The lithium-ion battery end-of-life market – *A baseline study*

For the Global Battery Alliance
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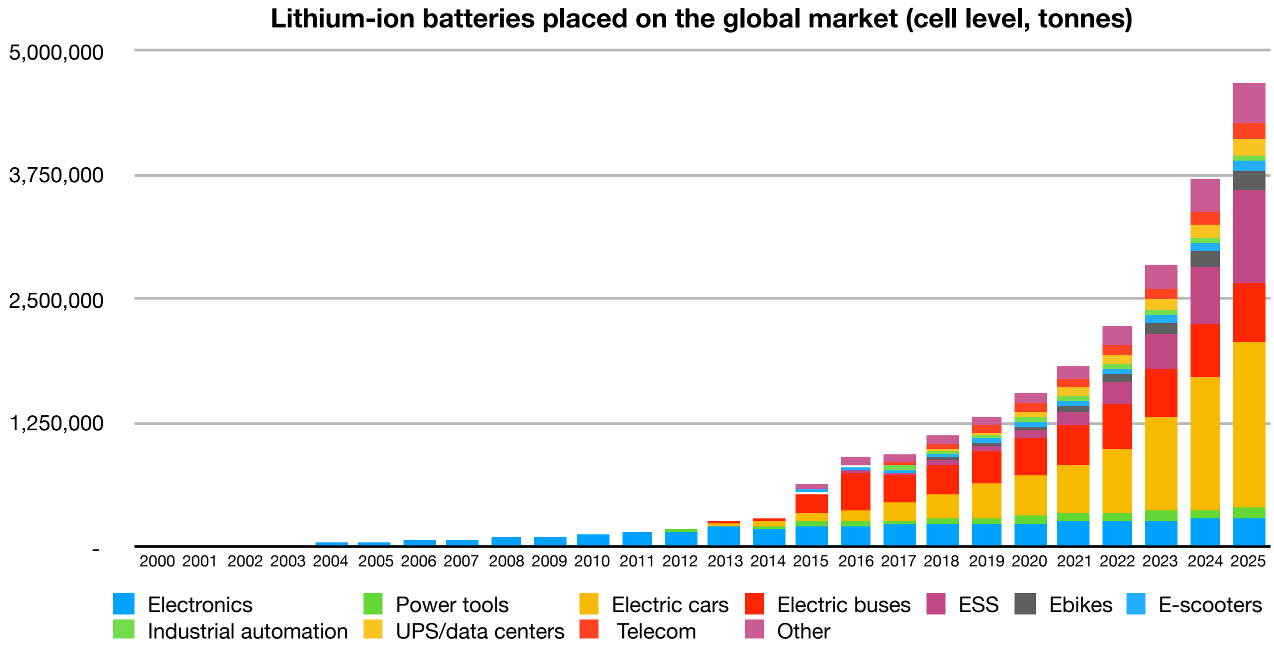
The market for lithium-ion batteries is growing rapidly. Since 2010 the annual deployed capacity of lithium-ion batteries has increased with 500 per cent[1]. From having been used mainly in consumer electronics during the nineties and early 2000, lithium-ion batteries are now powering everything from lawn mowers to ferries. The most significant increase is found in the automotive industry where the advances in battery technology has propelled the rapid adoption of electric cars and buses. In 2018 the cumulative number of electric cars in the world has already exceeded 4 million[2] and many estimates point at a global market share of 20 per cent for the electric car in 2025. Besides electric vehicles the lithium-ion battery is increasingly being used also in other applications such as backup power for telecom base stations and data centers, or to power fork lifts, electric scooters and bikes.

With more batteries placed on the market the need for solutions for dealing with them when they reach their end of life is rising. Although lithium-ion batteries are not toxic in the same way as lead-acid or nickel cadmium batteries, they do contain elements that should be prevented from being exposed to the environment. Equally important is the potential to recover the materials in

