FACULTY OF TECHNOLOGY

INVESTIGATING THE REVERSE SUPPLY CHAINS OF LI-ION BATTERIES IN FINLAND

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ABSTRACT

Investigating the reverse supply chains of li-ion batteries in Finland

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Electric vehicles play a vital role in the electrification of transportation, and therefore in slowing down climate change. Hence, the number of electric vehicles has been on the rise globally. This has been made possible by major leaps in battery technology and the battery industry. The Finnish battery industry has also experienced growth, and Finland has set goals of becoming a major power in the entire value chain of the battery industry. However, the production of lithium-ion batteries for electric vehicles has involved environmental and ethical problems. The challenge of properly handling end-of-life batteries has only made the situation even more difficult. Due to these problems, the life cycle of these batteries is to be lengthened with the methods of circular economy, like reusing, refurbishing, and recycling. These would allow to form a closed-loop system. The concept that closes the circular economy loop is called reverse supply chain.

In this bachelor's thesis, the reverse supply chains of the Finnish battery industry are studied, their current capacity is determined, and their adequacy in the future is assessed. The used research methods are literature review and desk research. With these, literature from international sources on reverse supply chains of the battery industry are assessed and reflected on the situation in Finland. The study revealed that in Finland there is adequate recycling capacity now, and in the future. Despite this, Finland is not fully self-sufficient in recycling at the moment. The greatest shortcomings were found to be in battery reuse and repurposing. The main cause for this is due to the lack of economies of scale, since the number of end-of-life batteries is limited.

Keywords: battery industry, circular economy, li-ion batteries, reverse supply chains

TIIVISTELMÄ

Litiumioniakkujen paluulogistiikka Suomessa

Tatu Hyvärinen

Oulun yliopisto, Tuotantotalouden tutkinto-ohjelma

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Sähköautot ovat tärkeässä roolissa liikenteen sähköistymisessä, ja samalla ilmastonmuutoksen hidastamisessa. Sähköautojen määrä onkin kasvussa maailmanlaajuisesti. Tämän ovat mahdollistaneet suuret harppaukset akkutekniikassa ja akkuteollisuudessa. Myös Suomen akkuteollisuus on suuressa kasvussa, ja Suomella onkin tavoitteena saavuttaa merkittävä asema koko akkuteollisuuden arvoketjussa. Kuitenkin sähköautojen litiumioniakkujen valmistukseen liittyy useita ympäristöllisiä ja eettisiä ongelmia, jotka tekevät yhtälöstä monimutkaisemman. Tilannetta vaikeuttaa myös akkujen käytöstä poistamiseen liittyvät haasteet. Näiden ongelmien vuoksi akkujen käyttöikää pyritään pidentämään kiertotalouden menetelmillä, kuten uudelleenkäytöllä, korjaamisella ja kierrättämisellä. Näin saadaan muodostettua suljetun tuotekierron järjestelmä. Käsitettä, joka sulkee kiertotalouden tuotekierron, kutsutaan paluulogistiikaksi.

Tämä kandidaatintyö tutkii Suomen akkuteollisuuden paluulogistiikkaa, ja pyrkii selvittämään sen nykyisen tason, ja arvioimaan sen riittävyyttä tulevaisuudessa. Tutkimuksessa käytettään kirjallisuuskatsausta ja työpöytätutkimusta selvittämään tietoa kansainvälisistä lähteistä akkuteollisuuden paluulogistiikasta, ja vertaamalla tätä Suomen tilanteeseen. Tutkimuksessa selvisi, että akkujen kierrätykseen Suomessa on hyvät valmiudet nyt ja tulevaisuudessa. Tästä huolimatta Suomi ei ole tällä hetkellä täysin omavarainen kierrätyksessä. Akkujen uudelleenkäytössä ja kunnostuksessa on kiertotalouden menetelmistä eniten puutetta Suomessa. Suurin syy tähän on mittakaavaedun puute, sillä käytöstä poistuneita akkuja on tällä hetkellä liian vähän.

Asiasanat: akkuteollisuus, kiertotalous, litiumioniakut, paluulogistiikka

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ABBREVIATIONS

BEV	Battery Electric Vehicle
CE	Circular Economy
EoL	End-of-Life
EPR	Extended Producer Responsibility
EV	Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
LIB	Li-ion battery
Li-ion	Lithium-ion
OEM	Original Equipment Manufacturers
PHEV	Plug-in Hybrid Electric Vehicle
(R)SCM	(Reverse) Supply Chain Management
SOH	State Of Health
V2G	Vehicle-to-Grid

1 INTRODUCTION

1.1 Background

As the fight to slow down global warming continues, some of our current ways of life must change. Globally, numerous plans and agreements have been approved to set collective goals for the purpose of solving this critical problem. One of the affected industries that has received ambitious goals of reducing emissions is the transportation industry. As 75% of transportation related greenhouse gas emissions in the EU are due to road transportation, improvements have become necessary (Albertsen et al. 2021). There is a lot of pressure to step away from internal combustion engines (ICEs), and electric vehicles (EVs) play a big part in this transformation. The electrification of vehicle traffic could drastically reduce its related emissions, and thus many policies have been implemented to incentivise EV ownership. The amount of EVs has been on the rise globally, and the sale of passenger EVs is expected to rise from 3.1 million in 2020, to 14 million in 2025 (Bloomberg NEF 2021a). This shift in vehicle propulsion can be partly contributed to big advancements in the battery industry, which have allowed for the rapid increase in production numbers and lower per-unit-costs. According to Bloomberg NEF (2021b), the price per kilowatt-hour of lithium-ion (Li-ion) batteries has fallen from $1200/kWh in 2010, to just $132/kWh in 2021. Such a radical fall in price has made the technology viable for larger applications like EVs.

