Nordic Council
of Ministers

Mapping of
LITHIUM-ION BATTERIES
for vehicles

A study of their fate in the Nordic countries

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Lisbeth Dahllöf, Mia Romare and Alexandra Wu

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Contents

Summary

This report regards the fate of the lithium-ion batteries used in vehicles in the Nordic countries. The intention was to give a background for the referral on the revision of the Battery Directive (EC, 2006). The report was written by researchers at IVL Swedish Environmental Research Institute and was commissioned by the Nordic Waste Group under the Nordic Council of Ministers.

There is currently lack of data regarding how many batteries that are sent for recycling, mainly because many other types of batteries are included in the same category as lithium-ion batteries for vehicles in the Battery Directive which stipulates how to report collection.

Even if it is hard to determine how many batteries that are collected and sent to recycling, data regarding the amount of batteries that reach end of life is possible to calculate. This means that it is possible to determine how many batteries that are *available* for recycling, even if we cannot say exactly how many that have been or will be recycled in a near future. Until today, very few batteries from cars and buses have been collected and many of them are from warranty and accident cases. For e-bikes around 30,000–43,000 batteries per year are calculated to currently reach end of life.

Regarding the weight of batteries entering end of life, car and bus batteries dominate the flow both now and even more so in the future, making them the most important flows to consider for recycling in order to recover the raw materials. Based on the life length of batteries in current electric cars, the current flows of new batteries (2015–2018) are the ones that will be available for recycling in 2025–2030. They are, however, quickly out-shadowed by the projected increase in number of car batteries on the market, growing from around 0.5 million units 2018 to 4 million units by 2030.

Batteries for e-bikes contribute a significant quantity but a low weight in the near term. In terms of quantity placed on the market in 2018 they were in the same order of magnitude as batteries for large vehicles, with an estimated 170,000 pieces for e-bikes and 140,000 for cars and buses. In terms of mass, however, batteries for e-bikes made up for about 320 tons, while larger vehicle batteries contributed in the order of 30,000 tons. This makes e-bike batteries important to target from a quantity perspective, but they contribute less to the availability of secondary resources from recycling. E-scooters are a product group similar to e-bikes from where we can expect several batteries ready for recycling.

As mentioned, the flows described above only represent the batteries that are available for recycling, but they will only be recycled if they are collected and sent for recycling. Currently, batteries from heavy duty vehicles are to a great extent collected in a controlled way by the producers, due to the producer's responsibility in the Battery Directive as well as thanks to business contracts. For cars the risk for uncontrolled second life use after the first use in the vehicle is somewhat higher due to more vehicles

and actors seeing value in used batteries. For smaller batteries as in e-bicycles, the risk lies in that private persons may keep them at home, since they may be useful occasionally or, less probable, they may throw the entire bicycle with its battery at the recycling station so that the battery wrongly ends up in metal recycling. It is important that used e-bike batteries are collected since they pose a small risk of fire.

If there is energy storage capacity left in the battery it will most probably not be sent for recycling, as it currently implies a cost, while additional use could imply additional revenue. Therefore, refurbishment for reuse in vehicles is already now a business. Second life of batteries in other applications will probably become increasingly popular as well, as the need for energy storage in society will increase drastically, but until now we have only seen projects, no regular business.

Even though second life of batteries is usually beneficial for the environment thanks to the avoidance of producing new batteries, there are technical problems to overcome, such as to measure state of health of each cell and do exchanges and re-arrangements of cell modules. Also, a potential drawback from a resource depletion perspective is the delayed recovery of the raw materials from the recycling,

When it comes to recycling and recycling technology China is a clear forerunner both when it comes to technology and volume, with potential to recover most of the metals in the battery (depending somewhat on the market of each operator). This is thanks to large amounts of used batteries and considerable battery production. However, recycling is also done in Europe and at least cobalt, nickel and copper are recovered with relatively high efficiency. In Europe lithium is not yet recycled in large scale, due to the recycling costs, relatively low material value, and low incoming volumes of batteries. The graphite is also not recovered.

In Europe, the dominant recycler uses pyrometallurgy with subsequent hydrometallurgy. Looking forward, there is a lot of ongoing research trying to make recycling more efficient, and pre-treatment with subsequent hydrometallurgy seems promising. Direct recycling, where the battery materials are recovered in processed form, would probably be even more efficient but seems also more difficult to accomplish. Automation and design for recycling are also areas that must progress.

1. Introduction

1.1 Background

This report regards the fate of the lithium-ion batteries used in vehicles in the Nordic countries. The intention was to give a background for the referral on the revision of the Battery Directive (EC, 2006). The report was written by researchers at IVL Swedish Environmental Research Institute and was commissioned by the Nordic Waste Group under the Nordic Council of Ministers.

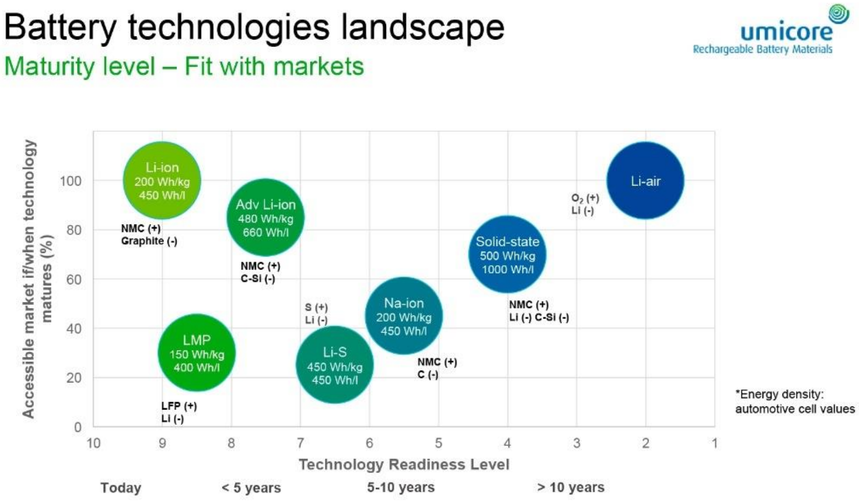
The number of electric vehicles (cars, buses, e-bikes, electric scooters and electric motorcycles) sold in the Nordic countries is currently increasing quickly. That means that more electricity is used for driving, and also that more of some important metals are being used than earlier. Typically, cobalt, nickel and lithium are such metals used in the lithium-ion batteries. The demand for them is also increasing fast with increasing number of electric vehicles, leading to a possible risk for "bottle-neck" effects in the supply availability in a short-term perspective. This is likely a substantial risk, at least for cobalt (Thomas *et al.*, 2018), but it was recently reported that for lithium there is currently no risk for deficiency (Millan Lombrana, 2019).

In a very long-term perspective, however, the extraction of cobalt and nickel from ore causes relatively high environmental damage costs (IVA, 2019) indicating that we are stretching the geological availability of these metals. This suggests that we need to take further care to make sure that the metals that are extracted stay in the technosphere, available for future use in products. It can also be worth considering conserving the processing value of the materials, for example with recovery and recycling methods that maintain as much of the material function as possible, for example recycling battery materials so that they can be reused in new batteries. The batteries can also under certain rare and unfortunate conditions catch fire (Battery University, 2019), an additional motivation for proper handling.

The currently available data suggests that we do not recover all the valuable content of the batteries in the Nordic countries today. Collection rates appear low, and the industrial recycling methods in Europe are not efficient enough in recovering the materials. Among potential reasons for this can be counted; that not many batteries have reached End-of-Life (EoL) yet, and that the old recycling facilities currently in use are not optimized for vehicle battery recycling.

When operating recycling facilities, it is beneficial to know at least roughly what type of batteries enters the recycling flow. The trend is that lithium-ion or advanced lithium-ion batteries dominate the vehicle battery market for years ahead. See Figure 1 as an example of an expert judgement of the current and future chemistries.

Figure 1: Maturity of different cell chemistries for batteries for electric cars



Note: On the x axis the time until the technology is ready for the market is reported in years and as Technology Readiness Level which is 10 when it is ready for the market and 1 when only the basic principles are observed. The Y axis shows how large share of the market the chemistry can have when or if it has matured.

Source: Tytgat (2019).

In Lebedeva *et al.* (2017) there is a forecast for solid-state batteries to enter the market from year 2022 and onwards, which is earlier than the prediction in Figure 1, and Li air batteries from about year 2029 and onwards which is in line with the figure. There is also a lithium metal polymer (LMP) technology for batteries, mainly sold for buses (Blue Solutions, 2018). In this study we however write about lithium-ion batteries that are clearly dominant today and in the near future.

Currently the "Battery Directive" (EC, 2006) which is a producer's responsibility directive, is under revision and this study is a knowledge base intended for use by the Nordic Environmental Protection Agencies for their referral response in the revision process.

This report focuses on the aspect of metal resources, but it does not elaborate on a broader range of environmental impacts, as these were outside the scope of this study.

1.2 Definitions and abbreviations

Battery	In this report the word battery means lithium-ion battery for a vehicle if no specification is provided.
BEV	Battery Electric Vehicle.
BMS	Battery Management System.
CV	Commercial Vehicle.
EoL	End of Life, when a product becomes ready for scrapping.
HEV	Hybrid Electric Vehicle.
Industrial battery	Battery used in industry or in a vehicle according to the Battery Directive 2006/66/EC.
LCO	Lithium Cobalt Oxide (a type of cathode chemistry defining the battery).
LFP	Lithium Iron Phosphate (a type of cathode chemistry defining the battery).
LMO	Lithium Manganese Oxide (a type of cathode chemistry defining the battery).
NMC	Lithium Nickel Manganese Cobalt Oxide (a type of cathode chemistry defining the battery).
PC	Personal Car.
PHEV	Plug in Hybrid Electric Vehicle.
POM	Placed On Market.
Second life	If the battery is used in another application after use in a vehicle it is called its second life.

1.3 Research questions and report structure

This report is centered around three main research questions:

- How many of the used lithium-ion batteries for vehicles are currently sent for recycling in the Nordic countries?
- How much weight and amounts of lithium-ion batteries for vehicles are put on the market in the Nordic countries and how many are available for recycling or second life year 2025–2030?
- What are the current and future techniques for re-use, second life and recycling, and what are the advantages and disadvantages with the different techniques? What is the material recovery efficiency?

In the final discussion and conclusions chapter these questions are revisited and the results from the study are summarized based on questions posed above.

Chapter 3 relates to the first research question regarding the current recycling and collection rates of batteries in the Nordic countries.

Chapter 4 covers the assessment of the number of batteries that are and have been placed on market, along with the assessment on what this implies for future waste flows of batteries.

Lastly, Chapter 5 aims to describe alternative fates that the batteries may encounter when reaching the end of life in vehicles. This aims to answer the third research question concerning future techniques for second life, re-use and recycling.

The results are discussed in summary in a final discussion and conclusions chapter.

2. Method

In this chapter the methodological choices corresponding to the research questions are presented.

2.1 Method for assessing current recycling rates of the used vehicle batteries

For the question on how many batteries that are currently collected and their fate after that, we contacted different actors in the Nordic countries and certain vehicle manufacturers and collection organizations.

