiao and Evans, 2016)

### 6.2.8 Extraction of raw materials through recycling

As outlined in the previous section, a traction battery is retired from service when it loses approximately 20%-30% of its initial capacity. To support a sustainable EV battery value chain,

[32] Based on feedback from project consultation with Professor Dave Greenwood, Warwick Manufacturing Group, University of Warwick.
[33] Based on feedback from project consultation with EV manufacturers.

recycling should therefore only be considered after reuse and re-purposing options have been exhausted. By 2025, one estimate indicates that ~73% of EV batteries currently on the road in the EU will be available for recycling (CEPS, 2018).

Extraction of raw materials through recycling serves two purposes in the (EU) EV battery value chain: (1) it reduces dependency on virgin raw materials; and (2) it reduces electro chemical waste and helps to minimise the environmental footprint of the EV battery value chain (net $CO_2$ saving of 1 kg $CO_2$ / kg of battery from recycling Li-ion battery, and also other environmental impacts) (CEPS, 2018).

The need to reduce dependency on virgin raw materials in the EV battery value chain relates particularly to those materials deemed significant to the EU economy and where supply is high risk (critical raw materials such as lithium, cobalt and nickel). With regards to cell manufacturing in the EV battery value chain, access to raw materials is recognised as a key challenge, particularly with regards to cobalt and lithium. While the latter is not classified a critical raw material, there are limited sources (in geographic terms rather than abundance of supply) and the material has grown considerably in economic significance since 2006.

Currently, cell manufacturing is limited in the EU (though there have been a number of announcements recently for planned capacity development). Cell manufacturing facilities are small in comparison to the global market and they are unable to run at full capacity owing to competition with manufacturers outside the EU (6.1.2). Overall, the manufacturing capacity of Europe comprises 15% of global capacity and yet utilisation is 1% (JRC, 2017). With the cost of raw materials comprising a considerable portion of manufacturing costs, access to raw materials can be regarded as a key barrier. Recycling traction batteries would provide the EU with direct access to the raw materials needed in cell manufacturing. It could also lead to job creation with one estimate indicating 15 jobs are created for every 1,000 tonnes of Li-ion waste (80% related to collection and dismantling; 20% related to recycling) (CEPS, 2018). However, currently, the cost of recycling is not competitive with the cost of extraction.

The main costs relate to collection and dismantling. According to results generated using the EverBatt model (ANL, 2018a), up to 50% of total recycling costs occur from transportation[34]. To reduce transportation costs, EV batteries are often dismantled close to collection, separating inactive substances and reducing the bulk of material being transported for treatment at recycling installations. Economies of scale are not expected to affect transportation costs, although they are expected to reduce dismantling and recycling costs[35]. Despite this promise of economic potential, it is recognised that this is not within an immediate timeframe[36].

Dismantling costs can be reduced according to the joining methods in cell manufacturing and battery pack design (prismatic cells are easiest to dismantle), among other things. As such, it is important to consider recycling needs during cell manufacturing to minimise costs in recycling of EV batteries.

As reiterated previously in this analysis, recycling is currently distinct to earlier phases in the value chain. Arguably there is some merit in establishing recycling credits within the earlier phases of the value chain to offset the primary material input. As also previously discussed, in the US recycling credits can offset between 16 and 23 kg $CO_2e$ / kWh. The use of recycling credits could be used to offset the costs of recycling, particularly where current techniques and scales render it unprofitable.

A key challenge for the recycling sector in facilitating access to the raw materials required in the EV battery value chain is supply of used batteries. Based on the weight of portable lithium-ion batteries put on the EU market in 2011 (~30,000 tonnes), approximately 3,000 tonnes of cobalt could have been recycled once the batteries reached their end-of-life. This would be sufficient to supply the production of 400,000 EV batteries. However, in 2016, only 3,000 tonnes of portable lithium-ion batteries were collected and recycled (able to supply the production of 40,000 EV batteries) (Umicore, n.d.). The key challenges for this according to representatives from the EU recycling industry is the collection performance and the use of recycling targets focussing on material recovery rather than the type of material recovered[37].

[34] Based on feedback from project consultation with Argonne National Laboratory, EV manufacturers.
[35] Based on feedback from project consultation with recyclers.
[36] Based on feedback from project consultation with the European Battery Recycling Organisation, trade association.
[37] Based on feedback from project consultation with the European Battery Recycling Organisation, trade association and other feedback from EV manufacturers.

Cobalt is being phased out by some cell manufacturers (e.g. Tesla). It is expected that there will be a decline in cobalt and increase in nickel; while this will have positive implications for SOx emissions, it will have adverse effects on the profitability of recycling (whereby extracted cobalt has the highest value)[38].

While there is evidence of battery waste being processed in municipal waste management systems, a considerable amount of portable battery waste is collected as waste electrical and electronic equipment (WEEE) and exported to third countries for waste management without adequate safety precautions to mitigate fire, health and environmental risks (Umicore, n.d.); and the extent to which the low collection rate is affected by the battery lifetime is unclear with the three-year average lifetime deemed too low for lithium-ion portable batteries (EUCOBAT and MOBIUS, 2017).

Another barrier to recycling in the EV battery value chain concerns cost. Recycling costs occur as the recycling industrial processes are energy intensive and the pre-treatment steps are resource intensive, while also operating at small scales thus extracting insufficient quantities of lithium to meet forecast demand (Sonoc et al., 2015). Furthermore, the safe handling of battery waste is costly[39].

While recycling is economically profitable for cobalt, the amount of cobalt available from recycling is limited and by 2025, recycling is forecast to supply only 10% of cobalt needed[40], recycling techniques to extract other raw materials used for cell manufacturing such as lithium are as yet unprofitable. In the case of lithium, relying on current recycling techniques, the market price of lithium salts would need to increase by about 17 times its market value in 2012 to make recycled lithium prices competitive (Mineta National Transit Research, 2014). Thus, despite the monetary value of reduced dependency on virgin raw materials (lithium extracted from recycled lithium-ion batteries can generate ~€200 per tonne) (Wang, Gaustad, Babbitt, & Richa, 2014), current recycling techniques are not cost effective compared to virgin lithium. Despite ongoing improvements in recycling techniques concerning recovery rates of raw materials, it is unclear the extent to which emerging techniques will help to minimise recycling costs. For example, American Manganese has published a patent for a hydrometallurgical process to recover 100% of lithium, cobalt, manganese and aluminium from Li-ion batteries. (Messenger, 2018). However, the extent to which this process is economically viable and the scale at which it must operate in order to be so is unclear.

Industry does not expect a significant change in raw material needs in the future[41] although there has been a shift from cobalt in recent years. For example, Tesla has also announced plans to phase out the use of cobalt (from 3% to 0%) (Fortuna, 2018). Currently, there is an average of 4.5 kg cobalt/ vehicle for Tesla BEVs according to (Field, 2018)

Representatives from the recycling industry maintain that the cost effectiveness of recycling would improve if supply of used batteries increased owing to economies of scale. However, the extent of used batteries required to reach the optimum economy of scale is uncertain. One industry stakeholder observed that one plant processing 500,000 tonnes of waste is more efficient than five plant processing 100,000 tonnes each; however, no indication as to the tipping point in the scales needed was provided[42].

An additional barrier relates to uncertainty in the quality of the recycled materials renders the end product less attractive (Mineta National Transit Research, 2014). To date, examples of recycling lithium-ion batteries only occur as part of cell manufacturing in-house processes, thus the quality of extracted lithium can be assured by the cell manufacturers.

The need for large scale recycling operations is expected in 10 to 20 years (whereby used EV batteries are heavier than portable batteries and this will be reflected in the problem). To date, the EU is well positioned with examples of commitments to increase recycling capacity, e.g. Umicore's announcement to increase its current recycling capacity in Belgium from between ~150,000/200,000 EV batteries 2 million in the next 10 years (Manthey, 2018). Recycling schemes for end-of-life EV batteries are already established in China, and Japanese vehicle manufacturers recently announcing their intention to launch a collection and recycle project for used EV batteries across seven regions in

[38] Based on feedback from project consultation with Argonne National Laboratory, EV manufacturers.
[39] Based on feedback from project consultation with the European Battery Recycling Organisation, trade association.
[40] Based on feedback from project consultation with recyclers.
[41] Based on feedback from project consultation with EV manufacturers.
[42] Based on feedback from project consultation with recyclers.

Japan (Randall, 2018). Among the stakeholders interviewed, the use of regulatory targets for recycling in the EU is considered a key factor supporting EU progress in recycling, although there is a need to strengthen EU targets. In other countries, targets are voluntary[43].

Based on current trends and experiences, the impact of recycling on the EV battery chain is likely to be:

- Cost savings associated with reduced waste export for end-of-life EV batteries
- Reduced dependency on virgin raw materials, facilitating EU access to the cell manufacturing market through reduced costs of raw materials

There are several barriers affecting the viability of recycle options in the EV battery value chain, as follows:

- Lack of sufficiently cost-effective recycling techniques to extract all critical raw materials
- Lack of standardised labelling and regulation to support safe handling and treatment of used EV batteries (Gaines, 2014)
- The need for improved battery designs (within the constraints of optimal battery performance) to facilitate end-of-life reuse/repurposing/recycling.
- Uncertainties concerning battery ownership and liability, increasing the risk of negative externalities occurring in relation to collection, transport, storage, measurement and grading, as well as at the end-of-life phase
- Lack of standardised criteria to identify where a used battery should be treated for reuse or recycle
- Growth will be intrinsically tied to battery cell manufacturers in third countries

### 6.2.9 Safe handling and treatment of waste

End-of-life waste disposal (of electro chemical waste) in the traction battery value chain does not present an immediate issue owing to the current scale of the problem and lifetime of traction batteries and reuse options. While global stockpiles of used traction batteries in 2018 amount to ~55,000 battery packs per annum, by 2025 this is expected to be 3.4 million (Ma, 2018).

Owing to the timescales involved and current uncertainties with recycling, it is not possible to explore the commercial viability of this opportunity in any detail. The needs relate to the safe collection, transportation, storage and export of non-recyclable waste[44]. The timeframe and multi-sector stakeholder involvement in the traction battery value chain present potential challenges for appropriate end-of-life waste disposal. Namely as these factors affect traceability and ownership of the waste and responsibilities for managing it.

While the impacts are highly uncertain, it is foreseeable that the planned extension to the EV battery value chain to incorporate direct and secondary reuse as well as recycling options may pose challenges for waste management and increase the likelihood of negative externalities occurring in the EV battery value chain.

## 6.3 Summary of options, opportunities and barriers

Options for developing a sustainable value chain for EV batteries in the EU are summarised in the table below along with high-level opportunities and barriers as identified in the analysis.

**Table 6.2: Summary of options, opportunities and barriers**

| Option | Market maturity | Summary of opportunities | Summary of barriers |
|---|---|---|---|

[43] Based on feedback from project consultation with the European Battery Recycling Organisation, trade association.
[44] Based on feedback from project consultation with Professor Dave Greenwood, Warwick Manufacturing Group, University of Warwick.

| Option | Market maturity | Summary of opportunities | Summary of barriers |
|---|---|---|---|
| Integrated value chain | Emerging | Reduced environmental footprint<br>Cost savings for industry<br>Greater flexibility for industry to integrate changes across the value chain<br>Improved efficiency for industry through streamlined processes | High investment cost for operators<br>End-of-first-life options are not economically viable as EVs still on the road<br>Lack of skilled labour<br>Administrative burden for industry where EVs sold outside the EU |
| EV sharing schemes | Operational | Reduced number of EVs on the road<br>Cost savings for the individual<br>Central ownership facilitates end-of-first-life/ end-of-life management | High investment cost for operators<br>Low consumer interest<br>Administrative issues related to insurance<br>Risk of unintended effects on battery performance<br>Direct competition to train and coach services |
| Battery leasing schemes | Operational | Ensures batteries operate above recommended performance threshold<br>Central ownership facilitates end-of-first-life/ end-of-life management | High investment cost for operators<br>Financial risk associated with multi-annual contracts<br>Low uptake<br>Administrative complexity concerning battery ownership |
| Battery swapping schemes | Not commercially viable | Facilitates optimum charging patterns for enhanced battery performance<br>Improves electricity usage flows<br>Central ownership facilitates end-of-first-life/ end-of-life management | High investment cost for operators<br>Limited by battery type<br>Uncertain timeframes, risk of battery technology becoming obsolete<br>Low consumer awareness |
| Vehicle to grid | Emerging | Improved energy security<br>Financial reward for the individual | Lack of supporting infrastructure (software)<br>Requires governance intervention (issues concerning data privacy and market regulation for energy going into the grid)<br>Requires cooperation between sectors |
| Re-use for application as EV battery | Operational | Reduced demand for new EV batteries<br>Cost savings for industry<br>Improved energy security | High investment cost for industry<br>Low consumer awareness<br>Logistical and legal uncertainties (collection, transport, storage and processing of used batteries) |

| Option | Market maturity | Summary of opportunities | Summary of barriers |
|---|---|---|---|
| Re-purposing for use in energy storage systems | Operational | Cost savings for industry<br>Improved energy security<br>Provides a safe storage option for EV batteries not on the road | High investment cost for industry<br>Low consumer awareness<br>Requires cooperation across sectors<br>Logistical and legal uncertainties (collection, transport, storage and processing of used batteries) |
| Raw material extraction through recycling | Not commercially viable | Reduced dependency on virgin materials<br>Reduced hazardous waste stream | Techniques are not cost effective<br>Scale of economy not possible in the immediate timeframe<br>Low consumer awareness<br>Logistical and legal uncertainties (collection, transport, storage and processing of used batteries) |
| Safe waste handling and management | Not operating at full scale | Uncertain | Lack of traceability in manufacturing processes affecting battery ownership and liability |

# 7 SWOT analysis for the EU economy (Subtask 2.5)

*What are the current strengths and weaknesses of the EU economy (industry, infrastructure, policy framework…) for dealing with the lifecycle of traction batteries in the perspective of road transport electrification?*

**Key outputs:**

- SWOT analysis structured around three pillars: Industry, Infrastructure and Policy

## 7.1 Introduction

This chapter presents the advantages and disadvantages the EU faces, in the global context, as EV adoption scales up for industry, infrastructure and EU policy. The analysis is structured according to the three pillars described below:

- Industry: technical capabilities and capacities
- Infrastructure: installation capacities, software systems and stakeholder networks
- Policy: governance structures and regulatory frameworks

## 7.2 Summary of the strengths and weaknesses, opportunities and threats to the EU economy

Limited access to raw materials has been identified as a key constraint for growth in the sector, although it is recognised that recycling is expected to play a role in alleviating this constraint through the return of extracted raw materials to the market. In addition, should there be more rapid developments / changes in battery chemistries (e.g. shift to sodium-ion, faster elimination of cobalt) this could reduce these constraints, though likely only in the medium-longer term.

Key areas of emerging growth for EU industry relate to battery cell (and cell component) manufacturing, re-use and re-purposing – from an industry perspective, securing access to skilled labour and expertise is essential. Growth is also envisaged for battery pack manufacturing and EV manufacturing, although these industries are already established in the EU and is well positioned in terms of its technical capabilities and capacities.

The current construction of installations in the EU indicates that much of the capital needs have already been met to facilitate growth in cell component manufacturing. The need for financial investments for infrastructures is ongoing in the light of continued planned growth. Investments are also required to establish software infrastructures to support the development of emerging circular economy business models.

The stakeholder network established through the Batteries Directive to facilitate communication is an important enabler for growth across the value chain.

Several weaknesses and threats have been identified in relation to the current policy framework across the complete value chain. Commonalties exist, and the following points are flagged:

- Lack of definitions for emerging markets (primarily with respect to re-use and re-purposing although other emerging circular economy business models would also benefit from clearer definitions).
- Lack of standards at EU level (standards are typically developed in-house and differ between producers).
- Transparency (producer responsibility but also financial transparency in the light of emerging circular economy business models such as V2G).

Figure 7.1 provides a visual overview of the strengths, weaknesses, opportunities and threats.

**Figure 7.1: Summary of SWOT analysis for the EV battery value chain in the EU**

| EV battery value chain | Industry | Infrastructure | Policy |
|---|---|---|---|
| Raw materials | Weak | Intermediate | Strong |
| Cell component manufacturing | Intermediate | Intermediate | Strong |
| Cell manufacturing | Intermediate | Intermediate | Intermediate |
| Battery pack manufacturing | Strong | Strong | Strong |
| EV manufacturing | Strong | Strong | Strong |
| Re-use | Intermediate | Intermediate | Weak |
| Re-purposing | Intermediate | Intermediate | Weak |
| Recycling | Strong | Strong | Strong |

*Note*: **Green** shows key strengths that future policy should continue to reinforce and support; **Amber** shows areas under development in the EU that should be monitored; and **Red** shows key barriers or constraints in the EU that future policy should look to ease.

## 7.3 Industry pillar

**Table 7.1: SWOT analysis for industry**

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| Raw materials | Limited access to virgin raw materials.<br>Established recycling industry technically capable of extracting raw materials from end-of-life traction batteries although recycling rates remain low for certain materials. | Technical capabilities available to extract raw materials from recycling.<br>Volume of traction batteries available for recycling will increase and is expected to enable recycling industry to reach economy of scale needed to turn a profit.<br>R&D funding available to support pilots and facilitate networking between industry and research. | Net importer of raw materials (associated risk of environmental impact leakage).<br>Extraction of raw materials through recycling not profitable at current scale and using current techniques.<br>Time lag between current demand for raw materials and supply of end-of-life EV batteries from which raw materials can be extracted. Risk of technological advances in that duration affecting types of raw materials used.<br>Gap in skilled labour expected requirements to dismantle end-of-life batteries. |
| Cell component manufacturing | Limited industrial activity but area of growth with investments secured for infrastructure to support planned growth. | Potential to establish integrated business model (whereby all value chain components are managed internally); subsequent potential to reduce environmental footprint and costs through energy efficiencies achieved in manufacturing.<br>Access to clean and secure energy.<br>R&D funding available to support pilots and facilitate networking between industry and research. | High competition from third countries.<br>Net importer of cell components (associated risk of environmental impact leakage).<br>Gap in skilled labour and expertise.<br>Fast evolving industry (technologies and equipment), requiring flexibility to adjust to changes.<br>Cost and performance are the main driver; re-use, re-purposing and recycling are not drivers. Information on material composition of batteries supplied with Material Safety Data Sheets (MSDS) are often too vague to be informative (owing to confidentiality reasons). |

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| Cell manufacturing | Not active in EV cell manufacturing itself (though there is in non-EV applications). Planned activity by 2020s with investments to support Gigafactory approach to cover manufacturing across full scope of EV battery value chain.<br>EU companies globally active in battery manufacturing process equipment. | High capability (leading expertise) in manufacturing process equipment for cell (and pack) manufacture.<br>Potential to establish integrated business model (whereby all value chain components are managed internally); subsequent potential to reduce environmental footprint and costs through energy efficiencies achieved in manufacturing.<br>Access to clean and secure energy.<br>R&D funding supports existing cell manufacturing projects and ongoing available to support pilots and facilitate networking between industry and research. | High competition from third countries.<br>Economically unviable (cheaper to import, associated risk of environmental impact leakage).<br>Gap in skilled labour and expertise.<br>Fast evolving industry (technologies and equipment), requiring flexibility to adjust to changes.<br>Cost and performance are the main driver; re-use, re-purposing and recycling are not drivers. Information on material composition of batteries supplied are often too vague to be informative (owing to confidentiality reasons). |
| Battery pack manufacturing | Established industry tied to EV manufacturing (namely passenger vehicles).<br>EU OEMs leading R&I to improve energy density performance through pack design. | Technical capabilities available to design and develop battery modules and packs and sufficient capacity to meet demand in established markets.<br>Access to clean and secure energy.<br>R&D funding available to support pilots and facilitate networking between industry and research. | Growing competition from third countries to produce battery packs for non-passenger EVs.<br>Gap in expertise, dependence on third countries for EV battery pack designs.<br>Cost and performance are the main driver; re-use, re-purposing and recycling are not drivers. Information on material composition of batteries supplied are often too vague to be informative (owing to confidentiality reasons). |

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| EV manufacturing | Established industry.<br>EU demand exceeding supply and projected ongoing growth in demand. | Key player in global market for passenger EVs.<br>Growing demand for wider range of EVs.<br>Access to clean and secure energy.<br>Leading R&I in vehicle design and ongoing R&D funding available to support pilots and facilitate networking between industry and research. | Growing competition from third countries.<br>Limited activity in wider range of EVs.<br>Cost and performance are the main driver; re-use, re-purposing and recycling are not drivers. Information on material composition of batteries supplied are often too vague to be informative (owing to confidentiality reasons). |
| Re-use | Emerging industry owing to the extent of available traction batteries for re-use.<br>Projected growth. | Economically viable.<br>Automation in battery cell assessment can bring down costs further.<br>Access to clean and secure energy.<br>R&D funding available to support pilots and facilitate networking between industry and research. | Uncertainty related to the timeframe, quantity and quality of traction batteries reaching first-end-of-life. Risk of oversupply where treated EV batteries for re-use are competing with higher performing new models.<br>Low consumer awareness affecting demand.<br>Administrative burden associated with recalling first-used EV batteries from third countries.<br>Administrative burden associated with EU regulatory requirements risk making other waste solutions more appealing – e.g. recycling or shipment of waste to third country. |

