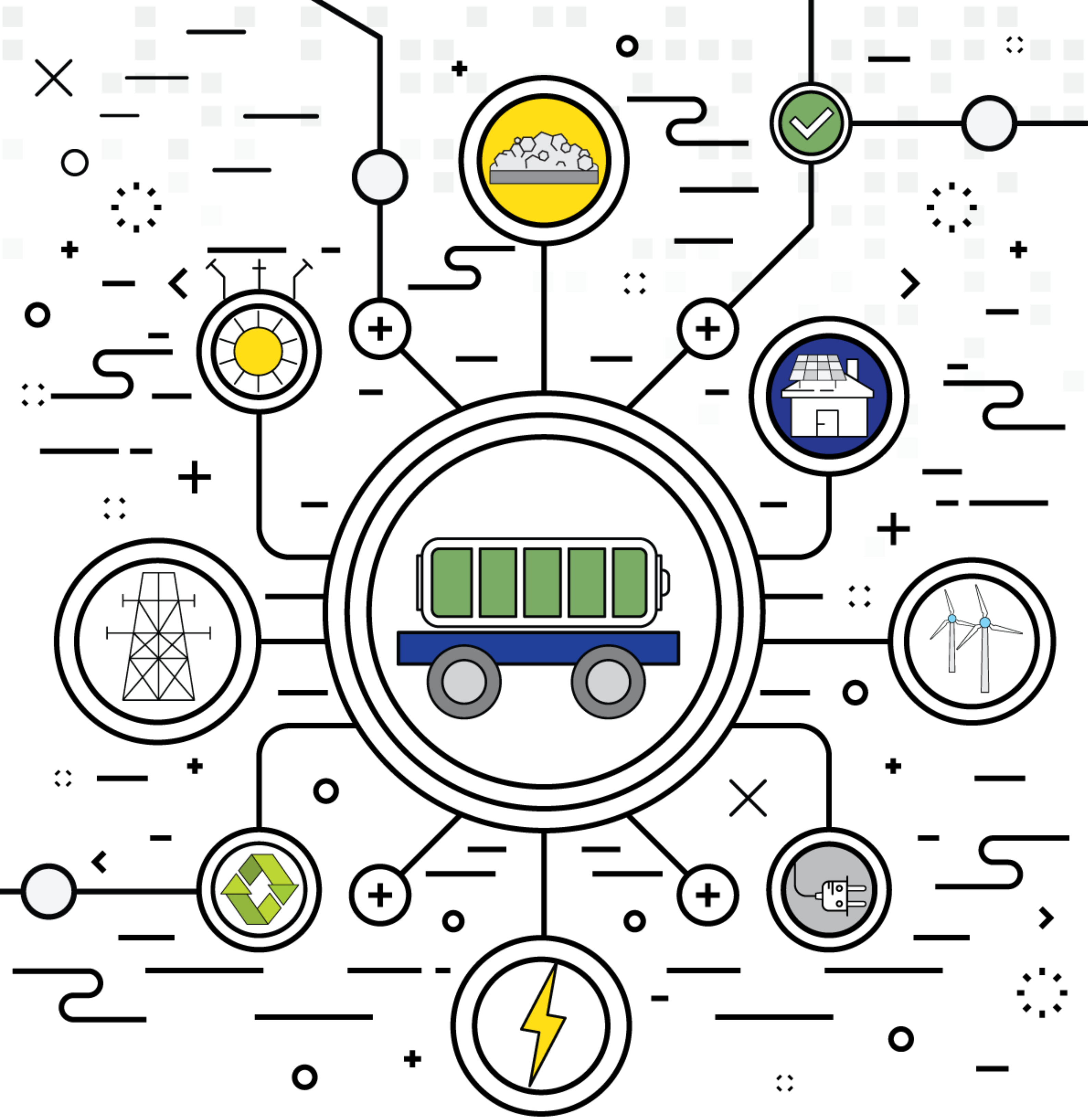


element energy

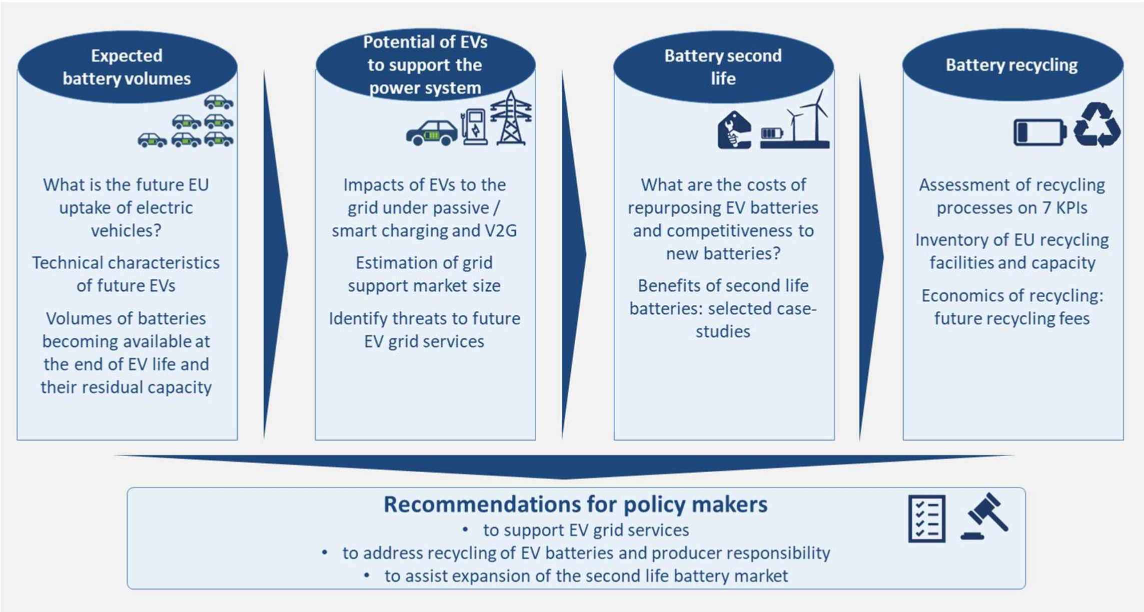
# Batteries on wheels: the role of battery electric cars in the EU power system and beyond

A report for: enel, IBERDROLA, TRANSPORT & ENVIRONMENT, GROUPE RENAULT

# Executive Summary

Batteries are the key technology enabling the decarbonisation of transport, and the value of the materials within them (both in absolute terms and strategically for Europe) has resulted in the development of policies and regulations around battery reuse and recycling, with the European Commission (EC) looking to review its Battery Directive in 2020. However, what is also emerging is the potential for batteries to work synergistically with the power system, providing a range of services that can increase renewable energy uptake, reduce constraints on networks, and provide security of energy supply. Performance requirements for grid support batteries are lower than those for electric vehicles, which points to grid support being a key second life application for EV batteries.

A joint consortium of Renault, ENEL, Iberdrola and Transport & Environment commissioned Element Energy to understand the impacts and opportunities related to EVs for the electricity system. By evaluating current recycling capabilities and processes, along with associated costs and legislative requirements, and comparing the different end of life options (re-use, recycling, etc.) this study informs on what is appropriate in terms of policy and regulation. The key topics and questions addressed by this study are shown below:



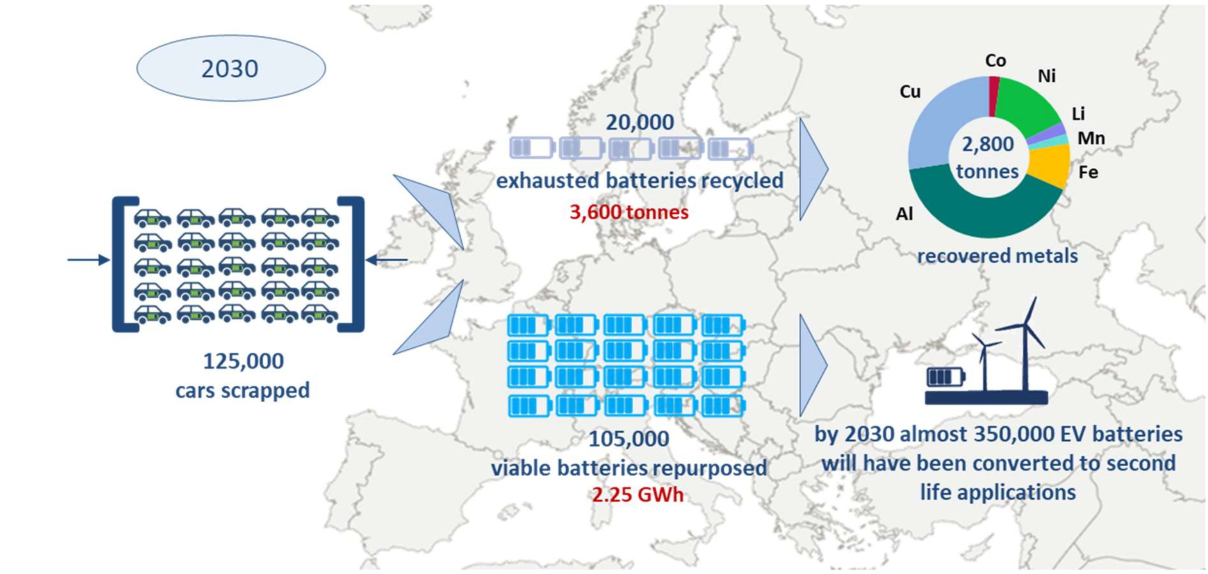

## Expected battery volumes for 2nd life and recycling

This study builds onto the EV deployment scenarios previously developed by Element Energy for the European Climate Foundation[1], combining the EU's push to limit the emissions of new vehicles and feedback from car OEMs. Although currently in early phase, the uptake of electric vehicles in Europe is expected to accelerate through the mid-2020s. Whilst in 2025 only 10% of the total European new vehicle sales will consist of zero and low emission vehicles[2] (ZLEVs), this number is expected to increase to 25% in 2030 under the baseline case. Within ZLEVs, battery electric vehicles (BEVs) would be the dominant powertrain technology from early 2020s.

This would mean that in 2030 85% of the vehicle stock will still be powered by internal combustion engines (ICE). However, by 2050, electric vehicles are expected to dominate the stock, reducing the proportion of ICE cars to 20%. Due to the uptake of ZLEV ramping-up in the mid-2020s, most of the

[1] Low-carbon cars in Europe: A socioeconomic assessment, Element Energy and Cambridge Econometrics for European Climate Foundation, Final Report, Feb 2018.
[2] ZLEVs refer to vehicles with emissions of less than 50gCO2/km and comprise Plug-in Hybrid Vehicles (PHEVs), Battery Electric Vehicles (BEVs), and Fuel Cell Electric Vehicles (FCEVs).

17.5 million electric vehicles on Europe's roads in 2030 will be relatively young. However, around 125,000 older electric vehicles will be retired that year, and their batteries will be recovered. Around 15% of these batteries would be too deteriorated for second life applications and will be sent to recycling, generating almost 2,800 tonnes of valuable metals. On the other hand, almost 105,000 EV batteries, representing around 2.25 GWh of residual capacity, would be repurposed in 2030 alone, adding to the approx. 250,000 EV batteries that would have already entered second life applications before 2030.

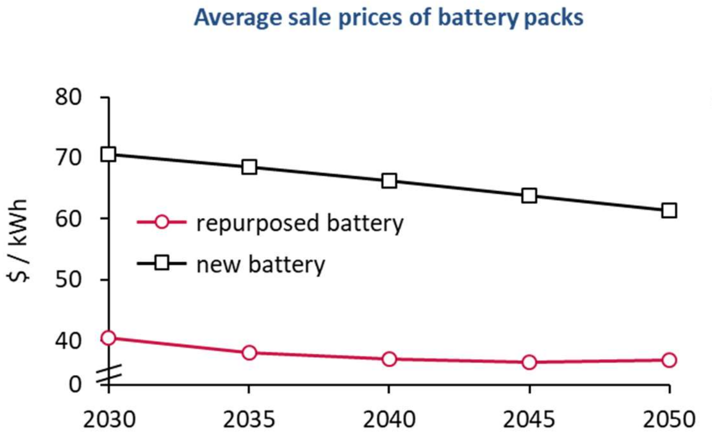



## Impact of EVs and storage in decarbonised electricity systems

Following widespread deployment, EV charging could represent an important load on the power system. The way in which vehicles are charged will determine whether EV charging represents a net cost or net benefit to the power system. In this study, new research comprising whole power system analyses of four countries (FR, GB, ES, IT) demonstrated that unmanaged/passive charging would result in a significant additional cost to the power system, mainly network related investments due to the increase in peak loads. In contrast, smart charging could provide a net benefit to the energy system, by reducing curtailment of variable renewable energy sources (VRES), reducing fossil fuel use in power plants, and avoiding investment in peaking plant.

**A net benefit of smart charging (relative to passive) was consistent across countries, although the amount varied between €0.5-1.3Bn/annum** (evaluated in 2040 – see chapter 3). The impact was greatest in countries where wind energy was significant; overnight smart charging improved consumption of wind energy that would otherwise be curtailed. In future PV dominated energy systems, there was a very large requirement for flexibility technologies, like smart charging but also utility battery storage. The analysis found a synergistic relationship between smart charging, batteries and PV in particular: the daily patterns of PV output increase the utilisation of batteries and increase the level of their economic deployment. Modelling indicated that there will be some competition between flexibility sources, however the 2040 capacities were many times larger than current levels of battery deployment. There is a synergistic relationship between battery deployment and VRES: increased storage deployment supports greater levels of VRES by reducing curtailment, in turn the increased variability of power generation supports the high cycling that batteries need to be economic. Vehicle to Grid – where EVs discharge back to the power system at critical times – may represent an extremely large store of electricity of national importance. Utilising V2G can be cost effective if barriers related to customer behaviour and battery degradation are overcome.

## Battery second life




Whilst (non-Li-Ion) battery recycling is a well-established industry already, battery repurposing is still an emerging sector, with a handful of small-scale European players, and under limited regulatory control. For example, in 2030, out the 125,000 EVs scrapped, 105,000 battery packs would be considered for second life applications, the equivalent of 2.25 GWh. As the sector is expanding in line with the growth in the EV uptake, the increase in the volumes of used batteries and price reductions in terms of logistics and repurposing techniques will make second life batteries cost-competitive with new batteries. The advantages of second life batteries are not limited to using a readily available cheaper technology - which would have otherwise been recycled - and avoiding the resources and emissions associated with manufacturing new batteries. The material benefits to the end-user are tangible – a 42% price reduction compared to new batteries. Battery repurposing will also bring additional benefits for the players involved. Car OEMs would be able to save an average of $67/battery unit repurposed instead of recycling them. The industry and supply-chain created around repurposing will generate additional jobs and revenues (~$79m in 2030 for the 93,000 EV viable battery packs) [3].

**Second life batteries will also boost storage and renewables deployment**: the expected lower costs of 2nd life modules and cells (compared to new) will boost the levels of deployed storage capacities on energy networks beyond the level achievable with new grid batteries. In turn, this will boost VRES deployment, displace more fossil fuels and peaking plant, reduce energy cost to consumers and reduce $CO_2$ emissions.

## Battery recycling

The demand for suitable automotive batteries and for battery raw materials, in particular cobalt and lithium, has soared and will continue to increase as the EV market expands, making battery recycling paramount. With an average battery mass of ~180 kg, each 125,000 EVs scrapped in 2030 will lead to 22,500 tonnes battery requiring processing, out of which 3,600 will be recycled, leading to ~2,800 tonnes of valuable metals[4]. This will mean that Europe will need to scale up its battery recycling capacity: the current Li-ion recycling capacity, estimated at 33,000 tonnes/year, will not be able to cope with the demand from exhausted EV batteries and some of the portable batteries not recycled today. **For electric cars alone the current recycling capacity will be surpassed as early as the mid-2030s** – with a recycling demand increasing to almost 100,000 tonnes of batteries in 2040. Recyclers will face further challenges, beyond the need for scaling up. In general, recycling is a capital-intensive business and the value of the recovered materials is usually not enough to cover recyclers' expenses. As a result, a recycling fee is often charged. Only a few metals contained in Li-ion batteries are recovered using today's recycling processes, mainly involving pyro- and hydro-metallurgical techniques, due to economic and scale considerations. As battery manufacturers are moving towards battery chemistries containing lower contents of valuable metals, especially cobalt which is difficult and expensive to source, recyclers will have to adopt new approaches to material recovery in order to ensure financial security. Improvements and developments in recycling processes are underway and will bring

[3] Figure contains only repurposed batteries. Other second life applications (e.g. reconditioning and non-storage applications) not included.
[4] Average across PHEVs and BEVs; figures may vary depending on year with changes in fleet composition, battery energy density, battery chemistry, and, metal recovery efficiency

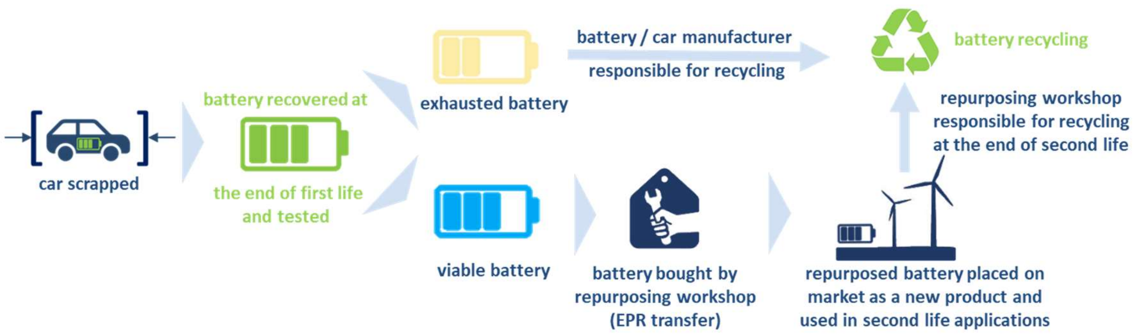
increased recovery efficiency, a wider range of end materials that could be recovered and reused (e.g. battery components through direct recycling processes) and a reduction in the environmental impacts of battery recycling, ensuring sustainable sourcing of battery chemicals. A comprehensive review of battery recycling processes, their assessment, and the main industry players is provided in section 4 .

Under the current European Battery Directive, the battery manufacturer or the vehicle OEM is responsible for covering any expenses related to battery collection and recycling. The improvements in recycling targets and the economies of scale associated with mass collection of EV batteries will lead to a reduction in the recycling fees by more than 50% compared to today's levels. The full array of contributing factors including battery chemistry, recovery efficiency and commodity prices are described in section 5.1 of this report, along with several sensitivities applied to the future recycling fees.

## Recommendations for policy makers

The second life market will be a collaboration between several players. Several policy measures, addressing the supply chain, must thus be implemented to achieve the full potential of second life batteries:

- **Ensure smooth and fair transfer of the recycling responsibility:** Car OEMs are already required - as part of the Extended Producer Responsibility (EPR) stipulated in the Battery Directive (BD) - to assist in collecting and recycling EV batteries at the end of vehicle life. However, in the current form of the directive, issued in 2006, there is no indication regarding battery repurposing and second life usage, leaving the responsibility for recycling at the end-of-the-second-life out of the policy framework. Since repurposing workshops are likely to be a different entity than the OEMs, future legislation must ensure a fair transfer of the EPR upon the purchase of the used battery by the workshops from the OEMs. In this way, repurposing workshops would be responsible for recycling the repurposed batteries they would place on the market.




- **Reduce logistics complexity to encourage the battery aftermarket:** to avoid restrictions imposed on waste transport and ensure workshops' swift access to used batteries, batteries viable for second life applications should be classed as raw materials and not waste when delivered to repurposing workshops. Given the testing involved in determining and confirming their viability, such batteries should also face lighter restrictions under the Hazardous Goods Transportation legislation.
- **Classify repurposed batteries as new products:** to ensure consistency, the "raw materials" will be turned by repurposing workshops into second life battery packs that would have to be classified as new products when placed on the second life market and sold to the new users. This nomenclature change ensures that the new OEM, namely the battery repurposer, will be responsible for the end of second life recycling and not the vehicle OEM.

Several other measures, addressing both battery recycling and repurposing, should also be implemented in order to ensure Europe is on the right track for transport decarbonisation and grid storage assisted by second life batteries:

- **Battery tracking and identification must be encouraged:** a European battery registry and standardized labelling could help reduce recycling costs by decreasing sorting complexity, resolve the problem of orphan batteries, speed-up the repurposing process and reduce testing times since the state of health of the battery and its history would be digitally available.
- **Recycling of EV batteries should remain strict and recovery targets must be reviewed:** contrary to the current form of the Battery Directive, future updates must address Li-ion batteries specifically as a separate battery category. Furthermore, recovery targets should be set in line with the best available technology (BAT) and supported by a thorough techno-economic analysis.
- **Flexibility around new battery chemistries must be allowed:** legislation should be flexible such that new chemistries (i.e. not Li-ion) can be recycled reasonably, without needing to change the Battery Directive again.
- **Future batteries should be designed to be easy to recycle and repurpose**. During the course of this study it became apparent the need of streamlining battery recycling and repurposing in order to ensure sustainability and reduce costs. Future regulations, including the revision of the Ecodesign Directive should ensure standardised manufacturing and labelling of EV batteries.

Several policies are required to ensure consumers benefit from lowest energy bills and cleaner energy:

**Smart charging as a minimum mandatory standard for EV charging:** the economic case for making smart charging the minimum performance standard is very clear. There are a variety of ways in which this could be implemented:

- While the market is growing, member states could provide grants targeted to support only the deployment of smart charging. This could be in the form of grants for smart chargers, or support for “smart” EVs i.e. with the facility to schedule charge times and rates (for example via an app) which would be linked to passive charging infrastructure.
- Any support for smart chargers will need to be augmented with incentives so that customers actually utilise these in a smart way. Market based electricity pricing mechanisms could encourage this behaviour. For example, simple time-of-use electricity tariffs combined with smart meters, could provide an economic incentive to encourage smart charging.
- Regulatory instruments could also be used. An example would be to make mandatory the installation of smart recharging point in residential buildings and workplaces, in the transposition of EPBD directive by Member States

**Support the development of whole system flexibility markets:** The rules around the operation of flexible demand assets – specifically whether these protect electricity networks or respond to variations in energy supply - need to be developed, to avoid conflict and ensure optimal system configuration.

- Member states should encourage dialogue between national System Operators and Distribution Network/System Operators to evaluate critical system needs and therefore the priorities of operation of flexible demands such as smart charging.
- Dynamic pricing, with energy and network tariff components, could reveal scarcity /abundancy situations on the supply side and grid stress conditions.
- Aggregation of distributed resources and non-discriminatory access to flexibility markets (such as balancing markets, non-frequency ancillary service markets and CRMs) are paramount as well.
- Flexibility markets should be open to aggregated resources connected at distribution level and provide sufficient and stable incentives to de-risking investor decisions.
- As flexible assets could augment or replace many system critical assets, trials of flexibility technologies will be necessary to prove-out operational benefits. Supporting these will inform and underpin the necessary changes in regulation.

