



# Finland-based Circular Ecosystem of Battery Metals – BATCircle

2019-2021

Final Report

***This report has been produced as part of the BATCircle project (4853/31/2018) and funded by Business Finland.***

***The report has been compiled from the project partner's contributions, edited by Pyy-Mikko Hannula (Aalto University), Sipi Seisko (Aalto University), Pertti Kauranen (Aalto University) and Mari Lundström (Aalto University).***

## Foreword

It has been fascinating to follow the rapid development of electrification during the last few years, with batteries playing a key role in enabling energy storage in various applications. Along with the shift in consumers' interest from gasoline to electric vehicles, also the general understanding of the necessity — and even criticality — of battery metals has increased substantially. Finland has a long history of metallurgical technology development and operations, as well as close partnership between academia and companies. Based on such collaboration, we already had great tools to start building a strong research ecosystem in the field of battery metals. BATtobe was initiated in April 2018 for the planning of a Finland-based battery metals ecosystem and this led directly to BATCircle, which became active in early 2019.

BATCircle initially consisted of 23 companies, 6 research organizations and 2 municipalities with the participants, as well as the research topics, reflecting the key strengths and broad interests within the Finnish battery value chain. For example, investigations have not only focused on the technological aspects of exploration, refining, recycling, and active materials, but also on the systematic changes required for circular economy business models. Some of the big research questions considered relate to mineral resources and their sustainable utilization, metals refining to battery grade materials, battery recycling (with a specific focus on retrieval of currently under-recovered elements), development of new active materials, as well as life cycle analysis and the environmental impacts of all linked processes. Of course, many of these research questions are global, and BATCircle has also been active on the international stage through collaboration in several European research projects and in identifying the future R&D needs of the EU in the field of battery raw materials and recycling – more than ever, an attitude of “working together for the common good” is needed.

Today, we know much more than three years ago. BATCircle has resulted in a substantial level of R&D activities in companies and academia, as well as in published research. This work has not only increased the deep knowledge available in open literature, but has also been one key component in raising Finland's profile in the battery sector. We in industry and academia want to be known as sustainable and responsible actors, and these principles drive our work in the ecosystem. Still, much remains unknown, some research questions have yet to be answered and several industrial processes can still be improved. Therefore, the motivation to take this research ecosystem to the next level remains and funding for BATCircle2.0 has already been applied for. But for now, it is time to thank all the partners of BATCircle for their efforts and to reflect that this is something we can all be truly proud of.

*Prof. Mari Lundström, Principal Investigator of BATCircle, Aalto University*



## Contents

Foreword .....	2
Summary.....	4
Consortium members.....	5
Finnish battery sector .....	6
Project activities.....	7
Greetings from the stakeholders .....	9
Public research in BATCircle.....	12
WP 1 Sustainable primary resources.....	13
WP 2 Value addition in metals production .....	19
WP 3 Recycling of batteries .....	29
WP 4 Tailored precursors and active electrode materials.....	40
WP 5 Business potential .....	59
WP 6 Project management .....	65
WP 7 European network.....	66
Publications.....	69

## Summary

The “Finland-based circular ecosystem of battery metals – BATCircle” consortium was formed in March 2019 from the key research organizations and companies working in the field of battery metals in Finland, coordinated by Aalto University. Together, the members form a domestic battery metals ecosystem with a strong emphasis on battery minerals, metals refining, chemicals, active material preparation and battery recycling. The aim of the ecosystem project was to conduct high quality research throughout this whole value chain, both in academia and industry, to increase the competitiveness and business potential of Finnish partners working in the battery metals sector. Furthermore, the aim was to enhance co-operation between research organizations and industry, and to bring competitive and sustainable solutions to the market. BATCircle has positively influenced Finnish collaboration in European research, with multiple new international research projects in the pipeline. The ecosystem also has an international Advisory Board with a focus on knowledge exchange between the members.