We got very good information regarding batteries from cars from the Norwegian collection company Batteriretur® which was very valuable, since Norway has by for most electric cars in the Nordic countries.

We also looked for information regarding life expectancy from automotive companies on the internet, since recent studies (Lam *et al.*, 2019) indicate that it is longer than earlier stated by the manufacturers (usually 8 years, in line with the guarantee). For batteries from heavy duty vehicles we asked and got valuable information from Volvo Buses, since they have sold different types of electrified buses for some years now.

For e-bikes we asked collectors and we got some quantitative information from the Swedish company El-Kretsen AB (Eriksson, 2019) and Stena Recycling (Hall, 2019), but this was not enough for a calculation of the total. Therefore, we used data from Urban Mine Platform (2017). We did not actively search for information on e-scooters, since they are too new on the market.

The amount of vehicle batteries currently sent to recycling was calculated based on the combination of information from these different actors.

2.2 Method for estimating flow data for batteries 2025–2030

Regarding the question on how many batteries that are ready for recycling in year 2025–2030, data for sold electric vehicles were used in combination with information on life time expectancy of the batteries and amounts of batteries in one vehicle, which was taken from literature and organizations. A model to run different scenarios was set up (in Microsoft Excel) based on the variables sales of batteries, batteries in one vehicle, life time expectancy, degree of refurbishing and second life data. Input data to the variables were collected from literature and organizations.

2.2.1 Data sources – current use, collection and recycling

To find appropriate data sources, we first searched for country level data, including those from government authorities (environmental protection, waste management and statistics agencies) as well as transport industry associations. We also wrote to and spoke with some contacts from these organizations as well as vehicle manufacturers.

In this search we found the European Alternative Fuels Observatory (EAFO) website which provides vehicle fleet data across EU countries on multiple fuel types *and* vehicle classes. Due to its applicability to all Nordic countries it was chosen as main data source for the assessment of batteries placed on market. The EAFO is an EC-funded initiative that supports Member States with the implementation of EU Directive 2014/94 on the deployment of alternative fuels infrastructure. It updates its data monthly for passenger cars and quarterly for all other vehicles, depending on data availability (EAFO, 2019).

Other data sources were used as complements where necessary although reporting differed. For example, while one data source in Norway provided the number of BEVs placed on market by year, another source did not differentiate between different electric vehicle types (Lillemork, 2019, Gjønnæss, 2019).

Given limitations of time and data availability, in our investigation we also assumed that the trade of vehicles between Nordic countries was zero, though it is possible that that there is indeed trade of vehicles between countries.

In searching directly for waste and recycling data, we found that many gaps exist in the data or that data are unavailable. An ambitious study exists – the Urban Mine Platform from the EU project ProSUM – which projected placed on market (POM) and volumes of waste generated from 2015 (Urban Mine Platform, 2017). However, there was indication that for some countries these projections are no longer reliable (Chanson, 2019).

We also turned to Eurostat for EU-wide data given the expected comparability and standardization of data scope between countries. However, given that the data produced on Eurostat aligns with the definitions of vehicles under the End of Life Vehicle Directive (EC, 2000) and Battery Directive (EC, 2006) it created limitations for our project as electric vehicles could not be isolated from other vehicles.

Similarly, it was not feasible to isolate data on lithium-ion batteries for electric vehicles under Eurostat data on the Battery Directive because the current iteration of the directive classifies vehicle batteries in category 3 (other batteries and accumulators), along with for example batteries for back-up power in hospitals and airports, as well as hand-held devices and electronics.

We also asked different actors in the Nordic countries for statistics on vehicles put on market and sent for recycling but concluded that the statistics from EAFO were most complete and comparable.

2.2.2 *Calculation method and assumptions*

The life cycle stages of the vehicle batteries included in this study start with the vehicle being placed on market. At some point in the vehicle's use life, the battery may be refurbished (depending on the vehicle type) before the vehicle reaches end of life, after which the batteries are assumed to be sent either to a second use or directly to recycling.

The base scenario of the flow assessment representing the highest tonnage of batteries is based on Lam *et al.* (2019) together with information from industry experts, Olofsson (2019) and Chanson (2019). The base case figures and scenarios are found in chapter 4. Our model does not include the uncertainty of the battery lifetime expectancy.

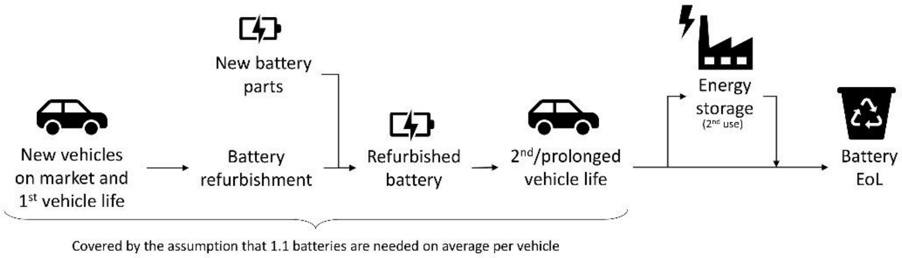
E-bikes were not included in the overall scenario assessment, due to lack of comparable data. Instead they were assessed separately and discussed in relation to the scenario results. There were for example no EAFO sales statistics for bicycles or other smaller vehicles, nor any data for life expectancy of batteries for these applications. Instead this assessment was based on Urban Mine Platform projections of sales and batteries having reached end-of-life (Urban Mine Platform, 2017) along with estimates of reasonable life lengths.

We also learned that data for batteries for heavy duty trucks are not available because electric heavy-duty trucks only reached the market over the past year. Since the flow of batteries from this group is nearly zero and since we assume the increase in absolute numbers the coming five years is low, this group was left out of the assessment. Only fully electric (heavy) buses were therefore included from the heavy-duty segment in the EAFO data and scenario assessment.

Hybrid electric vehicles (HEV) are not counted as alternative fuel vehicles (and thus are not in the EAFO statistics), but contain batteries, albeit smaller ones. Also, these vehicles were assessed separately based on data from the Urban Mine Platform (2017).

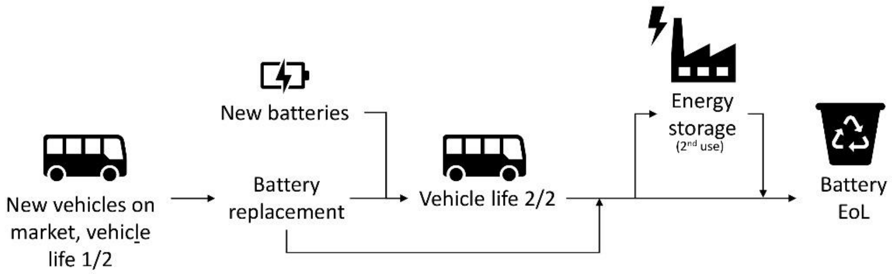
Below in Figure 2 and Figure 3 the possible fates of the lithium-ion batteries in electric cars and buses are illustrated. This schematic represents the assumptions made when assessing the flow of batteries to different uses and treatments.

Figure 2: The probable fates of the car lithium-ion batteries



Note: The first life in cars includes an average battery refurbishment so that over the first life 1.1 batteries are used per car on average. After the first life the batteries can either go directly to recycling, or via a second use in for example energy storage.

Figure 3: The probable fates of the heavy bus lithium-ion batteries



Note: Two batteries are needed on average and they are additionally replaced once during the bus life. After use either in the first or second half of the bus life, the batteries can be used in a second application, like energy storage, or they can be sent directly to recycling.

2.3 Method for current and future techniques for reuse, second life and recycling

The assessment of techniques for reuse, second life and recycling is based on our literature study. We also had personal communication with experts, most notably personal communication with the recycling researcher Martina Petranikova at Chalmers University of Technology (Petranikova, 2019) who also gave valuable comments on the first version on the text regarding recycling.

3. How many of the used vehicle batteries that are currently sent for recycling

This chapter deals with the first research question: How many of the used lithium-ion batteries for vehicles are currently sent for recycling in the Nordic countries?

The answers and analyses are divided based on the source of the battery, that is, from cars, buses or smaller vehicles.

3.1 Batteries from cars

The car producers have a producer's responsibility for the batteries, implying that they are responsible for sending them for recycling, according to the Battery Directive (EC, 2006). They may have arrangements with other actors to secure that this is fulfilled. One problem when it comes to assessing the volume of collected batteries, however, is that they are to be reported as industrial batteries, a category in which also many other types are included.

Batteriretur in Norway is the actor, in addition to the vehicle manufacturers, that has most experience with car batteries since they handle more than 90% of Norway's car batteries, and since Norway is the country with clearly most electric cars, see Figure 4. They together with other actors, have dedicated significant funds to inform insurance companies and car workshops about the safety risks associated with batteries, and the necessity of measuring for example the state of health before a battery can be resold. They have at the same time also informed about Norwegian laws in this area. Since they have conducted research in measuring the state of health and have seven years of experience, they claim they have unique competence and are usually hired for this type of assessment, although it is not a monopoly in Norway (Andresen, 2019).

So far, the batteries coming in from cars have mainly been from accidents or warranty cases. Batteriretur took care of approximately 1,000 BEV batteries in 2018 of which about 20% were further reused for second life projects while 80% were sent to recycling (Andresen, 2019). As also stated, in chapter 3.1 Norway has had a share of between 63% and 70% of the total number of vehicles placed on market in the Nordic countries over the past years. This in turn would indicate that the total numbers of scrapped batteries from electric cars on the Nordic markets should be around 1,700 pieces, based on Batteriretur's collected batteries representing 90% of the batteries in Norway.

Current indications are that the batteries generally last longer in the vehicle application than has been expected, as we have seen in Lam *et al.* (2019), and this assessment is further supported by the Managing director at Batteriretur (Andresen, 2019). Also, Tesla, Nissan and Volkswagen have published examples of longer life expectancy (Tesla, 2019, Nissan, 2019 and Volkswagen, 2019a).

A last question to pose regarding the current collection and recycling of batteries is why there are so few batteries being sent for recycling. The first part of the answer is that there are not so many batteries available to recycle yet. Additionally, in Europe it is currently costly to send the batteries for recycling. Therefore, it is not probable that the battery will be sent for recycling, if the owner of the battery can see a current or future value in holding on to the battery. Very few batteries, except perhaps those damaged by accidents, are at a point where they do not have a value or future value at all.