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| Re-purposing | Emerging industry owing to the extent of available traction batteries for re-purposing.<br>Projected growth. | EU has established industry in energy storage systems.<br>There is a significant activity / number of projects investigating repurposing and second-life applications in Europe.<br>Automation and scale in battery cell assessment can potentially bring down costs further.<br>Access to clean and secure energy.<br>R&D funding available to support pilots and facilitate networking between industry and research. | Uncertainty related to the timeframe, quantity and quality of traction batteries reaching first-end-of-life, and in demand for second-life applications.<br>Uncertainty related to producer responsibilities which may make OEMs reluctant to supply used EV batteries for re-purposing.<br>Disconnect between energy and vehicle industries. Information on material composition of batteries supplied are often too vague to be informative (owing to confidentiality reasons).<br>Administrative burden associated with EU regulatory requirements risk making other waste solutions more appealing – e.g. recycling or shipment of waste to third country.<br>Administrative burden associated with access to the grid. |

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| Recycling | Established industry more widely but the transition to recycle end-of-life traction batteries is still emerging owing to the extent of available traction batteries.<br>Projected growth. | Automation in the battery dismantling phase could bring down costs.<br>Technical capabilities available to extract raw materials from recycling.<br>Economically viable to extract some raw materials but not all at current scales.<br>Local dismantling and preliminary treatment of EV batteries to bring down recycling costs.<br>Volume of traction batteries available for recycling will increase and is expected to enable recycling industry to reach economy of scale needed to reduce costs significantly.<br>Long product life of EV battery allows sufficient time for industry to respond technically to emerging recycling needs.<br>Demand for lithium is expected to continue. EV battery chemistries expected to rely on lithium-based chemistries for the foreseeable future.<br>Access to clean and secure energy.<br>R&D funding available to support pilots and facilitate networking between industry and research. | Disconnect between vehicle and recycling industries. Information on material composition of batteries supplied are often too vague to be informative (owing to confidentiality reasons).<br>Gap in skilled labour expected requirements to dismantle end-of-life batteries.<br>Administrative burden associated with recalling first-used EV batteries from third countries.<br>Cost is the main driver rather than supporting a circular economy. Risk that recyclable waste from future battery chemistries will have even less value (e.g. Li-S). |

## 7.4 Infrastructure pillar

**Table 7.2: SWOT analysis for infrastructure**

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| Raw materials | Limited access to virgin raw materials.<br>Established recycling industry with infrastructure to facilitate the extraction of raw materials from end-of-life traction batteries although capacity of infrastructures will need to increase to meet expected supply of end-of-life traction batteries. | Established recycling infrastructure (systems for collection, handling, storage and treatment).<br>Stakeholder network established through the Batteries Directive to facilitate communication.<br>Stable market environment to attract potential investors. | Additional infrastructure required to meet expected scale of recycling operations and subsequent high capital investment required to develop new infrastructures. |
| Cell component manufacturing | Limited infrastructures but area of growth with investments in infrastructure agreed to facilitate greater EU role in cell component manufacturing. | Attractive investment opportunity.<br>Limited existing infrastructures provides flexibility for growth to establish a Gigafactory, following the integrated approach by Tesla in the US.<br>Stable market environment to attract potential investors.<br>Stakeholder network established through the Batteries Directive to facilitate communication. | High capital investment required to develop new infrastructures. |

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| Cell manufacturing | Not active in EV cell manufacturing itself (though there is in non-EV applications). Planned activity by 2020s with investments to support Gigafactory infrastructure to cover manufacturing across full scope of EV battery value chain. | Lack of existing infrastructures provides flexibility for growth to establish a Gigafactory, following the integrated approach by Tesla in the US.<br>Stable market environment to attract potential investors.<br>Stakeholder network established through the Batteries Directive to facilitate communication. | High capital investment required to establish new infrastructures. |
| Battery pack manufacturing | Established infrastructure in the EU to support manufacturing, tied to EV manufacturing (namely passenger vehicles). | Emerging markets for battery packs suitable for a wider range of EVs (requires investment).<br>Stable market environment to attract potential investors.<br>Stakeholder network established through the Batteries Directive to facilitate communication. | High capital investment required to establish new infrastructures capable of manufacturing battery packs suitable for a wider range of EVs. |
| EV manufacturing | Established infrastructure in the EU to support manufacturing. | Emerging markets for a wider range of EVs.<br>Stable market environment to attract potential investors.<br>Emergence of circular economy business models presenting an opportunity to EV manufacturers (e.g. car share, battery swapping and battery leasing).<br>Stakeholder network established through the Batteries Directive to facilitate communication. | High capital investment required for different EV types and for the emerging circular economy business models (e.g. car share, battery swapping and battery leasing).<br>Software infrastructure required to facilitate emerging circular economy business models (e.g. vehicle to grid schemes and overseeing energy supply, financial reward, etc.). |

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| Re-use | Emerging industry owing to the extent of available traction batteries for re-use.<br>Projected growth. | Stable market environment to attract potential investors.<br>Stakeholder network established through the Batteries Directive to facilitate communication. | Logistical infrastructure to facilitate recalling first-used EV batteries is weak, (particularly where third countries are involved).<br>High capital investment required for infrastructures required to store, assess, repair and store traction batteries.<br>Time delay means there is a risk of battery technology becoming obsolete. |
| Re-purposing | Emerging industry owing to the extent of available traction batteries for re-purposing.<br>Projected growth. | Stable market environment to attract potential investors.<br>Strengthen energy security.<br>Provides a safe storage option for EV batteries not on the road.<br>Stakeholder network established through the Batteries Directive to facilitate communication. | High capital investment required for infrastructures required to store, assess, repair and store batteries.<br>High capital investment required for developing energy storage systems.<br>Logistical infrastructure to facilitate recalling first-used EV batteries is weak, (particularly where third countries are involved).<br>Time delay means there is a risk of battery technology becoming obsolete. |
| Recycling | Established industry more widely but the transition to recycle end-of-life traction batteries is still emerging owing to the extent of available traction batteries.<br>Projected growth. | Established recycling infrastructure (systems for collection, handling, storage and treatment).<br>Stable market environment to attract potential investors.<br>Stakeholder network established through the Batteries Directive to facilitate communication. | Additional infrastructure required to meet expected scale of recycling operations and subsequent high capital investment required to develop new infrastructures.<br>Time lag between business opportunity and investment need. Financial incentives required to attract potential investors. |

## 7.5 Policy pillar

**Table 7.3: SWOT analysis for policy**

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| Raw materials | List of critical raw materials to facilitate supply of raw materials (including strategy and support for trade agreements). Coverage of raw materials relevant to EV battery manufacturing is not comprehensive.<br>Established policy framework to facilitate recycling and entry into the market of recycled raw materials.<br>Established policy framework to support R&D. | Opportunity to build on existing standards to support entry of recycled raw materials back into the market.<br>Established R&D policies and funding instruments to facilitate new and emerging techniques. | List of critical raw materials is not comprehensive for key raw materials needed for EV battery manufacturing.<br>Coherence needed between policies regulating virgin raw materials and raw materials extracting through recycling. E.g. recycling targets are not material specific.<br>Low level of data and information to support policy development. |
| Cell component manufacturing | Established policy framework under the Batteries Directive outlining requirements for cell component manufacturing in the EU. Limited environmental requirements compared to wider industry.<br>Established policy framework to support R&D.<br>PEF (Product Environmental Footprint) Category Rules (CR) for High Specific Energy Rechargeable Batteries for Mobile Applications. | Opportunity to establish regulated standards to facilitate transparency and streamline processes across the value chain.<br>Established R&D policies and funding instruments to facilitate new and emerging techniques.<br>The PEF CR provide a voluntary framework for conducting a battery lifecycle assessment in a standardised way. | As a net importer of cell components, EU EV manufacturers have limited control over manufacturing processes to mitigate environmental impact.<br>Low level of data and information to support policy development. |

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| Cell manufacturing | Established policy framework under the Batteries Directive outlining requirements for cell component manufacturing in the EU. Limited environmental requirements compared to wider industry.<br>Established policy framework to support R&D.<br>PEF CR for Rechargeable Batteries for Mobile Applications. | Opportunity to establish regulated standards to facilitate transparency in the value chain.<br>Established R&D policies and funding instruments to facilitate new and emerging techniques.<br>The PEF CR provide a voluntary framework for conducting a battery LCA in a standardised way. | As a net importer of cell components, EU EV manufacturers have limited control over manufacturing processes to mitigate environmental impact.<br>Low level of data and information to support policy development. |
| Battery pack manufacturing | Established policy framework under the Batteries Directive outlining requirements for cell component manufacturing in the EU. Limited environmental requirements compared to wider industry.<br>Established policy framework to support R&D.<br>PEF CR for Rechargeable Batteries for Mobile Applications. | Opportunity to establish regulated standards to facilitate transparency in the value chain.<br>Established R&D policies and funding instruments to facilitate new and emerging techniques.<br>The PEF CR provide a voluntary framework for conducting a battery LCA in a standardised way. | As a net importer of cell components, EU EV manufacturers have limited control over manufacturing processes to mitigate environmental impact.<br>Low level of data and information to support policy development. |

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| EV manufacturing | Established policy framework under several legislative instruments, tied together under mobility strategy.<br>Established policy framework to support R&D. | Opportunity to facilitate growth in circular economy business models through regulatory frameworks (to address issues relating to transparency, coherence with wider policy initiatives and between related stakeholders, etc.).<br>Opportunity to facilitate growth in wider EV manufacturing through regulatory frameworks.<br>Established R&D policies and funding instruments to facilitate new and emerging techniques in re-use. | Breaking into emerging V2G market requires governance intervention (issues concerning data privacy and market regulation for energy going into the grid).<br>Under the Waste Directive, different end-of-waste criteria are adopted by Member States creating uncertainties for EV OEMs when managing end-of-life for certain substances. |
| Re-use | Emerging industry owing to the extent of available traction batteries for re-use. EU policy framework needed to support growth.<br>Established policy framework to support R&D. | Opportunity to define re-use concepts for the EV battery.<br>Established R&D policies and funding instruments to facilitate new and emerging techniques in re-use. | Lack of standards and definitions.<br>Lack of targets.<br>Legal uncertainties (quality of traction batteries reaching first-end-of-life, collection, transport, storage and processing of used batteries).<br>Current framework results in batteries at end of first life being classed as waste, increasing transport costs significantly.<br>Risk of negative externalities where re-use fails to transfer producer responsibilities.<br>Risk of high regulatory burden in the EU distorting competition with third countries in their favour. E.g. administrative burden associated with REACH and the shipment of waste Directive. |

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| Re-purposing | Emerging industry owing to the extent of available traction batteries for re-purposing. EU policy framework needed to support growth.<br><br>Established policy framework to support R&D. | Opportunity to define re-purpose concepts for the EV battery.<br><br>Established R&D policies and funding instruments to facilitate new and emerging techniques in re-use. | Lack of standards and definitions.<br><br>Lack of targets.<br><br>Lack of cross-sectoral policy to facilitate collaboration.<br><br>Legal uncertainties (quality of traction batteries reaching first-end-of-life, collection, transport, storage and processing of used batteries).<br><br>Current framework results in batteries at end of first life being classed as waste, increasing transport costs significantly.<br><br>Risk of negative externalities where re-purposing fails to transfer producer responsibilities.<br><br>Risk of high regulatory burden in the EU distorting competition with third countries in their favour. E.g. administrative burden associated with REACH and the shipment of waste Directive. |

| EV battery value chain | Summary of EU state of play | Strengths and opportunities | Weaknesses and threats |
|---|---|---|---|
| Recycling | Established policy framework to facilitate the recycling of end-of-life traction batteries.<br>Established policy framework to support R&D.<br>PEF CR for Rechargeable Batteries for Mobile Applications. | Regulatory framework setting recycling obligations and targets. Opportunity to strengthen the existing framework by defining reuse and recycling concepts for the EV battery.<br>Established framework for environmental permitting of recycling operations under the IED.<br>Opportunity to streamline processes across the value chain with respect to meeting policy requirements (e.g. REACH).Established R&D policies and funding instruments to facilitate new and emerging techniques in recycling.<br>The PEF CR provide a voluntary framework for conducting a battery LCA in a standardised way. | Lack of standards and definitions.<br>Risk of recycling targets not being coherent with need to reduce dependency on raw material imports.<br>Risk of negative externalities where re-use and re-purposing fail to transfer producer responsibilities related to recycling requirements.<br>Timeframes are not reflected in current Batteries Directive (there will be a delay in recycling needs).<br>Legal uncertainties (collection, transport, storage and processing of used batteries).<br>Low level of data and information to support policy development.<br>Waste disposal policies and shipment of waste can lead to transferal of waste to third countries where waste management policies may be inadequate with negative implications for environment and health. |

# 8 Policies to support circular lifecycles to maximise EU opportunities (Subtask 2.7)

*What public policies could be envisaged to ensure truly circular lifecycles for traction batteries, and to harness the opportunities for growth and jobs in the EU?*

**Key outputs:**

- Short list of policy alternatives and their assessment

## 8.1 Challenges facing the development of a sustainable EV battery value chain in the EU

The analysis undertaken in Chapters 6 and 7 identifies in more detailed terms the challenges facing the development of a sustainable EV battery value chain in the EU. For each of the issues listed below, additional detail is provided in Table 8.1 with respect to an initial list of policy alternatives proposed to address the respective challenges:

1. Limited access to raw materials in the EU, including examples of raw materials not included in the CRM list despite their economic importance to the EV battery value chain and supply risk associated with current imports. (Challenge 1 in Table 8.1).
2. Out of date standards and definitions in current policies resulting in gaps and overlaps. Coherence needed with existing standards and definitions used across different policies, where relevant. Opportunity for simplification through streamlining. (Challenges 2, 3 and 7 in Table 8.1).
3. Lack of targets for EV battery re-use and re-purposing. (Challenges 4, 5 and 6 in Table 8.1).
4. Administrative burden associated with multi-stakeholder involvement with potential to reduce through enhanced communication and streamlined processes. This challenge is also related to the lack of definitions and standards, particularly in the case of regulatory requirements relating to end-of-life management where clarification concerning re-use and re-purposing could simplify current legal requirements. (Challenge 7 in Table 8.1).
5. Multi-stakeholder involvement (within the value chain, across sectors and between countries) with no incentive to factor in re-use, re-purposing or recycling needs in earlier phases of the EV battery value chain where cost and performance are the main drivers affecting manufacturing processes. (Challenge 8 in Table 8.1).
6. Multi-stakeholder involvement (within the value chain, across sectors and between countries) often leads to a lack of traceability and risk of environmental impact leakage owing to the EU being a net importer of raw materials and battery cell components, as well as net exporter of non-recyclable battery waste. (Challenge 9 in Table 8.1).
7. Extended value chain to include re-use and re-purposing can have implications for battery ownership and liability. This leads to a risk of negative externalities later in the value chain where there is failure to transfer producer responsibilities as well as legal uncertainties (collection, transport, storage and processing of used batteries). (Challenge 10 in Table 8.1).
8. Planned growth across the value chain is dependent on securing significant capital investments for infrastructures, skilled labour and technical expertise. Segregated components within the value chain, restricting flexibility within industry to respond to changing consumer demands. (See Challenges 11, 12 and 13 in Table 8.1).
9. Lack of up-to-date and comparable information on EV battery lifecycle analysis, hindering understanding on this / how this is evolving, and which options might lead to more optimal outcomes. (See challenge 14 in Table 8.1).
10. Information on battery state-of-health / status and use history is not readily available, nor in a consistent format, both during the lifetime of the battery and at the end-of-life. Better / more transparent data is needed to help track battery performance, and to enable more efficient

assessment of battery pack / module / cell status at the end of first life, so that reuse and repurposing can be optimised with lower assessment costs. (See challenge 15 in Table 8.1).

11. Evidence of emerging circular economy business models requiring policy intervention to support functioning markets. Coherence needed with existing interrelated policies. Low consumer awareness and understanding of emerging markets. Low level of data and information available to support development of emerging markets. (See challenges 16 and 17 in Table 8.1).
12. Need for ongoing support for R&D. (See challenge 18 in Table 8.1).

## 8.2 Feedback on EU policy from stakeholders

As part of the consultation undertaken for this study, stakeholders were invited to identify policy alternatives. An overview of the discussion is set out below with options grouped according to the classification used by the European Commission Better Regulation guidelines (Tool #18) (European Commission, 2017).

The alternatives outlined below have been incorporated within the list of initial policy alternatives, to create a comprehensive overview of possibilities with the intention of establishing a shortlist for further discussion. During the consultation process it was highlighted that the need to prioritise actions is considered as important as the need for policy intervention and this is reflected in the assessment undertaken to shortlist policy alternatives.

Stakeholders also stressed that policy intervention must offer sufficient flexibility to encourage innovation and ensure that the EU is able to respond in a timely and efficient manner to the fast-evolving EV battery landscape. Nonetheless, the need for hard legally binding rules was confirmed by all interviewed, together with the need for softer regulation, education and information measures and economic instruments.

**Hard legally binding rules**

Particularly in the light of emerging re-use and re-purposing markets, stakeholders recognised the need for policy intervention to establish definitions, objectives, and targets that relate to the complete value chain.

For definitions, it was suggested that the following are needed specific to the EV battery: waste, re-use, re-purposing, end-of-life and end-of-waste. It was also suggested that a definition is needed for extended producer responsibilities with respect to the complete value chain and in the light of the extended value chain. One stakeholder suggested that there should be a second life operator defined under the Waste Directive. The need for selection criteria for reuse and re-purposing was also raised.

Several aspects relating to targets were discussed by stakeholders, in sum:

- In the context of establishing a circular economy to manage end-of-life options, introduce re-use and re-purposing targets under the Batteries Directive;
- Recycling targets should be revised to reflect the fact that cost is the main driver. E.g. a specific target under the Batteries Directive for rechargeable batteries may be appropriate, or setting targets according to material (rather than by weight). However, the extent to which this is feasible is uncertain owing to the constantly changing nature of the EV battery.
- Opportunity to align re-purposed EV battery targets with those established for renewable energy;
- Targets should be realistic according to existing footprints and capabilities as well as provide sufficient flexibility to cater for changes in the future.

In addition, it was proposed that policy intervention is needed to establish logistical requirements for the re-use and re-purposing of EV batteries (including collection, transportation and storage). Furthermore, this would regulate health and safety risks associated with the collection, transportation and storage of EV batteries.

Another policy alternative proposed is the inclusion of re-use and re-purposing information within the producer registration process to facilitate the monitoring and reporting against targets, as well as supporting logistical needs.

Stakeholders generally did not specify the most appropriate legal instrument to implement the above proposals. This would ensure that implementation is mandatory and uniform across all Member States.

With respect to the regulation on shipment of wastes, provisions were also proposed to facilitate the transnational transportation of EV battery waste. One alternative includes establishing a fast-track system so that EV battery waste is not subject to the same requirements established for hazardous waste under the regulation on shipment of wastes. Another suggestion establishes an agreement between Member States to facilitate free transnational movement to transport EV batteries for re-use, re-purposing, recycling and waste, without the notification requirements and exempting handlers from other provisions under the shipment of wastes regulation.

**Soft regulation**

Taking a more soft and flexible approach, the following suggestions were made by stakeholders:

- Criteria for achieving a circular economy for the EV battery was identified as a useful tool for guiding the sustainable development of the value chain.
- EU certification scheme for recyclers to comply with ISO standards to facilitate a fair playing field with recycling operators in third countries.
- Network to support local dismantling of EV batteries that is coordinated with recycling installations in order to reduce the weight of hazardous weight being transported for treatment.
- Lifecycle approach across the complete value chain with a standardised lifecycle assessment methodology.

**Education and information**

Stakeholders highlighted that ongoing R&D support is needed to improve battery performance; horizon scanning to identify emerging research priorities; and support for testing and trialling emerging techniques through pilot and demonstration studies.

Other proposals include the development of the following initiatives:

- Guidelines to inform operators in the EV battery value chain about identifying re-use and re-purposing opportunities and optimising the potential of these markets.
- An information inventory to track EV battery history (use and performance).
- A forum to facilitate discussion between government, industry and civil society. Note that this option has not been developed further owing to inherent overlaps with the European Association for Advanced Rechargeable Batteries which serves this function.

**Economic instruments**

Stakeholders flagged the need for financial incentives to attract investors although no specific examples were discussed in the interviews.

## 8.3 Initial identification of policy alternatives

The following policy alternatives are designed to address the above challenges and intended to support a broader enabling and consistent regulatory framework for the EV battery value chain (in accordance with the need set out in the European Commission's Strategic Action Plan on Batteries (COM(2018) 293 final, 2018)).

