B.A

BatteryMBA

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Battery circularity and economics of recycling

Introduction

The race to net zero has begun. Now more than ever sustainability and circularity will play an important role in our electrified future. The transportation sector is one the biggest sectors contributing towards global greenhouse gas emissions. While moving towards electrified transportation can support reductions in it, it introduces new ESG issues around the use of battery critical commodities such as cobalt, nickel, manganese and lithium. The transportation sector was estimated to contribute 30% of total CO2e in the UK in 2019 (according to the UK Government, see Exhibit 1).

Government legislations and sanctions are incrementally tightening to achieve a net zero future as we move towards electrification in a sustainable way.

A recycling strategy of batteries is necessary taking into account legislation and ESG goals. However, this includes several challenges assessing the financial viability of recycling across regions and the steps taken towards a closed loop approach. See some major car manufacturers in Exhibit 2.

Questions to discuss:

(1) Are collaborations required to make successful circular economies?

(2) Is second life/ESS application more attractive than recycling as a first choice? Why or why not?

Chaitali K Agale, and Malene Fumany, prepared the original version of this note "Battery circularity and economics of recycling" reviewed by B.A Mariano Rubio No. BA-CS-011, as the basis for class discussion. Only for B.A open case study on 2012.12.12.

(3) How is the battery recycling industry going to cope with loss in value when we move towards LFP taking into account the increasing number of recycling facilities in the EU?

(4) Is in-house recycling more financially attractive from an OEMs perspective than outsourced third party recycling?

(5) What challenges does the Battery Passport present with respect to data privacy from OEMs?

Desire for a circular & independent EU battery industry

- The growing strategic and environmental importance of EVs to the wider EU economy along with the supply chain disruptions caused by the COVID-19 pandemic, the war in Ukraine, and sanctions on Russia have further increased the need to create a circular and ideally more resilient and independent EU battery industry (Arthur D. Little, 2022).
- Generous subsidies and incentives have led to a wave of announcements of new battery manufacturing facilities, from both new entrants and existing international players. National governments, as well as the EU, are investing heavily to attract these gigafactories, with capacity expected to reach more than 1,100 GWh by 2030 if all plans are fully realised (Arthur D. Little, 2022).
- For gigafactories to succeed, there needs to be access to raw materials. However, the commodities market currently suffers from significant material pricing volatility - especially for battery critical commodities. This is leading to a reversal of the trend of annual declines in cell prices. Graphite, lithium, and cobalt are already on the European Commission's list of critical raw materials (i.e. commodities of potential high importance and with supply risks). (Arthur D. Little, 2022).
- As global battery demand steadily increases, global battery supply is increasing to try to meet demand. Battery recycling is seen as a way to support meeting battery demand, as well as an avenue to lower the environmental impact associated with mining virgin battery commodities (Arthur D. Little, 2022).

Closed loop approach

a) Circular economy Levers

i) Repair and refurbishment

Repair and refurbishment can extend the lifetime of EV and ESS batteries, reducing the demand for new capacity and improving lifetime costs. While repair targets batteries that fail during the intended lifetime, refurbishment applies to batteries reaching the regular end of life. In each case, it is assumed that degraded or faulty battery modules are exchanged to enable the capacity of the remaining modules to be used further in an EV or alternative function.

Key enabling conditions required for battery repair/refurbishment include:

- **Battery analytics technology**: The development of this technology embedded within batteries or as separate tools, and the sharing of key information derived from them (e.g., via a battery passport), will help to efficiently determine the state of health and chemistry of battery cells or modules and will help to manage them appropriately.
- **Design for disassembly**: Designing batteries to be easy to open so that modules can be exchanged with a high degree of automation – ideally with little variation between different manufacturers, so that tools can be harmonised.
- **Logistics operators and service stations**: An ecosystem that will make repairs convenient and will keep transaction costs low.

ii) Repurposing of end-of-life batteries

Some EV batteries may be repurposed for ESSs after their end-of-life (i.e., second-life application). For this, batteries are removed from vehicles, tested, refurbished if needed and, after being recertified for performance and safety, repurposed as-is or in parts.

The main enablers for the target state are:

- **Substantial R&D efforts**: These efforts in battery optimization, chemistry and layout allow for the meaningful residual life of most EV batteries for ESS after first life.
- **Battery diagnostic systems and shared data systems (battery passport)**: To make the assessment of a battery's performance after its first life transparent, quick and economical.
- **Scaling of second-life business models**: Improving the economics of second-life applications.

iii) Recycling

Recovering materials from end-of-life batteries and from gigafactory manufacturing scrap limits the need for virgin resources long term, ensures economical and safe end of-life management and prevents losses of valuable materials

b) Auto OEMS approach to carbon neutrality

Many (if not most) major car manufacturers (Original Equipment Manufacturers or OEMs) have publicly announced a target to achieve net zero by 2050 and intermediary plans to improve broader ESG metrics by 2030. This section looks at some major players in the car industry and their plans for sustainability and circularity (see Table 1).

To reach ESG goals, OEMs can employ partnerships to acquire needed capabilities - such as the formation of joint ventures among OEMs and battery recycling companies to acquire battery recycling capabilities. For instance, SK Innovation and Kia are developing both re-use and recycling initiatives. Kia evaluates used batteries and repackages ones suitable for re-use in stationary storage and the rest are sent to SK Innovation's recycling process for material recovery. Renault, Veolia and Solvay have similarly formed a consortium for the same purpose. Additionally, BMW, Umicore and Northvolt have also formed a consortium to create a closed loop for battery cells, involving both reuse and recycling (Arthur D. Little, 2022, see Exhibit 3 and Exhibit 4).

i) BMW

BMW group has recently announced plans to develop a carbon neutral car supply chain. With their 4R approach (RE: THINK, RE: DUCE, RE: USE, RE: CYCLE), the group is leading the way on their road to net zero and aims to have up to 95% of each BMW car be recyclable.

- BMW Group's approach to using green electricity, generated from renewable sources, has reduced carbon emission by around 23% in 2020 compared to 2019 (see Exhibit 5).
- The group advocates the use of secondary materials and have demonstrated the possibility of manufacturing a car with 100% secondary/recycled materials (BMW I-Vision, see Exhibit 6). Today, BMW has implemented ~25% secondary steel, up to 50% secondary aluminium in certain components and up to 20% secondary thermoplastics.
- In 30 countries, BMW operates 3,000 take-back points for end of life vehicle recycling (BMW, 2022).
- The BMW i3 has a recycling rate of 95%. 30% of the i3's interior comes from kenaf, a regenerative hibiscus plant, while the textile materials are produced

using an innovative yarn manufactured from granules made of recycled PET bottles. The i3's batteries also have a designated 'second life' use as stationary storage systems supplying clean energy to BMW production plants (BMW, 2022).
- BMW and Mini have launched a new battery recycling solution that will see used EV batteries have a second life as mobile power and fast charging units.
- BMW Group partnered with Duesenfield, a German recycling specialist to develop a method to achieve a recycling rate of up to 96 per cent from EV batteries.

ii) Nissan

Nissan Motor, like many other OEMs, has also been committed to closing the loop and applying circularity along its supply chain (see Exhibit 7). Below are a few project Nissan has publicly announced on recycling, re-use or second life of EV batteries:

- In 2021, Nissan Japan, in partnership with Waseda University announced the development of a new recycling process that efficiently recovers high-purity rare-earth compounds from EV motor magnets, with the aim of commercialising the new process by the mid-2020s. Nissan is also committed to reducing the amount of heavy rare-earth elements (REEs) needed in Nissan motor magnets
- In 2021 Nissan announced plans to build new battery recycling plants in the U.S and Europe by the end of financial year 2025.
- In 2022 Nissan announced a partnership with Enel to launch a second life storage system for used EV batteries in Spain. The project aims to use End of Life (EoL) Nissan EV batteries at a power plant in Melilla in order to enhance grid stability and help meet the needs of isolated networks (see Exhibit 8).
- In a recent collaboration between Nissan and 4R Energy Corp, used Nissan Leaf EVs batteries are sent for assessment. The batteries are categorised into three grades:
    - A: excellent condition and could be re-used in the new EV battery pack;
    - B: suitable for use in industrial machinery (e.g. forklifts, large ESSs); and
    - C: suitable for use in backup supply power units (Mohammed Haram et al., 2021).

iii) Tesla

- Tesla does everything it can to extend the useful life of each battery pack. This includes sending out over-the-air software updates to Tesla vehicles to improve battery efficiency
- Every battery used in R&D or returned from the field that cannot be remanufactured are recycled. None of the scrapped lithium-ion batteries go to landfills;100% are recycled.

- While Tesla works with third-party recyclers, they are also developing in-house recycling capability. . Today, the Tesla Nevada Gigafactory has on site battery recycling. (See Exhibit 9).

iv) Renault

- Veolia, Renault Group and Solvay have formed a consortium to recycle end-of-life EV battery metals in a closed loop.Renault Group is contributing its expertise in electric vehicle battery life cycle management, Solvay its expertise in the chemical extraction of battery metals, and Veolia its 10 years of experience in dismantling and recycling lithium-ion batteries via a hydrometallurgical process. The consortium created in September 2020 between Veolia and Solvay is thus strengthened by the automotive manufacturer's expertise.
- Renault aims to increase the share of recycled strategic materials (Li, Co, Ni) in their EV batteries to 80% by 2030

Summary of Major OEMs circularity approach, see Exhibit 10.

c) Recycling & Financial viability EV battery recycling

``Economically viable electric vehicle lithium-ion battery recycling is increasingly needed; however, routes to profitability are still unclear" as written in a recent study by Dr. Laura Lander, from Imperial College London, who published a paper on the financial viability of EV LIB recycling. The economic viability of battery recycling depends on the cost of collection, handling, disassembly and the value of commodities in the batteries to be recycled. . While EV sales have been steadily increasing, EV batteries generally have a life expectancy of 15 to 20 years. Therefore, EV batteries scrap is currently the most abundant recycling feedstock, while EoL batteries will only become a major feedstock into recycling after 2030.. Europe's recycling market is still very much at its infancy compared to China. Currently, China has a more advanced ecosystem for recycling and second life uses (Lander et al., 2021 & see Exhibit 12).