3.2 Batteries from buses

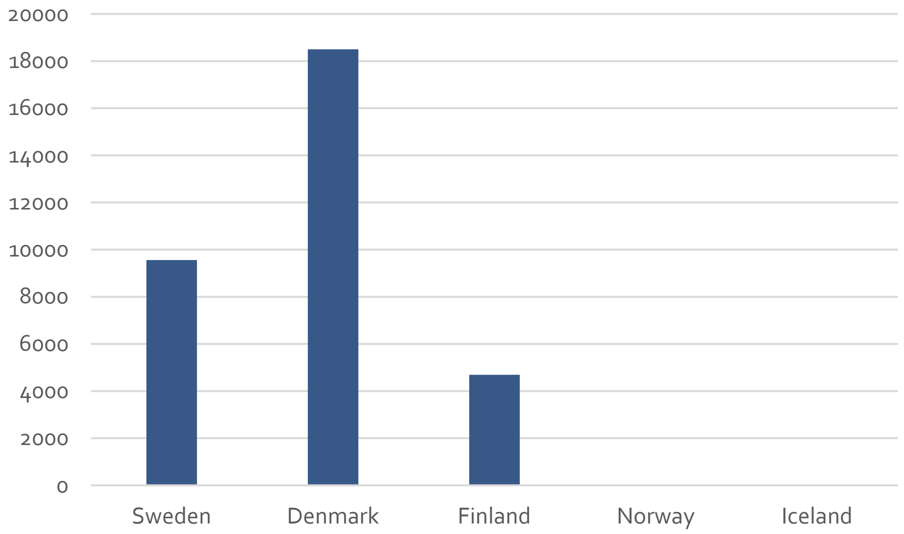
Electric buses are the type of modern heavy-duty vehicles that have been the longest on the market. We got information from Volvo Group who produces buses that the batteries in hybrid electric buses generally lasts 4–6 years depending on how the bus is driven, topography and climate (Olofsson, 2019).

The bus producers have producer's responsibility for the used batteries (EC, 2006) and therefore Volvo estimates that around 50–70 bus batteries will come back yearly to Volvo for recycling (Olofsson, 2019). Without knowing the number for the rest of buses from other producers, we assume that there are slightly less from the other Nordic bus producer, Scania, and that the non-Nordic bus brands take care of most of the batteries outside the Nordic countries. The estimation of the total will then be about 100–150 batteries being collected yearly.

3.3 Small batteries from e-bikes and e-scooters

We could not get quantitative information on amounts of bicycle batteries reaching recycling, only indications that the amounts have been small until now (Hall, 2019; Eriksson, 2019). Instead, data from the Urban Mine Platform (2017) was used to assess the potential flows, presented in Figure 4.

Figure 4: Amount of e-bike batteries that were projected to have reached end-of-life 2018 according to Urban Mine Platform (2017)



Note: Data were lacking for Iceland and Norway.

The total number of batteries from e-bikes should, based on these data, be about 18,200 + 9,800 + 4,600 + 4,000[1] = 36,600. Based on this result, an estimate of the amount of batteries that have reached their end of life is in the range of 30,000–43,200.

E-scooters have only recently become popular in the Nordic countries, so it is likely that not so many have already reached their end of life. There is no specific data available for this product group.

It is not certain that all small vehicle batteries will be sent for recycling directly when they reach end of life. Most small vehicle batteries will sooner or later be collected, if they are not scrapped together with the bicycles themselves at the scrapyard, although the risk for that is probably low. The risk is however high that many batteries are stored in people's homes for a long while before they are scrapped (much like batteries for electronics), which induces a small, but still noteworthy, risk that the batteries cause fires. Currently, it does not cost the vehicle owner anything to scrap a battery, so the cost is in the collector's business models in relation to the party holding the producer responsibility.

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[1] Estimate for Norway+Iceland. Since data for them were not found in Urban Mine Platform (2017) we assumed 2,000 e-bikes per country.

4. Number and weight of batteries placed on market and reaching EoL

This chapter deals with the second research question: How much weight and amounts of lithium-ion batteries for vehicles are put on the market in the Nordic countries and how many have reached second or end of life in year 2025–2030?

In contrast to the relatively poor data on current handling of waste batteries, data for what is placed on the market today is more readily available, at least for the most product groups representing the highest tonnage. Combined with information of life length, replacement and second life it is possible to assess how the stock of batteries in electric vehicles will develop.

Based on this it is possible to estimate how the future flows of waste batteries may look, as well as to evaluate how these flows may be influenced by different important parameters. These base figures and scenarios are summarized in Table 1.

Table 1: Base case assumptions made for electric vehicles

	Cars BEVs (M1)[1]	Cars PHEVs (M1)[2]	Light el. buses (M2)[3]	Buses (M3)[4]	Light comm. vehicles (N1)[5]	Mopeds & MC (L)
Av. Batteries per vehicle	1.1	1.1	1	2	1	No data
Battery life per vehicle	14	14	14	6	14	No data
Vehicle life	14	14	14	12	14	No data
Number of battery exchanges	None	None	None	1.0	None	No data
% going to 2nd use in storage (2018)	20%	20%	20%	50%	50%	No data
Yearly increase 2nd use[6]	2%	2%	2%	2%	2%	No data
Years in 2nd life[7]	6	6	6	8	8	No data

Note:

[1] The parameters for BEV passenger cars are based on "Base Case PC BEV Low" in Lam *et al.* (2019).

[2] The parameters for PHEV M1 vehicles are based on "Base Case PC PHEV" in Lam *et al.* (2019). For simplification 1.1 batteries per car is also assumed to account for potential battery replacement or refurbishment.

[3] The parameters for M2 vehicles are based on "Base Case Truck BEV" in Lam *et al.* (2019).

[4] Only fully electric buses were included in the statistics. The parameters for M3 vehicles are based on industry expert input.

[5] The parameters for N1 vehicles are based on "BC4 Truck BEV" in Lam *et al.* (2019).

[6] It was hard to find data for a specific growth, and for this reason the growth is included in the sensitivity analysis in section 5.3.

[7] The years in storage is based on "BC7 Commercial ESS" [Energy Storage Solution] in Lam *et al.* (2019).

Source: Based on Lam *et al.* (2019), Olofsson (2019) who gave an estimate for the lifetime and number of batteries per bus range, and Chanson (2019) who elaborated the total amount of needed batteries in a car for the car's assumed lifetime of 14 years.

We account for the occasional battery exchange and refurbishment by estimating that 1.1 batteries are needed per car placed on market and assume instead that no batteries are sent for refurbishment/replacement over lifecycle stages.

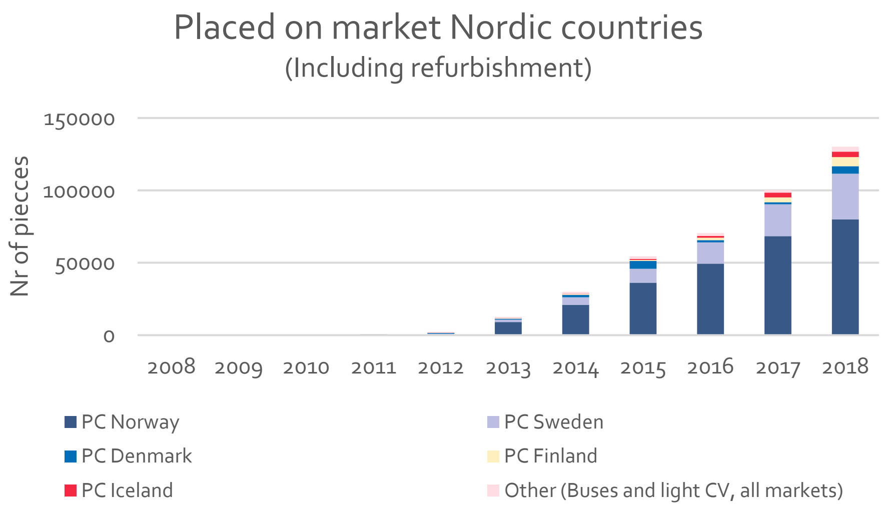
The average amount of batteries placed in a vehicle represents the production of new batteries both for the first instalment, but also for any replacements. For cars the base assumption is that the batteries will last the life time of the car, but since it is likely that some will break, a 10% replacement is assumed which was on the upper limit according to Chanson, 2019. For heavy buses there will be a need for replacement, due to heavier driving cycles, and this is represented by 2 average batteries needed per bus life. This conclusion can be further seen in the data for the life of battery versus vehicle, where the cars and light duty vehicle batteries last the entire life of the vehicle, while a bus battery only lasts half of the vehicle life.

When it comes to second life it is assumed that second life efforts start out at 20% in 2018, information that is taken from the current Norwegian situation (Andresen, 2019). In addition to this, a growth is assumed, at 2% per year. It was hard to find data for a specific growth, and for this reason the growth is included in the sensitivity analysis in section 4.4.

4.1 Batteries placed on market – Base case results

Figure 5 shows the results for the base case assumptions regarding batteries placed on market per application type (including refurbishment). The figures represent the base case, as presented in Table 1.

Figure 5: The figure shows the number of batteries placed on market for the vehicle groups identified as contributing most to the total tonnage of batteries, according to assumptions presented in Table 1



Note: PC stands for passenger cars and covers both BEV and PHEV cars. Buses include both light and heavy. The last category represented is light commercial vehicles denoted as CV. Passenger cars dominate the flow of batteries placed on market, and Norway represents the strongest market.

It is clear that when it comes to amount of batteries placed on market, the passenger cars dominate, making up over 90% of the batteries placed on market every year since 2013. The percentage contributed by the passenger cars has also been growing reaching 97% in 2018. There are of course large variations in battery weight between models and manufacturers but based on data from the Urban Mine Platform, 2017, a reasonable estimate is that the car batteries currently weigh about 230 kg as an average. This would imply that the weight of batteries placed on market in 2018 is around 30,000 tons.

A second noticeable statistic is that Norway dominates the Nordic market. Between 2013 and 2017 Norway contributed around 70% of the batteries placed on market. The number seemed to go down slightly in 2018 (to 63%), but it is not possible to tell if this implies the other countries catching up, or if it was a variation in that year.

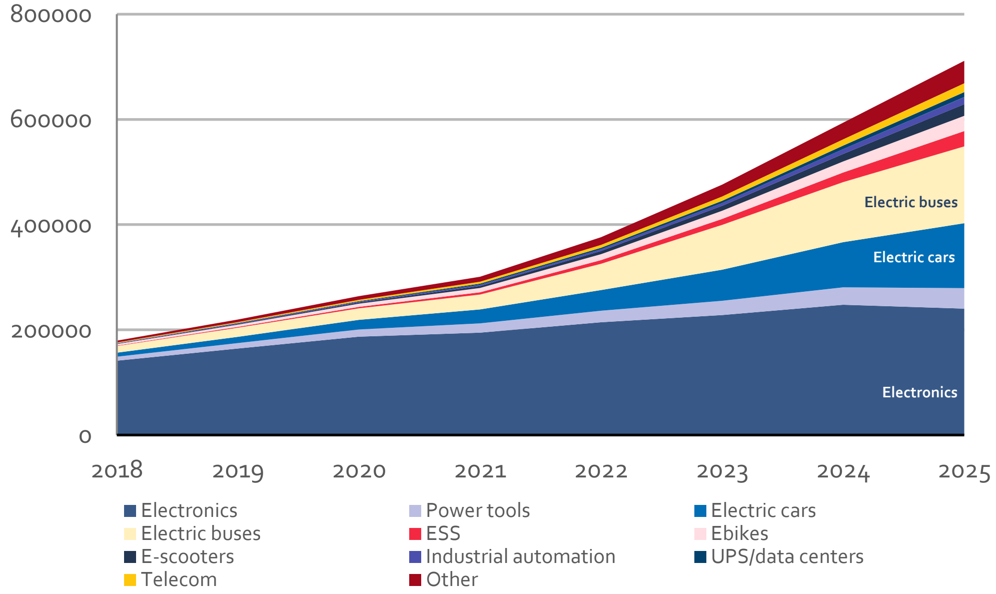
An additional factor to consider when relating the flow of batteries to the availability of secondary resources is of course the size and weight of the battery. In the EAFO data only BEV and PHEV vehicles were included. However, other sources like the Urban Mine Platform indicate that due to the differences in weight, HEV batteries only contribute a minor part of the total tonnage (1% in 2015) being placed on market (Urban Mine Platform, 2017) indicating that the exclusion of HEV is an acceptable approximation.