**Flexibility and continued deployment of VRES:** The analysis showed that flexible technologies (including energy storage and smart charging) have a synergistic relationship with increased VRES deployment.

- This synergy should be acknowledged as being central to delivering plans for deep decarbonisation of power systems. This aligns with the Commission objective to empower European consumers to become fully active players in the energy transition. While the Clean Energy for all Europeans package acknowledges the need for certain types of flexibility (increased transmission interconnection capacity) but this should be augmented with a broader range of demand-based flexibility assets such as those described in this report.
- The importance of this flexibility resource would then need to be reflected in national energy and climate plans.

**Encouraging daytime charging in countries with high PV deployment:** The analysis shows that daytime charging of EVs is beneficial to power systems with high levels of PV penetration. National plans for EV charging infrastructure should account for this whole system synergy with grid decarbonisation.

- The location of charging should respond, not only to driver needs, but also to expected patterns of renewable energy supply, in order to deliver the greatest net-benefit to customers.
- Actions encouraging ambitious daytime charging infrastructure could support rapid charging; workplace charging could be supported by Member State transposition of the Energy Performance in Buildings Directive.
- The Alternative Fuels Infrastructure Directive allows Member States to decide whether to “concentrate deployment efforts on normal or high-power recharging points”. Member states should take a whole system approach, aligned with national decarbonisation trajectories to evaluate the full cost-benefit of charging infrastructure deployment in their national policy frameworks.

# Contents



This report is produced under the Study on EV Batteries project, commissioned and funded by Transport & Environment, in collaboration with Renault-Nissan, ENEL, and Iberdrola.

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## Version

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# Acronyms

| | |
|---|---|
| Ah | Ampere hours |
| BAT | Best Available Technology |
| BD | Battery Directive (2006/66/EC) |
| BEV | Battery Electric Vehicle |
| BMS | Battery Management System |
| Co | Cobalt |
| CRM | Capacity Remuneration Mechanism |
| DG | Distributed Generation |
| DH | District Heat |
| DNO | Distribution Network Operator |
| DOD | Depth of Discharge |
| DSR | Demand Side Response |
| EC | European Commission |
| ELV | End-of-Life Vehicle |
| EPR | Extended Producer Responsibility |
| EPDB | Energy Performance of Buildings Directive |
| ES | Spain |
| EV | Electric Vehicle |
| FCEV | Fuel Cell Electric Vehicle |
| FFR | Firm Frequency Response |
| FR | France |
| GB | Great Britain |
| HEV | Hybrid Electric Vehicle |
| HF | Hydrofluoric acid |
| HP | Heat pump |
| ICE | Internal Combustion Engine |
| INL | Idaho National Laboratory |
| IT | Italy |
| KPI | Key Performance Indicator |
| LCO | Lithium Cobalt Oxide |
| LFP | Lithium Iron Phosphate |
| Li | Lithium |
| LIB | Lithium Ion Battery |
| Li-S | Lithium Sulphur (battery) |
| LMO | Lithium Manganese Oxide |
| LTO | Lithium Titanium Oxide |
| Mn | Manganese |
| NCA | Lithium Nickel Cobalt Aluminium Oxide |
| NGO | Non-Governmental Organisation |
| Ni | Nickel |
| NMC | Lithium Nickel Manganese Cobalt Oxide |
| OEM | Original Equipment Manufacturer |
| Opex | Operating Expenditure |
| PCR | Primary Control Reserve |
| PHEV | Plug-in Hybrid Electric Vehicle |
| PV | Photovoltaic |
| QR | Quick Response (code) |
| R&D | Research and Development |
| SOC | State of Charge |
| SOH | State of Health |
| STOR | Short Term Operating Reserve |
| TCO | Total Cost of Ownership |
| ToU | Time of Use |
| TSO | Transmission System Operator |
| V2G | Vehicle to Grid |
| VRES | Variable Renewable Energy Sources |
| ZLEV | Zero and Low Emission Vehicle |

# Note on terminology

Throughout the report, ‘EV’ refers to a plug-in vehicle, which can be either a PHEV or BEV. Zero and Low Emission Vehicles (‘ZLEVs’) refer to PHEVs, BEVs, and FCEVs.

# 1 Introduction

## 1.1 Background

Batteries are the key technology enabling the decarbonisation of transport, and the value of the materials within them (both in absolute terms and strategically for Europe) has resulted in the development of policies and regulations around battery reuse and recycling. However, what is also emerging is the potential for batteries to work synergistically with the grid, providing a range of services that can increase renewable energy uptake, reduce constraints on networks, and provide security of energy supply. Performance requirements for grid support batteries are lower than those for electric vehicles (EVs), which points to grid support being a key “second life” application for EV batteries. According to the waste hierarchy, reuse should be promoted above recycling, so it is important to understand at what point reuse/second life becomes clearly less sensible (economically and environmentally) than recycling.

The relatively low number of EVs that have been scrapped so far has resulted in limited availability of batteries for second life applications. This is about to change, in light of the expected increase in EV sales. The EU’s recently voted on $CO_2$ reduction target for 2030 (-37.5% compared to 2021 for the average new car’s gCO2/km[5]) in effect guarantees EV sales will increase well past their current low share of <5%. This would mean that the scrappage of EVs will increase from 1000s in the early 2020s to millions in 2030-40. If batteries can be used for stationary storage applications, Europe and the world would move one step further on the path to grid decarbonisation. However, current European regulations, developed in the mid-2000s (the days of EV infancy), do not address the value chains behind batteries’ fate at the end of their EV life. The European Commission, through its ambitious plans to develop a circular economy, acknowledges the need for change by including battery regulations on the list of waste policies requiring revision[6].

## 1.2 Objectives and scope of the work

This study examines the opportunities presented by batteries beyond their EV lives and discusses how future regulations could address the issues of battery recovery, recycling, and reuse, and help unleash these opportunities. This report brings together the views of stakeholders from across all areas of second life batteries’ value chains- from car OEMs (Renault-Nissan) and energy suppliers (ENEL and Iberdrola) to NGOs (Transport & Environment) and benefitted from the inputs of European industry bodies, such as the European Battery Recycling Association (EBRA) and RECHARGE (The Advanced Rechargeable and Lithium Batteries Association). The study was conducted by Element Energy (EE), a leading low-carbon energy management consultancy, and focussed on the following topics:

- Quantifying the future deployment of electric vehicles in Europe and understanding their usage and battery degradation profiles. This is used to determine the ‘stock’ of battery packs becoming available at the end of their automotive life.
- A thorough analysis of the impacts and opportunities related to EVs for the electricity system, both during their EV life and for second life applications.
- Evaluation of battery end of life options, including a review of recycling processes, facilities, and related legislation in Europe.
- Establishing the second life value chains and the favourable regulatory framework required.
- Economic analysis of battery recycling and repurposing, and their impacts on industry stakeholders.
- Understanding the economic benefits of using second life batteries in a series of case studies.

[5] Electrive.com, EU agrees on 37.5% CO2 reduction for cars by 2030, Dec 2018, https://www.electrive.com/2018/12/18/eu-agrees-on-37-5-co2-reduction-for-cars-by-2030/

[6] European Commission: Legislative Train Schedule, New Boost for Jobs, Growth and Investment, Circular Economy Package, http://www.europarl.europa.eu/legislative-train/theme-new-boost-for-jobs-growth-and-investment/package-circular-economy-package

## 1.3 Approach and structure of the report

The remainder of this report is structured into 5 chapters as follows:

Chapter 2 describes the uptake of electric vehicles and the characteristics of their batteries. The main end-of-life options are described, with the volumes of available second life batteries being presented.

Chapter 3 examines in detail the increasing role of storage in decarbonised energy systems, and within this context the role that EVs and $2^{nd}$ life batteries can play regarding the services they can provide to the grid operator.

Chapter 4 evaluates the current relations between European battery recycling technologies, available capacity, and regulation. Future technology insights and proposed legislation revisions are provided.

Chapter 5 details the economics of each end of life option, considering several policy scenarios and application case studies.

Key findings and recommendations are included in Chapter 6.

The last section of this report includes the bibliography. The report is also accompanied by an appendix detailing the modelling approach and assumptions.

# 2 Projected market size of EVs and batteries for cars in Europe

## 2.1 EV uptake scenarios

The study uses two of the car[7] uptake scenarios published in 2018 and developed by Element Energy and Cambridge Econometrics as part of a socioeconomic assessment of low-carbon cars in Europe that benefited from the inputs of an industrial steering group[8]:

- The *Baseline* scenario simulates a world where the transition to low-emission vehicles is slow and proceeds through a significant initial uptake of hybrid cars (HEVs). A gradual increase in the share of advanced powertrains up to 2030 is assumed, with a rapid growth in sales of ultra-low emission vehicles (ZLEV) post 2030. PHEVs and HEVs are deployed initially but in 2040 sales of HEVs and PHEVs decline sharply. Sales of ZLEVs account for ~10% of sales in 2025, and from 2040, ZLEVs account for 100% of new car sales.

- The *Accelerated EV uptake* scenario is characterised by OEMs responding to policies by ceasing production of ICE vehicles from 2035, followed by HEVs in 2040, with an accelerated market penetration of plug-in hybrid EVs and Battery EVs (BEVs). This highly accelerated uptake translates into a share of ZLEVs of ~25% of 2025 sales.

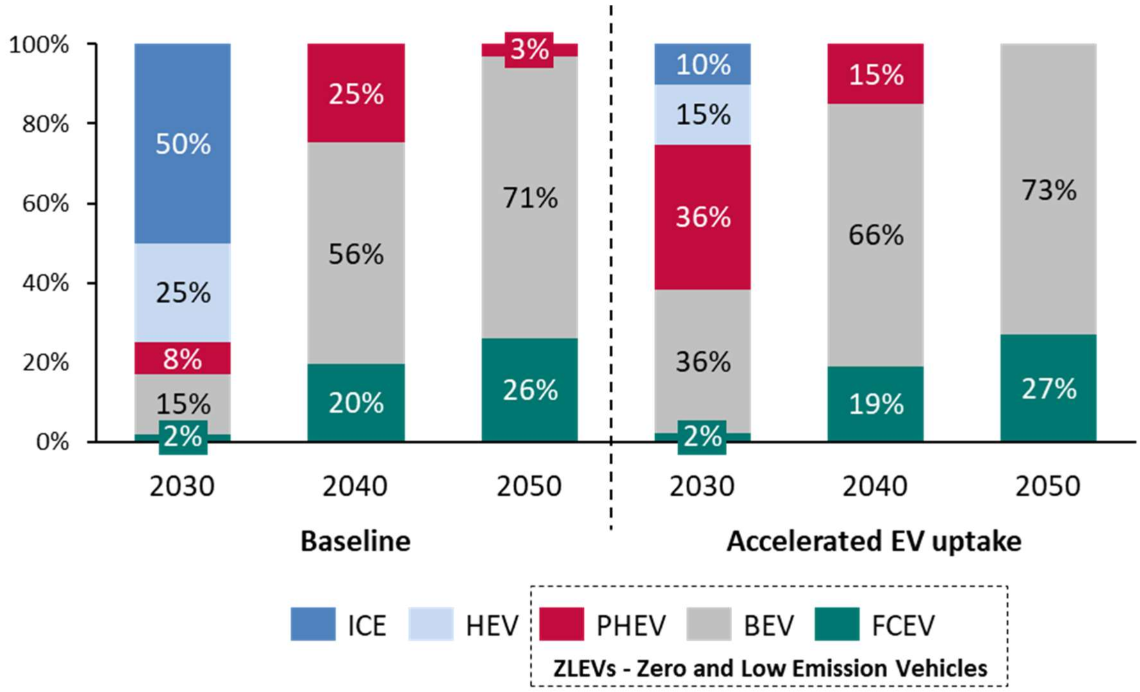


**Figure 1: Overview of vehicle sales in 2030 and 2050 under the two scenarios**

The Baseline scenario is broadly in line with the aforementioned European new car $CO_2$ reduction targets (37.5% reduction of $gCO_2$/km compared to 2021 levels), whereas the Accelerated EV uptake scenario is much more ambitious. This scenario is included as a sensitivity and its outputs are shown

[7] This study only addresses the potential of batteries used in cars. However, due to the use of batteries to electrify and decarbonise other vehicle sectors (e.g. vans, buses, e-trucks) the actual long-term battery volumes is expected to be larger. However, cars are expected to represent over 75% of the available battery capacity in 2050.

[8] Low-carbon cars in Europe: A socioeconomic assessment, Element Energy and Cambridge Econometrics for European Climate Foundation, Final Report, Feb 2018. The TECH and TECH OEMs scenarios from this 2018 report are used, renamed 'Baseline' and 'Accelerated EV uptake". Several OEMs and industry bodies contributed in the development and validation of this study, including Renault-Nissan, BMW, Valeo, and Lease Europe.

in this chapter only. The modelling of the impacts of EVs on electric grids and the economic analysis of battery end-of-life options are reported exclusively for the Baseline scenario.

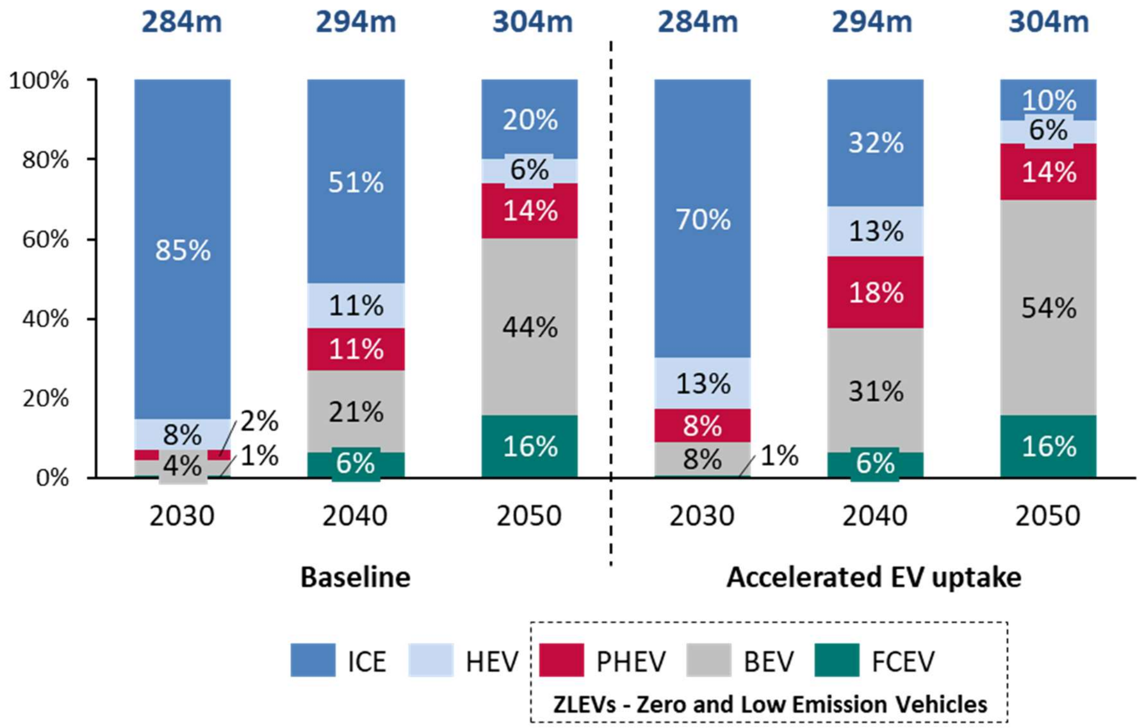


**Figure 2: Structure of the European vehicle stock by powertrain in two key years (figures on top of stacks refer to the absolute EU car stock size)**

The uptake scenarios define the proportion of new sales across each powertrain, which are then divided into fuel type (e.g. ICE, HEV, PHEV, BEV) and size segment (small, medium and large cars). The number of electric-powered vehicles present in the European Union was computed using Element Energy's vehicle stock model (Figure 2). Vehicles are expected to leave the EU stock depending on their age and powertrain type. Our modelling used different exit curves for both ICE vehicles and EVs. Based on OEMs' and customers' experiences to date, both powertrains are expected to have similar average lives, however EVs will experience a lower scrappage rate in the early years (e.g. under the age of 5) relative to ICE-powered vehicles. This is because they are retained in the EU stock for longer, with no EU exports, as neighbouring non-EU importing countries (e.g. Turkey, Russia, North Africa) will lack appropriate charging infrastructure and exporters would face administrative burdens to sell EVs across borders. The full list of assumptions can be consulted in the supporting document accompanying this report.

In 2040 alone, it is expected that between 2 to 4 million HEVs and ZLEVs will be leaving the EU stock, 47% - 58% being plug-in vehicles (Figure 3). Under the Accelerated EV uptake scenario around 10 million battery packs could be recovered from vehicles leaving the stock in 2050.

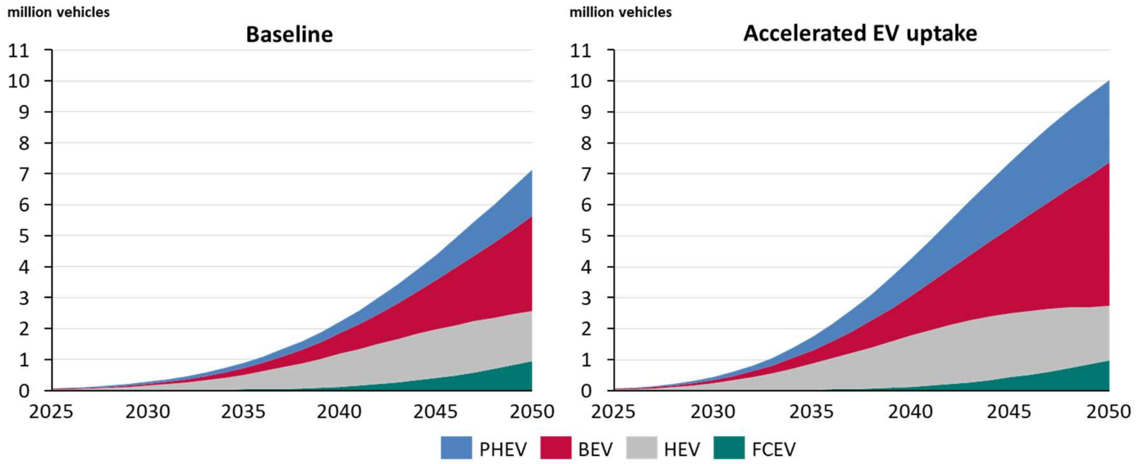


**Figure 3: Number of vehicles leaving the EU stock with batteries recovered (millions per year)**

## 2.2 Vehicle and battery characteristics

As Europe is moving towards road transport decarbonisation, electric vehicles will undergo a series of technological improvements and transformations that, in turn, would shape both the battery recycling and the second-life batteries markets. As a result, the number of batteries recovered, shown in Figure 3, will be a mix of different sizes and electrode chemistries, according to the vehicle type scrapped, its size, and manufacturing year.

- **Vehicle size split**: It is assumed that future vehicles would resemble the characteristics of current ICE powertrains, with the size ratio remaining constant through the years (Small: 32%, Medium: 44%, Large: 24%).
- **Battery energy density**: Batteries are expected to become more compact in the future, with significant energy density (Wh/kg) improvements post-2030.
- **Battery size**: weight reductions due to improvements in battery energy density and the need for longer ranges will enable future vehicles to exhibit battery packs with larger capacities.
- **Battery chemistry**: all results shown in this report refer to Li-ion batteries recovered from EVs as other battery chemistries are not expected to enter the mass EV market within the next 10 years. PHEVs and BEVs already use Li-ion batteries (LIB), however HEVs and FCEVs are currently equipped with small non-Li-ion batteries. HEVs and FCEVs produced post-2025 are expected to use LIBs. The effects of different battery composition variations of LIBs on the economics of recycling are discussed in Section 5.1.
- **Battery costs**: as the industry is moving more towards automation and newer manufacturing technology, the costs of batteries will continue to decrease, making electric vehicles more affordable and increasing their uptake, and eventually the availability of used EV batteries.

The evolution of some of these factors is depicted in Figure 4 below for the batteries utilised in large size BEVs.

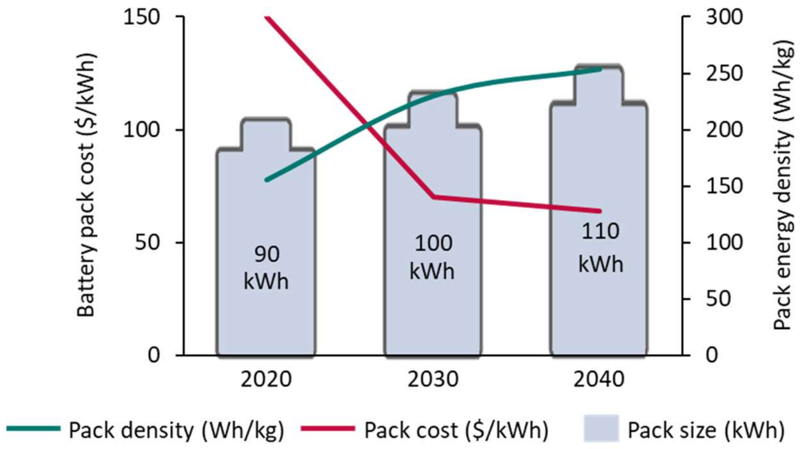


**Figure 4: Key features of future batteries deployed in large size BEVs[9]**

- **Battery chemistry**: as explained in later sections, new battery chemistries are rolled out on a continuous basis. This trend is expected to continue as battery OEMs are trying to achieve better performance and lower battery costs. Since most Li-ion battery uses significant amounts of expensive metals (particularly Cobalt), future vehicles will be equipped with batteries containing lower amounts of Cobalt and higher quantities of cheaper substitute metals (Nickel and Manganese). For example, the dominant battery technology in vehicles manufactured in 2020 is NMC 622 (containing a ratio of Ni:Co:Mn of 6:2:2), whilst 2025's vehicle will utilise a higher proportion (35%) of NMC 811 batteries (8 Ni: 1 Co: 1 Mn), as depicted in the diagram below. As the development of low cobalt batteries progresses, NMC 9.5.5 batteries (containing 9 parts Ni, 0.5 part Co, and 0.5 parts Mn) will cannibalise older and more expensive technologies by 2030.