Using a techno-economic framework (EverBatt model developed by ReCell Centre and Argonne Laboratories, see Exhibit 13 and Exhibit 14), the team performed an in-depth economic assessment of EV battery recycling. The study reviewed every step of the process from transportation, to recycling facility, all the way to the reselling of recovered materials. The study compared the disassembly costs of commercial battery packs, by country, from the Porsche Taycan, Tesla model S and the 2011 Nissan Leaf. . The Tesla Model S was the most profitable, having low disassembly costs and high revenues primarily from its cobalt content. In-country recycling is suggested, to lower emissions and transportation costs and localise the materials supply chain (see Exhibit 15).

The study also compared cost per stage of recycling by country. After the recycling process itself, China's second biggest cost is transportation, while the UK's second biggest cost is disassembly. If in-country recycling to be made viable in the UK, disassembly costs need to be reduced. (Lander et al, 2021, see Exhibit 16).

Next the study looked at the cost of each recycling method : pyrometallurgy, hydrometallurgy and direct recycling (Lander et al, 2021, see Exhibit 17). Each technology has different challenges especially in an undeveloped market such as Europe as opposed to China.

In terms of technology maturity:

- Direct recycling is still very much R&D scale;
- Pyrometallurgy, is widely used today;
- hydrometallurgy is scaling up quite quickly.

In terms of recycling cost:

- Hydrometallurgy is the cheapest process despite higher material costs, due to chemicals for leaching
- Pyrometallurgy is the most expensive process with higher utility and labour costs

In terms of revenue (Lander et al, 2021, see Exhibit 18):

- Direct recycling leads to higher revenues compared to pyro/ hydrometallurgical processes, as more material can be recovered with minimal processes.
- LFP and LMO very low revenue for hydro and pyro, but high revenue for direct recycling
    - They looking at net recycling profit and based on 8,000 tonnes cells to be recycled (Lander et al, 2021, see Exhibit 19):he highest net recycling profits s are achieved for:
        - Recycling in China
        - Direct recycling
        - Recycling of NCA batteries
    - Negative net recycling profits are achieved for:
        - Recycling in Belgium
        - Pyrometallurgy
        - LMO and LFP chemistries

Looking at recycling cost and net recycling profits as a function of the yearly cell throughput for a UK facility recycling NCA battery packs(Lander et al, 2021, see Exhibit 20):

- Recycling breakeven points established in study:

    - 17,000 tonnes/year for pyrometallurgical recycling
    - 7,000 tonnes/year for hydrometallurgical recycling
    - 3,000 tonnes/year for direct recycling
- Breakeven points for recycling profitability might vary strongly as materials prices might fluctuate strongly

Battery chemistry trends are moving away from high cobalt contents towards Ni-rich and LFP battery chemistries. This impacts recycling profitability as cobalt is the most valuable battery commodity recycling today. Looking at net recycling profits as a function of the yearly cell throughput for a UK facility recycling NCA battery packs - with/without cobalt (Lander et al, 2021, see Exhibit 21) :

- Recycling breakeven points increase to:
    - >50,000 tonnes/year for pyrometallurgical recycling
    - 17,000 tonnes/year for hydrometallurgical recycling

Overall, economic recycling is currently difficult to achieve in Europe. Achieving high enough processing capacities remains Europe's major constraint. Whereas,China has already achieved profitable battery recycling models in part due to lower transportation and dismantling costs.

i. How does different battery chemistry impact the circular economy?

The chemistries used in battery cells are becoming increasingly diverse, with a widening variety of cathode material usage. This is driven by the constant need for battery makers to optimise performance specs, while balancing costs and expected material availability. There has been a noticeable reduction in cobalt-rich chemistries, with trends toward nickel-rich, manganese-rich, or nickel/cobalt-free cells. All of these potential feedstock combinations must be processed efficiently by recyclers the same way and will inherently provide different associated revenue streams.

Exhibit 22 (Arthur D. Little, 2022) provides indications of expected revenue streams (per ton of recycled batteries) for a typical recycling plant. It shows that processing high-value chemistries, using NMC chemistries as a benchmark, already provides a profitable business case. In Europe, OEMs are also reportedly paying a “disposal fee” to recyclers. Along with extended producer responsibility legislation, this serves as an additional revenue stream and incentive to the recycling ecosystem. The disposal fee for processing low-value chemistries (e.g. LFP) is higher than fees paid for NMC, balancing the overall recycling business case.

The existence and stability of disposal fees will be critical for recyclers’ financial returns, as the recycling ecosystem will need to effectively process a variety of chemistries.

LFP battery cathode chemistries are set to surge globally. Recently, major non-Chinese EV manufacturers, such as Tesla and Volkswagen, announced moves to LFP chemistries for entry-level, high volume, EV models. Almost half of all Tesla EVs produced in the first quarter of 2022 used LFP. Additionally, LFP battery production is now planned across Europe and the United States to meet anticipated LFP demand for EVs in these regions. A surge in LFP poses a challenge for battery recycling as it is difficult to make a profit recovering iron and phosphorus. Without valuable metals such as nickel and cobalt, the value that can be recovered from batteries drops considerably from conventional recycling methods and its economic viability is a concern. LFP appears to require direct recycling to be profitable or will require regulatory intervention, frameworks and/or alternative business models (Arthur D. Little, 2022).

d) Second life or Energy storage System

The state-of-health and the battery residual values are the two key elements that will determine if EoL batteries will be repaired, reused, or recycled. Now, the key drivers for battery recycling (especially in the European market) are the security of raw material supply, boosting production efficiency, battery recycling legislations and achieving a low ESG footprint.

Second life applications come with a few challenges such as matching the battery chemistry with the application or similar State of Health of cells required. A general rule of thumb for a battery to be considered for second life application depends on the State of Health as follow:

- 80% capacity: good enough to go back into a vehicle;
- 60-80% capacity: good enough for demanding second life application;
- 60-70% capacity: good enough for large scale storage applications;
- <60% capacity: good enough for small scale storage.

In the case of second life, battery as a service (BaaS) is another area that needs to be considered since OEMS such as Nio are dominating the market at the moment by offering this service. One question to ask is: Can battery as a service be a major contributor to a closed loop system? In the case of BaaS, two plausible business cases would be:

- To have battery manufacturers leasing batteries to OEMs whilst customers can then use those batteries as a service. In this case, OEMs are only providing the platforms.
- To have the leasing of the battery from the OEM. OEMs will be in full control of their car as a service ecosystem (i.e. they will purchase the battery as with any other component from their tier one suppliers). Then the whole vehicle would be offered as a service, where the cost of the service varies based on the specifications selected/level of battery/mileage etc. The reason for this could be that the OEMs will have a strategic interest in controlling the 4Rs process in

a closed loop, and with so much value left in the battery they'll want to retain full control of it to ensure proper recycling/reuse will occur at EoL.

In the case of Energy Storage System (ESS) applications, this approach offers a few benefits to EoL batteries such as recovery of the residual value of the battery and reduces the need for new batteries in the power sector. Recycling is inevitable for the battery sector to minimise ESG impact. However, the second life applications as a first choice would be environmentally more beneficial and therefore preferable over immediate recycling.

Legislations

a) New regulations set targets & mandate recycling

The EU has existing, but outdated, legislation in place that sets efficiency targets for recycling specific battery types and minimum rates for battery collection. These recycling regulations do not adequately cover the growth in Li-ion vehicle batteries. Consequently, the regulations are currently undergoing significant revisions, which encompass the following key points:

- These regulations will be EU-wide, entering into force immediately in all countries;
- For the first time, specific targets will be attached to lithium-based batteries and will include recovery rates of specific materials, including cobalt, nickel, and lithium;
- The framework will reinforce extended producer responsibilities for OEMs, such as automotive or grid storage manufacturers, while increasing tracking, diligence, and visibility across the supply chain and via coordination mechanisms;
- Targets are expected to increase and tighten in the coming decade. The European Parliament recently voted on current amendments to these targets, which are expected to begin implementation by 2023. These amendments highlight a trend toward more ambitious recycling requirements and will increase the scope and need for battery recycling.

b) Standards and Regulations for Second Life Batteries

Currently available standards for automotive Li-ion batteries, such as ISO 12405-2:2012 and IEC 62660-2, can prove effective to construct the new standards for second-life batteries. Nonetheless, safety can be assumed to be a major concern in standards, as it must be ensured for proper operation of batteries in the second life.

One standard for battery reuse that is currently being developed is the SAE J2997 which states battery state-of-health (SoH), labelling, and transportation as the evaluating criteria for determining the safety of reuse (see Exhibit 23).