**Table 8.1: Matrix showing initial identification of policy alternatives according to challenges described**

| Ref | Challenge | Challenge description | Primary stakeholders affected | Policy alternatives | | | |
|---|---|---|---|---|---|---|---|
| 1 | Limited access to raw materials in the EU, including examples of raw materials not included in the CRM list despite their economic importance to the EV battery value chain and supply risk associated with current imports | Currently, only cobalt and natural graphite are included in the CRM list, despite improved access needed for other raw materials including lithium, nickel and manganese. | Cell component manufacturing (with knock-on effects for whole value chain) | Update CRM list to include lithium and other raw materials [CRM] | Establish **mandatory** recycling target based on material and weight [RecM] | Establish **voluntary** recycling target based on material and weight [RecV] | |
| 2 | No definition or standards for re-use or re-purposing in the Batteries Directive (i.e. legal uncertainty concerning re-use and re-purposing activities in the EU) | Current definitions in the Batteries Directive do not distinguish between re-use or repurposing and end-of-life; thus, re-used and re-purposed EV batteries are thus subject to regulatory requirements pertaining to waste management. There is no definition or criteria to establish when re-use or re-purposing is appropriate or to maintain quality standards for such batteries on the market. There are no standards to ensure that collection, treatment and storage are carried out to an adequate level, meeting basic health and safety needs. There is no definition concerning extended producer responsibility and re-used EV batteries. | Re-use; Re-purposing (addressing the problem may result in burden to EV manufacturer) | Set out clear and comprehensive list of definitions for components within the EV battery value chain [Prod3] | Define minimum quality standards for used batteries (and suitability for re-use, re-purposing and recycling) and for treated batteries and/ or the raw materials extracted [Prod4] | Define requirements for collection systems [Coll] | Define battery ownership and liability across the value chain to reflect emerging opportunities for re-use, re-purposing and recycled raw materials [Own] |
| 3 | End-of-waste criteria for EVs and their components vary between Member States | Member States have established different end-of-life criteria for vehicles, affecting EVs and their traction batteries. This creates challenges for the transnational movement of EV battery waste where a vehicle needs to be transported to a recycling installation. Further, it can lead to market distortion where one Member State defines re-use, re-purposing and recycling options in relation to the traction battery. | EV manufacturer | Adopt end-of-waste criteria at EU level [EoW] | | | |
| 4 | No targets for re-use in the Batteries Directive (i.e. re-use is not explicitly targeted by policy instruments) | Cost is the main driver affecting industry choices for end-of-life EV battery management. Without targets in place, the main incentives are cost-driven and consumer demand - both of which cannot be guaranteed owing to the fast-evolving nature of the market. | Re-use (addressing the problem may result in burden to EV manufacturer) | Adopt **voluntary** re-use targets [ReuV] | Adopt **mandatory** re-use targets [ReuM] | | |
| 5 | No targets for re-purposing in the Batteries Directive (Re-purposing not explicitly targeted by policy instruments) | Cost is the main driver affecting industry choices for end-of-life EV battery management. Without targets in place, the main incentives are cost-driven and consumer demand - both of which cannot be guaranteed owing to the fast-evolving nature of the market. | Re-purposing (addressing the problem may result in burden to EV manufacturer) | Adopt **voluntary** re-purposing targets [RepV] | Adopt **mandatory** re-purposing targets [RepM] | | |
| 6 | Targets for recycling do not facilitate extraction of raw materials as needed | Cost is the main driver affecting industry choices for end-of-life EV battery management. Without targets in place, the main incentives are cost-driven and consumer | Cell component manufacturing (addressing the problem | Establish **voluntary** recycling target based on material and weight | Establish **mandatory** recycling target based on material and weight | | |

| Ref | Challenge | Challenge description | Primary stakeholders affected | Policy alternatives | | | |
|---|---|---|---|---|---|---|---|
| | by the industry | demand - e.g. current market demand and cost of recycling favours the extraction of raw materials that do not marry up with industry wider needs. | may result in burden to EV manufacturers and recyclers) | [RecV] | [RecM] | | |
| 7 | Costly to transport EV battery waste | Recycling facilities are located in a handful of Member States and it is costly to transport EV battery waste (many regulatory requirements associated with transnational transportation of hazardous waste) | EV manufacturer | Adopt end-of-waste criteria at EU level [EoW] | Define requirements for collection systems [Coll] | Establish fast-track system for EV manufacturers transporting EV battery waste within the EU [Trans1] | Establish system of no boundary restrictions for EV manufacturers transporting EV battery waste [Trans2] |
| 8 | No incentive to factor in re-use, re-purposing or recycling needs in earlier phases of the EV battery value chain | There is a disconnect between the various components of the value chain. Cost is the main driver affecting manufacturing practices and there is a lower emphasis on accounting for what implications arise further down the value chain from manufacturing decisions. Current reporting requirements on manufacturers are vague (for reasons of confidentiality); however, without exact knowledge of battery chemistries or battery design, it is challenging to collect and treat EV batteries for re-use, re-purposing or recycling. There is also a risk of unnecessary administrative burden to meet regulatory requirements associated with end-of-life management and re-entry to the market. There is also an opportunity to cater for emerging circular economy business models, e.g. battery swapping schemes that would benefit from more standardised battery designs to facilitate mass charging. | Re-use; Re-purposing; Recycling (addressing the problem may result in burden to the whole value chain) | Regulate the integration of environmental aspects into product design to improve environmental performance throughout the product life cycle under the Eco-design Directive [Prod1] | Regulate design for disassembly of products so that the battery can be easily removed for later stages in the value chain [Prod5] | Ensure that during the vehicle design, parts and materials are considered for re-use, recycling and recovery [Prod2] | Regulate the integration of environmental aspects into product design to improve environmental performance throughout the product life cycle under the Batteries Directive [Prod7] |
| 9 | Lack of traceability across the manufacturing processes | There is a disconnect between the various components of the value chain. There is no reporting mechanism to facilitate insights in the whole lifecycle impacts. Risk of environmental leakage owing to the EU being a net importer of raw materials and battery cell components, as well as net exporter of non-recyclable battery waste. | Whole value chain | Establish **mandatory** certification scheme requiring the use of international standards for manufacturing to facilitate traceability across borders and ensure minimum standards in emerging markets [Mfg1] | Extend requirements for environmental permitting and compliance with best available techniques to whole value of the EV battery manufacturing rather than just recycling [Mfg2] | Establish ID numbers for battery components to facilitate traceability (e.g. also with link to the vehicle identification number - VIN) [Mfg3] | |
| 10 | Conflict between manufacturers relating to producer responsibilities as a result of extending the value chain | The extended EV battery value chain to include re-use and re-purposing options can lead to new market opportunities; however, there is no mechanism to extend producer responsibility along with the new market opportunity. Issues relating to EV battery ownership and liability may act as a disincentive to the EV manufacturers and prevent them from engaging in the new markets. Without adequate definitions to support the emerging markets there is a risk of negative externalities occurring, where EV batteries have a thirty-year product life in various forms at the end of which it is unclear where responsibility for end-of-life management falls. | EV manufacturer; Re-use; Re-purposing; Recycling | Define battery ownership and liability across the value chain to reflect emerging opportunities for re-use, re-purposing and recycled raw materials [Own] | | | |
| 11 | Low flexibility in industry to respond to changing technologies and consumer demands | The disconnect between the various components of the value chain makes it difficult to establish changes where several actors within the value chain must cooperate. The fast evolving technological and chemical landscape of the EV battery requires considerable flexibility to adopt | Whole value chain | Increase flexibility in industry to respond to changing technologies and consumer demands | | | |

| Ref | Challenge | Challenge description | Primary stakeholders affected | Policy alternatives | | | |
|---|---|---|---|---|---|---|---|
| | | new techniques and chemistries as and when they are available to allow competition with third countries and meet consumer demands for high performing batteries. | | [Ind1] | | | |
| 12 | Capital investment needed to meet infrastructure needs | To strengthen capacity in cell component manufacturing and establish an industrial presence in cell manufacturing, as well as expand recycling capacities, considerable capital is required. In addition to allocating public funding, provisions are needed to create an attractive environment to investors (including economic, political and legal stability; access to land, natural resources, raw materials and human resources; and a clear regulatory framework to enhance and not impede competition and growth). National provisions can also be used to attract investors, e.g. tax credits, land permitting, infrastructure, etc.). The time lag between market needs and investment needs is also a problem - particularly for the recycling industry where increased capacity is not an immediate priority and yet investments are needed to ensure infrastructures are established in good time to meet forthcoming market demand. | Whole value chain | Establish EU funding strategy [Ind5] | Strengthen capacity in cell component manufacturing and establish an industrial presence in cell manufacturing, as well as expand recycling capacities [Ind3] | | |
| 13 | Larger skilled workforce and technical expertise needed | There are insufficient human resources to support planned growth across the value chain. Training needed to develop a larger skilled workforce and technical expertise. | Whole value chain | Foster the development of a skilled workforce and technical expertise [Ind3] | | | |
| 14 | Information needs relating to the environmental footprint of the EV battery value chain | Lack of information/ low access to/ inconsistent reporting on environmental impacts across the EV battery value chain. | EV manufacturer; Consumers (as a result of extended value chain) (improved evidence base would also benefit policy makers) | Establish a monitoring and reporting framework to facilitate voluntary evidence gathering on lifecycle environmental footprint [LCAV] | Establish legal reporting requirements on lifecycle environmental footprint [LCAM] | | |
| 15 | Information needs relating to battery performance | Lack of information/ low access to/ inconsistent reporting on battery state-of-health, status and use history. | Re-use; Re-purposing; Consumers (as a result of extended value chain) (improved evidence base would also benefit policy makers and provide assurances to the consumer as to the quality of the battery) | Establish a monitoring and reporting framework to facilitate *voluntary* evidence gathering on battery performance [PerfV] | Establish legal reporting requirements on battery performance [PerfM] | Introduce minimum requirement on the Battery Management System (BMS) to facilitate access to key battery data (helping to determine SoH) [Prod6] | |
| 16 | Lack of policy to regulate emerging circular economy business models, namely V2G | The emergence of the V2G circular economy business model requires policy intervention to facilitate a fair, transparent and competitive market. V2G is an example relevant to the current market although there may be more as the EV battery industry matures; thus, there is an ongoing need to review and identify emerging business models requiring policy intervention. | EV manufacturer; Consumers (as a result of extended value chain) | Incorporate within EU wide value chain wide strategy [Ind4] | Foster emerging circular economy business models, namely V2G [V2GV] | Regulate emerging circular economy business models, namely V2G [V2GM] | |
| 17 | Circular economy business models are emerging at local level with little coordination at national or EU level | Circular economy business models to extend product life through intensified EV battery use are emerging locally (e.g. battery leasing, battery swapping, vehicle swapping). This bottom-up approach allows local demands to be met but could be strengthened through | EV manufacturer; Emerging businesses (as a result of extended value chain) | Establish EU platform for sharing best practices and lessons learned from local initiatives [BP] | Incorporate within EU wide value chain wide strategy [Ind4] | Foster emerging circular economy business models, namely V2G [V2GV] | Regulate emerging circular economy business models, namely V2G [V2GM] |

| Ref | Challenge | Challenge description | Primary stakeholders affected | Policy alternatives | | | |
|---|---|---|---|---|---|---|---|
| | | the sharing of best practices and lessons learned and enhanced networks between stakeholders. There is also a need to establish demand for such business models where there is low awareness among consumers and little drive to break into such emerging markets. | | | | | |
| 18 | Need for ongoing support for R&D and horizon scanning to identify new research priorities | The research agenda for EV batteries is determined in accordance with EU budget planning under Horizon 2020. Adequate funding is set aside to ensure collaboration between scientists, industry and policy makers. Need to ensure that ongoing horizon scanning is undertaken to identify emerging research priorities and that the research agenda allows sufficient flexibility to meet these priorities. Need to ensure ongoing support to trial emerging techniques and support pilot projects. | Whole value chain | Support for ongoing R&I projects (R&D to improve battery performance – both chemistries and battery cell/module/pack management) [R&D1] | Horizon scanning to identify new R&I needs and ensure that new areas are incorporated within budget planning [R&D2] | Establish suitable networks to facilitate the testing of emerging practices through demonstration projects [Demo] | |

A complete list of the policy alternatives identified in the problem matrix is set out in the table below. The policy alternatives are grouped by instrument type and relevant existing policies have been identified. The brief description code can be used to identify each of the policy alternatives listed.

**Table 2: Initial list of policy alternatives**

| Brief desc. | Subtype | Policy alternative | Relevant existing policies | |
|---|---|---|---|---|
| | | | Primary | Secondary / overlap |
| ***Policy / regulatory*** | | | | |
| RecM | Mandatory | Establish **mandatory** recycling target based on material and weight | Batteries Directive (2006/66/EC) | ELV Directive (2000/53/EC)<br>Waste Directive (Directive (EU) 2018/851)) |
| RecV | Voluntary | Establish **voluntary** recycling target based on material and weight | Batteries Directive (2006/66/EC) | ELV Directive (2000/53/EC)<br>Waste Directive (Directive (EU) 2018/851)) |
| Coll | Mandatory | Define requirements for collection systems | Batteries Directive (2006/66/EC) | ELV Directive (2000/53/EC)<br>Waste Directive (Directive (EU) 2018/851))<br>Regulation on Shipment of Wastes (Regulation (EU) No 660/2014) |
| ReuM | Mandatory | Adopt **mandatory** re-use targets | Batteries Directive (2006/66/EC) | ELV Directive (2000/53/EC)<br>Waste Directive (Directive (EU) 2018/851)) |
| ReuV | Voluntary | Adopt **voluntary** re-use targets | Batteries Directive (2006/66/EC) | ELV Directive (2000/53/EC)<br>Waste Directive (Directive (EU) 2018/851)) |
| RepM | Mandatory | Adopt **mandatory** re-purposing targets | Batteries Directive (2006/66/EC) | ELV Directive (2000/53/EC)<br>Waste Directive (Directive (EU) 2018/851))<br>EU renewable energy targets |
| RepV | Voluntary | Adopt **voluntary** re-purposing targets | Batteries Directive (2006/66/EC) | ELV Directive (2000/53/EC)<br>Waste Directive (Directive (EU) 2018/851))<br>EU renewable energy targets |
| Trans1 | Mandatory | Establish fast-track system for EV manufacturers transporting EV battery waste within the EU | Waste Directive (Directive (EU) 2018/851)) Regulation on Shipment of Wastes (Regulation (EU) No 660/2014) | Batteries Directive (2006/66/EC) |
| Trans2 | Mandatory | Establish system of no boundary restrictions for EV manufacturers transporting EV battery waste | Waste Directive (Directive (EU) 2018/851)) Regulation on Shipment of Wastes (Regulation (EU) No 660/2014) | Batteries Directive (2006/66/EC) |
| Prod1 | Mandatory | Regulate the integration of environmental aspects into product design to improve environmental performance throughout the product life cycle. | Eco-design Directive (2009/125/EC) | Batteries Directive (2006/66/EC) |

| Brief desc. | Subtype | Policy alternative | Relevant existing policies | |
|---|---|---|---|---|
| | | | Primary | Secondary / overlap |
| Prod2 | Mandatory | Ensure that during the vehicle design, parts and materials are considered for re-use, recycling and recovery. | Type-approval of motor vehicles with regard to their reusability, recyclability and recoverability Directive (2005/64/EC) | |
| Prod3 | Mandatory | Set out a clear and comprehensive list of definitions for components within the EV battery value chain | Batteries Directive (2006/66/EC) | Waste Directive (Directive (EU) 2018/851)) |
| Prod4 | Mandatory | Define minimum quality standards for used batteries (and suitability for re-use, re-purposing and recycling) and for treated batteries and/ or the raw materials extracted | Batteries Directive (2006/66/EC)<br>Eco-design Directive (2009/125/EC) | ELV Directive (2000/53/EC)<br>Waste Directive (Directive (EU) 2018/851))<br>Electricity Directive ( (COM(2016)864)) |
| EoW | Mandatory | Adopt end-of-waste criteria at EU level | Waste Directive (Directive (EU) 2018/851) | Batteries Directive (2006/66/EC)<br>ELV Directive (2000/53/EC)<br>Regulation on Shipment of Wastes (Regulation (EU) No 660/2014) |
| Prod5 | Mandatory | Regulate design for disassembly of products so that the battery can be easily removed for later stages in the value chain. | WEEE Directive (2012/19/EU) | Eco-design Directive (2009/125/EC) |
| Prod6 | Mandatory | Introduce minimum requirement on the Battery Management System (BMS) to facilitate access to key battery data (helping to determine SoH) | Eco-design Directive (2009/125/EC)<br>Batteries Directive (2006/66/EC) | |
| Prod7 | Mandatory | Regulate the integration of environmental aspects into product design to improve environmental performance throughout the product life cycle under the Batteries Directive | Batteries Directive (2006/66/EC) | |
| Mfg1 | Mandatory | Establish **mandatory** certification scheme requiring the use of international standards for manufacturing to facilitate traceability across borders and ensure minimum standards in emerging markets. | | |
| Mfg2 | Mandatory | Extend requirements for environmental permitting and compliance with best available techniques to whole value of the EV battery manufacturing rather than just recycling. | IED (Directive 2010/75/EU) | |
| [Mfg3] | Mandatory | Establish ID numbers for battery components to facilitate traceability (e.g. also with link to the vehicle identification number - VIN) | | |

| Brief desc. | Subtype | Policy alternative | Relevant existing policies | |
|---|---|---|---|---|
| | | | Primary | Secondary / overlap |
| PerfM | Mandatory | Establish legal reporting requirements on battery performance. | Batteries Directive (2006/66/EC)<br>Eco-design Directive (2009/125/EC) | CEN-CENELEC standards |
| LCAV | Voluntary | Establish a monitoring and reporting framework to facilitate *voluntary* evidence gathering on lifecycle environmental footprint. | CO2 Regulation (EC443/2009) | |
| LCAM | Mandatory | Establish legal reporting requirements on lifecycle environmental footprint. | CO2 Regulation (EC443/2009)<br>Batteries Directive (2006/66/EC)<br>Eco-design Directive (2009/125/EC) | CEN-CENELEC standards |
| V2GV | Voluntary | Foster emerging circular economy business models, namely V2G | EBA - SAPB | Electricity Directive ( (COM(2016)864) |
| V2GM | Mandatory | Regulate emerging circular economy business models, namely V2G | Electricity Directive ( (COM(2016)864) | |
| Own | Mandatory | Define battery ownership and liability across the value chain to reflect emerging opportunities for re-use, re-purposing and recycled raw materials | Batteries Directive (2006/66/EC)<br>ELV Directive (2000/53/EC) | Waste Directive (Directive (EU) 2018/851))<br>Electricity Directive (COM(2016)864) |
| ***Policy / orientation*** | | | | |
| CRM | Voluntary | Include lithium and other raw materials needed for cell component manufacturing as critical raw materials to facilitate access through improved monitoring and reporting and a strategic approach to trade negotiations. | CRM list | |
| Ind1 | Voluntary | Increase flexibility in industry to respond to changing technologies and consumer demands | EBA - SAPB | |
| Ind2 | Voluntary | Strengthen capacity in cell component manufacturing and establish an industrial presence in cell manufacturing, as well as expand recycling capacities | EBA - SAPB | |
| Ind3 | Voluntary | Foster the development of a skilled workforce and technical expertise | EBA - SAPB | |
| Ind4 | Voluntary | Incorporate within EU wide value chain wide strategy | | |
| Ind5 | Voluntary | Establish EU funding strategy | | |
| BP | Voluntary | Establish EU platform for sharing best practices and lessons learned from local initiatives. | Smart Specialisation Platform / interregional partnership | EBA – SAPB |

| Brief desc. | Subtype | Policy alternative | Relevant existing policies | |
|---|---|---|---|---|
| | | | Primary | Secondary / overlap |
| ***Policy / standardisation*** | | | | |
| PerfV | Voluntary | Establish a monitoring and reporting framework to facilitate *voluntary* evidence gathering on battery performance. | CEN-CENELEC standards | |
| ***Policy / funding*** | | | | |
| R&D1 | | Support for ongoing R&I projects (R&D to improve battery performance – both chemistries and battery cell/module/pack management). | H2020 / Horizon Europe | |
| R&D2 | | Horizon scanning to identify new R&I needs and ensure that new areas are incorporated within budget planning. | H2020 / Horizon Europe | |
| ***Demonstration projects*** | | | | |
| Demo | | Establish suitable networks to facilitate the testing of emerging practices through demonstration projects. | | |

## 8.4 Development of a short list of policy alternatives

In the following section, screening criteria is applied to the initial list of policy alternatives developed in Section 8.3 to determine a short list. Each policy alternative is presented according to the challenge it is designed to address, a high-level outline is provided to establish the resources required to implement the option and its expected outcomes. Further detail is included for the shortlisted policy alternatives in Section 8.4.18 [45].

The screening criteria are based on the guidance set out in the European Commission Better Regulation Guidelines (Tool #17), as follows:

- Coherence: The extent to which the policy alternative addresses gaps and overlaps in relation to political, legal and technical issues.
- Effectiveness & efficiency: The extent to which the policy alternative is expected to address the challenge. The resources required to implement the policy alternative compared with the challenge it is intended to address.
- EU added value: Whether the challenge can be better resolved at a local, regional or national level.

A RAG (Red, Amber, Green) rating is used to indicate relative importance (whereby red denotes low negative impact, amber denotes neutral impact and green denotes positive impact). Policy alternatives with a red rating against any of the screening criteria are excluded from further assessment.

### 8.4.1 Challenge 1: Limited access to raw materials

The alternatives proposed are not mutually exclusive and could be used together to improve EU access to the raw materials required for EV battery manufacturing.

[45] Note: The policy alternatives are not restricted by a defined timeframe and it is acknowledged the market is developing and therefore some actions are more immediate than others.

Based on the assessment below, the use of targets to strengthen the use of raw materials extracted through recycling is shortlisted. The use of the CRM list is not efficient given the fast-changing nature of the market.