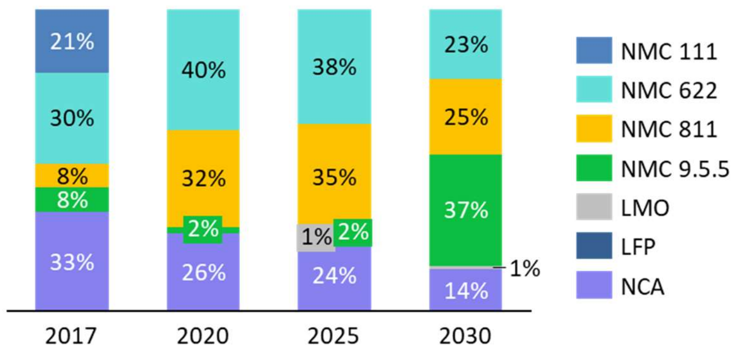


**Figure 5: Demand of EV batteries by chemistry in Europe[10]**

In addition, two factors determine the residual capacity of the recovered batteries:

- **Calendar degradation**: battery capacity loss due to the battery being stored under certain environmental (e.g. temperature) and operational conditions (e.g. State of Charge).
- **Cycling degradation**: determined by the cycling and battery utilisation whilst in the vehicle.

## 2.3 Availability of battery volumes from first life to end of life

Upon removal from vehicles, it is expected that batteries will undergo testing to determine their residual capacity and their fate at the end-of-first-life. The value chains, stakeholders involved, and the

[9] Battery pack costs based on Bloomberg New Energy Finance (June 2018), battery size and density based on Consumers, Vehicles and Energy Integration Project - Battery Cost and Performance and Battery Management System Capability Report and Battery Database, Element Energy for Energy Technologies Institute, 2016
[10] Lithium and Cobalt – a tale of two commodities, McKinsey Energy Insights, June 2018

regulations and economics around each pathway are discussed in the following chapters. The two main end-of-first-life pathways discussed in this report are:

- **Direct recycling**: batteries considered too exhausted for second life applications would have to be recycled. The majority of very old batteries, which spent over 15 years in vehicles, as well as some younger batteries that exhibit premature degradation, would face this fate. Depending on the scenario and year, up to 45% of recovered batteries may be recycled directly in 2050 under the baseline scenario (Figure 6).

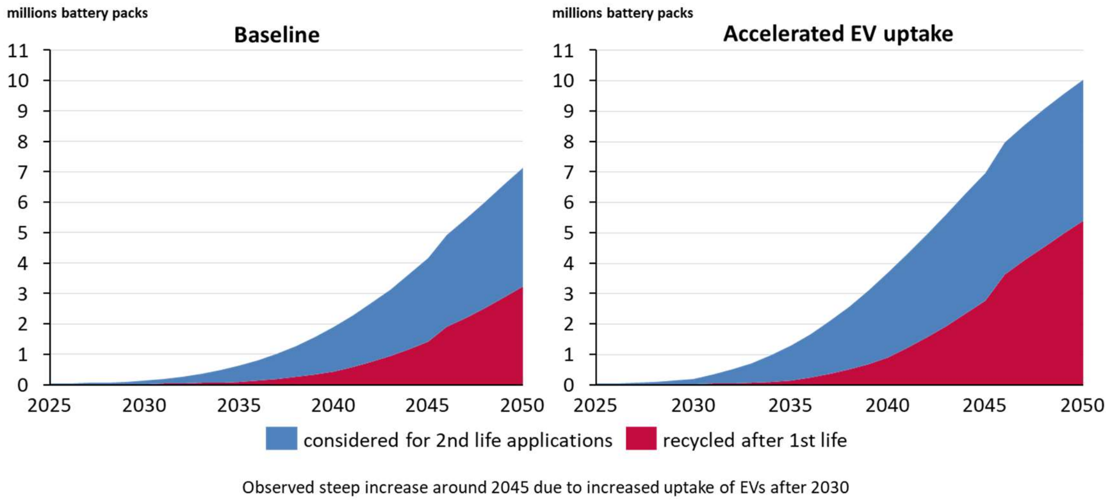


**Figure 6: Fate of recovered batteries (million battery packs per annum)**

- **Use in second life applications**: newer batteries would be more likely to be considered for 2nd life applications as they would have a higher residual capacity. Volumes and residual capacity vary by scenario, but by 2040, 23 to 48 GWh of second-hand battery capacity will be available (Figure 7), both corresponding to 80% of the available battery units in 2040.

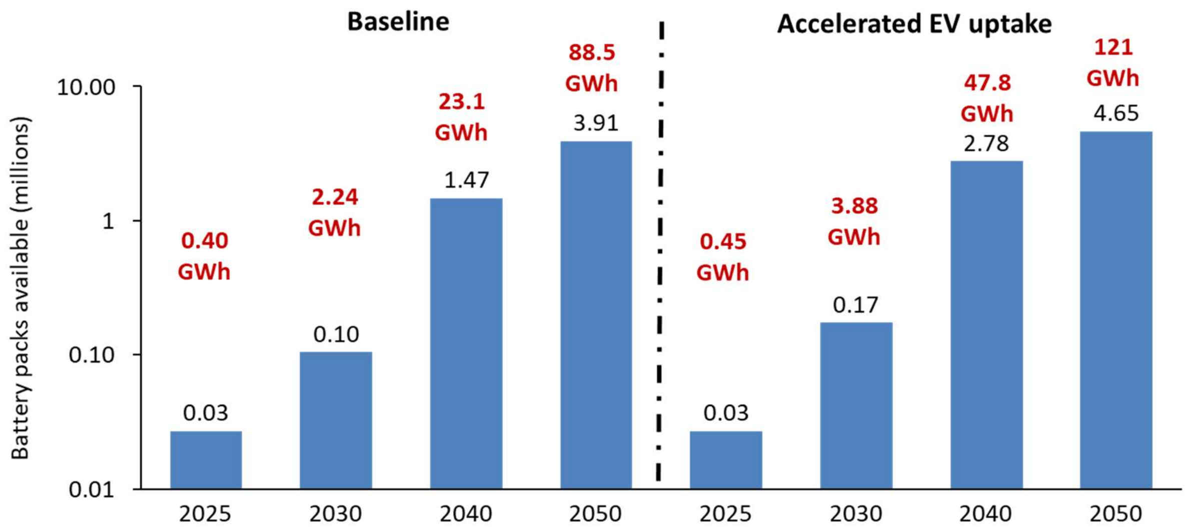


**Figure 7: Number of EV battery packs viable for second life applications (bar chart, log scale) and total residual capacity becoming available in key years (GWh per annum)**

There are a few pathways that second life batteries could take, subject to the remaining capacity and economics:

- **Reconditioning**: battery packs exhibiting only a mild degree of degradation can be processed such that degraded modules and/or cells are removed and replaced with new ones. The battery pack is then rebuilt and reused in EV applications. Battery reconditioning is expected to only be conducted on a small proportion of used batteries, since the economic case is considered unfavourable by OEMs, given that battery degradation may take place homogeneously and newer, improved, and cheaper battery technologies may be available and would supersede older and/or even technologically-obsolete reconditioned batteries.
- **Repurposing**: the vast majority of batteries considered suitable for second life applications would be repurposed by third party workshops or OEMs/battery manufacturers themselves. This process would consist of battery testing, partial pack disassembly and module separation, and connection of different packs, depending on the market requirements – in some cases, direct re-use of the battery after testing might be possible. The end application is expected to be related to stationary energy storage, for different purposes. A series of economic case studies of potential storage applications is included in Section 5.2. The impact of storage on electricity systems in selected European countries is detailed in Chapter 3.
- **Other applications**: a small proportion of batteries could be used in other non-storage applications (e.g. research).

Different second life expectancies are modelled depending on the battery age and residual capacity at the time of recovery from the EV, and type of second life application. 4 to 10 million batteries could be in second life applications in 2040, and up to 35 million in 2050. The structure of the second life application stock is shown in Figure 8.

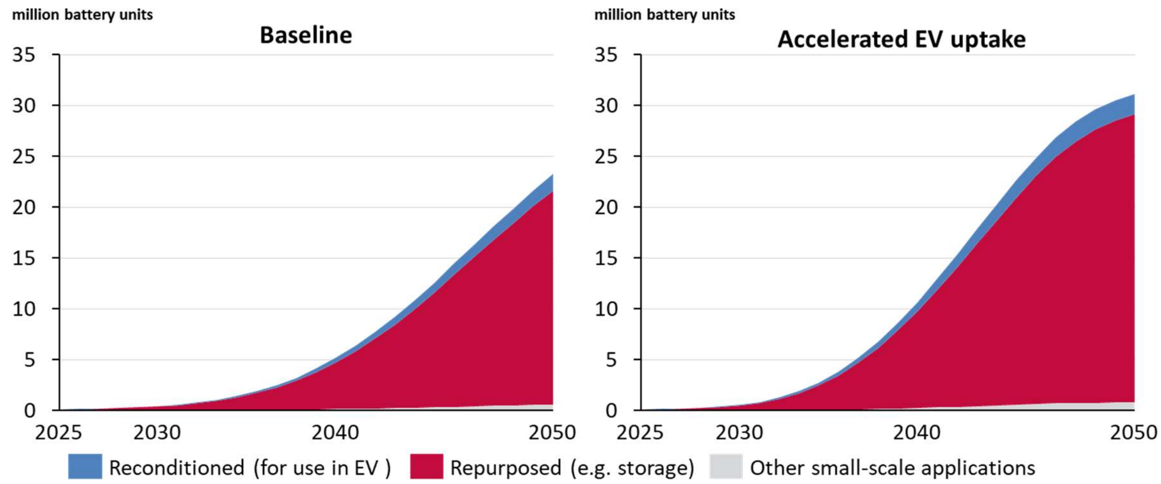


**Figure 8: Structure of the second life battery stock (million units)**

Second life batteries will eventually face recycling and will represent a significant volume of the Li-ion batteries processed each year by recyclers (Figure 9), however most of the recycled volumes will still consist of batteries recovered after the first life. The Accelerated EV uptake Scenario (accelerated uptake of BEVs) will almost double the weight of batteries recycled in 2050 in comparison to the Baseline Scenario (slower uptake) – 1,100 vs 574 kilotonnes.

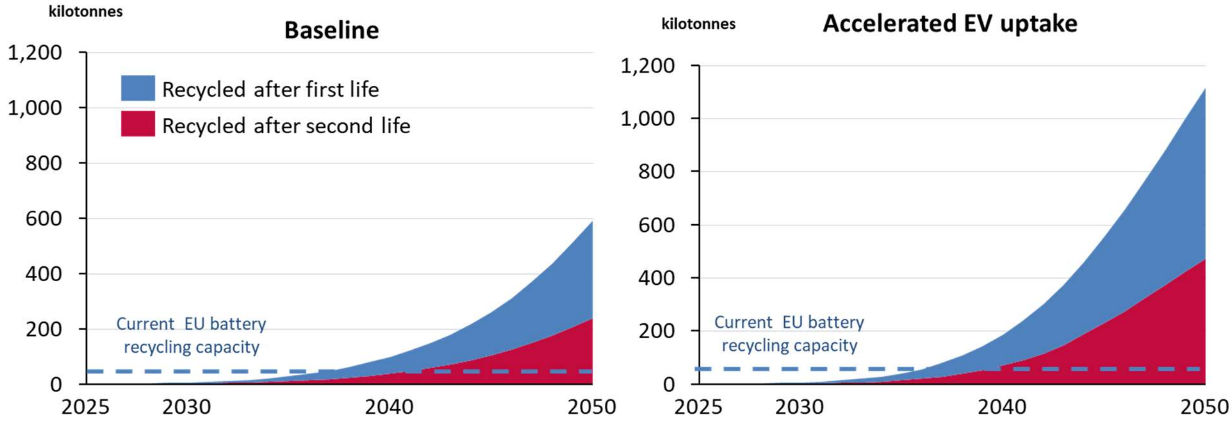


**Figure 9: Batteries recycled each year in the EU (kilotonnes)**

# 3 Impact of EVs and storage in decarbonised electricity systems

## 3.1 How decarbonisation changes the electricity system

Achieving the level of decarbonisation required to limit global warming to 1.5 degrees is hugely challenging across all sectors. Increasingly, the electricity sector is acknowledged as leading the way, supplying low carbon electricity as a decarbonisation for end use sectors.

Decarbonisation of the power sector will rely heavily on the increasing penetration of variable renewable energy sources (VRES) such as wind and PV, on to electricity grids. This presents a fundamental challenge to the operation of the power system, which has historically been reliant on flexible thermal plant to be dispatched in response to end use demand. In power systems dominated with VRES, operation of the system will move away from responding to load and instead will need to respond to managing net load - this is the residual load *after* renewable energy generation is netted off from demand.

The graph below shows an example net demand curve for a decarbonised power system, over a year of hourly data. The data is arranged from hours of largest positive net demand to minimum net demand. In the upper portion, the challenge is to ensure security of supply during the hours of largest residual net-demand (left side) and to minimise the requirement for dispatchable low carbon generation (such as flexible hydro, biogas generation, or interconnectors) to fill the supply gap. When the net demand is negative (excess VRES – visualised on the right side of the graphs) the challenge is to limit the wasteful curtailment of VRES.

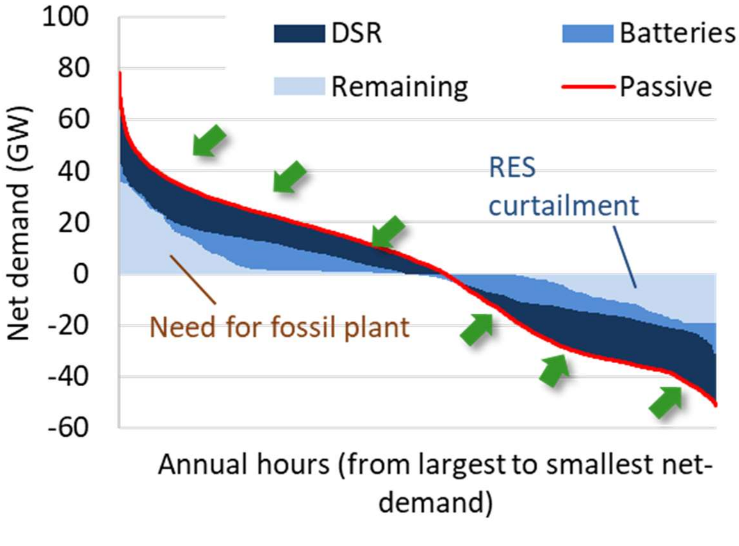


**Figure 10 Example annual net load for a decarbonised power system**

Increasingly the objective of managing low carbon power systems will be to flatten the net demand curve. The graph above shows the potential impact of flexible demand resources such as grid responsive "smart" EV charging which can move EV charging demand out of times of peak demand, and into times where there is a surfeit of renewable energy. The graph also shows the impact of utility battery energy storage in flattening the net demand curve, an effect that V2G could also generate. These flexible end uses will become increasingly central to managing power systems.

## 3.2 The increasing roles for storage in decarbonised energy systems

Flexibility of electricity demand, and electricity storage have the potential to provide many services to the power system. At present, cost of storage is high (ca. 300€/kWh although reducing). As a result, the most viable utility storage applications relate to the provision of high specific value services such as Primary Control Reserve (PCR – for many EU member states), or Frequency Response (a similar service in Great Britain). These services reward high power but only limited amounts of energy, and so battery storage costs can be low. However, these markets are small, and when open to competition prices have dropped significantly (such in GB where FR prices are now about one-third of those 3 years ago).

Longer term, as storage prices continue to drop, the storage market will transition to competing and displacing fossil fuelled peaking plants, with durations of 4-8 hours. Flexible assets can avoid the capital expenditures on peaking plant, as well as the fossil fuel used in these (relatively inefficient) power plants. This duration, expected by 2030, is close to the diurnal storage requirement for firming up PV energy, and so from 2030s onwards[11], storage assets can undertake daily energy arbitrage to minimise renewable energy curtailment, reduce fossil fuel use and reduce energy costs to consumers.

Another important service that flexible assets can provide is avoiding network constraints, particularly at distribution level. The electrification of heating and transport will add significantly to the loads on the electricity system which may require network upgrades to accommodate. Flexible demand for electricity, via smart (grid responsive) charging can delay network upgrades and save the power system significant costs.

## 3.3 Modelling system impacts of electric vehicles and storage (2040)

### Whole system modelling

Element Energy's electricity dispatch model predicts electricity production and consumption on national level and hourly basis for 1 year; outputs include fuel and carbon costs, RES curtailment, peaking generation and network capacity requirements. The main principles of whole system operation are summarised here.

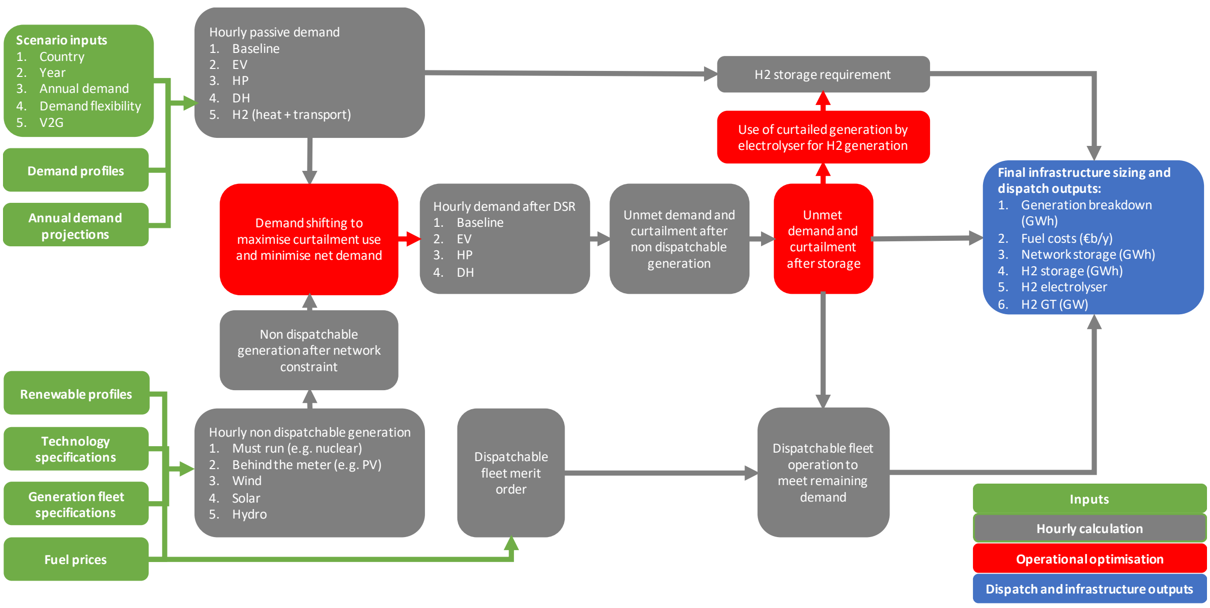


**Figure 11 Whole System Modelling**

[11] In line with GTM prediction of 4h battery storage becoming competitive with new peaker plants in 2027

The starting point is the ENTSO-E TYNDP 2018, Global Climate Action (GCA) 2040 scenario. This determines power capacity data (GW per generator type) and baseline electricity demands (i.e. before accounting for significant additional consumption in transport and heat sectors). The dataset also provides hourly profiles of these baseline demands.

Transport specific electricity demand is based on the stock of electric vehicles, their efficiency, the daily usage, and data on arrival/departure times from home and work to generate baseline electrified transport demand. Smart charging can schedule charging to times of most use to the power system, while still ensuring vehicles have sufficient charge for transport.

The supply-side hourly generation output is determined from hourly weather data and the ENTSO-E set of capacities. Hourly VRES output and hourly demand are then compared. Demand shifting is deployed to minimise net demand (i.e. residual demand for thermal generation and minimise renewable generation curtailment). Network capacity is adjusted to optimise between demand-driven and network curtailment. The dispatchable generation fleet is then deployed in merit order to fill in the supply gap. Once all hourly demands are met, annual system performance metrics are evaluated (emissions, fuel use, infrastructure sizing and the costs associated with those).

## Whole system scenarios

The set of scenarios modelled is shown below. They are designed to test and explore important dimensions:

**Inflexible vs. flexible:** As a base case, the ENTSO-E scenario does not assume significant levels of flexibility in the system – loads are predominantly passive. This is used as a base case to compare other scenarios against.

**Competition between sources of flexibility:** Utility batteries and smart EV charging can provide alternative sources of flexibility and this is explored. Stationary battery storage is sized by the model based on economic viability.

**Smart vs. V2G:** The regeneration of electricity from EVs back into the grid increases flexibility of EV assets.

| Scenario | Description |
|---|---|
| ***Baseline*** | • Reference scenario corresponding to ENTSO-E model<br>• EV demand is modelled flat and no stationary batteries are deployed |
| ***Passive*** | • EV charging is uncontrolled<br>• No stationary batteries are deployed |
| ***Passive + storage*** | • EV charging is uncontrolled<br>• Stationary battery storage is deployed up to an economic level |
| ***Smart*** | • EV charging is managed providing flexibility to the system<br>• Stationary battery storage is deployed up to an economic level |
| ***V2G*** | • EV charging is managed and in addition, electricity is discharged back from vehicles to the grid (V2G)<br>• V2G infrastructure is deployed at the economically optimal level<br>• Stationary battery storage is deployed up to an economic level |

**Figure 12: Scenarios tested using the Whole System Model**

The deployment of battery storage in each scenario is limited to an economic threshold. This threshold is based on projections of 2040 battery storage cost and the revenues that could be generated from daily electricity arbitrage as well as network congestion relief and security of supply services. It is determined by comparing the marginal system benefit of deploying battery storage in terms of savings of investment in infrastructure such as peaking plants and electricity grids as well as savings in operational cost of electricity production with the marginal cost of deploying this storage. The storage is deployed up to a level where the marginal benefit equals the marginal cost. This level is dynamically derived from the net demand profile and so varies per scenario. In most cases the economic constraints lead to a level of GWh battery deployment that achieves more than 130 cumulative full charge/discharge cycles per annum. 130 cycles require the battery to be utilised quite frequently, for example requiring relatively significant depth of discharge on a near-daily basis. Battery storage is deployed after DSR has flattened the net demand curve.

### Sensitivity studies

In addition to the scenarios above, a number of sensitivities are modelled:

- The impact of low cost 2nd life batteries that improve the economics and overall level of utility storage and the relative cost effectiveness of smart charging and V2G.
- In sunnier countries, there is a positive relationship between battery storage and PV deployment. Batteries can reduce daily curtailment of peak PV energy output, regenerating back to the grid in evenings/overnight; while the regular diurnal output of PV helps batteries achieve the annual cycles required for economic viability and thus increases economic storage deployment. This beneficial impact can be improved with additional daytime charging, which is explored in this scenario.
- The ENTSO-E GCA 2040 scenario for Italy has lower VRES deployment (as a % of demand) than in other countries. As a sensitivity, the solar PV deployment levels in Italy were increased to explore the impact this has on flexibility.