The widespread use of Second Life Batteries (SLB) is eventually facing some challenges such as the availability of similar SLB characteristics at large scale and difficulty in assessing SLB accurately. However, such challenges could be overcome with the rapid growth of the EV industry, SLB standards, automation of assessment and further economic studies. Examples of such standards are the newly released standard, UL1974 and J2997 by SAE which is still under development.

c) Region wise actions

i. The EU

Currently the European legislative frameworks for EoL batteries are:

- Directive 2000/53/EC which regulates how EoL EVs must be managed: reuse and recovery of EoL vehicles is set at 95% minimum (weight percentage), and reuse and recycling set to a minimum of 85%.
- Directive 2006/66/EC which regulates treatment of industrial batteries after removal from vehicles, and more broadly regulates both cell manufacturing and disposal. EU member states generally retain some degree of freedom on how the directive is implemented nationally. The two key notions to consider are recycling efficiency, which must be 50% by weight for LIBs (which is considered an unambitious target), and the extended producer responsibility, (i.e., producers are responsible for collecting, treating and recycling waste batteries). In principle, sending industrial batteries to landfill is prohibited.
- The proposed new Battery Act/Regulations include requirements relating to the 2nd Life of EV battery manufacturing such as imposing minimum amounts of recycled contents and material recovery targets (see Exhibit 24).

The new directive would cover the whole lifecycle of a battery (Nikolas Hill (Ricardo), 2022 see Exhibit 25). For battery producers, it will be necessary to report the number of batteries collected and delivered for treatment and recycling. Recycling operators will need to report the amount of waste batteries entering recycling, recycling efficiencies and level of recovered materials from waste batteries, and the number of treated batteries. Member states will need to report the amount of waste batteries collected, levels of recycling, and ensure that the targets for producers and operators are met.

This new directive will require:

- Carbon footprint measurement: including declaration, performance classes and maximum lifecycle carbon footprint threshold;

- Recycled content measurement and recycling efficiency: including mandatory levels of recycled content by 2030;
- Labelling and information:includes Battery Passport and carbon footprint performance class QR Code.

ii. The U.S.A

There is currently no EV battery recycling policy at a federal level in the US. The Biden administration announced its EV strategy in June 2021, based on its 100-day review of key US supply chains. The strategy includes boosting the EV battery recycling supply chain in the US while sourcing raw materials from allies. Details of its EV battery recycling push have not been revealed yet.

iii. China

- In 2019, MIIT released the General Guideline on the Reuse/Recycling of Used EV Batteries. Starting from 01/01/2020, EV battery recycling companies are encouraged to apply for qualifications and follow the industry guideline. According to the document, recycling rates for nickel, cobalt, and manganese should reach 98% (97% for other rare metals) and higher than 85% for lithium. The recycling rate for wastewater should be at least 90%.
- On the 16th of December 2020, MIIT released the updated version of the whitelist of EV battery recycling companies. There are 22 companies on the whitelist in total. The second-life battery supplier is the key element of this update.

Conclusion

Battery recycling, reuse and remanufacturing and tightening legislations are important elements driving the creation of a circular battery economy. The European battery recycling ecosystem is developing quickly although still at its infancy. Competition will be intense, with partnerships, ambition, and funding all required for success. Thus, players need to take the following actions:

- **Form the right partnerships:** across the ecosystem, which are ready to scale up. Find the most attractive complementary technology and business partners with aligned ambitions and interests.
- **Build knowledge and physical capabilities**: Creating new facilities and skills requires an investment of money and time. Most players are still early in their journey.
- **Position flexibly**: This ecosystem is in the process of being formed, with multiple moving parts in terms of technologies, chemistries to be recycled, business, and financial models.

This case study reviewed battery recycling regulatory frameworks across EU, the US and China, considered the financial viability of recycling by company and shared what some of the major OEMS are currently doing and planning to achieve full circularity across their EV supply chains.

As part of the solution, the second life EV battery value chain is expected to play a role in lowering mineral resources extracted from mining. For the investments to be economically viable, a recycling process including collecting, storing, and processing needs to be cost-competitive and incentivised relative to primary raw material extraction. Several OEMs have already taken positions in the reuse of lithium-ion batteries for ESS, such as Daimler, before proceeding to recycling.

The question always remains whether second life/ESS applications are more attractive than recycling as a first choice.This depends upon the financial viability of each application. However, car manufacturers such as Tesla have opted for 100% recycling and no second life project for its EoL EV batteries which begs the question as to why?

Another aspect to consider is the move away from NMC chemistry and towards more LFP chemistry which will impact recycling profits. Here a few questions to consider:

- Will companies make a loss from recycling? - since no profit will be generated from cobalt/nickel recovery. Currently only China has managed to make recycling of LFP and direct recycling profitable.
- Would companies consider China for LFP battery recycling until it becomes profitable outside of China?

- Would switching to LFP force companies to consider ESS or second life applications as a more attractive first choice over recycling in its European and American markets?
- How is the European recycling industry going to cope with loss in revenue from the move towards LFP chemistry (+ increasing number of recycling facilities)?
- Is in-house recycling more financially attractive from an OEMs perspective than outsourced third party recycling?
- What challenges would a battery passport introduce in terms of data privacy?How much potentially proprietary information will OEMs be required to share?

International convention bodies, regulators, battery manufacturers and vehicle manufacturers need to work together to enable the exchange of data among key stakeholders, foster product design and technical development, and harmonize national and international rules to ensure safe and economic use and recycling of batteries. The introduction of a battery passport would support data sharing, provide a powerful way of identifying and track batteries throughout their lifecycle, thus, support the establishment of systems for life extension and end of life treatment. However, with the new battery passport, comes another issue around data sharing or perhaps how much data can be shared publicly. Would OEMs want to disclose certain information that they judge to be confidential? Government bodies and industry players will need to come together and agree on what is to be shared in order to ensure safe data sharing and privacy is respected.

Questions to discuss:

(1) Are collaborations required to make successful circular economies?

(2) Is 2nd life/ESS application more attractive than recycling as a first choice? Why or why not?

(3) How is the battery recycling industry going to cope with loss in value when we move towards LFP taking into account the increasing number of recycling facilities in the EU?

(4) Is in-house recycling more financially attractive from an OEMs perspective than outsourced third party recycling?

(5) What challenges does the Battery Passport present with respect to data privacy from OEMs?

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Nomenclature

ASSB	All Solid-State Battery
BaaS	Battery as a Service
EoL	End of Life
ESS	Energy Storage and system
OEM	Original Equipment Manufacturer
SLB	Second life batteries
SSB	Solid state batteries

Exhibits

Exhibit 1 - Why Battery Electric Vehicle: CO2 emissions: CO2 emissions (BEIS, 2020)

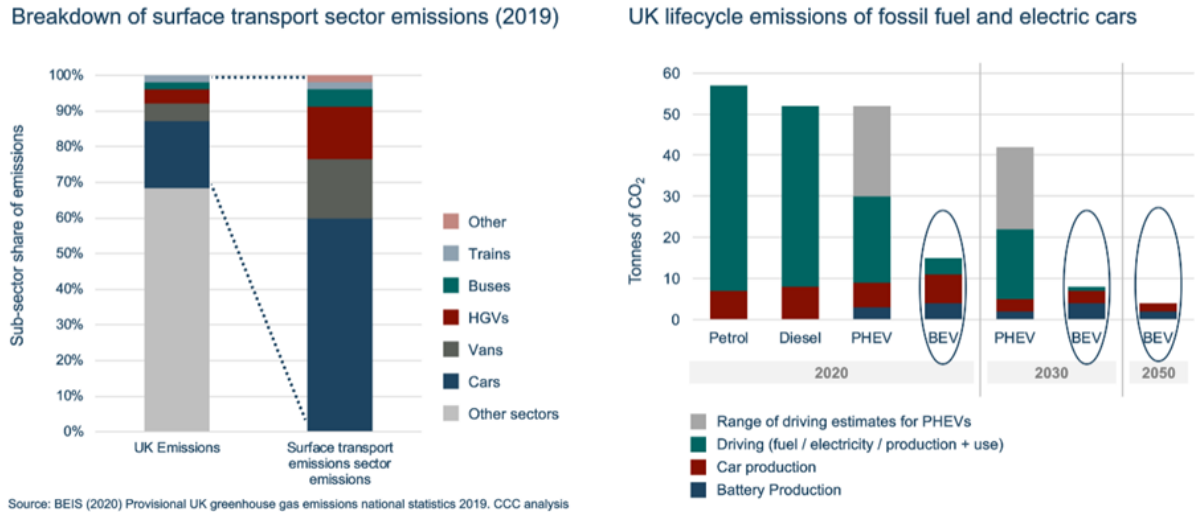

Exhibit 2 - Example of Circular Economy

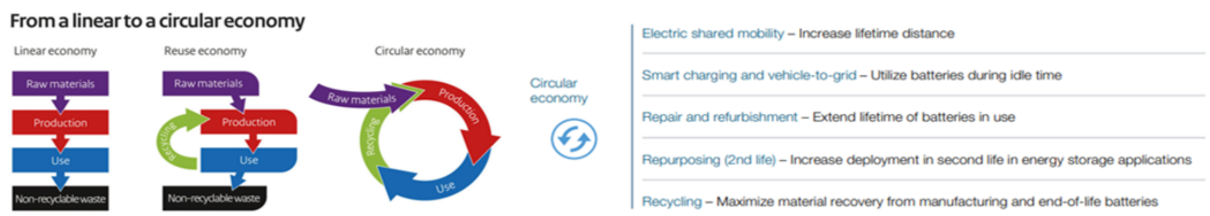

Exhibit 3 - Industries in the EU Li-ion battery recycling (Arthur D. Little, 2022)

