The lithium-ion battery life cycle report

2021

Circular Energy Storage
Research and Consulting

Table of contents

Version 1.0, published the 4th of December 2020

About this report

This report is about what happens with lithium-ion batteries when they are placed on the market, how they are used, reused and recycled. We are outlining both the current and future development of the volumes of batteries as they go through the different stages of their lifecycle.

There are thousands of studies done on how batteries age and degrade from an electrochemical perspective. Several studies have also been done on the environmental footprint batteries have from cradle to grave. We know significantly less about what actually happens when we use a battery, or rather, when we use the equipment and devices in which the batteries sit. A battery is usually only an enabler – of a smartphone, an electrically powered scooter or an electric car. The battery is rarely the main product. Therefore, if we want to understand how batteries are used, reused and recycled we need to understand which job the batteries do for these products and how its ability to perform the job changes over time. Likewise if we want to understand the flows of the batteries we need to follow the flow of the products to, and after, the point when the battery is liberated and start to live its own life.

The report contains the background research we are doing in Circular Energy Storage Research & Consulting to understand this. What eventually becomes a number in a table is based on our own research on the ageing of products, of trade volumes and the economics of both reuse and recycling activities. The aim has been to convey our insights to users for a better understanding of the dynamic and complex lifecycle of this embedded product the world more and more will rely on for everything from transportation to energy distribution.

From the beginning we wanted to create a report which was updated every six months. As the ambition grew we changed it to an annual report. It eventually became something even bigger than that. We look at it as a platform for both our data collection and our publication of data and analysis on CES Online and through our partnerships. Based on its content we aim tor produce in-depth analysis which will be available for our subscribers. The report might also be updated with adjustments, corrections and new findings which have an impact on the overall data and conclusions.

London, December 2020

Hans Eric Melin
Managing Director
Circular Energy Storage Research & Consulting

Executive Summary

The lithium-ion battery market has been growing in an extraordinary pace the last 10 years and will continue to grow in at least the same pace over the next 10 years. Batteries in electric vehicles, both light and heavy duty, are driving the growth and will in 2030 represent 77% of the total installed lithium-ion battery capacity – a remarkable increase from today's 51%. The volumes that will reach end of life will grow slower than the volumes placed on the market because new applications, and their batteries, will last significantly longer than previous applications. Batteries are also traded and exported over their lifetime which will affect both where and when batteries will be available for both reuse and recycling.

Lithium-ion batteries are set to become the most important energy storage technology in the world with a flexibility that enables its use in so different applications such as wireless headphones and grid-scale energy storage solutions. With an historical volume increase with a CAGR of 23.4% since 2009, driven primarily by electrification of cars and buses, the manufacturing capacity is rapidly expanding in several key markets.

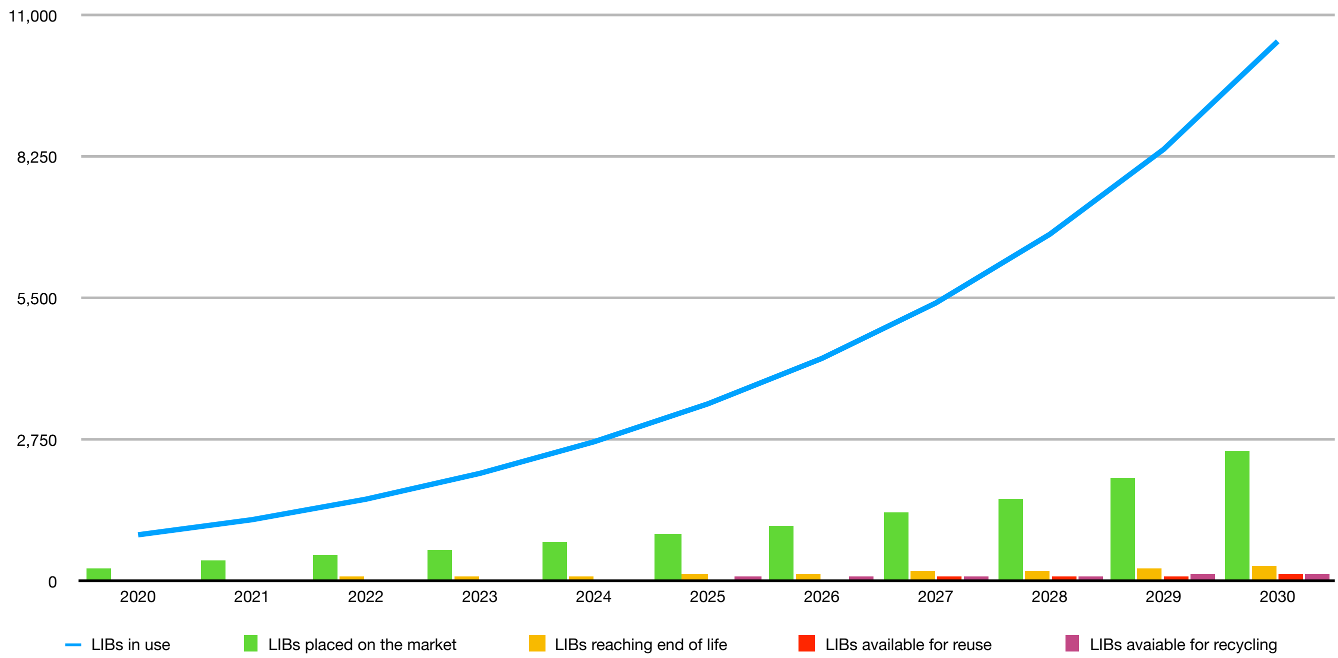
This expansion will likely cement the use of lithium-ion batteries for years to come in markets such as electric cars, buses, scooters, and e-bikes while the technology is also about to take a leading position in stationary energy storage, backup power, and industrial applications such as fork lifts, utility vehicles and robots. The rapid expansion brings important economies of scale to the industry which already have brought down the cost for cells and enabled electrification of new applications such as ferries and aircrafts.

In 2019 the installed capacity of lithium-ion batteries in the world exceeded 700 GWh. Of this 51% was installed in light or heavy duty electric vehicles. The same number in 2015 was 19% and in 2010 it was less than 1%.

