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THE FUTURE OF BATTERY RECYCLING: INNOVATIVE TECHNOLOGIES AND ENVIRONMENTAL SOLUTIONS

A Study on VTT Technical Research Centre of Finland

International Project Management

2025

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ABSTRACT

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Title	The Future of Battery Recycling: Innovative Technologies and Environmental Solutions, A Study on VTT Technical Research Centre of Finland
Year	2025
Language	English
Pages	91
Name of Supervisor	Binod Timilsina

This thesis explored the role of emerging recycling technologies and sustainable practices in the battery sector, with a focus on the VTT Technical Research Centre of Finland. The research addressed the growing environmental and economic challenges of end-of-life battery management, particularly the need to recover critical raw materials and reduce carbon emissions. The study aimed to evaluate the technological innovations developed by VTT and assess their alignment with circular economy goals and European regulatory frameworks.

The study was grounded in sustainability theory and circular economy principles. Key concepts included lifecycle assessment, resource recovery, and digital traceability. The research employed a qualitative methodology based on secondary data analysis, including technical reports, policy documents and project outcomes from EU-funded initiatives. The study followed a thematic structure to analyse technological, environmental and economic dimensions of VTT's work.

The findings indicated that VTT's innovations in hydrometallurgical and direct recycling methods significantly reduce greenhouse gas emissions and increase material recovery efficiency. Economic modelling suggested long-term viability as recycling scales up. The study concluded that VTT's integrative approach provides a replicable model for sustainable battery recycling, contributing to European climate targets and advancing circular industry transformation.

Keywords battery recycling, lithium-ion batteries, direct recycling, circular economy, sustainable development, VTT technical research centre of Finland

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1 INTRODUCTION

1.1 Background on Battery Recycling

A key component of the global shift to low-carbon energy systems is batteries. They are vital parts of grid-scale renewable energy storage systems, electric vehicles (EVs), and consumer gadgets. Because of their high energy density, minimal self-discharge, and extended cycle life, lithium-ion batteries (LIBs) have become the most popular battery chemistries on the market (Gaines, 2014). Global demand for LIBs is predicted to grow rapidly, particularly as countries invest more in clean technology and work towards decarbonisation goals.

The International Energy Agency (IEA) projects a substantial increase in the demand for lithium, cobalt, and nickel, essential components in lithium-ion batteries (LIBs), by 2030. Lithium consumption is anticipated to surge almost 40-fold from 2020 levels, but cobalt and nickel demand are forecast to rise by more than 20 and 19 times, respectively (IEA, 2022, p. 45). This increase is primarily propelled by the expected expansion of the electric vehicle market and energy storage systems, with the lithium-ion battery market projected to exceed 2 TWh of annual production capacity by 2030 (Jennifer, 2023).

Although LIBs greatly help to lower greenhouse gas emissions throughout their usage phase, their End-of- Life (EoL) presents major environmental and health issues. Many of the vital raw components found in LIBs lithium, cobalt, nickel, and manganese are classed as such by the European Union because of their economic relevance and supply risk (European Union, 2020a, p. 7). But they also comprise dangerous elements including organic electrolytes, fluoride-based molecules, and heavy metals that, if improperly controlled, might contaminate the surroundings (Zeng et al., 2014, p. 55). Inappropriate disposal of LIBs in landfills can cause thermal runaway, fires, and poisoning of soil and groundwater, therefore endangering ecosystems and public health (Gaines, 2018).

Among other things, we will begin with the idea that recycling batteries is vitally important for a lot of reasons. It's not only about keeping the environment safe, but also about saving resources that we don't have an endless supply of, helping us use fewer resources from the earth, and ensuring materials get reused sharply. This entire concept is part of the circular economy. This means we try to be more sustainable by doing things such as reusing, repairing, making old things new again, remaking products, and recycling. When it comes to batteries, it concerns taking the notably positive elements out of old batteries and using them again, so we don't waste anything. And we don't run out of the materials we need.

The course of recycling lithium-ion batteries can help our planet, cutting down gas emissions by a lot - we are contemplating up to 80% (Stanford University, 2025). What matters here is how we recycle them and what power we use to get it done. Before we become excited about getting new resources, such as cobalt, especially when it comes from places where working conditions are not good, such as in the Democratic Republic of Congo mines, we really should think more about being green and recycling more (Amnesty International, 2016). The clear and unbiased evaluation of facts shows the direction to go.

Despite these benefits, the global battery recycling rate remains low, with estimates suggesting that less than 5% of LIBs are currently recycled effectively, particularly in consumer electronics (Harper et al., 2019). Technological, economic, and regulatory barriers persist, including inefficient collection systems, high processing costs, and inconsistent international policies.

In this context, developing efficient, scalable, and environmentally benign battery recycling methods is critical. Research and innovation in this space, especially within organizations such as the VTT Technical

Research Centre of Finland can enable countries to meet their circular economy goals, reduce environmental impact, and secure material supply chains for the clean energy transition.

1.2 Importance of the Study

The importance of battery recycling is multi-dimensional, encompassing environmental sustainability, economic resilience, geopolitical stability, and policy compliance. As global dependence on rechargeable batteries intensifies driven by electric mobility, renewable energy integration, and the digitization of infrastructure so too does the urgency to develop efficient, safe, and circular end-of-life (EoL) battery management systems (IEA, 2022).

1.2.1 Environmental Importance

The improper disposal of spent batteries poses significant environmental threats. When batteries are landfilled or incinerated without treatment, toxic metals such as cadmium, mercury, lead, and nickel can leach into soils and water bodies, thereby contaminating groundwater, harming aquatic life, and ultimately entering the human food chain (Gaines, 2014). Moreover, LIBs contain flammable electrolytes that can ignite under certain conditions, posing fire hazards during waste processing (Harper et al., 2019).

If we recycle batteries the right way, we can use far less energy and produce fewer greenhouse gas like to an 80% drop compared to just digging up new materials from the earth. It's indubitably true that sometimes, when recycling is done well, it really cuts down on how much we destroy the planet during the entire battery life cycle. By recycling, we also don't have to destroy important places for animals and trees so much, because it means less mining. Liu et al. (2019) said that a mining mess results in fewer trees, less diverse animal life, and damaged ground.

Given that almost 70% of the world's cobalt comes from the Democratic Republic of Congo (DRC), where unethical and ecologically harmful mining methods are used, there is special worry. According to reports, dangerous working conditions and child labour are rather common in artisanal miners (Amnesty International, 2016). The battery sector can lessen its reliance on such dubious supply chains by boosting the availability of secondary raw materials by means of recycling.

1.2.2 Economic and Geopolitical Importance

Economically, battery recycling presents a solution to mitigate raw material supply risks and price volatility. For example, the price of cobalt soared from around $32,000 per metric ton in 2016 to over $95,000 in 2018, largely due to supply constraints and speculative trading (Alves Dias et al., 2018, p. 22). Such market instability not only disrupts battery manufacturing but also raises the costs of EVs and renewable energy storage systems. Recycling helps stabilize supply by recovering valuable materials from EoL products, often at a lower cost and with fewer environmental implications than virgin mining.

Moreover, global geopolitical tensions surrounding access to critical minerals make domestic and regional recycling capacities strategically valuable. The European Union, in its 2020 Action Plan on Critical Raw Materials, emphasized the need to boost “urban mining” and reduce external dependency on imports from politically unstable regions (European Union, 2020b). Recycling contributes to building a more secure, autonomous, and resilient supply chain for Europe’s clean energy transition.

1.2.3 Regulatory and Institutional Relevance

The European Green Deal and the proposed EU Battery Regulation (2020/0353) are redefining sustainability in battery manufacturing and disposal at the legislative level. The law adds Extended Producer Responsibility (EPR), therefore making manufacturers liable for the whole battery life cycle (European Commission, 2020) and sets aggressive targets for material recovery (e.g., 90% for cobalt and nickel, 35% for lithium by 2026). These models are also projected to affect research facilities such as the VTT Technical Research Centre of Finland, which significantly supports industry innovation and policy execution in the Nordic area.

The national plan of Finland thus fits these EU objectives. Emphasising the need of technology innovation, material efficiency, and responsible consumption, the Finnish Circular Economy Program seeks for the nation to become carbon-neutral by 2035 (Ministry of the Environment Finland, 2021). Being a state-owned research and development company, VTT has a great responsibility to help these goals by developing environmentally friendly battery technologies and recycling techniques.

This research is so strategic and relevant. It promotes institutional objectives at VTT in addition to matching the orientations of global and regional policies. The results of this study have the power to guide practice, influence legislation, and add to the worldwide conversation on environmentally friendly batteries.

1.3 Objectives of the Thesis

Effective battery recycling techniques are more urgently needed as reliance on lithium-ion batteries (LIBs) and demand for sustainable energy alternatives grow. This thesis aims to encourage scientific and industrial innovation by means of evidence-based analysis and pragmatic advice in line with environmental demands and legal developments. With this aim, especially within the operational framework of VTT Technical Research Centre of Finland, this study seeks to satisfy four linked objectives bridging theory and application.

1.3.1 Analysis of Current & Emerging Recycling Technologies

Apart from the present technologies applied in battery recycling, pyrometallurgy, hydrometallurgy, and direct recycling, the primary aim is to examine modern, developing technologies including mechanochemical processing and bioleaching. Every method offers special advantages and trade-off in terms of energy efficiency, recovery rates, economic feasibility, and environmental safety (Harper et al., 2019; Gaines, 2014). For high-purity metals with rather low energy input, for example, hydrometallurgical methods have shown promise; pyrometallurgical techniques are better suited to handle large volumes but generate more emissions (Georgi-Maschler et al., 2012). By means of a comparison analysis, one will be able to identify the technologies with the best strategic value for use at VTT.

1.3.2 Assessment of Environmental Impacts

Nonetheless, this paper is centred on looking at how good or poor it is for the planet it is to recycle batteries in old ways and with new technology. It's going to dive into measuring the unfortunate things each method tosses out, such as how much they heat the planet, how much power they suck up, how they use up resources we're running out of, and how poisonous they can be. Going through the points, it's using a life-cycle assessment (LCA) to do the math on all of that. Nevertheless, recycling's not perfect since some ways can still produce a disaster, leaving behind nasty toxins, or swallowing down a sizeable amount of water and energy. That's why it's key to ascertain which recycling tricks really ameliorate the issues and aren't simply pretending to be green and good.

1.3.3 VTT vs International Best Practices

We're looking at how good VTT is at recycling batteries and comparing it with the top standards and rules across the world. First, we need to check how well VTT does things against significant rules, such as the upcoming Battery Regulation from the European Union, ideas around keeping resources in use as much as possible, and the rules for being good to the environment according to ISO 14001 standards (European Union, 2020b; Geissdoerfer et al., 2017; ISO 14001). We'll look at what top companies such as Umicore from Belgium, Redwood Materials from the USA, and Duesenfeld from Germany are doing. Companies are unfathomably proficient at recycling batteries and have some really sharp ways of running their business that don't hurt the planet (Heelan et al., 2016; Mayyas et al., 2019). The goal here is to reveal particulars by spotting where VTT is lagging behind significant players and uncover spots where they can become even better.

1.3.4 Development of Strategic Recommendations for VTT

Our main goal is to come up with some solid advice to improve VTT's battery recycling. We're going to adjust suggestions, so they fit what VTT has got going, such as their research tools, promises they've made about policy, and their part in Finland's circular economy goal. In the grand scheme, we are looking at adding marvellously novel recycling technology, getting together with companies that matter, starting test projects and beginning digital tools that track how resources are used from start to finish. But, in all honesty, all the aforementioned advice isn't only for fun. It's to push Finland closer to its dream of not tinkering with the planet by 2035 and being the top dog in sharp recycling and use of materials (Ministry of the Environment Finland, 2021).

By tackling these goals, this thesis seeks to empower VTT to lead future-oriented recycling innovation, enable knowledge transfer, and contribute to a more sustainable battery ecosystem.

1.4 Research Question

The main research question directing this thesis is:

"How can innovative battery recycling technologies and sustainable practices enhance environmental performance and material recovery efficiency at the VTT Technical Research Centre of Finland?"

The following sub questions help to substantiate this one:

What are the limitations of current battery recycling practices globally and at VTT?

Which innovative technologies offer the most promise for improving recovery efficiency and reducing environmental impact?

What are the environmental, technical, and policy implications of integrating these technologies into VTT's operations?

1.5 Use of AI in This Thesis

We have used very few AI tools as auxiliary instruments in this thesis to increase productivity, clarify analysis, and guarantee a high level of academic rigour. AI was used at some crucial points in the thesis process. During the first research and literature review stage, pertinent peer-reviewed papers and official reports about battery recycling, sustainability practices, and technological advancements were found and summarised using AI-powered academic databases and research assistants.

When working on AI-assisted tasks, we ensured the AI use was solidly inside the guidelines for academic ethics. We used AI tools such as Microsoft Copilot for generating ideas and searching sources, and Grammarly for enhancing the quality of writing. We try our best to keep everything above board and by the book.

2 LITERATURE REVIEW

2.1 Types of Batteries and Their Components

Usually divided into two main types, primary and secondary batteries, batteries are essential energy storage tools. Designed for one-use purposes, primary batteries cannot be recharged once they run empty. Commonly consisting of zinc and manganese oxide, alkaline batteries and zinc-carbon batteries which are widely used in daily household appliances including remote controls, clocks, and flashlights are among them (Encyclopaedia Britannica, 2023).