## 3.4 Potential for EV and grid storage (2040)

### Whole system Cost and benefits: GB and FR

The power systems of four countries (France, Spain, Italy and the Great Britain) were modelled in 2040 under the scenarios described above. The results for GB and FR are shown below (Figure 13). Wind (about 30%) and solar (about 10%) shares of electricity generation are similar in GB and FR. The vertical axis shows additional costs and benefits relative to the counterfactual baseline scenario. This baseline scenario is the ENTSO-E GCA 2040 with EV electricity load added to the system to be consistent with the other scenarios.

The Passive scenario is when EVs are allowed to charge as soon as they arrive at work or home. As there is a significant overlap between baseline electricity load and end of evening commute, this adds a significant additional load to the grid (peak load increase between 9-18% depending on country). The primary impact of this is the additional network capacity that would be required to carry electricity at peak times. Further impacts are an increase in peaking plant capacity and in generator fuel use because of the increased use of these peaking plants relative to the baseline.

In “Passive + Storage”, grid utility batteries are deployed up to the economic threshold defined above. As can be seen, these help to avoid new peaking plant and the additional fossil fuel use in the Passive scenario. However, the impact of passive charging on networks is still significant.

When smart charging is deployed, there is a cost to the system due to the smart charging infrastructure. This cost is more than offset by savings throughout the energy system. Notable is the saving at generation opex (fuel) because EV charging is able to flow into periods with significant VRES output, displacing fossil plant. However, curtailment is not significant and so the impact is not as large as Spain (see below). Note also that grid battery deployment is significantly reduced, because smart charging significantly reduces the supply-demand mismatch that batteries rely on for revenues.

In the V2G scenario, only a fraction of the total EV fleet is made V2G, because the additional arbitrage value is only slightly larger than the increased V2G infrastructure cost. In GB, only 10% of the potential V2G storage capacity is used, in France, 15%.

Overall the net system benefit of smart charging is ca. €1.2-1.3billion/annum compared to passive.

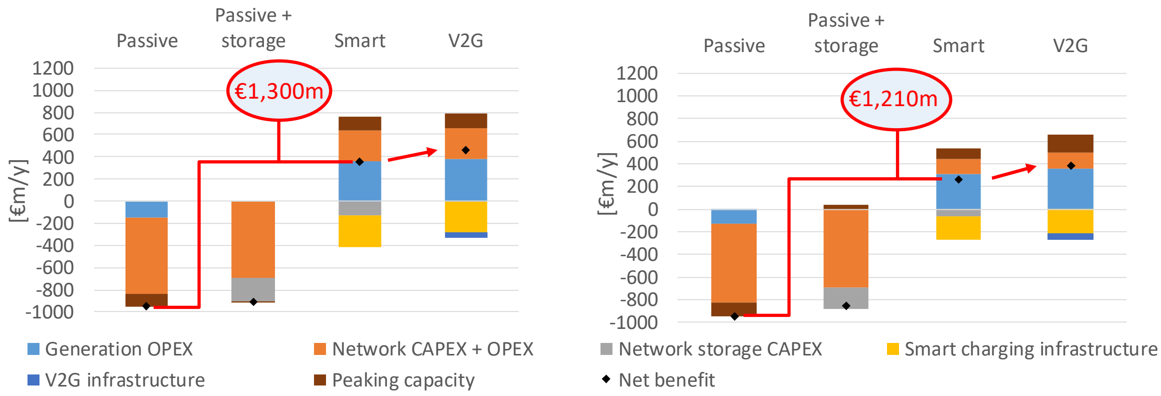


**Figure 13: Whole system cost and benefits 2040: GB (left); FR (right)**

## Whole system Cost and benefits: ES and IT

The whole system net costs for Spain and Italy are shown below. As with the first two countries, the Passive scenario results in a significant increase in peak network loads and there is a significant cost associated with this. However, the results are very different for the remaining scenarios.

In Spain, the Passive + Storage scenario results in a very large improvement in net benefit. This is because the high Solar PV deployment levels lead to significant daily curtailment, which is largely avoided through storage. This is the reason for the significant generation opex saving: the PV energy stored in the batteries displaces fossil plant when released. Relative to this (highly flexible) scenario, smart charging does show a net benefit, but it is not as marked as in GB, FR, because in Spain the utility battery storage already has captured much of the value from flexibility. One significant benefit of smart charging is reduced network investments. In Spain, V2G deployment (as a fraction of EV) is high (74%) again because of PV curtailment.

In Italy, the network related savings are more important than generation opex savings because the ENTSO-E GCA 2040 scenario has lower levels of VRES deployment (and curtailment) compared to Spain. Passive charging would result in significant network costs; these can only be avoided with Smart charging which shows a net benefit of almost €1.3B/annum compared to passive.

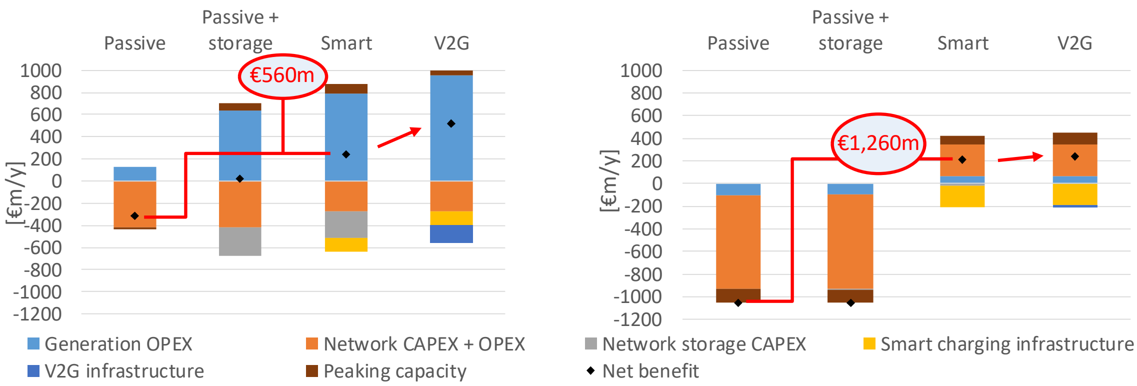


Figure 14: Whole system cost and benefits 2040: ES (left); IT (right)

## 3.5 Curtailment and $CO_2$ intensities

The environmental performance of the power systems of four countries is shown below, under each scenario. In GB, storage does reduce annual curtailment and grid $CO_2$ intensity reduces, but the impact is much more marked when smart charging is deployed. Compared to passive, smart charging reduces $CO_2$ intensity from 87 to 78 g $CO_2$/kWh, and annual curtailment is reduced by 60%. However, the beneficial impact of V2G is marginal.

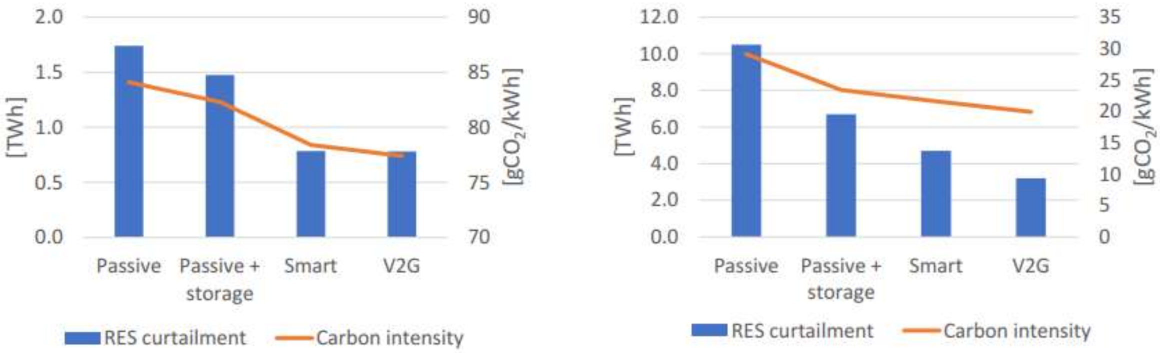


Figure 15: Curtailment and grid averaged CO2 reduction: GB (left); ES (right)

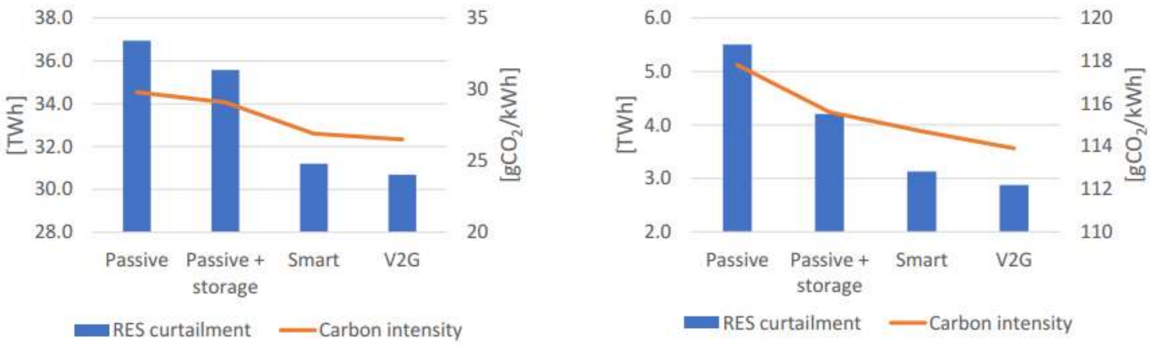


Figure 16: Curtailment and grid averaged CO2 reduction: FR (left); IT (right)

In Spain, grid storage has a significant beneficial impact on curtailment and $CO_2$; and the benefit continues to increase with Smart charging and then V2G. Overall, curtailment is reduced from 10.5TWh to just over 3TWh/annum, while grid $CO_2$ intensity drops by one-third.

### Sensitivity: Higher PV deployment in Italy

The data below shows the result of increasing PV deployment in Italy, compared to the ENTSO-E GCA 2040 data used elsewhere in the report. This scenario uses the ENTSO-E DG 2040 generation mix, which has twice the solar capacity of the GCA scenario in Italy.

Note that because solar generation is different in these sensitivity models, then the starting point “base case” is also different. For example, to accommodate high PV deployment, the network capacity is increased in order to limit network curtailment of PV energy. This is why the high PV scenario (right hand graph) does not show such a large network disbenefit of passive EVs: the higher grid capacity available in the base case is already able to accommodate much of the passive EV demand. Given the DG generation mix, with high PV the V2G scenario shows a significant additional benefit compared to the Smart scenario. The result is similar to the performance of Spain which shows the most marked benefit in reducing generation opex (fossil fuel) costs.

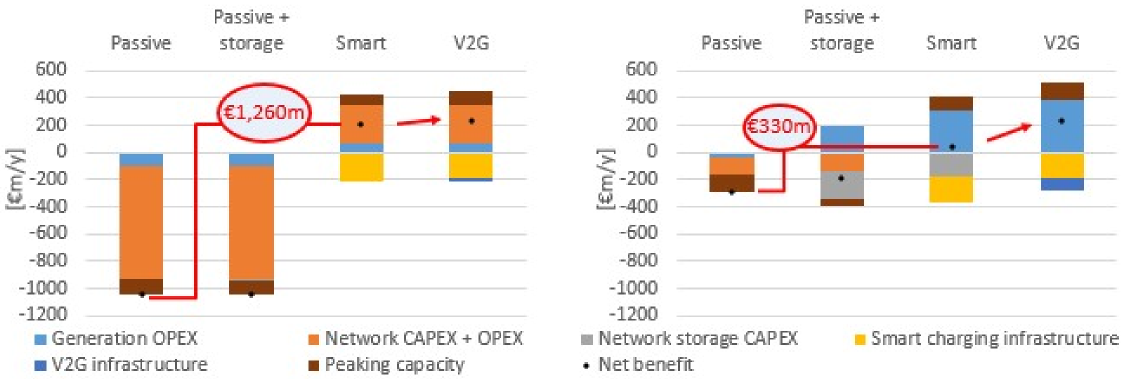


**Figure 17: Whole system cost and benefits 2040 in Italy: original scenarios (left) and sensitivity with higher PV deployment (right)**

### Sensitivity: Higher daytime charging in Spain

This scenario explores the system impacts of having a higher daytime charging ratio, compared with the base case assumption used elsewhere in this report (see relevant section in the appendix). Note that this sensitivity is applied to all scenarios not just flexible scenarios. Daytime charging reduces charging at home in evenings, which was observed to require grid reinforcement. Therefore, the largest benefit is in improving the Passive scenario; where previously this was estimated to cost €M300/annum in Spain, higher daytime charging could make Passive cost neutral. This is due to reduced evening peak loads, and higher use of daytime PV, which reduces fossil fuel in power plants.

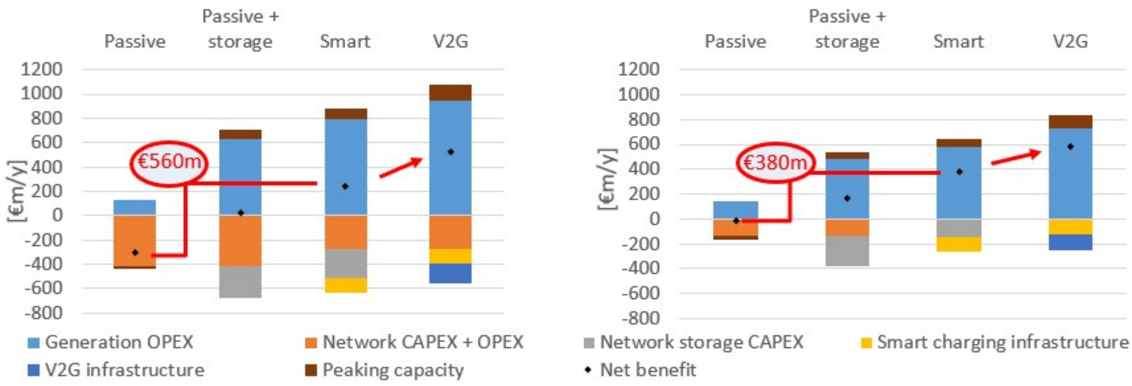


**Figure 18: Whole system cost and benefits 2040 in Spain: with original EV charging pattern (left) and with higher daytime charging ratio (right)**

## 3.6 Challenges to smart charging deployment

The above results demonstrate the value that smart charging can provide to all levels of the power system, reducing investment costs, fossil fuel use, $CO_2$ emissions and ultimately reducing consumers energy bills. The analysis also shows that there will be interaction between technologies providing the flexibility that power systems will increasingly need.

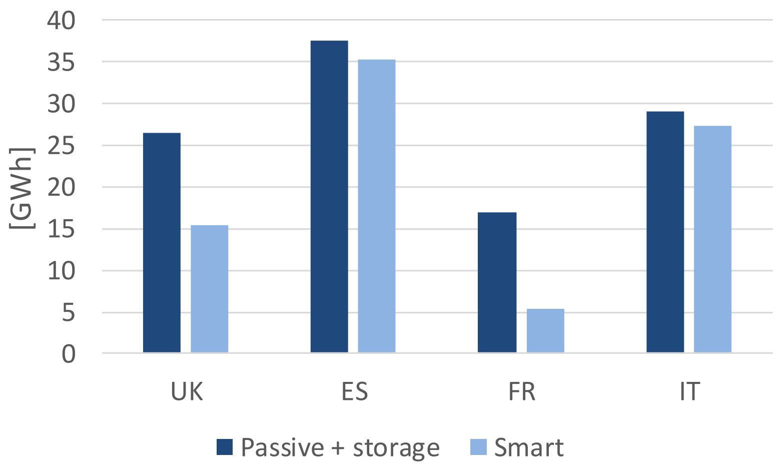


**Figure 19: interaction between grid batteries and smart demand (2040)**

The graph above shows the amount of utility battery deployed in each country, for two scenarios in 2040. Deployment of smart charging reduces the level of economic deployment that utility-batteries can achieve. The impact is greatest in UK and FR; passive charging makes it more challenging to match supply and demand, and this results in high levels of battery deployment. In the Smart charging scenario, the supply/demand mismatch is not so acute, and so battery deployment is lower in UK and FR. The impact is not so large in ES and IT (we report on the IT sensitivity with higher PV). This is because PV deployment is very high, which results in significant levels of VRES supply curtailment. Both utility batteries and smart demand work to reduce this level of curtailment; also the daily cycling of batteries in response to PV supply patterns supports grid battery deployment. In all cases, growth of storage is extremely high: the economic capacity in the UK (15.3GWh) is 34 times as high as the battery storage capacity deployed today.

## Competition from 2nd life batteries

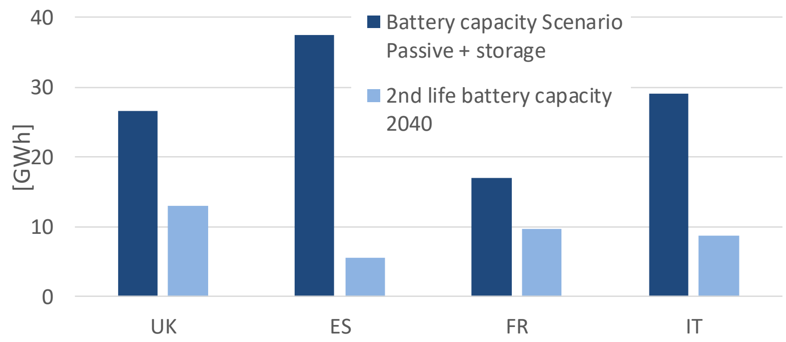


**Figure 20: Impact of cheaper (2nd life) batteries on grid storage**

As shown elsewhere in this report, 2nd life batteries will emerge from the vehicle stock in large numbers and at lower costs than the incumbent. As these costs are lower, we can expect this to lead to greater levels of economic grid deployment. This would be good for the energy system but would be challenging for the continued deployment of new utility batteries, which would be outcompeted by the cheaper 2nd life cells. The graph above shows the cumulative capacity of 2nd life batteries from national EV fleets, available in 2040 compared to the storage capacity that could be economically deployed in the same period based on the costs of new battery cells. It shows that 2nd life cells could displace a fraction of the required capacity, but that this is supply constrained – there are not enough 2nd life cells available to supply the full demand for batteries and thus there are still significant opportunities for deployment of new stationary batteries.

As a sensitivity, the Smart scenario has been modelled in Spain assuming plentiful availability of cheap 2nd life batteries for applications in stationary grid storage. Even after accounting for a shorter lifetime of 2nd life the economically deployable storage capacity is increased by more than 50%, driven by lower storage costs. The additional storage capacity helps to achieve an additional net benefit of €70M per year and to reduce the carbon intensity by 4%.

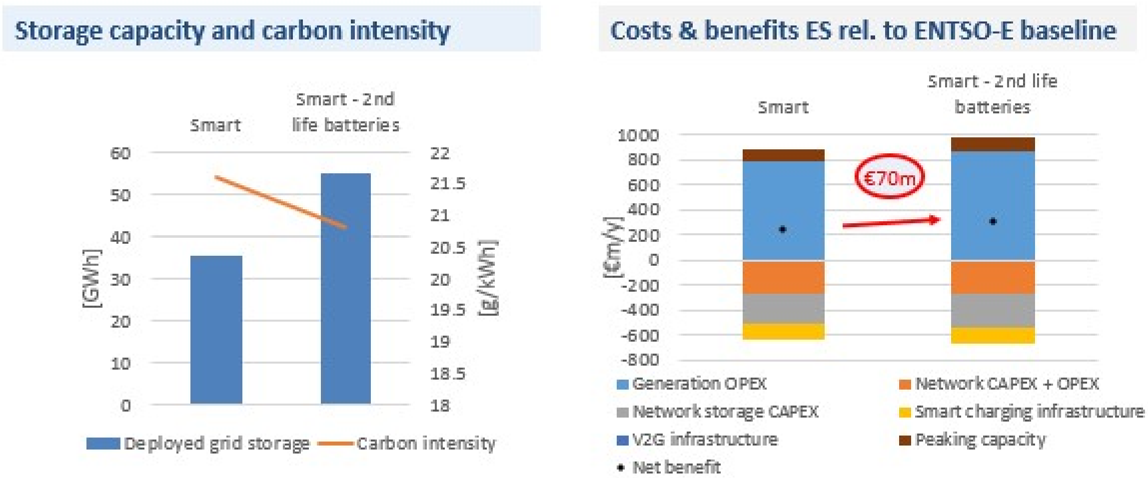


**Figure 21: storage capacity and carbon intensity (left) and system costs and benefits in the Smart scenario in Spain with new batteries and 2nd life batteries (right)**

While 2nd life batteries could thus play a significant role in European markets for storage in stationary grid applications, there are many other potential areas where 2nd life batteries could be deployed such as behind the meter applications as well as in international markets for backup generation assets in particular in countries with areas with still emerging electricity grids. There is likely to be some downward pressure on grid storage prices due to 2nd life batteries, but this will be limited by 2nd life supply constraints.

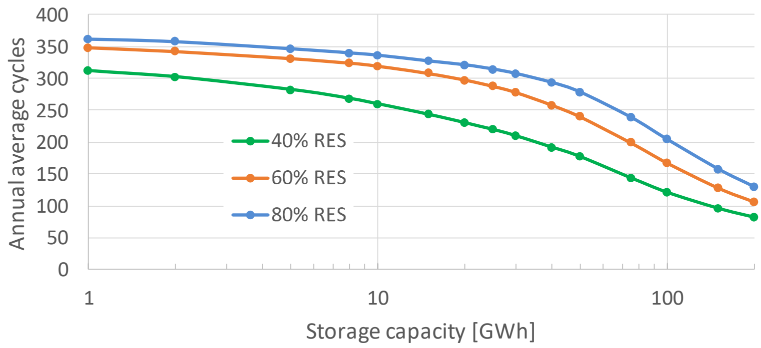


**Figure 22: The reducing marginal benefit of storage and the impact of high VRES**

Within an energy system with a fixed capacity of VRES, as increasing storage volumes are deployed, the utilisation rate of batteries decreases. As the graph above shows, initial deployments of batteries are utilised highly to smooth out supply/demand mismatches. Subsequent deployments achieve lower utilisation. Lower utilisation means reducing the average annual cycling (revenues) of the battery fleet.

However, there is a positive synergy between the deployment of storage capacity and increase of VRES in power systems. Higher VRES deployments tend to increase the mismatch between supply/demand, and greater battery energy capacities can be economically deployed. Continued deployment of VRES in line with decarbonisation targets will support the continued deployment of flexibility solution such as batteries. This is an essential part of the self-reinforcing dynamic between greening electricity and smartening demand flexibility.

## 3.7 Necessary actions on policy and legislation to support EV grid services

**Smart charging as a minimum standard for EV charging**

The analysis clearly shows the high system cost of passive EV charging, particularly at distribution level, which can be addressed very cost effectively with smart charging. The case for making smart charging the minimum performance standard is very clear. Legislation should be developed to encourage this, including the review of residential distribution connections which currently socialise the cost of passive residential charging.