With annual volumes of batteries placed on the market, growing with a CAGR of 25.45%, the installed capacity of lithium-ion batteries in 2030 is predicted to increase to 10.5 TWh with 8.1 TWh, or 77%, installed in electric vehicles.

The amount of batteries reaching end of life will grow much slower, from 47.7GWh in 2019 to 314 GWh in 2030, a CAGR of 18.8%. The main reason for this is that an increasing share

Lithium-ion batteries on the global market, forecast nameplate capacity, GWh



of the batteries are used in applications with significantly longer lifetime than previously.

In this report we present research that shows that:

- The average age of light duty EV batteries will be 14.7 years when they reach the first end of life, with 50% having reached end of life after 15 years.

- Battery age is not only connected to battery performance but as much to the actual application, ownership, value and user behaviour.

- One reason why EV batteries can last for decades is that the batteries are usually cycled less than 80 times per year and that mileage drops with vehicle age, causing both less wear and requirements of the battery in later stages.

- Commercial vehicles, especially buses, are driven significantly more and the batteries in these vehicles will therefore reach end of life earlier than in light duty vehicles. However, other commercial vehicles will not necessarily be driven much longer than light duty EVs.

- As much as 30%-40% of the electric vehicles will leave the markets where they were originally placed on, to enter markets overseas where countries are facilitating import of electric vehicles in order to kickstart fleet electrification. This global trade is causing large volumes of batteries to leave their original markets. The same kind of trade has already been the case for portable electronics for many years bringing portable batteries out of markets such as Europe, Japan and the US.

Over the next years several technical, regulatory and economical changes are expected in the market, including introduction of new battery technologies, the emergence of autonomous vehicles and new ownership models of both vehicles and batteries. However with the long lifetimes of the batteries and with no substantial changes in sight the coming years none of these changes are predicted to have a meaningful impact of neither the volumes of batteries in use, nor the end-of-life volumes during the coming decade.

In 2030 we predict that the total amount of lithium-ion batteries that will go to reuse will be 145 GWh or 799,000 tonnes while 170 GWh or 820,000 tonnes will be available for recycling. Of this only 16% will be available in Europe and only 10% in the US.

Batteries are expected to be reused in a large variety of applications. However the later the batteries will be removed from their applications the more distributed the second life solutions are expected to be. Batteries reused in larger stationary energy storage will primarily be sourced through programs where the batteries are removed prematurely from cars and buses.

The current global recycling capacity exceeds the total volume of waste material from LIBs, also when battery production scrap is included. The distribution is however uneven with significant overcapacity in China and a few Southeast Asian markets while there is under-capacity in Europe and North America. In a few years time this is about to change and in 2025 all larger lithium-ion battery markets will have recycling capacity that greatly exceeds the supply of waste batteries, given that planned and predicted expansions will go ahead. More capacity is however needed to meet the generation of waste in 2030. A challenge for recyclers will be how to capture sufficient volumes in order to obtain economies of scale in a market which still yields low end-of-life volumes.

There is a big potential for business model innovation not least in order to eliminate obstacles in the value chain such as high upfront investments, negative values on end-of-life batteries and low efficiencies due to insufficient scale in various processes. There is also a potential to better monetise the batteries throughout its lifetime through processes like vehicle-to-grid and second use of batteries.

Methodology

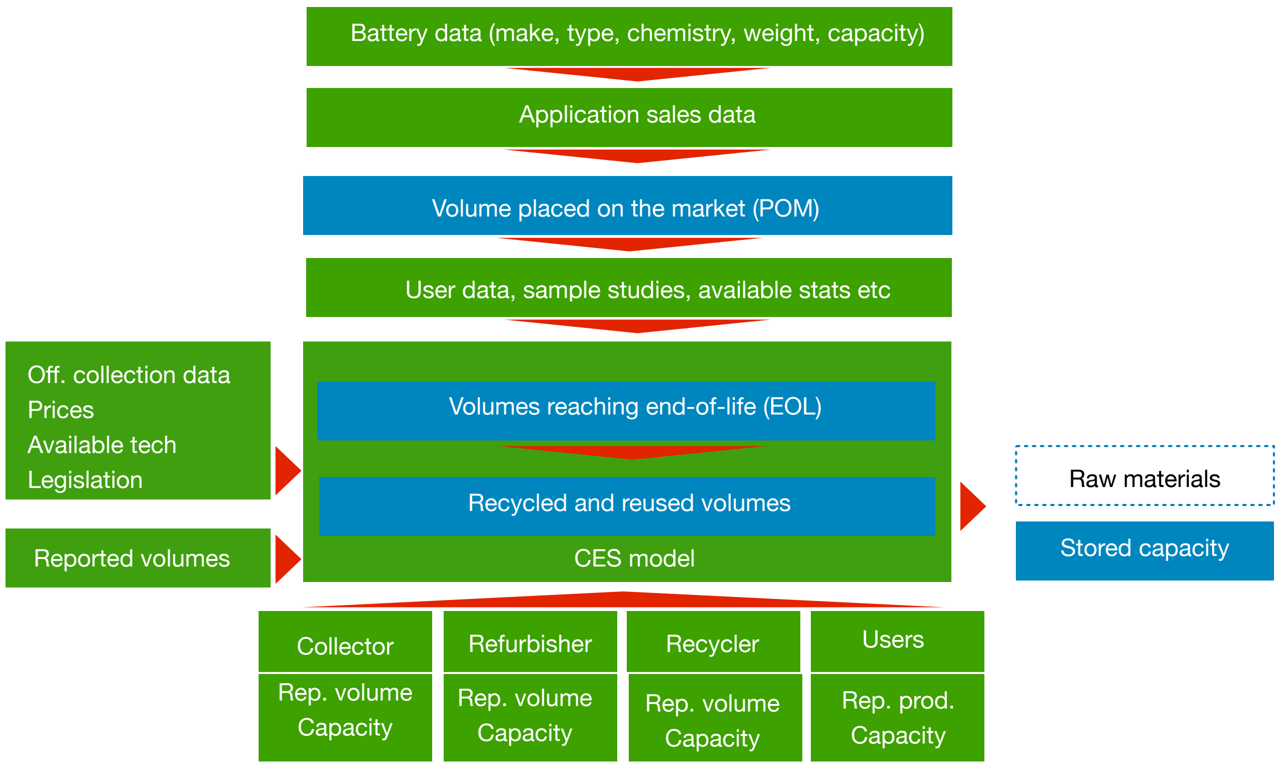
The volume data on lithium-ion batteries in use, placed on the market, available for reuse and recycling is the core of Circular Energy Storage's research. As we are working with so many variables, and often with data which is not publicly available or not even collected by anyone else our approach is a combination of bottom-up and top-down research with help us to narrow the truth as close as possible. Here we describe our approach to our data and how it is constructed.