Conversely, secondary batteries also called rechargeable batteries can be discharged and recharged several times, which makes them more sustainable and appropriate for uses requiring increased energy density and lifetime. Lead-acid batteries, nickel-metal hydride (NiMH), and lithium-ion (Li-ion) batteries are the most often used kinds of secondary batteries. Li-ion batteries' low self-discharge, high energy-to-weight ratio, and extended cycle life help them to dominate the market for consumer electronics, electric vehicles (EVs), and grid-scale energy storage (Li et al., 2018). Every kind of battery consists of three basic parts.

2.1.1 Anode (Negative Electrode)

In modern batteries, especially the Li-ion types, the anode is vitally important because it does a couple of significant jobs. Firstly, when you're charging your phone or laptop, this part grabs onto lithium ions and hangs onto them until you need the power. Then, when you're using your device, it lets ions go to power it up. The material they usually construct the anode out of is graphite. It does the job well because it can handle a large amount of charge and recharge cycles without getting all ruined, which is thanks to its special structure and good electrical conditions. In addition, it doesn't hurt that it's not too pricey. Here, it should be pointed out clearly that graphite's role is key for the battery - not simply to last a while, but also to keep your gadgets running smoothly across countless times of charging and using them up (Nagaura & Tozawa, 1990).

Despite some problems, graphite is still what everyone uses for battery applications because we understand how it works and it fits right into how we produce things now. There's a part in the study that clearly addresses trying out new materials for batteries, such as ones with silicon, which could hold more charge, but have issues because they can swell up and break down after a while

2.1.2 Cathode (Positive Electrode)

On the plus side, the cathode of a lithium-ion battery is where all the lithium ions originate from during power output. It's mostly constructed of lithium metal oxide materials that react back and forth during the entire battery life-cycle, that's the redox reaction. When it comes down to what forms an important part of the battery, Lithium Cobalt Oxide ($LiCoO_2$) is top-notch because it packs a lot of energy, making it perfect for powering things such as smartphones and laptops. Then there's Lithium Iron Phosphate ($LiFePO_4$), which doesn't fume under hot conditions and is unintelligibly safe for things such as electric buses and keeping energy stationary. Next in the line of essential compounds, we've got Nickel Manganese Cobalt Oxide (NMC), a real triple-threat offering great energy, the right amount of power, and the flag for safety, driving the show in electric cars.

In practical technology, materials start to become crucial. Usually, you will find the three musketeers $LiCoO_2$ for your devices, $LiFePO_4$ for strong uses, and NMC in those cribs on wheels guiding the push towards electrification. The voltage, energy capacity, safety aspects, and cost of the battery depend much on the cathode material chosen. $LiCoO_2$, for example, offers high energy but is thermally less stable and more costly than $LiFePO_4$ or NMC (Zheng et al., 2018).

2.1.3 Electrolyte

An electrolyte is the component within batteries that enables their charge and discharge. From one end of the battery, the anode, it transports lithium ions across to the cathode and back once more. This work is remarkable since it is driven by a combination including a lithium salt, say Lithium Hexafluorophosphate ($LiPF_6$). They combine it with numerous natural carbonates like Diethyl Carbonate (DEC), Dimethyl Carbonate (DMC), and Ethylene Carbonate (EC). Whether hot or cold, the mixture should be safe, efficient in allowing ions pass through, and hold up without breaking down (Xu, 2004).

The electrolyte causes Solid Electrolyte Interphase (SEI) to develop on the anode surface during first battery charge. Fundamentally, the electrolyte is quite crucial since it is essential to create this layer and facilitates the movement of ions. Since this layer, or SEI, stops the battery from degrading too rapidly, it is quite favourable for it. It lets the lithium ions glide by while stopping the electrolyte from disintegrating throughout the months and years (Renogy, 2024).

The road to clarity and awareness casts a light upon a foundational issue: the danger of liquid electrolytes because they can easily catch fire. To this end, a notable number of researchers aim their focus on trying something different; they are diving into the world, as massive as it is, of solid-state electrolytes. This innovative approach is appealing as it may result in batteries that store more energy and are less prone to overheating. However, transitioning to the new system poses its own set of hurdles, such as expanding the technology to larger scales without compromise, and smoothing over where it connects with other technologies.

There's a part inside most new batteries that's supposed to keep the two ends, the anode and cathode, from touching each other but let’s ions move around. They call it a separator, and it's analogous to a sponge between them. For you, it is very much apparent that this particular one is vitally important because, if those ends touch, it could cause the battery to short-circuit (Nagaura & Tozawa, 1990).

To ascertain how to recycle batteries properly, it's vitally key to really grasp the structure and chemistry of different battery types. This is because as the world moves more towards using renewable energy and making cars that run on electricity, more batteries are needed. The things that go into making batteries, including Lithium, Cobalt, Nickel, Manganese, and Lead, are hard on the environment and take a lot of resources to get.

Not to mention, if they're not taken care of in the right way when they're done being used, there are some serious environmental and ethical issues. According to Gaines (2014), there may be a rather redeeming aspect in understanding how batteries are made and determining, through careful analysis, how to successfully deal with them in their lives.

2.2 Existing Recycling Methods and Technologies

Recycling spent batteries has become essential for resource conservation and environmental sustainability as the use of lithium-ion batteries (LIBs) in consumer devices, electric vehicles (EVs), and renewable energy storage increases exponentially. In addition to recovering precious vital raw resources, including lithium, cobalt, and nickel, recycling lessens the environmental hazards presented by hazardous products. To solve these problems, several recycling techniques are either in development or use already. Among them, the most often used are direct recycling, hydrometallurgical, and pyrometallurgical methods.

2.2.1 Pyrometallurgical Recycling

Under very high temperatures usually above 1,500°C, pyrometallurgy is a thermal treatment method whereby end-of- life LIBs are smelted. While other materials like lithium and aluminium are often lost in the slag or require additional processing to recover, the process breaks down organic binders and burns off the electrolyte to produce a metallic alloy including recoverable materials like cobalt, nickel, copper, and iron (Wang et al., 2014).

Though a developed and generally accepted industrial process, especially at Belgian facilities like Umicore, pyrometallurgical recycling is highly energy-intensive and produces notable CO_2 emissions (Gaines, 2018). Generally speaking, the process also calls for pre-treatment steps like battery discharge and casing removal, which add complexity and expenses.

2.2.2 Hydrometallurgical Recycling

Hydrometallurgy extracts metals from shredded battery materials by chemical leaching using aqueous solutions (usually acids like sulphuric acid mixed with reducing agents like hydrogen peroxide). Under milder temperature conditions than pyrometallurgy, this approach enables selective and high-purity recovery of lithium, cobalt, nickel, and manganese (Harper et al., 2019).

The acceptable thing about hydrometallurgy is that it doesn't use a lot of energy and it can save lithium that is usually gets added away in the pyrometallurgy methods. Two companies, Aqua Metals and Redwood Materials, are working hard to develop methods in hydrometallurgy that will help recycle EV batteries and industrial waste (AquaMetals, 2023). But there's a downside too, because this method of recycling needs harsh chemicals that need to be carefully handled so they don't cause more pollution. To understand this, a clear and unbiased evaluation is important.

2.2.3 Direct Recycling

Closed-loop recycling, also mentioned as direct recycling, takes a fresh and hopeful stance towards keeping cathode materials, like lithium nickel manganese cobalt oxide or LFP, whole rather than splitting them up. The main thought is that by physically separating, adding lithium back, and pumping new life into the active components, we can maintain their chemical and structural uses.

Research institutions such as the ReCell Centre, which the U.S. Department of Energy supports, are pushing forward with direct recycling (ReCell Centre, 2023). This method of recycling really helps because it uses less energy and fewer chemicals, saving money and being better for the environment compared to bygone-era methods. Although this recycling method is still being tested and hasn't quite hit the mainstream market, it holds a lot of promise for widespread use in the next ten years, especially for the new types of batteries we're starting to see more of.

In summary, each recycling technique offers distinct advantages and limitations. Pyrometallurgical methods are robust but energy-intensive, hydrometallurgy offers greater material recovery with less energy input, and direct recycling holds promise for future circular economy models. An optimal battery recycling system may integrate elements of all three techniques depending on battery chemistry, economic constraints, and environmental regulations.

2.3 Challenges in Current Recycling Processes

Despite the increasing global emphasis on battery recycling as a cornerstone of the circular economy, the sector faces numerous operational, economic, and regulatory obstacles that hinder its widespread adoption and efficiency. These challenges must be critically addressed to make battery recycling both environmentally sustainable and economically viable.

2.3.1 Complex Battery Architectures & Material Integration

Lithium-ion batteries used in phones and electric cars are complex devices with science and safety features, making them difficult to dismantle and recycle. Essentially, cutting into one of the batteries to recycle it is tough because they've got so many different metals, such as lithium, copper, and aluminium, all mixed, making machines that can sort and clean them up somewhat useless. Batteries are constructed of a large number of tiny cells all squished and stuck together with a forceful glue, and wrapped up in materials that keep them from catching fire or getting damaged (Harper et al. 2019). This melting pot of materials makes using robots to sort and purify them exceptionally harder (Gaines, 2018). Because it's so hard to grasp the great items inside without some serious manual work, making the recycling process larger and cost-effective isn't happening today.

2.3.2 Economic Barriers and Market Volatility

Economic feasibility issues make it tough for recycling to work out sometimes. Recycling generates money through the sale of materials they get back, such as lithium, nickel, and cobalt. But the prices for materials can jump around a lot because of things such as market demand increases, political issues, and how much of the materials can be mined at a time.

From 2017 to 2021, cobalt prices fluctuated greatly, making recycling profits difficult to predict (Alves Dias et al., 2018). On top of that, to use new recycling methods, such as taking metals out of solutions or breaking materials down directly, you have to spend a lot of money at the start. This cost goes towards research, special machines and ensuring fully you're not harming the environment much with dangerous waste. ReCell Centre (2023) mentioned how individuals or businesses in smaller or developing places face obstacles in starting or growing their recycling operations.

2.3.3 Environmental and Occupational Safety Risks

Taking batteries apart, moving them, or heating them in certain ways, such as when metals are extracted with heat (that's called pyrometallurgy), can be unfathomably risky. If it's not done right, batteries could catch fire on their own or let out dangerous gases, including hydrofluoric acid. Also, places that recycle batteries but don't have forceful rules or the ways they do it aren't that great, could be a threat for the people and the nature. Batteries have some really poor resources in them, such as flammable components subject matter called fluorinated compounds, heavy metals and liquids that can dissolve things (scientists call them organic solvents).

In poor countries, there are a lot of recycling spots that don't have the gear or setup to keep toxic things from getting into the air and ground. Places put the workers and our environment at risk of long-term damage.

According to Bobba et al. (2018), when batteries that are almost down aren't sorted out correctly, or they get ruined during moving and keeping them somewhere, there's a larger chance they could start a fire or cause short circuits. This mostly happens because there isn't a set direction everyone follows for picking up old batteries: checking them out, and taking them apart. The clear and unbiased evaluation says it adds to the danger.

2.4 Innovations in Battery Recycling Technologies

Portable electronics, renewable energy systems, and traditional recycling techniques such as pyrometallurgy and hydrometallurgy face criticism for their inefficiencies, high energy consumption, and environmental effects as the worldwide demand for lithium-ion batteries (LIBs) continues to soar, fuelled by the spread of electric vehicles (EVs). New and creative battery recycling technologies are thus under development to improve material recovery rates, lower processing costs, and assist the transition towards a circular economy. Two outstanding projects leading the front stage in this movement are the ReCell Centre and Redwood Materials.

2.4.1 Redwood Materials

Originally launched in 2017 by former CTO JB Straubel, co-founder of Tesla, Redwood Materials has become a leader in next-generation battery recycling. Recovering and improving important battery components such lithium, nickel, cobalt, and copper from end-of-life batteries and scrap materials helps the company to construct a circular supply chain for lithium-ion batteries.

Redwood Materials claims to have developed sophisticated recycling techniques that recover more than 95% of important materials, which may subsequently be reused in the manufacture of fresh batteries (Wikipedia, 2025). Redwood dramatically lowers energy consumption and greenhouse gas emissions by combining hydrometallurgical and mechanical separation processes, unlike conventional pyrometallurgical methods involving high temperatures.

This closed-loop approach not only mitigates the environmental harms associated with mining but also enhances supply chain resilience by sourcing materials domestically. Redwood has partnered with several major companies, including Panasonic, Ford, and Amazon, to scale its operations and integrate recycled materials back into the battery manufacturing process (Redwood Materials, 2023).

2.4.2 ReCell Centre

Managed by Argonne National Laboratory, the ReCell Center was created by the U.S. Department of Energy (DOE) as a groundbreaking effort in the public sector for battery recycling improvements. The centre has a main focus on direct recycling, which is a technique that has the plan to keep battery materials, including cathodes, anodes, and separators, working properly, so they can be reused with hardly any processing. The centre does not simply or only focus on battery recycling but also strives to preserve the functional integrity of materials (ReCell Center, 2023).

Recycling directly is exceptionally better than the regular ways we used to do it. In the past, this was hard to fathom, but we don't have to melt things with super-hot fire (Pyrometallurgy) or use forceful acid to dissolve materials now (Hydrometallurgy). What happens instead? There are genius scientific methods that just touch up the things we need to use again without messing them, keeping everything working just right. This great technique produces everything cheaper, better for the planet, and saves a large amount of energy, too.