[1] Avicenne Energy
[2] Bloomberg New Energy Finance



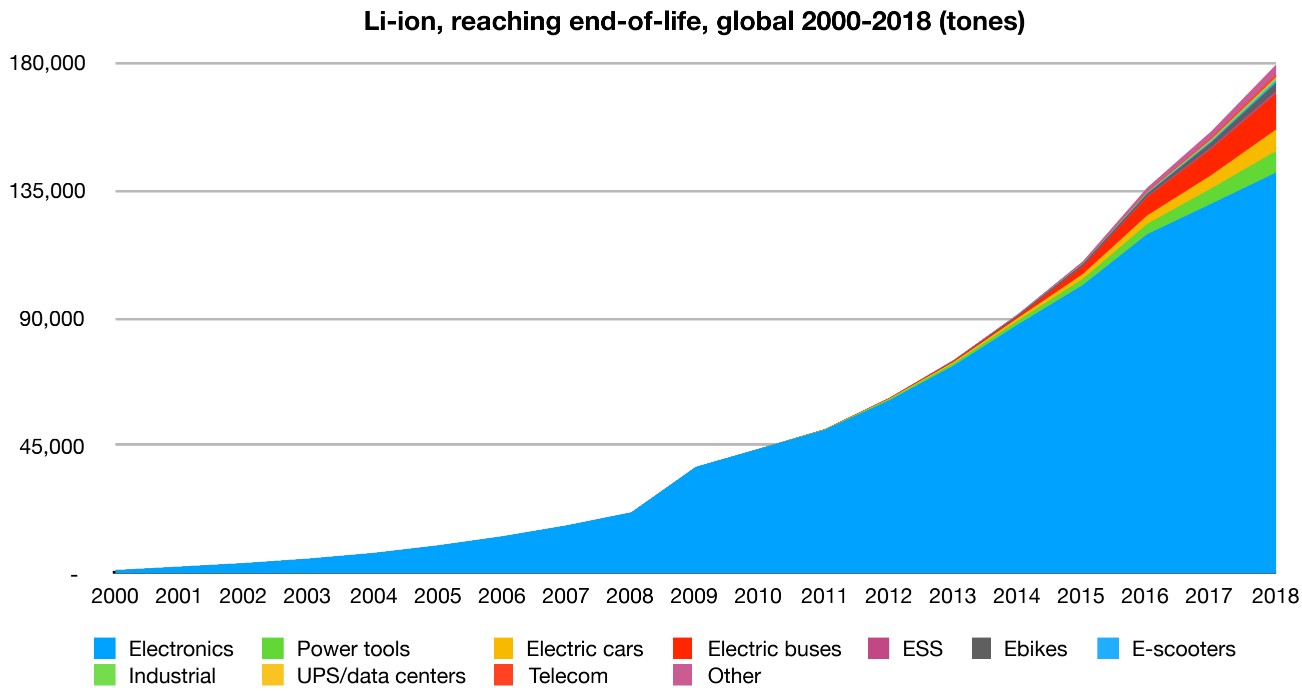
waste batteries for the reuse in new batteries. With the unprecedented growth in the market the demand for raw materials has increased significantly and recycled materials can be a positive contribution from both an environmental and an economical perspective.

The purpose of this baseline study is to give an overview of the status of the end-of-life market today and how it is predicted to evolve during the next decade. The data and analysis is retrieved from the report "The lithium-ion battery end-of-life market 2018-2025, which is published by Circular Energy Storage and written by the same author as this study.

Batteries reaching end-of-life

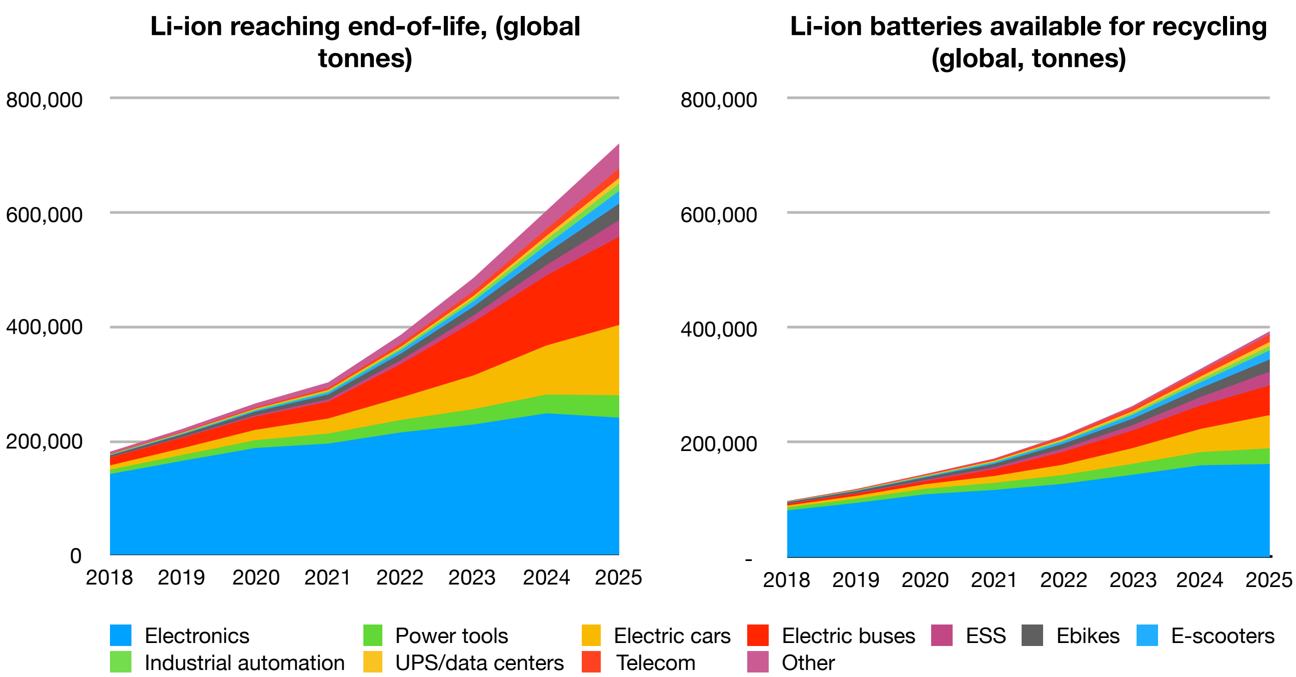
Compared to primary batteries such as alkaline and zinc carbon, which are designed to be consumed just like any other consumable, a rechargeable battery is designed to last for a long time, over and over again. However, even a rechargeable battery is degrading over time and ultimately all lithium-ion batteries will cease to work. Depending on chemistry, size, configuration and purpose a lithium-ion can perform between 500 to over 10 000 cycles of charging and discharging. This means that a battery that is used every day in a power tool by a professional craft worker might reach end-of-life in a few months while a battery used in some energy storage applications can last for over 20 years. Therefore the pace in which batteries will reach end-of-life depends highly on the application they are used in. So far the largest amounts of batteries that have reached end-of-life are portable batteries used in consumer electronics and power tools. This is a consequence of both their market dominance and the fact that they don't last as long as batteries used in vehicles or other industrial applications.