The deployment of smart (rather than passive) chargers could be encouraged via grants to cover the cost difference between them. As an alternative to smart chargers, the deployment of smart vehicles should also be encouraged. This is where the decisions related to charging and power are retained by/routed through the EV, which would be connected to a passive charging infrastructure.

Deploying smart charger infrastructure is not sufficient to ensure smart charging, and drivers will need incentives to charge in the appropriate way. This could include grid time of use tariffs linked to smart metering.

**Support the development of whole system flexibility markets**

The analysis showed that smart charging can work to reduce network congestion/investments (grid responsive), and also to reduce investments and operational costs at generation level as well as curtailment of renewable energy (energy responsive). Our analysis showed that the smart charging response to network congestion, energy curtailment or grid service provision is not always aligned. Clear rules about the operation of flexible demand will need to be developed for the whole system to run efficiently. In deregulated energy markets, where taking a whole system view is not only difficult but often contrary to legislation, these rules will be vital to develop. Member states should encourage dialogue between national System Operators and Distribution Network/System Operators to evaluate critical system needs and therefore the priorities of operation of flexible demands such as smart charging.

Dynamic pricing, with energy and network tariff components, could reveal scarcity /abundancy situations on the supply side and grid stress conditions. To ensure that distributed assets can play their role in supporting grid decarbonisation, aggregation of distributed resources and non-discriminatory access to flexibility markets (such as balancing markets, non-frequency ancillary service markets and CRMs) are paramount as well. Flexibility markets should be open to aggregated resources connected at distribution level and provide sufficient and stable incentives to de-risking investor decisions. As flexible assets could augment or replace many system critical assets, trials of flexibility technologies will be necessary to prove-out operational benefits. Supporting these will inform and underpin the necessary changes in regulation.

**Flexibility and continued deployment of VRES**

The analysis showed that flexible technologies (storage and smart charging) have a synergistic relationship with VRES. Without flexibility, high deployments of VRES will become less and less viable due to curtailment of output. Similarly, batteries need high levels of VRES deployment in order to maintain the levels of annual battery cycling required to generate required revenues.

This synergy should be acknowledged as being central to delivering plans for deep decarbonisation of power systems, and should be reflected in national energy and climate plans. This aligns with the Commission objective to empower European consumers to become fully active players in the energy transition. While the Clean Energy for all Europeans package acknowledges the need for certain types of flexibility (increased transmission interconnection capacity) but this should be augmented with a broader range of demand based flexibility assets such as those described in this report.

**Encouraging daytime charging in countries with high PV deployment**

Our analysis showed that daytime charging of EVs is extremely beneficial to power systems with high levels of PV penetration. National plans for EV charging infrastructure should respond, not only to driver needs, but also to expected patterns of energy supply, in order to deliver the greatest net benefit to customers.

Daytime charger archetypes include workplace charging as well as rapid charging facilities. As improvements in battery technologies allows EV charging rates increase, rapid charging (100’s kW peak power) could be deployed not just on highways to support long distance travel, but also in cities to support more frequent top up charging during the day. Actions encouraging ambitious daytime charging infrastructure could support rapid charging; workplace charging could be supported by Member State transposition of the Energy Performance in Buildings Directive. The Alternative Fuels Infrastructure Directive allows Member States to decide whether to “concentrate deployment efforts on normal or high-power recharging points”. Member states should take a whole system approach, aligned with national decarbonisation trajectories to evaluate the full cost-benefit of charging infrastructure deployment in their national policy frameworks.

# 4 Evaluation of battery recycling

## 4.1 Recycling processes

### Overview of recycling processes

Battery packs are complex goods, with each pack containing dozens of different components made of various materials. Battery recycling is thus a selective process which must ensure a high recovery of the scarce materials and proper management of any dangerous components. At the same time, battery packs come in different sizes, shapes and chemistries, increasing pressure on recyclers to optimise recovery processes in order to achieve high flexibility between different battery batches whilst maintaining scalability and financial sustainability.

Each battery pack undergoing recycling goes through a series of steps where it is transformed and broken down into simpler components. A series of physical preparatory steps usually involve sorting batteries by chemistry type, dismantling the battery pack to a module or cell level, which could then be directly fed into the recycling scheme or further fragmented by physical means (e.g. shredding or grinding). In terms of recycling schemes, depending on the battery chemistry and process chosen, several steps involving physical, mechanical, and/or chemical transformations may be needed. Although each recycler may use a variation or combination of different individual steps, recycling processes (or schemes) can be broadly classified as follows:

- **Pyrometallurgical recycling** involves the use of heat to recover (mainly) metallic battery components.
- **Hydrometallurgical recycling** usually follows initial battery shredding and involves a series of chemical steps in which the metals in the battery powder are brought into solution (hence the name of hydro-metallurgical), separated and extracted.
- **Mechanical or physical recycling** schemes avoid any use of thermal or chemical energy and rely on the mechanical and/or physical separation of battery components into battery-grade ready materials. This is a new recycling technology, different from some other physical processes that may be used in preparing batteries for pyro- and hydro-metallurgic recycling (e.g. milling, shredding, or thermal pre-treatment).

**Individual Processes**

| Physical | Chemical |
|---|---|
| Mechanical Separation | Acid leaching |
| Thermal Treatment | Bioleaching |
| Mechanochemical Processing | Solvent Extraction |
| Dissolution | Chemical Precipitation |
| | Electrochemical Process |
| | Smelting |

| Recycling schemes |
|---|
| Pyrometallurgic |
| Hydrometallurgical |
| Mechanical / Physical |

Figure 23: Overview of recycling processes and schemes

Different schemes may eliminate new battery production steps, hence increasing the value of recycling. Depending on the steps involved, battery recycling schemes may:

- Return some raw materials recovered from batteries (pyro and hydro-metallurgical)
- Return raw materials in a form that removes some processing steps in the battery supply chain – intermediate recycling (physical, hydro-metallurgical or a pyro/hydro combination)
- Return materials in a form that can immediately be reused to form electrodes and electrolytes – direct recycling (physical)

Reconditioning can be considered an extreme form of physical recycling under which a new battery pack is made out of used cells.

### Pyrometallurgical recycling

Pyrometallurgical recycling schemes rely on the use of high-temperature furnaces in which the batteries are placed. In some cases, particularly for large battery packs (as those of EVs), some preliminary dismantling of the pack is needed. The high temperature inside the furnace causes combustible battery materials to burn (e.g. graphite anode, aluminium wires, paper and plastic casing), with the generated heat being re-used in the process. At the same time, other chemical components (e.g. copper, cobalt, nickel, iron) are reduced to molten metals which are collected as alloys at the end of the process. The solid alloy is usually sent to metal refineries for further processing and recycling. A furnace slag, consisting of ashes of the burnt components and primarily containing lithium, aluminium, silicon, calcium and some iron compounds, is also recovered. Generally, it is considered uneconomical to recover individual components from the slag. However, some recyclers sell or reuse the slag (rich in structural oxides) as a cement additive whilst others (e.g. Umicore) submit the slag to further recovery steps using hydrometallurgy. Pyrometallurgical processes are the most mature battery recycling technology and have the main advantage that all battery chemistries can be recycled simultaneously, however the range of recovered materials is rather limited as discussed in the following section.

### Hydrometallurgical recycling

Hydrometallurgy uses acids to dissolve the metal components of batteries (primarily found in the cathode of LIBs) in a process known as leaching. In order to facilitate dissolution, battery packs are dismantled, and cells are usually further fragmented by crushing and/or shredding. Once the metals are brought into solution, depending on the recycling facility, several solvent extraction, chemical precipitation and/or electrolysis steps may be required to separate the constituent elements. In general, the recovery rate is high, with individual elements being separated as inorganic salts. The main drawback of hydrometallurgical processes is the difficulty associated with processing different battery chemistries and types, as each recycling sequence has to be optimised for a certain battery chemistry to ensure high recovery and favourable economics. In addition, emissions associated with the electricity and manufacturer of chemicals used are not negligible.

### Physical/mechanical recycling

This consists of manual and/or automated dismantling of the battery pack, with key components being recovered in their original state (e.g. electrodes, wiring, casing). Some recovered components (e.g. electrodes) may be used directly in the manufacturing of new batteries whilst other components (e.g. wiring) can be recycled using usual pyro or hydro schemes (as metals). Although this type of process provides components that can be reused in new batteries immediately, without much additional processing, it is still under development and in pilots only, without large-scale applications. Potential barriers to success could be associated with the reusability and the performance of recovered battery components as well as with the risk as some of those components (electrodes) may become obsolete in the future since the battery market is moving towards new electrode types (e.g. decreased cobalt content) or chemistry (e.g. solid state, Li-S).

## 4.2 Recycling process assessment

We conducted a thorough review of current recycling processes used in Europe, through a broad literature review on the types of materials recovered and the emissions associated with each process. The three main process types (pyro, hydro, and mechanical) were then assessed against seven different performance metrics. It must be noted that the recycling industry is highly regulated with recyclers facing challenges to meet policy targets whilst implementing a sustainable business strategy. This is reflected in some of our findings, especially those regarding technology efficiency, recovery targets or process emissions. The findings described in this section represent the current outlook (as of 2019Q2) of recycling processes employed in Europe, under the current regulatory frameworks, and with the potential to change in light of different policies.

### Materials recovered

In theory a large array of materials could be recovered within each recycling scheme. However under current recycling regulations, where the recovery target for LIBs is 50% of total weight, the full potential of recycling processes is not exploited. There is limited information about the types of materials recovered within each type of recycling process. In many cases, recyclers only list the main types of materials that they are currently recovering, and it is thus reasonable to assume that economics play a major role in their choice.

A study conducted by researchers at the Australian National University[12] examining reported data by 8 global battery recycling facilities using different processes found that:

- Highly valuable elements (copper, cobalt, and nickel) were recovered by all companies surveyed
- Other metals such as steel (iron) and aluminium were commonly recovered due to a series of factors. Iron alloys are deemed low value but are easy to recover magnetically. Aluminium, a relatively low value metal, is recovered due to the high demand for recycled aluminium, a result of the high cost and energy requirements of aluminium production from raw materials. Recovery of nickel is expected to be implemented on a wider scale in the future.
- Plastic was recovered by most companies, except those using pyrometallurgical processes where plastic is burnt. Plastic is either recycled, incinerated for energy recovery or landfilled.
- Other materials (Li, Mn, and C) were not found to be fully recovered.

Process-wise, the Australian National University study and several additional studies[13,14] found that:

- Pyrometallurgical processes recover the lowest number of materials. The inherent flexible nature of pyro process allows recycling of a wide range of battery chemistries but recovered materials cannot easily be separated without further refining.
- Hydrometallurgical processes are more specific to battery type, and are thus able to recover a larger number of materials, notably lithium.
- Hydro-pyro combinations allow recovery of a wider range of materials and at a greater efficiency, although it is usually more expensive and more emission-intensive.
- Mechanical/physical processes were shown to recover the highest number of materials, albeit in pilots only, however every processing sequence is specifically tailored to the battery chemistry and pack type fed.

[12] Anna Boyden et al., The Environmental Impacts of Recycling Portable Lithium-Ion Batteries, Procedia CIRP 48 (2016) 188 – 193
[13] L. Gaines, The future of automotive lithium-ion battery recycling: Charting a sustainable course, Sustainable Materials and Technologies 1–2 (2014) 2–7
[14] X. Zheng et al., A Mini-Review on Metal Recycling from Spent Lithium Ion Batteries , Engineering 4 (2018) 361–370

## Carbon emissions review

In terms of $CO_2$ emissions, current European regulations do not prescribe any carbon emissions targets to be met by recyclers and thus no real-world emissions data is available. Intuitively, energy-intensive processes, such as pyrometallurgy, are expected to have the highest emissions whilst direct recycling, which mainly involves mechanical separation, the lowest emissions. At the same time, the number and nature of recovered materials must also be accounted for in the emissions assessment of recycling processes, as by recovering materials the emissions associated with their manufacturing from raw materials are avoided. The diagram below reviews the calculated emissions associated with battery recycling. The data is based on several publications (estimates using Life Cycle Analysis software) and industry inputs[15]. The scale of the plot shows the difference between the battery recycling and battery manufacturing emissions – negative values show a net avoidance of emissions by battery recycling, whilst positives represent an overall increase in carbon emissions. Battery chemistry and recycling scale and technology vary, as do emissions associated with electricity generation, and thus the results are not directly comparable, however a general trend is observed. In terms of emissions savings, direct recycling scores best, followed by hydro processes, both resulting in emissions below those of battery production, whilst pyrometallurgy emits over 1,200 $gCO_{2\ eq.}$ / kg battery more relative to manufacturing.

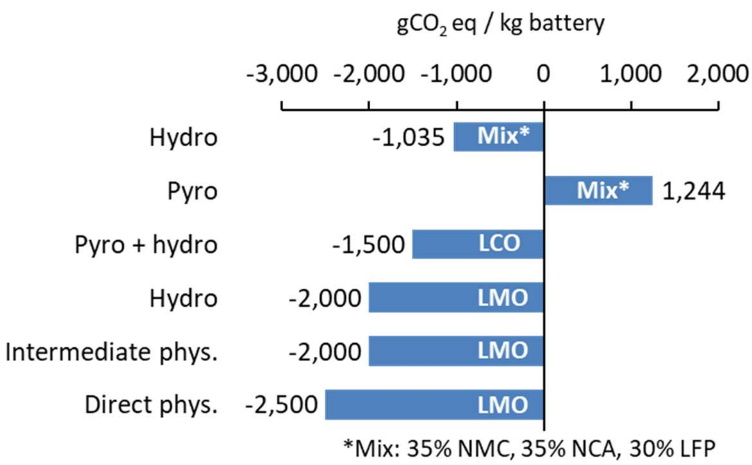


**Figure 24: Comparison of emissions associated with recycling of different LIB chemistries and includes emissions associated with required chemicals for the hydrometallurgical process. Negative values are emissions avoided in the manufacturing of recovered materials thanks to battery recycling**

## Current situation

The assessment of recycling processes was performed against seven different key performance indicators (KPIs) and is shown in Figure 25 below. This table depicts the current situation, under the current (2019Q2) economic and regulatory environments, and it is worth noting that some processes may appear unfavourable under certain KPIs. This is determined by the low recovery targets (min. 50% weight for Li-ion batteries) and by the process economics, unfavourable due to low LIB volumes. A full description of the KPI assessment can be found in the appendix.

[15] The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries, IVL Swedish Environmental Research Institute, 2017

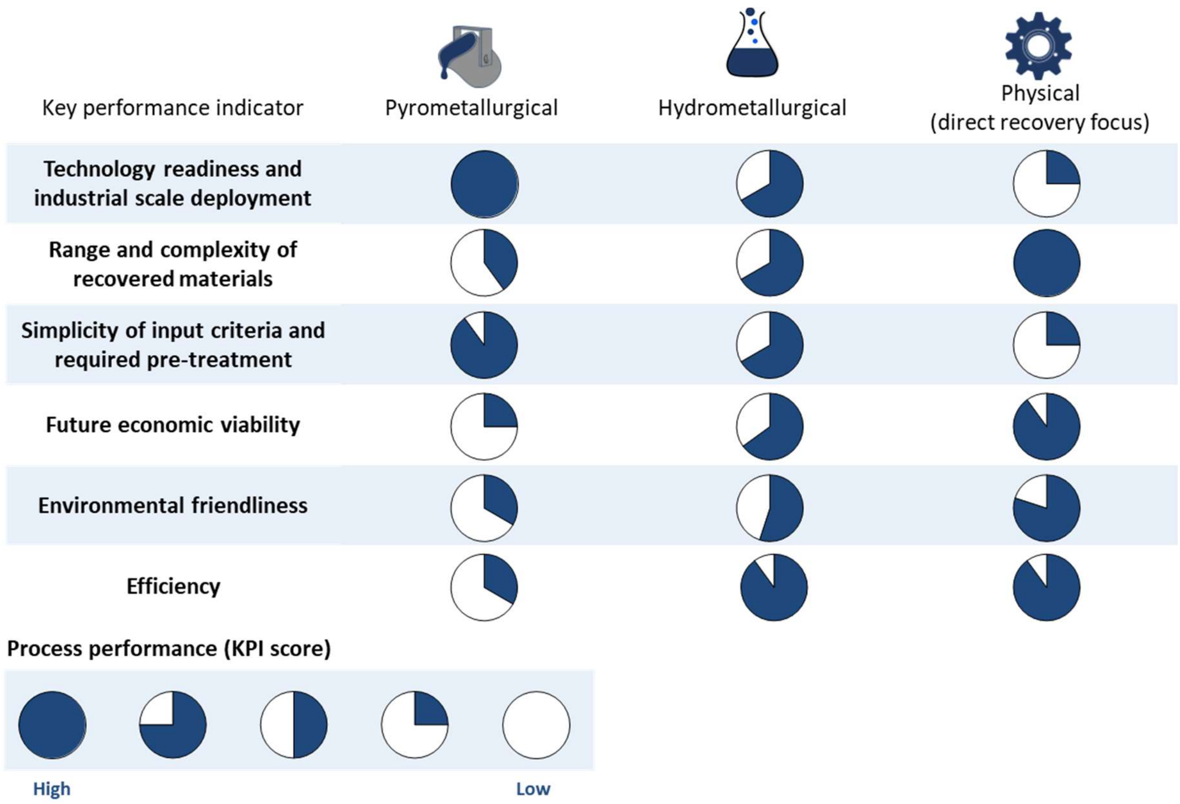


Figure 25: Qualitative comparison of recycling processes (2019Q1)

## 4.3 Recycling facilities

### 4.3.1 Current capacity

A review of the battery recycling facilities in Europe showed that over 15 facilities process and recycle lithium-ion batteries currently, but are at different maturity levels with many being pilots only. It must be noted that most facilities shown on the map below also process some other battery types (Table 1) and thus exact figures regarding the volumes of LIBs processed are unavailable. In some cases (those marked with *), the total volume processed by the facilities is listed – these, plus the LIB only numbers, add up to a capacity of around 33,000 tonnes/year. At the same time, in many cases the facility's capacity is not publicly disclosed. It is expected that some recyclers will focus more on LIBs once the volumes build up. There are other battery recyclers in Europe that do not currently process LIBs (thus not shown on this map) which are likely to enter the LIB recycling market in the future. The map below also includes a series of significant battery collection points throughout Europe. In some cases, these entities just collect batteries whilst others may provide initial dismantling and/or shredding only.

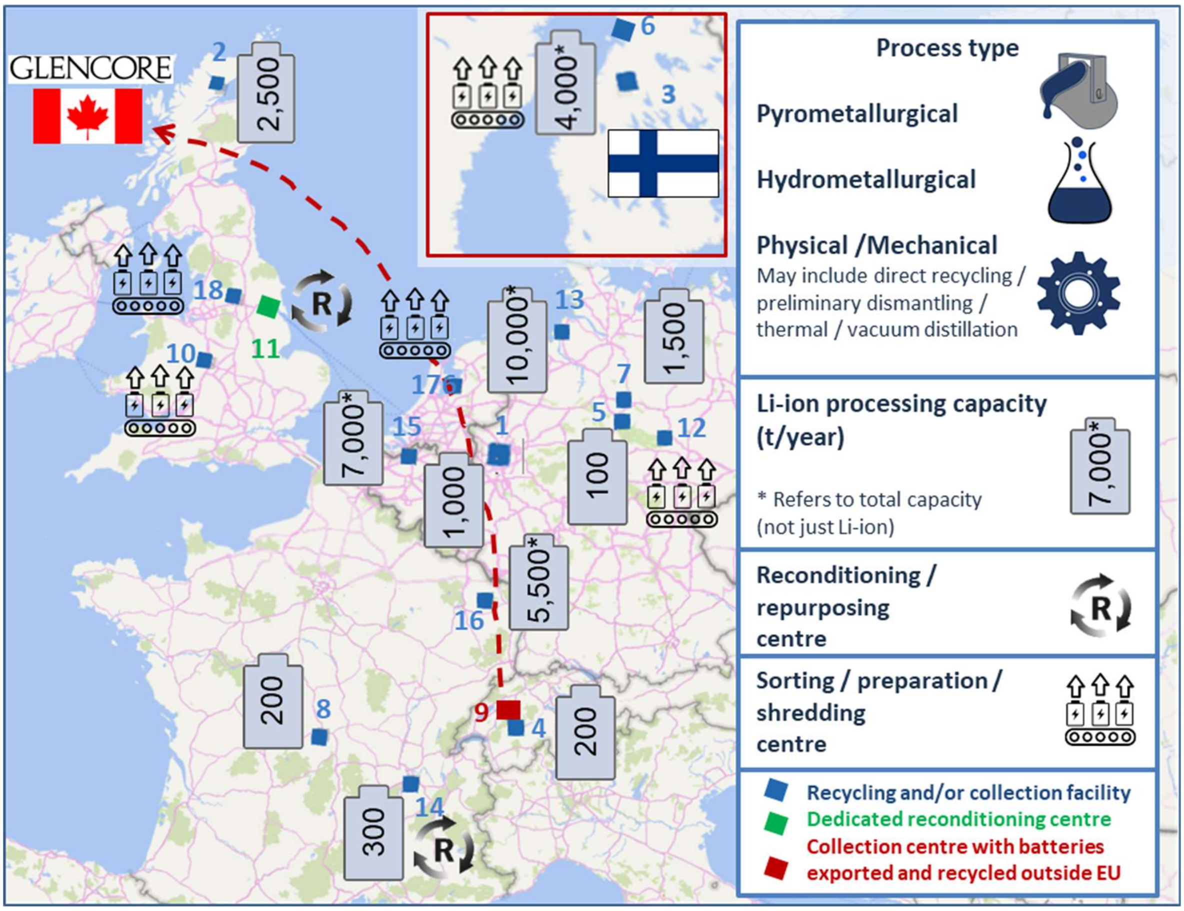


**Figure 26: Overview of facilities processing and recycling Li-ion batteries in Europe (2018) based on publicly available data collated by Element Energy (capabilities shown in Table 1)**

There is also a strong interest from car OEMs to invest in and expand the battery recycling business, in anticipation of the retirement of large EV fleets. For example, in February 2019 Volkswagen announced the opening of a pilot plant to process electric car batteries in Salzgitter, Germany. The facility will open in 2020, with an initial capacity of 1,200 tonnes per year[16]. Batteries will be tested, with viable batteries sent to second life applications and exhausted batteries shredded and recycled.

In addition, Fortum, the Finnish energy supplier, has recently announced entering the lithium-ion battery-recycling market by partnering with Crisolteq[17]. Li-ion batteries are recycled using a hydrometallurgical process, with materials recovered being used in the production on new batteries. Fortum is also testing second life applications of EV batteries as stationary energy within its network.