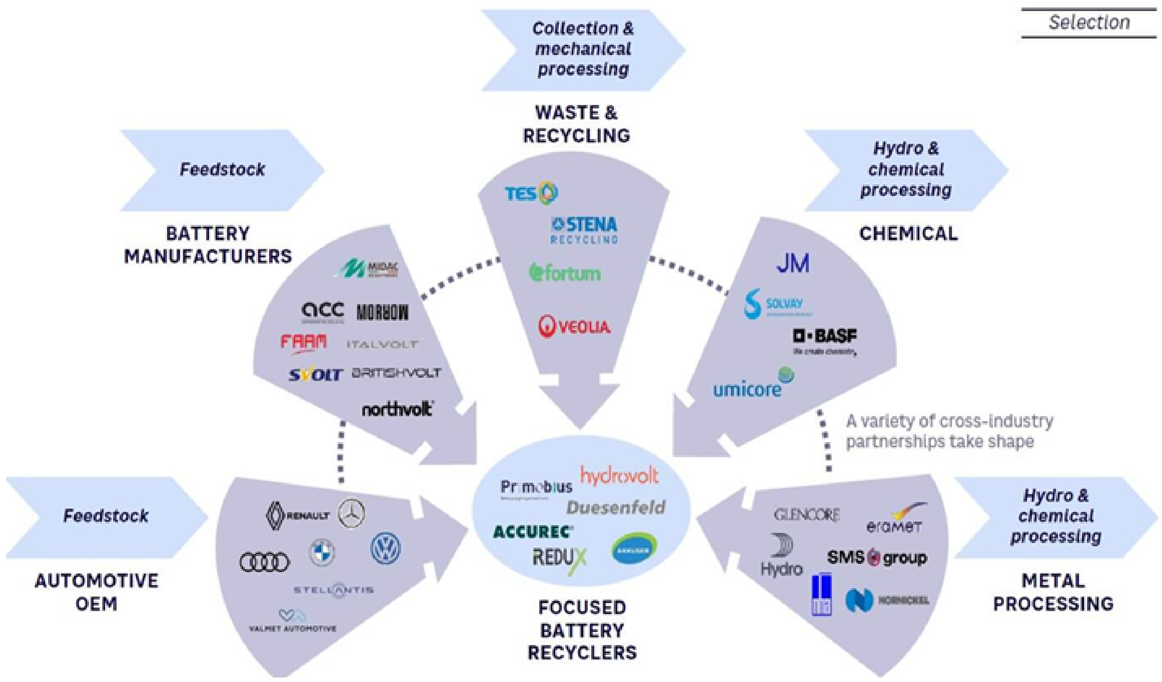

Exhibit 4 - Recycling players prepare for European battery gigafactories (Arthur D. Little, 2022)

Exhibit 5 - BMW CO2 emissions per vehicle produced (BMW sustainability report, 2020)

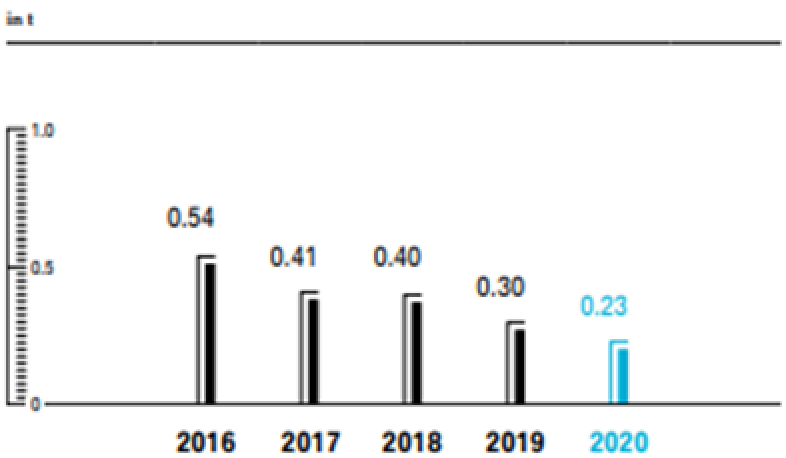

Exhibit 6 - BMW iVision

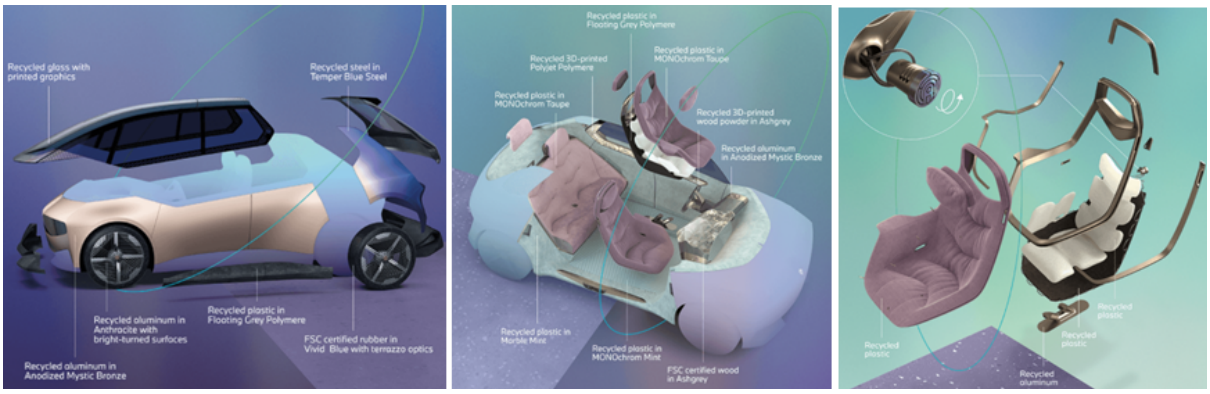

Exhibit 7 - Nissan's proposed 4Rs diagram (Nissan Motor Corp, 2010)

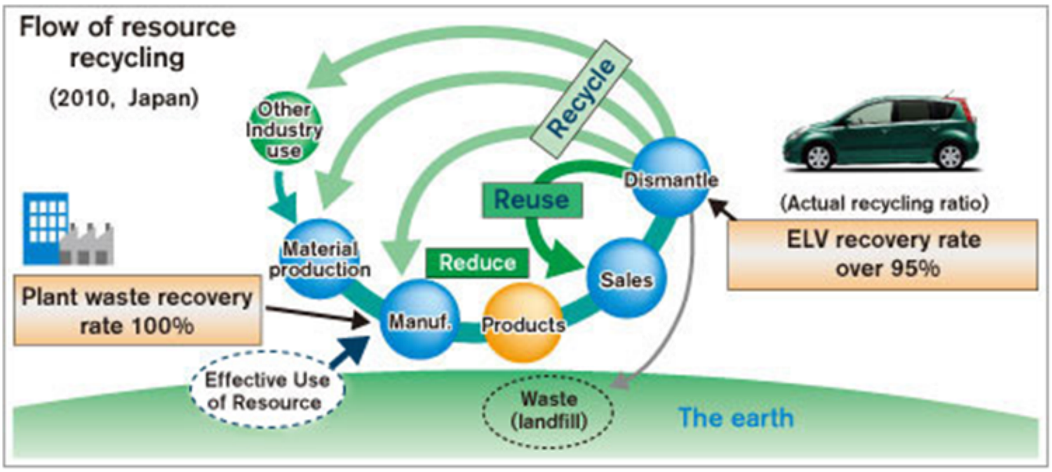

Exhibit 8 - Nissan Spain second life project (Battery News, 2022)

Exhibit 9 - Tesla's recycling process flowchart (Tesla, 2021)

Exhibit 10 - Summary of Major OEMs circularity approach

OEMs	• Li, Co, Ni, Mn, Graphite (C) • Al, Cu, Plastics & other 	Recycling	Second Life/Reman	Timeframe
BMW, Rolls-Royce, MINI	Announced the recycling rate for Co, Ni and batteries to be >90% and Aluminum to be >90%.	• BMW recycling is outsourced with Alliance between Northvolt and Umicore. • Umicore is the partner responsible for active anode and cathode materials development and recycling in the technology alliance.	• Battery 2nd Life project by Vattenfall, BMW and Bosch for a large storage facility in Hamburg, Germany. • A 2MW/2MWh large-scale energy storage system will be built using lithium-ion batteries from BMWs ActivE and i3	By 2030 for battery packs recycled contents.
NISSAN		• Nissan Japan currently developing a new recycling process that efficiently recovers high-purity rare-earth compounds from EV motor magnets	• Partnership with Enel to launch second life storage system for used EV batteries in Spain • Collaboration between Nissan and 4R Energy Corp	Carbon neutral by 2050
VW, BENTLEY, SEAT, Audi, MAN, Porsche	Recycle 97 percent of all raw materials. Today, it is 53 percent	• Volkswagen Group Components in Salzgitter is currently setting up its own pilot plant for battery recycling. • Audi and Umicore are developing a closed loop for the recycling of high voltage batteries	• In 2019, VW unveils a mobile charging station designed to used second life EV (MEB platform) battery packs	To be net carbon neutral by 2050 at the latest
TESLA	• Tesla reports current material recovery rates are already at 92%.	• Recycling is done in-house and in partnership with Redwood Materials & Umicore	• No mention of any major re-use or 2nd life project at the moment	

Exhibit 11 - Recycling process (Rho Motion, 2022)

Technology	Description	Examples
Pyrometallurgy (generally with hydrometallurgical refinement)	Treatment of end-of life batteries by high temperature (1450-1650°C) in furnaces, e.g., shaft furnace or electric arc furnaces	umicore, REDWOOD MATERIALS, GLENCORE
Hydrometallurgy	Process focusing on selective leaching, extraction and precipitation of metal salts or precursors, using water/solvent-based techniques	umicore, northvolt, Li-Cycle, REDWOOD MATERIALS
Combined processes (hydro and pyrometallurgical)	Most of the processes include several pyrometallurgical/pyrolysis steps, followed by hydrometallurgical treatment to extract valuable metal. The exact type and economics of the process needs to be considered on a case-by-case scenario	umicore
Mechanical pre-treatment (or other pre-treatment techniques) and black mass separation	Conventionally included in several process flows. Recyclers consider it necessary to localise EOL battery collection and treat them up to black mass (output)	Li-Cycle, VEOLIA
Direct Recycling	Process focusing on separation, recovery and regeneration/reconditioning of cathode and anode active materials, using a variety of different techniques	JM Johnson Matthey Inspiring science, enhancing life, FARASIS, 6K

Exhibit 12 - World mine production for raw materials contained in LIBs in 2019 and locations of recycling facilities (Mineral Commodity Summaries 2020, 2020).