The alternative would need to be developed in such a way that ensures coherence with relevant policies, as specified in the previously.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Update CRM list to include lithium and other raw materials [CRM] | Coherent with wider approach taken for sourcing raw materials. | The CRM list is updated every three years and the last update was in 2017; question of efficiency to review and update list outside its standard review cycle. EV battery chemistries are fast evolving and there is a risk that raw material requirements will change faster than the update cycle of the CRM list (making the list redundant and resulting in new gaps). In addition, simply updating the list is viewed by stakeholders as unlikely to result in significant impacts. | Standardised approach at EU level is needed for consistency and to facilitate transparency, comparability and a strategic approach to trade negotiations. |
| Establish **mandatory** recycling target based on material and weight [RecM] | Risk of incoherence with wider recycling targets which are done by weight, regardless of material. | Would support more targeted extraction of raw materials in line with wider industry needs but risk of targets becoming outdated as battery chemistries and manufacturing techniques evolve. | EU targets would facilitate scale of recycling needed to have meaningful impact on industry. Provides consistency (fair competition) and facilitates comparability (for reporting). |

The alternative to review recycling targets is shortlisted for further assessment.

### 8.4.2 Challenge 2: No definition or standards for re-use or re-purposing in the Batteries Directive

The four policy alternatives below are not mutually exclusive and could be used together to address the lack of definitions and standards for re-use and re-purposing. The review finds that each alternative is feasible according to the assessment criteria with no clear preferred alternative. Furthermore, the alternatives are found to help address other challenges – these synergies are highlighted in subsequent sections.

The policy alternatives are defined with respect to the Batteries Directive, as a legally binding instrument to ensure a mandatory and uniform implementation across Member States.

The alternatives would need to be developed in such a way that ensures coherence with relevant policies, as specified in the previously.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Set out clear and comprehensive list of definitions for components within the EV battery value chain [Prod3] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Would address policy gap and fits within the current policy cycle of the Batteries Directive. By distinguishing between end-of-life and re-use and re-purposing, subsequent regulatory requirements applying to waste management would not necessarily apply (thus simplifying processes). | EU definitions would provide consistency (fair competition) and facilitate clear framework for industry growth. |
| Define minimum quality standards for used batteries (and suitability for re-use, re-purposing and recycling) and for treated batteries and/ or the raw materials extracted [Prod4] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Would address policy gap and fits within the current policy cycle of the Batteries Directive. Would help EV manufacturers identify best option for processing EV batteries according to the quality of the battery. | EU standards would provide consistency (fair competition) and facilitate clear framework for industry growth. |
| Define requirements for collection systems [Coll] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Would address policy gap and fits within the current policy cycle of the Batteries Directive. Would improve understanding among industry of collection system needs and facilitate coherent approach across the EU. Could reduce administrative burden and cost to EV manufacturer e.g. by outlining requirements to dismantle EV battery waste before collection. By distinguishing between end-of-life and re-use and re-purposing, subsequent regulatory requirements applying to waste management would not necessarily apply (thus simplifying processes). | EU requirements would provide consistency (fair competition) and facilitate clear framework for industry growth. |
| Define battery ownership and liability across the value chain to reflect emerging opportunities for re-use, re-purposing and recycled raw materials [Own] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Would address policy gap and fits within the current policy cycle of the Batteries Directive. By recognising the potential value associated with re-use, re-purposing and recycling, this option would provide a framework for emerging markets to grow. | EU definitions would provide consistency (fair competition) and facilitate clear framework for industry growth. |

As each option addresses different aspects relating to the emerging re-use and re-purposing markets, it is considered appropriate to shortlist all four policy alternatives and that they can be grouped as a package of policy alternatives in the more detailed assessment.

### 8.4.3 Challenge 3: End-of-waste criteria for EVs and their components varies between Member States

The review finds that while the option is feasible according to the assessment criteria, the extent of efficiency could be improved if aligned with previous policy alternatives to set out definitions and standards for emerging markets within the EV battery value chain. Although the option would be developed in such a way that ensures coherence with relevant policies (as specified previously), there is a risk of unfair burden on Member States where changes may have greater impact on respective developed end-of-waste criteria. Thus, the option is not shortlisted.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Adopt end-of-waste criteria at EU level [EoW] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. Risk of unfair burden on Member States where changes may have greater impact on respective developed end-of-waste criteria. | Would address problem but the extent to which it is the most efficient option is unclear in the light of previous options to include of definitions, standards and criteria relating to re-use and re-purposing under the Batteries Directive. | EU criteria would provide consistency (fair competition) and facilitate clear framework for industry growth. |

Policy alternative is not carried forward to the shortlist, rather it is envisaged that the challenge will be more efficiently addressed through the development of definitions and standards as outlined with respect to Challenge 2.

### 8.4.4 Challenge 4: No targets for re-use in the Batteries Directive

The policy alternatives below are alternatives, with one softer approach setting voluntary targets and the other taking a hard approach with legally binding targets. To ensure the most effective outcome, the use of mandatory targets is considered most appropriate. The options would be developed in such a way that ensures coherence with relevant policies (as specified in the previously).

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Adopt voluntary re-use targets [ReuV] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Would address policy gap. Voluntary targets are unlikely to be adopted at an adequate scale to have a meaningful impact. | Risk of unfair playing field and inconsistencies between Member States |
| Adopt mandatory re-use targets [ReuM] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Would address policy gap. Mandatory targets will ensure adopted at an adequate scale to have a meaningful impact. | EU targets would facilitate scale of re-use needed to have meaningful impact on industry. Provides consistency (fair competition) and facilitates comparability (for reporting). |

The use of mandatory targets is shortlisted.

### 8.4.5 Challenge 5: No targets for re-purposing in the Batteries Directive

The two alternatives consider a soft approach setting voluntary targets versus a hard approach with legally binding targets. To ensure the most effective outcome, the use of mandatory targets is considered most appropriate.

The alternatives would be developed in such a way that ensures coherence with relevant policies (as specified in the previously).

The alternative to coordinate targets with those set for renewable energy was also considered in order to. strengthen coherence with clean energy policies; however, the burden of reporting was not deemed proportionate and goes beyond the remit of the EV battery value chain.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Adopt voluntary re-purpose targets [RepV] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Would address policy gap. Voluntary targets are unlikely to be adopted at an adequate scale to have a meaningful impact. | Risk of unfair playing field and inconsistencies between Member States |
| Adopt mandatory re-purpose targets [RepM] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Would address policy gap. Mandatory targets will ensure adopted at an adequate scale to have a meaningful impact. | EU targets would facilitate scale of re-purposing needed to have meaningful impact on industry. Provides consistency (fair competition) and facilitates comparability (for reporting). |

The use of mandatory targets under the Batteries Directive is shortlisted.

### 8.4.6 Challenge 6: Targets for recycling do not facilitate extraction of raw materials as needed by the industry

To ensure the most effective outcome, the use of mandatory targets is considered most appropriate. However, while the use of targets to strengthen the use of raw materials extracted through recycling would be effective, the fact that such targets would not have flexibility to adapt to changes in the value chain present a challenge.

The alternatives would be developed in such a way that ensures coherence with relevant policies (as specified in the previously).

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Establish voluntary recycling target based on material and weight [RecV] | Incoherent with wider recycling targets. | Would address policy gap but risk of targets becoming outdated as battery chemistries and manufacturing techniques evolve. Voluntary targets are unlikely to be adopted at an adequate scale to have a meaningful impact. | Risk of unfair playing field and inconsistencies between Member States |

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Establish mandatory recycling target based on material and weight [RecM] | Risk of incoherence with wider recycling targets. | Would address policy gap but risk of targets becoming outdated as battery chemistries and manufacturing techniques evolve. Mandatory targets will ensure adopted at an adequate scale to have a meaningful impact. | EU targets would facilitate scale of recycling needed to have meaningful impact on industry. Provides consistency (fair competition) and facilitates comparability (for reporting). |

The use of a mandatory recycling target based on material and weight is shortlisted. It is envisaged that improved alignment between the extraction of raw materials from EV battery waste and industry would also contribute to improved access to critical raw materials (as outlined with respect to Challenge 1).

### 8.4.7 Challenge 7: Costly to transport EV battery waste

The four alternatives discussed would need to be developed in such a way that ensures coherence with relevant policies, as specified in the previously.

The review finds that defining standards for an EV battery waste collection system is the preferred option according to the assessment criteria. The policy alternatives are defined with respect to the Batteries Directive, as a legally binding instrument to ensure a mandatory and uniform implementation across Member States. Furthermore, it serves the added purpose of addressing Challenge 2.

The other alternatives have not been shortlisted owing to the risk of environmental deregulation (for those relating to the shipment of waste are not favoured in this assessment) and a risk of unfair burden on Member States where changes may have greater impact on respective developed end-of-waste criteria (for the option relating to the end-of-waste criteria).

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Adopt end-of-waste criteria at EU level [EoW] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. Risk of unfair burden on Member States where changes may have greater impact on respective developed end-of-waste criteria. | Would address problem but the extent to which it is the most efficient option is unclear in the light of previous options to include of definitions, standards and criteria relating to re-use and re-purposing under the Batteries Directive. | EU criteria would provide consistency (fair competition) and facilitate clear framework for industry growth. |
| Define requirements for collection systems [Coll] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Would address policy gap and fits within the current policy cycle of the Batteries Directive. Would improve understanding among industry of collection system needs and facilitate coherent approach across the EU. Could reduce administrative burden and cost to EV manufacturer e.g. by outlining requirements to dismantle EV battery waste | EU requirements would provide consistency (fair competition) and facilitate clear framework for industry growth. |

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| | | before collection. By distinguishing between end-of-life and re-use and re-purposing, subsequent regulatory requirements applying to waste management would not necessarily apply (thus simplifying processes). | |
| Establish fast-track system for EV manufacturers transporting EV battery waste within the EU [Trans1] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. Risk of deregulating environmental protection. | To be effective the system would require proof from the responsible producer that the EV battery is being transported for re-use, re-purposing or recycling. Such a system would reduce administrative burden for involved stakeholders. However, high risk of unintended adverse effects (on environment and human health) from deregulated transportation of hazardous waste. | Policy alternative would require coordination across Member States to be effective. |
| Establish system of no boundary restrictions for EV manufacturers transporting EV battery waste [Trans2] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. Risk of deregulating environmental protection. | High risk of unintended adverse effects (on environment and human health) from deregulated transportation of hazardous waste. | Policy alternative would require coordination across Member States to be effective. |

The policy alternative to define requirements for a collection system is shortlisted.

### 8.4.8 Challenge 8: No incentive to factor in re-use, re-purposing or recycling needs in earlier phases of the EV battery value chain

At a high level, the review finds that the integration of the EV battery under the WEEE Directive may create confusion owing to existing exemptions under the Directive for batteries. The Batteries Directive is considered to offer insufficient flexibility to foster innovation in the long-run.

Both the use of the Eco-design Directive and the type-approval of motor vehicles with regards to their reusability, recyclability and recoverability Directive are considered appropriate options for regulating re-use, re-purposing and recycling needs in the design and manufacturing phases of the EV battery. With no clear preferred alternative, both are shortlisted for further assessment.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Regulate the integration of environmental aspects into product design to improve environmental performance throughout the product life cycle under the Batteries | Coherent with the intention of the Batteries Directive | It would provide a clear framework for minimising the environmental footprint of the EV battery and for ensuring a degree of accountability across the various components of the value chain. However, adopting such aspects under the | EU requirements would provide consistency (fair competition) and facilitate clear |

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Directive [Prod7] | | Batteries Directive would require sufficient flexibility to avoid restricting innovation in the sector. | framework for industry growth. |
| Regulate the integration of environmental aspects into product design to improve environmental performance throughout the product life cycle under the Eco-design Directive [Prod1] | Coherent with the intention of the Eco-design Directive and with the wider approach adopted at EU level for overseeing the placing of the market of widely used products in the EU. | Integration under the Eco-design Directive would not require changes to the body of the legislation as the Directive is implemented through product-specific regulations. It would provide a clear framework for minimising the environmental footprint of the EV battery and for ensuring a degree of accountability across the various components of the value chain. Such a framework would be understandable to producers as much as consumers. | EU requirements would provide consistency (fair competition) and facilitate clear framework for industry growth. |
| Regulate design for disassembly of products so that the battery can be easily removed for later stages in the value chain [Prod5] | Coherent with the intention of the WEEE Directive and with the wider approach adopted at EU level for overseeing battery design. | The WEEE Directive regulates substance use in electrical and electronic equipment which do not relate to batteries and therefore using the Directive to only regulate aspects of the EV battery value chain will be confusing to operators and not efficient. | EU requirements would provide consistency (fair competition) and facilitate clear framework for industry growth. |
| Ensure that during the vehicle design, parts and materials are considered for re-use, recycling and recovery [Prod2] | Coherent with the intention of the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability Directive and with the wider approach adopted at EU level for overseeing vehicle design. | Integration under the type-approval of motor vehicles with regard to their reusability, recyclability and recoverability Directive would require changes to the body of the legislation. It would provide a clear framework for minimising the environmental footprint of the EV battery and for ensuring a degree of accountability across the various components of the value chain. It would ensure all relevant design aspects related to the vehicle are covered under one piece of legislation. | EU requirements would provide consistency (fair competition) and facilitate clear framework for industry growth. |

The policy alternatives to integrate EV batteries under the Eco-design and the type-approval of motor vehicles Directives are shortlisted.

### 8.4.9 Challenge 9: Lack of traceability across the manufacturing processes

Establishing a mandatory certification scheme for industry operators (across the value chain) to comply with international standards would help achieve consistency with operators outside the EU and improve transparency across the value chain. Such an alternative would need to be developed in such a way that ensures coherence with relevant policies, as specified in the previously.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Establish mandatory certification scheme requiring the use of international standards for manufacturing to facilitate traceability across borders [Mfg1] | Facilitates consistent and comparable standards across the value chain (including with third countries). | Risk of reduced competition with third countries where less stringent requirements apply. | Standardised approach at a global level is needed for consistency and to facilitate transparency and comparability. Ensures fair playing field across the value chain and between Member States. |
| Extend requirements for environmental permitting and compliance with best available techniques to whole value of the EV battery manufacturing rather than just recycling. | Ensures coherence between policies. Risk of unfair playing field for EU operators compared to global operators where environmental regulations are more stringent. | Strengthens environmental regulation of EV manufacturing. Risk of adverse effect on attracting foreign investment where environmental regulations are too cumbersome. | EU approach would facilitate consistency between Member States. |
| Establish ID numbers for battery components to facilitate traceability (also with a link to the VIN) [Mfg3] | Facilitates consistent and comparable standards across the value chain (including with third countries). | Extent of efficiency depends on uptake. | Standardised approach at a global level is needed for consistency and to facilitate transparency and comparability. Ensures fair playing field across the value chain and between Member States. |

The policy alternative to establish a mandatory certification scheme is shortlisted.

### 8.4.10 Challenge 10: Conflict between manufacturers relating to producer responsibilities as a result of extending the value chain

The review finds that the alternative proposed is appropriate to shortlist according to the assessment criteria. The policy alternatives are defined with respect to the Batteries Directive, as a legally binding instrument to ensure a mandatory and uniform implementation across Member States. Furthermore, it serves the added purpose of addressing Challenge 2.

The alternatives would need to be developed in such a way that ensures coherence with relevant policies, as specified in the previously.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Define battery ownership and liability across the value chain to reflect emerging opportunities for re-use, re-purposing and recycled raw materials [Own] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Would address policy gap and fits within the current policy cycle of the Batteries Directive. By recognising the potential value associated with re-use, re-purposing and recycling, this option would provide a | EU definitions would provide consistency (fair competition) and facilitate clear framework for industry growth. |

| | | | |
|---|---|---|---|
| | | framework for emerging markets to grow. | |

### 8.4.11 Challenge 11: Low flexibility in industry to respond to changing technologies and consumer demands

The policy alternative presented below is shown to have no added value as existing efforts to address this problem are already underway. The alternative therefore is not shortlisted.

Furthermore, it is considered that the development of definitions and standards as outlined with respect to Challenge 2 will contribute to addressing this problem by helping to create a clear policy framework for industry to grow in.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Increase flexibility in industry to respond to changing technologies and consumer demands [Ind1] | Overlap with existing battery strategy under the remit of working towards a circular economy in the EU. | No added value to existing strategy | No added value to existing strategy |

### 8.4.12 Challenge 12: Capital investment needed to meet infrastructure needs

The policy alternatives presented below are not mutually exclusive although there are overlaps between them. They are shown to have no added value as existing efforts to address this problem are already underway. The alternatives therefore are not shortlisted.

Furthermore, it is considered that the development of definitions and standards as outlined with respect to Challenge 2 will contribute to addressing this problem by helping to create a clear policy framework for industry to grow in.

Recent examples in the EU of secured investment to meet infrastructure needs can be referred to as good practice, where national and local authorities have combined efforts with EU funds to attract investors (section 6.1.2). This approach is not included here as it does not fall under EU competency.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Establish EU funding strategy [Ind5] | Overlap with existing funding strategies for EU budget programmes | Identifying investment needs is needed to attract investment and secure skilled labour. No added value to existing battery strategy. | Need for national action as well as EU. No added value to existing battery strategy. |
| Strengthen capacity in cell component manufacturing and establish an industrial presence in cell manufacturing, as well as expand recycling capacities [Ind3] | Overlap with existing battery strategy under the remit of working towards a circular economy in the EU. | No added value to existing battery strategy. | No added value to existing battery strategy. |

### 8.4.13 Challenge 13: Larger skilled workforce and technical expertise needed

The policy alternative presented below is shown to have no added value as existing efforts to address this problem are already underway. The option therefore is not shortlisted.

Furthermore, it is considered that the development of definitions and standards as outlined with respect to Challenge 2 will contribute to addressing this problem by helping to create a clear policy framework for industry to grow in.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Foster the development of a skilled workforce and technical expertise [Ind3] | Overlap with existing battery strategy under the remit of working towards a circular economy in the EU. | No added value to existing battery strategy. | No added value to existing battery strategy. |

### 8.4.14 Challenge 14: Information needs relating to the environmental footprint of the EV battery value chain

The policy alternatives below are alternatives, with one softer approach setting voluntary monitoring and reporting with a defined framework and the other taking a hard approach with legally binding reporting requirements. To ensure the most effective outcome, the use of mandatory reporting is considered most appropriate.

*Note*: In terms of the policy infrastructure in place to support an integrated value chain, in the EU, Product Environmental Footprint Category Rules have been developed for e-mobility (including traction batteries used by e-bikes, EV, PHEV, cars, bus/trucks) (RECHARGE, 2018). These rules provide a framework for conducting a lifecycle assessment.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Establish a monitoring and reporting framework to facilitate voluntary evidence gathering on lifecycle environmental footprint [LCAV] | Provides evidence base to better understand relevance of developing a sustainable EV battery value chain. | Would address the challenge identified but resource intensive to gather and report information. No guarantee that the framework would be used by stakeholders, limiting its value. | EU dataset has greater relevance to supporting an EU market. Facilitates consistent and comparable reporting across Member States. |
| Establish legal reporting requirements on lifecycle environmental footprint [LCAM] | Provides evidence base to better understand relevance of developing a sustainable EV battery value chain. | Would address the challenge identified and legal mandate would ensure a certain quality in reporting is achieved despite resources needed to gather and report information. | EU dataset has greater relevance to supporting an EU market. Facilitates consistent and comparable reporting across Member States. |

The alternative to establish legal reporting requirements is shortlisted.

### 8.4.15 Challenge 15: Information needs relating to battery performance

The policy alternatives include one softer approach setting voluntary monitoring and reporting with a defined framework and the other two taking a hard approach with legally binding reporting requirements. To ensure the most effective outcome, the use of a legal requirement is considered most appropriate, and in particular, the alternative to introduce a minimum requirement on the Battery Management System (BMS) to facilitate access to key battery data - although there are several risks noted that would need to be mitigated.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Establish a monitoring and reporting framework to facilitate voluntary evidence gathering on battery performance [PerfV] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Low efficiency if there is a low uptake. | Limited EU added value as voluntary nature of the alternative cannot guarantee EU wide uptake. |
| Establish legal reporting requirements on battery performance [PerfM] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Low efficiency if reported data cannot be readily accessed by industry. | Consistency in reporting to establish EU wide database that can be used across Member States. |
| Introduce minimum requirement on the Battery Management System (BMS) to facilitate access to key battery data (helping to determine SoH) [Prod6] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. Ensure no conflict with data protection rights | Establish evidence base for industry to access and use which will facilitate growth in reuse and re-purposing. Risk of reporting system becoming outdated with technology changes. | Consistency in reporting to establish EU wide database that can be used across Member States. Risk of low-quality reporting if system is not managed harmoniously. |

### 8.4.16 Challenge 16: Lack of policy to regulate emerging circular economy business models, namely V2G

An EU-wide value chain wide strategy would help to identify emerging circular economy business opportunities and form a plan of action to optimise their potential. While there is a need for this, the assessment finds no added value to existing efforts that are already underway to address this problem.

With specific regard to the emerging V2G market (as reviewed in section 6.2.5), the significance of the barriers foreseen indicate the need for the European Commission to support growth of the market; however, the development of regulation to support the market is considered premature.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Incorporate within EU wide value chain wide strategy [Ind4] | Overlap with existing battery strategy under the remit of working towards a circular economy in the EU. | Separate policy area requiring specific and additional policy analysis. | Risk of unfair playing field and inconsistencies between Member States |
| Foster emerging circular economy business models, namely V2G [V2GV] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Separate policy area requiring specific and additional policy analysis. | Facilitate fair playing field between Member States |
| Regulate emerging circular economy business models, namely V2G [V2GM] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Risk of hindering growth. Markets are not sufficiently mature for regulation. | Facilitate fair playing field between Member States |

### 8.4.17 Challenge 17: Circular economy business models are emerging at local level with little coordination at national or EU level

The policy alternatives presented below are shown to have no added value as existing efforts to address this problem are already underway and emerging markets are not sufficiently mature for regulatory intervention. The alternatives therefore are not shortlisted.