Current EV batteries typically have a lifespan of 8-10 years (HSSMI 2020, p. 5). This means that during the next decade, we will have an unprecedented number of batteries that are no longer viable for their original purpose. Companies and governments are now trying to figure out what to do with them before it is too late.

The production of new Li-ion batteries involves many environmental and ethical problems related to the acquisition of raw materials required for the production. Because of this proper recycling and extension of the battery life cycle have become key goals for success in the future. The need for circular economy solutions for Li-ion batteries is essential if we are ever to sustainably move away from ICEs and electrify our roads.

Recently, Finland has been on the forefront of battery development, especially on the circular economy solutions for Li-ion batteries. New production and recycling sites have been planned and built on multiple locations throughout the country. In order to have a sustainable circular-economy, both environmentally and financially, the supply chain is vital to ensure the closed-loop system. In the context of circular economy, the term **reverse supply chain** is used to represent the supply chain starting from the original product and resulting in the eventual recycling of materials.

1.2 Aim of the study and research questions

This study focuses on the Finnish Li-ion battery industry and its reverse supply chains. The subject is further defined to focus on the batteries of EVs, and thus does not consider other battery types or applications. The used research methods are literature review and desk research. Information about the entire value chain of Li-ion batteries is studied from international literature with an emphasis on European examples. These are then compared to the current state of the Finnish Li-ion battery industry. The research questions of this thesis are as follows:

1. What kind of reverse supply chains are there for EV batteries in Finland at the moment?
2. Is the capacity of these reverse supply chains adequate to deal with the increased number of batteries in the future?

The aim of the study is to find out the current level of the circular economy and reverse supply chains in the Li-ion battery industry in Finland. This study should also help to lay the groundwork for possible development efforts in the future.

In the second part of the thesis the terms circular economy and reverse supply chains are explained, and how these are applied in the Li-ion battery industry. The third chapter focuses on investigating the Finnish Li-ion battery reverse supply chain and answering the research questions. In the last two chapters the subject is discussed further, and conclusions are made.

2 LITERATURE REVIEW

2.1 Li-ion batteries

Li-ion batteries (LIBs) have become the dominating technology for powering modern electronics. Ever since their commercialization in the 1990s, LIBs have outperformed other battery types in their original purpose, which was to power portable electronics (Pistoia 2014, p. 22). A LIB cell most often consists of a lithium-cobalt-based cathode, a graphite-based anode, a micro-permeable separator, and an electrolyte that allows for the movement of lithium ions between the electrodes (Clean Energy Institute 2022).

The main benefits of LIBs are higher energy density due to a higher operating voltage, no memory effect, low self-discharge rate, and stability in different environments (Pistoia 2014, p. 22; Manthiram 2017). These benefits allowed the LIB to dominate the market for small batteries. With the rise in demand for portable electronics in the 1990s, the technology around LIBs improved further. By the beginning of 2010s, the energy density of Li-ion batteries has tripled, while the cost of producing LIBs has fallen 96,5% (Pistoia 2014, p. 6). In the last decade the trend has only continued. A further 89% decrease in price has made the technology viable for EVs as well, although they still account for approximately 40% of the total cost of an EV (Bloomberg NEF 2021b; Shahjalal et al. 2022).

As mentioned earlier, a big reason for the existence of EVs, alongside regulations and policies, has been due to the development of LIBs. EVs come in different vehicle types and depending on the vehicle type, the size of their LIB varies. The main EV types are, in order of their battery size from smallest to largest, Hybrid Electric Vehicle (HEV), Plug-in Hybrid Electric Vehicle (PHEV) and Battery Electric Vehicle (BEV). (Richardson 2013) For the use in EVs, LIBs are composed of thousands of small cells and different management systems. The cell-based design of LIBs allows for a safer output of power and reduces the impact of a failure in a single cell. On the other hand, the large number of cells required, and the inconsistent cell designs make inspecting, disassembling, and repairing LIBs more expensive and labour intensive. (Shahjalal et al. 2022; Pistoia 2014, p. 128-133)

Even though LIBs do not require as much dangerous elements as their predecessors, they are still considered hazardous, and are handled accordingly. More significantly, the negative environmental and ethical impact of mining key resources has plagued the sustainability of LIBs. Many materials required in the manufacturing process, like lithium and cobalt, are scarce and have thus caused problems with availability and price. (Steward et al. 2019) Because of the scarcity of these materials, plans of fully electrifying vehicle transportation has caused concerns about demand surpassing supply. Mining cobalt in less-developed countries has involved unsafe working conditions and the use of child labour (Nature 2021). The mining of lithium on the other hand is extremely water consuming and has caused conflicts related to the use of water while mining in water deprived areas (Paakkinen 2020). These problems only increase the need for further development for more sustainable batteries, and circular economy solutions, which are discussed next.