Among other things, the ReCell Centre has a plan to make recycling for lithium-ion batteries both good for the planet and cost-effective. They're doing this by teaming up with universities, places that produce laws, and companies that are into things. Their mission is centred on helping the U.S. get to a location where they can be self-reliant for energy and super eco-friendly.

Seeing as Redwood Materials and the ReCell Centre are leading the charge, it's key to verbalize about how recalibrating how batteries get recycled is a massive deal today. Public teams and private corporate institutions are getting it done with fresh ideas that not only save cash but are also easier on the planet. At this singular time, there's a significant movement towards not bothering the earth much when catching those key components we need to produce more batteries, thanks to new ways of doing things. Without destroying the environment nearly as much, new methods support sizeable goals in looking after our world by getting back materials that are essential, without needing to dig the earth up as much. This ensures getting ready for a future where we reuse and look after resources way better and ensures our battery technique is solid and doesn't hurt the planet.

2.5 Environmental Rules and Policies

The world's boosting its technique on being green and spinning things back around through what's known as the circular economy. Because of this significant push, it's vitally important that there are rules and plans in place for things such as recycling batteries. We must tackle all the unfortunate things that happen when batteries aren't thrown away properly and also think about taking advantage of the old batteries to get hold of precious materials. With more people wanting batteries--especially for things such as electric cars and saving energy with green technology there's a heavier push for ensuring fully-used batteries don't only turn into trash. They're working harder to poke people toward getting better at recycling, cutting down on wasting resources, and using fewer new resources. To grasp all of this, there are several key rules and agreements from different places around the world that lay down the law on how to recycle batteries correctly.

2.5.1 European Union Regulations

In the European Union, there's the Battery Directive that they came up with in 2006 and then decided to upgrade in 2013. This particular one is essentially centred on being entirely sure: batteries, such as the ones in your phone or significant industrial ones, don't simply sit in a landfill, destroying the planet. They have to meet tough rules now for how to collect, recycle, and dispose of batteries without harming the environment. Specifically, the directive's got strict recycling goals. For the small batteries we use in gadgets, 65% of their weight has to be recycled, and for the beefier industrial batteries, it must be 75% (European Commission, 2020b). And that's not only random numbers, they mean business in ensuring a significant tranche of batteries gets a second chance instead of polluting the earth.

What's more, the rule book doesn't simply talk, it puts the pressure on the companies making batteries. They must be in it for the long haul, looking after their batteries from the moment they're produced 'til the end of their life. This is called Extended Producer Responsibility (EPR), and it's a significant deal because it forces companies to come up with batteries that won't be a nightmare to recycle. With the appropriate amount of resolve, one can see how this approach might be what we need to make technology greener and our planet a bit safer.

The EU Battery Regulation (2020/2093) and the European Green Deal (2019) have a plan to take on the issue of battery waste, with a significant goal of making everything more resource-efficient and pushing towards zero emissions. They focus on collecting, treating, and recycling every battery better, while also keeping a close eye on where the materials for batteries come from. What they want to achieve includes getting back much-needed materials, such as lithium, cobalt, and nickel, because they are vitally key for moving into energy that doesn't dirty the planet (European Commission, 2020).

2.5.2 United States Regulations

Most of the time, it is not deniable that the United States handles hazardous trash a little differently, especially with batteries containing harmful elements like lead, mercury, and cadmium. They understand the Resource Conservation and Recovery Act (RCRA), which basically outlines how dangerous materials should be removed and recycled.

Next comes the 1996 Mercury-Containing and Rechargeable Battery Management Act. This one is about being very sure rechargeable batteries are recycled correctly to prevent the regrettable elements, cadmium and mercury, from harming humans. America does not, however, set specific targets for the number of batteries that should be recycled, unlike other European countries. Rather, they let every state create their own rules and hope businesses would simply offer to do the right thing.

The ReCell Centre is focused on increasing direct recycling methods for lithium-ion batteries, therefore lowering costs and environmental impact (ReCell Centre, 2023). Under Argonne National Laboratory, this is a major agreement from the U.S. government. Furthermore, the U.S. Department of Energy (DOE) is heavily supporting technological research aimed at improving and reasonably pricing recycling batteries. This initiative reflects the government's commitment to reduce not only the financial expenses but also the negative effects on the surroundings resulting from battery disposal, or in a similar manner.

2.5.3 China's Battery Recycling Policy

China is very deeply into making and using batteries, especially for electric cars. The country's got several rules now for recycling old batteries. Before, determining through careful analysis how to successfully deal with all those used batteries was a significant problem, but now they're trying to become better at it. They even set up a special system to collect old batteries, make the recycling process better, and ensure batteries can be recycled into new ones. There's this group, the China Battery Industry Association that says we should have certain ways to deal with car batteries after they're no longer good anymore. Also, as part of their significant plan to be nicer to the environment between 2016 and 2020, China decided it would boost its recycling techniques, so it can reuse materials and not be wasteful.

2.5.4 International Agreements and Future Trends

There's a significant concern: the Minamata Convention about Mercury, which was set up in 2013 it's trying to cut down on how much mercury we use in things, especially batteries. In addition, it's telling us we need to take care of throwing and recycling batteries safely if they've got mercury in them. This is a hefty issue for the recycling people because it's really about those nickel-cadmium (Ni-Cd) batteries and also some alkaline ones. The final analysis will reveal, it affects how we recycle kinds of batteries on a large scale.

Ensuring fully, we waste fewer resources and recycle more is now vitally key because of the Sustainable Development Goals, or SDGs. Specifically, there is a goal, SDG 12, that's centred on using resources wisely and not destroying things we could reuse. With the appropriate amount of resolve, one can notice how this significant plan is not only trying to make us throw away less, but also is wholly invested in finding better ways to deal with old batteries. Because that way, we don't simply dump them somewhere and forget about them, we try to get back the useful components. This entire thing, which started globally, really wants to change how we remove waste and construct everything about keeping what's valuable from what we toss (United Nations, 2020).

In all honesty, ensuring the responsible recycling of batteries is really significant because of how technology especially battery-powered technology, such as electric vehicles (EVs) and systems that store renewable energy is becoming unfathomably popular all over the world. Rules and plans for recycling from places such as the EU, the U.S. and China are vitally important because they help us recycle better and come up with smarter ways to process batteries.

The truth is, we've never needed forceful recycling programs as much as we do now. Also, significant global promises, through things such as the Minamata Convention and the Sustainable Development Goals (SDGs), are highlighting how everyone around the world is agreeing to do less harm to our planet and work towards a future that won't blunder our environment.

2.6 Future Trends in Battery Recycling

As everyone starts buying more electric cars, gadgets, and large batteries to store energy, the need to get better at recycling lithium-ion (Li-ion) batteries is soaring. Why? Because our planet's going to need a lot more batteries soon, and if we don't ascertain how to reuse the things inside them, we're in for a rough ride. It is somewhat significant to make battery recycling better, more efficient, cheaper, and less harmful to Mother Earth. In addition, if we become proficient at cycling resources back into use instead of destroying them, there may be some sort of redemption in how we handle technology waste. It appears that the way we recycle batteries is going to change. Innovation, marvellously novel company ideas, and rules promoting green conditions and not letting great items go to waste are leading the charge.

2.6.1 Advanced Recycling Technologies

New technology is being created to fix the problems with recycling batteries. At the moment, the way we recycle them, such as pulling them apart mechanically or finding different chemicals, it's tough on the environment and uses a lot of energy. But there's good news because advanced recycling technologies are being worked on to recover battery materials more effectively and less harmfully. This is all part of the road to clarity and awareness in how we handle recycling and helping the planet.

Direct recycling is exceptionally positive and getting a lot of attention because it's innovative. Instead of doing things the bygone-era way, where they would break down all the battery parts and start from scratch, this method focuses on taking the main working components, such as the cathode and anode, and producing them as good as new without destroying them much (ReCell Centre, 2023). The goal here is not to use up as much energy or produce a large carbon footprint compared to the normal way of recycling things. There's the ReCell Centre, and individuals are right at the front of finding methods to bring parts back to life and work perfectly, which could end up saving a substantial amount of money and make things more efficient. Invariably, this might really change the trade, for how we handle recycling, especially for batteries, by looking into early efforts from groups such as the ReCell Centre (Manthiram, 2017).

Also, people are looking at other acceptable methods to get back resources such as lithium, cobalt, and nickel from used-up batteries better and without doing so much harm. Here, it should be pointed out clearly that they're trying out bioleaching, where you use bacteria to pull out the good metals, and pyrolysis, which is heating things up a lot until they break down.

2.6.2 Integration of AI and Automation

What's exceptionally positive is that AI and machines doing things on their own are going to completely change how we recycle batteries. Sharp computer programs, or AI, are going to be able to pick out and separate batteries unfathomably well so we don't mix the wrong types together, making everything cleaner and reducing mistakes. Also, by using machine learning (which is, in a direct sense, to teach computers to think better through the months and years), AI systems can ascertain which recycling methods are the best for each sort of battery resources. This makes it exceptionally easier to decide how to successfully deal with and sort all the materials right.

Some recycling places are starting to use sharp sorting systems to break down and sort battery parts. The goal was to make sorting faster and more accurate, while also cutting down on the cost of labour, making fewer mistakes, and helping recycle things better.

If we really summarize, at its simplest core, keeping the recycle machines running longer and better is something AI can do by determining, through careful analysis, the problems before they even happen. This way, the machines won't break down as much, which means they work more smoothly.

2.6.3 Circular Economy Business Models

In the future of battery recycling, a major trend is going to be following circular economy (CE) principles within the battery industry. A circular economy is centred on making products last longer, cutting down on trash, and taking the most advantage of resources. When it comes down to batteries, this means repairing old batteries, finding new uses for battery parts, and creating systems where materials are always being recycled and used again, instead of thrown away. This unambiguously demonstrates the clear and unbiased evaluation of how managing our resources better can big change things.

In the electric vehicle (EV) sector, the battery-as-a-service (BaaS) model is becoming more well-liked. It's not only just about stinting on battery production but also cutting down on how much it hurts the environment. This setup involves battery makers, energy providers, and recycling businesses working hand in hand. They focus on keeping batteries going for longer by continuously refurbishing, maintaining, and recycling them. Redwood Materials and Tesla are striving to achieve self-sustaining supply chains. Through efforts, the materials used in batteries get recycled and utilized over and over again (Redwood Materials, 2023).

Companies are also working on battery units where you can just swap out broken parts instead of tossing the entire thing. By doing that, materials are used more effectively, and recycling becomes far easier. A sharp reader wouldn't be surprised to hear about companies stepping it with BaaS and neat build-your-own battery systems.

2.6.4 Policy and Regulatory Advancements

Amazingly, or maybe not, governments all across are tightening regulations on how we handle batteries' disposal and recycling. The rules and legislation that nations create will be absolutely crucial in determining how we recycle batteries going forward as more and more battery waste accumulates. With a battery legislation set for 2020, the EU thinks that other nations may follow suit and has some major objectives for returning resources. This regulation also states that we should recycle better, that those manufacturing batteries have more responsibility, and that we should consider the environment as we generate batteries.

The Paris Agreement describes the worldwide endeavour to be carbon neutral, and it will definitely force nations and businesses to intensify their efforts to reduce the carbon footprint of their energy storage devices, such as batteries. According to the International Energy Agency's projection for 2022, the extended producer responsibility (EPR) model will most likely be followed more rigorously (International Energy Agency [IEA]). After we're done using their items, this approach helps producers to handle their whole lifetime, including the recyclability aspect. This whole thing is, rather directly, a perceptive story about our direction with environmental initiatives.

Governments might put money into different spots, essentially everywhere better by injecting cash, assisting places that recycle resources, dealing with both private companies and themselves to support super eco-friendly making, and starting with green. Frankly, this section allows people and companies to jump in and do their part in helping the planet more easily.

2.6.5 Focus on Sustainability and Ethical Sourcing

More people are paying attention to issues with people's treatment in mining jobs and environmental damage. This is the reason a heavy issue we will see more of in battery recycling is guaranteeing that it's fully done in an eco-friendly manner and that nobody is being treated unfairly. My assumption is that businesses will begin to give greater thought to the sources of their battery materials, such as cobalt, nickel, and lithium. They will want to make sure supplies are acquired in a way that does not damage people or the earth.

Also, making batteries that last longer, are less problematic to recycle, and don't have as many nasty things in them is something companies will probably put money into. This subject matter not only cuts down on grasping new raw materials from Earth but also means we throw away fewer things. Regardless, if you want to, you might think this is a nifty technique to back up saving the planet by adjusting battery technology.

In the push for a better planet, recycling batteries is becoming vitally important because we're all starting to use electric cars and solar panels more. Sacred subject matter called advanced technology, building things so they can be taken apart and used again and ensuring laws fully support recycling are the ideal location. More people need sharp, cheap, and green ways to deal with old batteries quickly. Invariably, you should see significant innovations, such as recycling batteries without breaking them down completely, robots that sort things out--and batteries constructed in pieces, becoming important, so we can keep up with all the batteries we'll have. Also, having laws that push companies to recycle more, and business ideas that are centred on reuse and recycling will ensure we can keep our planet clean while we use all of the aforementioned great technology.