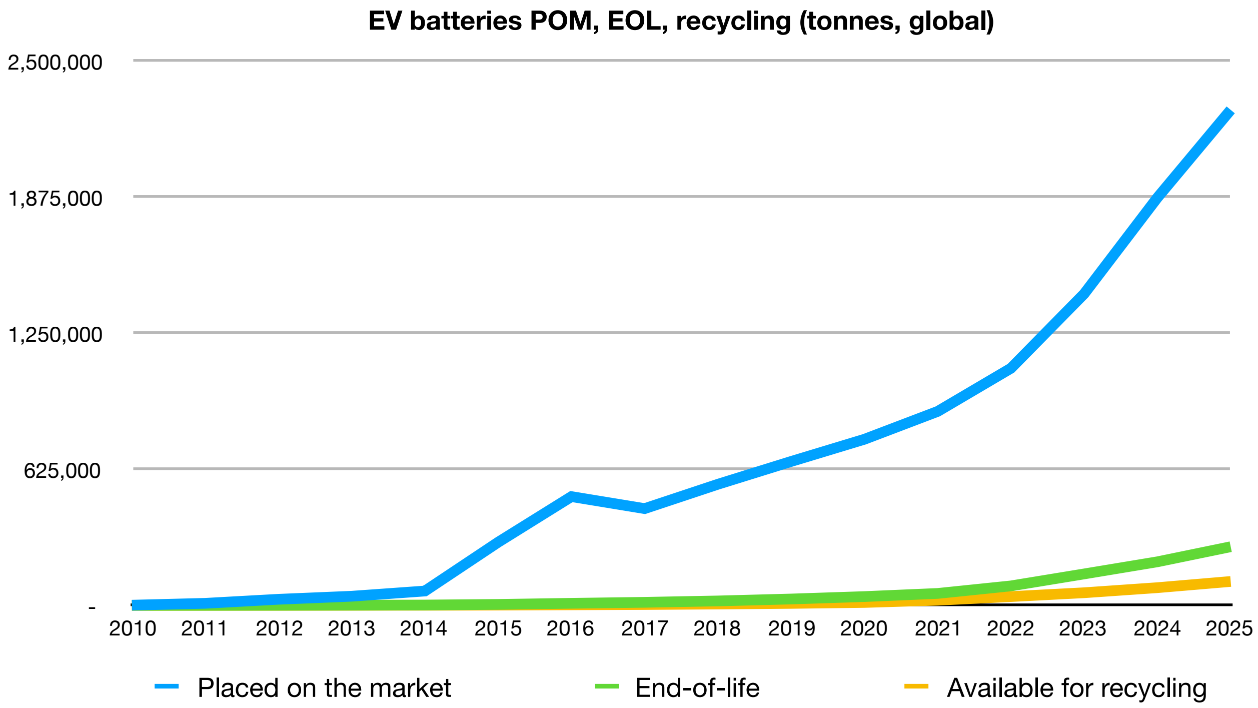
With the rapid growth in other segments this will change over the next 10 years. However, due to different user characteristics of the batteries, and their applications, the end-of-life volumes will have a different distribution compared to what has been placed on the market. Batteries in electric cars are expected to last much longer than those in buses, primarily because batteries in



buses are charged and discharged much more frequently. Also segments such as e-scooters, e-bikes and forklifts are cycled harder than most car batteries which, despite the modest volume in kWh placed on the market, will make them reach end of life faster and generating a joint EOL volume equivalent to half of what will come out from electric cars in 2025.

That batteries reach the end of their lives does not mean that they automatically become available for recycling. In fact only about 50 per cent of the batteries that reach end-of-life find their way to recyclers around the world. The reasons for this are many: batteries are stored or hoarded, they are disposed of but not recycled, or they are reused in other applications.





The latter is valid for both portable and industrial batteries (batteries that are installed in other equipment, including vehicles, and which can not be easily carried by hand). Lithium-ion batteries that have been used in one application are often assessed for their ability to be used in other, less demanding applications. For portable batteries this can be new battery packs or products such as power banks. Batteries from electric vehicles are used in everything from back up power to energy storage systems.

Although no official numbers are available which can show how much of the portable end-of-life batteries that will be reused, it is clear that a significant amount of the batteries reaching battery collectors, electronic waste processors and refurbishment companies will at least be assessed for reuse. For EV batteries reuse, or "Second life" is in many cases becoming the norm when a batteries no longer are fit for the vehicle. The most important reason for this is that the values of the batteries that go to reuse are much higher than batteries sent to recycling.

The diversion of end-of-life batteries to reuse is causing a delay for the amount of batteries available for recycling. Of this reason it will also take a long time until materials from recycling will have a larger impact on the raw material market. However for certain elements, such as cobalt, recycling is already playing an important role.

First step – Second life

While portable lithium-ion batteries have been reused for a long time without much public attention, batteries from electric vehicles, which has become the dominant segment in the lithium-ion market, get more and more attention for its potential to be used in other applications. In Europe several vehicle manufacturers, in particular companies that pioneered the electric car market, have installed used batteries primarily in different kind of energy storage systems, ranging from small residential systems to larger containerised grid-scale solutions.