The research in BATCircle is conducted both in private projects (company-specific confidential R&D) and in open research by the research organizations Aalto University, University of Oulu, LUT University, University of Eastern Finland, Geological Survey of Finland (GTK) and the Technical Research Centre of Finland (VTT). This report will summarize the open research results obtained during the project from March 2019 to April 2021. A continuation project “BATCircle2.0” has been applied for, aiming to build on the strong foundations laid during the first phase of BATCircle.



Figure 1. Partners in the BATCircle project with research organizations at the centre.

## Consortium members

The BATCircle consortium consists of four universities, two research centres, nine large companies, 14 small and medium-size enterprises, two cities and an Advisory Board consisting of national and international organizations working in the field.

### Research organizations

Aalto University | University of Eastern Finland (UEF) | LUT University | University of Oulu  
Geological Survey of Finland (GTK) | VTT Technical Research Centre of Finland

### Large companies

Boliden Harjavalta | Boliden Kokkola | Elementis Minerals | Finnish Minerals Group  
Fortum | Fortum Waste Solutions | Metso Outotec | Nornickel Harjavalta  
Terrafame | Umicore Finland

### Small and medium-size enterprises

Akkuser | Crisolteq | Fennoscandian Resources | FinnCobalt Oy  
IMA Engineering | Keliber | Latitude 66 Cobalt  
Magsort | Mawson | Mine On-Line Service  
Suhanko Arctic Platinum | Teraloop | Tracegrow

### Municipalities

Town of Harjavalta | City of Pori

### Advisory Board

Akkukierrätys Pb | Association of Finnish Steel and Metal Producers | BASF  
CLIC Innovation | EIT InnoEnergy | EIT RawMaterials | Hitachi Hightech Europe  
Kemira | Kuusakoski Recycling | National Emergency Supply Agency | Nikkelverk  
Northvolt | Sitra | Valmet Automotive | Varta Microbattery | Yrityssalo

## Finnish battery sector

Since the formation of the BATCircle ecosystem, the Finnish battery sector has undergone many significant developments. From company mergers between Metso and Outotec to acquisitions of the Freeport Cobalt precursor cathode active material (pCAM) operations at Kokkola by Umicore to Fortum Waste Solutions acquiring the battery recycling company Crisolteq with the aim of industrial hydrometallurgical battery recycling. Terrafame has now finished construction of their new battery chemicals facility at Sotkamo to produce battery grade nickel and cobalt sulphates during 2021 and the German multinational chemical company BASF is currently building a new pCAM plant in Harjavalta to start in 2022. Other main operators at Harjavalta, Nornickel and Boliden Harjavalta, are also investing considerably in expanding nickel production during 2021 and the coming years to meet increasing demand. Keliber is aiming to start mining and refining Finnish lithium hydroxide in the coming years at Kaustinen. In April 2021, Johnson Matthey announced their plans to locate a cathode material plant in Vaasa, partnering with Finnish Minerals Group, which is also developing two other locations for battery materials production at Hamina and Kotka. These are just some of the news stories that have come out in recent years in Finland and it is obvious that the battery sector is only going to expand in the coming years.

Supporting these activities, the Finnish National Battery Strategy was unveiled in early 2021 with many BATCircle members participating in the work to strengthen Finland's competitiveness in the battery sector. To promote implementation of the strategy, a national battery cooperation body was then set up, bringing together the various stakeholders in the sector. In international activities, the Batteries European Partnership Association (BEPA) was formed in late 2020 with several Finnish representatives appointed: Finnish Minerals Group (Jani Kiuru), Fortum (Tero Holländer), Metso-Outotec (Tuomas van der Meer) and Geysler Batteries (Daria Hedberg). Finland (Metso Outotec & Aalto University) was also selected to lead Working Group 2 of Batteries Europe "Raw materials and recycling" from 2020 with a [roadmap](#) launched in 2/2021.