2.2 Circular economy

When sustainable development is discussed, the term circular economy (CE) often comes across. CE is an economy model and a development strategy where the material flows form a closed loop, which helps to eliminate waste. In the closed loop the product returns to raw materials after multiple uses and recycling. (Weetman 2021; Ellen MacArthur Foundation 2013; Heshmati 2017) CE is by one definition, “an industrial system that is restorative by intention, and it replaces the concept of End-of-Life (EoL) with restoration” (Ellen MacArthur Foundation 2013, p. 7). According to the European Parliaments (2021) definition, Circular Economy is model of production and consumption, in which the product life cycle is extended with reusing, repairing, recycling etc. with the aim of reducing the amount of waste to a minimum. Weetman (2021) defines CE as moving away from linear economy, where the production and consumption process follows a pattern of “take-make-use-waste” and replacing it with the closed loop system (see figure 1). Similar to the European Parliaments definition, Weetman emphasizes that the supply chain must be extended to reusing and remaking before eventually recycling. This requires rethinking of the entire process and adopting a circular business model (Weetman 2021, p. 78).

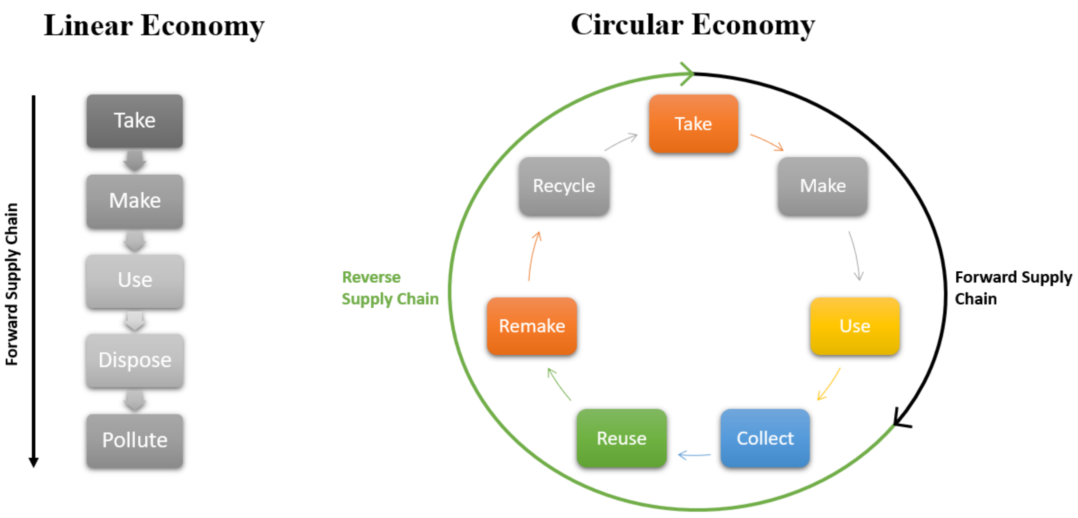

Figure 1. Linear Economy compared to Circular Economy (modified from Weetman 2021, p. 5)

Waste management is an essential part of CE, and it can be approached with the 3R method. The three Rs represent: **Reduce, Reuse and Recycle** (Heshmati 2017; Pistoia 2014, p. 484). These three all contribute to the same goal of reducing waste by reducing the need for new products, reusing the products, thus lengthening their life cycle, and lastly recycling them to become food for other processes (Weetman 2021). Alternatively, the 3Rs can be extended to 10Rs, adding the following steps: **Refuse, Rethink, Repair, Refurbish, Remanufacture, Repurposing and Recover** (HSSMI 2020, p. 8).

2.2.1 Reduce

Reducing represents the action of improving the production to use less raw materials and energy for the manufacturing of a product (Heshmati 2017). Yang et al. (2014) add that the improvements should include the production of efficient products that consume less resources when used and are made of environmentally friendly materials. Weetman (2021) refers to the reducing part as “narrowing the loop”, where more is done with less. The reducing part is closely related to both reusing and recycling, as when products are reused, need for new products is reduced. And as resources are recycled, need for virgin materials is reduced.

2.2.2 Reuse

In order to extend the product's life cycle, the same product should be used multiple times whenever it is possible. Essentially, when a product is used again for the same purpose after its first life, it is considered reuse, while using the product for something else would be considered repurposing (Ellen MacArthur Foundation 2013; Weetman 2021, p. 35). Weetman (2021) also suggests leasing as an aid in reusability. This would mean that instead of traditional ownership of products, products could often be leased, allowing for an easy return to the provider and further resell and reuse. Leasing as a business model in CE has been studied by for example Ionașcu & Ionașcu (2018). The results suggested that leasing allowed a more sustainable development for businesses, without penalizing their economic performance.

There are many ways to carry out reusing, some being better than others. The easiest and most economical method of reusing is reselling or sharing the used product with someone else. A durable and timeless design are essential for making reuse work. (Weetman 2021, p. 67) Reusing reduces the demand for new products and is thus linked to the reducing part of CE as well. If direct reusing is not possible, there are still some options that prevent the disposing of the product and at least partly lengthening the life cycle of the product. Repairing is one way of allowing for the further use of a product. Repairing involves returning the product or component back to its original form, meaning that new materials are not necessarily required (Weetman 2021; HSSMI 2020). The least efficient forms are refurbishment and remanufacturing. These two terms are sometimes used as equivalents, but they are slightly different. In refurbishment, the product is returned to a good-enough state by replacing only the faulty parts and leaving the functioning parts of the product as they were. In remanufacturing, the same process is done, but now the product is returned to a like-new or even better state. (Ellen MacArthur Foundation 2013; Weetman 2021). In a sense, refurbishment and remanufacturing are compromises of reusing and replacing, meaning that while they are not as good as reselling or repairing, they are still better than disposing of the entire product.