There is a paradox in all research covering end-of-life markets which is not found in research about new products or raw materials: There is more information about the future than there is about today and the past.

For most applications such as cars, buses, and consumer electronics there is consistent information about how many units that are shipped on a quarterly or even monthly basis. Matched with data about user behaviour, import and export movements etc, it's then possible to say how much of these products that eventually will come back in the future. To verify exactly how much that reached recycling last year is much more difficult.

The main reason is that both the recycling and refurbishment industries are secretive by nature. The business model is to acquire materials for as little as possible to then sell it with a premium on a much more transparent commodity, device or energy market. This means that processed volumes, acquisition prices and level of refinement is information which many keep tight within the companies.

Secondly, most companies in the industry are small or mid-sized enterprises with no obligation to disclose information. Neither are there reliable official sources as the reporting requirements to authorities usually is on a too high level and many times incomplete.



As consultants and researchers with long experience in the industry we usually get this information anyway. However there are always gaps and the rapid development of the market with, new capacity coming online every month, requires a more comprehensive method than to only ask what recyclers have in their warehouse. Therefore we use a combination of top-down and bottom-up approach.

We combine secondary data with our own intelligence acquired from discussions with companies in the industry. We match modelled volumes with real capacity. And we combine future demand and raw material availability with current and planned recycling capacity and forecasted energy storage capacity with both end-of-life volumes and capacity to refurbish the batteries.

We want to make the reader aware of that it's nearly impossible to get to a fully accurate picture of all different volumes in the end-of-life market or even how much batteries that are placed on the market. We don't guarantee that neither our numbers of today nor of the future are 100 per cent correct. We do however believe this is the most qualified estimate that has been done so far in this fast-growing market.

The volume data we are using today is a mix of several sources and the granularity is different:

Portable electronics – Top down analysis based on different sources of which Gartner is the most important for historic data on mobile phones, laptops and tablets. For all other devices we are using data from industry associations, other analysts such as Avicenne Energy and IDC, as well as academic research. The battery data is derived from our own research made at refurbishers and recyclers as well as information from manufacturers.

Personal mobility – Top down analysis based on our own assessment based on information from industry associations, financial reports from manufacturers, and media reports. Battery data comes from contacts with collectors, manufacturers and our own research done in refurbishment and recycling operations.

Light duty EV – Bottom-up analysis based on national vehicles statistics complemented with information from EV-analysts. Data is completely bottom up in the three key markets, with every car model tracked, and then modelled in the rest of the world.

Heavy duty EV – Combined bottom up and top down analysis based on national vehicles data, historic information from Bloomberg and our own database of orders since 2018. Analysis of vans and light trucks are done completely bottom up, tracking the vehicles in the key markets.

ESS – Capacity data from Bloomberg and Wood Mackenzie combined with our own modelling of different segments, chemistries and battery sizes based on contacts in the market.

Industrial – Top down analysis based on our own assessment based on information from industry associations, financial reports from manufacturers, and media reports.

UPS/backup – Top down analysis based on our own assessment based on information from industry associations, financial reports from manufacturers, and media reports.

Maritime – Top down analysis based on our own assessment based on information from industry associations, financial reports from manufacturers, and media reports.

About the author

The report is authored by Hans Eric Melin, founder and managing director at Circular Energy Storage. Hans Eric has been working more than 15 years in the recycling and renewable energy industries. Before starting Circular Energy Storage in 2017 he served as Vice President of New Markets at the largest waste battery collector in the US, Battery Solutions. Before that he was a co-founder and CEO of Refind Technologies which is the world leader in AI-based classification and sorting of batteries and electronics for reuse and recycling.

Hans Eric has authored reports for the World Economic Forum, Transport & Environment, the Swedish Energy Agency and the Nordic Council of Ministers. He is also co-author of the article "Circular economy strategies for electric vehicle batteries reduce reliance on raw materials" published in Nature in 2020. He sits on several advisory boards for research projects on lithium-ion battery development in Norway and Sweden and is member of the program committee of the Swedish Battery Fund, the largest funder of battery research in Sweden.

Lithium-ion batteries placed on the market

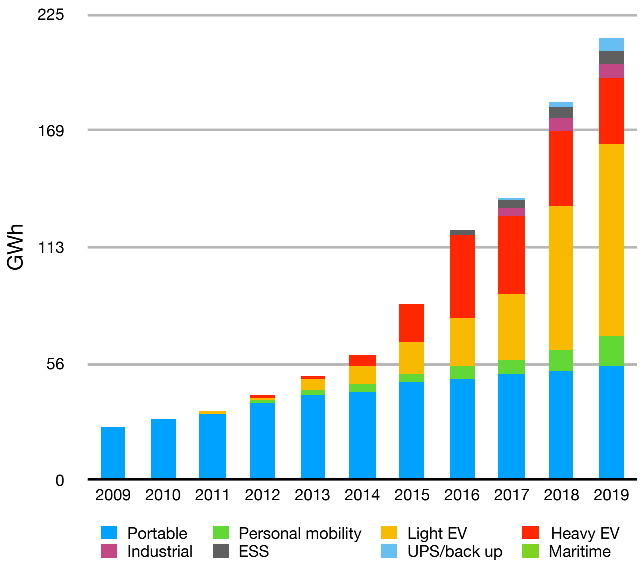
Over just 10 years the lithium-ion battery has gone from powering mobile phones and laptops to become a platform technology for everything from transportation to energy storage. The growth has been enormous but still nothing compared to what awaits. However in order to understand what actually is used today and what and when batteries finally will come back from the market it is important to understand the history as well as the future.