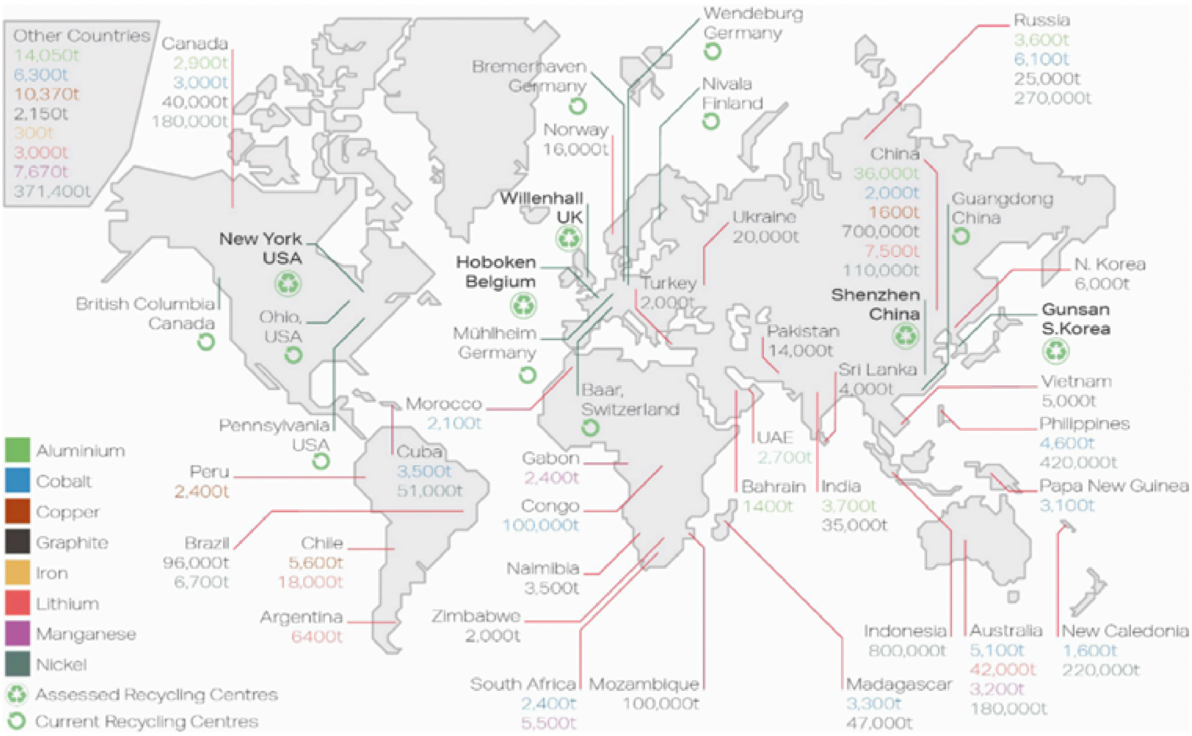

Exhibit 13 - Schematic of EverBatt Model(Argonne Laboratories and ReCell Centre,2022)

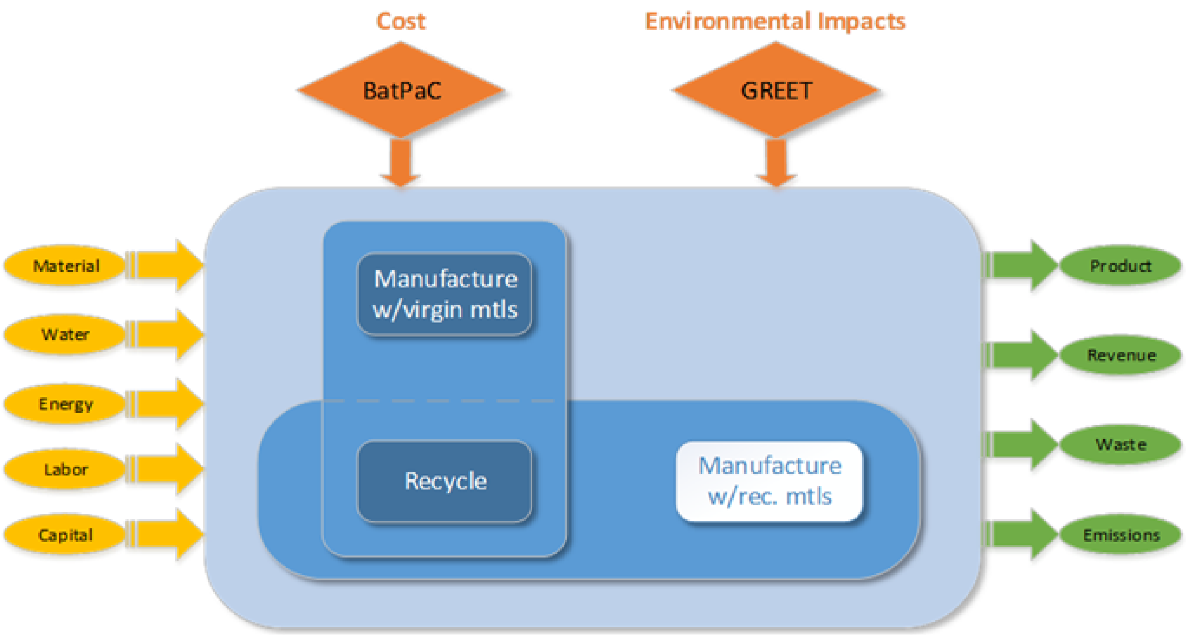

Exhibit 14 - Schematic of the Recycle Module (Argonne Laboratories and ReCell Centre, 2022)

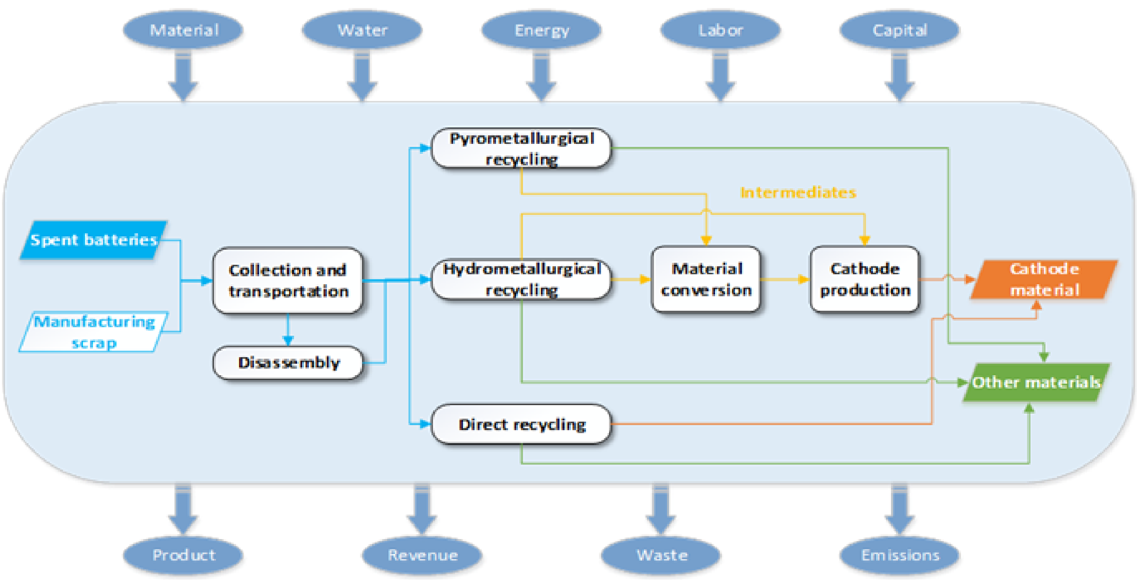

Exhibit 15 - Disassembly cost of commercial battery packs (Lander et al., 2021).