3 RESEARCH METHODOLOGY

With particular attention on creative technologies and environmental solutions developed or sponsored by VTT Technical Study Centre of Finland, this chapter describes the study technique applied to investigate the future of battery recycling. This study uses a qualitative secondary data analysis method considering the technological and institutional character of the research topic. The chapter covers research design, data collecting strategies, secondary data sources, analytical approaches, and ethical issues.

3.1 Research Design

This work employs a qualitative exploratory research technique to evaluate novel technologies and sustainable battery recycling strategies. It centres on the Finnish VTT Technical Research Centre's efforts. A qualitative approach is more suited than statistical generalisations or causal hypothesis testing (Creswell, 2014, p. 186) when examining complex, transdisciplinary, fast-moving subjects that call for a comprehensive contextual knowledge. Capturing the nuances of institutional activities, sustainability transitions, and technological innovation in the battery recycling sector calls specifically for this approach.

Because of the exploratory nature of the research, dynamic and understudied topics can be flexibly investigated. In battery recycling, where ongoing developments are occurring in fields like hydrometallurgy, direct cathode recycling, lifetime assessment (LCA), and the application of the circular economy, this is especially pertinent. These advancements have a strong connection to interdisciplinary fields like environmental engineering, materials science, policy formation, and industrial sustainability systems, all of which gain from narrative analysis and qualitative interpretation (Saunders, Lewis, & Thornhill, 2019, p. 175).

Unlike studies based on primary data collection via polls or interviews, this one depends totally on secondary data analysis. This decision is methodologically justified for numerous reasons. Firstly, secondary data analysis as a methodological approach has gained increased recognition for its consistency and efficiency (Johnston, 2017). Secondly, peer-reviewed journal publications, technical white papers, institutional reports, policy frameworks, and project documentation produced by VTT and associated EU research initiatives represent the initial instances of high-quality and extensive data that is currently accessible. Moreover, these sources provide timely, trustworthy, and relevant insights on current advancements in battery recycling technology and VTT's environmental plans without necessitating the initiation of new empirical data collection.

Exploratory research is especially helpful when dealing with scattered data or newly developing fields since it helps researchers to uncover patterns, trends, and fresh ideas for theory and practice (Stebbins 2001, p. 7). Comparatively, Yin (2018, p. 15) emphasises how well qualitative exploratory designs handle "how" and "why" questions about institutional goals and execution policies. This effort intends to analyse, critically, VTT's impact on the development of environmentally friendly alternatives for European battery recycling.

Furthermore, time-efficient and cost-effective secondary data analysis offers broad coverage of policy developments, expert opinions, and global trends. Within a logical analytical framework, this method helps the researcher to carefully integrate and evaluate several facets of battery recycling innovation, including technological, environmental, financial, and regulatory concerns. This work triangulates results from several secondary sources to maintain theoretical rigour, practical relevance, and analytical depth.

3.2 Research Strategy

This work uses a case study approach with the main analytical unit being the VTT Technical Research Centre of Finland. In current real-world settings, when the researcher has little to no control over the events under examination, the "how" and "why" questions are best answered with the case study approach (Yin, 2018, p. 15). This methodological choice corresponds with the research objectives of analysing how a top European academic institution supports sustainability-driven developments in battery recycling.

VTT's established leadership in battery research, environmental technology, and applied industrial innovation throughout the European Union is the basis for choosing it as a case study. Due to its active involvement in developing lifetime assessment tools, eco-design methods, and closed-loop recycling technologies, VTT is a highly relevant and informative scenario (VTT, 2023a). By concentrating on a single, comprehensive case, the study may investigate the technological advancements, institutional dynamics, and strategic decisions that characterize VTT's contribution to sustainable battery lifetime management.

When the research attempts to generate contextual and interpretive insights rather than test generalizable hypotheses, case studies are highly useful (1995, p. 135). Similarly, Cre-swell and Poth (2018, p. 98) stress that researchers can "illustrate a process, a program, or an activity" with detailed descriptions and thematic depth by using the case study approach. This strategy is particularly pertinent to comprehending how VTT uses applied research and cross-sectoral partnerships to address global environmental concerns.

Additionally, methodological triangulation is facilitated by using a case study technique in conjunction with secondary data analysis, which increases the results' comprehensiveness and dependability (Bowen, 2009). Examining scientific publications, project reports, EU policy briefs, and VTT’s sustainability records guarantees a comprehensive knowledge of the problem from many data sources and stakeholder points of view. To increase the validity and dependability of the findings in this thesis, we established triangulation by means of data, methodological, and theoretical approaches. Data triangulation was the method of compiling data from several secondary sources, including technical reports, peer-reviewed journals, conference proceedings, and EU policy documents. Methodological triangulation was achieved with NVivo (trial version) software for thematic classification, hand content analysis for interpretation rich in context, and visual aids like graphs and system diagrams. Combining many frameworks, such as lifespan assessment, sustainability transitions, and circular economy theory, theoretical triangulation offered a multifarious perspective of VTT's innovations.

3.3 Data Collection Method

With an especially focus on the function of VTT Technical Research Centre of Finland, this study depends just on secondary data to investigate novel technologies and environmental methods in battery recycling. Especially in fields marked by fast technological progress and substantial documentation, secondary data analysis is a useful technique in qualitative research when the objective is to get deep insight into a subject by means of existing resources (Johnston, 2017, p. 622). By means of wide coverage of the scientific, institutional, regulatory, and technological facets of battery recycling, free from the limitations of primary data collecting, the exclusive use of secondary sources enables.

Acceptable resources, such as universities, significant institutions, and professional sites, gave us many second-hand sources. We grasped sources in a very careful manner so that the study's information is trustworthy, full of details, and checked from different angles. They helped understand an entire lot about how battery recycling technology and ways to keep things good for the planet are changing, focusing on what's going on at the Finnish VTT Technical Research Centre. This was important for the clear and unbiased evaluation.

3.3.1 Peer-reviewed academic journal articles

Peer-reviewed scholarly publications give the theoretical and empirical basis for this research since they offer exact, validated insights into the evolving topic of battery recycling. Many have focused on the capacity of hydrometallurgical and pyrometallurgical processes to recover essential basic elements, including nickel, cobalt, and lithium, from spent lithium-ion batteries. Liu et al. (2019, p. 802) underlined in their exhaustive study of lithium recovery techniques that, although being less detrimental to the environment than conventional smelting, hydrometallurgical operations need careful pH control and wastewater treatment. Although hydrometallurgy is scalable, its great energy consumption and carbon emissions cause major issues (Liu et al., 2019, p. 853).

Apart from theoretical models, including the circular economy, lifecycle analysis (LCA), and extended producer responsibility (EPR), these academic publications provide conceptual instruments for understanding the larger consequences of technical innovations. New research also highlights methods like direct recycling, which reduces environmental effects and preserves more of the structure of the battery (Harper et al., 2019, p. 13).

3.3.2 Technical reports and white papers

Technical reports and white papers from the VTT Technical Research Centre of Finland and associated companies mostly offer real-time documentation of pilot-scale projects and roadmaps. Describing how VTT employs research at the operational level, that is, its involvement in projects like BATCircle and ReLieVe, aimed to boost the sustainability and efficiency of battery recycling in Finland and the EU. These materials are absolutely essential (VTT, 2024a).

For example, Finland's national circular economy strategy and the EU Green Deal's climate targets line with the hydrometallurgical pilot lines and closed-loop design initiatives detailed in VTT's 2023 report on circular battery ecosystems (VTT, 2023a, pp. 6–9). These papers offer understanding of how VTT might promote an industrial symbiosis among battery manufacture, recycling, and reuse.

Reports under Horizon Europe also highlight how the EU has prioritised domestic recycling infrastructure above decreasing dependency on imported raw materials. By means of these papers, the study gains more knowledge regarding the link between policy and technology as well as VTT's contribution in implementing sustainable recycling technologies inside EU frameworks.

3.3.3 Conference proceedings

Pre-publication observations, creative dialogues, and stakeholder opinions can all be recorded rather well by conference proceedings from events like the International Battery Recycling Congress (ICBR) and the World Circular Economy Forum (WCEF). These conferences provide important forums for information flow as researchers from VTT, and other research institutes present their findings.

At ICBR 2023, VTT researchers presented direct recycling solutions that are, ones aimed at recovering functional battery-grade components without compromising the battery cathode structure. This method reduces environmental effects and processing time (ICM AG, 2023). Often include talks from government agencies, academic institutions, and corporate sector players, these seminars also offer insight into real-world industrial challenges and collaborative opportunities. Apart from scholarly and institutional publications, these platforms provide a forward-looking viewpoint on the direction the field is following, including changes in policy, investment patterns, and legal challenges.

3.3.4 Policy Documents from the European Commission

Understanding the legislative environment affecting battery recycling innovation in Europe calls for a close reading of European Commission policy publications. Overcoming the past Battery Directive, the EU Battery Regulation (Regulation (EU) 2023/1542) presents a legally enforceable framework that controls the complete battery lifetime from design and production to reuse, repurposing, and recycling.

One of the primary principles of this guideline is the necessity of adding recycled elements into new batteries. New industrial batteries must, for example, employ 85% lead from recycled sources, at least 16% cobalt, and 6% lithium by 2031 (European Commission, 2023, p. 39). The rule also mandates the use of digital battery passports, which allow for real-time tracking of the origin of materials, carbon footprint, and recycling history.

Another key framework is the EU Circular Economy Action Plan (European Union, 2020a), which outlines strategies to separate economic growth from resource use. This approach underlines the statutory concept of Extended Producer Responsibility (EPR), which holds producers operationally and financially responsible for post-consumer waste management. EPR promotes the design of more battery sector recyclable products and investment in end-of-life treatment technology.

The rules we are contemplating. They do more than just ensure that corporate institutions in the EU follow the same rules. They are also a bit pushing significant places, such as VTT, to think up new things. Not only that, but they tinker with how battery recycling systems are planned out and how significant they can become, because systems have to meet certain rules and regulations.

3.3.5 Sustainability Reports and Strategy Documents

VTT Technical Research Centre of Finland and its associated EU-funded projects provide detailed insights into operational methods, environmental KPIs, and collaborative governance frameworks through their sustainability and strategy reports. VTT regularly aligns its research goals with the European Green Deal through its sustainability plan documents, which emphasise resource efficiency, climate neutrality, and the digitisation of industrial ecosystems (VTT, 2023b, pp. 7–12). The way that their involvement in initiatives like BATCircle (Finnish Batteries) and ReLieVe (Recycling Li-Ion Batteries for Electric Vehicle Applications) demonstrates how institutional objectives are translated into useful research.

Coordinated by VTT and supported by the Strategic Research Council of Finland and Horizon Europe, BATCircle seeks to enhance battery metals' material efficiency through the creation of regional value chains. Closed-loop ecosystems include colleges, mining businesses, manufacturers, and recyclers (BATCircle, 2024). Comprising Eramet, BASF, and VTT, the cross-border collaboration Re LieVe investigates direct recycling and hydrometallurgical techniques. VTT evaluates environmental trade-offs, material recovery yields, and process scalability (ReLieVe Project, 2023) for instance using lifecycle assessment (LCA) techniques.

These institutional publications represent long-term goals, funding strategies, and research priorities in addition to serving as archives of project progress. They demonstrate how VTT is a component of a broader system of mission-oriented innovation and operationalises EU policy frameworks into technical solutions.

3.3.6 Scientific Databases

Using scientific databases including Scopus, ScienceDirect, SpringerLink, and Google Scholar, a thorough search was undertaken for peer-reviewed papers and grey literature on battery recycling techniques. These platforms were selected for their ability to provide both basic and current research on topics including direct recycling, lifecycle assessment (LCA), hydrometallurgical and pyrometallurgical processes, and circular economy models.

SpringerLink was especially helpful for obtaining technical conference proceedings, while Scopus and ScienceDirect provided access to high-impact publications in environmental sciences and chemical engineering. Notwithstanding its lack of selection, Google Scholar was useful for finding institutional documents, white papers, and preprints that were not found in other databases. Though the above sources cover a huge area, we find them very useful for our related information source.

By ensuring that data sources were triangulated, this multi-database method enhanced the findings' validity and comprehensiveness. Gusenbauer and Haddaway (2020, p. 205) suggest that accessing a variety of scientific databases improves the calibre and scope of systematic literature reviews by accounting for differences in indexing practices and disciplinary scope.

3.3.7 Technology and Industry News Sources

Data were also gathered from reliable technological and industry news websites, including Green Car Congress, Recharge News, and Battery News Europe, to supplement the scholarly literature and document changing industry practices. These sites offered current information on pilot projects, real-world applications, regulatory updates, and battery recycling commercialisation tactics. Green Car Congress, for instance, provided regular updates on legislation changes and advancements in electric car battery recovery, while Re-charge News and Battery News Europe showcased partnerships and infrastructure developments throughout the EU. The academic analysis was enhanced by the practical, application-oriented viewpoints that these industry sources contributed, which also gave a current understanding of the intersections between innovation, policy, and industrial activity in battery recycling.

The review concentrated on materials released between 2015 and 2025, a time of greater innovation in energy storage, electric transportation, and environmental regulation, to preserve relevance and technological contemporaneity. Important technological and strategic advancements, including life cycle assessment (LCA), digital traceability systems, pyrometallurgy, hydrometallurgy, direct recycling, and the integration of the circular economy, were prioritised.