Even though the batteries placed in different types of vehicles (PC versus buses and light commercial vehicles) may vary in size, the variations are within the same order of magnitude. The POM results indicate that for the flows that are currently on the market, the largest amount of resources is locked in passenger electric cars, of both PHEV and BEV types, with BEV likely becoming more and more dominating due to the fact that they often are larger than the PHEV batteries. Even though large buses often may have larger batteries they still represent lower total volumes.

It can be relevant to question how well the product categories included in the base case represent the significant mass of current and future batteries placed on market. As there are no previous specific projections for the Nordic markets, world data can be used to consider trends and determine important flows.

Circular Energy Storage (2018) presents a figure on total weight of batteries available for recycling in the world, and this graph can be used to identify the battery flows representing the highest mass flows. In this figure, Figure 6, we can see that batteries from cars and buses will increase the most calculated on weight until 2025. This indicates that the base case vehicle categories used to determine EoL flows in 2025–2030 are the most relevant ones to include.

Figure 6: The figure shows the total weight of battery cells available for recycling on a global scale, reported in tons



Note: The figure highlights that within the realm of batteries for vehicles, it is cars and buses that dominate the near-term flows. This indicates that the base-case focus on cars and buses is relevant.

Source: Circular Energy Storage, 2018, with permission by the author.

4.2 Placed on market for battery flows with smaller tonnage

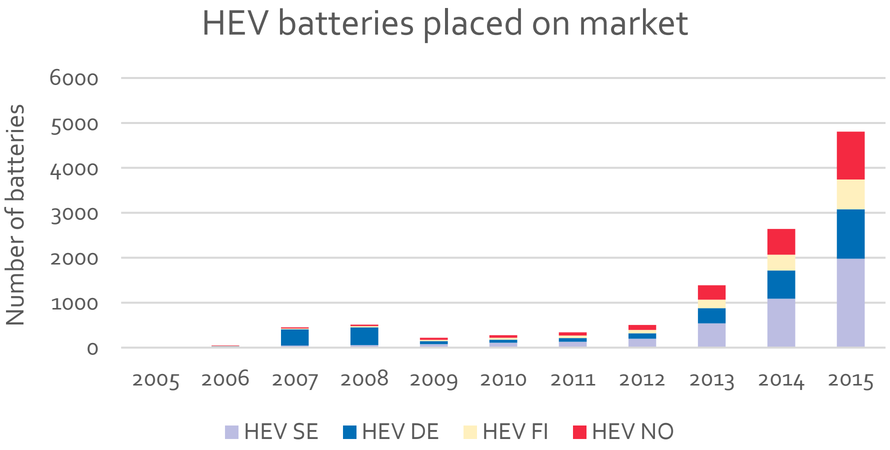
Figure 5, and the discussion in section 4.1 gives the results for the number of batteries placed on market in the product categories included in the base case. The reasons for including these specific categories is detailed in chapter 2.2 but has to do with the lack of consistent real-life data for these smaller batteries.

The assessment presented here is instead based on information from the project Urban Mine Platform (2017). The results should be viewed as an indication of size and relevance of these flows but cannot be directly compared to the base case.

Figure 7 shows the results for the available data regarding HEV placed on market, assuming as for PHEV and BEV that 1.1 batteries are needed per vehicle. Although the data does include statistics for the years 2016–2018 as the EAFO data the indication is that HEV batteries represent a relatively small part of the total number of batteries placed on market. The estimated total of 5,000 units from HEV cars in 2015 is only a small part of the PHEV and BEV flows (around 50,000 batteries).

In addition to the lower quantity, HEV batteries are also smaller than PHEV and BEV batteries, as they only serve as optimization and for storage of braking energy.

Figure 7: Based on data from Urban Mine Platform the number of batteries placed on market in HEV cars is presented

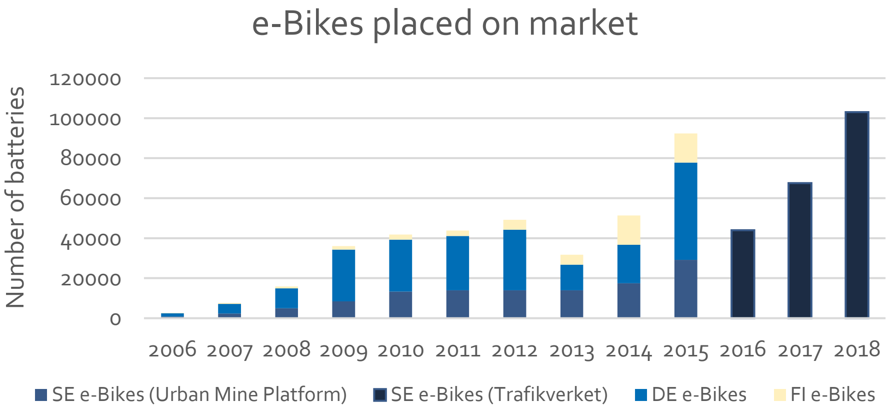


Note: The number of batteries is significantly lower than those placed in plug-in and fully electric cars indicating that the HEV cars are not a major source of batteries.

To assess the potential impact of waste batteries for small applications like bicycles, motorcycles and scooters we focus on the bicycle data in Urban Mine Platform (which does not have data for Norway or Iceland). For the year 2016–2018 this data was complemented by a Swedish report on bicycle sales (Trafikverket, 2019), to indicate growth during these years.

The general conclusions from e-bikes can be applied to other vehicles types with smaller batteries, for example the e-scooters, but due to very recent adoptions of these products there is not specific data to be assessed for them.

Figure 8: The figure shows number of batteries placed on market in electric bikes



Note: For the later years of the decade the data from Urban Mine Platform is complemented with Swedish data from Trafikverket. As for other vehicle groups there is a trend towards increasing sales, but Sweden and Denmark have stronger positions compared to cars sales where Norway currently dominates.

Although the data for e-bicycle sales is a bit uncertain, there is a clear trend towards increasing number of sales. In the Swedish data we can see that the sales accelerate in the latter half of the decade, where the new subsidies for buying e-bikes has played a role. Compared to their contribution to electric cars, Denmark has a much stronger position when it comes to e-bikes.

As an indication on data quality in Urban Mine Platform (2017), the report by Trafikverket (2019) reports approximately (they report per season) 30,000–45,000 sold e-bikes in Sweden in 2015 compared to 30,000 reported in the platform.

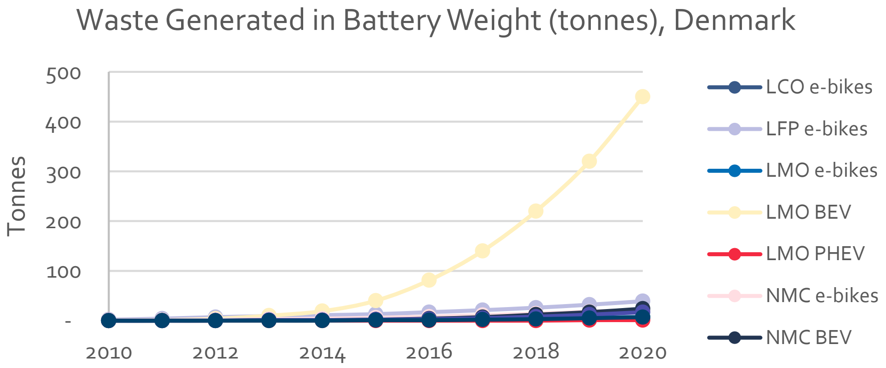
In absolute quantities e-bike batteries can represent significant flows when they reach EoL. Additionally, in contrast to the batteries of electric vehicles, it is likely that these batteries will reach EoL and become waste at an earlier stage. The lifespan of a bike battery is generally shorter, and since the batteries are smaller, they are not as likely to be candidates for second life, at least not at a larger scale or in the near future. A bike battery can last around 800–1,000 cycles (Crescent, 2018), which would be about 3–5 years for the average user.

When it comes to waste batteries being viewed as a source of raw materials it is of course beneficial that these batteries reach EoL earlier, although there is no specific data on how long the life is assumed to be. Considering this, and in light of the small risk of catching fire, it is important to ensure that the batteries are collected and sent to recycling (and not for example discarded with the rest of the bicycle).

The weight of the e-bike batteries will limit the extent to which the raw material content will a be relevant source. An e-bike battery only weighs about 1/100 of a BEV battery (2 kg compared to 230 kg), indicating that even though the flows are large, and thus important to handle, the tonnage of raw materials will still be low.

In Urban Mine Platform (2017), the weight of batteries is also reported. To exemplify the effect that the lower weight of e-bike batteries has on the tonnage Denmark can be used as an example. Figure 9 shows the weight of battery waste generated for both bikes and electric cars. Clearly, even though the quantity of e-bike batteries is large, the weight of them is small compared to the growing amount of BEV and PHEV car batteries.

Figure 9: Weight of batteries going to waste



Note: Even though e-bikes had an earlier adoption and larger flows, the tonnage of waste car batteries is quickly surpassing that of e-bikes.

Source: Data from Urban Mine Platform (2017).

For years later than 2015 there were no specific data for the Danish and Finnish markets, but in order to understand the order of magnitude of difference in total battery weight placed on market in 2018 it can be assumed that the levels are at least the same as in 2015. This would imply that a minimum of 170,000 e-bike batteries were placed on market in 2018, compared to about 130,000 pieces for buses and cars.

In terms of weight, however, these flows represent in the order of magnitude of 30,000 tons of battery from cars and 340 tons from e-bikes, assuming an average weight of 230 kg/cars and bus battery and 2 kg per e-bike battery based on data from Urban Mine Platform. This approximative calculation further highlights the low tonnage contributed by e-bikes.