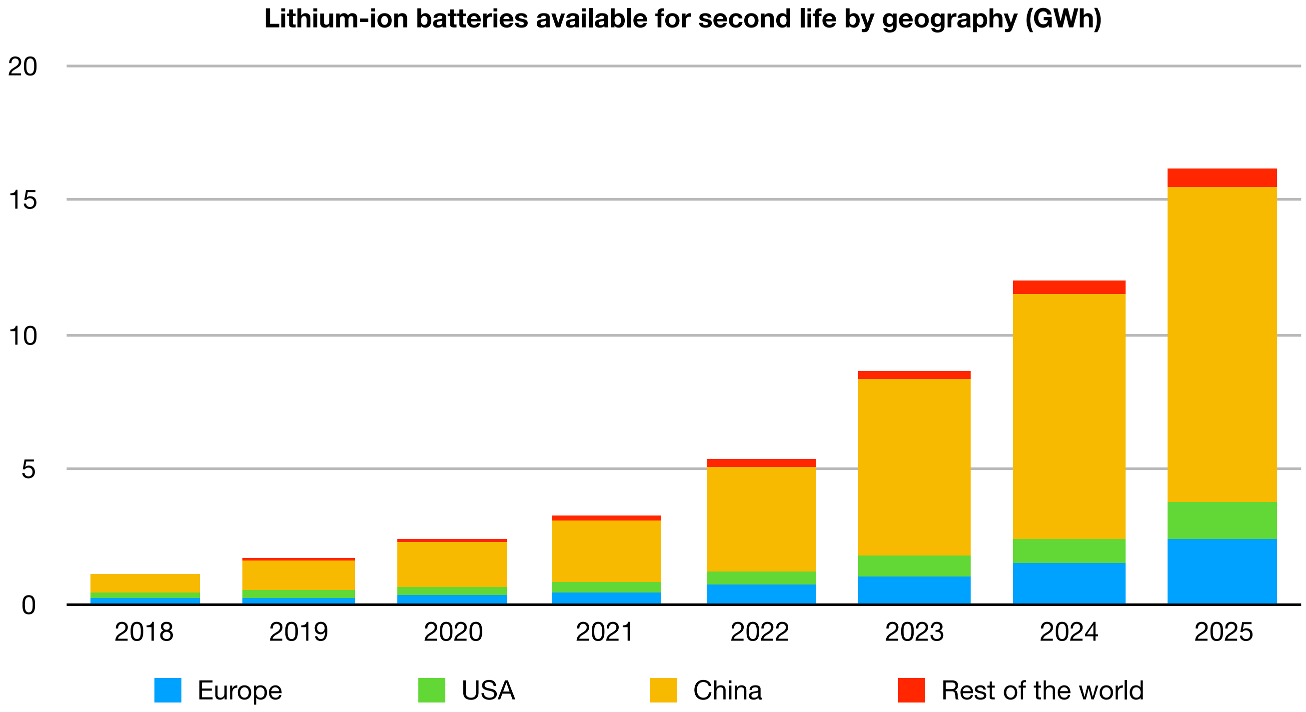
Car maker	Second life initiative
BJEV	EV-charging, backup power
BMW	Grid-scale energy storage, EV-charging
BYD	Grid-scale energy storage, backup power
Chengan	Backup power
Daimler	Grid-scale energy storage, C&I energy storage
General Motors	Remanufacturing,
Great Walll Motor	Backup power
Hyundai	Grid-scale energy storage, C&I energy storage
Nissan	Remanufacturing, C&I energy storage, EV-charging
Mitsubishi	C&I energy storage
PSA	C&I energy storage
Renault	EV-charging, residential energy storage, grid-scale energy storage
Tesla	Remanufacturing
Toyota	C&I energy storage, grid-scale energy storage (NiMH)
SAIC	Backup power
Volkswagen (Audi)	C&I energy storage
Volvo	Residential energy storage
Volvo Cars	Residential energy storage
Yin-Long	Backup power, C&I energy storage

These systems are used for a variety of services including time-shift management (charging when energy is cheap and discharging when it's expensive), frequency response, backup power, demand side response and auxiliary capacity. Batteries are also being used for energy storage coupled to EV charging in order to reduce stress on the grid and to decrease the demand during peaks. Similar initiatives have been announced in the US.

In China new regulations calls for battery and vehicle companies to arrange for both recycling and assessment of second life potential. Within that framework an agreement has been signed by the largest telecom infrastructure company and several battery and automotive manufacturers on using retired EV batteries to replace lead-acid batteries in the backup systems of base stations.

Still there exist many different strategies and processes behind second life batteries. While some makers have partnered with energy companies, third party vendors and startups, to which batteries are sold, other manufacturers have established dedicated energy companies, using the batteries in their own operations. Some batteries are kept as whole packs, usually in larger energy storage systems while other packs are disassembled to module level for configuration in bespoke second life products.