There are essentially no publicly available sources of information on how much LIBs that are placed on the global market as there a few reporting obligations outside the automotive sector. Circular Energy Storage's data is based on various sources on the volumes of the applications in which the batteries are used as well as data on the actual batteries such as weight and capacity.

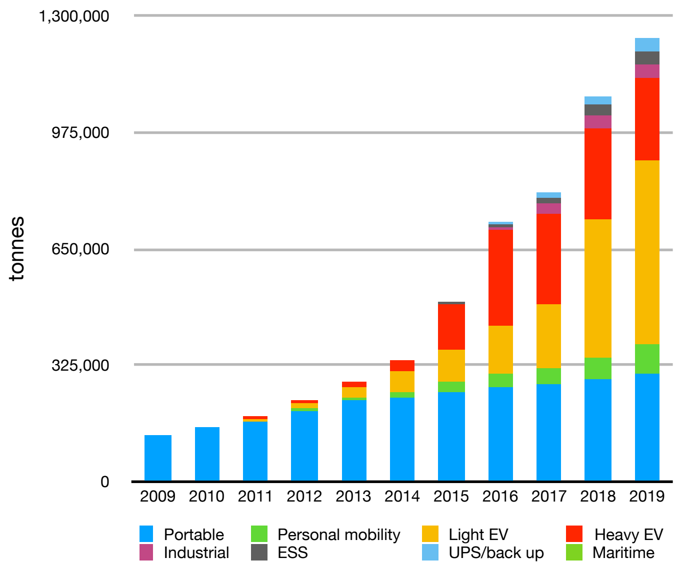
During 2019 an estimated 218 GWh of LIB energy storage capacity was placed on the global market, equivalent to 1.2 million tonnes of cells. This represent a 16% increase from 2018, a slowdown from the prior year when the market grew with as much as 33%. The main reason was a significant slowdown in the Chinese market for both light duty and commercial electric vehicles which was caused by new requirements on higher energy density in the batteries in order for OEMs to receive subsidies. It illustrates how volatile the LIB market is with a demand largely driven by policy which has caused an rapid growth of a previously under-developed value chain reliant on both highly specialised chemical processes and products, as well as on large commodities. As a reference it was first in 2018 as the output of lithium-ion batteries exceeded the output of single-use alkaline batteries. Since 2009 the LIB market in GWh has grown by 720%, a CAGR of 23.4%, and is about to turnover more than 60 billion USD according to Avicenne Energy.

Until 2012 the LIB market was almost completely dominated by portable batteries. In 2013 the volumes of electric vehicles started to increase in all three key markets, Europe (EES), the United States and in China. In 2014 cities in China started to acquire electric buses in large quantities, following generous government subsidies. Subsidies, and several different bonus-malus incentives also spurred the growth of light duty vehicles both for commercial and private use. This has made China to not only the largest user of batteries but also the world's largest producer, controlling more than 70% of the total value chain, including chemical production, cell manufacturing and pack assembly. It has also spurred the

LIBs placed on the global market 2009 - 2019, nameplate capacity by application



LIBs placed on the global market 2009 - 2019, tonnes, cell level by application



Lithium-ion batteries in use

The lithium-ion battery is extremely diverse in terms of applications it can be used for. From powering miniature speakers in ear phones to ferries and trucks. They also are used to perform fundamentally different kind of jobs. From a UPS battery which only is needed during rare power outages to batteries in automated guided vehicle working 24/7. The different usages but also the users' relation to the applications which the batteries are powering are key to understand how long the batteries will stay in the market and how well they will serve the needs of the user.

From the point when a battery is sold there is very little information about what actually is happening with both the battery and its application. Except for cars and other registered vehicles owners of battery-powered applications have no obligation to report to what extent they are using the product, if they have sold it or if they have disposed of it. This means that the assessment of how much batteries that are in use and how many that every year will reach end of life must be done by modelling the volumes, either using information about a battery's technical boundaries or by using information about people's and organisations' usage of the actual applications.

In Circular Energy Storage's data we use both of these parameters where the technical information tells us what possibly *can* happen while information about people's behaviour and data from trade of both applications and the batteries tell us what actually *is* happening.

Defining batteries' different lifecycles

Despite using different cathode materials all lithium-ion batteries essentially work in a similar way with lithium ions moving back and fourth between the cathode and anode when being charged and discharged. The different chemistries have derived from both the aims to obtain a high stability of the battery but also in search for cost reduction, independence of certain materials as well as different performance criteria such as power or energy intensity. The different chemistries also affect the longevity of the batteries by essentially determining how many charge and discharge cycles the batteries can be used for. For instance will batteries with LCO cathode, often used in so called lithium-polymer batteries for portable electronics, degrade after fewer cycles than LFP batteries which are used in everything from scooters and cars to energy storage units. The flip side for the LCO battery is a high energy density and specific energy which is important for small electronics devices such as smartphones in which the battery only weigh 20-30 grams.