2.2.3 Recycle

Recycling is the process in which all the reusable resources are to be obtained from the product. Before recycling the structure and purpose of the original product is conserved, but in this phase the product is essentially destructively disassembled. (Wang & Gupta 2011, p. 201) Recycling should be the last phase in the CE loop, and the part that actually closes the loop. Recycling allows for the things that are commonly regarded as waste, to be treated as resources for other original production process or completely other processes. Still, recycling is the least effective part of the closed loop, as it requires a lot of energy and is often very labour intensive. (Weetman 2021)

2.3 Circular economy of LIBs

When the capacity of EV LIBs falls to 70-80% of its original value, it is deemed unsuitable for vehicle applications (HSSMI 2020). This is the point in which the first life of the LIB ends, and the options of CE become relevant. To enforce CE for the Original Equipment Manufacturers (OEM) for LIBs, the EU has had directives with the purpose of increasing producer responsibility. For example, the EU Directive 2006/66/EC, often referred to as the "Battery Directive", brought battery waste under the influence of Extended Producer Responsibility (EPR). This meant that the producers of LIBs are responsible for handling and financing the collection, processing, and recycling of LIBs after their first use. (Lebedeva et al. 2017, p. 55) Most other countries, like Japan, China, and South Korea, have similar regulations for used LIBs and EoL vehicles as well (Steward et al. 2019).

Because of regulations like the EPR, especially the repurposing of used LIBs has been on the rise. Even though used LIBs are not suitable for vehicle propulsion, they can still store a large amount of electricity. This ability has been utilised to solve a problem in another field, which is also experiencing a change towards sustainability: the energy industry. Renewable energy sources like solar and wind power are not capable of producing electricity steadily around the clock, and they struggle to handle the demand for electricity during peak hours (Shahjalal et al. 2022). Used LIBs can be reused as energy storages, in order to compensate for the irregularities of the energy grid, i.e., charge during low demand and discharge during peak hours. This application method is known as stationary storage system. (Capgemini 2019; Shahjalal et al. 2022) Vehicle-to-grid (V2G) applications on the other hand can utilise EVs on charging stations as a power source during peak hours and continue charging them during low demand (Shahjalal et al. 2022). Vehicle manufactures like Audi (2019) and Renault (2017) have utilised used LIBs from their own EVs in research and V2G applications. A noteworthy point is that 93% of LIBs used in Renault's EVs are rented, allowing them to more easily control their EoL applications (Renault 2017). Another possible power storage application is the off-grid power storage for backup and microgrid purposes. (HSSMI 2020)

A LIB can be reused in an EV when the reduced capacity is not problematic. Example of this could be recreational EVs, that are used only for short travels. Some 75% of trips taken can be made with a reused battery with 60% capacity left (Shahjalal et al. 2022). A reused LIB costs less than 25% of the price of a new LIB, meaning that it can lead to a potentially 30% cheaper EV (assuming that the LIB composes 40% of the costs of an EV). This method is also by far the most environmentally friendly way of extending the life cycle of a LIB. (HSSMI 2020; Shahjalal et al. 2022)

Recycling of LIBs is a little different story. The recycling process of a LIB is often difficult and expensive due to non-reversible bonding in the cells, different cell chemistries, and a lack of standardization (HSSMI 2020). All the development in cost reductions of LIBs has had the side effect of making them much harder to recycle (McMahon 2018). Still, recycling is an essential part of CE, as the life cycle of a LIB will come to an end at some point for all. Although most of the LIB recycling is done in the EU and China (Mayyas et al. 2016), the recycling rate and collection rate for LIBs is hard to estimate, as data availability for recycling EV LIBs is poor. Currently, there are no reporting obligations for automotive and industrial LIBs in the EU (Stahl et al. 2018). This is why estimates of the actual recycling rate vary drastically. Many articles (BBC 2021; Davey 2022; Heelan et al. 2016; Jacoby 2019) state that the recycling rate of EV LIBs is around 5%. However, Alves Dias et al. (2018) estimate that the number in the EU would be around 90% for BEVs and 50% for PHEVs, assuming no second use before recycling. And similarly, Gattiglio (2019) estimates that the number is "in the high 90%" (Gattiglio 2019, according to Abdelbaky et al. 2020, p. 2).

Even before reaching the actual recycling process, the batteries must be inspected and most likely partly disassembled by hand, which takes a lot of time and effort. This process is also dangerous, as the batteries contain hazardous materials, still produce a high voltage, and because the battery can explode if not disassembled properly. Because of these challenges, the process of disassembly can take between 8 and 16 hours for a single LIB. (Steward et al. 2019; Shahjalal et al. 2022)

The main methods of the actual recycling of LIBs include mechanical, hydrometallurgy, pyrometallurgy, and combined hydro- and pyrometallurgy. With these methods materials like cobalt, lithium, nickel, copper, manganese etc. can be extracted. (Lebedeva et al. 2017, p. 55–56) From these, cobalt is clearly the most desirable, as it contributes almost 50 % of the value per kg of the recycled material from a LIB (HSSMI 2020, p. 5). The efficiency of LIB recycling is determined not only by the efficiency of the recycling process itself, but also by the collection rate. Depending on the recycling method and the element that is to be extracted (mostly cobalt), the efficiency can reach almost 100%. (Lebedeva et al. 2017) But as mentioned earlier, the values for the collection rate of LIBs are wildly inconsistent. Therefore, the efficiency of LIB recycling as a whole is also hard to determine. The EU's battery directive has set the target of 60% efficiency and a minimum of 50% efficiency for the recycling of LIBs, meaning that if the worst-case estimates are true, there is still need for improvements (Lebedeva et al. 2017).