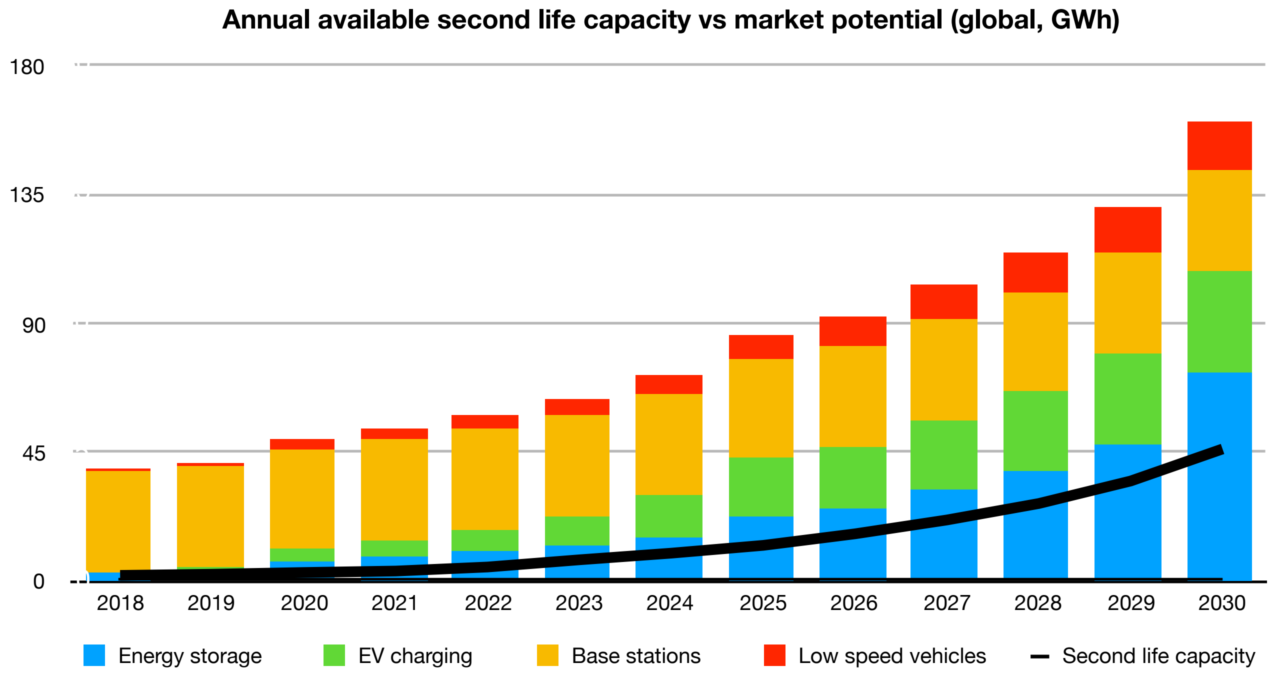
The amount of batteries used in second life applications is still very small. Primarily this is due to the fact that most batteries still serve their first life in cars and buses. In Europe second life installations are still to reach 100 MWh with North America trailing with less than 10 MWh of installed capacity. The largest volume, both in installed capacity and in forecasted volume the coming years, will become available in China, primarily because of the large amount of batteries placed in electric buses since 2015. These batteries are cycled heavily every day which makes them reaching end-of-life much earlier than batteries used in privately owned cars. Consequently, almost 1 GWh of used batteries were installed in different second life applications in China in 2018, of which most were placed in base stations as backup power.



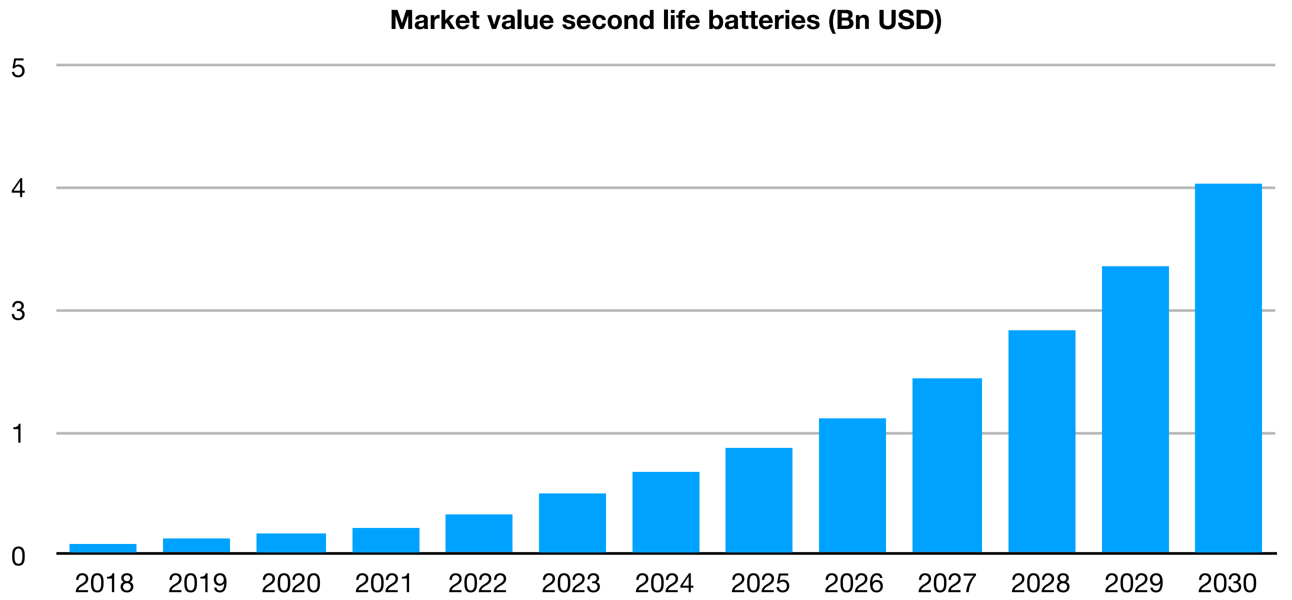
Not all car and battery makers have embraced the idea of a second life for EV batteries, usually with the argument that the vehicle will last for more than 10 years and at a point where the battery will not be competitive compared to new, more efficient and cheaper batteries which by then will be available on the market. There is also research suggesting that the degradation profile of many batteries may cause inefficiencies and malfunctions which will make the batteries less attractive. Of these reasons it is clear that not all batteries, despite if they are free from damage, will be used in second life applications but will instead be recycled as a first option. Still, with many initiatives and entire businesses created around second life in both Europe and Asia, and with a high demand for batteries overall today, second life batteries are predicted to be an important source for several energy storage and stationary battery applications.