Research on energy and sustainability, in particular, has generally recognised secondary document analysis as a rigorous and effective approach to studying complex systems (Bowen, 2009, p. 32). This strategy also fits in with qualitative case study approaches, which allow researchers to thoroughly analyse institutional responses to sustainability issues (Yin, 2018, p. 104).

3.4 Summary of Secondary Data Sources

As mentioned in earlier sections, this study also utilized several secondary data sources. The following Table 1 outlines the documents considered as a source of secondary data, including their publication year, title, author(s), and type.

Year published	Title	Author	Type of document
2018	Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on	Bobba, S, Mathieux, F., Ardente, F., Blengini, G., Cusenza, M., Podias, A. & Pfrang, A.	Peer-reviewed Articles

	modelling energy flows		
2024	Finland-based Circular Ecosystem of Battery Metals – BATCircle2.0 Final Report (2021–2024)	BATCircle2.0 - Aalto University	Institutional Report
2017	An outlook on lithium-ion battery technology	Manthiram, A.	Peer-reviewed Articles
2018	Unsupervised machine learning accelerates solid electrolyte discovery	Zhang, X., Tang, B. & Zhou, Z	Peer-reviewed Articles
2019	Recycling of spent lithium-ion batteries in view of lithium recovery: A critical review	Liu, C., Lin, J., Cao, H., Zhang, Y., & Sun, Z.	Peer-reviewed Articles
2024	Leaching of NMC industrial black mass in the presence of LFP	Zou, Y., Chernyaev, A., Ossama, M., Sipi Seisko, S. & Lundström, M.	Scientific reports
2019	European Green Deal	European Commission	EU Policy and Legal Documents

2022	Hydrometallurgy for EV batteries	Ali, A., & Adjoumane, M.	Science publication
2018	The role of cobalt in supporting the global energy transition	Alves Dias, P., Bobba, S., Carrara, S., & Plazzotta, B.	EU publications
2023	AquaRefining: The future of sustainable battery recycling	AquaMetals	Press releases
2023	Council adopts new regulation on batteries and waste batteries (Regulation EU 2023/1542)	Council of the European Union	Press releases
2023	Lithium-ion battery recycling: The ReLieVe project confirms the success of the technology developed by Eramet	Eramet	Technical report
2024	Battery recycling	Eramet	Technical report
2020	A new Circular Economy Action Plan for a cleaner and more	European Union	EU Policy and Legal Documents

	competitive Europe		
2020	Circular Economy Action Plan: For a cleaner and more competitive Europe	European Commission	EU Policy and Legal Documents
2025	Batteries	European Commission	EU Policy and Legal Documents
2023	REGULATION (EU) 2023/1542 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL	European Union	EU Policy and Legal Documents
2019	The ethical principles of research with human participants and ethical review in the human sciences in Finland	Finnish National Board on Research Integrity (TENK)	Organizational Report
2021	Strategic program to promote a circular economy	Ministry of the Environment Finland	Organizational Report

2019	Recycling lithium-ion batteries from electric vehicles	Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., & Anderson, P.	Peer-reviewed Articles
2016	Current and prospective Li-ion battery recycling and recovery processes	Heelan, J., Gratz, E., Zheng, Z., Wang, Q., Chen, M., Apelian, D., & Wang, Y.	Peer-reviewed Articles
2023	Assessment of environmental impacts and circularity of lithium-ion batteries	Pohjalainen, E., Marttila, V., & Kinnunen, K.	VTT Research Report No. VTT-R-00714-23
2023	Sustainable battery materials for a clean energy future	Redwood Materials	Technical reports
2023	About the ReCell Center	ReCell Center	Technical reports
2025	Environmental Impacts of Pyro- and Hydrometallurgical Recycling for Lithium-Ion	Stegemann, L. & Gutsch, M.	Peer-reviewed Articles

	Batteries – A Review		
2020	Sustainable Development Goal 12: Responsible consumption and production	United Nations	United Nations
2024	Annual Report 2023	VTT Technical Research Centre of Finland Ltd	Annual reports
2022	Digital Product Passport promotes sustainable manufacturing	VTT Technical Research Centre of Finland	White paper
2023	Battery Technologies	VTT Technical Research Centre of Finland	Technical reports
2025	Hydrometallurgy and Mechanical Treatment.	VTT Technical Research Centre of Finland	Technical reports
2025	Battery recycling	Wikipedia	Wikipedia
2023	Recycling and reuse of end-of-life batteries	ReLieVe Project	Industry reports
2017	What is a circular economy?	Ellen MacArthur Foundation	Organizational report

Table 1: List of documents considered as secondary data sources in this research

3.5 Data Analysis Technique

We used the qualitative content analysis approach for data analysis of this study to methodically review the extensive range of acquired secondary sources. This is an established method for methodical and interpretive research of textual materials is qualitative content analysis. Investigating complex and dynamic topics like environmental policy and technological innovation (Bryman, 2016, p. 564) is especially suited for it. We have done the procedure with a familiarising phase, whereby paperwork was meticulously examined to grasp the whole picture of battery recycling and VTT's influence on industry innovation. This allowed us to identify the first areas of interest and engage with the subject.

Among the recurring themes and patterns subject to thematic coding were technical innovation, environmental performance, policy integration, recycling method scalability, and circular economy models. These ideas provided coding labels to guide a more exhaustive understanding. Pattern identification, which entails a comparison of several sources to show how these themes interact with one another and how VTT's strategies meet worldwide sustainability goals like the UN Sustainable Development Goals and the EU Circular Economy Action Plan. This enhanced analytical rigour and coding transparency (Silver & Lewins, 2014, p. 55).

The treatment consisted of several phases. Several times, reading all the information enables us to become familiar with it and acquire a comprehensive knowledge. First coding is done focusing on key ideas, paragraphs, and sentences. Using codes, classification into more generic nodes or categories covers technology, sustainability, legislation, and collaboration. By limiting these categories to precisely defined themes suited for the questions and objectives of the research, we achieved theme development. We used this method to ensure that interpretations stayed grounded in the facts and provided flexibility to manage several types of documentation.

3.6 Reliability and Validity

Generating dependable and trustworthy results from qualitative research depends on ensuring that the outputs are valid and reliable. Strict data selection rules and triangulation and transparency in data administration helped to increase the validity and dependability of this research. We strictly followed rules and guidelines to ensure the validity and reliability. Yin (2018) defines validity as the originality and accuracy of the findings; reliability, then, is the consistency of the research technique (p. 47).

3.6.1 Data Selection and Credibility

We decided to only look at forceful sources for our project, such as articles that experts have looked at, important reports, and databases that people trust. This is because, when experts check an article before it's published, it means you're getting data that other sharp people checked over and said was good (Gusenbauer & Haddaway, 2020, p. 202). Your work gets a gold star this way. We also didn't simply look into any sources, we focused on the significant deal documents and studies coming from the VTT Technical Research Centre, and also papers from serious places, such as the European Commission. This is because the basic potential exists to grasp facts that have directly to do with what we're trying to find out. Holding to sources that are well-trusted and checked by professionals means there's less chance of our project getting ruined by information that's wrong or hasn't been proven yet.

3.6.2 Triangulation

We have gathered data from many sources, and approaches were compared using triangulation to support the conclusions. This approach is often used in qualitative research to increase validity by employing cross-referencing data from several sources, therefore ensuring that interpretations are not just dependent on one type of data (Yin, 2018, p. 103). This effort looked at and weighed data from technical reports, news items, policy documents, and peer-reviewed publications. For example, results of academic studies on battery recycling technologies were matched with institutional reports and governmental recommendations on circular economy strategies. We have done this cross-verification to ensure the research findings were free from the prejudices and limitations inherent in any one data source.

3.6.3 Transparency and Replicability

In the entire setup, we used to go through the data that was laid out so everyone else could do the study over and see if things really added up. This section allows everyone to be fully aligned and to ensure everything's above board. We made a significant deal about making everything crystal clear to show the study wasn't simply made up.

Every location we got data from, such as different journals and databases, got a shout-out so others could double-check and possibly rerun the experiment themselves. This honesty is of immense consequence if someone wants the research to stand up forcefully and let others consider it on their own. Ensuring everyone fully understood how we grasped and looked at the data a bit boosted everyone's confidence in what the study found and its helpfulness for more digging in the future.

3.7 Ethical Considerations

Even if secondary data analysis normally requires less ethical complexity than primary data collecting methods, there are still important ethical questions that must be considered. Technical reports, governmental documents, and peer-reviewed academic publications were among the first ethically obtained and publicly available sources used in this investigation. These works were either made public or provided by organisations to guarantee that intellectual property rights and copyright were not compromised. It was imperative to respect ethical standards when compiling data; all mentioned sources were correctly referenced in keeping with academic recommendations (Creswell & Poth, 2018).

At this moment, there was no need for getting the OK from people who check on studies or asking people if they were acceptable to be studied, because the research only looked at data that was already out there. But still, it was vitally important to ensure all the data was faultless and not tinkering with the truth. Also, when it came to using news articles and reports from the business world, it was key to double-check the facts with reliable sources to ensure no fake news was getting mixed in, as per Gusenbauer & Haddaway (2020, p. 204). They were concentrated on keeping the data honest and ensuring fully no strange stories were being told.

3.8 Limitations of Secondary Data Analysis

Although secondary data analysis has many benefits, like cost effectiveness and access to a large amount of high-quality data, it also has drawbacks that must be acknowledged. This method's primary drawback is its inability to regulate the initial data collection procedure. The data utilised in this study were gathered by other researchers or institutions, who might have employed other approaches, paradigms, or goals that could limit comparability with the research issues of this study or introduce bias (Bryman, 2016, p. 33).

Secondary data sources could also be too general or specific to cover specific battery recycling technology topics, like the most recent advancements or specialised research areas within VTT's operations. The complete complexity of technology and operational strategies may be hard to fully comprehend due to the aggregated data presented by some sources, including industry reports and policy documents.

The possibility of publishing bias is an additional restriction. Publicly accessible documents, which might provide a more positive or favourable portrayal of the technologies and efforts under analysis, are the main source of secondary data used in this study. Because these sources are frequently created by institutions or groups that support technology or policies, there could be an excessive focus on achievements and developments and insufficient attention given to difficulties or setbacks. The statistics may therefore not fully represent all facets of the battery recycling process, particularly those that are less well-known or documented, even if our study draws from a variety of reliable sources.

4 CASE STUDY: VTT

4.1 Organizational Overview

Established in 1942, the VTT Technical Research Centre of Finland Ltd is run by the state and focuses on research and technology subject matter. It's essentially like a significant deal in Finland because it's under the Finnish Ministry of Economic Affairs and Employment. This location is centred on coming up with new and different concepts and solutions that help both government resources and businesses do better. They've got a sizeable team, consisting of over 2,300 people, who know a lot about several different topics. Mainly, VTT is into using science to build things better for the planet, helping companies compete, and ensuring society can fully bounce back from hard times, or, in a similar essence (VTT, 2024a, p. 2).

VTT’s core mission is to solve global challenges through applied research and to translate scientific knowledge into practical innovations. The organization is strategically aligned with Finland’s national priorities for green transition, digital transformation, and circular economy. Three main focal areas define VTT's operational model: knowledge-intensive products and services; smart industry and energy systems; solutions for natural resources and the environment (VTT, 2024b, pp. 5–7).

Within the field of knowledge-intensive goods and services, VTT supports companies in developing data-driven and intelligent technologies, including AI, robotics, and bio-based materials. Within smart industry and energy systems, VTT advances energy-efficient solutions, renewable energy integration, and industrial digitalization. Finally, under solutions for natural resources and the environment, VTT focuses on sustainable materials, waste reduction, and environmental monitoring areas where it has made substantial contributions, especially in battery recycling and circular economy frameworks (VTT, 2024c, p. 7).

VTT’s multidisciplinary approach is reflected in its wide range of collaborations with international research bodies, EU-funded projects, and Finnish industry stakeholders. With state-of-the-art research facilities and pilot plants, VTT operates at the critical intersection of research, innovation, and commercialization. The organization’s commitment to sustainability and innovation positions it as a key driver of technological advancement in Europe.

4.2 Battery Research and Recycling Activities

Central in Europe's battery innovation landscape, VTT Technical Research Centre of Finland is driven especially by improving the sustainability, performance, and recyclability of modern battery systems. In keeping with its broader strategy of attention on smart energy systems and the circular economy, VTT conducts comprehensive research and development on battery technologies, including design, testing, and end-of-life treatment of batteries (VTT, 2024c, pp. 8–10).

4.2.1 Battery Research and Innovation

One of VTT's key areas of basic research in battery technology is the development of better materials for lithium-ion and other battery chemistries. The company aims to reduce the environmental impact of the battery system and raise energy density and battery life cycles. These projects involve improvements in cathode and anode materials, solid electrolytes, and binder technologies (VTT, 2024c, p. 9), specifically with an eye on replacing more sustainable alternatives for vital raw elements like cobalt and nickel.

VTT tests battery cells, modules, and packs, trying them in different places and situations. They put them through tests such as dealing with electricity, heat, and physical stress. This helps produce batteries that are safer and last longer. At the same time, VTT's engineers are working on creating digital models and tools that deal with the entire system. Models help improve how a battery is manufactured, how it charges, and how it deals with temperature. Because of this work, batteries can last longer, and we don't have to throw them away so soon. The effect of this current piece is to emphasize the goals of enhancing battery performance and durability through an interesting combination of testing and digital innovations (VTT, 2024a, p. 10).