Reducing the size and weight of EV LIBs is essential for the efficiency of the whole EV. Simply adding a heavy battery with a huge capacity would not work, because the battery has to move itself as well. This is why battery manufacturers want to use light materials like magnesium, aluminium, and plastics as much as possible (Pistoia 2014, p. 136). And as the cell materials for the LIB cell are the most valuable, many different cell chemistries have been studied to find the most efficient and least material-dependent method. A good solution would use less critical materials, but the best option would not use them at all.

2.4 Reverse supply chains

Conventional forward supply chains are most often defined in the context of linear economy. Blanchard (2010) defines a supply chain as "the sequence of events that cover the life cycle of a product from conception to its consumption" (Blanchard 2010, p. 3). In the context of CE on the other hand, the process is extended to a closed loop, in which the material flow is reversed after the first use. This part is defined as reverse supply chain or reverse logistics. Tibben-Lembke (2002) defines reverse supply chains as the actions in the process of material flow from consumption to the point of origin, with the purpose of recapturing value, or for disposal (Tibben-Lembke 2002, according to Sarkis 2014, p. 40). All organisations that have production and supply chains must also establish reverse supply chains to a certain extent because of some regulations and to enable product returns. However, the reverse supply chain can be further developed for the sake of sustainability. For some, the reverse supply chains can be an integral part of their business model and basis for success. (Guide Jr. & Van Wassenhove 2002) Reverse supply chains can be viewed holistically to include both the reversed distribution of materials, reusing, and recycling, but also as the reduction of the material in the forward supply chain (Sarkis 2014, p. 40).

Similar to the forward supply chains, reverse supply chains have a set of activities that are managed with reverse supply chain management (RSCM). These activities can vary between different products and industries, but generally they include collection, separation/inspection, disassembly/processing, compaction, and outbound logistics (Sarkis 2014, p. 41-42). Managing the activities of reverse supply chains has some unique challenges compared to forward supply chain management. RSCM typically has more uncertainty factors compared to regular SCM. Because the RSCM process begins with the acquisition of the EoL products from the customer, the products can have very different characteristics compared to each other. This means that the products need to be inspected and further divided into different categories before further processing. This extra step increases variance and decreases efficiency. (Wang & Gupta 2011, p. 125-126).

2.5 Reverse supply chains of LIBs

After the 8-10 years of use, the LIBs of EVs need to be replaced, at which point the reverse supply chain starts. So far, EVs with LIBs have been sold for 5-10 years, so the number of LIBs reaching the end of their first life has remained relatively low (HSSMI 2020). This is obviously going to change quite soon, and the number will skyrocket in future (Steward et al. 2019). The 8–10-year period of the first life use also means that even if any new technology would replace LIBs, we would still need to find solutions for LIBs that are currently in use.

After a LIB has reached the end of its first life, the first step is to have it collected. The EPR mandates the OEM to be responsible for the collection of LIBs and no costs should be put on the EV owner (Slattery et al. 2021). The collection points can be at car dealerships, repair shops, or scrapyards. The LIB can either be inspected and disassembled there or transported to a dedicated plant for inspection and disassembly (Steward et al. 2019).

After the LIB is transported to the inspection point, the state of the LIB is assessed, and its State of Health (SOH) is tested (HSSMI 2020). SOH expresses the state of the used LIB in percentage compared to its original state, taking to account for example, the capacity, internal resistance, and power fade (Shahjalal et al. 2022). Depending on the resulting SOH score, the best option for the future of the LIB can be determined (see Figure 2). If the LIB seems to be in too poor condition or having too low capacity, reusing or repurposing might be unfeasible. Then the best option is to repair, refurbish, or recycle it. If the condition and capacity allow for further use, the LIB should move to the disassembly phase. A healthy LIB with over 88% SOH can be reused directly, while still having 88-75% SOH left allows for repurposing, refurbishing, or some reusing as well. SOH of less than 75% likely leads to either recycling or repurposing in applications with lower capacity requirements, such as E-bikes. (HSSMI 2020)

If the LIB is going to be reused for the exact same purpose that it was originally used, disassembly is not necessary. Otherwise, it must be at least partly disassembled. (Shahjalal et al. 2022; Steward et al. 2019) After disassembly the possible defects and faulty cells can be replaced, and the battery is reassembled again if necessary. When the following purpose for the LIB has been determined, it is once again transported to its next location. After the LIB has been reused or repurposed the chain starts again at the collection phase. The LIBs are to be used until they are no longer usable or repairable, after which they should be recycled (HSSMI 2020).