[16] https://www.electrive.com/2019/02/21/vw-releases-battery-recycling-details/
[17] https://www.electrive.com/2019/03/25/fortum-capable-of-80-recycling-on-industrial-scale/

**Table 1: List of companies involved in Li-ion battery recycling in Europe, the types of batteries also recycled, the involved processes and the range of recovered materials.**

| # | Company | Battery types processed | | | | | Recycling process | | | Collection / prep. | Materials recovered |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Li-ion | Alk/Zn-C | Ni-Cd | Ni-Mh | Pb-acid | | | | | |
| 1 | ACCUREC | ✓ | | ✓ | ✓ | | | | ✓ | | Li, Cu, Fe, Ni, Co, Al, plastic |
| 2 | AEA Technology, Inc. | ✓ | | | | | | ✓ | | | Li, Co<br>R&D – not industrial scale |
| 3 | AKKUSER | ✓ | ✓ | ✓ | ✓ | ✓ | | | | ✓ | Shredding only – output fed to metal refineries |
| 4 | BATREC | ✓ | ✓ | | ✓ | | ✓ | | ✓ | | unknown |
| 5 | Chemetall expect more | ✓ | | | | | | ✓ | | | Cu, Co, Ni, Li (small scale) |
| 6 | CRISOLTEQ<br>fortum | ✓ | | | | | | ✓ | | | Li, Co, Ni - Fortum is also testing 2nd life applications |
| 7 | Duesenfeld | ✓ | | | | | | ✓ | | | Li, Co, Ni, Fe, Cu, Al |
| 8 | eramet | ✓ | ✓ | | | | | | ✓ | | Li, Co, Ni, Fe, Cu, Al |
| 9 | GLENCORE | ✓ | | | ✓ | | ✓ | | ✓ | ✓ | Battery collection only in Europe – exports to Canada |
| 10 | GP | ✓ | | | | | | | | | Battery collection only |
| 11 | NISSAN | | | | | | | | | ✓ | Battery repurposing only |
| 12 | PROMESA recovering resources | ✓ | | | | | | | | ✓ | Battery shredding only |
| 13 | REDUX | ✓ | ✓ | | | | | | ✓ | | Fe, Al, Cu, plastic |
| 14 | SNAM | ✓ | | ✓ | ✓ | | ✓ | | | | Co, Cu, Al, Fe<br>+ Repurposing |
| 15 | umicore | ✓ | | | ✓ | | ✓ | ✓ | | | Li, Co, Ni, Cu |
| 16 | VEOLIA | ✓ | ✓ | | ✓ | | | ✓ | | | Li, Ni, Fe |
| 17 | | ✓ | | | | | | | | ✓ | Battery collection only |
| 18 | WasteCare | ✓ | | | | | | | | ✓ | Battery collection only |

Data regarding recycling capacity outside Europe is rather patchy, especially in Asia. However, it must be noted that China has recently published legislation obliging battery and EV manufacturers to recycle exhausted EV batteries at the end of their first life[18]. Given the EV sales in China, it is expected that the recycling capacity in China will exceed that of Europe.

Whilst legislation-enforced battery recycling requirement do not exist in most of the US States, the US Department of Energy (DOE) has recently announced the launch of its first lithium-ion battery recycling facility, called the ReCell Center, which brings together the expertise of car and battery OEMs, recycling centres, and academia. The aim is to use recycled materials and reduce production costs by 10 to 30 percent, narrowing the gap and helping achieve DOE's battery cost goal of $80/kWh. The facility will benefit of funding of $15m over three years and will focus its research on four key areas: improving direct cathode recycling processes, enhanced recovery of other battery materials, design optimisation of new battery types to increase ease to recycle, and centre performance monitoring and streamlining[19].

### 4.3.2 Future challenges, opportunities, and uncertainties

Our estimates indicated that even under the expected uptake of electric vehicles (Baseline Scenario), the current recycling capacity, estimated at around 33,000 tonnes/year, will become insufficient as early as 2035. Element Energy estimates that in 2050, between 550 and 1,100 ktonnes of LIB would have to be recycled annually within the EU, as shown earlier in this report (Figure 9). In addition, it is expected that updated regulation requiring higher collection targets for portable batteries (such as those contained in mobile phones and other consumer electronic devices, many of which use LIBs) would put further pressure on current battery recycling capacity.

Increased battery volumes and policy requirements will change the industry assessment and KPI performance from its current situation (Figure 25), in the following areas:

- **Technology Readiness**: commercial larger scale hydro and direct recycling likely to become more common in the future, however it is unclear which process type will dominate or whether innovation will bring new recycling possibilities.
- **Range of recovered materials and efficiency:** mainly driven by the regulated recovery targets and economics. Wider range of materials will be recovered under more stringent regulations; however, pyro will still focus on metals/alloys, hydro on inorganic salts, and direct recycling on physical components. Automation could bring additional improvements, both in terms of recovered materials and reduced costs.
- **Emissions and process environmental friendliness:** as Europe is moving towards decarbonisation not only in the transport sector, it is likely that future regulations will impose lower emissions for industrial activities, including battery recycling. Lower direct emissions and the additional benefits of a higher uptake of renewables and lower electricity grid emissions will improve the emission assessment of each process. However, the degree to which current and future process can be adapted to abide to future emission regulations is unclear.
- **Future economic viability:** similarly driven by regulations and future battery technologies. All processes would be affected by a decrease in the cobalt battery content. Uncertainty around the cost of implementing regulatory requirements and new technologies, could affect the economics of each process, potentially affecting the value of recycling fees.

Several technology innovations and policy requirements, along with the increased volumes of batteries will create both challenges and opportunities for recyclers:

- **Recyclers will need to increase the capacity dedicated to LIBs coming out of EVs**. Under the current low volumes of EV retired batteries, recyclers have relied on shifting capacity from other types of batteries (e.g. portable consumer batteries) that are recycled within the same facilities. This

[18] https://roskill.com/news/batteries-china-ev-battery-recycling-faces-challenges/
[19] https://www.greencarcongress.com/2019/02/20190216-recell.html

capacity-shift mechanism would not be sufficient in the future, especially as the portable battery market is also expected to expand. Investments into facility upgrades will thus be needed.

- **Automation** could revolutionise the recycling industry. Automated battery sorting, integrated automated transport across of batteries around the recycling facilities, and increased control and automatic optimisation of chemical processes could lead to significant savings not only in costs but also in time, allowing higher recycling productivity, increased recovery of materials, and lower recycling fees.
- **New entrants**: our industry consultation pointed out that some recyclers face financial difficulties, with one European processing facility closing down in 2018. Given the low returns due to the relatively low volumes of batteries currently processed, and the great need for capacity expansions within the next 10 years, it may be the case that current recyclers will not have access to the capital required for further expansions and upgrades. Thus, the industry may see the expansion of well-established recyclers, mergers and acquisitions, as well as new entrants with no experience in battery recycling but with expertise on metal processing.
- **Specialisation into repurposing:** as the industry is moving towards repurposing and reuse of viable EV batteries, it is likely that some current players will diversify their portfolios and offer battery testing, reconditioning, and repurposing services. Such diversifications could be achieved through joint-ventures and partnerships with car OEMs, who will bring onboard their battery knowledge. Depending on the returns of each service, it is possible that some facilities will, in time, become exclusive repurposers, completely abandoning their capital-intensive recycling business.
- **Battery management system access and SOH assessment:** information regarding the battery state of health will be required in order to understand batteries' potential for second life, information which could be extracted from the battery management system combining specialised software and hardware testing. It is likely that a market will develop around this need, with players ranging from the OEMs to recyclers offering diagnostic and assessment services.
- **Geography:** Figure 26 shows that almost all of Europe's current LIB recycling facilities are based in Central and Western Europe. Although the current uptake of EVs is currently more pronounced in these regions, recycling demand from Eastern European countries will eventually become significant. The notoriously high costs of transporting waste batteries, explained in the following sections, will make difficult cross-European hauling and will incentivise the opening of local recycling facilities. This could bring new players to the European recycling arena, as well as expansion opportunities for well-positioned current recyclers. However, whilst recyclers may expand to countries with energy intensive electricity grids (e.g. Poland), policy makers should ensure that incentives for clean electricity use are provided in order to support sustainable battery recycling.
- **Battery chemistry change**: there is still uncertainty in the battery market on which technology will be the dominant storage medium in future electric vehicles. Two main technologies seem likely to dominate future markets: solid state batteries and lithium-sulphur batteries. Solid state batteries have the advantage of using a solid-state electrolyte, which is not flammable, unlike the liquid electrolyte used in current batteries. Following this transition, physical processes would require a different cathode separation procedure, whilst hydro and pyro processes would remain largely unaffected. On the other hand, lithium-sulphur batteries would render pyrometallurgical recycling unusable as the sulphur would poison the process.

## 4.4 Review of recycling legislation

### 4.4.1 Battery Directive

#### Overview

In 2017, The European Commission adopted the Circular Economy Package, aiming towards a circular economy which will boost global competitiveness, foster sustainable economic growth and generate new jobs. As part of this ambitious plan, revised legislative proposals on waste, including those supporting recovery and recycling of batteries, are to be adopted. In Europe, the Battery Directive (2006/66/EC) controls the types of batteries that could be placed on the Community's market and defines the actions that must be taken at the end of the battery life. The primary aim of the BD is to restrict the usage of hazardous chemicals (e.g. Cadmium or Mercury) in batteries and to ensure proper disposal and treatment of waste batteries. Designed with portable batteries in mind, the Directive sets collection targets for each battery type and places the collection and recycling responsibility on the battery producer or placer on the EU market – a concept called Extended Producer Responsibility (EPR). The BD directive has been transposed in the legislation of all European Member States, with EU-wide collection and recycling schemes being implemented for portable batteries.

Although the uptake of electric vehicles was rather limited in 2006, batteries used in electric vehicles are mentioned in the BD and are classified as "industrial batteries", designated to be recycled at 50% of their weight at the end of life, implying recycling being the only end-of-life option. Complications around the transfer of the battery EPR impede the development of the second-life battery market, as discussed in the following section.

#### Potential issues

Although the Battery Directive is essential for ensuring batteries are disposed of properly, there are several issues within its current form that Element Energy, in collaboration with the industrial stakeholders, has identified. To ensure sustainable battery end-of-life and unlock markets for innovative battery uses the following topics must be addressed.

#### *The problem of waste batteries*

Batteries defined as *industrial batteries* under the current BD, including those coming out of EVs, must be recycled, and thus their residual life cannot be exploited to its full value. Even if batteries could be repurposed, under the current BD the entities processing such batteries (defined as *repurposing workshops* in this report), would have to be authorised as recycling facilities, which requires a lengthy and expensive process. As such facilities would have to process batteries to be recycled, the transport of those batteries would have to be conducted under the designation of "waste transport" and would be subject to additional financial and logistical burdens. Additional testing required in order to validate batteries' potential for second life application will also confirm their functional health and compliance with safety requirements. As a result, with demonstrated battery integrity and known history (through the battery registry, see page 42), batteries considered for second life application should face more relaxed regulations, that would normally apply to "hazardous goods"[20]. This series of additional designations and requirements is likely to reduce potential businesses and substantially increase the price of 2$^{nd}$ life batteries, thus making them an unappealing technology unable to compete with new batteries.

A revised Battery Directive would require a revised definition of batteries at the end of their EV life, which would allow repurposing workshops to operate smoothly, buying used batteries as "raw materials" and turning them into new products.

[20] For example, relating to United Nations' European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR), 2017

### *Tackling Recycling Responsibility*

The Battery Directive introduces the concept of Extended Producer Responsibility (EPR) as a strategy to achieve environmental targets. In this way, the producer or placer on the market is asked to take full responsibility of the product's whole lifecycle. This may include take-back schemes and/or financing the recycling of products at the end of life. Whilst EPR schemes are norms in many industries, the potential repurposing and reuse of EV batteries in stationary applications is complicated by the current EPR definition. Under the current regulation, the market placer (i.e. the car OEM) is responsible for financing the recycling at the end of battery life. This should remain the case for batteries that are considered too exhausted at the end of their first life. However, for batteries that are deemed viable for second life applications, it is unclear who would be responsible for their eventual recycling.

Considering the two issues described so far, there are several business models that could be deployed in the future. Element Energy envisages a future market in which EV batteries are recovered upon vehicle scrappage, collected and tested, most likely by OEMs or third-party contractors. Exhausted batteries are then recycled at the expense of car manufacturers, whilst viable batteries, which do not fit the "waste" criteria, are sold to repurposing workshops as "raw materials". Upon this transaction, the EPR is transferred from the car OEM to the repurposing workshop. These batteries are further processed and converted into 2$^{nd}$ life battery packs that are sold as "new products". Upon retirement from second life stationary applications, the repurposing workshop, if it was a different entity from the car OEMs, will be responsible for the recycling.

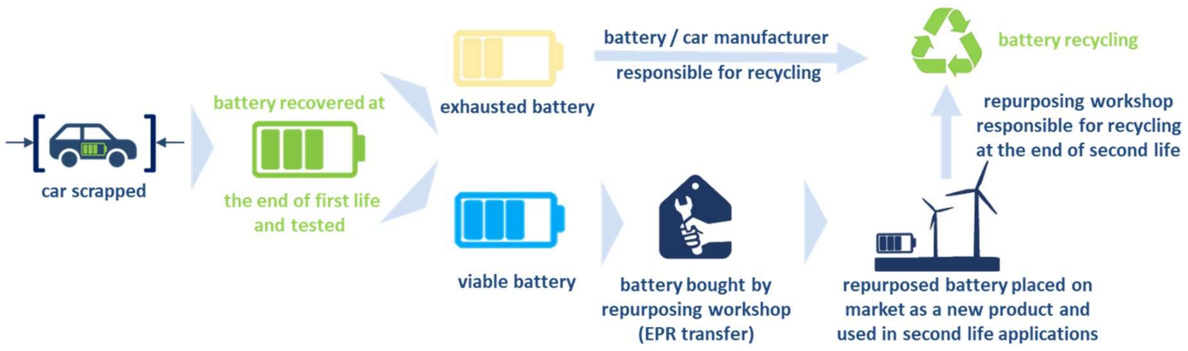


**Figure 27: Potential business and EPR transfer model for EV batteries**

This model would ensure OEMs are incentivised to collect, sort and sell any viable batteries, whilst repurposing workshops would have access to cheap used batteries. The full responsibilities of each stakeholder would have to be defined by the European Commission, however any scenario containing the OEMs and repurposing workshops will not affect the price paid by the end user of the repurposed battery (as discussed in Section 5.2).

### *Recycling of Lithium-ion batteries*

When it comes to battery recycling, under the current Battery Directive, in terms of chemistry, Li-ion batteries are classified as "other", with a recycling target of minimum 50% by average weight.

**Table 2: Recycling targets established by the current Battery Directive**

| Battery type | Recycling targets |
|---|---|
| Pb-acid | 65% by average weight, incl. Pb to the highest feasible level |
| Ni-Cd | 75% by average weight, incl. Cd to the highest feasible level |
| All other (inc. Li-ion) | 50% by average weight |

This means that EV LIBs are recycled with the lowest minimum recycling efficiency targets. The reason for this is that the 50% target was chosen to be representative for the most common battery type (alkaline batteries) at the time the Directive was drafted and is not specific to Li-ion batteries.

Consultation with the recycling industry pointed out that higher recycling targets are technologically possible. As a result, a revision of recycling targets must be conducted, and set on the best available technology (BAT) for recovering critical materials to their full potential. However, higher recovery targets could lead to an increase in recycling fees, which in turn, could impact the cost of electric vehicles.

In addition, current targets are based on the weight of the battery (including battery pack for EV batteries) and do not focus on critical materials such as cobalt, or lithium which is extremely light.

#### *Battery exports*

Under the current Battery Directive, exporting of waste batteries outside EU countries is permitted as long as the receiving country can provide similar recycling facilities. The BD does not specify any recovery targets that such countries need to meet.  Industry consultation pointed out that this phrasing is too lax and could potentially lead to a leakage of waste batteries to non-EU countries where they may not be properly disposed of and may lead to environmental damage.

Furthermore, since the BD was developed at a time when EVs were still in their infancy, current legislation does not consider the possibility of vehicles containing batteries being exported outside the EU as second-hand vehicles.

#### Battery registry

A battery registry, containing the history of all EV batteries, from cradle to grave, may solve the issues around effectively identifying batteries and their attributes. Such a registry would provide information about the battery type and history, any technical issues identified during regular EV maintenance, and the EPR holder (either the car OEM or the repurposing workshop). With data fed from modern in-battery diagnostic tools into the registry, such a registry may also prove valuable in reducing the battery testing time at the end of its EV life and reducing the time and resources needed for repurposing batteries. Such a registry, along with standardised battery labelling, would also help recyclers identify the exact battery chemistry and reduce time and expenses related to battery sorting prior to recycling. China has already developed such a battery recycling and traceability management platform: EV batteries produced will be given a unique ID to help track the batteries during their entire lifecycle from production through to sales, usage, scrapping/second use and recycling[21]. Such technologies could be based on QR core printed on the battery packs and modules, or by even using disruptive technologies, such as a digital ledge based on blockchain[22]. This approach has already been successfully used by Everledger in tracking the origin of diamonds. The company is now developing a similar concept or tracking Li-ion batteries throughout their life, from mining of the materials, to the manufacturer, car dealership, second life repurposer and user, and recycling[23].

### 4.4.2 Directive on End-of-Life Vehicles

#### Overview

The Directive on End-of-Life Vehicles (2000/53/EC) sets targets for reuse, recycling and recovery of the end-of-life vehicles (ELVs) and their components (including batteries). It creates a favourable framework such that the last ELV's owner can return the vehicle to authorised facilities without any cost. Producers are expected to meet all or a significant part of the ELV treatment. The directive sets targets for parts reuse and recovery of min. 95% vehicle weight by 2015 (EV batteries included).

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[21] https://www.idtechex.com/research/articles/all-ev-batteries-born-after-august-2018-in-china-will-have-unique-ids-00015455.asp
[22] White & Case, Building a sustainable battery supply chain: Is blockchain the solution?, 2018
[23] Bloomberg New Energy Finance, Blockchain Can Extend Battery Life by Revealing Origin, Oct 2018 - https://about.bnef.com/blog/blockchain-can-extend-battery-life-revealing-origin-qa/

### Potential issues

A key issue tackled by the ELV Directive is the reuse of components recovered from vehicles. In the current phrasing of the Directive the definition of *reuse* only considers the recovered components used for the same purpose and component repurposing is not considered at all. This strict definition may restrict the recovery of EV batteries and usage for other applications, thus potentially hampering the take-off of the second-life battery market. A recent evaluation and fitness check of the ELV Directive is currently conducted by the European Commission and is due to finish in Q3 2019. Preliminary evaluation documents point out that ELV Directive assessment should consider the influence and interaction of newly arising challenges such as electric and connected vehicles and with other legislative instruments, including the Batteries Directive[24].

### 4.4.3 Summary of recommendations for revised/future legislation

Whilst the purpose of this report is not to establish the exact details contained in any future regulations, this section summarises five areas of policy improvement that have been identified during the policy review, with a more details being provided in Chapter 6.

**Policy must address all steps in the end-of-life batteries' value chain**: updated regulations must tackle the responsibility of all stakeholders. A clear definition of the EPR of second life batteries must be included. Whilst several business models are possible, the EPR transfer would most likely occur when car OEMs sell the EV battery to the repurposing workshops. On the other hand, the responsibility of OEMs for exhausted batteries, unsuitable for second life applications and recycled after first life, should remain the same.

**Battery tracking and identification must be encouraged by future regulations**: establishing a European battery registry via IT tools (QR code or digital ledger) and a scheme of standardized battery labelling could help reduce recycling costs by decreasing sorting complexity, resolve the problem of illegal battery exports, and speed-up the repurposing process, since the battery's history would be known.

**Recycling of EV batteries should remain strict and based on Best Available Technology**: the updated Battery Directive should address Li-ion batteries, specifically focus on recovering critical materials such as cobalt and lithium. Recycling requirements (including amount of recovered materials) should be set in line with BAT.

**Flexibility around new battery chemistries must be allowed:** legislation should be flexible such that future new chemistries (i.e. not Li-ion) can be recycled reasonably, and for legislation to remain future-proof given the fast pace development of battery technology.

**Future EV batteries must be manufactured to ease second life repurposing and recycling:** clear guidelines on standardised manufacturing and labelling of new batteries must be included in future legislations (including the revision of Ecodesign Directive (2009/125/EC) currently underway). Easy identification of the manufacturer and standardised pack design could reduce processing times and costs during both repurposing and recycling, and thus future batteries must have a standardised, streamlined design, and must be include proxies used for swift access to battery's history.

[24] End-of-life vehicles, Evaluation and Fitness Check Roadmap - Ares(2018)5101035, Nov 2018

# 5 Economics of battery end of life options

This chapter builds on the findings from the previous chapters to draw a comparison of end of life options and thus derive the most likely outcome in terms of share of automotive batteries going into a second life application before being recycled. During this analysis both economic and practical aspects were considered. The following topics regarding the economics of battery fates at the end of first life were examined:

- **Economics of recycling:** understanding recyclers' business models and how volumes of used EV batteries will affect the industry. How much will OEMs and recycling workshops have to pay as recycling fees in the future?
- **Economics of repurposing**: investigating future workshops buying, repurposing, and selling used batteries. How much does it cost to repurpose a battery and how does the resulting price compare to a new battery?
- **Economics of second life**: the value of used batteries in service. What are the cost savings associated with using a used battery? How does that compare with using a new battery instead?

## 5.1 Economics of recycling

### 5.1.1 Business model and economic drivers

As discussed in the previous sections, the recycling responsibility for EV batteries in Europe currently falls on the vehicle OEM. Although it is unclear how future regulations will address the recycling responsibility of second-life batteries, battery recycling will nonetheless be required. Currently, battery recycling facilities receive batteries to be recycled for a fee – often called *recycling fee* or *gate fee*. As previously detailed, battery recycling consists of complex processes, requiring expensive facilities and chemicals. The main revenue source for recyclers consists of the value of recovered materials (mainly metals) that are sold on. A recycling fee is required as recyclers cannot recover and sell on enough materials from used batteries in order to cover expenses and make a profit. This is illustratively shown in Figure 28 below.