4.2.2 Battery Recycling Research

VTT is also a recognized leader in battery recycling research, addressing critical issues in the recovery and reuse of valuable materials from end-of-life batteries and manufacturing scraps. A significant area of VTT's work involves characterizing impurities and managing their effects during the recycling process. This research supports the development of cleaner, closed-loop recycling systems where chemicals and materials can be reintroduced into production with minimal quality loss (VTT, 2023c, pp. 4–6).

VTT has investigated hydrometallurgical and direct recycling technologies, for instance, with an eye towards maximising chemical leaching, mechanical separation, and purification processes to recover lithium, cobalt, nickel, and graphite from spent lithium-ion batteries. Reducing reliance on virgin raw resources and helping the EU's circular economy ambitions depend on such work (VTT, 2023c, p. 6).

4.3 Key Collaborative Projects

VTT Technical Research Centre of Finland Ltd. actively leads and cooperatively works in several high-impact national and European research initiatives to improve the sustainability and circularity of battery value chains. These initiatives are strategically designed to advance innovations in battery recycling, material recovery, and safer battery manufacturing methods. Two notable projects BATCircle2.0 and the SOLiD Project exemplify VTT’s leadership in these domains.

4.3.1 BATCircle2.0

One of Finland's most ambitious projects aiming at creating a competitive and sustainable battery ecosystem is BATCircle2.0, Battery Circular Economy. Supported by Business Finland and under direction by Aalto University, the initiative spans a broad spectrum of participants, including research institutes, colleges, and top Finnish corporations, including VTT (BATCircle2.0, 2024). The development of new battery recycling techniques and the support of the integration of refined materials back into battery manufacturing chains depend on VTT to a major extent.

Emphasising the whole battery life cycle, including the extraction of battery metals, refining, active material synthesis, cell manufacturing, and end-of-life recycling (BATCircle2.0, 2024). Particularly highlighting technological advancements in hydrometallurgical recovery, material characterisation, and process optimisation, VTT's contributions highlight by means of its pilot facilities and sophisticated analytical capacity, VTT helps to develop scalable recycling methods and closed-loop solutions for important battery materials including lithium, nickel, cobalt, and graphite.

Here, it should be pointed out clearly that the BATCircle2.0 project is vitally important because it aims to ensure Europe can obtain its raw materials, without depending much on resources from other places. This is centred on boosting Europe's ability to grasp important resources and ties into the larger plan of the EU Battery Regulation and Green Deal. In addition, according to VTT (2024a, p. 12), this project is analogous to the main building block for making Finland a top name in the industry of creating eco-friendly battery systems.

4.3.2 SOLiD Project

The SOLiD Project (Sustainable Solid-State Lithium-Metal Battery Manufacturing) is a Horizon Europe-funded research collaboration aimed at pioneering a new generation of lithium-metal batteries that are not only safer and more energy-dense but also designed with recyclability in mind. VTT is one of the key R&D partners contributing expertise in materials development, pilot-scale manufacturing, and environmental impact assessment.

Unlike traditional lithium-ion batteries, solid-state lithium-metal batteries use non-flammable solid electrolytes, which significantly enhance thermal stability and safety. Additionally, these batteries offer higher energy densities and longer lifespans, which are crucial for next-generation electric vehicles and stationary storage applications (SOLiD Project, 2024). VTT’s role involves developing scalable fabrication methods for battery cells and investigating eco-efficient recycling pathways for end-of-life solid-state batteries (VTT, 2024a, p. 14).

An essential deliverable of the SOLiD Project is the establishment of a pilot-scale manufacturing process that minimizes chemical waste and energy consumption, thereby aligning production with EU sustainability benchmarks. Reaching these results and guaranteeing the circularity of battery components (SOLiD Project, 2024) depend critically on VTT's pilot platforms and life cycle analysis technologies.

These initiatives together represent VTT's larger goal to create a resilient, circular, low-carbon battery ecosystem in Europe, therefore increasing the technical sovereignty of the area and environmental responsibility.

5 RESULTS AND FINDINGS

The basic results of the secondary data analysis are presented in this chapter. Drawing on academic literature, policy documents, VTT Technical Research Centre publications, and EU-funded project reports, the results are arranged under five main themes that surfaced from qualitative content analysis. These results together show the technical, environmental, and financial ramifications of VTT's creative battery recycling research and its congruence with ideas of the circular economy.

5.1 Results of thematic content analysis

We use thematic content analysis in this thesis, as Bryman (2016) discusses the thematic content analysis strategy. This method involves coding textual information to identify recurrent patterns and themes. This approach allowed us to have a more nuanced interpretation of how VTT's technological and policy-aligned advances support recycling efficiency, lifecycle sustainability in battery use, and circular economy activities. Based on the analysis, we identified the following results.

5.1.1 Innovation in Battery Recycling Technologies

One key topic that comes out from the secondary data is VTT Technical Research Centre of Finland's significant contribution to the development of next-generation battery recycling technology. The growing demand for electric vehicles and energy storage technologies calls for the quick recovery of vital raw materials, including lithium, cobalt, and nickel. Given that the European Union imports a lot of these components, this is especially crucial there. By developing and enhancing a portfolio of recycling technologies, VTT has positioned itself at the forefront of this issue, helping to boost recovery rates, minimise environmental effects, and enable circular material flows.

The most advanced and scalable technologies for recycling spent lithium-ion batteries (LIBs) are hydrometallurgical and pyrometallurgical processes, which are among the main technologies examined. Aqueous chemical solutions are used in hydrometallurgy to extract precious metals from degraded battery components (Liu et al., 2019). Particularly for lithium and cobalt, this process offers a comparatively high metal recovery efficiency with lower emissions than high-temperature procedures. But it can use a lot of chemicals, and it needs to be handled carefully (Liu et al., 2019, p. 802). In contrast, pyrometallurgy uses high-temperature smelting to extract metals like copper, nickel, and cobalt from rock. Pyrometallurgical techniques are reliable and widely used in commerce, but they can be less effective and energy-intensive when it comes to lithium recovery (Liu et al., 2019, p. 803).

VTT has overcome these constraints by advancing direct recycling techniques and low-temperature chemical separation procedures (VTT, 2023b). Because direct recycling preserves the cathode materials' structure, it allows for their refurbishment and reuse with less chemical intervention. As a more sustainable option to conventional procedures, this also minimizes energy consumption and material degradation (Harper et al., 2019, p. 76). For maintaining high-purity materials and assisting in the production of closed-loop batteries, these strategies hold special promise.

VTT plays a key research and coordination role in EU-funded initiatives like BATCircle and ReLieVe, which demonstrate the practical use of these technologies. By combining mining, processing, manufacturing, and recycling activities, the BATCircle2.0 initiative aims to create an effective and sustainable battery metals value chain in Finland. BATCircle is maximizing hydrometallurgical processes through pilot-scale experiments to lessen environmental impact and boost economic feasibility (VTT, 2024a). In the meantime, the ReLieVe initiative, which is a partnership between Eramet, SUEZ, and other stakeholders, aims to recover LIB components on an industrial scale using creative, environmentally friendly recycling techniques. Lifecycle assessment (LCA), techno-economic analysis, and process optimization are some of the contributions made by VTT (Eramet, 2023).

VTT's technology advancements not only solve technical obstacles in battery recycling but also complement the EU's circular economy objectives and strategic autonomy aspirations. By leading cooperative research and expanding environmentally friendly technologies, VTT is helping to build a robust and ecologically conscious European battery sector.

5.1.2 Policy and Regulatory Alignment

The policy frameworks of the European Union (EU) and the battery recycling innovations of the VTT Technical Research Centre of Finland have deliberate and planned synergy. Key to this alignment is adopted in July 2023 and passed in August 2023, the EU Battery Regulation (EU) 2023/1542. This rule, which emphasises the extended producer responsibility (EPR) ideas, mandates that producers of batteries ensure that obsolete batteries are gathered, handled, and reused. In new industrial and electric vehicle batteries, it also lays obligatory recycled content criteria by 2031: 16% for cobalt, 6% for lithium and nickel, and 85% for lead (European Union, 2023). By digitally documenting the battery's composition, origin, performance, and environmental impact, a digital battery passport must also be developed to increase openness all through the battery's lifetime (European Commission, 2023).

Complementing this regulation is the 2020 approval of the Circular Economy Action Plan (CEAP), which presents a complete policy framework to speed the EU's shift to a circular economy. Particularly focusing on industries with high resource consumption and circularity potential, such as batteries, the CEAP advocates for eco-design principles and resource-efficient production methods (European Commission, 2020). Both frameworks demonstrate a clear movement in EU legislation towards circular economy models and product lifecycle sustainability.

These policy goals closely correspond with VTT's activities. By aggressively creating instruments that facilitate traceability and compliance, the institute has incorporated policy responsiveness into its research and development plans. To support EU traceability and labelling rules, the company has released a white paper on Digital Product Passports (DPPs) that explores technical frameworks for integrating environmental data into goods (VTT, 2022a)." The EU's requirements for circular design, reuse, and responsible end-of-life battery management are made easier to meet by these technologies.

Additionally, VTT is at the forefront of several EU-funded initiatives, including BATCircle3.0, which aims to increase the effectiveness of battery material circulation in Finland and the EU at large (VTT, 2023a). The project's emphasis on material recovery, chemical purification methods, and sustainable supply chain models helps it achieve the goals set forth in the CEAP. Working closely with legislators, regulatory bodies, and industry players, VTT's policy-conscious innovation allows it to support the EU's green transition as a technology enabler and scientific advisor.

VTT's standing in the battery recycling ecosystem is reinforced by its conformity to European policy frameworks. The organization advances technology and helps create a robust and sustainable circular economy in Europe by incorporating regulatory compliance into its technical research.

5.1.3 Circular Economy Integration

At the VTT Technical Study Centre of Finland, they're fond of the entire circular economy. They look at things that have already been looked at to learn more. They care a lot about reusing things, making old things new again, and designing products so they can be easily taken apart when they're not needed anymore. This approach is unfathomably aligned with what the EU wants with its Sustainable Products Initiative and the European Green Deal. All of efforts show there may be a rather redemption in the way we handle things, moving beyond just tossing it into the recycling bin when we're done with it.

As the Ellen MacArthur Foundation says, the three pillars of the circular economy concept are eliminating waste and pollution, regenerating nature, and circulating products and resources at their highest value. The Ellen MacArthur Foundation (2017) claims that this approach emphasises the need to design products and systems that are restorative and regenerative by nature to divorce economic activity from the use of few resources.

VTT's dedication to these ideals is demonstrated by its research and development initiatives, which give the full battery material lifetime first priority. For example, VTT has taken an active part in programs that concentrate on battery component reuse and remanufacturing, as well as battery design that facilitates disassembly and recycling. The EU's Circular Economy Action Plan, which promotes circular business models and sustainable product design, is consistent with these initiatives (European Commission, 2020a).

Furthermore, the circular economy's ideas are applied in practice through VTT's pilot projects. As an illustration of closed-loop manufacturing, VTT has worked with industry partners to develop closed-loop systems in the BATCircle project, where recovered battery materials are reintegrated into new production cycles (VTT, 2023b).

By lowering material prices and opening up new business prospects, circular economy tactics can result in substantial economic gains, according to the Ellen MacArthur Foundation, which supports the economic case for such circular models (Ellen MacArthur Foundation, 2017). This viewpoint is represented in VTT's roadmap materials, which emphasise how implementing circular economy principles can generate economic value.

Unsurprisingly, the final analysis will reveal that VTT is showcasing how to do the circular economic subject matter in real life, both in their labs and in the business world. They've shown that it's economically feasible and sharp to have circular models for batteries by folding those ideas into what they research and produce. In addition, things line up with what the EU wants policy-wise. They're leading by example with their complete package deal of designing products to be taken apart easily, remanufacturing and finding new uses for old things.

5.1.4 Institutional Collaboration and Capacity Building

In his study, it is quite clear that Finland's VTT Technical Research Centre greatly contributes to the improvement in European battery recycling. They closely interact with government agencies, companies, and educational institutions. Important aspects for producing fresh discoveries in how to recycle batteries are knowledge sharing, changing awkward technical regulations, and removing each other's blind spots.

Strong participation in Horizon Europe consortia by VTT is one of the key means it promotes cooperation. Among the several stakeholders these consortia bring together to cooperate on research and innovation projects are large manufacturers, universities, small and medium-sized businesses (SMEs). For example, VTT collaborated with various partners on the BATCircle2.0 initiative to raise the efficiency of the battery materials circular economy in Finland and Europe. VTT (2023a) claims that among participants in this initiative, knowledge sharing and capacity building took front stage alongside technological innovations.

The International Congress for Battery Recycling (ICBR) and other international events are further examples of VTT's dedication to capacity building. The most recent advancements in battery recycling technologies and procedures were highlighted by VTT's co-authored research findings at the 28th ICBR, which was held in Valencia in 2023. These talks provide forums for sharing research results, creating cross-border collaborations, and sharing best practices (ICM AG, 2023).

Furthermore, VTT works together through partnerships with groups such as the Batteries European Partnership Association (BEPA). To ensure that capacity-building programs are in line with both industry demands and more general policy goals, VTT uses BEPA to help shape the strategic research and innovation agenda for batteries in Europe (BATT4EU, 2025).