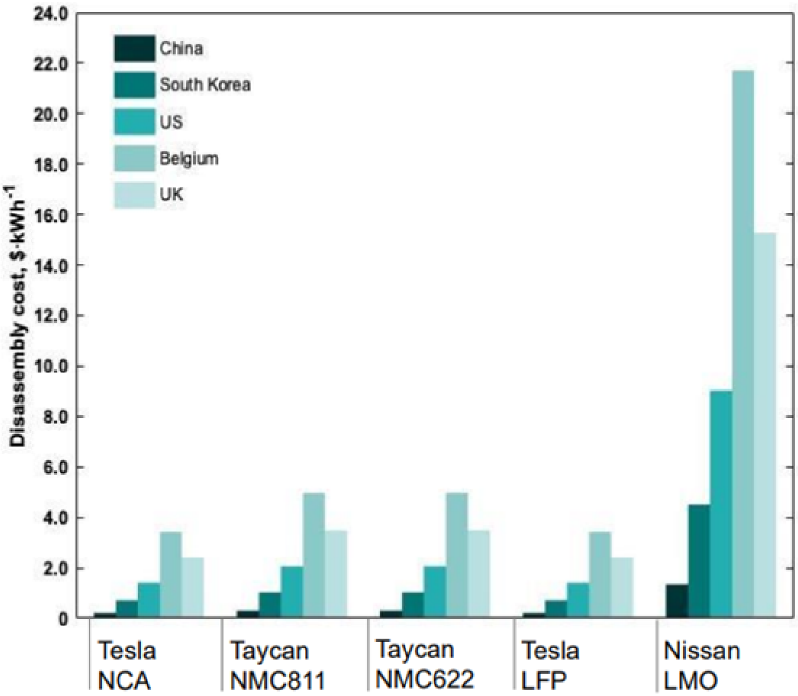

Exhibit 16 - Disassembly cost per region (Lander et al., 2021).

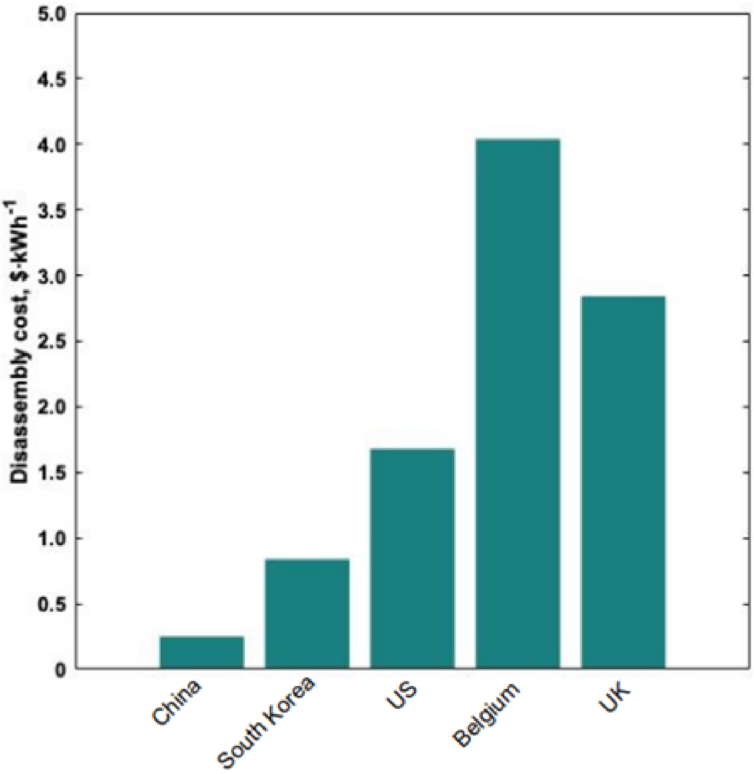

Exhibit 17 - Cost of each recycling method (Lander et al., 2021).

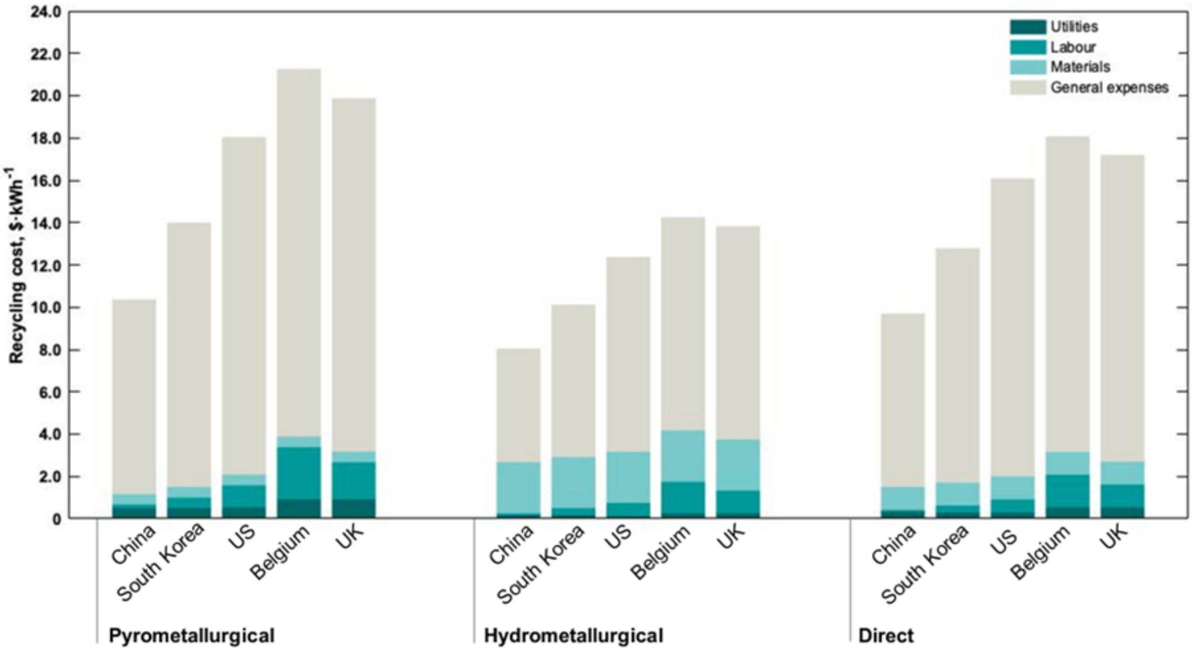

Exhibit 18 - Revenue from each recycling method (Lander et al., 2021).

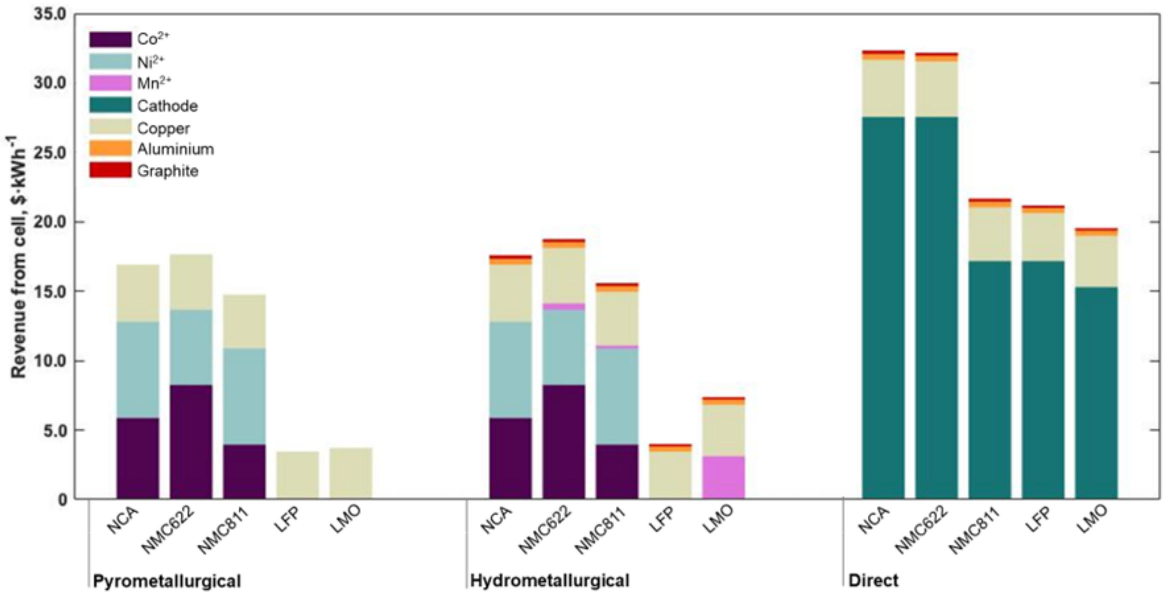

Exhibit 19 - Net recycling profit for each method per region and battery chemistry (Lander et al., 2021).