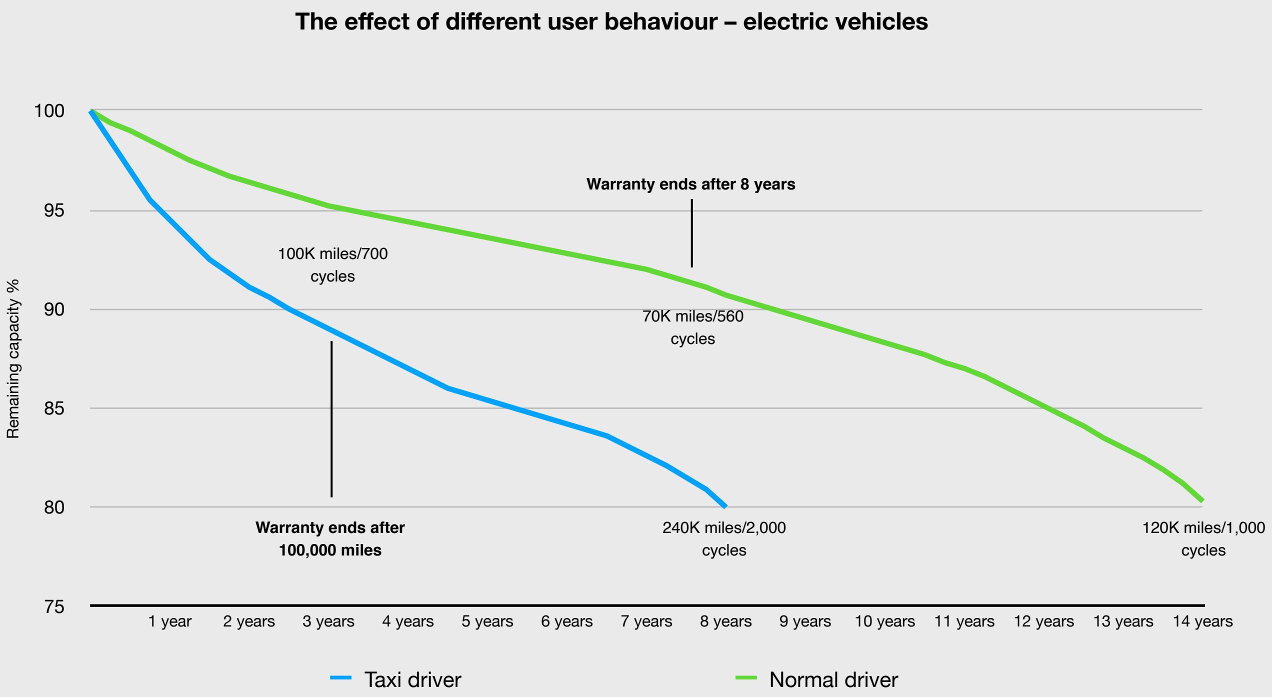
How long a battery will last depends both on how it is used and how it is ageing. Typically batteries that are charged and discharged with high C-rates will degrade faster than batteries that are used more gently. Likewise will batteries which are used with less depth of discharge last longer than batteries that utilise their entire available capacity and are stored at a high state of charge.

Batteries which are used and stored in hot climate will degrade faster than batteries in cooler areas and in battery packs with active cooling.

It is therefore difficult to know exactly how long batteries will last. Research from NREL in the US which has tested several different cells and packs with different chemistries shows that lithium-ion batteries with typical chemistries for use in EVs should be able to retain 80% of its capacity after 2,000 cycles. There are however many examples which suggest both more and less.

The battery-application-user relationship

A battery's health is obviously essential for determining how long a battery can be used. However, from the point a battery is placed in the device or equipment it is tasked to power, its life will also be dependant on the actual application and not solely on its own technical boundaries, although the particular battery of course usually is selected based on its specifications and the requirements the application has upon it. Moreover, the lives of



Several studies suggest that EV batteries should be able to retain 80% after 2,000 cycles. In real life this varies depending on battery type, battery size, driver behaviour, charging pattern and not least climate. This is just an example.

A taxi is driven 250 days a year and use the full range of a 40 kWh EV of 140 miles every day. It will take 8 years until the battery is cycled 2,000 times. The warranty will end after three years when the car has reached 100,000 miles. After 8 years the car will have a range of 112 miles.

If the car instead is used by a private person it will be driven 9,800 miles per year which means it will be cycled 70 times per year. The car will not have been driven more than 70,000 miles when the warranty ends after 8 years. If 10% calendar degradation is considered the car should have a range of 112 miles after 14 years.

both the battery and its application are highly depending on how the application is used and by whom.

One of the most extreme devices are power tools. For a professional construction worker the battery might be discharged and charged once a day and multiple batteries will be used. For a normal person who only need to fix a shelf or put up a painting from time to time it might be enough to charge the battery once a year. Still, although there are certainly differences among power tool batteries and their performance, a battery even for a layman is still expected to last at least 20 minutes of continuous work if the user has the need for it. Hence the battery often is over-designed for the job it usually needs to do.

The situation for cars is not very different. While an Uber or taxi driver can drive 140 miles every day at work most people don't drive much more than 25 miles per day. For a 40 kWh Nissan Leaf that's a difference between 60-70 cycles for the private person per year and more than 250 for the taxi driver.

The different user behaviours are affecting the pace in which the battery will degrade. But it will also affect the actual acceptance of degradation. In fact the power tool battery a construction worker will discard could be good for a normal user for several years and might be discarded first when the user wants a more modern or aesthetic device. However even at this point there could be other users who might be fine to use the old, but often barely used, device. The same pattern is obviously valid for cars.

The lifecycle of portable batteries

Since 2017 almost all portable batteries which are not either used for power tools or cameras are built into the devices they power. That means that most people are not capable of switching the battery in the device themselves. For some

Lithium-ion batteries reaching end of life

Lithium-ion batteries do not last forever. They may however last longer than the application they power which means that their destiny depends as much on how phones, cars and e-bikes are used as much as the batteries' actual performance. This is also the reason why end of life rarely is just that, but rather the beginning of a new life in a new application. Wether that will happen depends on how the battery reach end of life and which player that controls it.

In Circular Energy Storage's definition a battery reach end of life when it has been removed from its original application with no intention to put it back into the same equipment. Hence a battery that is removed in order to be repaired will not be deemed end of life while a battery that will be reused in another application is considered to have reached end of life, although it's only its first life of potentially several ones.

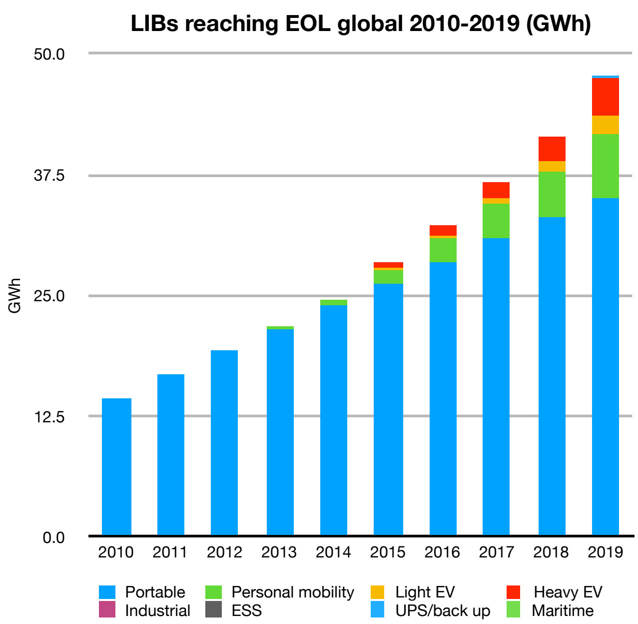
Batteries that still sit in equipment that could be classified as end-of-life such as cars or portable electronics is not automatically classified as end of life. The reason for this is that this equipment, ranging from phones to cars, can many times be re-classified as products and will continue to use the batteries inside. This happen to smartphones that have been dropped off in recycling centres as well as for car wrecks which might be repaired and placed back on the road.