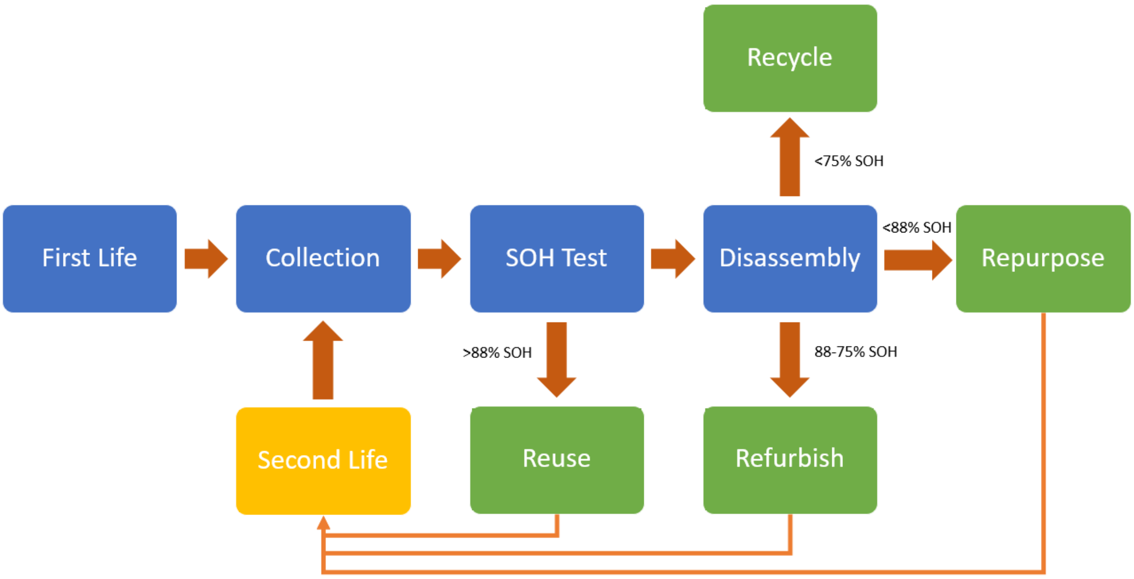

Figure 2. Reverse supply chain of the EoL LIB. Adapted from HSSMI (2020).

When transporting LIBs, it must be done following the regulations set by the United Nations. In Europe, LIB transportation is regulated by two European Standards, that define the details of dealing with electricity, electrolytes, inflammable gas mixtures, storing, and the transportation itself. Other standards that effect the transportation of LIBs on roads and railways are the European Agreements concerning International Carriage of Dangerous Goods by Road (ADR) and the International Carriage of Dangerous Goods by Rail (RID) (Huo et al. 2017, p. 23). The most efficient mode of transport according to Slattery et al. (2021) is by truck, assuming full truckload. Even with the most efficient methods, the transportation is the costliest part of the reverse supply chain for LIBs. According to a case study in Poland by Gołębiewski et al. (2013) the transportation costs made up 70% of the total cost of recycling of an EoL vehicle. Transportation optimization is also important, as there would be no use to implement RSCM for sustainability if it causes more harm due to inefficient and fossil fuel dependent transportation. And sometimes, the proper reverse supply chain will not start because the EoL vehicle and battery never reach collection. This can be due to for example, abandoning or “garaging” by the owner of the first life vehicle, or OEM bypassing the EPR regulations by exporting the EoL vehicles to countries that are not mandated by the EPR regulations. (Steward et al. 2019, p. 275)

In a case-study of the reverse supply chains of Swedish LIB recycling by Tadaros et al. (2022) the authors attempted to determine a model for predicting the optimal network of inspection and recycling sites by the year 2045. The case-study utilised an unlinked discrete multi-period method. Assumptions were that by 2040 EVs will make up 55% of all globally sold cars and depending on whether the LIB was reused, the LIBs had a lifecycle of 6-30 years. The methods of transportation for the LIBs were trucks with three different load capacities. Results of the study indicated that depending on the level of reusing for the EoL LIBs (0-60%), there needs to be 10-16 inspection sites and 4-10 recycling sites in Sweden by 2045 to handle the increase in EoL LIBs. (Tadaros et al. 2022, p. 7-16)

3 LIB REVERSE SUPPLY CHAINS IN FINLAND

Finland has had a strong position in the battery industry thanks to its vast resources, established refining and mining capabilities, and access to renewable energy (MEAE 2021). Finland is the only country in Europe that has all the important elements needed for LIB production in its bedrock. Finland does not only want to focus on the raw materials, but rather become a major power in the entire value chain of LIBs. (Business Finland 2021; Dehaine et al. 2020; YLE 2020) The position is not necessarily guaranteed, and the Finnish Ministry of Economical Affairs and Employment (MEAE) has made a strategy for the development of the Finnish battery industry to the year 2025. The National Battery Strategy 2025 defines six visions for the future of battery industry in Finland, which was summarized in a single sentence: ”We create the low carbon future through batteries and electrification: Shift Climate. Build Circularity. Champion People. Create Innovations. Enable Growth.” (MEAE 2021, p. 11). The key players in the Finnish battery value chain are sevenfold, and it comprises of research institutes, mining companies, battery material producers, cell- and battery producers, first-life battery utilisers, second-life utilisers, and recycling companies (MEAE 2021, p. 13). In this chapter, the focus is on second-life utilisers, and recycling companies.