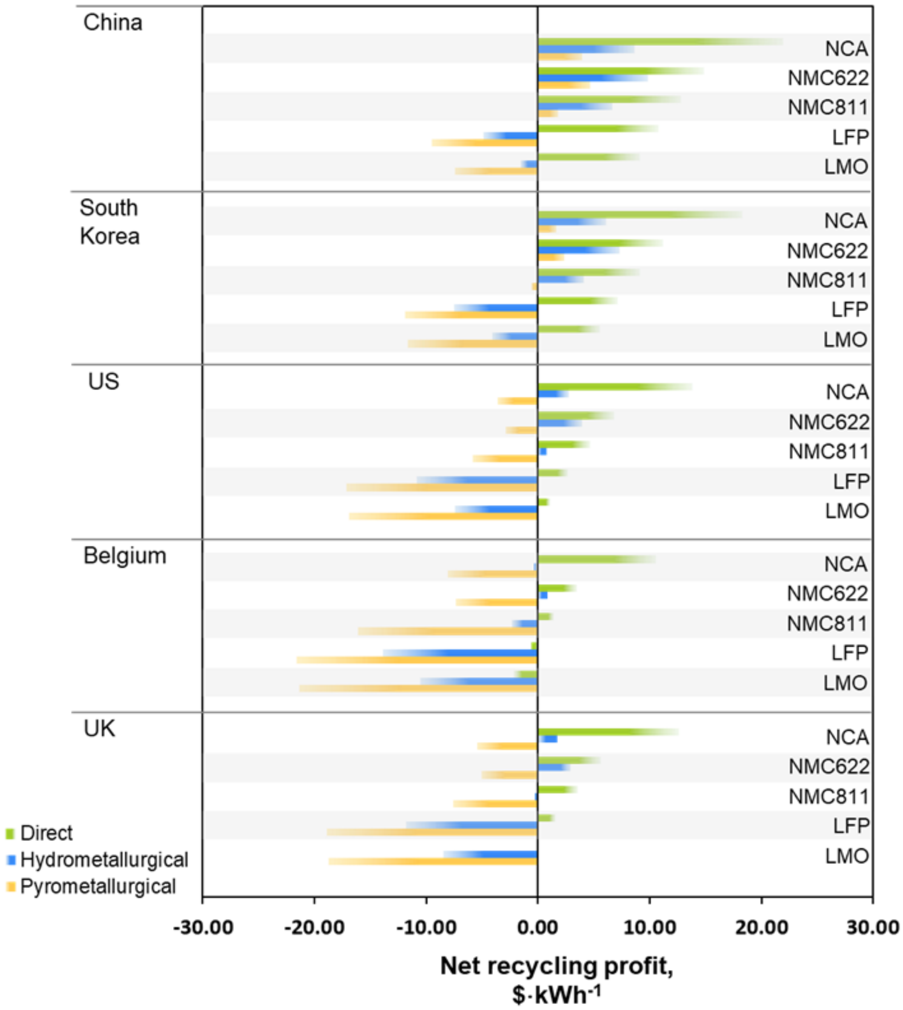

Exhibit 20 - Recycling cost and net profit per year (Lander et al., 2021).

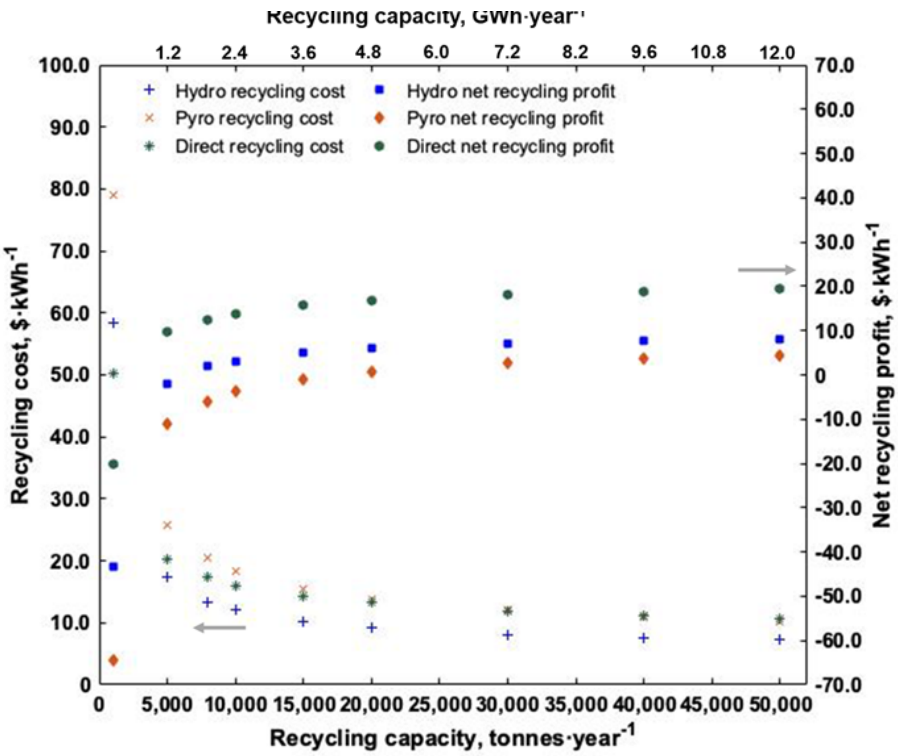

Exhibit 21 - Recycling profit with/without cobalt (Lander et al., 2021).

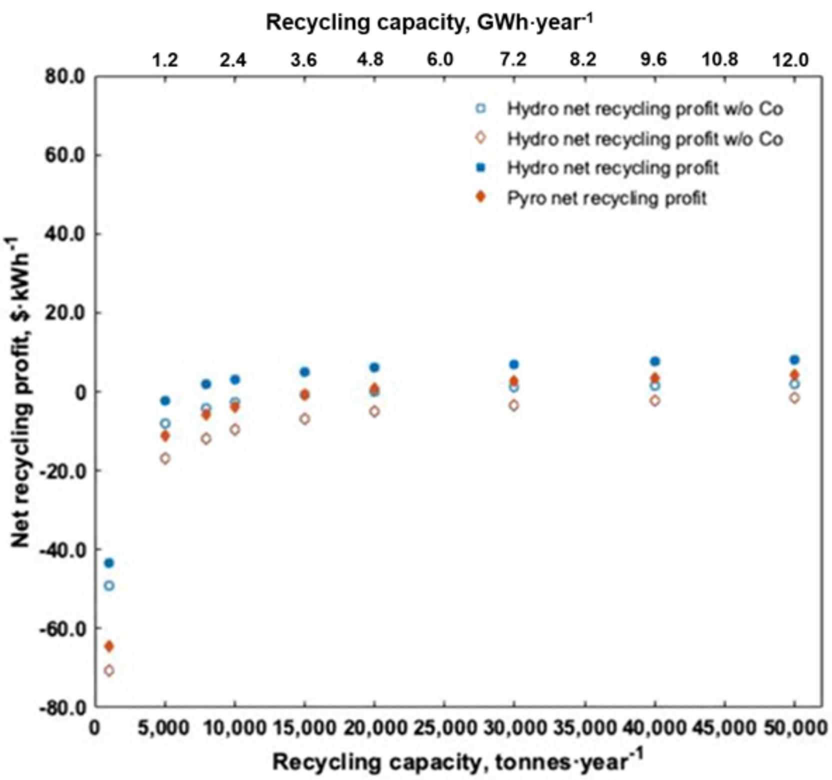

Exhibit 22 - Battery recycler EU revenue streams by feedstock chemistry (Arthur D. Little, 2022)

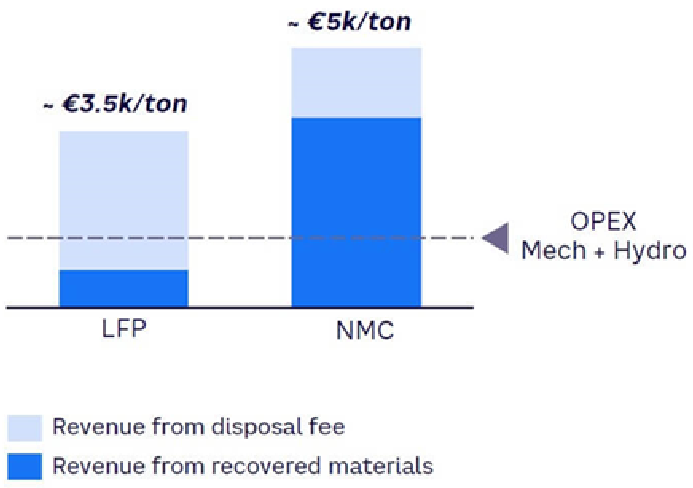

Exhibit 23 - Standard currently under development relative to the second use of EV batteries

Standard	Title	Technical committee	Stage (expected publication date)
SAE J2997	Standards for Battery secondary use J2997	Secondary Battery Use Committee	WIP
ANSI/CAN/UL 1974	Standard for Evaluation for Repurposing Batteries	S400D Committee On Batteries For Use In Electric Vehicles	UL CSDS Proposal

Exhibit 24 - Recovered materials from proposal EU Battery Regulation

Recovered materials	2025	2030
Cobalt, copper, lead, and nickel	90%	95%
Lithium	35%	70%

Exhibit 25 - Timeline of EU legislative for EoL batteries (Nikolas Hill (Ricardo), 2022)

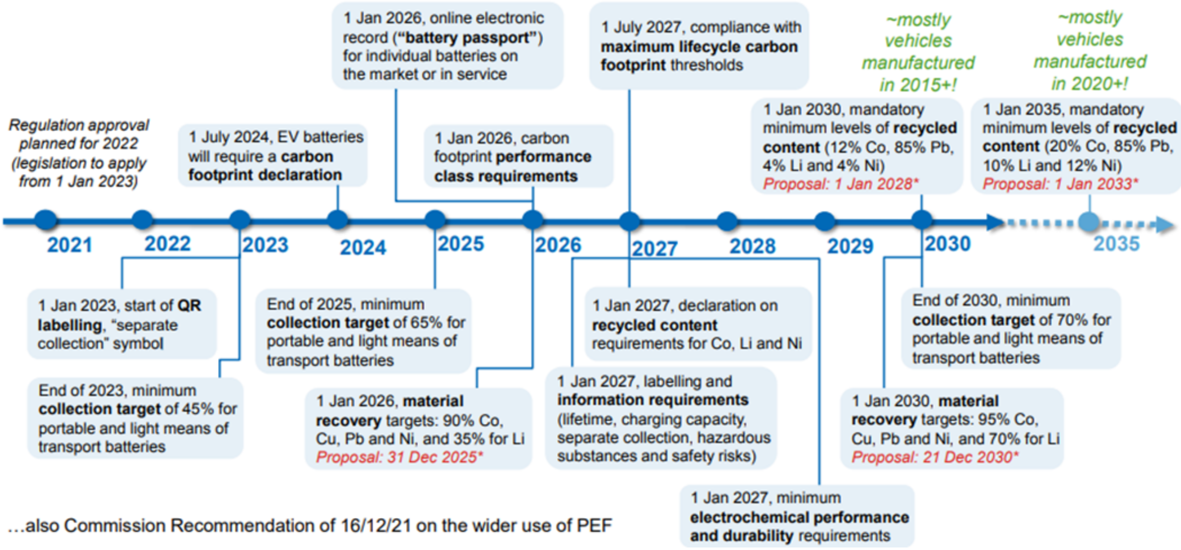

Exhibit 26 - Recycling: Circular economy (World Economic Forum, 2019)