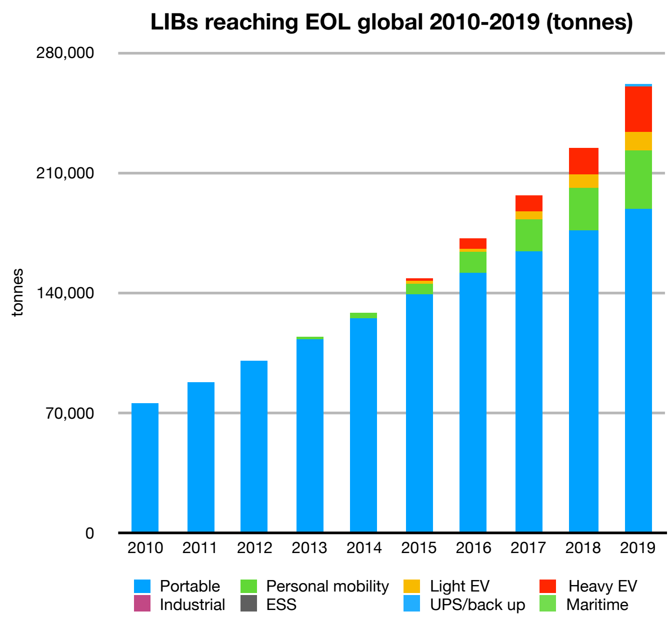
In 2019 an estimated 47.8 GWh of LIBs reached end of life in the world which is equal to 262K tonnes. This can be compared with the 218GWh that were placed on the market which reflect both the rapid growth of the LIB market but also how long time the batteries actually are in use.

The numbers are based on what has been placed on the market historically and has been matched with data on how long the batteries normally are in use. It is also matched with observations of batteries that enter ATFs (authorised treatment facilities for cars) as well as e-waste and battery collectors all over the world.

End of life batteries by application

Most of the batteries that reached end of life came from portable electronics, a consequence of the fact that other applications haven't been used in larger numbers before 2010 and have more than 10 years of useful life. Second to batteries from portable electronics come batteries used in personal mobility. Most of these volumes are generated in China with its large fleet of both e-scooters and e-bikes but the volume is increasing also in Europe and in the US due to both increased adoption but also because of a boom in rental programs for





Reuse of lithium-ion batteries

When a lithium-ion battery reach end of life it has often significant capacity left. This has created a market with several different segments and applications where the batteries are used instead of brand new batteries. The logics are often not different from other second hand markets such as for cars, machinery or fashion except for one key difference – a battery can be repurposed and used in completely different applications than what they originally were made for. Something that makes the market both more dynamic and complex.

Based on the volume of batteries we estimate is reaching end of life we also make an assessment of how much of the volume that will go to reuse, to recycling or that will be disposed of in other ways. Like in the case of how much that is reaching end of life this is an area where no official data is available and where we have to rely on modelling to get the numbers even historically. We do that by studying the actual market and combine it with data on state of health in EOL batteries as well as on commercial and technological innovations in the field.

The discussion about reuse or second life for lithium-ion batteries is often focused on its feasibility and if it makes technical and economical sense. For a long term development these are very important questions. However in order to understand what is driving batteries in different directions when they reach end of life the correct question is not if it makes sense. The key question is: Does it make economic or technical sense for *somebody*?

As mentioned in the chapter about end of life, batteries which become freely available on the market will be sold to the highest bidder. Despite the fact that the material in the batteries are valuable the most value from a battery comes from its usage. Alternatively it comes from its ability to substitute a new battery. If a battery can be reused it will therefore most often be sold to somebody that will do just that, unless there are regulations, cost for transportation or lack of access to market which can prevent a deal to be done.

The market for reuse is diverse and the different segments have often little in common. Still they rely on the same logic: that if batteries have sufficient capacity left to perform several different kind of tasks and it can be economical to prepare the batteries for this task that is where they will go. Almost all LIBs can technically be reused at least on cell level unless they are physically damaged. Most batteries that reach end of life do that because the product they power has been damaged, obsolete or just phased out. In tests done by Circular Energy Storage at sorting facilities in both Europe and the US, over 80% of batteries ranging from laptop batteries to 1 kWh backup power units has been proven good for further use both for their original application and for new, less demanding applications. In fact as much as 24% of single-use batteries that have been dropped off for recycling have proven to be in perfect conditions. Usually the worst performing batteries are those that either are replaced such as power tool batteries or batteries that are heavily used such as smartphone batteries. For larger packs used in vehicles and machinery the batteries are usually in good conditions at least for some applications.

The most important reuse segments are:

- Direct reuse
- Remanufacturing of battery packs
- Stationary energy storage
- Conversion of ICE vehicles to electric vehicles
- Do-it-Yourself-projects
- Cell refurbishment

Direct reuse

This means that a battery will be used again for the same application it originally was intended for. A battery which has been placed in a PHEV will be sold by for instance an ATF to car workshops that need to find spares for their customers. This is how engines, gear boxes and smaller components such as doors, rear mirrors etc have been reused since ages. A battery from new vehicle that has been written off may be in great condition and can therefor be sold to an owner of the same model but with a faulty or degraded battery. The pricing of these batteries is therefore more based on what a new component would cost, or what other ATFs are charging for the same battery. Similar markets exist for portable batteries such as laptop and smartphone batteries where companies are many times only making a visual inspection of the battery and then sell it on Ebay or to repair shops following the same pattern as for car batteries.