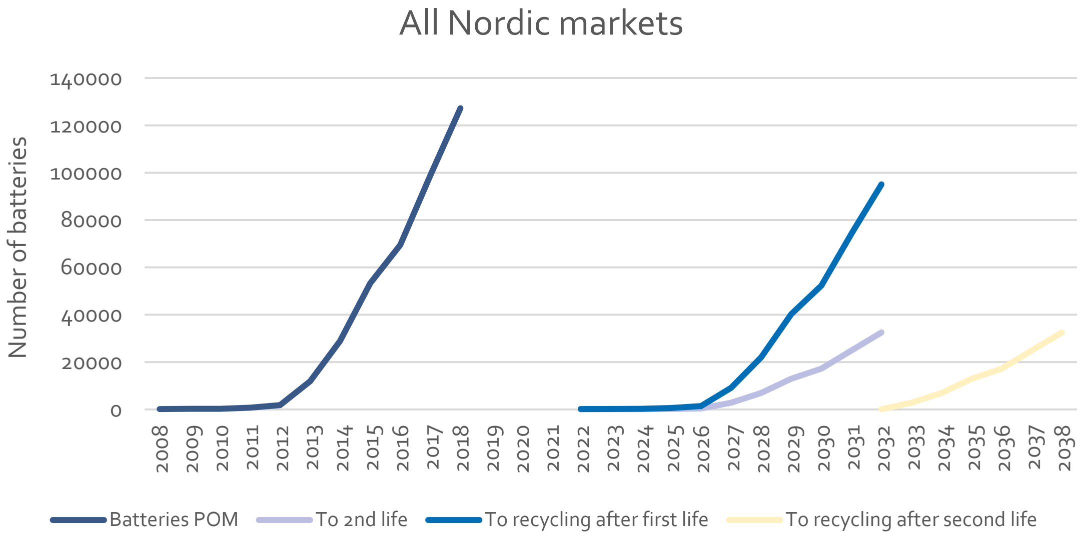
4.3 Batteries reaching end of first life – Base case

Figure 10 shows an aggregated form of the amount of batteries placed on market (POM) for all the Nordic countries. Corresponding to these flows, the figure also shows how and when the batteries will reach second or end of life, ready for recycling.

In short, there are two effects that determine when the batteries placed on market will reach recycling. The first is the life length of the batteries in their application, and the second is if the batteries are used for a second life or not.

Figure 10 only considers the batteries already placed on the market, but in reality, the curves will continue upward due to the increasing volumes placed on market after 2018.

Figure 10: The figure shows how the batteries placed on market up until 2018 will enter the second life and recycling markets



Note: The availability for recycling will depend on the amount of batteries that go to second life, and second life will in turn imply a later introduction to the recycling market. In the base case 20% of car batteries and 50% of commercial vehicle and bus batteries go to second life.

Figure 10 illustrates that it will take until about 2030 before even the relatively small volumes of 2015–2018 will reach end of life. In addition, Nordic EV Outlook projects a large growth in the electric vehicle fleet, from roughly 0.5 million in 2019 to 4 million by 2030 (IEA, 2018). The projected magnitude of electric vehicles in the future puts the current volumes into more perspective, highlighting that the majority of end-of life batteries are a long way into the future.

Regardless, Figure 10 highlights the type of delay that can be expected between placed on market and end of life. Secondly the results show the effect that second life can have on the availability for recycling. In general, the addition of a second life can ensure that the batteries' life is used fully. The reason is that the life in a certain application (like a car) may be shorter than the batteries life, due to for example demands on performance.

The batteries of today can be assumed to technically last 20 years in total over all uses, even though their energy storage capacity reduced during these years. This will make them useable in cars for closer to 14 of these years (Durand *et al.*, 2019 [draft]), while after this allowing them up to 6 years in a second use. Second life will thus delay the availability for recycling to the length of the battery life (20 years), while batteries without second life will be available for recycling after the life in the vehicle (14 years).

4.4 The sensitivity to changes in EoL handling

In this section the results from the previous section are analysed to determine their sensitivity to important parameters regarding battery life, exchanges, degree of second use and refurbishment. Since assessing the future is always projections this will increase the knowledge regarding which societal changes that will affect the availability of batteries for recycling.

In order to evaluate this several cases have been included to represent variations in the important parameters. Three cases are included:

1. High renovation (HR):
    a. Electric cars are assumed to last longer, and thus also their batteries. Life of batteries increased to 17 years. As offset, it is assumed that these batteries are less relevant for second use.
2. High second life (HSL):
    a. Tests a quick near-term increase of second life with 2018 starting levels of second life at 70% for cars and 80% for bus batteries. Slower increase after that with 1% and 0,7% respectively.
3. Low second life (LSL):
    a. Investigates a slower adoption of second life with starting levels and development. Cars start at 5% and evolve with 1% yearly, while buses start at 10% and grow 1% yearly.

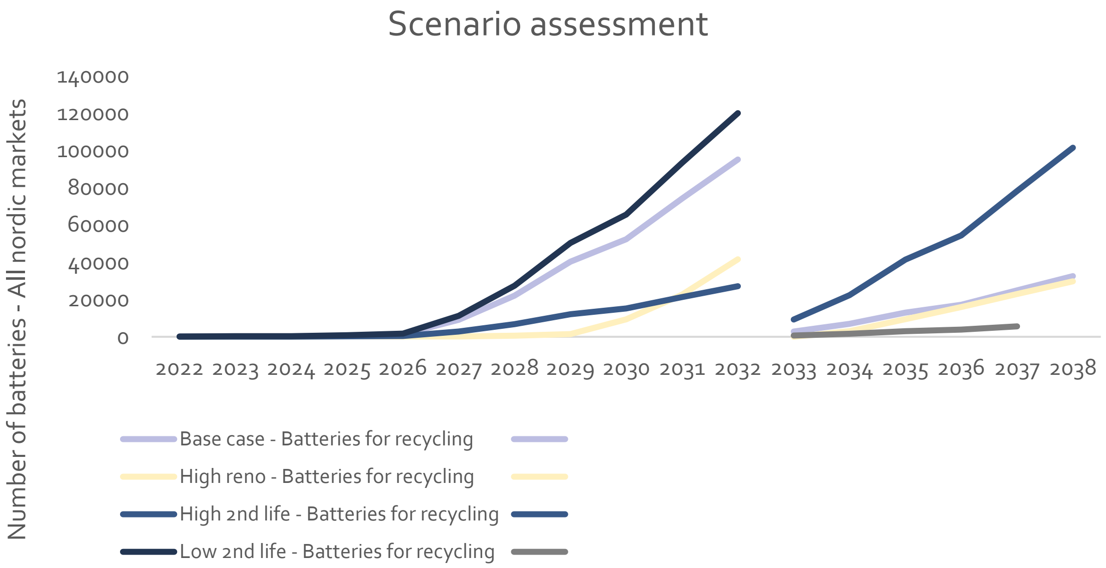
These cases are detailed in the table below.

Table 2: Scenarios for EoL flows. First the base parameters are presented and below the changes in the different scenarios are presented

	Cars BEVs	Cars PHEVs	Light buses	Buses	Light comm.	Mopeds & MC
Av. Batteries per vehicle	1.1	1.1	1	2	1	No data
Battery life per vehicle	14 *HR: 17*	14 *HR: 17*	14 *HR: 17*	6	14	No data
Vehicle life	14	14	14	12	14	No data
Number of battery exchanges	None	None	None	1.0	None	No data
% going to 2nd use in storage (2018)	20% *HSL: 70%* *LSL: 5%*	20% *HSL: 70%* *LSL: 5%*	20% *HSL: 70%* *LSL: 5%*	50% *HSL: 80%* *LSL: 10%*	50% *HSL: 80%* *LSL: 10%*	No data
Yearly increase 2nd use	2% *HR: 1%* *HSL: 1%* *LSL: 1%*	2% *HR: 1%* *HSL: 1%* *LSL: 1%*	2% *HR: 1%* *HSL: 1%* *LSL: 1%*	2% *HSL: 0,7%* *LSL: 1%*	2% *HSL: 0,7%* *LSL: 1%*	No data
Years in 2nd life	6	6	6	8	8	No data

Figure 11 presents the results from the scenario assessment for the three cases described above. A first conclusion is that the current base assumption for second life is relatively low, and that the lower second life scenario therefore does not change the results significantly. The main effect of less second life is that slightly more batteries are available for recycling in 2030 compared to when they go through second life as well.

Figure 11: The figure shows how the batteries placed on market up to 2018 will become available for recycling



Note: Prolonging the total life having the batteries in a second life application clearly shifts the time for recycling to a later point. Renovation may have an intermediate effect, where a longer first life delays the availability, while also decreasing the amount of second life.

The high second life scenario represent quite an extreme, with fast increase of second life. In such a case we see the most significant shift of batteries available for recycling, where few batteries are recycled after the vehicle life time (14 years). Instead the majority of the batteries will be waste after 20 years, then they have also been used in energy storage. This implies that even todays moderate volumes would not be available before 2038.

High renovation may instead cause an "in-between" situation, where the batteries vehicle life is prolonged, so that they reach EoL later, but where the increased use in vehicles makes second life less probable. In such a case we see most of the batteries being available for recycling at the end of the vehicle life, around 17 years after they were placed on the market. The reason that second life could become less relevant is that the use in vehicles will likely exhaust more of the technical life length.

In addition to these parameters that are available for consideration today, there are other aspects of development to consider. One very important factor, to which the assessment of end of life availability is very sensitive, is of course the max life of the battery (including all uses). In this study the focus is on 2025–2030, at which point the chemistry of the batteries reaching end of life is unlikely to change. In the future, however, it is likely that the technical life length of the batteries will increase, making it possible to have both a long first life and a long second life without one limiting the other.

Another parameter outside of the technical scope is if the market will evolve in a way that favours second life. It could be either that it is not economically preferable so that the batteries move directly to recycling, or that vehicle producers choose to keep this valuable resource within other areas of their operation. This could for example be as energy storage in production facilities or for use in less demanding products for market. If it is deemed desirable to achieve early recycling, then this option needs to compete with other alternatives that the battery owners have for their end of first life batteries.

5. Current and future techniques for reuse, second life and recycling

This chapter deals with the third research question: What are the current and future techniques for re-use, second life and recycling and how much of the batteries themselves are recycled and what is the material efficiency? What are the reasons behind the numbers? What are the advantages and disadvantages with the different techniques?

After ending its first use in the vehicle there is usually energy storage capacity left in the battery. Where the batteries will end-up for recycling, as well as future amounts and weights depends on the market for recycling and second use in Europe and in other parts of the World. As an example, the demand for energy storage will increase a lot (Circular Energy Storage, 2018) creating a potential second use market. Thus, indications are that the driving forces for second life are large, although second life batteries will have to compete with the trend of cheaper new batteries (Energy Storage News, 2019). Circular Energy Storage (2018) argues that there is room for both.

5.1 Reuse

Reuse means that the product is used for the same application as first use, in this case in a vehicle. The car industry has high interest to sell batteries for reuse to customers with used cars in need for battery replacement. However, they must be refurbished in most cases. Refurbishing means to clean the components, to measure remaining capacity and state of health of the battery on pack, module or cell level, and to change or rearrange cell module(s). Reprogramming of the battery management system is usually also needed (Berg, 2019). Andresen reports that most of the car batteries that Batteriretur collect in Norway are sent abroad for reuse (Andresen, 2019).

5.2 Second life

After use in the vehicle there is often capacity left in the battery for other purposes with lower demands than vehicles – the battery may get a so-called second life. There are many projects going on to see if it is economic and environmentally sound to let the batteries get a second life.

In the report by Circular Energy Storage (2018) it is predicted that there will be great need for energy storage and therefore battery second life is highly interesting. The author distinguishes the following types of second life:

- Optimization of the renewable energy production. One example is to collect photovoltaic energy when possible and use when needed;
- Utility-scale storage, where you have an energy back-up, temporary storage or frequency response service for electricity which is increasingly needed when more renewable electricity is to be handled in the grid;
- Electric vehicle charging;
- Lead-acid battery replacements since they have a longer lifespan, larger depth of discharge and are significantly lighter.