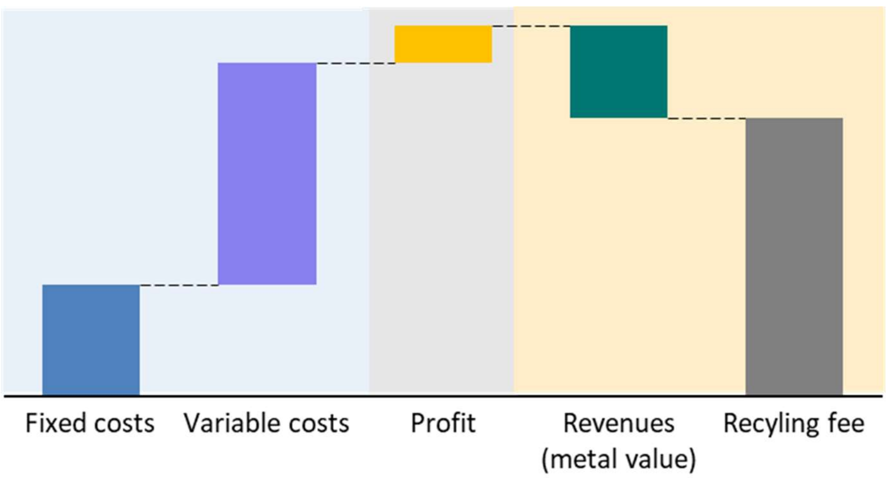


**Figure 28: Illustrative diagram showing the business model concept of battery recyclers**

The value of the recycling fees depends on a series of factors, including the size of the recycling facilities and related economies of scale and the value of metals that are routinely recovered by recyclers. The quantity of recovered materials is dependent on the battery chemistry and composition, recovery targets set in policy, and the efficiency of the recycling process. Their value can also fluctuate throughout the year in line with supply and demand of metal commodities. Our modelling of future costs of recycling addressed the connection between all these factors as shown and discussed below.

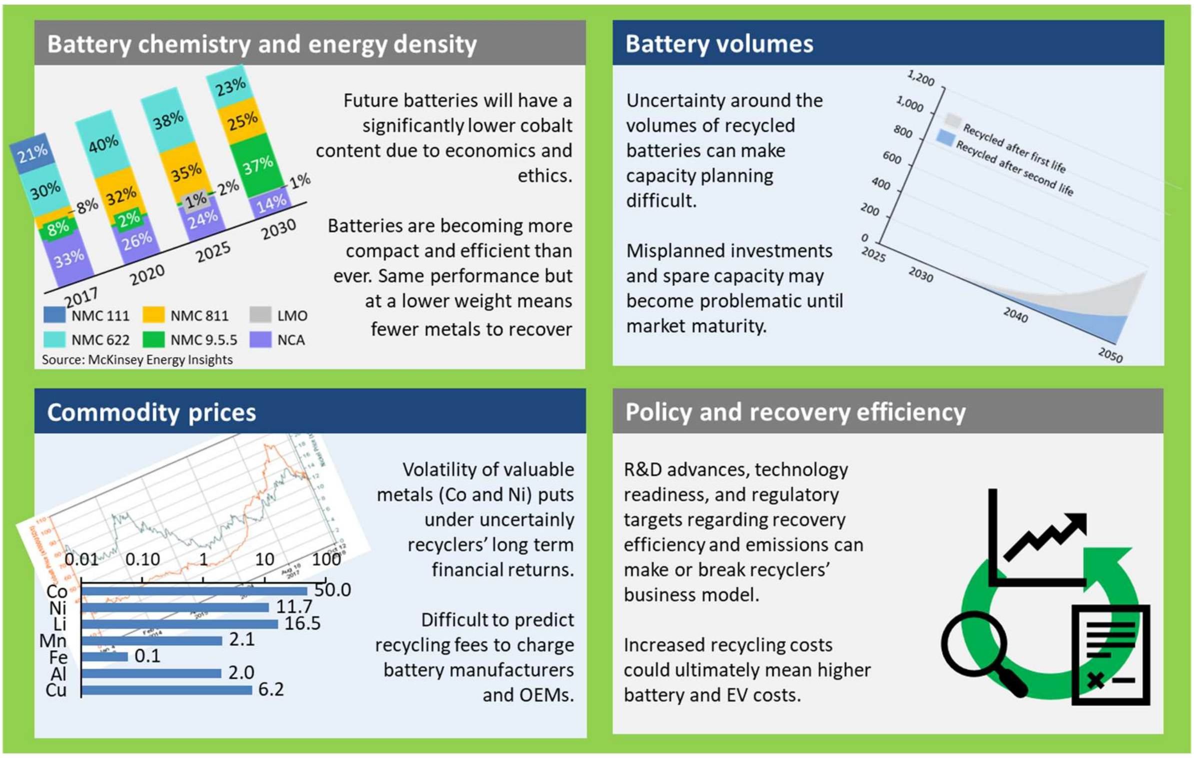


**Figure 29: Main drivers affecting the economics of battery recycling**

- **Battery chemistry**: the most valuable metal present in LIBs today is cobalt, which is extensively recovered during battery recycling. The high value of cobalt, which increased almost threefold between 2014 and late 2018. This was due to the increased demand for EV batteries, an uncertain supply and reliance on less democratic countries since 90% of Cobalt is obtained as a by-product of copper and nickel mining. Over half of the world's cobalt is mined in the Democratic Republic of Congo (DRC), with output mainly refined in China and expensive to procure by Western commodity traders. Due to social and human rights sensitivities, battery manufacturers are trying to replace the high cobalt content of batteries with nickel and manganese, in a quest to reduce battery costs and reduce association with the unethical mining practices in the DRC, often involving child labour[10]. Whilst the market price of cobalt declined in the early 2019 due to over-supply, increased demand will continue[25]. Even so, future batteries are expected to have lower cobalt content and completely new chemistries, the returns of recyclers would be affected.
- **Recovery targets and recovery efficiency**: recovery targets are set in the current battery directive (e.g. 50% of battery weight for LIBs). However, since battery recycling is a cost-intensive business, in many cases recyclers only recover the minimum required amount to minimise additional costs. Future increases in recovery targets could affect the profitability of recyclers and change the structure of recycling fees. Future recycling processes, some currently under R&D, may be able to achieve higher recovery at lower costs. In addition to process improvements, involvement of automation could bring additional savings, both in terms of labour costs and time.
- **Commodity prices**: recyclers often sell recovered materials to third parties (e.g. metal refineries or commodity traders). The market is known to suffer fluctuations and recyclers often hedge against such changes in the short term, however it is unclear how the metal prices will fluctuate in the long run. Our modelling assumed current prices in the baseline scenarios and tested the sensitivity of increased value for cobalt and nickel.

[25] https://www.proactiveinvestors.com.au/companies/news/212832/cobalt-set-for-bearish-2019-but-demand-fundamentals-remain-strong-212832.html

### 5.1.2 Industry outlook - projection of future recycling fees

As mentioned in section 4.3, the increased demand for recycling EV batteries will create new challenges and opportunities within the recycling industry. To assess the financial viability of future recycling facilities, we assessed both the costs of building new battery recycling facilities and the many factors affecting the amount and value of recovered materials, by developing several scenarios:

- **Baseline**: scenario characterised by steady metal prices, recycling efficiency reaching targets by 2030, unchanged recycling costs, and battery chemistry following current European trends.
- **Optimistic**: industry change with increased metal prices, recycling improvements implemented by 2030, reduced recycling costs due to automation, and standard battery chemistries.
- **Pessimistic**: scenario with decreased recycling value for recyclers determined by steady metal prices, delayed improved recycling efficiency (by 2040), and increased recycling costs.
- **Low Cobalt**: variation of the baseline scenario, keeping almost all assumptions as per baseline case but assuming a transition of battery chemistry towards low cobalt technologies (LFP, NCM 9.5.5, and LMO).
- **Resource scarcity:** simulates a world with lower available resources, both human (determining increased recycling labour costs) but also material, increasing the cost of metals. Due to the lack of resources and increased need for recycled metals, technology improvements follow the baseline trend, reaching targets by 2030.

These scenarios were developed based on both literature review and industry consultation and can be consulted in the accompanying appendix. It should be noted that many assumptions or model inputs have a high degree of uncertainty. The scenarios aim at exploring a range of values for key inputs but the outputs should still be seen as indicative.

Growing volumes of waste batteries will create economies of scale and reduce recycling fees by 2030 but uncertainties related to costs and metal prices remain. Recycling fees are expected to decrease from about $1,700-2,000/tonne today to around $480/tonne in 2030 (Baseline scenario). In the Optimistic scenario, the value of salvaged materials would rise significantly, exceeding the profits envisaged by recyclers. Subject to regulation and industry consensus, recyclers may be paying back up to $260/tonne in 2030 for the batteries received.

However, delayed policy implementation on recovery efficiency, increased labour costs, or an economic downturn, characterised by steady metal prices, could keep the recycling fees at current levels. Furthermore, a dramatic decrease in the cobalt content of batteries via a switch towards lithium iron phosphate cathodes for example, (Low Cobalt scenario) could almost double the recycling fees compared to the baseline scenario, while on the other hand would result in recovered cobalt available for more new batteries with reduced content

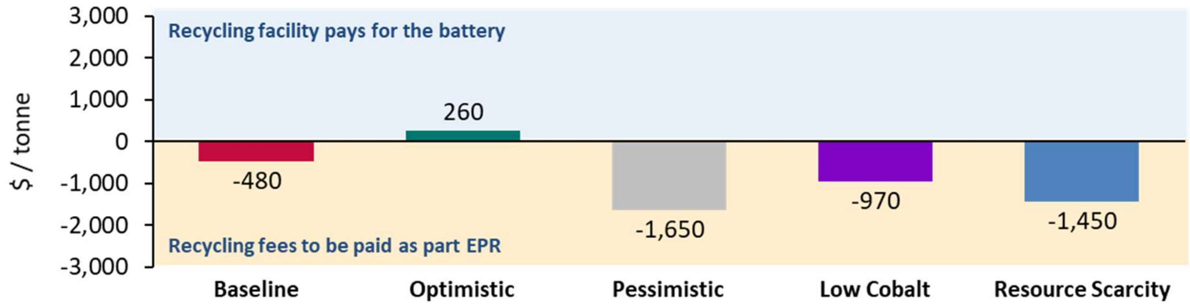


Figure 30: Economics of recycling in 2030 under five recycling scenarios

Even in the Baseline case, which does not consider a significant decrease in cobalt content and a switch to LFP technology, the cobalt content would reduce by almost 4kg/tonne-waste-battery from 2030 to 2040. However, increased technological efficiency and volumes are likely to keep recycling fees under control (Figure 31).

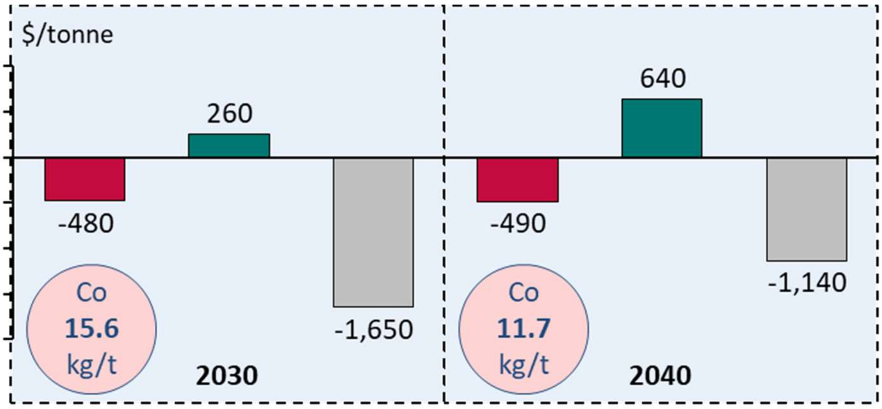


**Figure 31: Recycling fees evolution between 2030 and 2040 for 3 scenarios: Baseline (red), Optimistic (green), and Pessimistic (Grey). Figures in pink bubble show average cobalt content of recycled EV battery streams**

For example, recycling fees will only increase by $10/tonne between 2030 and 2040 under the baseline case, increase mainly related to the decline in the cobalt content. However, the increased battery volumes associated with the higher metal prices under the Optimistic scenario will outweigh the decline in Cobalt content and could increase the cash benefits for the battery legal owner. In addition, by 2040, improvements in battery recycling efficiency will have been fully implemented under the pessimistic scenario, allowing a higher recovery of valuable metals and leading to a 30% reduction in recycling fees compared to 2030.

## 5.2 Economics of second life applications

Several stakeholders are involved in the second-life battery value chain as previously discussed in Section 4.1, all affecting the future prices of repurposed batteries. The value associated with using a repurposed battery relative to a new battery or to not using a battery at all is examined in this section mainly through two representative case studies.

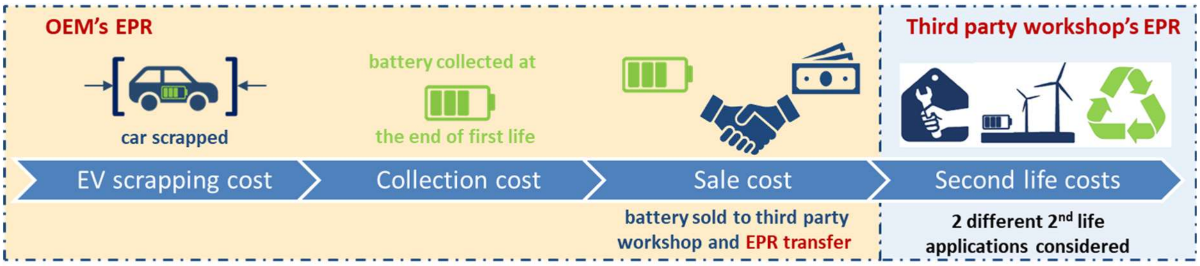


**Figure 32: Overview of the second life supply chain and EPR responsibility**

### 5.2.1 Repurposing costs

Batteries viable for second-life applications would be tested and identified at the collection point and sold by OEMs to repurposing workshops. The repurposing process is expected to consist of a series of steps, including some dismantling of the battery pack, potential separation and/or replacement of module, and reassembly into new packs. The batteries would then be purchased by end-customers. At the end of the battery's (second) life, the battery would have to be recycled. Under the business model described in Figure 27 and Figure 32, the recycling fee/cost would have to be covered by the repurposing workshops. Therefore, the final price paid by the end customer would have to include the recycling liability paid by the repurposing workshop at the end of the battery's life. In 2030, under the baseline recycling case and Baseline uptake scenario, the estimated price paid by the end-customer for repurposed batteries is $40.4/kWh[26].

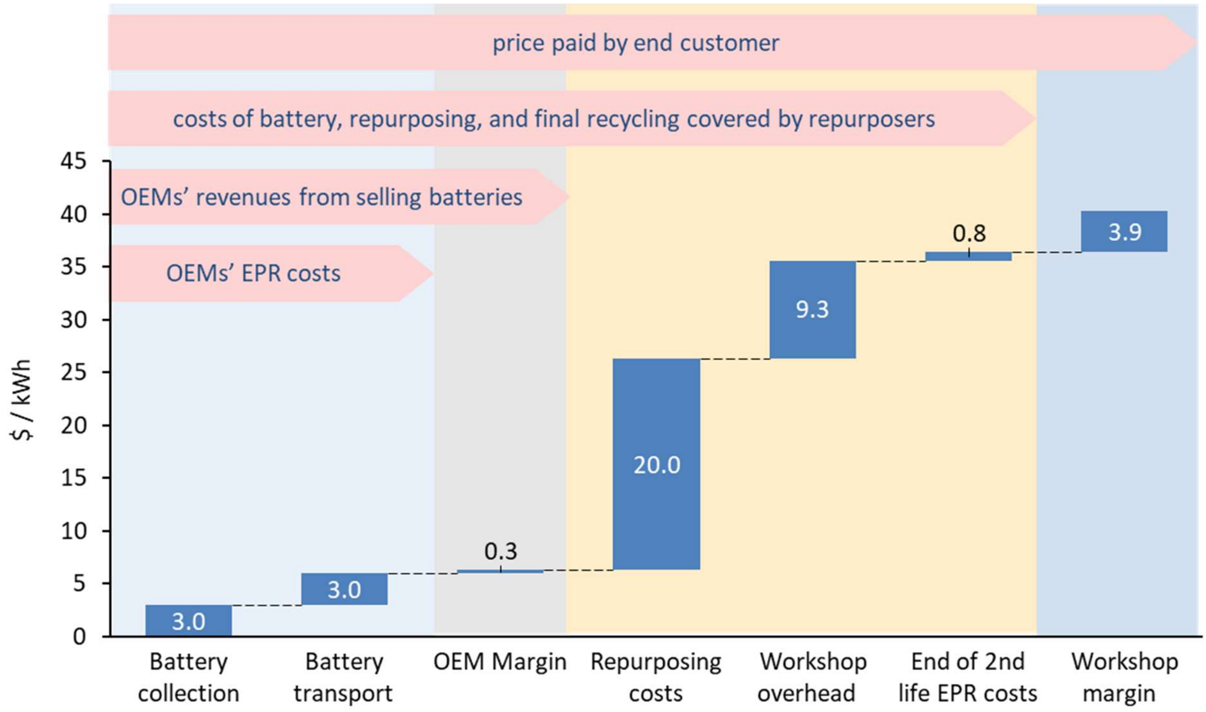


**Figure 33: Price breakdown of a repurposed battery placed on market in 2030[27] (business model based on and validated by industry)**

The cost of repurposed batteries is likely to continue to decrease up to 2040 as volumes build up. Increases in repurposed battery volumes will lead to large amounts of batteries needing recycling at the end of 2nd life. These recycling costs would have to be covered by repurposing workshops and passed on to new end customers. The EPR contribution to the final price is estimated at 2% in 2030, but is likely to exceed 9% in 2050 (Figure 34, right) as repurposing workshops will have to recycle larger volumes of exhausted second-life batteries. Despite increasing EPR burdens, reductions in projected recycling fees, improvements in logistics, and process efficiency with scale) will help keep prices of repurposed batteries competitive relative to new batteries (Figure 34, left). Even if the expected lifetime of repurposed batteries were lower, a cost reduction of up to 45% is likely to position repurposed batteries favourably on the market.

[26] It must be noted that additional system costs (e.g. engineering costs associated with building the storage facilities) would be added on top – these costs are discussed for each individual case study.
[27] Based on conversation with vehicle OEMs, EBRA, and IDTechEx webinar on Second life batteries (October 2018)

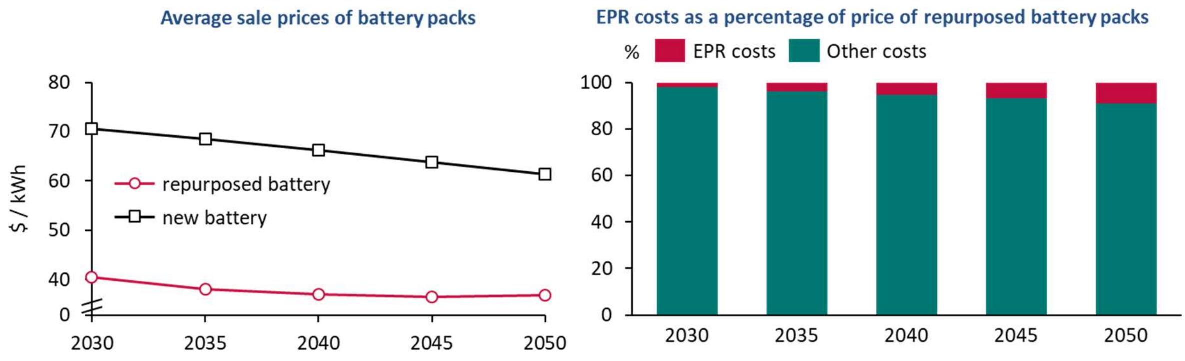


**Figure 34: Average sale prices of battery packs (left) and EPR contribution toward end repurposed pack costs (right) – Baseline recycling case and Baseline EV uptake**

When comparing the cost of second life batteries ($40/kWh in 2030) value to the cost of a new battery ($70/kWh, Figure 34), the benefits to the end-user are obvious – a 42% price reduction. Battery repurposing also brings additional benefits for the players involved. For example, car OEMs would be able to save $4.5/residual kWh as a result of avoided recycling fees[28] and generate $0.3/residual kWh as additional margins from selling collected batteries, totalling $67/battery unit, instead of recycling them. Furthermore, an industry and a whole supply chain will be built around repurposing, generating additional jobs and revenues. The almost 93,000 EV battery packs suitable for repurposing would generate a direct turnover of around $79m in 2030. This is ~22% larger than the value of $65m, created through the metal content and recycling fees, assuming the same amount of batteries were recycled instead.

### 5.2.2 2nd life application case studies

A number of potential case studies were presented to the client group and two were shortlisted for development:

| Application | Battery size | Rational / sources of revenues/savings | Market sectors / users |
|---|---|---|---|
| Distribution support (linked to large load) | 100's kWh up to several MWh | • Avoid / reduce network reinforcement<br>• Ancillary services | Truck / bus depots and rapid charging hubs |
| Peaker replacement | 10-500 MWh | • Network storage used at peak times | Replacement of peaking gas turbine facilities in the generation fleet |

Distribution support relates to the use of batteries to avoid a significant increase in peak demand arising from a new concentrated load, such as at an EV bus depot. Vehicle fleets (including buses) tend to refuel overnight in depots. A move towards 100% electrification would require the majority of the vehicles in the depot to recharge during the same period, creating a large localised electricity demand. This large localised demand issue would also apply in the case of electric ships.

If the capacity required by charging vehicles cannot be accommodated by the existing network, the fleet operator may have to contribute to the cost of network reinforcements (depending on regulation in each jurisdiction). Reinforcements for additional loads in excess of ~1MW capacity (e.g. more than 20

[28] A saving of $4.5/residual kWh corresponds to the ~18,220 tonnes (1.94 GWh) of batteries being recycled at a fee of $480/tonne instead of repurposed, whilst the EPR costs of $0.8/usable kWh in Figure 33 considers the collection, transport, and recycling (~$1,150/tonne) of ~1,300 tonne batteries reaching their end of second life in 2030, normalised for the capacity of repurposed batteries in 2030 (1.94 GWh).

vehicles charging at 50kW simultaneously) are likely to involve upgrades at the primary substation level, as well as requiring a dedicated local secondary substation for the depot. For example, in London, total network reinforcement costs are very dependent on location and due to the high loading of many primary substations and the high cost of civil works, costs could be as high as £7 million or even higher to upgrade a primary substation[29]. For an additional load of 5MW, up to around £2.5 million (£500k/MW) of this could be paid by the customer.

The commercial case for the battery is to reduce or avoid network reinforcement costs that might be required to accommodate large concentrated loads. In addition, the battery can provide some ancillary/balancing services to the TSO when not required for its primary function. Also, the battery can arbitrage daily energy prices; this is particularly useful for PV where the pattern of daytime charging correlates well with PV output.

Currently, peaking plants are relatively inefficient thermal power plants (often open cycle gas turbines) that are used to meet peak power demands. Their low annual utilisation provides an opportunity for batteries to meet peak demands. As batteries reduce in cost, it is expected that they will gradually replace peaking plants which are required over longer durations than for which batteries can currently sustain their power output (e.g. for 3-4 hours).