Very likely the market segments where second life batteries are being used will be sufficient to support sales for many years. In 2030 the forecasted volume of available batteries for second life applications will be 185 GWh. The same number for energy storage applications is expected to be over 300 GWh[3]. However, that does not take into account any other segments such as backup power for base stations, EV charging support or low speed vehicles. If they are, the installed capacity of lithium-ion batteries is close to 900 GWh of which second life batteries represent only 20 per cent. The geographical differences are big. In the US where the installed capacity of energy storage systems is expected to reach 75 GWh in 2030 the predicted cumulative volume of retired EV batteries for second life, will be less than 5 GWh. That should be compared to China where only the need during five years in the country's base stations, which have been considered a prioritised segment from the government, exceeds 100 GWh while the cumulative amount of second life batteries in 2030 will be 37 GWh.

[3] Bloomberg New Energy Finance



With the strong growth of the lithium-ion battery market it is predicted that the volume of the second life batteries will be defined by the supply of batteries rather than its demand. The demand, together with the supply and cost efficiency of new batteries will define the value. Today second life batteries are traded at between $60 and $300 per kWh, depending on market and application. These prices are predicted to follow the price development of the general market and is estimated to reach $43 per kWh in 2030, primarily as a response to falling prices of new batteries. This value is close to what materials in batteries are worth today. If that cost reduction is enabled by material substitution, primarily substation of cobalt, used batteries which still contain cobalt might be diverted to recycling as recyclers might pay the same or a higher price for the batteries.



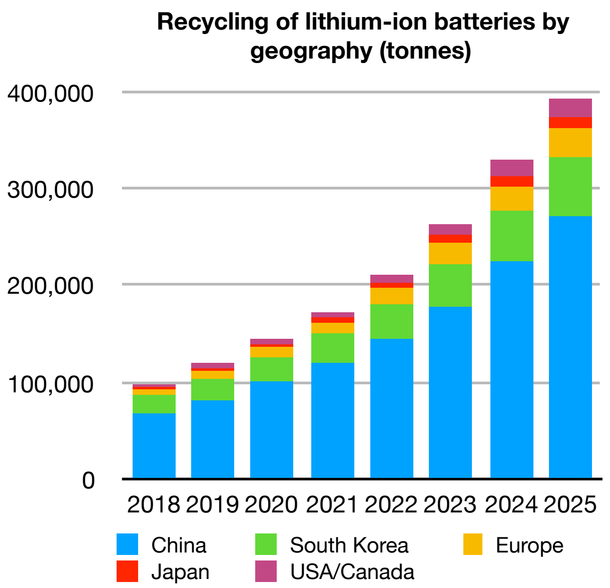
Recycling of lithium-ion batteries

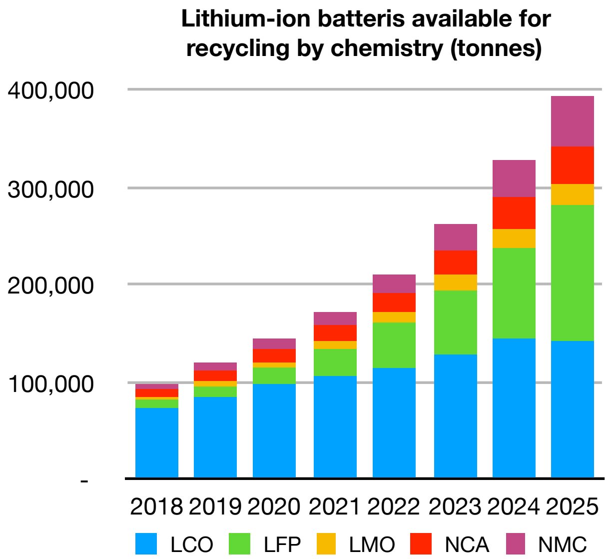
Today there are recyclers in several European countries, in the US, Canada, South Korea, Japan, China and a few other countries around the world. The processes used, and their efficiencies, vary. From processes where the most important yield is copper and aluminium while the rest of the material goes to waste, to highly efficient processes that can recover close to everything from the battery and refine it into end products such as lithium carbonate, cobalt sulphate and nickel sulphate. Almost all processes today are hydrometallurgical where the different elements are separated by the use of different types of liquids which react with the different elements in the battery . For the pre-processing different mechanical and pyrometallurgical methods are used. Usually by shredding or cutting (mechanical) and smelting or pyrolysis (pyrometallurgical).