Finnish research has been active alongside BATCircle with projects such as BATTRACE and the Battery Minerals project. BATTRACE is focused on the traceability of battery metals, minerals and materials and aims to develop means for traceability of battery materials throughout the value chain. The Battery Minerals project, on the other hand, aims to further investigate the potential of Finnish battery mineral deposits of cobalt, lithium and flake graphite. These projects complement the research done in BATCircle and are only a few examples of the diverse research activities ongoing within the Finnish battery ecosystem.

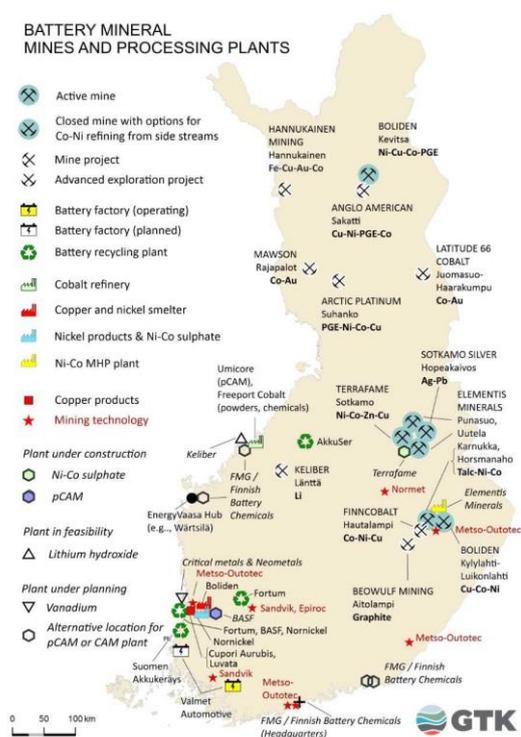


Figure 2. Finnish battery mineral mines and processing plants, courtesy of GTK.

## Project activities

The project officially began with a kick-off meeting on 22.3.2019 at Aalto University in Espoo, where the project partners jointly reviewed the workplan presented by researchers and proposed the next steps for starting the practical experimental work. In total, the project members met during seven seminars, three of which were open for invited participants outside the consortium on 22.3.2019, 2.-3.9.2019, 13.12.2019, 18.-20.3.2020, 2.-3.9.2020, 14.-15.12.2020 and 11.-12.3.2021. Due to the COVID-19 pandemic, the events held after February 2020 were online webinars.



*Figure 3. Project members at the kick-off meeting.*

A Finnish-Chinese Battery recycling workshop was held in November 2019 between BATCircle members and delegates from the Central South University (China) to discuss the trends and problematics of battery recycling. Presentations were given on the status of industrial recycling in both countries and the state-of-the-art recycling research conducted in academia was reviewed. The round table discussions ended with the playful joint statement “Batteries are easy, recycling is difficult!”



*Figure 4. Finnish-Chinese Battery recycling roundtable participants.*

Dissemination activities were an integral part of BATCircle and the project produced dozens of publications, presentations, talks, interviews as well as organizing various events. For instance, the International Process Metallurgy [Symposium](#) “Metallurgy as a tool for challenges in circular economy”

was held in November 2019 at Aalto University. The symposium had a BATCircle dedicated battery materials session focused on battery metals and chemicals production, recycling and other end-of-life options with talks from researchers and companies working in the field. The event was a great success, bringing together metallurgists and engineers from various fields with nearly 200 participants from all around the world.

The BATCircle Final [Seminar](#) was held as a webinar on 11.3.2021 with over 130 participants. The seminar was held in two parts, beginning with a Keynote session and international invited speakers complemented by a research-oriented Highlights session, where the BATCircle research organizations showcased the highlights of battery-related research from the past years. The invited speakers included Michael Lippert (Saft), Daniel Cios (European Commission DG Grow), Fabrice Stassin (Umicore Belgium), Tuomas van Der Meer (Metso Outotec) and Jyrki Alkio (Ministry of Economic Affairs) with talks focused on the current state and future development of the Finnish and European battery value chains, including raw material and R&I needs.