Different partnerships VTT started on show, it's centred on bringing people and places together to make things work better. They mix research, rules, subject matter, and real-world actions to ensure we get a crew that knows what they're doing and solid ground rules for how things should go. This is all vitally important if we want to see the recycling of batteries in the EU grow significantly and forcefully through the months and years. Also, by doing this, VTT is, in a direct sense, an insightful tale because they not only push for new gadgets and devices but also ensure everything works together smoothly.

5.1.5 Environmental Impact and Lifecycle Assessment

The VTT Technical Research Centre of Finland makes significant use of life cycle assessment (LCA) approaches to investigate the environmental impacts of battery technology. From the raw material extraction to manufacture, use, and disposal, life cycle assessment (LCA) is a methodical methodology that assesses environmental aspects and probable consequences throughout the life cycle of a product. Thanks to life cycle analysis (LCA), VTT can perform open sustainability benchmarking and ongoing improvement in the framework of battery recycling by assessing elements including carbon emissions, water consumption, and material recovery efficiency in pilot facilities.

Research from VTT shows that if we use hydrometallurgical recycling methods instead of the usual ways, we can really cut down on harming the environment. By being smarter with how we use energy, water, and chemicals, ways of recycling batteries not only do a better job, in terms of great contrast, at reducing how much we destroy the planet, but also make it so we get more out of our resources.

The European Union has set some significant climate goals. They've got the European Climate Law, which says they need to get to climate neutrality by 2050, and cut down net greenhouse gas emissions by a whopping 55% by 2030, compared to what it was in 1990. To help meet targets, VTT is using LCA when it recycles batteries. This is an upscale way of checking and encouraging steps that cut down on carbon emissions and make things more sustainable. Invariably, we should see how steps line up well with the total methods the EU is using to hit their climate goals.

Moreover, the United Nations Sustainable Development Goal 12: Responsible Consumption and Production is what the endeavour aimed for with VTT's help. This goal stresses how crucial it is to manage natural resources wisely and do things such as stopping waste from happening, making less of it, recycling, and finding new uses for old things. VTT contributes by sharing insights based on data about how battery recycling systems are doing in protecting our environment, all through LCA approaches.

Knowing this, you may be satisfied to learn that, by carefully checking how things impact our planet, VTT is working on making battery technology and how we recycle them, better for the earth. They ensure it all fits with what the laws in the EU say about climate and, even more importantly, worldwide goals about keeping our environment safe. When VTT studies batteries and how long they last, they're doing a lot more than just sharp science subject matter; they're helping out our planet and ensuring we fully follow important green rules.

5.2 Identifying the Analysis of Innovative Technology

The study found that how VTT is coming up with marvellously novel ways to recycle batteries. They are centred on using methods where you work with chemicals at low temperatures or just recycle the batteries as they are, without melting them down. This is sharp because it means getting back useful metals such as nickel, cobalt, and lithium without using a sizeable amount of energy like the old-fashioned high-heat methods do (Liu et al., 2019). It also turns out: they figured out how to grasp the usable parts from batteries and keep them working well, without having to break them down and then produce them from scratch again. This not only saves energy but also skips several steps in making new batteries.

VTT is quite fond of making batteries better for the planet by using technology resources to track them from the time someone produces them until it's time to remove them. This upscale approach to keeping an eye on batteries is a hallmark of battery passports. Digital systems let us know where materials in batteries are throughout their life, which is in some but not total contrast with the older ways that weren't as clear. It's spectacular because it helps everybody be clear about things and follow the rules better (Stretton, Daphne & Ramkumar, 2025).

In the past, this was hard to fathom, but now all the key details, such as what a battery is made of, how it's been used, and how to recycle it, are all kept in a battery passport (Stretton, Daphne & Ramkumar, 2025). A battery passport not only helps with making the work automatic but also ensures everyone involved in the making and selling of the battery stays fully aligned with fresh and correct data. This way, making choices becomes easier, and it's also better for following the rules that protect the environment.

5.3 Environmental Benefits of Advanced Recycling Approaches

The people at VTT Technical Research Centre in Finland came up with some stupendous ways to recycle batteries that are far better for the environment. We found out that using water to extract metals from old batteries can produce way less pollution. We are contemplating 30-40% less greenhouse gas emissions than the usual method of melting things down with extreme heat (Stegemann & Moritz Gutsch, 2025). We find that it's because water-based methods don't need as much heat, which is spectacular. There's research that shows disparate manners of recycling batteries and the difference it makes. For example, they looked at two methods: pyro-hydro and thermomechanical-hydro. The one VTT likes, which mixes thermal and water treatments, only produces about 1.53 kg of CO_2 for every kilogram of battery waste. But the other method, which is more analogous to just melting things, only produces 1.34 kg of CO_2. It's centred on finding a balance, but clearly, this new water method could change the industry by cutting down on pollution a lot.

VTT is on top of direct electrode recycling to help save on resources such as materials and water. The amazing part about it is that you don't even need to break down the batteries to fix them for reuse. This method helps to keep the battery resources working great without losing their power or needing extra steps to make them good again. This section allows for keeping the good components of batteries fit for making new ones. It's about bringing things full circle, economically speaking, so we're not wasting resources we could reuse. And this is super in line with Goal 12 from the Sustainable Development Agenda, which is about making and consuming things in a way that's not harming the planet. With VTT working on recycling ways, it's making a significant difference in making industry resources more green by cutting down on poor emissions, saving water, and not tossing out materials.

We've got positive tools from VTT that look at recycling resources in real-time and mix data from how things get done. This makes it so we can recycle more, blunder less, and sort things better. By fine-tuning how batteries are made and used, gadgets point out the poor spots for pollution and make the most of what we've got. Additionally, there are digital twins, incredibly, or maybe not, that take all kinds of data and mash it together. This trick allows the individuals, or people who produce batteries, to see right through the process, adjust how they do things on the fly and check if everything is top rate while they work. Keeping an eye on how materials move around with digital tools pushes us towards doing better by the environment.

5.4 The Economic Impact of New Technology

The ReLieVe project, combining the efforts of Eramet, Suez, and BASF (Eramet, 2024), has come up with a method: to use a hydrometallurgical technique that recycles over 90% of the valuable metals found in dead batteries and leftover materials from making them. The team at Finland's VTT Technical Research Centre is sort of leading the charge with this great battery recycling technology, which could bring in a lot of money and keep costs down.

By recovering important minerals such as cobalt and nickel right at home, VTT's advanced recycling methods are something to think carefully about. Because of what VTT can do, the European Union doesn't have to rely much on buying things from outside and becomes better at handling its supply chains, they say, at VTT Technical Research Centre of Finland (2023).

This entire recycling move matches up with the European Union's momentous goals of not needing to bring in as many raw materials from other countries and building, from the ground up, a cycle of use that not only throws things away an idea they call a circular economy. Having a complete cycle for materials ensures the EU keeps obtaining critical materials without having to request them from anyone else. In conclusion, we say that recycling advances are not simply good for keeping things in balance, but they help save money and produce, too.

According to economic modelling data from VTT's pilot-scale demonstrations, as the volume of battery waste increases, integrated recycling facilities, particularly those that operate within circular supply chains, can become cost competitive with conventional virgin material extraction methods (VTT Technical Research Centre of Finland, 2024).

The ReLieVe project intends to build the first fully integrated recycling facility in Europe, capable of processing 50,000 tonnes of battery modules per year, or roughly 200,000 electric vehicles (SUEZ Group, 2024). This model demonstrates the advanced battery recycling technologies' potential for economic scalability. Reusing recovered electrode materials directly provides another significant economic advantage. Direct recycling helps batteries retain their functional integrity, reducing the need for chemical reformulation or energy-intensive refining. The production cycle of new batteries is shortened, and material processing costs are significantly reduced as a result (VTT Technical Research Centre of Finland, 2023). The economic idea of circularity, which reduces waste and operating expenses by preserving materials in productive use for as long as possible, is reflected in such practices.

By using digital tracking technology, they can keep an eye on materials as they move, making things run smoothly and getting more out of them. (VTT Technical Research Centre of Finland, 2024). This not only helps the planet but also opens new doors in the market and ensures the European battery recycling business can keep making money for a long time. All of this greatly amazing work that VTT is doing supports the significant picture of keeping the economy running in a way that reuses resources instead of wasting them.

5.5 Comparison of the Current vs Future Recycling Processes

The VTT Technical Research Centre of Finland and other organisations are developing more sustainable alternatives to the traditional ways of recycling batteries, which are mostly pyrometallurgical processes. High temperatures are used in traditional pyrometallurgical processes to melt batteries, which is an energy-intensive process that also produces a large amount of slag waste and relatively low material recovery rates of 60–70% (Stegemann & Gutsch, 2025). The economic viability of these processes is largely dependent on external subsidies and usually results in significant greenhouse gas (GHG) emissions.

However, as part of a larger initiative to create high-efficiency, low-carbon systems, VTT has concentrated on developing hydrometallurgical and direct recycling technologies. Using hydrometallurgical techniques, precious metals like nickel, cobalt, and lithium can be selectively leached using aqueous chemical solutions at lower temperatures. With recovery efficiency of up to 90%, these techniques drastically cut down on energy use (Ali & Adjoumane, 2022, p. 2). Furthermore, direct recycling techniques eliminate the need for further processing processes and save energy and materials by maintaining the integrity of functional materials and allowing the reuse of electrode compounds without reducing them to base elements.

Comparing these future-state technologies to existing techniques, environmental studies have demonstrated a 40% reduction in greenhouse gas emissions (Ali & Adjoumane, 2022, p. 3). VTT's ideas have a great chance of being economically self-sustaining on a large scale. Reducing Europe's dependency on imported raw materials and enhancing its economic resilience are two benefits of integrated recycling systems that recover valuable, essential raw materials inside regional supply chains (ReLieVe Project, 2023).

Battery passports and material tracking systems are examples of digital technologies that VTT integrates to provide end-to-end transparency across the recycling cycle. Stakeholder confidence will be increased, operational efficiency will be improved, and compliance will be streamlined thanks to these digital solutions, which are in line with the revised EU Battery Regulation (European Commission, 2023).

Although the adoption of these cutting-edge techniques necessitates infrastructural investment and appropriate regulatory frameworks, the change is amply justified by the economic and environmental advantages offered by VTT's strategy. The combination of digital integration, policy alignment, and technical innovation makes VTT's forward-thinking procedures better than conventional recycling methods.

Aspect	**Current Methods**	**Future (VTT-led) Innovations**
Process Type	Pyrometallurgy	Hydrometallurgy & Direct Recycling
Energy Consumption	High	Low to Moderate
Material Recovery Rate	~60–70%	~90% or more
GHG Emissions	High	Reduced by up to 40%
Economic Viability	Dependent on subsidies	Potentially self-sustaining at scale
Digital Integration	Minimal	Full traceability with battery passports

Table 2: Comparison of the Current vs Future Recycling Processes (Pihlajamaa et al., 2023; Liu et al., 2019; European Commission, 2020; VTT, 2023a)

The transformational potential of advanced recycling technologies in terms of environmental, economic, and operational performance is highlighted by the comparison of current battery recycling practices with VTT-led future innovations (see Table 2), as described in internal project documentation and summarised from recent literature (Pihlajamaa et al., 2023; Liu et al., 2019).

High-temperature smelting is a key component of pyrometallurgical operations, which are the mainstay of conventional recycling techniques.

This method produces slag waste, a byproduct that needs further processing and disposal, and uses a lot of energy, even if it is effective in recovering materials. The hydrometallurgical and direct recycling methods, on the other hand, which function at lower temperatures and recover metals by chemical leaching or mechanical separation, are the focus of VTT's suggested future-oriented recycling system. These techniques are by nature more ecologically friendly and energy-efficient.

The heat needed to melt battery materials is the primary reason why pyrometallurgy is linked to high energy inputs. In contrast, VTT's hydrometallurgical systems are low to moderately energy-intensive because to their reduced thermal energy requirements. Recycling practices are better able to meet EU-wide energy and climate efficiency targets thanks to these improvements (European Commission, 2020).

About 60–70% of key materials, including nickel, cobalt, and lithium, are typically recovered using current techniques. However, recovery efficiency of 90% or more have been shown by VTT-led innovations, especially in direct recycling pilot-scale demonstrations (ReLieVe Project, 2023). This improved efficiency maximises material output from each battery, which not only lowers waste but also improves the economic viability of recycling operations.

Combustion and high-temperature processing are the main causes of the significant greenhouse gas emissions from traditional recycling. The lifecycle assessment (LCA) data indicates that VTT's more recent techniques are linked to GHG reductions of up to 40% (Pihlajamaa et al., 2023). The European Climate Law's climate neutrality goals for Finland and the EU are directly impacted by these decreases.