Furthermore, it is considered that the development of definitions and standards as outlined with respect to Challenge 2 will contribute to addressing this problem by helping to create a clear policy framework for industry to grow in.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Establish EU platform for sharing best practices and lessons learned from local initiatives [BP] | Provides a reference point for best practices. Ensure consistent with related policy objectives. Overlap with EU battery alliance. | Extent of effectiveness is dependent on outreach and uptake. Resource intensive to gather and report. Risk of inefficiency where efforts are duplicated with the EU battery alliance. | EU platform avoids multiple initiatives at national level and reduces the risk of information loss between Member States. |
| Incorporate within EU wide value chain wide strategy [Ind4] | Overlap with existing battery strategy under the remit of working towards a circular economy in the EU. | No added value to existing battery strategy. | Bottom-up approach is better suited to the organic growth of emerging circular economy business opportunities (often directly linked to consumer demand which cannot be scaled up to EU level). |
| Foster emerging circular economy business models, namely V2G [V2GV] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Separate policy area requiring specific and additional policy analysis. | Facilitate fair playing field between Member States |
| Regulate emerging circular economy business models, namely V2G [V2GM] | Policy alternative would need to be mindful of overlaps with other policy areas to ensure consistency. | Risk of hindering growth. Markets are not sufficiently mature for regulation. | Facilitate fair playing field between Member States |

### 8.4.18 Challenge 18: Need for ongoing support for R&D and horizon scanning to identify new research priorities

The policy alternatives presented below are shown to have no added value as existing efforts to address this problem are already underway. The options therefore are not shortlisted.

Furthermore, it is considered that the development of definitions and standards as outlined with respect to Challenge 2 will contribute to addressing this problem by helping to create a clear policy framework for industry to grow in.

| Policy alternative | Coherence | Efficiency & Effectiveness | EU added value |
|---|---|---|---|
| Support for ongoing R&I projects (R&D to improve battery performance – both chemistries and battery cell/module/pack management) [R&D1] | Coherence with Horizon 2020 already achieved; risk of overlap. | Ongoing changes to R&I landscape, impossible to plan for changes beyond flexibility already provided by Horizon 2020. | Horizon 2020 is the best vehicle for R&I planning. |
| Horizon scanning to identify new R&I needs and ensure that new areas are incorporated within budget planning [R&D2] | | | |
| Establish suitable networks to facilitate the testing of emerging practices through demonstration projects [Demo] | | | |

## 8.5 Assessment of shortlisted policy alternatives

The review of the initial policy alternatives resulted in the following shortlist:

1. Update and streamline existing standards and definitions (group of four policy alternatives) [Prod3] [Prod4] [Coll] [Own]
2. Establish mandatory recycling targets based on material and weight under the Batteries Directive [RecM]
3. Establish mandatory re-use and re-purposing targets under the Batteries Directive [ReuM] [RepM]
4. Establish new regulatory requirements to facilitate re-use, re-purposing and recycling (with two alternative approaches proposed) [Prod1] [Prod2]
5. Establish mandatory certification scheme requiring the use of international standards for manufacturing to facilitate traceability across borders [Mfg1]
6. Introduce minimum requirement on the Battery Management System (BMS) to facilitate access to key battery data (helping to determine SoH) [Prod6]

All those included in the shortlist can be defined as legally binding action. While it is recognised that policy intervention must offer sufficient flexibility to encourage sector growth, the need for hard legally binding rules in many cases (as confirmed by the stakeholders interviewed), is confirmed by the analysis undertaken in this report. However, feedback from the project workshop suggested that a softer approach might be preferred by some stakeholders as an alternative in certain cases.

Further assessment has been conducted for each of the policy alternatives shortlisted to determine the economic, social and environmental impacts in accordance with the criteria determined in the European Commission Better Regulation guidelines (Tool #17) (European Commission, 2017).

The high-level qualitative analysis to gauge their feasibility and to better understand the pros (+) and cons (-) of the shortlisted policy alternatives is set out in the following tables. The analysis undertaken is qualitative owing to restrictions in available data and time constraints of the project. In the light of ongoing developments to the EV battery value chain, and in line with the terms of reference for this study, the policy alternatives focus on the current and near-future developments.

| **Policy alternative 1: Update and streamline existing standards and definitions [Prod3] [Prod4] [Coll] [Own]** | |
|---|---|
| **Challenge definition** | **Challenge 2: No definition or standards for re-use or re-purposing in the Batteries Directive**<br>**Challenge 3: End-of-waste criteria for EVs and their components varies between Member States**<br>**Challenge 7: Costly to transport EV battery waste**<br>**Challenge 10: Conflict between manufacturers relating to producer responsibilities**<br>**Challenge 11: Low flexibility in industry to respond to changing technologies and consumer demands**<br>**Challenge 12: Capital investment needed to meet infrastructure needs**<br>**Challenge 13: Larger skilled workforce and technical expertise needed**<br>**Challenge 17: Circular economy business models are emerging at local level with little or no coordination at national or EU level** |
| **Economic** | - Additional requirements to economic operators, potential additional cost.<br>+ Clearly defined market is more likely to facilitate industry growth.<br>+ Clearly defined market is more likely to attract foreign investment.<br>+ Enhanced trade agreements with raw material export countries. |
| **Social** | + Expected industry growth will have positive implications for job growth. |
| **Environment** | + Positive environment for emerging circular economy business models and therefore likely to reduce environmental footprint and risk of negative externalities.<br>+ Opportunity to enhance coherence with other policies where the EV battery value chain is contributing to wider environmental policy objectives. |

| **Policy alternative 2: Establish mandatory recycling targets based on material and weight under the Batteries Directive [RecM]** | |
|---|---|
| **Challenge definition** | **Challenge 1: Raw materials missing from the CRM list**<br>**Challenge 6: Targets for recycling do not facilitate the extraction of raw materials as needed by the industry** |
| **Economic** | - New targets will require updates to the existing reporting and monitoring framework and new indicators, metrics and guidance to report progress against newly defined targets. Cost to EU institutions and economic operators.<br>- Cost of compliance to recycling industry.<br>+ Clearly defined targets will enhance industry access to raw materials. |
| **Social** | + Clearly defined targets and accessible progress reporting can strengthen EU role in supporting public participation in environmental decision making. |
| **Environment** | + Positive environment for emerging circular economy business models and therefore likely to reduce environmental footprint and risk of negative externalities<br>+ Clearly defined targets will enhance progress reporting to inform later policy evaluations.<br>+ Clearly defined targets will enhance progress reporting and facilitate access to funds.<br>+ Opportunity to enhance coherence with other policies where the EV battery value chain is contributing to wider environmental policy objectives. |

| Policy alternative 3: Establish mandatory re-use and re-purposing targets under the Batteries Directive [ReuM] [RepM] | |
|---|---|
| **Challenge definition** | **Challenge 4: No targets for re-use in the Batteries Directive**<br>**Challenge 5: No targets for re-purposing in the Batteries Directive**<br>**Challenge 8: No incentive to factor in re-use, re-purposing or recycling needs in earlier phases of the EV battery value chain** |
| **Economic** | - New targets will require updates to the existing reporting and monitoring framework and new indicators, metrics and guidance to report progress against newly defined targets. Cost to EU institutions and economic operators. |
| **Social** | + Clearly defined targets and accessible progress reporting can strengthen EU role in supporting public participation in environmental decision making. |
| **Environment** | + Positive environment for emerging circular economy business models and therefore likely to reduce environmental footprint and risk of negative externalities<br>+ Clearly defined targets will enhance progress reporting to inform later policy evaluations.<br>+ Clearly defined targets will enhance progress reporting and facilitate access to funds.<br>+ Opportunity to enhance coherence with other policies where the EV battery value chain is contributing to wider environmental policy objectives. |

| Policy alternative 4: Establish new regulatory requirements to facilitate re-use, re-purposing and recycling [Prod1] [Prod2] | |
|---|---|
| **Challenge definition** | **Challenge 8: No incentive to factor in re-use, re-purposing or recycling in earlier phases of the EV battery value chain**<br>**Challenge 9: Lack of traceability across the manufacturing processes** |
| **Economic** | - Additional requirements to economic operators, potential additional cost.<br>+ Clearly defined market is more likely to facilitate industry growth.<br>+ Clearly defined market is more likely to attract foreign investment. |
| **Social** | + Expected industry growth will have positive implications for job growth. |
| **Environment** | + Positive environment for emerging circular economy business models and therefore likely to reduce environmental footprint and risk of negative externalities.<br>+ Opportunity to enhance coherence with other policies where the EV battery value chain is contributing to wider environmental policy objectives. |

| Policy alternative 5: Establish mandatory certification scheme requiring the use of international standards for manufacturing to facilitate traceability across borders [Mfg1] | |
|---|---|
| **Challenge definition** | **Challenge 9: Lack of traceability across the manufacturing processes** |
| **Economic** | - Compliance with international standards will require monitoring and enforcement and additional administrative requirements to both EU institutions and economic operators.<br>+ Contribute to a fair playing field with third countries. |
| **Social** | *None identified.* |
| **Environment** | + Positive environment for emerging circular economy business models and therefore likely to reduce environmental footprint and risk of negative externalities |

| Policy alternative 6: Introduce minimum requirement on the Battery Management System (BMS) to facilitate access to key battery data (helping to determine SoH) [Prod6] | |
|---|---|
| **Challenge definition** | **Challenge 14: Information needs relating to the environmental footprint of the EV battery**<br>**Challenge 15: Information needs relating to battery performance** |
| **Economic** | - High cost to develop monitoring and reporting framework (e.g. indicator development, reporting metrics, guidance, etc.)<br>+ Evidence base to support industry growth (identify trends and establish capacity needs etc.)<br>+ Evidence base to strengthen standard of quality of EV batteries treated for re-use and re-purposing<br>+ Evidence base to inform research initiatives to strengthen R&I<br>+ Evidence base to develop robust policy response to facilitate market growth |
| **Social** | + Industry growth will have positive implications for job growth<br>+ Identifying and understanding trends will help to determine job needs<br>+ Potential job creation (to conduct and gather reporting)<br>+ Clearly defined and accessible information source can strengthen EU role in supporting public participation in environmental decision making. |
| **Environment** | + Positive environment for emerging circular economy business models and therefore likely to reduce environmental footprint and risk of negative externalities |

Combined, the shortlist of policy alternatives is found to cover most of the problems identified, either directly or indirectly. Two gaps are observed with respect to the need for policy to regulate emerging circular economy business models such as the V2G market (Problem 16) and the need for ongoing support for R&D (Problem 18). With respect to the V2G market it is considered that the European Commission undertakes an impact assessment to establish the extent of regulatory intervention required. For R&D support, it is recommended that Horizon 2020 is the most appropriate policy mechanism to review and guide ongoing R&D support.

## 8.6 Final summary and conclusions for policy alternatives

Based on the opportunities to optimise resource yields and reduced environmental impacts in the EV battery value chain, and the current policy landscape of the respective value chain components, a portfolio of policy alternatives to address the key challenges identified was assessed and discussed with expert stakeholders.

The outcome of this analysis set out priorities for current and near-future policy needs which include the following four areas (each covering detailed potential actions):

- Addressing legal uncertainties in existing standards and definitions:
  - the current regulatory landscape may either not be sufficient to cover a well-functioning market, or on the other hand may present overlaps or inconsistencies. Clarifying uncertainties (e.g. on product responsibility, waste definitions, etc.) is expected to facilitate the development of a robust market.
- Improving transparency across the different value chain components through extended regulation:
  - this could facilitate access to information throughout the supply chain to allow market actors to make more informed choice, e.g. on material sourcing or product performance.
- Establishing new and updating existing targets:
  - with respect to existing recycling targets and the option to establish new reuse and repurposing, where appropriate. This is expected to foster a more resource-efficient use of materials.

- Establishing a monitoring and reporting framework to facilitate evidence gathering:
    - this could help set a level playing field to better understand environmental impacts throughout the lifecycle of batteries.

The qualitative analysis undertaken for each of these policy options illustrates that there are associated regulatory costs as well as additional costs arising for economic operators to comply with changes to regulation (without further assessment it is not possible to ascertain the full extent of the associated costs).

However, the overall range of expected benefits outweighs the identified costs for the policy alternatives shortlisted; these positive impacts include industrial growth, job creation and enhanced environmental protection.

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# Appendices

# A1 Appendix 1: EU Fleet Scenario Analysis Assumptions

## A1.1 Simplified battery LCA assumptions

The tables below provide a summary of some of the key assumptions relating to the quantification of battery lifecycle impacts explored in the fleet impact scenario modelling:

- Battery composition and energy density
- Electricity and gas use and electricity source shares
- Electricity GHG intensity and decarbonisation trajectories for battery production (EU/Other) and end of life processing (EU)
- Material decarbonisation trajectories
- Energy consumption for battery manufacturing and end-of-life treatment

### A1.1.1 Battery composition and energy density

**Table A1: Assumptions on average battery energy density, Wh/kg**

| Component | Field | 2015 | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| Pack | Default | 153 | 202 | 288 | 392 | 590 | 628 |
| Cell | Default | 196 | 259 | 370 | 503 | 756 | 804 |
| Pack | Low | 153 | 183 | 245 | 318 | 478 | 508 |
| Cell | Low | 196 | 235 | 314 | 408 | 612 | 651 |

*Source*: Ricardo fleet impacts modelling analysis; *Notes*: Based on the mix of battery types provide in Figure 5.2, and additional assumptions on the potential for future improvement in battery energy density.

**Table A2: Assumptions on average battery material composition, % by mass of the total battery pack)**

| Component | Material | 2015 | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| **Pack** | **Total** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** | **100.0%** |
| **Periphery** | **Total** | **22.0%** | **22.0%** | **22.1%** | **22.0%** | **21.9%** | **21.9%** |
| Periphery | Steel | 1.5% | 1.5% | 1.5% | 1.5% | 1.4% | 1.4% |
| Periphery | Iron | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Periphery | Aluminium | 16.7% | 16.7% | 16.7% | 16.7% | 16.6% | 16.6% |
| Periphery | Plastics | 1.2% | 1.2% | 1.2% | 1.2% | 1.2% | 1.2% |
| Periphery | Electronics | 1.3% | 1.3% | 1.3% | 1.3% | 1.3% | 1.3% |
| Periphery | Copper | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% | 0.0% |
| Periphery | Coolant | 1.0% | 1.0% | 1.0% | 1.0% | 1.0% | 1.0% |
| Periphery | Thermal insulation | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% | 0.4% |
| **Cell** | **Total** | **78.0%** | **78.0%** | **77.9%** | **78.0%** | **78.1%** | **78.1%** |
| ***Cathode*** | ***Active Material*** | ***28.5%*** | ***28.3%*** | ***30.3%*** | ***32.4%*** | ***40.5%*** | ***40.5%*** |
| Cathode | Nickel | 3.5% | 5.4% | 9.1% | 12.8% | 18.0% | 18.0% |
| Cathode | Cobalt | 3.2% | 3.1% | 2.8% | 2.2% | 0.0% | 0.0% |
| Cathode | Lithium | 1.9% | 1.9% | 2.0% | 2.0% | 1.5% | 1.5% |
| Cathode | Sodium | 0.0% | 0.0% | 0.2% | 0.4% | 2.3% | 2.3% |

| Component | Material | 2015 | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| Cathode | Manganese | 6.1% | 4.9% | 3.5% | 2.6% | 3.7% | 3.7% |
| Cathode | Titanium | 0.0% | 0.0% | 0.4% | 1.1% | 3.4% | 3.4% |
| Cathode | Aluminium | 1.3% | 1.5% | 1.5% | 1.6% | 1.9% | 1.9% |
| Cathode | Phosphorus | 0.7% | 0.5% | 0.2% | 0.0% | 0.0% | 0.0% |
| Cathode | Iron | 1.3% | 0.9% | 0.4% | 0.0% | 0.0% | 0.0% |
| Cathode | Aluminium | 2.9% | 2.9% | 2.6% | 2.2% | 1.0% | 1.0% |
| Cathode | Other | 10.5% | 10.3% | 10.3% | 10.6% | 12.4% | 12.4% |
| Anode | Aluminium | 0.0% | 0.0% | 0.1% | 0.2% | 1.1% | 1.1% |
| Anode | Lithium | 0.0% | 0.0% | 1.0% | 2.1% | 5.8% | 5.8% |
| Anode | Copper | 11.4% | 11.4% | 11.3% | 11.4% | 9.6% | 9.6% |
| Anode | Graphite | 17.4% | 17.8% | 16.0% | 13.9% | 6.0% | 6.0% |
| Binder | Binder | 2.4% | 2.4% | 2.5% | 2.6% | 2.8% | 2.8% |
| Electrolyte | Electrolyte: LiPF6 | 2.0% | 1.9% | 1.6% | 1.3% | 0.0% | 0.0% |
| Electrolyte | Electrolyte: LiPON | 0.0% | 0.0% | 0.3% | 0.6% | 1.6% | 1.6% |
| Electrolyte | Electrolyte: NaPF6 | 0.0% | 0.0% | 0.1% | 0.1% | 0.9% | 0.9% |
| Electrolyte | Electrolyte: Ethylene Carbonate | 11.5% | 11.2% | 9.8% | 8.2% | 4.0% | 4.0% |
| Separator | Plastics | 2.0% | 2.0% | 2.0% | 2.0% | 2.0% | 2.0% |

*Source*: Ricardo fleet impacts modelling analysis; *Notes*: Based on the mix of battery types provide in Figure 5.2.

### A1.1.2 Other assumptions for the battery LCA calculations for the fleet scenario analysis

**Table A3: Assumptions on energy consumption and other non-material impacts from the battery life cycle**

| Impact /Credit | Type | Life cycle Stage | Sub-Stage | Unit | Value |
|---|---|---|---|---|---|
| Impact | Electricity | Production | Cell | MJ/kg battery | 80.6 |
| Impact | Electricity | Production | Other | MJ/kg battery | 0.001 |
| Impact | Gas | Production | Total | MJ/kg battery | - |
| Impact | Energy | Production | Total | $kgCO_2e/kg$ | 80.601 |
| Impact | Total | Reuse | Total | % of Production | 5% |
| Impact | Total | Repurposing | Total | % of Production | 10% |
| Credit | Total | Repurposing | Total | % of new battery lifecycle | -35% |
| Impact | Electricity | Recycling | Total | MJ/kg battery | 0.690 |
| Impact | Gas | Recycling | Total | MJ/kg battery | 8.550 |
| Impact | Energy | Recycling | Total | MJ/kg battery | 9.240 |

*Source*: Ricardo fleet impacts modelling analysis; *Notes*: Electrical energy consumption is based on an average of (Ford/LG Chem, 2016) and (RECHARGE, 2018); energy consumption for recycling is based on (RECHARGE, 2018). Assumptions for impacts for reuse and repurposing are based on the literature review and discussions with stakeholders. The credit for repurposing of new batteries is based on an energy storage lifetime for repurposed batteries of 50% of a new battery, and a 70% remaining state-of-charge for repurposed battery packs (i.e. to account for fewer available kWh from repurposed batteries vs the new batteries in the original EV).

**Table A4: Assumptions on the GHG intensity of electricity supply (including upstream/WTT emissions), $kgCO_2e/kWh$**

| Region | Value Chain Scenario | 2015 | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| Europe | Base case | 0.102 | 0.090 | 0.084 | 0.070 | 0.049 | 0.027 |
| Other | Base case | 0.139 | 0.132 | 0.125 | 0.119 | 0.107 | 0.097 |

*Source*: Ricardo fleet impacts modelling analysis; *Notes*: 'Other' includes an average of current GHG intensities of electricity for US, S. Korea and Japan based on their current market share of EV battery manufacturing; projection is based upon an assumed 30% reduction between 2015 and 2050. Data for Europe is taken from SULTAN.

**Table A5: Assumptions on decarbonisation trajectories for material production, as % of 2010 value**

| Sensitivity | Material | 2010 | 2015 | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|---|
| Default | Steel | 100% | 90% | 81% | 71% | 61% | 42% | 23% |
| Default | Aluminium | 100% | 89% | 79% | 68% | 58% | 37% | 16% |
| Default | Plastics | 100% | 84% | 67% | 52% | 38% | 33% | 28% |
| Default | Composites | 100% | 87% | 73% | 55% | 37% | 23% | 15% |
| Default | Other | 100% | 96% | 93% | 89% | 85% | 78% | 70% |
| High | Steel | 100% | 95% | 90% | 85% | 80% | 70% | 59% |
| High | Aluminium | 100% | 93% | 86% | 80% | 73% | 59% | 46% |
| High | Plastics | 100% | 92% | 84% | 76% | 69% | 66% | 64% |
| High | Composites | 100% | 90% | 80% | 63% | 46% | 37% | 43% |
| High | Other | 100% | 96% | 93% | 89% | 85% | 78% | 70% |

*Source*: Ricardo fleet impacts modelling analysis, based on previous analysis from (Ricardo-AEA, 2013);

*Notes*: Decarbonisation/emissions trajectory for 'Other' is used for the production impacts of all other materials.