In Martinez-Laserna *et al.* (2018) the following second life demonstration projects with car manufacturers as partners are reported.

Table 3: Second life demonstration projects with car manufactures as partners

Project name/partners	Year of publication	Type of second-life application
Bosch, BMW, Vattenfall	2015	Smart-grid
Daimler AG, Getec Energie	2016	Wholesale energy market
BMW, UC Sand Diego Second Life Battery	2016	Micro-grid with PV system
General Motors	?	Micro-grid with PV and wind energy system
UPC, SEAT	2015	Testing energy management strategies for system optimization
Mitsubishi, PSA, EDF Forsee Power	2015	Optimization of electricity storage, charging and generation technology
Nissan Eaton, The Mobility House	?	Draw energy from the grid, providing businesses with more control, better value and a more sustainable choice

Source: Martinez-Laserna *et al.*, 2018.

They also report seven research projects and twelve publications analyzing profitability with stationary applications for second-life batteries and in some articles, they conclude it is profitable. They also specifically write about an article where they found payback time of 6.9 years or more why they make the overall conclusion that profitability is uncertain. Environmentally it is generally positive if renewable energy is stored and used at a time where the grid mix is more fossil-based. Additionally, it is beneficial to have less need for production of new batteries (Martinez-Laserna *et al.*, 2018).

Volvo Group is for example part of the housing society Viva project regarding second life. They have placed 14 used lithium-ion batteries from in a newly built real estate house. The purpose is electric time shift, which implies collecting electricity in the batteries when the sun is shining on their solar cells or when renewable electricity is cheap (Elbilsnytt, 2018; Johanneberg Science park, 2019).

It is important for the future that the design of batteries facilitates second life. There is also a great need for legislation, for example regarding the warranty questions, and design standardization to make it possible to re-build parts of the battery for second life (Berg, 2019).

5.3 Recycling

In the end all batteries must be recycled. This is because of constraints in primary metal availability combined with the need for raw materials for new batteries.

The lithium-ion batteries for new cars are most commonly of the Nickel-Manganese-Cobalt oxide (NMC) type although Nickel-Cobalt-Aluminum (NCA) is used in the cars from Tesla. Lithium-iron-phosphate (LFP) can be an option where high power is needed, for example in buses. Lithium-manganese oxide (LMO) was earlier popular for cars, but use has fallen in favor of other chemistries (Romare and Dahllöf, 2017). See Table 4 for the approximative weight percent of materials in different types of batteries.

Table 4: Approximative weight percent of materials in different types of batteries in a typical 20 kWh pack including metals for cell container, pack housing and major metals for Battery Management System (BMS)

Metal	NMC (%)	NCA (%)	LMO (%)	LFP (%)
Litium	1.9	1.6	1.3	1.5
Aluminum	12.8	13.9	19.3	12.8
Copper	12.1	13.0	17.8	5.4
Nickel	6.3	10.6	0.1	0.1
Cobalt	3.1	1.9	0	0
Manganese	5.7	0	9.5	0
Iron	8.0	8.0	8.0	19.4
Phosphorous	3.0	0	0	9.4
Total	53	49.1	56.1	57.4

Source: Weil *et al.*, 2018.

The contents are depending on design and other authors have reported slightly other numbers, for example Zheng *et al.* (2018) and Melin (2019).

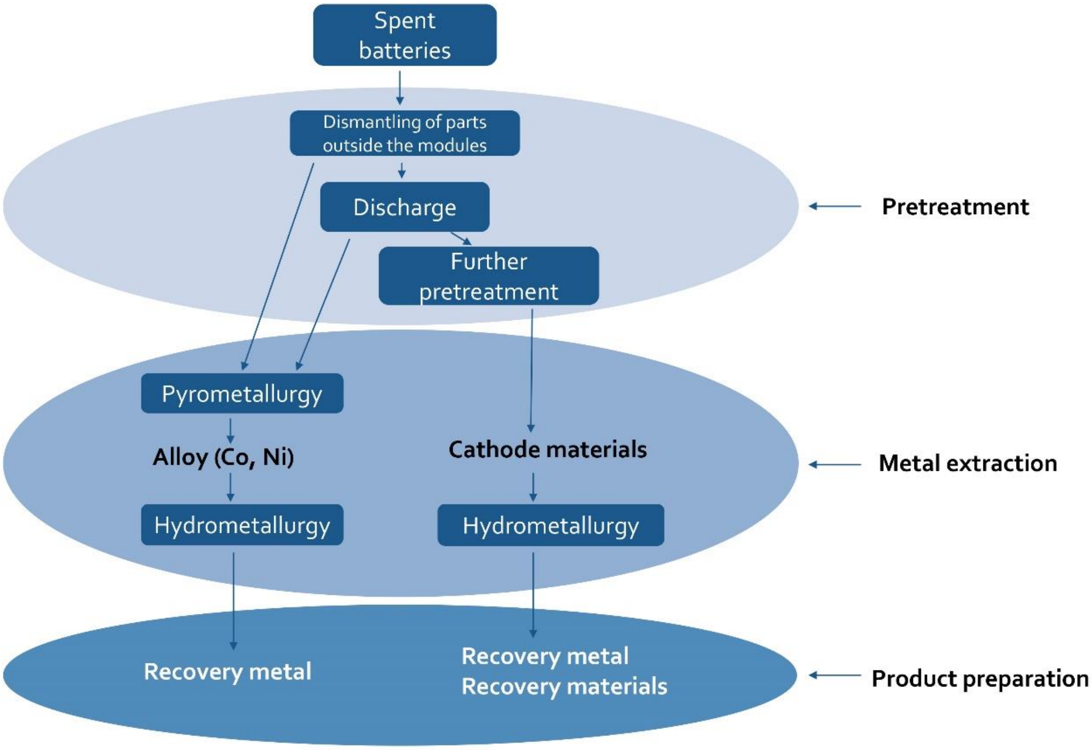
According to Heibig *et al.* (2018) lithium and cobalt have highest supply risk out of the battery materials, while aluminum has lowest risk. The other materials manganese, iron, nickel, copper and graphite have medium risk. New lithium mines have, however, mitigated the lithium supply risk (Millan Lombrana, 2019). In the long term, for many generations ahead, it is important to recycle all materials. Already today aluminum is important to recycle due to high energy use in primary production. Generally recycled materials cause lower environmental impact than primary, and metals are in principle 100% recyclable (Thomas *et al.*, 2018).

Recycling is currently mainly done in large scale in China, largely because they to date have had a more significant amount of batteries to recycle. Since they produce a lot of batteries and the battery precursors, they are used to using recycled metals from batteries as input for production. Commonly, they use mechanical pretreatment with subsequent hydrometallurgy (Melin, 2018), see chapter 5.3.1 for description.

5.3.1 Recycling technique

There are recycling techniques that are used in industrial scale, but there is still a lot of ongoing research, in order to make recycling more efficient. A general picture of the currently most common methodologies for recycling are found in Figure 12.

Figure 12: A general picture showing the most common recycling techniques for lithium-ion batteries



Source: Modified from Lv *et al.* (2018).

Pyrometallurgy means heating of batteries to smelt the metals while hydrometallurgy uses acids or bases for dissolving them instead, see Table 7 for further descriptions. The discharging step is not necessary for pyrometallurgy which is the process used by for example Umicore (Zheng *et al.*, 2018; Lv *et al.*, 2018).

Further pretreatment

After discharging there are different options for further pretreatment for the hydrometallurgical pathway. It was somewhat difficult to understand from the literature which steps that are used in industrial scale and which that are only on lab scale, but the most common industrial scale methods in Europe are mentioned in chapter 5.3.2.

Table 5: Pretreatment processes

Pretreatment process	Description	Advantages	Disadvantages
Further dismantling	Used to separate cathode, anode and other components. The shell is dismantled and after that what is possible is dismantled with help of liquid nitrogen to inactivate harmful substances and partly a saw. The cathode, anode and separator are separated and dried. After this step, metal extraction processes for the electrodes follow (Zheng *et al.*, 2018). This is only done on lab scale (Petranikova, 2019).		
Separation – different options for cathode separation			
Dissolution with solvent	An organic solvent weakens the adhesion of the binder so that the cathode materials are removed from the aluminum foil.	It is efficient and recovers also the aluminum foil.	Expensive solvent and severe environmental issues.
Dissolution with NaOH	As dissolution with solvent but with NaOH.	Simple operation and high efficiency.	Difficult to recover the aluminum foil, alkaline wastewater.
Ultrasonic-assisted separation	Ultrasonic cleaning in combination with mechanical agitation. This is used for stripping cathode material from aluminum foil. A cleaning solution needed.	Simple operation and very low exhaust emission.	Expensive equipment and noise.
Thermal treatment (smelting or pyrolysis)	High temperature causes the decomposition of binder in order to reduce the bonding force between particles of cathode material (Zheng *et al.*, 2018). This step can also discharge, and it removes the electrolyte (decomposition) (Petranikova, 2019).	Simple operation and high throughput.	High energy consumption, expensive equipment and poisonous gas emissions.
Mechanical treatment	An effective method of crushing, sieving, magnetic separation etc. Dismantling is not always necessary. Different fractions are obtained which can be further refined (Zheng *et al.*, 2018). Recovers so called black mass with Co, Mn, Ni, Li and copper and aluminum foils (magnetic parts can be recovered as well with the magnetic separation) (Petranikova, 2019).	Simple and convenient operation.	The separation is not complete for all materials. Poisonous gas emissions occur.

Source: Mainly based on Zheng *et al.* (2018).

Metal extraction

After the pretreatment(s) the metals in the electrodes are recovered with metal extraction. Materials outside the electrodes can be recovered in other processes, as for example the electronics that have been dismantled. They are usually sent for electronics recycling. Circular Energy Storage (2018) writes about the three methodologies for the metal extraction, pyrometallurgical, hydrometallurgical and mechanical treatment. Zheng *et al.* (2018) also describe bio metallurgy, and mechanochemical plus leaching. Pyrometallurgy is common in large scale often combined with hydrometallurgy, but it is energy consuming and usually less efficient than pure hydrometallurgy. Therefore, much research is going on to find the optimal process that is economic on a large scale. See Table 6 for short descriptions of different types of metal extraction. Pyrometallurgical and hydrometallurgical are most common large-scale options.