## Case study 1 - Distribution support

The operational model is run for a 100-bus depot, with an overall mileage of 20,000km/day. The daily operation of a battery providing local grid support, is shown below. The battery charges during periods when vehicles are in use, and then discharges to offset the significant vehicle charging load (demand). In this example, the battery leads to a 1.5MW peak demand reduction.

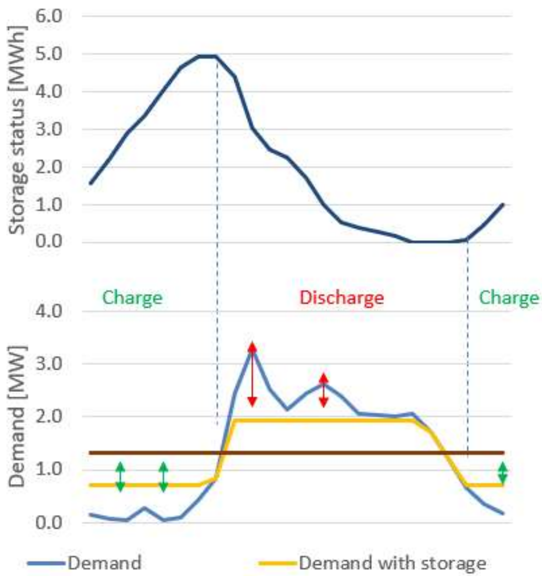


Figure 35: Daily operation of distribution support battery

Analysis regarding the sizing of the battery is shown below. As the battery duration increases, the peak demand reduction which it can enable also increases. Initial storage capacities remove peaks in demand and contribute effectively to peak avoidance, but the impact is reduced with longer durations. While this would imply that smaller batteries are most effective, it should be noted that battery storage systems have fixed costs as well as costs that scale with power and storage. Given the assumed load profile of this case study [Figure 36 on the left], a peak reduction by 1MW requires a 2MWh storage system, whereas a peak reduction by 2MW requires a 6MWh system. If avoided network cost is valued at ca €280k/MW (a conservative lower bound), this €560k saving can be compared to an equivalent new battery cost of ca €450k.

On the right-hand graph below, we show the beneficial impact of 2nd life batteries on the overall system cost. We assume new battery pack costs of €59/kWh and repurposed pack costs of €33/kWh in 2040. This allows a capital cost reduction of about 25% for 2h duration and about 35% for 6h duration storage (Figure 36, on the right).

[29] Indicative based on average costs of upgrades of large transformers. Note that constrained networks in growing cities are more likely to require costly network reinforcement.

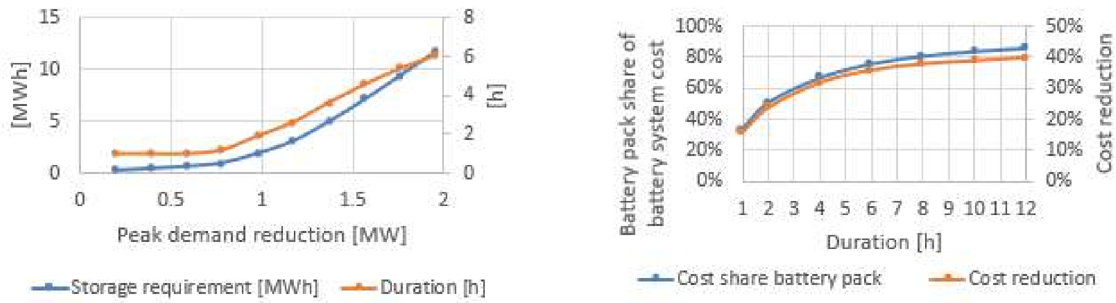


**Figure 36: Left: Impact of battery storage capacity on peak demand reduction. Right: trade off with larger batteries and the impact of 2nd life costs.**

## Case study 2 - Peaker replacement

The Whole Power System model was used to determine the potential benefit of new and 2nd life batteries in peaker replacements. Three levels of deployment were tested, each a combination of power (GW) and energy stored (GWh)

- Level 1: 2.1GW / 5.2GWh
- Level 2: 2.6GW / 11.9GWh
- Level 3: 3.5GW / 27.3GWh

The average duration in Level 1 is 2.5 hours discharge, while that in Level 3 is 7.8h. This covers a range of potential deployment of batteries as peaking plant replacements.

The results are shown below. In each case, there is a generation (fuel) saving and a smaller saving due to avoided investment in peak capacity. Total savings in each case are greater than the cost of the batteries. Note however that as the storage deployment increases, while there is still a net benefit, the size of this net benefit gets lower. This shows that Level 3 is approaching the maximum level of economic grid battery deployment with new batteries.

However, when 2nd life cells are used, their lower cost allows greater levels of deployment that is still economically viable. This can be more clearly seen on the right of the figure below. While the net savings reach a peak at deployment level 2 in the case of new batteries, for 2nd life cells the net benefit continues to increase in Level 3. This demonstrates that much higher levels of economic grid battery deployment can be supported if these cells are 2nd life.

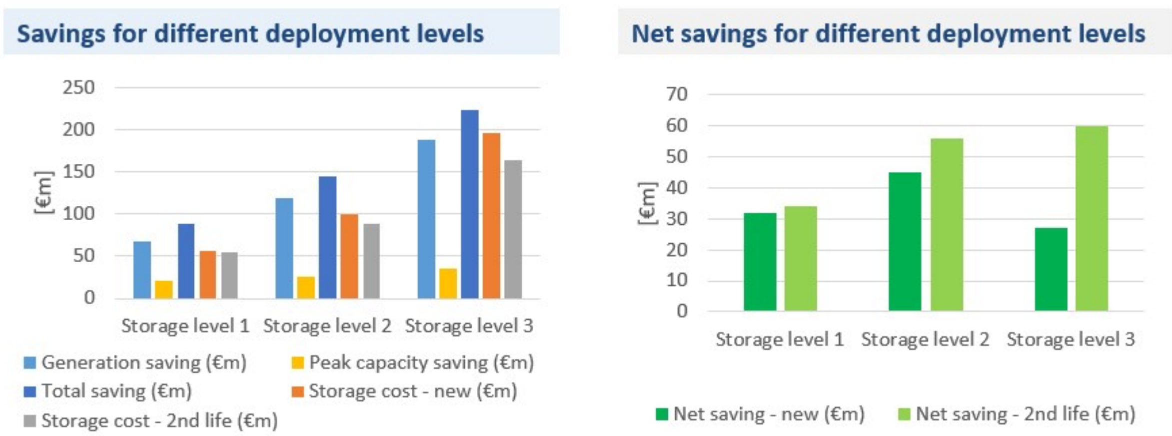


**Figure 37: Left: System savings for various deployment levels of 2nd life batteries. Right: relative (net) savings.**

# 6 Conclusions and recommendations

As battery prices decrease and performance improves, electric vehicles will grow to represent a significant share of Europe's vehicle stock (7% in 2030 and 74% in 2050). This will bring both challenges and opportunities during both the vehicle's life and upon scrappage, in the form of collected batteries.

## Impact of EVs on the power grids and recommendations

The analysis shows there would be a high system cost of passive EV charging, particularly at distribution level, which can be addressed very cost effectively with smart charging. The case for making smart charging the minimum performance standard is very clear. Legislation should be developed to encourage this, including the review of residential distribution connections which currently socialise the cost of passive residential charging. Grants could be provided to offset the on-costs of smart chargers relative to passive. Trials of smart EV based charging (linked to passive charging infrastructure) should also be trialled. In all cases, the action of smart charging will need to be encouraged with appropriate electricity price tariffs.

Smart charging can work to reduce network congestion/investments (grid responsive), and also to reduce investments and operational costs at generation level as well as reduce curtailment of renewable energy (energy responsive). Our analysis showed that the smart charging response to network congestion, energy curtailment or provision of ancillary services is not always identical and that clear rules about the operation of flexible demand will need to be developed if capital investments are to be avoided. In deregulated energy markets, where taking a whole system view is not only difficult but often contrary to legislation, these rules will be vital to develop. Trials of flexibility technology should be supported which will inform the necessary changes in regulation. Residential flexibility assets should be able to be aggregated and these assets should have fair and non-discriminatory access to flexibility markets.

Flexible technologies (storage and smart charging) have a synergistic relationship with VRES. Without flexibility, high deployments of VRES will become less and less viable due to increasing curtailment of output. Similarly, batteries need high levels of VRES deployment in order to maintain the levels of annual battery cycling required to generate required revenues. This positive whole system synergy should be central to any plan for the deep decarbonisation of power systems.

Daytime charging of EVs is extremely beneficial to power systems with high levels of PV penetration. National plans for EV charging infrastructure should respond, not only to driver needs, but also to expected patterns of energy supply, in order to deliver the greatest net benefit to customers. Relevant charging assets would include workplace charging and rapid charging sites.

The availability of cost competitive battery cells and modules from 2$^{nd}$ life applications, will increase the level of deployment of utility storage applications beyond what could be expected with new batteries. This impact will be particularly large in the longer term, not just because of the greater availability of 2$^{nd}$ life cells, but also because lower costs will support deployment of storage assets with longer duration (MWh of storage). In such systems, the cost component related to cells is larger and the cost differential of 2$^{nd}$ life cells will be more clearly seen. The result will be greater levels of VRES deployment, reduced fossil fuel use and peaking plant capacity investments, lower electricity prices and lower CO2.

By allowing regeneration from EVs back to the grid, V2G could allow EVs to become an (aggregated) storage asset of strategic importance. V2G deployment at some EV chargers could be cost effective, if concerns over customer behaviour, and cell degradation, can be overcome.

## Recycling

Most recyclers use pyro- and hydro-metallurgical processes, which are often energy intensive and involve substantial physical and chemical transformations of the battery packs. The outcome of these processes is raw materials in the form of metal alloys (pyrometallurgy) or inorganic salts and oxides (hydrometallurgy). New processes consisting of a series of physical steps are under development and testing. One such process, called direct recycling, involves a preliminary disassembly of battery packs and recovery as a whole of key battery components, such as the cathode or the electrolyte. The premise is that those components could be fed directly into the production of new batteries, reducing the cost and complexity of battery manufacturing. Given the differences in terms of process complexity, technology readiness, and commercial deployment, a thorough assessment is difficult. Under the current situation, physical / direct recycling processes outperform pyro and hydro in terms of range of recovered materials and associated emissions. However, this technology is still in its infancy, trialled at a pilot scale by only a few recyclers.

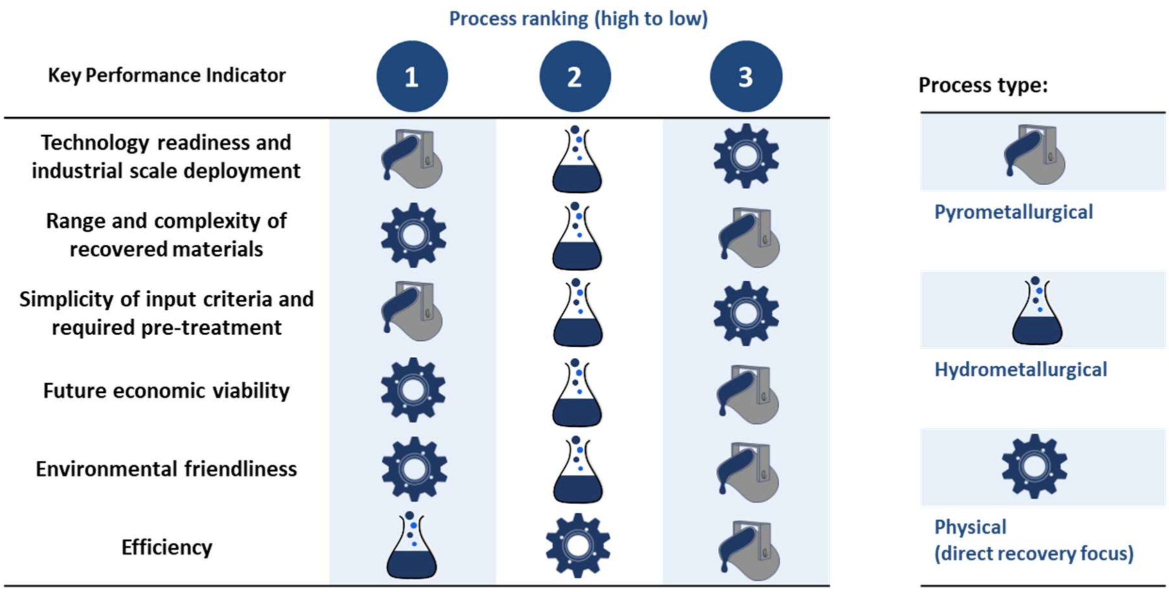


**Figure 38: Summary of assessment of battery recycling processes (ranking of performance against KPIs shown in section 4.2, 1 = high, 3 = low)**

This broad assessment could change in line with transitions in battery chemistry and revised regulations. For example, a transition towards solid-state batteries will likely affect physical recycling, whilst pyrometallurgical processes would be unsuitable for processing Li-S batteries due to the sulphur content acting as a process poison. At the same time, updated recovery targets and emission compliance imposed by new regulations could change both the economics and environmental friendliness of different recycling processes.

Battery chemistry and legislative changes are not the only challenges that recyclers will face in the future. Our modelling estimates that over 27,000 tonnes of batteries would require recycling in 2035, figure increasing almost three times, to over 78,000 tonnes in 2040. The current EU recycling capacity is insufficient to deal with EV battery volumes post-2035, with recyclers needing to make new investments into capacity upgrades. The market is expected to see both new entrants as well as specialisation of some players in certain roles down the recycling and second life application value chains.

Recycling is a capital-intensive business, with many factors - volumes, commodity prices, battery chemistry, recycling efficiencies and policies - determining the economics of recycling. The main revenue streams for recyclers consist of the value of recovered materials and recycling fees, paid by the entity responsible for battery recycling – in the case of EV batteries, the car OEM. Our economic analysis points out that recovered materials will likely be insufficient to cover recyclers' expenses. This means that OEMs will have to pay for recycling; nevertheless, recycling fees and the associated logistical costs are expected to decrease compared to current levels. For example, under the Baseline case, the recycling fees could reach $481/tonne in 2030. In the most optimistic case, OEMs may even expect a small payback.

## Potential of second life applications

Repurposing workshops will have access to cheap used batteries, delivering second life batteries at competitive prices compared to new batteries – ca. $40/kWh for a repurposed battery vs. $68/kWh for a new one in 2030.

Second life batteries will boost storage and renewables deployment: the expected lower costs of 2nd life modules and cells (compared to new) will boost the levels of deployed storage capacities on energy networks beyond the level with new grid batteries. In turn, this will boost VRES deployment, displace more fossil fuels and peaking plant, reduce energy cost to consumers and reduce $CO_2$ emissions.

## Policy recommendations for 2$^{nd}$ life use and battery recycling

In addition to encouraging the use of EVs for grid services, future policies must also address three key overarching goals: to encourage future EV deployments, ensure efficient recycling, and address the issue of second life batteries (Figure 39).

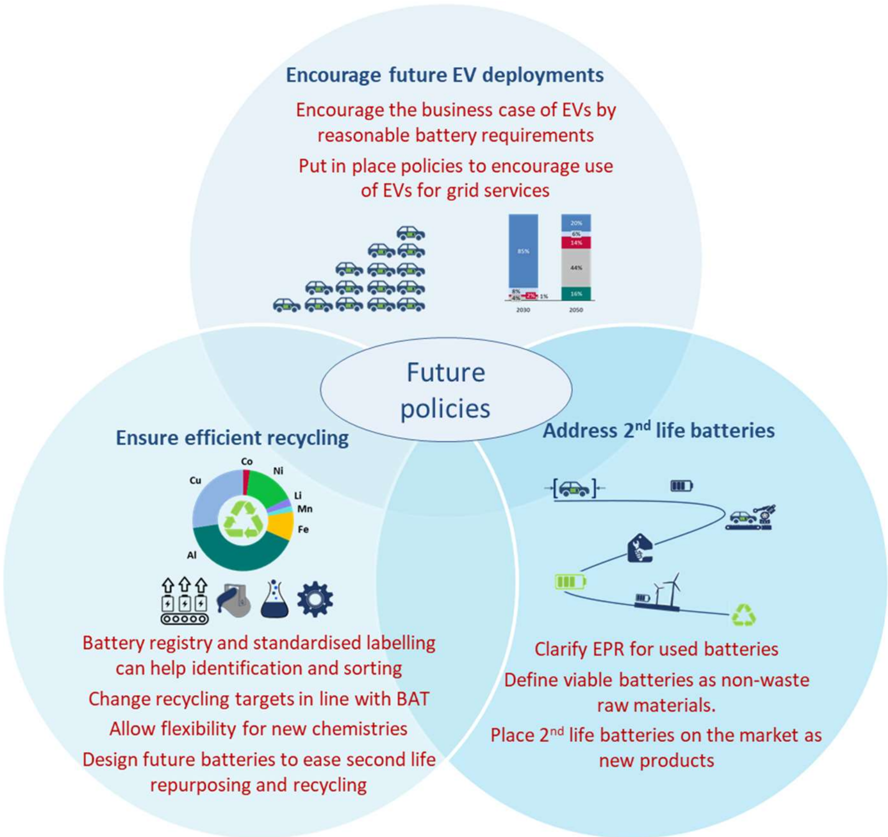


**Figure 39: Summary of topics to be covered by future policies relating to EV batteries**

To reach these goals, support the development of the second life battery market, and ensure battery recycling is fair for the involved stakeholders and for the environment, future policies must address six topics:

### *Policy must address all battery pack fates and the associated value chains*

A clear definition of the battery recovery for repurposing would have to be included, focusing in particular on the circular supply chain between scrap yards, vehicle/battery manufacturers, and repurposing workshops. For batteries considered too exhausted for second-life applications, the framework set in the current legislation would still apply, with the producer / car OEM being responsible for recycling. For batteries deemed viable for post-EV uses, revised legislation must address topics such as ownership of the battery, recovery and testing of used batteries, right to sell to workshops, transport to workshop, and potential authorisations to repurpose recovered EV batteries, as shown in Figure 40.

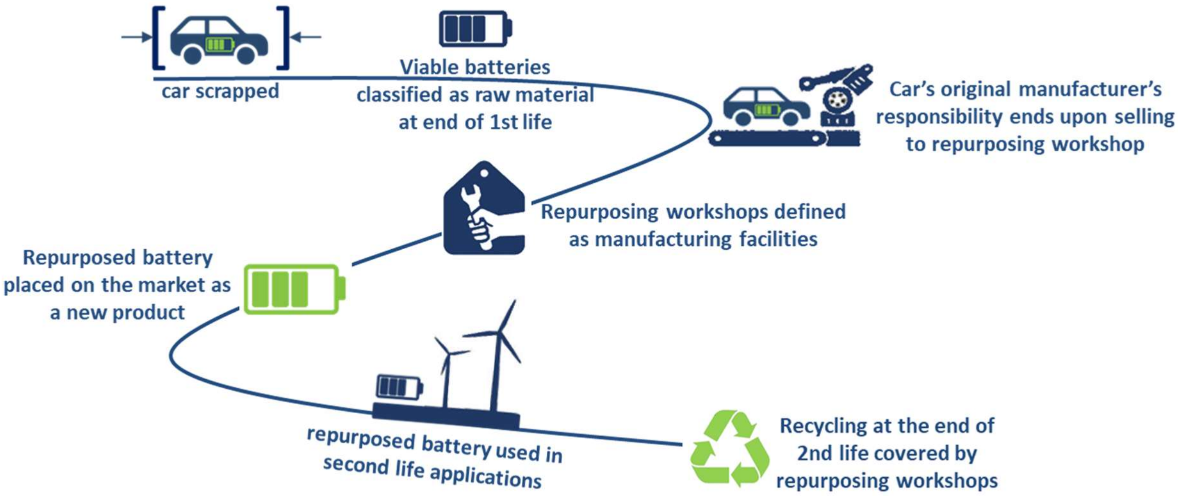


**Figure 40: Overview of the value chain behind second life batteries and the key aspects to be addressed by future regulation**

### *Battery tracking and identification must be encouraged by future regulations*

Online platforms serving as a battery registry could bring future benefits for both recyclers and battery repurposing workshops. A European-level registry would allow recyclers to quickly identify the entity responsible for battery recycling and would reduce the number of orphan batteries not recycled. At the same time battery chemistry could be easily identified using the registry and/or standardised battery labelling. Scrapyards, car OEMs and repurposing workshops would all benefit from data recorded by smart on-board analytic and diagnostic tools and fed into the battery registry, which would reduce the battery sorting and testing times and costs and would promote the second-life battery market.

### *Recycling of EV batteries should remain strict and in line with BAT*

Future policies must address the recycling of Li-ion batteries specifically. Based on the vehicles currently present on the EU market and in the OEMs' pipelines, LIBs are likely to be the most common battery technology to be recycled for the next 20 years[30].

### *Flexibility around new battery chemistries must be allowed*

Although Li-ion will be the main battery type used in the years to come, chemistry variations (such as those related to different metal compositions within LIBs) would affect the business case of recyclers as discussed in the following section. At the same time, new battery technologies expected to reach market maturity post-2030 (such as solid-state batteries or Li-S) may not fit the recovery targets set for LIBs. Future regulations must consider all these cases as much as possible and put in place flexible mechanisms in order to prevent provisions becoming outdated given fast technology development.

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[30] Assuming average vehicle lives and LIBs being used in stationary second-life applications.

### *Future batteries should be designed to be easy to recycle and repurpose*

With millions of EVs expected to be sold, used, and eventually scrapped in the EU, the design of future battery packs will play an important role in the EV battery recycling and repurposing efficiency and costs. European Commission is in the process of updating the Ecodesign Directive (2009/125/EC), aiming to set eco-design requirements for energy-related products, including batteries. It is thus important that this legislation review, and any subsequent revisions include clear guidelines on standardised manufacturing and labelling of new batteries. This would allow that key battery features, such as chemistry, to be easily identified. Easy identification of the manufacturer, alongside with a standardised pack design, will also reduce the time and costs related to dismantling of the battery packs and modules. In addition, future design should include tracking proxies (under the form of serial numbers or QR codes) which may be used to identify the battery manufacturer and owner, and that could be used during vehicle maintenance and repurposing to record and check the battery state of health.

### *Stimulate market demand by clarifying market size and role of 2nd life in grid applications*

As battery costs are reducing, energy system models are beginning to include higher volumes of batteries into decarbonized systems, but the system benefit of 2nd life, in terms of greatly increased storage deployment and reduced curtailment, is rarely acknowledged. By making energy stakeholders aware of the benefits of 2nd life batteries in grids, a large an immediate market pull could provide an incentive for the 2nd life industry to develop quickly.