## A1.2 Battery circular economy scenario assumptions

The tables below provide a summary of some of the key assumptions relating to the two circular economy scenarios explored in the fleet impact modelling:

- Base case (BC)
- Sustainable value chain (SVC)

### A1.2.1 Location of battery manufacturing

**Table A6: Assumptions on the share of European battery manufacturing – used to define the average carbon intensity if electricity used**

| Stage | Value Chain Scenario | 2015 | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|
| Cell | Base case | 0% | 0% | 10% | 25% | 40% | 40% |
| Other | Base case | 20% | 20% | 20% | 25% | 40% | 40% |
| Cell | Sustainable value chain | 0% | 10% | 25% | 50% | 80% | 80% |
| Other | Sustainable value chain | 20% | 20% | 25% | 50% | 80% | 80% |

*Source*: Ricardo fleet impacts modelling analysis; *Notes*: 'Other' includes all stages following cell manufacturing, i.e. includes battery module/pack production/assembly, etc.

### A1.2.2 Recycling rates and recycled content

**Table A7: Assumptions on recycling rates and recycled content**

| Material | Recycled Content | Recycling Recovery Rate: Base Case | | | Recycling Recovery Rate: Sustainable Value Chain | | |
|---|---|---|---|---|---|---|---|
| | All Years | 2015 | 2025 | 2030+ | 2015 | 2025 | 2030+ |
| Steel | 26% | 58% | 58% | 58% | 58% | 59% | 60% |
| Iron | 39% | 0% | 0% | 0% | 0% | 0% | 0% |
| Aluminium | 11% | 80% | 98% | 98% | 80% | 98% | 98% |
| Plastics | 0% | 10% | 10% | 10% | 10% | 10% | 10% |
| Electronics | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Copper | 37% | 98% | 98% | 98% | 98% | 98% | 98% |
| Coolant | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Thermal insulation | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Graphite | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Nickel | 44% | 95% | 95% | 95% | 95% | 96% | 97% |
| Cobalt | 0% | 94% | 94% | 94% | 94% | 97% | 99% |
| Lithium | 0% | 0% | 57% | 57% | 0% | 94% | 94% |
| Sodium | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Manganese | 0% | 84% | 84% | 84% | 84% | 92% | 100% |
| Titanium | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Phosphorus | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Binder | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Electrolyte: LiPF6 | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Electrolyte: LiPON | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Electrolyte: NaPF6 | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Electrolyte: Ethylene Carbonate | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| Other | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

*Source*: Ricardo fleet impacts modelling analysis

### A1.2.3 Reuse/Repurposing/Recycling shares

**Table A8: Assumptions on EV battery reuse, repurposing and recycling shares for first and second life**

| Scenario | Life | Phase | | Units | 2015 | 2020 | 2025 | 2030 | 2040 | 2050 |
|---|---|---|---|---|---|---|---|---|---|---|
| Base | First | Reuse | % re-use (to battery) | % | 0% | 5% | 5% | 5% | 5% | 5% |
| Base | First | Repurposing | % re-purposed (to second use) | % | 5% | 7% | 10% | 10% | 10% | 10% |
| Base | First | Recycling | % recycled | % | 45% | 58% | 55% | 55% | 55% | 55% |
| Base | First | Disposal | % disposed | % | 50% | 30% | 30% | 30% | 30% | 30% |
| Base | Second | Repurposing | % of virgin batteries replaced for each 'second use' | Years | 50% | 50% | 50% | 50% | 50% | 50% |
| Base | Second | Repurposing | % of virgin capacity | % | 70% | 70% | 70% | 70% | 70% | 70% |
| Base | Second | Recycling | % recycled | % | 50% | 70% | 70% | 70% | 70% | 70% |
| Base | Second | Disposal | % disposed | % | 50% | 30% | 30% | 30% | 30% | 30% |
| SVC | First | Reuse | % re-use (to battery) | % | 0% | 5% | 10% | 10% | 10% | 10% |
| SVC | First | Repurposing | % re-purposed (to second use) | % | 5% | 7% | 20% | 30% | 30% | 30% |
| SVC | First | Recycling | % recycled | % | 45% | 58% | 50% | 45% | 45% | 45% |
| SVC | First | Disposal | % disposed | % | 50% | 30% | 20% | 15% | 15% | 15% |
| SVC | Second | Repurposing | % of virgin batteries replaced for each 'second use' | Years | 50% | 50% | 50% | 50% | 50% | 50% |
| SVC | Second | Repurposing | % of virgin capacity | % | 70% | 70% | 70% | 70% | 70% | 70% |
| SVC | Second | Recycling | % recycled | % | 50% | 70% | 75% | 85% | 85% | 85% |
| SVC | Second | Disposal | % disposed | % | 50% | 30% | 25% | 15% | 15% | 15% |

*Source*: Ricardo fleet impacts modelling analysis; *Notes*: 'Disposed' batteries are assumed to be not recovered within the EU – i.e. either through exports of vehicles themselves or the batteries only (e.g. for other purposes).

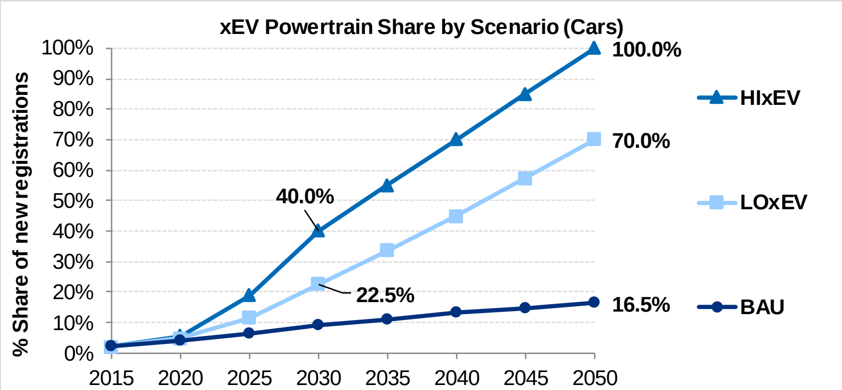
## A1.3 xEV Powertrain deployment scenarios

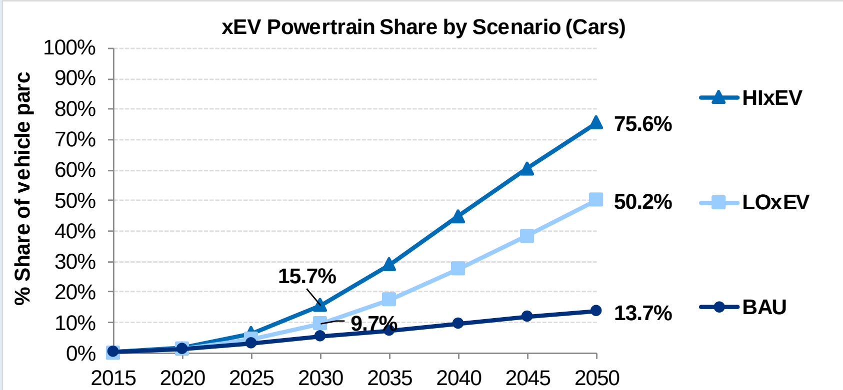
The following Figure A1 to Figure A6 provide a summary of the assumptions regarding the uptake of different xEV (and other) powertrains in different road transport modes for new vehicles, and the corresponding vehicle parc uptake derived by SULTAN's stock model from these inputs..

**Figure A1: xEV Powertrain Deployment Scenarios for Cars**

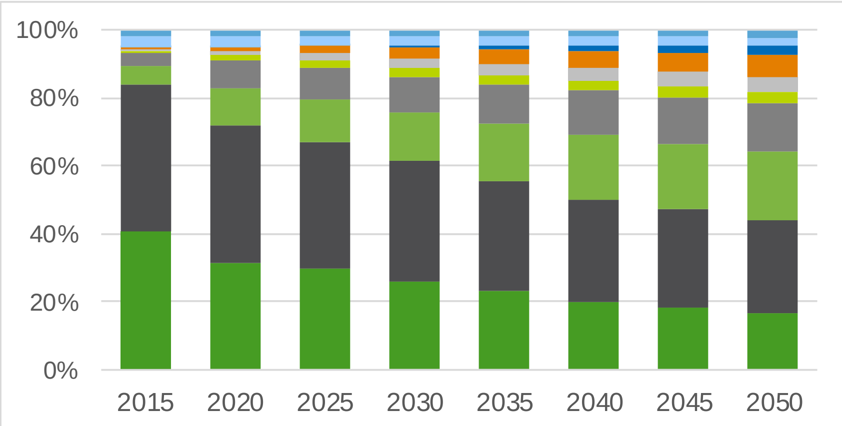
| Cars | New Registrations (INPUT) | Vehicle Parc (OUTPUT) |
|---|---|---|

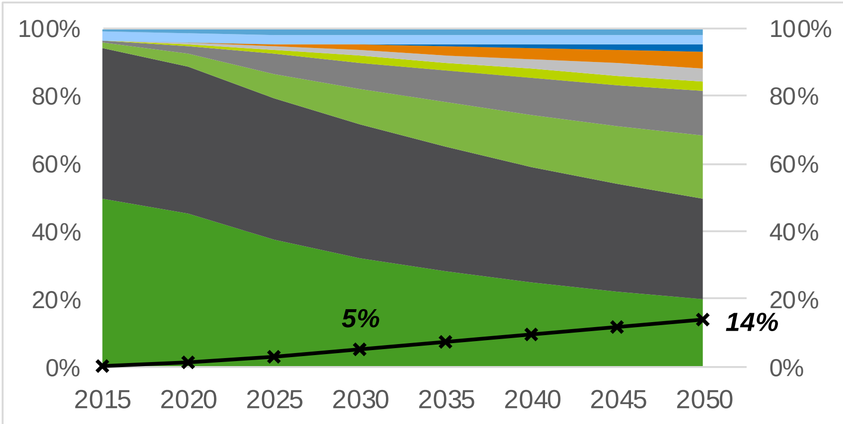
**All**

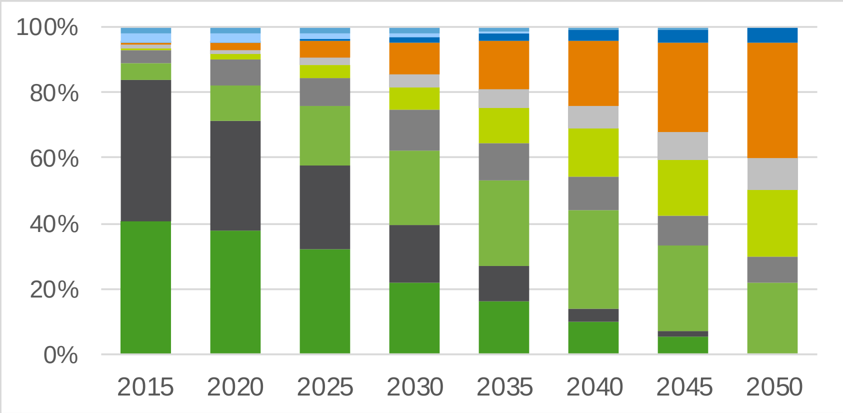
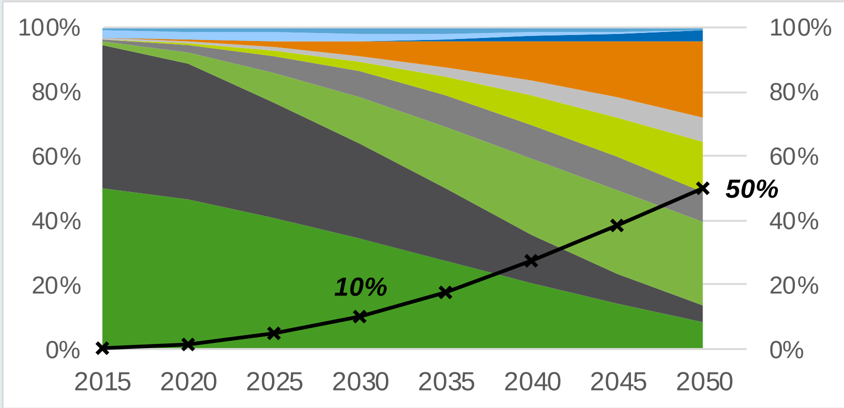
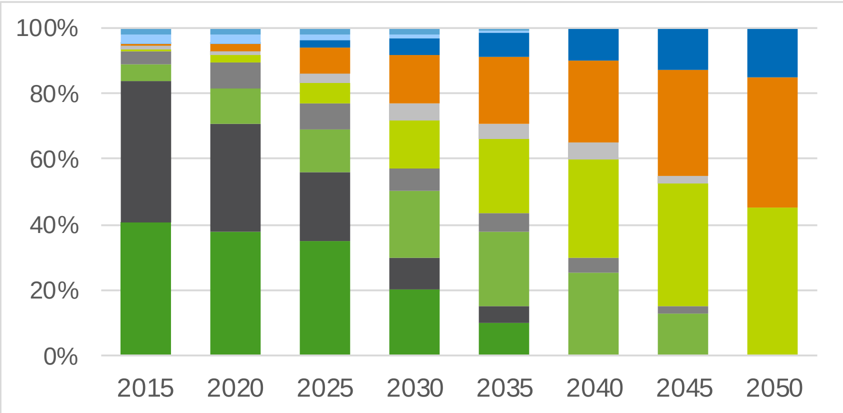
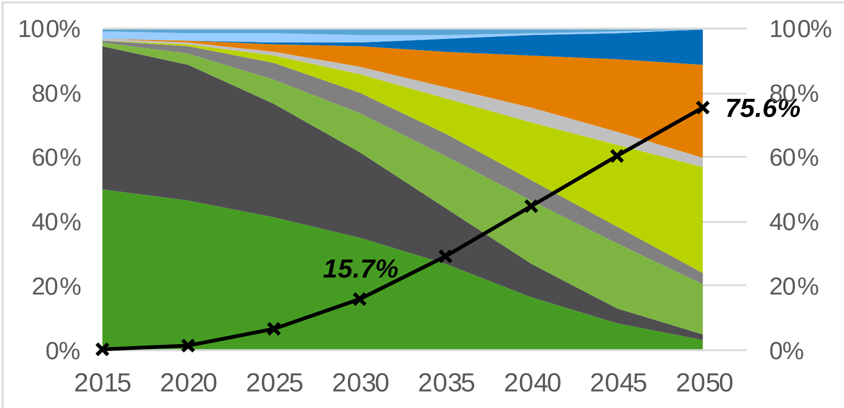



**Baseline**



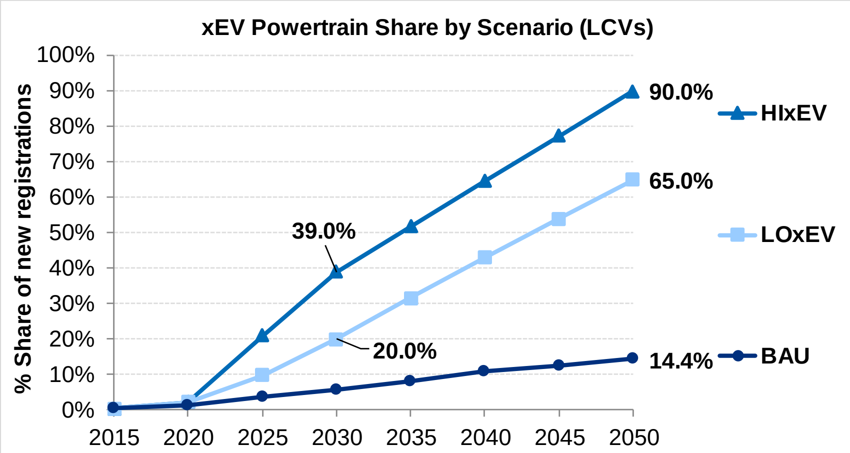
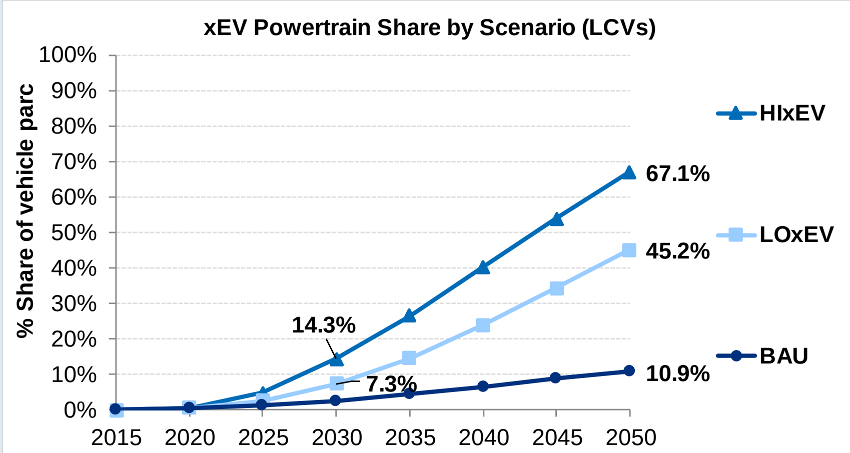
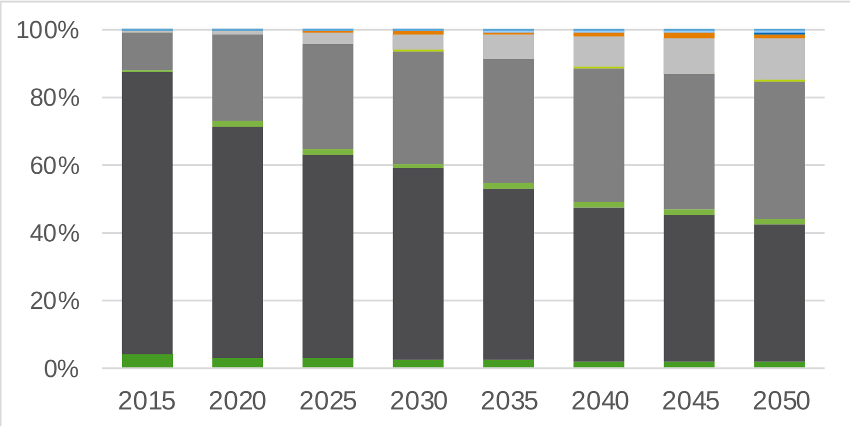
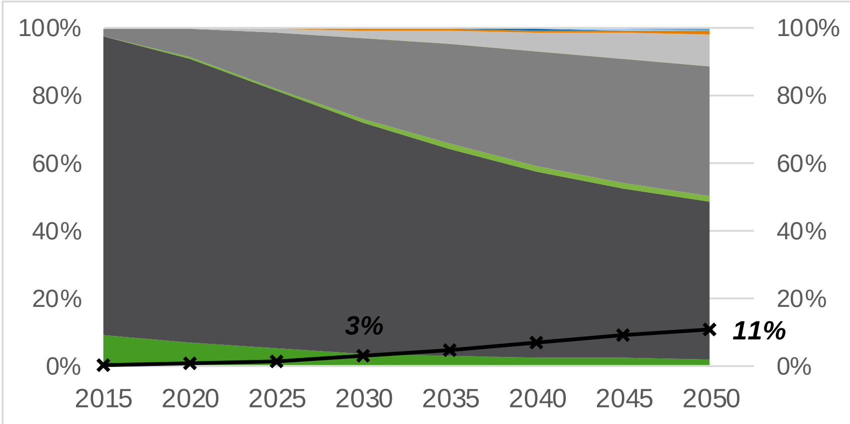



| Cars | New Registrations (INPUT) | Vehicle Parc (OUTPUT) |
|---|---|---|
| **LOxEV** |   |   |
| **HIxEV** |   |   |

*Key:*

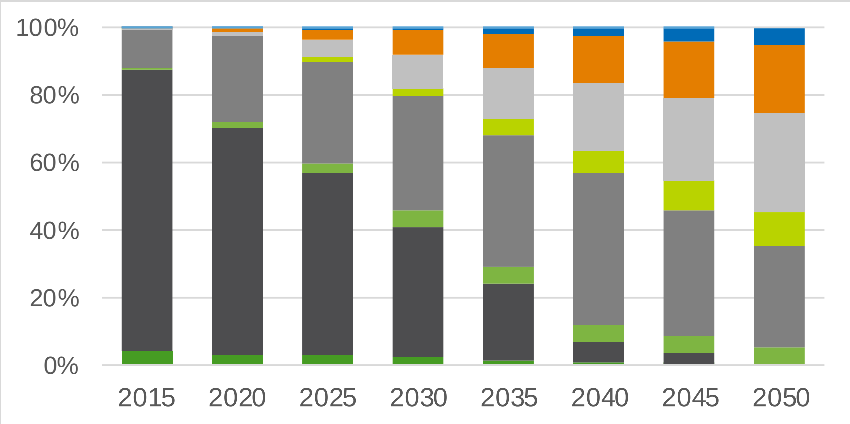
| Gasoline (incl. mild hybrid) | Diesel (incl. mild hybrid) | HEV Gasoline | HEV Diesel | PHEV Gasoline | PHEV Diesel | EV | FCEV | LPG | CNG | xEVs |
|---|---|---|---|---|---|---|---|---|---|---|