Recycling of lithium-ion batteries

Recycling of lithium-ion batteries has been done for more than 15 years but with various efficiencies and recovery rates. With demand from battery material producers, access to production scrap and consolidated volumes of waste batteries recyclers in China and South Korea have paved the way for processes with high efficiencies that allow waste materials back into the battery value chain again. In the rest of the world recyclers have struggled to consolidate sufficient volumes. This is now changing.

Recycling of LIBs has been done as long as the battery chemistry has been on the market. However, the efficiency was for a long time low as the LIBs often were used as secondary feedstock in non-dedicated processes. An obvious reason for this is that the volume have been very low, especially compared to other waste batteries such as lead-acid, alkaline, nickel cadmium and nickel metal hydride.

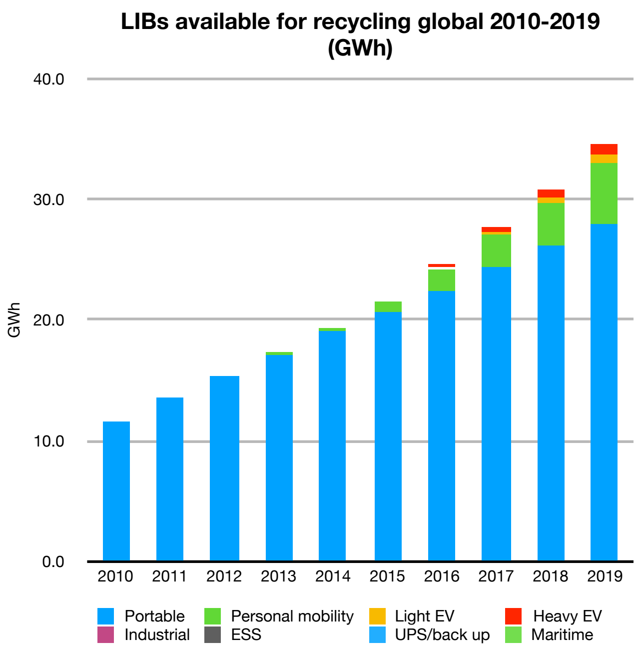
Available volumes for recycling

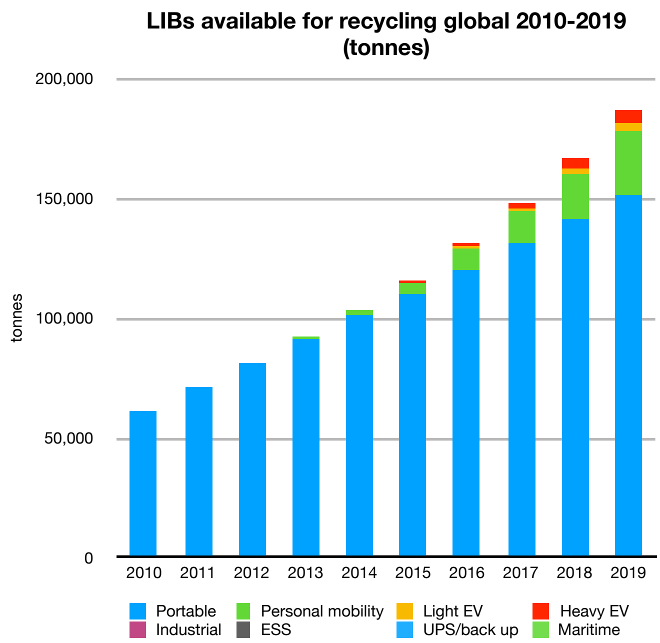
As clearly is shown in the chapter about end-of-life batteries the amount of batteries that have been available for both reuse and recycling have been low for a long time, especially considering that these batteries are installed in devices distributed over the whole world. It was first in 2014 the global volume of end-of-life batteries available for recycling amounted to more than 100,000 tonnes. Of this as much as 97% came from portable applications.

In 2019 we estimate that the end-of-life volumes available for recycling reached 188,000 tonnes. Batteries from portable applications dominated the volume with a share of 80%. The second largest segments was personal mobility with batteries from e-scooters and e-bikes, which in many parts of the world has become an important stream for recyclers.

Batteries from light duty electric vehicles are, relative to other segments still rare, with an estimated 2,775 tonnes on cell level which equates to around 5,400 tonnes on pack level. With heavy duty EV batteries included the amount on cell level increases to 9,200 tonnes. Important to note is that this volume is only the batteries that come back from from the market. It does not include batteries from tests, production scrap or unsold volumes.

Another important remark is the geographical differences. 45% of the volume available for recycling is found in China and





The 2030 scenario

How much batteries that will be in use on the global market depends on two factors. How much batteries that are placed on the market and in which pace these are reaching end of life. Here we use our collected data together with our analysis of the market to establish a forecast of the volumes of batteries that will sold, used, reused and finally recycled.

Development of a base scenario

Our forecast for 2030 is based on a series of assumptions which derive from our historic assessment and strategic outlook. From that we work out five key battery volumes:

1. How much batteries that are placed on the market
2. How much that remain in use
3. How much batteries that will reach end of life
4. How much that will be reused
5. How much that will be recycled

In a rapidly growing market all these forecasts rely heavily on on the first one – of how much battery capacity that is placed on the market. A market which grows 20% per year will in less than 3 years double its size it obtained in the prior 7 years.

The rapid growth also increases the risk for volatility and that single events or initiatives may have a proportionally high impact. A good example is the expansion of the Chinese bus market, which more or less unnoticed by the outside world accelerated from almost zero to an annual output of more than 100,000 vehicles in two years. Tesla's launch of gigafactories which have become the "machines that build the machines" are another example, adding new capacity in the 100,000s of vehicles on an annual basis in less than 12 months.

However with a much broader market with significantly more players in all parts of the value chain the effects of these extraordinary events will increasingly be absorbed and become part of the predicted growth. The market will basically also sustain its own growth by rapidly adding capacity which raises barriers to entry which will be increasingly difficult to break down. For instance, an increase in the number of specialised manufacturers of LIBs will cement the use of technology in applications such as electric cars and buses. First of all because they will have cost advantages which will be impossible for new technologies to beat, and secondly they will do anything to survive, including cutting costs further and seeking additional support from private and public funders which supported them from the beginning. Likewise, the further into an electrified future incumbent car makers step, the closer they come to a point of no return when customer preferences and investments in production capacity only point in one direction.