Usually the difference in efficiency can be traced back to the recycler's options upstream and downstream. If there is a limited access to batteries to recycle (upstream) it is difficult to obtain an efficient process. Likewise, if there is no buyer of the processed material (downstream) the final effort to refine the end product might not be worthwhile.

In 2018 the amount of batteries that will reach recyclers is estimated to 97,000 tonnes. Of these as much as 67,000 tonnes will be processed in China and 18,000 tonnes in South Korea. The two countries host a significant share of the manufacturing of battery materials, as well as the production of cells. This has created a strong demand for raw materials, which consequently lays the foundation for an important market for recyclers, or opportunities for material companies to become recyclers themselves.

Today over 20 companies are involved in recycling of waste batteries in China and at least six companies in South Korea.The feedstock originate both from domestic collection and batteries from overseas. In China several companies benefit from access to batteries from refurbishment



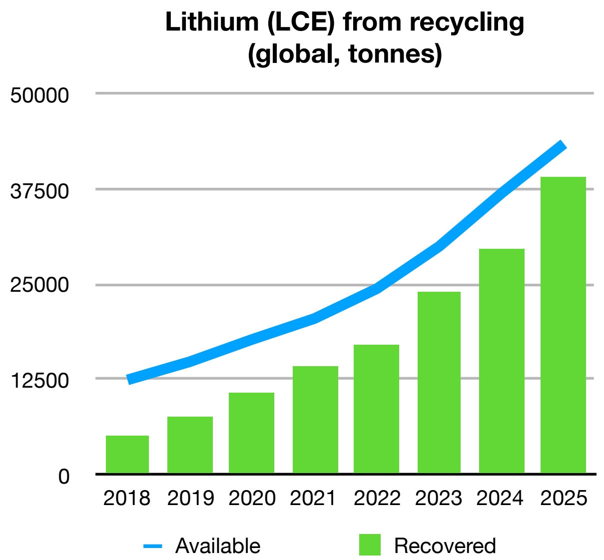


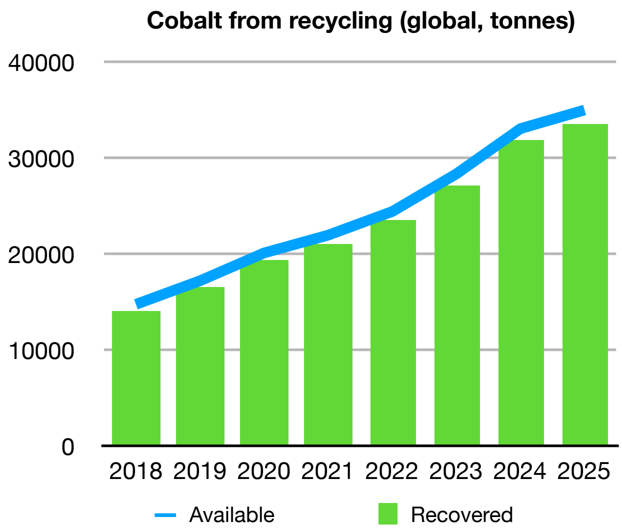
operations which not only bring volume but also a material which is well prepared for further processing, sorted in different types and dismantled to individual cells. In South Korea many batteries are imported directly from collectors in other parts of Asia, in Australia, Europe and North America. Increasingly batteries are also pre-processed in other parts of the world for more efficient and safer transportation.

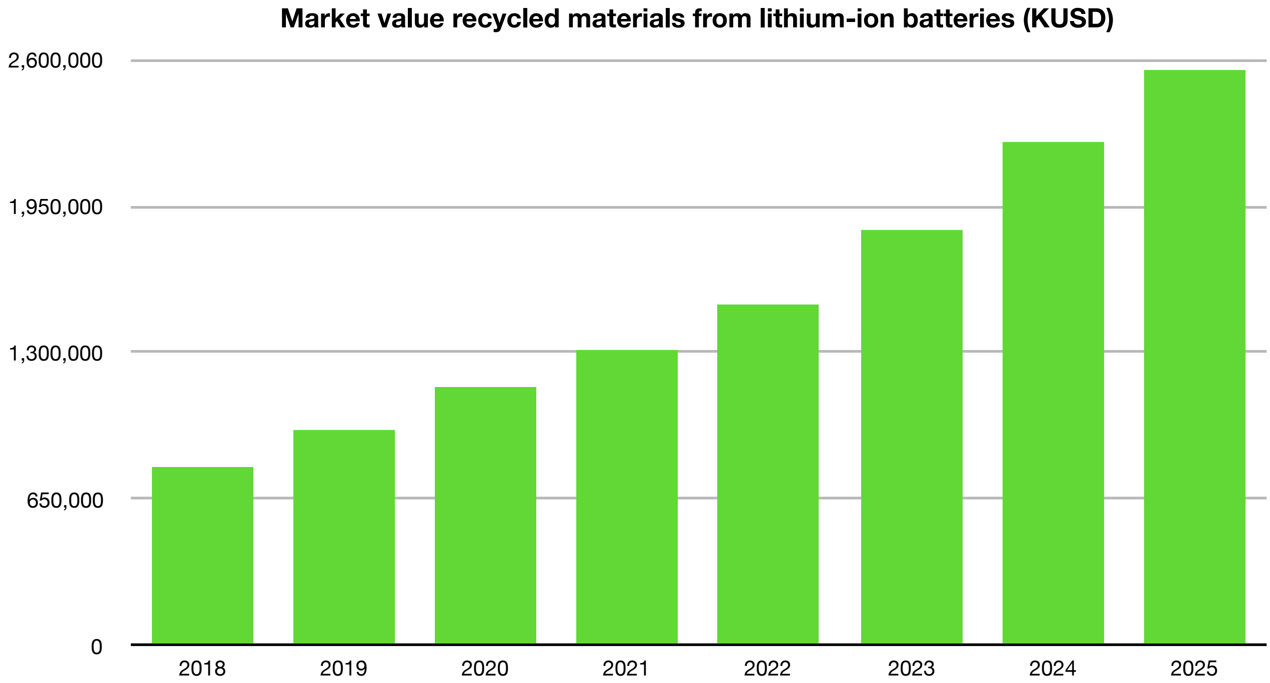
In Europe and North America the processed volumes of lithium-ion batteries are still fairly low. The main reason for this is that batteries are not primarily collected through ordinary collection schemes but are exported, contained in equipment or sold for reuse to Asian processors. Most of the recyclers outside of South Korea and China also lack the direct connection to the battery material market.