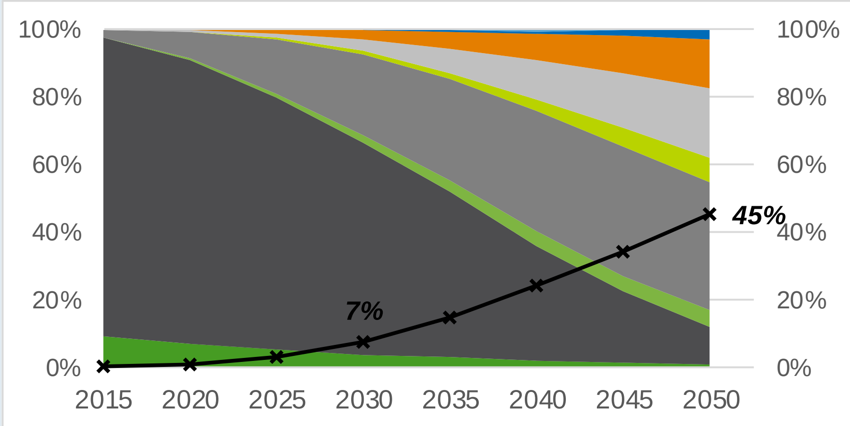
**Figure A2: xEV Powertrain Deployment Scenarios for LCVs**

| LCVs | New Registrations (INPUT) | Vehicle Parc (OUTPUT) |
|---|---|---|
| **All** |  |  |
| **Baseline** |  |  |

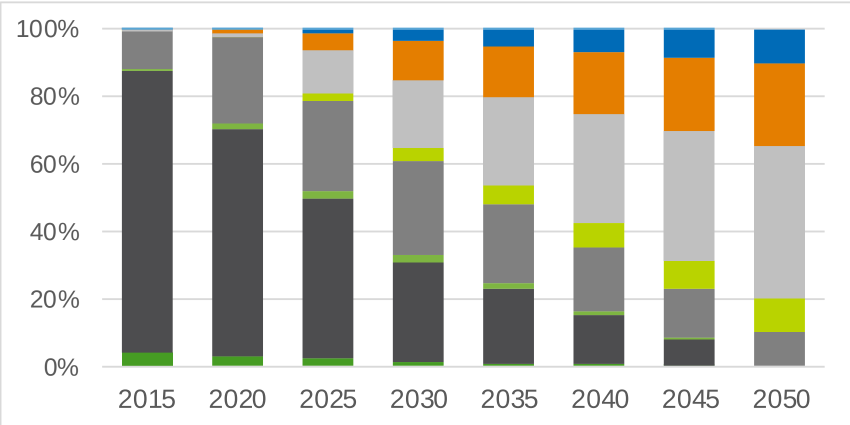
| LCVs | New Registrations (INPUT) | Vehicle Parc (OUTPUT) |
|---|---|---|

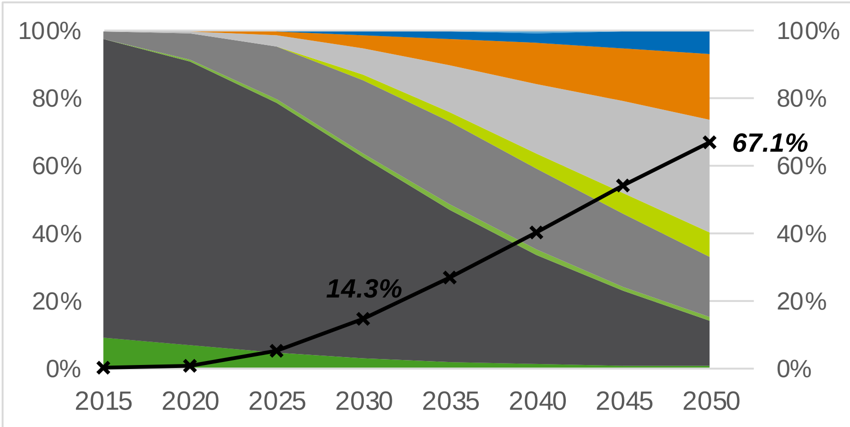
**LOxEV**




**HIxEV**



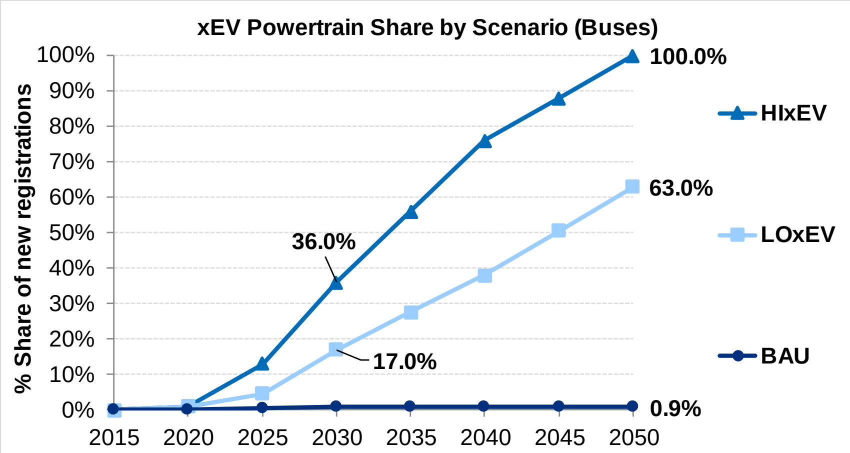

*Key:*

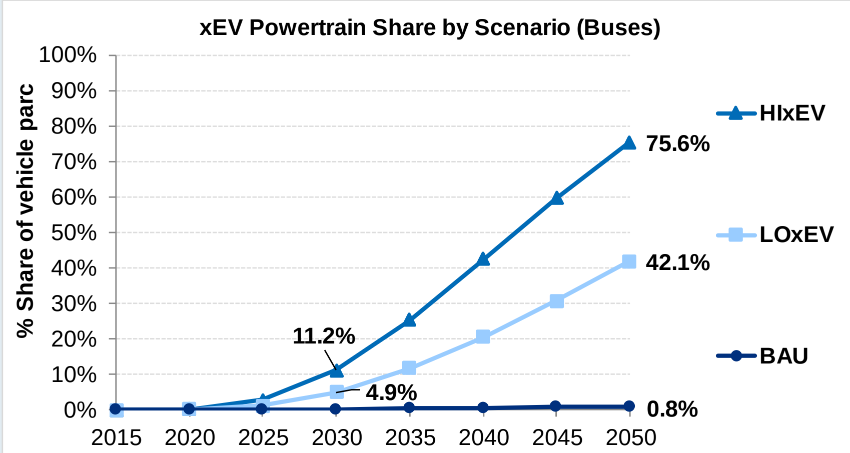
| Gasoline (incl. mild hybrid) | Diesel (incl. mild hybrid) | HEV Gasoline | HEV Diesel | PHEV Gasoline | PHEV Diesel | EV | FCEV | LPG | CNG | xEVs |
|---|---|---|---|---|---|---|---|---|---|---|

**Figure A3: xEV Powertrain Deployment Scenarios for Buses**

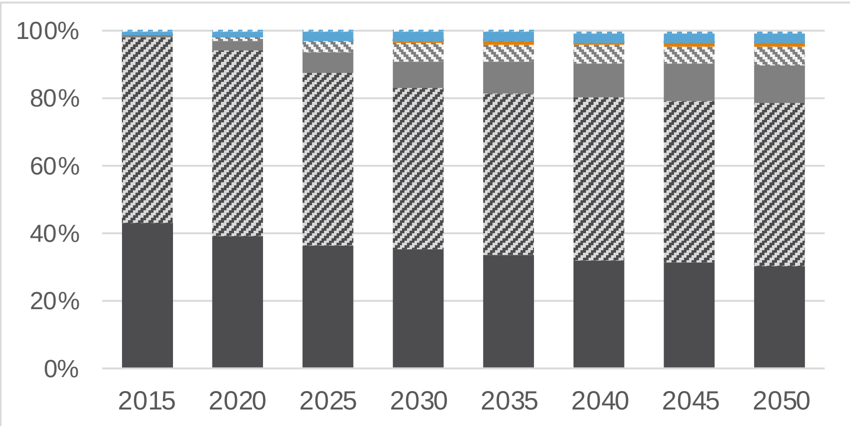
**Buses** | **New Registrations (INPUT)** | **Vehicle Parc (OUTPUT)**

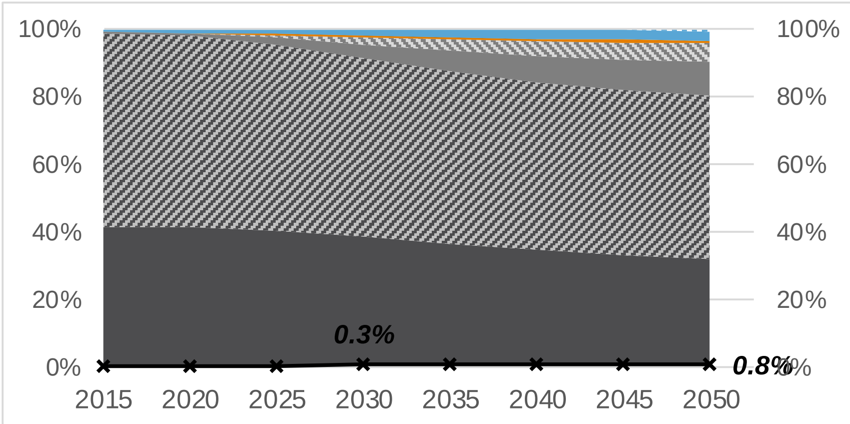
**All**




**Baseline**



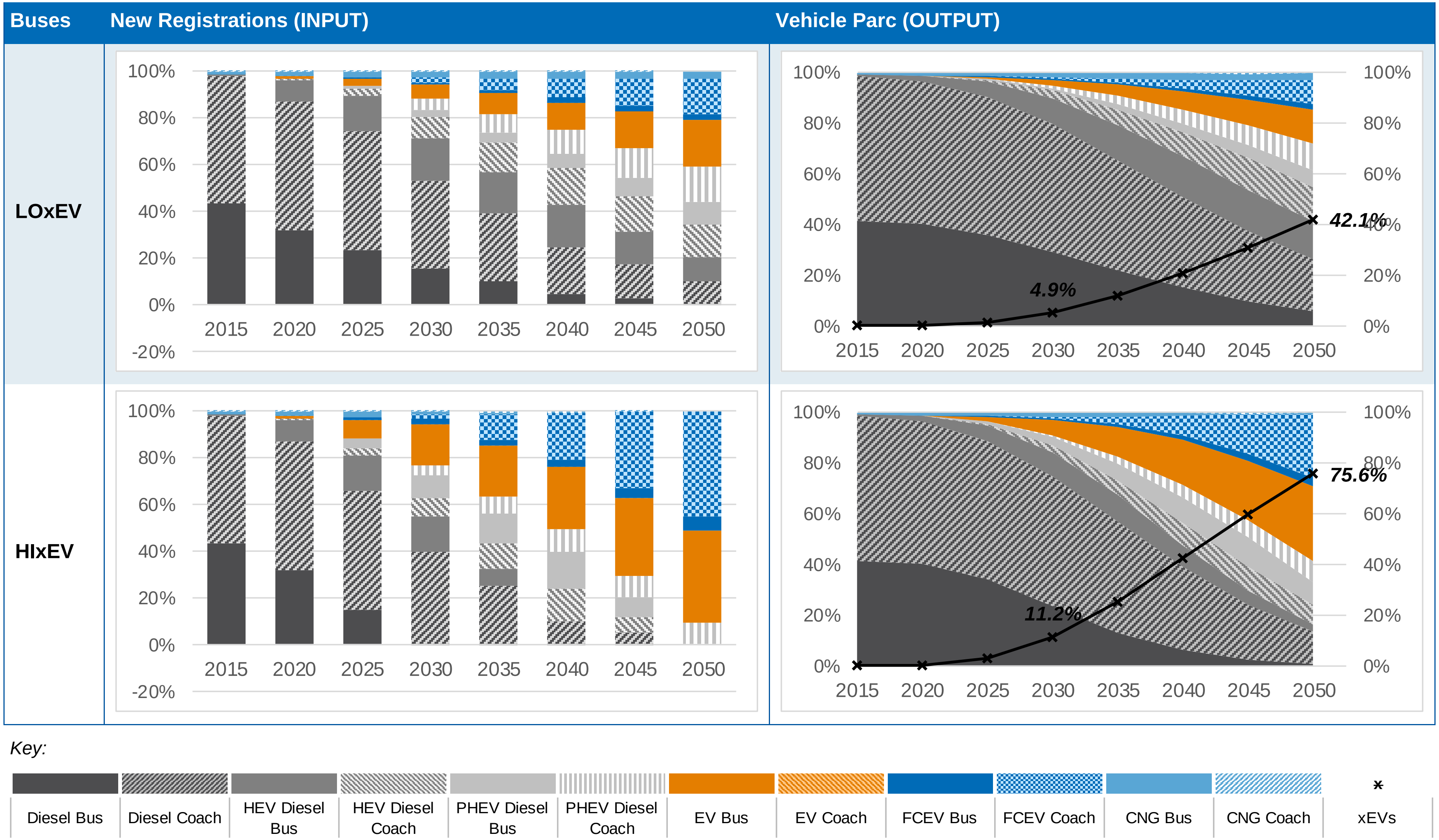
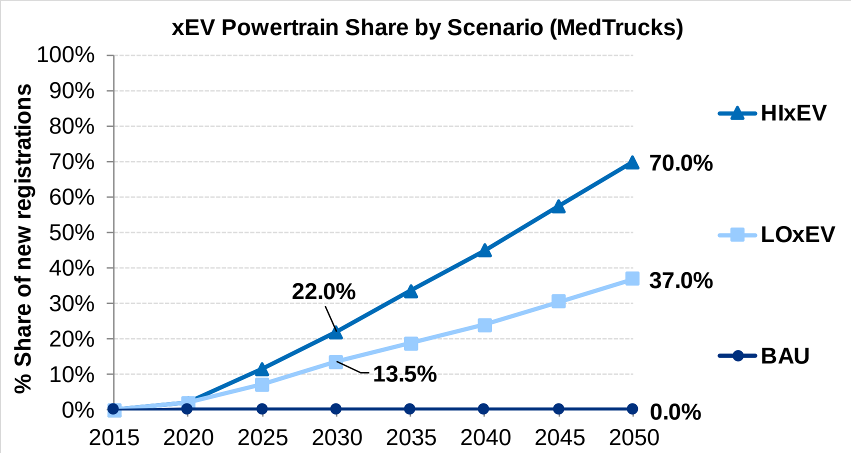
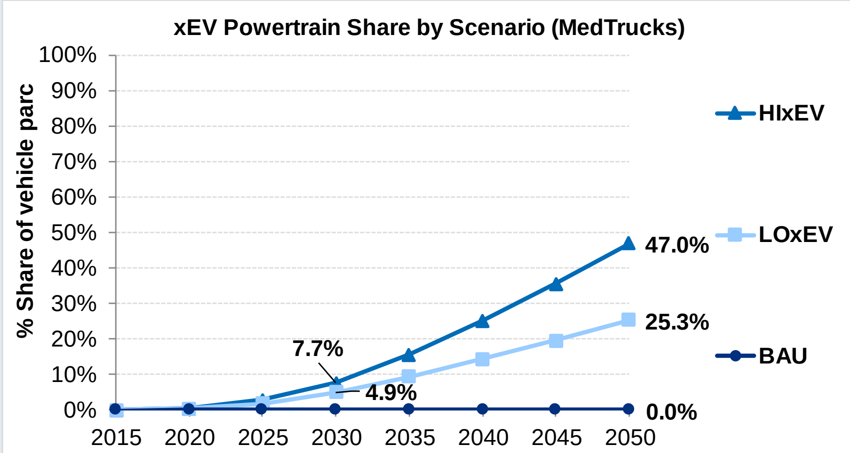
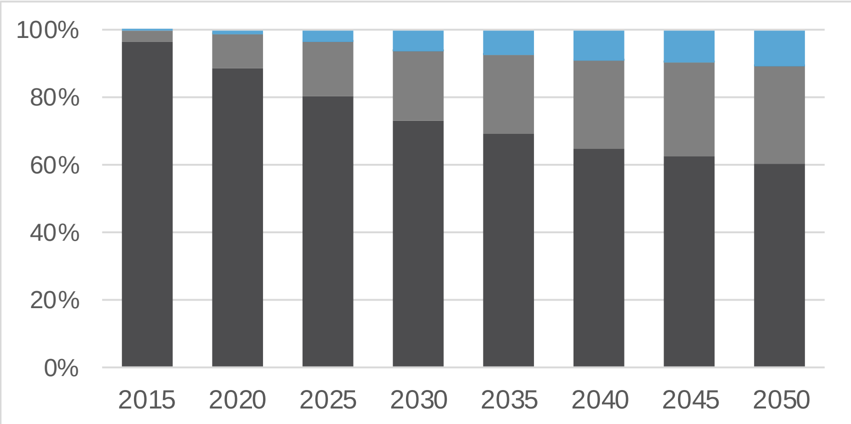
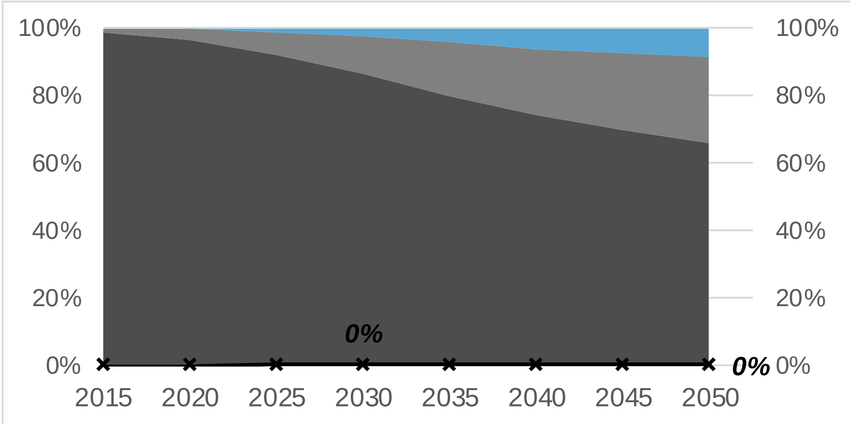
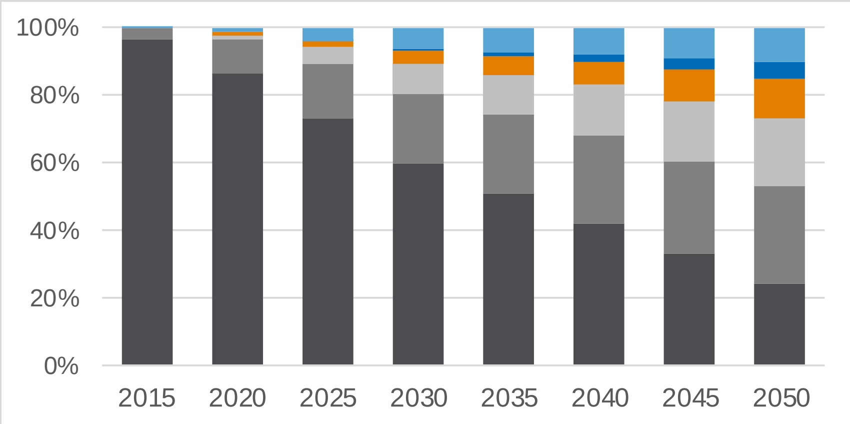

Buses
New Registrations (INPUT)
Vehicle Parc (OUTPUT)
LOxEV
HIxEV
100%
80%
60%
40%
20%
0%
-20%
2015
2020
2025
2030
2035
2040
2045
2050
4.9%
42.1%
11.2%
75.6%
Key:
Diesel Bus
Diesel Coach
HEV Diesel Bus
HEV Diesel Coach
PHEV Diesel Bus
PHEV Diesel Coach
EV Bus
EV Coach
FCEV Bus
FCEV Coach
CNG Bus
CNG Coach
xEVs

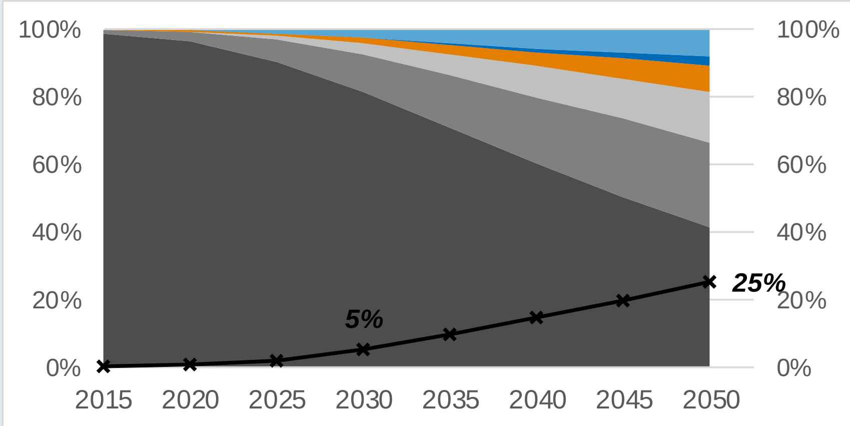
**Figure A4: xEV Powertrain Deployment Scenarios for Medium Trucks**

| MedTruck | New Registrations (INPUT) | Vehicle Parc (OUTPUT) |
|---|---|---|
| **All** |   |   |
| **Baseline** |   |   |