On the other side there are also limits to how fast the industry can expand, mainly due to access to raw materials and capacity to turn it into the specialty chemicals needed to make battery materials.

The actual use phase is moving in the same direction, towards maturity. The markets for reuse and refurbishment of portable electronics that have grown rapidly the last 10 years now supports the device market and contributes to its continued growth as consumers can sell on their devices already after one or two years without losing the entire value. This is how the automotive and machinery markets have worked for years. We now see a similar pattern for batteries which are removed from their original applications which ensures that the value will be preserved or that the depreciation at least will be slowed down. An effective market enables transfer of ownership which in turn enables optimisation of resource utilisation.

The market conditions can still change over time and in certain markets the changes might be abrupt due to legislation or trade barriers. However the market for consumer electronics as well as for used equipment has shown that the underlying forces are strong, contributing to a stable market where goods find its way to the new demand when certain markets close and vice verse.

The market for electric vehicles and the cemented preference for LIBs makes the case for circularity particularly strong. By replacing an incumbent technology without disrupting the market in itself it is fairly easy to predict the future size of the market although the pace to reach there might differ over time. This creates the certainty, that there will be a need for materials over at least the next 20 and most probably beyond, which is important for the establishment of an efficient reverse value chain ending in recycling and production of materials that can put back into the battery supply chain.

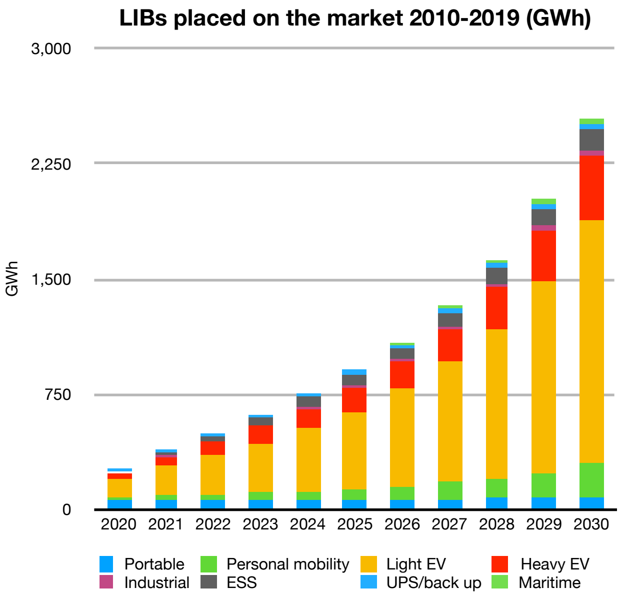
The overall growth, especially in combination with the expansion of renewable energy which continuously add demand for energy storage, will also support the market for reused batteries. Especially when market volatility can create shortages in certain segments but also when certain markets or segments require access to cost efficient battery systems. This market is however more sensitive than the recycling market for saturation and cost reductions in new batteries might kill the business case at least in high-wage markets.

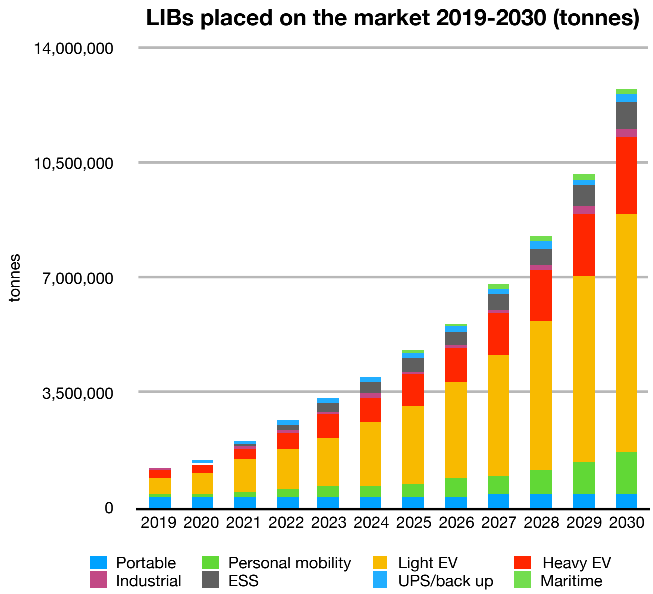
Batteries placed on the market

Our forecast for LIBs placed on the market is based on five major assumptions:

1. The electrification of transportation will drive the growth of the LIB market and will pave the way for increased cell manufacturing capacity, intermediary material production and raw material extraction.
2. Except for portable electronics, all LIB segments of today will grow in similar pace as the EV segment and will take advantage of the increased availability and price reductions. If the demand temporarily will fade in certain vehicle segments battery producers will increase the efforts in alternative segments such as ESS, maritime or industrial solutions.
3. From 2023 the market will be constrained by supply of raw materials and should demand take off considerably the market will simply not be able to deliver, due to lack of capacity. Such a situation might however spur the expansion of the supply chain and thereby considerably increase the output in the later parts of the decade.
4. Over the next years the batteries placed on the market will be traditional lithium-ion batteries with cathode with either layered (NMC, NCA and LCO) or olivine structure (LFP). Incremental changes such as nickel-rich cathodes, silicon-based anodes, solid or gel-based electrolyte (but with graphite/silicon anode) will be launched and adopted at scale, as well as new cell formats. New technologies might be introduced on the market any year from now but will need to be used in niche applications such as high-performance cars, drones or aircrafts. The share of new batteries is anticipated to be small before 2030.
5. China will continue to dominate battery manufacturing and the production of battery materials. Despite a decline in volume in both 2019 and 2020 the country will also be the largest consumer of batteries, followed by Europe and the US.

The market is expected to grow from 259 GWh in 2020 to 2.5 TWh in 2030, a CAGR of 25.45%. The growth will primarily be driven by the light and the heavy electric vehicle segments which will go from 60% to 78% of the total LIB market. This estimate is based on 26 million light electric vehicles in 2030 and 3.7 million commercial and heavy duty vehicles which is in line with what other analysts are projecting (Bloomberg 28M LEV/≈3.85M C/HEV, IEA SP scenario 23M LEV, IEA SD scenario 43M LEV).





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