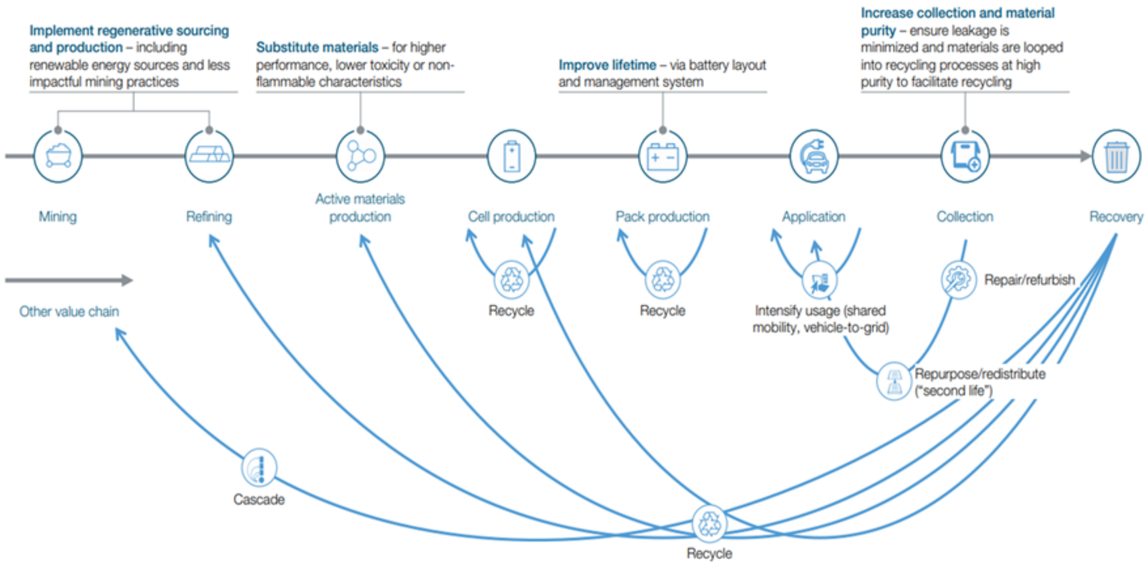

Exhibit 27 - Techno-economic model used, EverBatt (Lander et al., 2021)

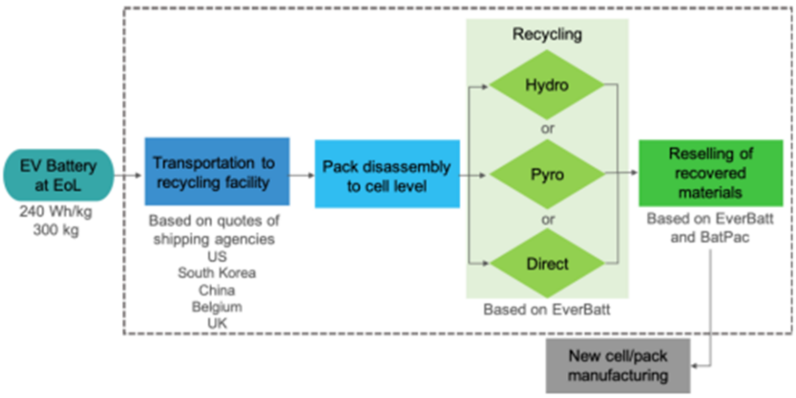

Exhibit 28 - Net recycling profits of battery packs (Lander et al., 2021)

		Pyrometallurgical ($·kWh^{-1})	Hydrometallurgical ($·kWh^{-1})	Direct ($·kWh^{-1})
China	Tesla NCA	3.56	7.95	19.74
	Taycan NMC622	4.39	9.61	14.42
	Taycan NMC811	1.06	5.04	9.74
	Tesla LFP	-20.42	-9.85	24.72
	Nissan LMO	-15.18	-3.29	12.63
South Korea	Tesla NCA	1.49	5.54	16.50
	Taycan NMC622	1.95	6.79	10.70
	Taycan NMC811	-1.04	2.63	6.60
	Tesla LFP	-24.91	-15.08	17.46
	Nissan LMO	-21.05	-9.66	4.88
US	Tesla NCA	-3.14	2.56	12.55
	Taycan NMC622	-3.41	3.29	6.12
	Taycan NMC811	-5.60	-0.40	2.72
	Tesla LFP	-35.71	-21.72	8.41
	Nissan LMO	-32.27	-18.05	-5.15
Belgium	Tesla NCA	-7.05	-0.07	9.76
	Taycan NMC622	-8.39	-0.34	2.33
	Taycan NMC811	-10.05	-3.80	-0.81
	Tesla LFP	-42.49	-25.43	4.32
	Nissan LMO	-47.89	-31.54	-18.89
UK	Tesla NCA	-4.65	2.10	11.75
	Taycan NMC622	-5.40	2.40	4.87
	Taycan NMC811	-7.36	-1.31	1.52
	Tesla LFP	-38.23	-21.55	7.74
	Nissan LMO	-39.26	-23.15	-10.82

Exhibit 29 - Battery pack specifics (Lander et al., 2021)

	Tesla Model S	Porsche Taycan NMC622	Porsche Taycan NMC811	Tesla Model S LFP	Nissan Leaf
Total pack weight (kg)	540	630	553	1009	295
Weight cells only (kg)	319	382	305	788	151
Number of modules	16	33	33	16	48
Number of cells	7104	396	396	10,368	192
Cell weight (kg)	0.045	0.965	0.772	0.076	0.785
Energy (kWh)	85	93	93	85	24
Energy density (Wh/kg)	266	243	304	108	159

Appendix

A - Challenges in battery recycling ecosystem

- End-of-life: The average life of an EV battery is between eight and 15 years. With a rapidly growing EV fleet, an increasing number of batteries will need to be returned, and possibly recycled, moving forward.
- Manufacturing scrap: The complexity of battery production results in very high scrap rates (about 10%-30%), especially during production ramp-up in newly established Gigafactories. As soon as production scales, a significant amount of scrap will need to be recycled on an ongoing basis

See Exhibit 26 on Recycling: Circular economy (World Economic Forum, 2019)

Strategically planning recycling operations means not just choosing between extraction technologies; organising logistics and sites is necessary. Essentially the choice spans two models:

- Centralised model:
  End-of-life batteries are transported to a central location, where they are processed and refined. This method leads to greater transport and storage costs, primarily because of tight regulations around transporting hazardous lithium batteries. However, this model delivers greater operational efficiency as recyclers can process and refine on a larger scale.

- Decentralised model:
  End-of-life batteries are processed locally, creating the intermediary product, black mass. Black mass is less hazardous and both easier and cheaper to transport for final refining. While this model results in lower transport costs, it reduces economies of scale as recyclers are unable to process centrally. The industry seems to be leaning toward a decentralised model for initial processing and a more centralised model for hydro and final refining steps. Collection and mechanical separation hubs close to production sites will favour recyclers with strong partnerships with battery makers and OEMs, while securing a stable feedstock supply of materials. Hydro and refining will likely centre around traditional industrial chemical and metal processing

B - Challenges of Second life batteries

Currently, the implementation of second life batteries is facing some barriers and challenges. Some of such challenges are predicted to be overcome by some initiatives and policymaking while others are still uncertain. In this section, major challenges are presented, which some of them related to each other such as:

- Uncertainty of second life application economics
- Lack of automation in battery dismantling
- Variety of EV battery types and chemistries and availability of second life batteries
- Difficulty to accurately identify the battery's SOH and RUL
- Absence of standards and policies
- Unavailability of first life data

Batteries come in different types, shapes, and chemistries, adding a new concern and challenge to the usage of second life batteries.

SOH assessment will differ for the different types and chemistries, making the assessment process become more complicated and possibly, adding to the assessment cost.

Availability of Second Life Batteries of similar types and chemistries: Since they come with different voltage levels, capacities, chemistries, and types, finding similar batteries becomes challenging. It is due to the fact that matching batteries is important for a better second life application performance and longer lifespan. Another major challenge is the accurate measurement of a battery's SOH and Remaining Useful Life. In the absence of standards, inconsistency in assessing batteries would be there. If the battery's first life data are stored, it is easier to estimate its SOH and Remaining Useful Life more accurately (Jia et al., 2020).

C- Data used for financial viability of recycling

See (Lander et al., 2021)
Exhibit 27 on Techno-economic model used;
Exhibit 28 on Net recycling profits of battery packs;
Exhibit 29 on Battery pack specifics