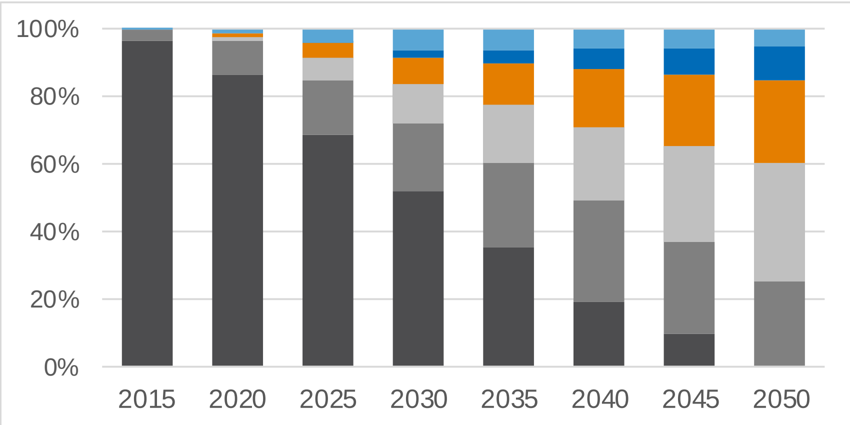
**MedTruck** **New Registrations (INPUT)** **Vehicle Parc (OUTPUT)**

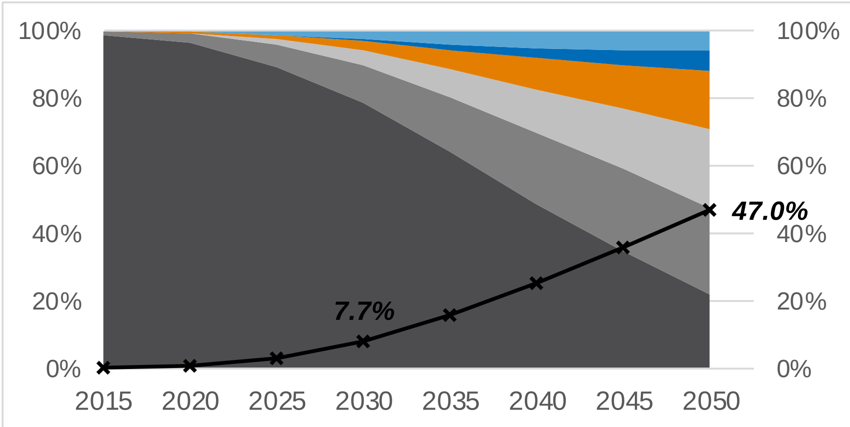
**LOxEV**




**HIxEV**

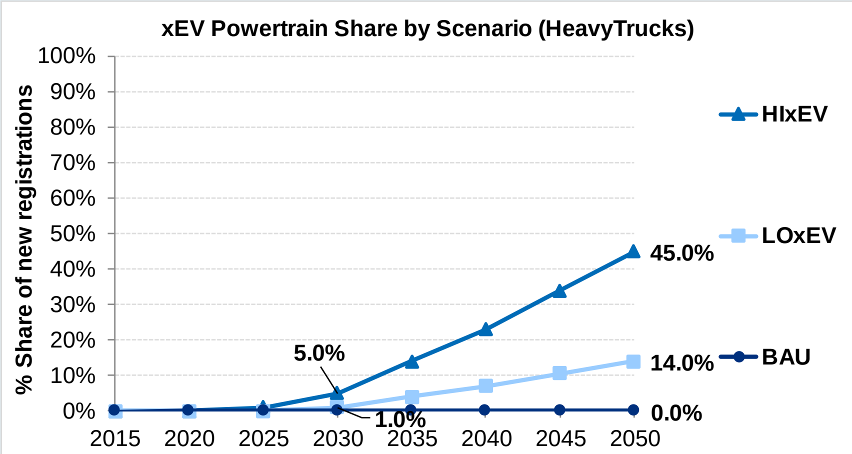
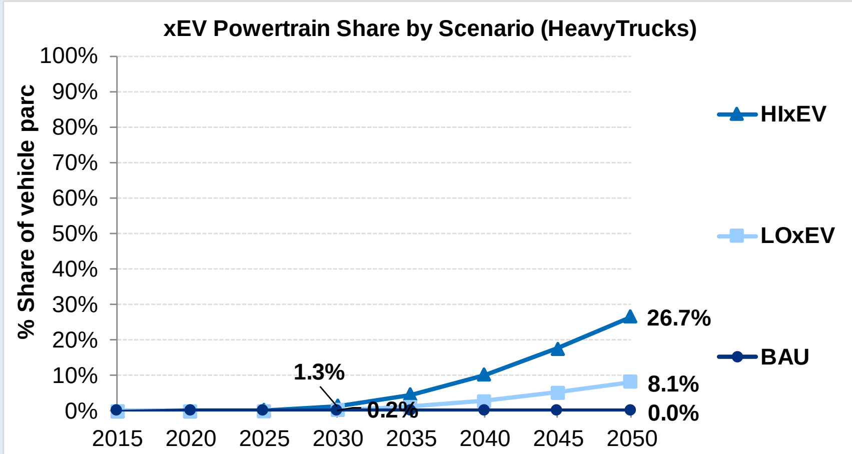
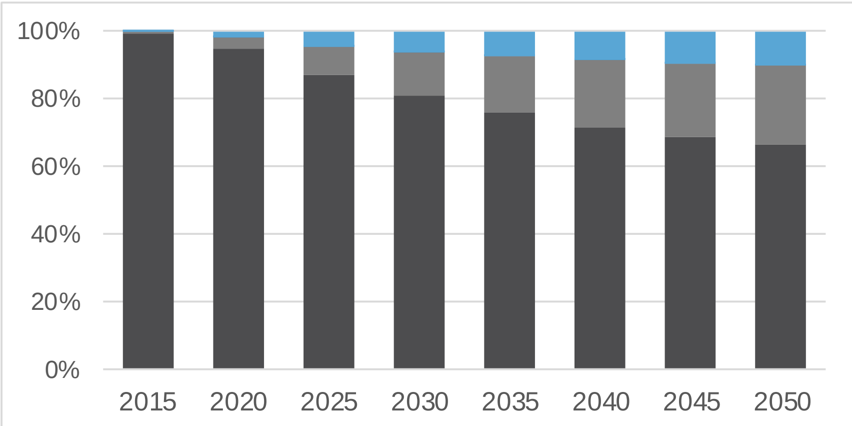
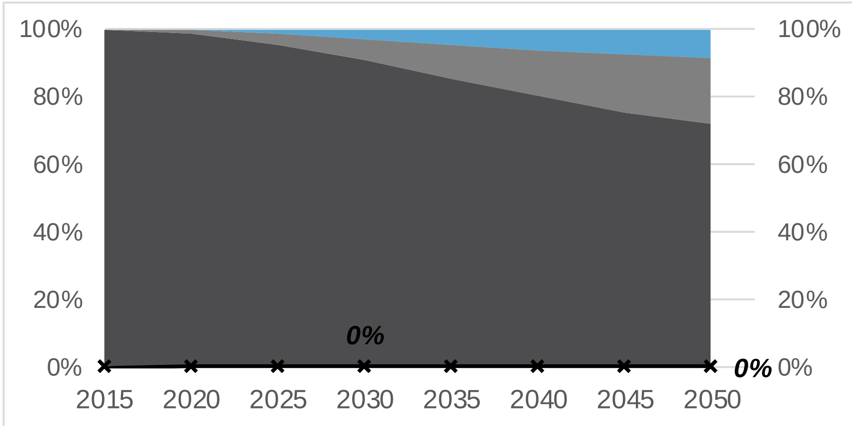


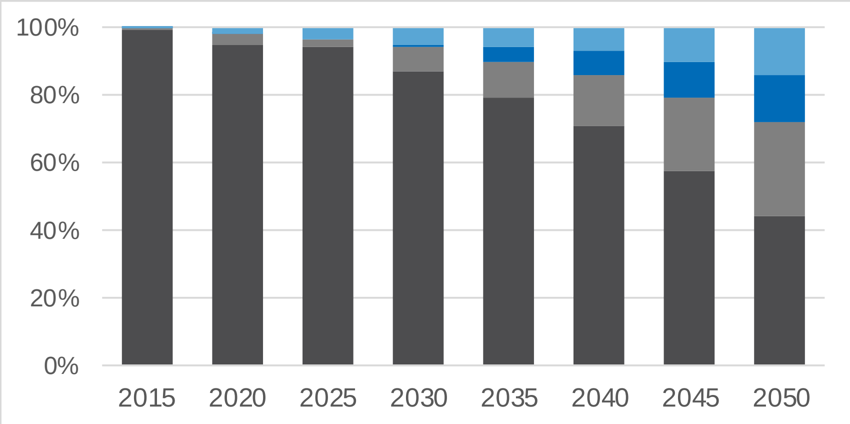
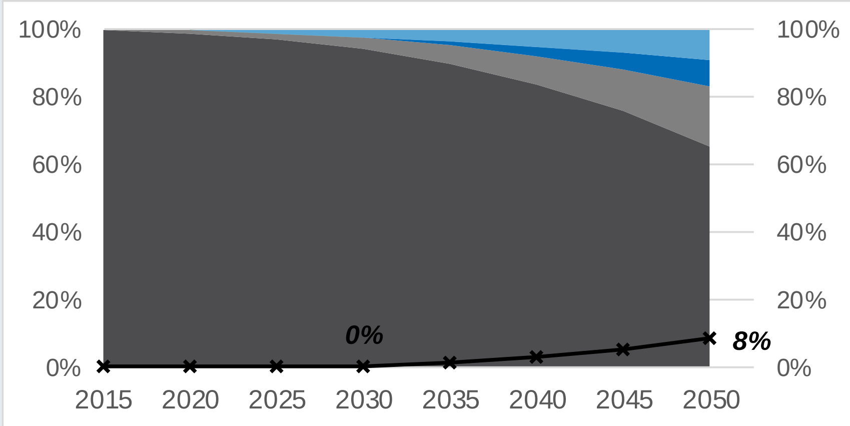
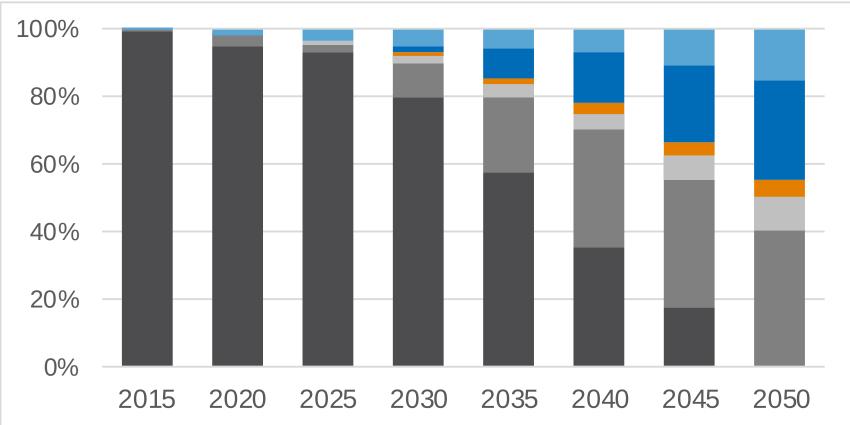
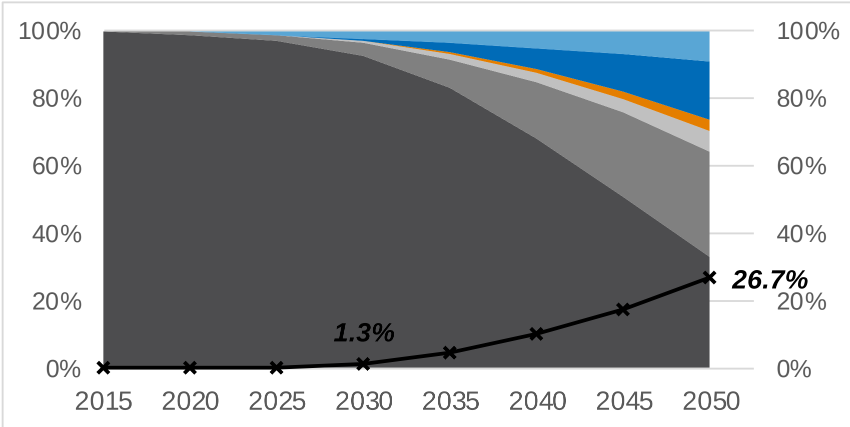




*Key:*

| Gasoline (incl. mild hybrid) | Diesel (incl. mild hybrid) | HEV Gasoline | HEV Diesel | PHEV Gasoline | PHEV Diesel | EV | FCEV | LPG | CNG | xEVs |
|---|---|---|---|---|---|---|---|---|---|---|

**Figure A5: xEV Powertrain Deployment Scenarios for Heavy Trucks**

| HvyTruck | New Registrations (INPUT) | Vehicle Parc (OUTPUT) |
|---|---|---|
| **All** |  |  |
| **Baseline** |  |  |

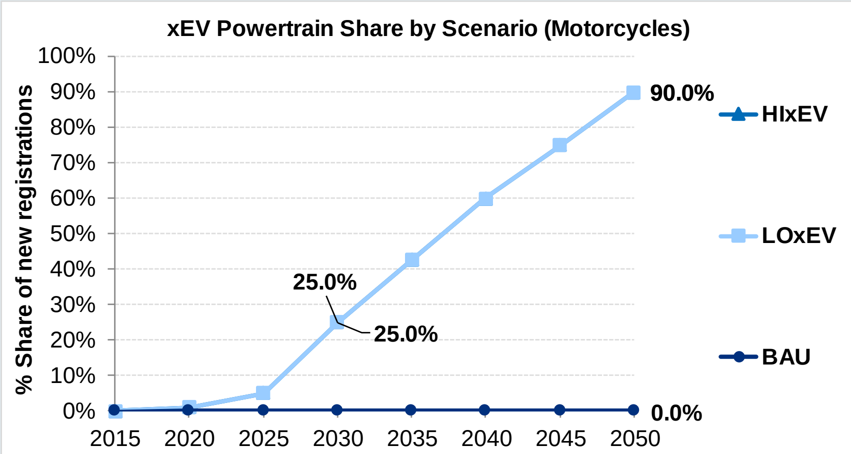
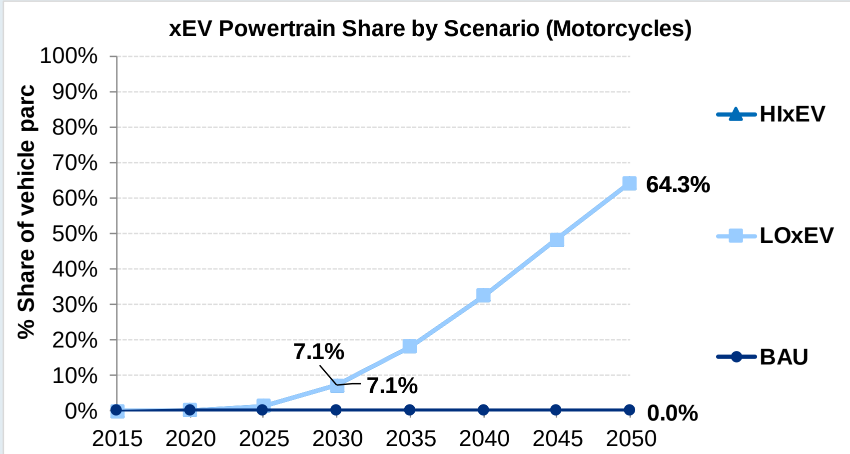
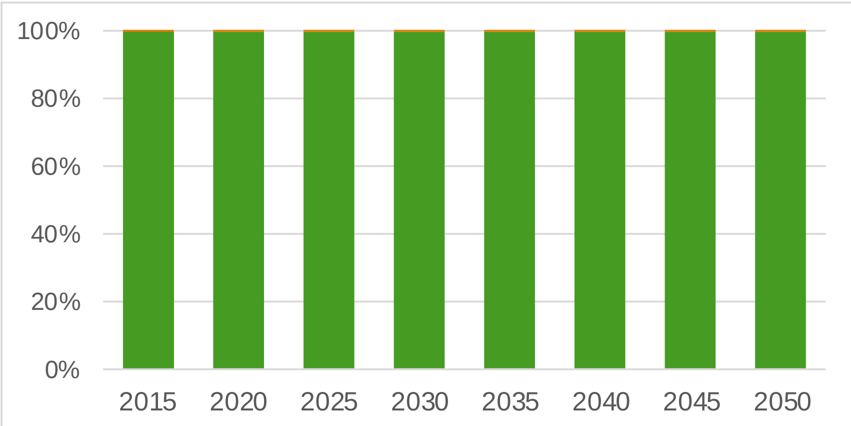
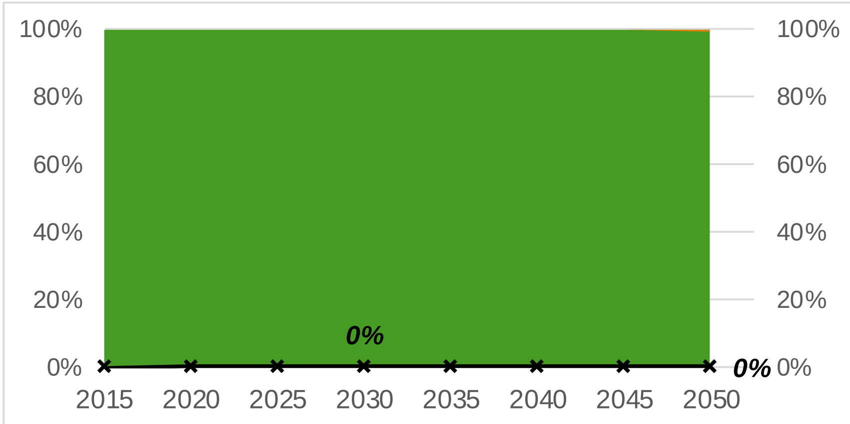
| HvyTruck | New Registrations (INPUT) | Vehicle Parc (OUTPUT) |
|---|---|---|
| **LOxEV** |  |  |
| **HIxEV** |  |  |

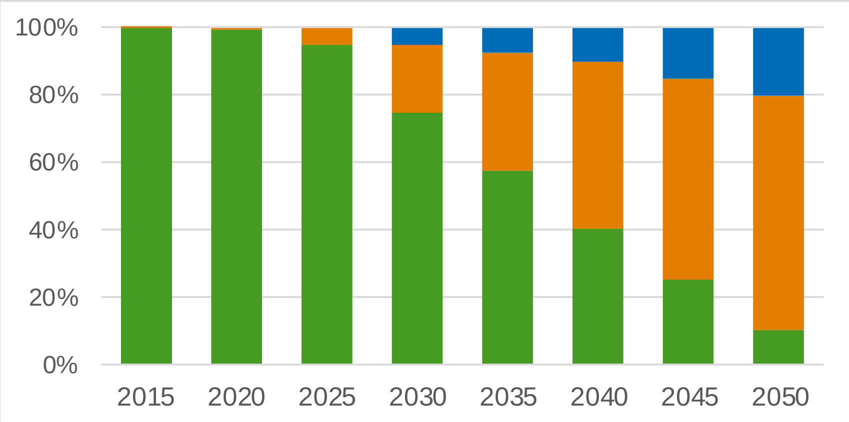
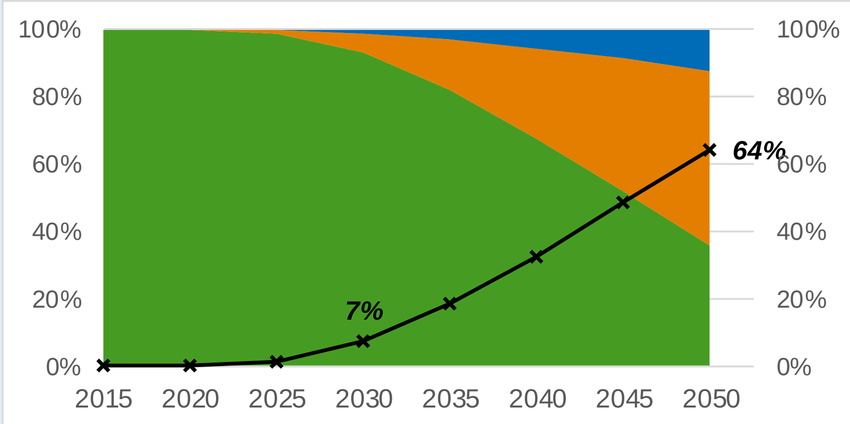


*Key:*

| Gasoline (incl. mild hybrid) | Diesel (incl. mild hybrid) | HEV Gasoline | HEV Diesel | PHEV Gasoline | PHEV Diesel | EV | FCEV | LPG | CNG | xEVs |
|---|---|---|---|---|---|---|---|---|---|---|

**Figure A6: xEV Powertrain Deployment Scenarios for Motorcycles**

| HvyTruck | New Registrations (INPUT) | Vehicle Parc (OUTPUT) |
|---|---|---|
| **All** |   |   |
| **Baseline** |   |   |

| HvyTruck | New Registrations (INPUT) | Vehicle Parc (OUTPUT) |
|---|---|---|
| **LOxEV** |  |  |
| **HIxEV** | Same as LOxEV | Same as LOxEV |

*Key:*

| Gasoline (incl. mild hybrid) | Diesel (incl. mild hybrid) | HEV Gasoline | HEV Diesel | PHEV Gasoline | PHEV Diesel | EV | FCEV | LPG | CNG | xEVs |
|---|---|---|---|---|---|---|---|---|---|---|

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