Table 6: Different types of metal extraction based on information in Circular Energy Storage (2018) and Zheng *et al*. (2018)

Metal extraction technique	How it works (in short), pros and cons	Metals recovered, recovery rate and comments
Pyrometallurgic	Heating batteries in a furnace to smelt metals at high temperature. Electrolytes and plastics are burned. Metal alloys remain as well as a slag that contains e.g. lithium and aluminum oxide: +Minimal disassembly needed. +Flexible, you can recycle different chemistry at the same time. +Relatively cheap. -Loss of quality of material. -Hard to further separate the alloys and to separate from slag. -Energy intensive, causes relatively high CO_2 emissions (Circular Energy Storage, 2018). -Low metal recovery rate. -High metal loss if not combined with hydrometallurgy. -Release of harmful gases that have to be treated (Zheng *et al.*, 2018). -Has to be a continuous process (Petranikova, 2019).	Always Co, Ni and possibility for Cu, Fe alloy (Zheng *et al.*, 2018). Usually combined with a second step e.g. leaching to get Co oxides and NiOH. Also, then possible to recover lithium carbonate (Zheng *et al.*, 2018). Lithium can be recovered as pure metal, lithium oxide or carbonate with carbothermal reduction which is a new type of pyrometallurgic method (Lv *et al.*, 2018).
Metal extraction technique	How it works (in short), pros and cons.	Metals recovered, recovery rate and comments.
Hydrometallurgical	Use of acids or bases to dissolve the metals: +Very high recovery rate and any metal can be recycled. +Not energy intensive (Circular Energy Storage, 2018). +Batches with different chemistries can be run (Petranikova, 2019). +Many chemical reagents can be reused, and some by-products can be integrated into the recycling process (Petranikova, 2019). -High need for sorting of chemistry and disassembly. -Toxic gases released. -Can be problems with purity of the recovered metals (Circular Energy Storage, 2018). -Large amounts of chemical reagents used. -Expensive (Zheng *et al.*, 2018).	Very high, depending of technique. Any metal can be recycled. (not graphite). For Al, Co, Li the ultimate recovery rates can reach >99%. (Gao *et al.*, 2018).
Mechanical/physical treatment	Crushing and shredding and then either low yield method targeting only copper and aluminum or advanced methods where the aim is to keep cathode powder intact (Circular Energy Storage, 2018), which can be tricky (Petranikova, 2019): +No chemicals needed. +Can be automized. -Risk for violent reactions. O2 free environments needed or freezing of batteries before shredding (Circular Energy Storage, 2018).	It is currently not used alone on large scale, further processing such as hydrometallurgy is used (Circular Energy Storage, 2018).
Biometallurgic	Sulfur-oxidizing and iron-oxidizing bacteria produce inorganic and organic acids which promotes leaching of the metals: +Low energy consumption. +Mild conditions. +High metal recovery rate. -Long reaction period. -Difficult to cultivate the bacteria (Zheng *et al.*, 2018). -Leaching time is usually very long (Petranikova, 2019).	High recovery rate (Zheng *et al.*, 2018).
Mechanochemical	Grinding together with for example polyvinyl chloride to produce lithium and cobalt chlorides that are extracted with for example water: +Simple. +Lower energy use, less chemical reagents, lower environmental pollution. -Higher energy use than hydrometallurgical. -Large equipment cost. -Long processing time (Zheng *et al.*, 2018).	For example, Li, Co (Zheng *et al.*, 2018).

Li *et al.* (2018) and Zhang *et al.* (2018) give descriptions with focus on hydrometallurgy. All materials and fluids can be recycled with dismantling followed by separation, hydrometallurgy and metal recovery.

Lv *et al.* (2018) describe different methods that different recycling companies use, which is usually pyrometallurgical, hydrometallurgical or a combination of them both. They report that there is no industrial method that can recycle mixed cathodes in a good way. They also estimate and compare energy need for different technology with energy need for extraction from ore for the cathode materials which can be high, and which is also an important parameter apart from closing the loop of the materials. According to them, the direct physical process is the least energy consuming while the pyrometallurgical is the highest closely followed by the hydrometallurgical. New processes have less steps and are more economic such as selective extraction, regeneration and repairing.

Recycling rates for the combination of pyrometallurgical and hydrometallurgical processes are somewhat lower than for pure hydrometallurgical. As indication see for data in Table 7. It is however not clear if data are on laboratory or industrial scale.

Table 7: Recycling efficiency according to Lebedeva *et al.* (2017)

Material	Combination of pyro- and hydrometallurgical process – NMC and LFP batteries	Purely hydrometallurgical process – NMC only	Purely hydrometallurgical process – LFP only
Lithium	57%	97%	81%
Nickel	95%	97%	NA
Manganese	0%	Approximately 100%	NA
Cobalt	94%	Approximately 100%	NA
Iron	0%	NA	0%
Phosphate	0%	NA	0%
Natural graphite	0%	0%	0%

Product preparation process

After metal leaching or dissolution, the last step is product preparation with recovery of metals from leachate or preparation of cathode material. For recovery of metals, the positive metal and the negative ions in the leachate are crystallized or precipitated in another way to form the desired substances. Different steps are needed since the transition metals, such as cobalt, nickel and manganese, are similar and difficult to separate.

For preparation of cathode materials separation of the metals could be avoided if they are used together as new cathode materials (Zheng *et al.*, 2018). One question is what happens if the ratio between the metals in the cathode composition is changed for new batteries? If the metal mix is directly recovered as new cathode material it would be possible to modify the composition if needed when battery chemistry in new design is changed. In practice, preparation of cathode materials from recovered metal mixes is difficult since it is costly to separate the chemistries before recycling, which would be necessary. Perhaps sorting will be less costly if it is automated (Petranikova, 2019).

Graphite from the anode is not recycled to battery quality in any of the processes reported above. Zhang *et al.* (2018) propose as one option that it could be used to synthesize graphene.

In Li *et al.* (2018) it is described how it is possible to resynthesize to cathode materials after the leaching processes. They also report up to 100% recovery rate of lithium and cobalt after leaching in lab scale depending on reagents.

5.3.2 Recycling in practice in Europe

Zheng *et al.* (2018) write that the pyrometallurgical process is the dominant one for industrial scale in the World, but according to Circular Energy Storage (2018) and Li *et al.* (2018) at least two large recyclers, GEM and Brunp, use hydrometallurgy in China. China has a history of recycling lithium-ion batteries from electronics, also from Europe (Circular Energy Storage, 2018).

In Table 8 companies doing battery recycling in Europe are listed. They were also contacted by mail, but very little information was received in that way. Thomas *et al.* (2018) had a similar experience. In Europe, a large recycler is Umicore with their pyrometallurgical method and subsequent hydrometallurgy (Umicore, 2019). Volkswagen plans to integrate recycling of the used batteries from cars with their brand, but first the batteries will be tested for possible second life. They invest in recycling because of less procurement costs and environmental reasons – to reuse the materials (Volkswagen, 2019b).

What also makes recycling material flows difficult to follow is that some of the recyclers only do the first step and sell the so-called black mass (the grinded electrode materials mix) to other companies for further extraction and product preparation.

Table 8: Vehicle lithium-ion battery recycling companies in Europe

Company	Country	Pretreatment and/or metal extraction technologies	Capacity/current volumes (tonnes/year)	Main products
Accurec	Germany	Mechanical, electric furnace	6,000/? (Lv *et al.*, 2018)	Co alloy, Li_2CO_3 (Lv *et al.*, 2018)
AkkuSer + Boliden	Finland	Mechanical. The coarse fraction is delivered to Boliden for copper refining	?/? AkkuSer started/will start vehicle bat rec 2019 (Karjalainen, 2019)	Cu, + black mass (Karjalainen, 2019)
BatRec (Sarpi/ Veolia)	Switzerland	Mechanical (Thomas *et al.*, 2018) Pyrometallurgical (Li *et al.*, 2018)	?/? Large scale (Thomas *et al.*, 2018)	Different fractions that are sold
Duesenfeld	Germany	Combination of mechanical and hydrometallurgical (Duesenfeld, 2019). Based on processes developed in the project LithoRec (Circular Energy Storage, 2018)	3,000 /? (Circular Energy Storage, 2018)	Co, Ni, Mn as active materials, Electrolyte
Neometals	Austria	Mechanical plus hydrometallurgical (Neometals, 2019)	Lab scale	Possible to recover Co, Ni, Cu, Li, Gr
Recupyl	France	Mechanical+hydrometallurgy, (Recupyl, 2018, Thomas *et al.*, 2018)	?/? Large scale (Thomas *et al.*, 2018)	Possible to recover Mn, Co, Li, Ni
Redux	Germany, Austria	Mechanical (Redux, 2019). Hydrometallurgical (Circular Energy Storage, 2018)	10,000/? (Circular Energy Storage, 2018)	Plastics, Fe, Cu, Al + ?
SNAM	France	Pyrometallurgic (Li *et al.*, 2018)	?/?	?/? (but probably cobalt, nickel and copper (Petranikova, 2019)
Umicore	Belgium	Pyrometallurgy with subsequent hydrometallurgy (Umicore, 2019)	7,000/?	Co, Ni, Cu
uRecycle	Sweden	Mechanical: make black mass which they sell (uRecycle, 2019)	?/?	Black mass

Note: Four of them were considered to have large-scale recycling: Accurec, Umicore, Recupyl and BatRec according to Thomas *et al.* (2018). These are also mentioned as industrial recycling processes in Li *et al.* (2018).

5.3.3 Recycling research in Europe and in the US

Melin (2019) reports that many research projects are ongoing or completed in Europe. The reasons are to make recycling more economic, efficient and less environmentally impacting. Only one of the EU projects developed a complete recycling process for vehicle batteries, Lithorec. They developed a combination of thermal, mechanical and hydrometallurgical processes where a very high recycling rate is achieved for different chemistries (their LCA study is found in Buchert *et al.* [2011]).

Ongoing projects are for example AutoBatRec 2020 where the entire value chain is investigated. CROCODILE is a demonstration project for a viable value chain. In Great Britain, one project, ReLib, is developing a system for batteries, autonomous testing and robot-based sorting, new recycling methods and development of business models (Melin, 2019).

In the US the ReCell center does research on direct recycling back to cathode materials including lithium recycling. It is based on physical processes and the aim is to keep the highly structured material intact in order to save environmental impact and money (ReCell, 2019). The potential lower energy use is also shown in Lv *et al.* (2018).

In Sweden two projects are ongoing in Luleå. Mechanical activation is tested for facilitating separation of metals. The project ReLion, led by Swerim, investigates the prerequisites for a recycling system for large-scale recycling of batteries mainly with existing Swedish technology that can recycle copper, aluminum, lithium, manganese and nickel (Melin, 2019).

Industrial Materials recycling group at Chalmers University of Technology have had several projects related to the recycling of Li-ion batteries, both European and national. They have been using two main approaches. One is the combination of pyrolysis and hydrometallurgy and second one is the hydrometallurgy only. Pyrolysis (500–700 °C) using inert atmosphere (N_2) is performed to remove the organic compounds and binders specially to improve the separation of valuable components. Moreover, carbon from the battery waste is used to transform the metal compounds to more soluble state – including lithium. Then hydrometallurgy is applied to dissolve those metals in the acidic solutions. Also, solvent extraction is used for metal separation by using specific organic molecules, which are very selective for particular metals. One advantage of both their approaches is that also lithium is recovered. Another is the high purity of the final products that can be achieved. Moreover, the processes are more efficient than the conventional ones since organic compounds can be re-used many times (Petranikova, 2019).

In order to create more efficient recycling automation is one key as mentioned above. Another is to improve the design of the batteries. One important step to facilitate sorting before recycling would be marking the cell chemistry on the cells.

6. Discussion and conclusions

For the discussion and conclusions, we return to the defined research questions.