3.1 Current reverse supply chains of EV LIBs

In Finland, the responsibility of handling and recycling EV LIBs is under **Suomen Autokierrätys Oy**. Suomen Autokierrätys is only responsible for the EV batteries, as the recycling of traditional lead batteries is under the control of Akkukierrätys Pb Oy. (Suomen Autokierrätys Oy 2022a) Even though Suomen Autokierrätys has the responsibility of managing the reverse supply chain of EV LIBs, the actual handling of LIBs is done by four independent operators. These are **Fortum Waste Solutions Oy, Eurajoen Romu Oy, Kuusakoski Oy, and Stena Recycling Oy** (Suomen Autokierrätys Oy 2022b).

Currently, there are 288 dedicated collection points for EoL vehicles and LIBs all around Finland. An additional 450 registered car repair shops also collect used LIBs. (Suomen Autokierrätys Oy 2022c; Suomen Autokierrätys Oy 2022d) EV owners can go to any of these and return their EV LIBs free of charge. These points are either dedicated scrapyards, or authorised repair shops that collect used LIBs and replace them if the EV is still usable. It is recommended that when only the LIB gets replaced and the EV stays in use, the primary point of collection should be these repair shops. (Suomen Autokierrätys Oy 2022c) After collection, the LIBs are transported to the aforementioned operators that assess the SOH of the LIBs and decide their future. All of the collection points for the LIBs have a dedicated operator, who is responsible for the handling of the LIB after it has been handed over by the EVs owner (Suomen Autokierrätys 2022c).

Fortum Waste Solutions Oy, a part of Fortum Corporation, has ambitious goals of becoming the top recycler of EV batteries in Europe (Fortum 2021a). The company has provided solutions for both recycling and repurposing of EV LIBs, although the focus seems to be on recycling. In addition, Fortum also provides services for safe handling, transportation and storing of LIBs for other companies, utilising their already established logistics network (Fortum 2022a). In February of 2021, Fortum opened a LIB recycling plant in Ikaalinen, which can recycle around 10 000 EV LIBs annually, using a mechanical recycling process (Fortum 2021b). The capacity is significant, since within the years 2015-2018, the number of recycled EV LIBs in Finland totalled 52 (YLE 2021). The plant in Ikaalinen is also responsible for the disassembly and treatment of LIBs. In the future, the Ikaalinen plant is supposed to complement a new state-of-the-art hydrometallurgical recycling facility in Harjavalta. The facility is still under construction and is expected to be operational by the year 2023. The combination of these two would allow for 95% of the critical metals, and 80% of the entire battery to be recycled. (Fortum 2021c; Fortum 2022b) The repurposing of LIBs has been in piloting phase for Fortum, and so far the company has piloted repurposed LIBs in stationary energy storages in hydropower plants in Sweden, but not in Finland as of yet (Fortum 2022c).

Eurajoen Romu Oy is the newest of the four operators in the management of used LIBs. Eurajoen Romu has had history of recycling EoL vehicles and lead-batteries, but as of June 2021 they now recycle EV LIBs as well (Suomen Autokierrätys Oy 2022d). Eurajoen Romu does not report on their LIB recycling methods, but they have a mechanical battery recycling plant in Eurajoki, that is focused on recycling lead-batteries. (Eurajoen Romu Oy 2022) Compared to Fortum for example, Eurajoen Romu seems to keep a low profile in its LIB recycling operations.

In 2019, Kuusakoski Oy became one of the operators for the recycling of EV LIBs (Kuusakoski Oy 2020). Currently, Kuusakoski has 22 collection sites for EoL vehicles, where EV LIBs are also collected (Kuusakoski Oy 2022). Kuusakoski does not report on their recycling methods either, but rather they only claim to "handle the batteries to cell-level and salvage recyclable materials", and that "recycling rate easily exceeds the minimum requirement of 50%". In terms of reusing LIBs, Kuusakoski claims to "constantly look for new reusing applications". (Kuusakoski Oy 2022) Overall, the public reporting of LIB recycling seems to be lacking entirely.

Stena Recycling, part of Stena Metall concern, is the last of the four operators that handle EoL LIBs (Stena Recycling 2022a). Stena Recycling currently has recycling and inspection centers in Sweden, Germany and Poland, but they are planning on adding sites to Finland, Norway, Denmark and Italy (Stena Recycling 2022b). In Finland there are 10 dedicated collection sites, where EoL EVs and LIBs can be handed over (Stena Recycling 2022c). The Stena Nordic Recycling Center in Halmstad Sweden is the company's largest recycling and sorting site, and EoL LIBs that are collected by Stena Recycling in Finland are transported here. The transportation to Halmstad can be done by either trucks, trains, or ships. (Stena Recycling 2022d; Uusiouutiset 2019) In Halmstad, the LIBs are disassembled, and their SOH is determined. Before the handling of the LIBs, they are short-circuited, and the remaining electricity is fed into the facility's internal grid. If the LIB is suitable for reuse or repurposing, it can be prepared for that on site or in house and transported to the place of reuse. (Stena Recycling 2022e) Stena Recycling also does some repurposing themselves through their subsidiary company Batteryloop, which provides stationary power storages for EV loading stations (Stena Recycling 2022c).