Legacy recycling ways usually need money from the administration to work since they spend a lot and don't produce many resources. And separately, VTT's new ideas could work on their own, especially if they're part of the loop in making and reusing things. When we get more batteries to recycle and become better at getting things back from them

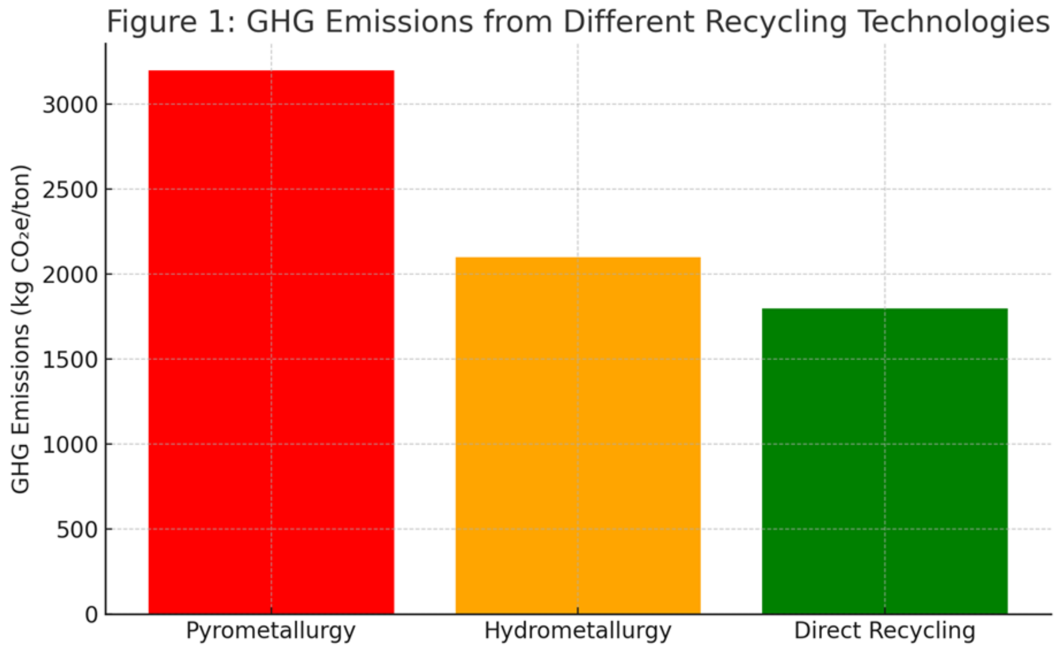
(VTT, 2023a), recycling might become cheaper and, quite possibly, of import compared to taking fresh materials.

The procedures used now show little digital integration and no tools for monitoring battery components across the production chain. The use of battery passports and digital tracking systems, which allow for real-time material traceability and compliance with changing EU regulatory standards, such as the updated Battery Regulation (European Commission, 2023), is being pioneered by VTT. Through this connection, recycling logistics become more effective, transparency is improved, and policy enforcement is supported. The comparative data in the table are derived from secondary analysis of technical reports and scientific literature.

5.6 Visual Illustration of the Results

The technological, environmental, and financial ramifications of the battery recycling technologies this study looks at are made clearer, thanks in large part to the use of graphic representations. An overview of the relative effectiveness of different recycling strategies and the contribution of VTT to the development of closed-loop battery systems is provided by the figures, even though they are not graphically depicted here.

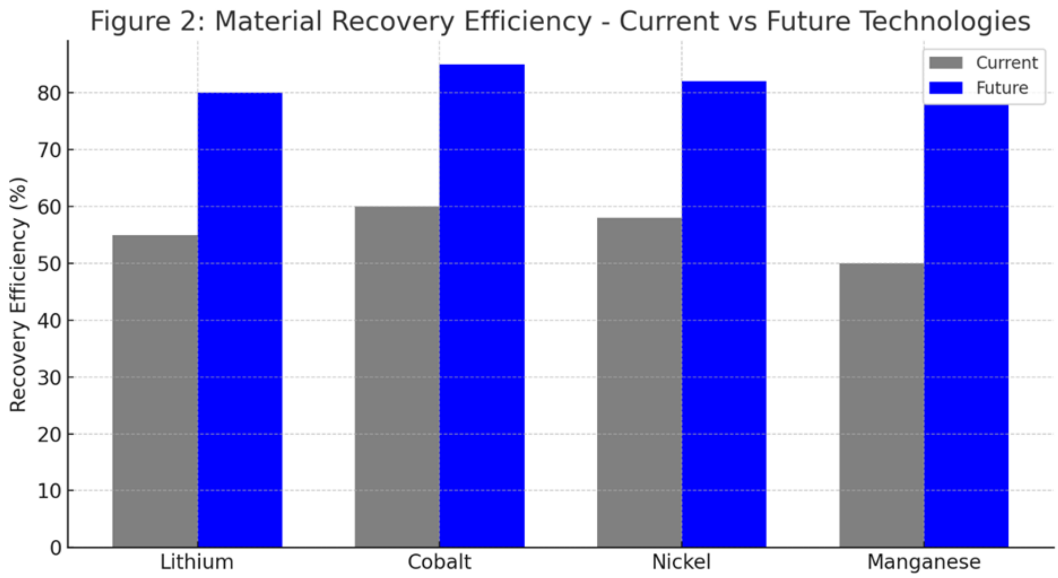
Figure 1: Comparative GHG Emissions from Different Recycling Technologies



This hypothetical bar graph (see Figure 1) illustrates the greenhouse gas (GHG) emissions linked to various methods of battery recycling. Carbon dioxide equivalent (CO_2e) emissions from traditional pyrometallurgical procedures are significantly higher, frequently surpassing 2,000 kg CO_2e per tonne of battery trash because of high temperatures and ineffective material recovery (Liu et al., 2019, p. 742). Hydro-metallurgical techniques that use low-temperature aqueous leaching, on the other hand, have been demonstrated to cut emissions by 30–40%. Because it preserves materials and requires little heat, direct recycling, which is still in the pilot stage, has the lowest emissions.

By using chemical leaching and operating at lower temperatures, hydrometallurgical processes, on the other hand, drastically cut emissions. Their average emissions fall between 1,200 and 1,400 kg CO_2e per tonne. Direct recycling techniques yield the best results for the environment because they preserve working battery components and need no processing. These techniques can reduce GHG emissions by up to 80%, yielding numbers as low as 400–500 kg CO_2e per tonne, which is in close agreement with Pihlajamaa et al.'s life cycle assessment (LCA) findings (2022).

Figure 2: Material Recovery Efficiency by Recycling Method



With an emphasis on three vital metals such as, nickel (Ni), cobalt (Co), and lithium (Li) this line graph (see Figure 2) illustrates the relative effectiveness of material recovery across various recycling procedures. While lithium frequently experiences losses from volatilisation, with recovery rates falling below 50%, cobalt and nickel are more readily recoverable (60–70%) in conventional pyrometallurgical processes.

Particularly for lithium, hydrometallurgical techniques work better due to improved chemical targeting and reduced heat degradation; recovery rates approach 70–80%. Direct recycling technologies, which maintain the structural integrity of active materials and provide recovery efficiencies of up to 85–90% for lithium and 90–95% for cobalt and nickel, therefore show the most promise.

The results are in line with research by Liu et al. (2019) and data from significant projects funded by the EU, such as BATCircle and ReLieVe. All the aforementioned really shows us how important it is to become better at using our resources carefully. The amazing benefits of the recycling programs created by VTT are made extremely unmistakable through diagrams and images. Initiatives showcase how we can bring technology together more effectively, use our resources more smartly, and harm the environment less. This subject matter matches up perfectly with the significant environmental goals the EU has set and what people buying things are starting to demand more and more.

6 DISCUSSION AND CONCLUSION

With an eye towards Finland's VTT Technical Research Centre's contributions, this thesis's main objective was to look at how innovative technology and environmentally friendly methods can affect battery recycling going forward. The study answered the research questions rather successfully using secondary data analysis.

Our thesis, predictably, is that VTT is really stepping up the trade in improving how batteries get recycled. They've found some acceptable ways to get around the old problems that came with the usual methods of recycling batteries, focusing more on hydrometallurgical and direct recycling. What's exceptionally positive is that methods don't only increase, marginally, how much cobalt and lithium we can get back, we are contemplating over 90% recovery rates, but they also cut down on energy use and lessen the damage to our planet. On top of that, adding digital components, such as battery passports, makes the entire recycling process transparent and in line with rules, not to mention, it streamlines everything from start to finish.

As we have the plan to unmask, it is certainly obvious that the research VTT is doing is spot on with what the European Green Deal, the Action Plan for a Circular Economy, and the latest rules on batteries from the EU (European Commission, 2020, 2023) are cantered on. They found things that boost ideas on reusing and fixing parts instead of just making new things, holding to what's called a circular economy. This not only means batteries could last longer, but we also wouldn't need to grasp fresh raw materials as much (Ellen MacArthur Foundation, 2017). In plain terms, the significant intellectual ideas behind this make a lot of sense and show VTT is heading in the right direction.

Among other things, we will begin by answering the second research question. The study showed that, because of VTT's recycling technologies, we can see real benefits for the environment. This includes things such as needing less energy, using less water, and cutting down on GHG emissions by up to 40%. Economically, the recovery of vital raw materials locally supports Europe's strategic independence, and cost analysis points to long-term financial sustainability as recycling increases and direct material reuse becomes commonplace (ReLieVe Project, 2023).

The battery recycling industry will be significantly impacted by these discoveries. First, the switch from traditional pyrometallurgy to more ecologically friendly methods marked a significant turning point. VTT's pilot projects and partnerships under programs like BATCircle2.0 show how innovation in different regions and research institutions is driven by technological excellence and sustainability requirements.

Second, policy alignment is a major enabler. Through the implementation of novel regulatory measures like minimum recyclable content, enhanced producer accountability, and support for digital material passports, VTT has emerged as a prominent research organisation and a crucial advisor in the EU's endeavours to establish a sustainable battery ecosystem. The industry's adoption of cleaner technologies is anticipated to be accelerated by this aggressive approach, especially when manufacturers and recyclers alike are unable to comply with EU standards.

The thesis also highlights the significance of institutional cooperation and capacity building. By means of its collaborations with governmental, commercial, and academic institutions, VTT fosters standardisation, knowledge sharing, and the potential for expansion. To lower current financial and infrastructure hurdles in the battery recycling value chain, several cooperative strategies are essential.

Because closed-loop material use increases energy efficiency, reduces emissions, and benefits the environment, there is solid evidence to justify the deployment of advanced recycling systems. Particularly SDGs 12 and 13 on climate action and responsible consumption and production, respectively, these benefits complement national climate targets and help the UN's Sustainable Development Goals to be advanced.

As a result of its innovative technologies, tactics that adapt to changing legislation, and dedication to the circular economy, the VTT Technical report Centre of Finland is significantly influencing the future of battery recycling, according to the report. The advantages of this theory for the economy and the environment offer strong support for the broad use of innovative recycling techniques. The necessity of institutional cooperation and policy-driven innovation in tackling the environmental problems confronting the battery industry is further highlighted by VTT's work's conformity to EU policy frameworks.

6.1 A short answer to research questions

Significant greenhouse gas emissions, low lithium recovery rates, and high energy consumption are the main drawbacks of current recycling techniques, especially pyrometallurgical ones. Recycling systems around the world also struggle because of poor digital integration, restricted traceability, and reliance on subsidies. Despite tremendous advancements, VTT's infrastructure and regulatory preparedness gaps still prevent the complete scaling of direct recycling technologies and their smooth integration into closed-loop systems at the industrial level.

The most promising methods are hydrometallurgical and direct recycling, which VTT has developed and tested through programs like ReLieVe and BATCircle. By enabling material recovery rates greater than 90%, cutting emissions by up to 80% when compared to pyrometallurgy, and preserving active battery components for future use, these technologies dramatically reduce economic and environmental costs.

Environmentally speaking, implementing these technologies could promote lifecycle sustainability and significantly lower carbon emissions. Technically speaking, to maximise recovery, they need investments in automation, battery passports, and disassembly systems. Full integration strengthens VTT's position as a pioneer in climate-resilient innovation and encourages policy-driven scalability throughout Europe by bringing it into compliance with the European Green Deal and the EU Battery Regulation.

6.2 Limitations and future research possibilities

This thesis used a substantial number of resources already written, such as articles from journals, reports from groups, important papers, from projects. Invariably, you should see that because of this, we didn't get to visit any of VTT's recycling places or do any surveys or talks with people to get fresh data. Because we didn't do that, it was hard to grasp what problems they face every day, how they decide things inside, and what workers who are putting technology to use think.

This study allows for a detailed look into VTT's inventions, but it's held back by the fact that it only uses resources you can find in the open. Since we're missing private or secret project information, we can't dive deep into the technology or financial side of things especially when it comes to how much resources cost and how successful test projects were.

Another drawback is that battery recycling regulations are always changing, especially considering the EU Battery Regulation. In the upcoming years, when implementation details are finalised, some policy interpretations may become obsolete due to continuous legislative changes. Future advancements could change the results of this study because hydrometallurgical systems and direct recycling are still in the pilot level of technological maturity.

If we greatly desire to get a better grasp on what's holding things back, how people feel about using resources, and how technology moves from the lab to the real world, future studies must go straight to the source. They should converse with people at VTT, people working in the industry, or those policy professionals. This plan is substantially analogous to touching the actual building blocks of issues, finally determining through careful analysis what's going on.

Thinking about which way to recycle batteries and understanding how it impacts our wallets and the planet better, this study allows looking into the lifespan of different battery types, such as lithium-iron-phosphate and nickel-manganese-cobalt. This idea is something else VTT might look at in their starting projects.

If we take VTT and compare it to firms such as Germany's Fraunhofer or Norway's Hydrovolt, we might find some interesting things about how new ideas are shared, what the top ways of doing things are and how rules are constructed similarly across Europe. It would quite possibly be of importance to also focus on the work and society side of recycling batteries in future research. This means looking into how people think about digital things, such as battery passports, fairly getting materials, and training for workers.

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