6.1 How many of the used lithium-ion batteries for vehicles are currently sent for recycling in the Nordic countries?

One of the most interesting conclusions is one that goes against the questions itself, namely that there is a significant lack of data regarding what happens to current waste batteries. This is mainly due to the Battery Directive's (EC, 2006) merger of different types of batteries for collection reporting. However, for heavy duty vehicles, business contracts where the producer promises to take care of the used batteries makes it easier to track the fate if the producer is willing to share the information.

For the amount of *car batteries* that have reached end of life we gained collection information from the main battery waste collector in Norway, Batteriretur. They get about 90% of all scrapped lithium-ion batteries from electric cars in Norway and that they had taken care of about 1,000 pieces last year (mainly from accidents or other warranty issues). Using that number in combination with the known share of electric cars in Norway compared to all Nordic countries gave the total *approximative number of 1,700* lithium-ion batteries collected last year. Some of these batteries, about 20% at Batteriretur are sent for second use projects, but not before careful analysis.

For the amount of *heavy-duty vehicle batteries*, we acknowledge that the largest part comes from buses and that the information from Volvo Group could guide to an approximative value. *About 100–150 heavy-duty (bus) batteries* had reached end of (first) life in 2018.

For *electric bikes* the amount was calculated from the Urban Mine Platform (2017) assuming that they last about 4 years. *Between 30,000 and 43,200 of batteries* from e-bikes had reached their end of life last year. As seen in the research question 2, the total weight is low compared to the total weight of the car and bus batteries, why collection for metal recovery is less important, but nevertheless, there is a fire safety risk with all batteries, why it is important to send them for recycling. It can however be suspected that many are still stored in people's homes or elsewhere, and we have received information from Swedish and Norwegian collectors that the current collection rate is low.

Regarding e-scooters they are so new on the marked, that there is no relevant collection data available for them. Batteries from e-mopeds and motorcycles could not be assessed specifically due to lack of data.

6.2 How much weight and amounts of lithium-ion batteries for vehicles are put on the market in the Nordic countries and how many have reached second or end of life in year 2025–2030?

In terms of quantity e-bikes thus represent an interesting flow, mainly because they were adopted early, have short life lengths and will thus be reaching end of life in the years 2025–2030. They are, however, so small in comparison to car or bus batteries that the total flow of resources to end of life already is dominated by these larger batteries, as was exemplified in Figure 9.

Focusing then on the flow of batteries from cars and buses (trucks omitted as they so far have very low adoption rates) an important conclusion is that the number of batteries placed on market was negligible before 2015. Since the batteries are projected to last 14 years in cars, and 6 years in buses this implies that very few batteries will be reaching end of life before 2025. In addition, cars represent the vast majority of the flows of large batteries, implying that even in 2025 the flows will be low, and that the largest part of batteries placed on market today will not be available for recycling even by 2030.

Looking further ahead, all projections indicate that the amount of batteries placed on market will grow significantly. Since the predicted life length now has risen to 14 years, this means that the amount of batteries ending up in end of life in 2025–2030 is small compared to the volumes that can be expected in the future.

In addition to the delay between placed on market and availability for recycling caused by the first use, a second life can further extend the time between production and scrapping. Current assessments suggest that second life will extend the batteries useful years to 20, based on the technical lifetime of current batteries. This will of course imply that batteries will be available for recycling even later than 2030. Depending on the balance between first use and second use the exact time for scrapping will vary. The duration that the battery is used in the vehicle might also cause differences in the potential to use the batteries for second life, for example if less energy is left in the battery or if the degradation is larger. This can mean that there is an uncertainty if longer use in vehicles causes either earlier or later availability for recycling depending on how the second life market adapts and evolves.

6.3 What are the current and future techniques for re-use, second life and recycling, and what are advantages and disadvantages with the different techniques? What is the material recovery efficiency?

Batteries for cars are currently reused in cars, if possible, and for that refurbishing is usually needed, that means cleaning and exchanging of parts and careful measuring the state-of-health and remaining capacity. There will also be large demand for energy storage in general in the society, why there is room for second life batteries. This will reduce the need for new ones.

It is possible to recycle all materials with very high efficiency (>97%) with a hydrometallurgical process, but costly since many steps are needed. The pyrometallurgic process with subsequent leaching process(es), on the other hand, is robust and not sensitive to different chemistries and pretreatment is not needed. There are about four companies offering recycling on large scale in Europe. They use either pyrometallurgy with subsequent hydrometallurgy or hydrometallurgy only as metal extraction process. Many recyclers have a mechanical step in their pretreatment process before the hydrometallurgical metal extraction step.

Some issues regarding pyrometallurgy with subsequent hydrometallurgy are higher energy use and less recycling efficiency compared to metal extraction with only hydrometallurgy. Direct physical processes would be the least energy consuming types.

For facilitating the succeeding product preparation, it would reduce environmental impact to directly prepare cathode materials compared to metals recovery, since separation of the cathode metals would not be needed. That would however require very good sorting of battery waste which is not economical yet.

Because the processes are not yet sufficiently efficient there are several ongoing research projects. It looks promising to have pre-treatment process(es) before hydrometallurgy and product preparation. An even more efficient, but probably a more difficult way, would be direct recycling back to the highly structured materials used in the batteries.

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Svensk sammanfattning

Denna rapport redovisar resultaten från en studie av vad som händer med litiumjonbatterierna när de är uttjänta i el-fordon i de nordiska länderna. Avsikten var att bidra med kunskap till de nordiska naturvårdsverken för att de ska kunna ge råd till översynen av Batteridirektivet (EG, 2006). Rapporten är skriven av forskare på IVL Svenska Miljöinstitutet och var beställd av Nordiska avfallsgruppen (NAG) inom Nordiska Ministerrådet.

Det saknas för närvarande information om hur många batterier som skickas för återvinning, främst på grund av att många andra typer av batterier ingår i samma kategori som litiumjonbatterier för fordon i Batteridirektivet som anger hur man ska rapportera insamling.

Även om det är svårt att bestämma hur många batterier som samlas in och skickas till återvinning, är data om mängden batterier som når sin medellivslängd möjligt att beräkna. Det betyder att det är möjligt att bestämma hur många batterier som finns *tillgängliga* för återvinning, även om vi inte kan säga exakt hur många som har återvunnits eller kommer att återvinnas inom en snar framtid. Fram till idag har mycket få batterier från bilar och bussar samlats in och många av dem kommer från garanti- och olycksfall. För elcyklar beräknas cirka 30 000–43 000 batterier per år för närvarande nå slutet av livslängden.

När det gäller vikten på batterierna som nått slutet av sin livslängd, dominerar bil- och bussbatterier flödet både nu och ännu mer i framtiden, vilket gör dem till de viktigaste flödena att beakta för materialåtervinning. Baserat på batteriets livslängd i nuvarande elbilar är det nuvarande flödet av nya batterier (2015–2018) de som kommer att finnas tillgängliga för återvinning 2025–2030. Det kommer fortfarande att vara ganska få med tanke på den beräknade ökningen av antalet bilbatterier på marknaden som kommer att växa från cirka 0,5 miljoner enheter 2018 till ungefär 4 miljoner enheter år 2030.

Batterier för elcyklar bidrar med en betydande mängd men med låg vikt. När det gäller den kvantitet som släpptes ut på marknaden under 2018 var de i samma storleksordning som batterier för stora fordon, med uppskattningsvis 170 000 stycken för elcyklar och 140 000 för bilar och bussar. Viktsmässigt utgjorde emellertid batterier för elcyklar endast cirka 320 ton, medan större fordonsbatterier bidrog med i storleksordningen 30 000 ton. Detta gör att elcykelbatterier är viktiga att rikta in sig på från ett kvantitetsperspektiv, men de bidrar mindre till tillgången till sekundära resurser från återvinning. Elscootrar är en produktgrupp som liknar elcyklar där vi kan förvänta oss många batterier som är redo för återvinning.

Som nämnts representerar de ovan beskrivna flödena bara de batterier som finns tillgängliga för återvinning, men de kommer endast att återvinnas om de samlas in och skickas för återvinning. För närvarande samlas batterier från tunga fordon till stor del på ett kontrollerat sätt av producenterna tack vare producentansvaret i Batteridirektivet samt tack vare affärsavtal. För bilar är risken för okontrollerad användning efter första användning i fordonet något högre på grund av att fler fordon och aktörer ser värde i begagnade batterier. För mindre batterier som i elcyklar ligger risken att privatpersoner kan behålla dem som reserv hemma, eftersom de kan vara användbara ibland eller, mindre troligt, att de kan kasta hela cykeln med sitt batteri på återvinningsstationen så att batteriet hamnar felaktigt i metallåtervinning. Det är viktigt att elcykelbatterier samlas in eftersom de utgör en viss brandrisk.

Om det finns energi-lagringskapacitet kvar i batteriet kommer det förmodligen inte att skickas till återvinning, eftersom det för närvarande innebär en kostnad, medan ytterligare användning kan innebära ytterligare intäkter. Därför sker renovering för återanvändning i fordon redan idag. Ett andra liv för batterierna i andra applikationer kommer troligen också att bli alltmer populärt, eftersom behovet av energilagring i samhället kommer att öka drastiskt, men fram till nu har vi bara sett detta i projekt, inte som reguljär verksamhet.

Trots att ett andra liv för batterierna vanligtvis är gynnsamt för miljön tack vare att man undviker att producera nya batterier finns det tekniska problem att övervinna, till exempel att mäta hälsotillståndet för varje cell och byta ut och arrangera om cellmoduler. En potentiell nackdel från resursperspektivet hos materialen är också den försenade återvinningen av råvarorna.

När det gäller återvinning och återvinningsteknologi är Kina en tydlig föregångare både när det gäller teknik och volym, med potential att återvinna de flesta metaller i batteriet (beroende på marknaden för varje operatör). Detta är tack vare stora mängder begagnade batterier och betydande batteriproduktion. Återvinning sker dock också i Europa och åtminstone återvinns kobolt, nickel och koppar med relativt hög effektivitet. I Europa återvinns litium ännu inte i stor skala på grund av återvinningskostnader, relativt lågt råvarupris och låga volymer inkommande batterier. Grafiten återvinns inte heller.

I Europa använder den dominerande återvinningsanläggningen pyrometallurgi med efterföljande hydrometallurgi. Det pågår mycket forskning som försöker effektivisera återvinningen, och förbehandling med efterföljande hydrometallurgi verkar lovande. Direkt återvinning, där batterimaterialet återvinns i bearbetad form, skulle förmodligen vara ännu effektivare men tycks också svårare att åstadkomma. Automation och design för återvinning är också områden som måste utvecklas.

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Mapping of lithium-ion batteries for vehicles

The number of electric vehicles (cars, buses, e-bikes, electric scooters and electric motorcycles) sold in the Nordic countries is currently increasing quickly. That means that more electricity is used for driving, and also that more of some important metals are being used than earlier. This report regards the fate of the lithium-ion batteries used in vehicles in the Nordic countries. Currently the "Battery Directive" (EC, 2006) which is a producer's responsibility directive, is under revision and this study is a knowledge base intended for use by the Nordic Environmental Protection Agencies for their referral response in the revision process. This report focuses on the aspect of metal resources, but it does not elaborate on a broader range of environmental impacts, as these were outside the scope of this study.

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