Even though these four operators are the designated companies that drive the reverse supply chain of LIBs, there are other companies that also work with used LIBs. However, most of them are still in the process of entering the market. Examples of these are Akkuser and Cactos. Akkuser is an established company in battery recycling, and it has been recycling batteries since 2006. Currently Akkuser recycles 100% of the portable and non-chargeable batteries in Finland. (Akkuser 2022a) Akkuser is currently developing a modification of their recycling process, which would allow them to recycle EV LIBs as well (Akkuser 2022b). Conversely, Cactos is a new player to the whole battery market. Cactos buys used Tesla Model S batteries from Norway, for example, and repurposes them in energy storage applications, with a capacity of 100 kWh (Cactos 2022). Instead of selling them, Cactos leases the energy storages to grocery stores, hotels, and offices etc. Cactos also offers software utilising artificial intelligence and cloud services, that allow for efficient loading and discharging of the storage. (Cactos 2022; Helsingin Sanomat 2022)

3.2 Assessing the capacity of the reverse supply chains of EV LIBs

The reverse supply chains for EV LIBs in Finland are in a relatively good state at the moment. In terms of collection, EV users have plenty of sites where they can return the LIB free of charge, when it does not fulfil its original purpose. As it appears to be in many other countries, the reporting on the EoL uses for LIBs is lacking, and finding credible information is harder than it probably should be. From transportation's perspective, there are no apparent challenges at the moment. No reports of violations of EPR or major incidents when transporting LIBs in Finland were found when making this study.

On a global scale, Finland has good recycling capabilities, and the capacity seems to be increasing, as small and large companies alike are investing in new recycling facilities. Still, compared to neighbouring Nordic countries like Sweden and Norway, the capacity is not as good. Some of the recyclable LIBs are transported from Finland to Sweden by Stena Recycling, meaning that currently Finland is not fully self-sufficient in recycling. Considering the future of EoL LIBs, the case study by Tadaros et al. (2022) gives a reference point on the need for inspection and recycling facilities that would fulfil the surge in demand in the future. The study found that Sweden would need 10-16 inspection sites and 4-10 recycling sites by 2045 to meet the demand (Tadaros et al. 2022). If the number of EoL LIBs in Finland is assumed to be roughly half of that (based on population alone), Finland would need 5-8 inspection sites and 2-5 recycling sites by 2045. In reality, Sweden has a larger proportion of registered EVs when adjusted for population, meaning that the need for inspection and recycling facilities in Finland would most likely be less than that (European Environment Agency 2020). Thus, the recycling capabilities of Fortum's facilities alone would probably meet the requirements in the near future.

Reusing and repurposing of LIBs is where Finland seems to be lagging behind others the most. The repurposing business in Finland involves only small pilot-projects and start-up companies. Larger companies that work in multiple Nordic countries, like Fortum and Stena Recycling, have already been repurposing LIBs on a bigger scale, but not in Finland. Reason for this seems to be in the number of EoL LIBs in these countries. Compared to Finland, Sweden has a population roughly twice as big, and a slightly higher proportion of registered EVs (Tilastokeskus 2022; European Environment Agency 2020). Norway on the other hand had over 20 times more BEVs than Finland in 2021, while it has a similar population than Finland (Tilastokeskus 2022; Autoalan Tiedotuskeskus 2022; Norsk elbilforening 2022). This suggests that the number of EoL LIBs in Finland at the moment is not enough to reach economies of scale for repurposing.

4 DISCUSSION AND CONCLUSION

The invention of the LIB has undoubtedly changed our world in multiple industries, but the technology has some challenges that need to be solved to keep the production and use of LIBs environmentally friendly and ethical. The possible new battery technologies, like solid-state batteries, could affect the sales of LIBs in the future. However, it does not change the fact that the LIBs currently in use need to be handled properly. And thus, the relevancy of EoL LIB handling is guaranteed even if LIB technology would get replaced entirely. It is also important to remember that EVs alone will not be enough to meet the emission reduction goal of the transportation industry. This requires reducing our dependency on ICEs and fossil fuels with the means of, for instance, public transportation and motorless transportation as well.

The aim of the study was to investigate the current level of the circular economy and reverse supply chains of EV LIBs in Finland. The study revealed that on a global scale the Finnish reverse supply chains are in a quite good state at the moment, even though it is hampered by the small quantities of EoL LIBs, which makes reaching economies of scale difficult. From the consumers point of view, the process has been made easy. There are plenty of collection sites for EoL LIBs, meaning that collection should not bottleneck the efficiency of the reverse supply chain. As for the future, Finland has many plans and investments in the entire value chain of the battery industry, including Fortum's recycling facility in Harjavalta. Alongside the site in Ikaalinen these two could arguably handle all the recycling of Finnish EoL LIBs in the near future. And these facilities are not alone either, as there are other established facilities and potentially new ones coming as well. As a conclusion, the Finnish recycling of LIBs, although currently not fully self-sufficient, is adequate enough to meet the demand in the future.

As reusing and repurposing of EoL LIBs was found to be the most inadequate aspect of the LIB reverse supply chain in Finland, improving of the reusing and repurposing would be a good place for future research. More specifically, a possible future study could try to predict the point in which economies of scale could be reached for large-scale repurposing of EoL LIBs in Finland.

The information gathered in the desk research is based on publicly released online information. But as mentioned earlier, there is a significant lack of reporting on EoL LIB handling by companies. Some information was not public at all, and assumptions had to be made. Finding some of this information would have most likely required directly inquiring from the companies. This would have been out of scope from the original purpose of the study. Some of the used sources were relatively old, but the content that they include is still up to date. The average publishing year of the sources was 2019, although the number could be distorted by multiple web documents without any publishing dates, that were assumed to be published in 2022.

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