As most of the batteries which today reach end-of-life primarily have been used in electronics the dominant battery chemistry today is LCO. With a content of 17 per cent cobalt these batteries are attractive and generally highly profitable to recycle. It means that the recycling of these batteries, at least when the cobalt price is on the high side, can be positive throughout the value chain, from the collector to the recycler.

Still, the growth in both new batteries and end-of-life batteries is now found in other chemistries with significantly less, or no, cobalt such as NCA, LFP and LMO batteries. With favourable commodity prices, and with efficient processes and valuable end products most of these chemistries can be recycled with a profit if they are received as cells. However today the growth comes from industrial batteries in which the cells are assembled in modules and packs together with cooling systems and electronics. These large devices require expertise and special safety routines when disassembled. Moreover, many packs are not designed with disassembly in mind and will take many hours to process. This has made recycling many times to a costly process. With larger, consolidated streams of similar battery types this will gradually change as it enables recyclers to build up expertise and experience around each battery model, and use a higher level of automation. Still there will always be a economic challenge to recycle batteries with the lowest material values such as LFP batteries.







With today's volume of material reaching recycling, both from waste batteris and production scrap, the amount of recovered materials is still only a small part of the total market. As the raw material markets are expanding to keep up with the rapid growth in the battery market this relationship will continue for a long time. Although lithium increasingly is recycled and even refined into battery grade material, the amounts are still very small to have any effect on the total lithium market. The situation is the same for metals such as nickel, aluminium and copper.

The exception is cobalt. As the largest amount of recyclable materials comes from LCO batteries which have been on the market for a long time and have a higher amount of cobalt per kg then what is the case for NMC and NCA, the volume of recycled cobalt is not insignificant compared to what currently is used in production . In 2018 as much as 14,000 tonnes of cobalt, equivalent to more than 10 per cent of the supply from mined sources will be available from recycling. However, as the overall cobalt market increases the share of recycled cobalt will decrease as new cobalt-containing chemistries as NCA and NMC won't come back in the same pace as the LCO batteries.

In terms of market value the lithium-ion battery recycling industry will in 2025 process batteries and battery scrap materials to a value of 2.6 Billion USD at today's (December 2018) metal prices. Of this, cobalt represent 58 per cent and lithium 17 per cent. If the prices from the first quarter of 2018, when both the cobalt and lithium price reached its highest levels, would be used instead the total market value in 2025 would exceed 3.8 Billion USD. This shows how sensitive the market is for changes in the commodity market.

The value of the recycling market is important not only for the actual profitability in the recycling industry. It also affect the dynamics of the collection of the batteries and which downstream route that will be chosen. With higher commodity prices there will be more money in the market to use for incentivising users to send in batteries for recycling. If it's combined with further reductions of battery costs it may also discourage second use of the batteries as recyclers will be able to pay the same or even higher prices for the batteries as refurbishers and second life processors.

Future development of the market

Although the end-of-life market for lithium-ion batteries already show some clear patterns it is still a young market with room for innovation and change. Not least this involves different circular models that can cut waste and marginal costs out of the value chain.

For second life challenges such as information about the battery's state of health and difficulties in the disassembly process are increasingly addressed through the development of smart battery management systems and modular design of the batteries. However more needs to be done and the improvements that are implemented now will only have a larger effect in five to ten years time.

For automotive and battery makers there is a challenge to retain control of the battery in order to squeeze out as much value as possible without losing value in unnecessary transactions. Models such as leasing of the battery has already been proven. The model makes even more sense for professional fleets of buses, taxis and delivery vehicles as these are cycled much heavier than privately owned cars and therefore need more frequent replacements of the batteries.

The more batteries that are under control by one player the easier it will be to consolidate the batteries in streams of similar models. This will benefit the recycling industry and keep the costs down. It might also bring opportunities to the battery material industry which through partnerships or vertical integration can obtain a secured supply of future raw materials.

There is really no lack of process technology to recycle batteries or to refine the recycled material into new products such as precursors or cathodes. Instead more focus should be directed to need for efficient disassembly processes, both of packs and cells.