### **BATCircle in figures**

Over **40** talks and interviews given related to BATCircle and the Finnish battery value chain

**30** Published theses

**39** Published peer-reviewed publications (~25 manuscripts submitted/to be submitted)

**13** Technical reports

**41** Conference presentations

**7** Magazine articles

## Greetings from the stakeholders

The Association of Finnish Steel and Metal Producers (AFSMP) would like to thank the BATCircle project research community for an excellently implemented project and for producing valuable results. The research has in a crucial way supported both the development of AFSMP and the whole Finnish battery cluster and the project has enabled the strong advancement of the battery sector. It should also be noted that the project's leadership has been able to anticipate the growing research needs of European and Finnish battery industries. Organizations participating in AFSMP wish to emphasize that this type of persistent collaboration between industry and academia will create the future basis for well-being in Finland.



*Kimmo Järvinen, CEO  
Association of Finnish Steel and Metal Producers*

The Ministry of Economic Affairs and Employment of Finland (MEAE) is strongly committed to building a successful battery value chain in Finland, ranging from sustainable production of battery minerals and chemicals to the electrification of various areas of the Finnish society, all the way to the reuse of batteries and finally to responsible and efficient recycling of battery materials. From this perspective, the BATCircle project has been an essential piece of the puzzle, bringing together a large number of key players of the Finnish battery value chain, from academia to leading companies and government organisations.

Furthermore, the BATCircle project has raised the awareness of the Finnish battery ecosystem in Europe and globally. MEAE is particularly pleased with the strong representation of Finnish experts in the European battery initiatives, such as the European Battery Alliance (EBA250), and more recently in the Batteries European Partnership. The excellent work and visibility of BATCircle has been a key enabler in this process.

And finally, in addition to world-class academic research, one of the biggest achievements of the BATCircle project has been the networking of key players, from promising start-ups to established corporations. It has always been a pleasure to meet, physically or online, so many key influencers and operators of the Finnish battery value chain around the same table in numerous BATCircle meetings and webinars. In this role, the BATCircle project has given excellent support to the objectives of MEAE in their work towards a competitive battery landscape. As stated in the newly released Battery Strategy of Finland, the success of the Finnish battery ecosystems builds on high-level research and education, producing world-class talent and skills for the Finnish battery value chain.



*Jyrki Alkio, Chief Specialist  
Ministry of Economic Affairs and Employment of Finland*

I have been a member of the steering group of BATCircle and participated actively in the planning of the project. The BATCircle project has successfully improved the knowledge base of the battery metals and materials value chain. It has also enabled good collaboration between the industry and academia.

The BATCircle scope has been wide, including mining, metals refining, recycling, SME companies and business development stakeholders. It is important to point out that within this project the Finnish non-ferrous sector and recyclers now have a better view of the opportunities and risks related to the fast-moving battery metals value chain.

As a specific result within this project, Boliden Kokkola has obtained promising results on the hydrometallurgical processing of secondary manganese-containing sludge into fine battery precursor material followed by successful cell cycling tests with different NCM chemistries. Along with Boliden Harjavalta, we have been happy with the outcome of this well-managed project.

*Justin Salminen, Research Manager  
Boliden Kokkola*

Boliden Harjavalta operates the largest nickel smelter in the European Union. The smelter also recovers a significant amount of cobalt to nickel matte. With the BATCircle program, Boliden Harjavalta has been able to increase its knowledge of factors influencing the production efficiency of smelting primary raw materials in the nickel smelter. Also, innovative ideas of utilizing secondary raw materials containing battery elements has been tested in co-operation with the pyrometallurgy group in Aalto University.

Boliden Harjavalta is currently investing 40 MEUR in an expansion of its nickel operations. The investment strengthens the smelter's productivity and competitiveness while further improving Boliden Harjavalta's already very strong environmental performance. This investment will respond to the growing demand for nickel from, among others, the battery manufacturing sector. This kind of investment would not be possible without strong world-class knowhow of nickel smelting. With programs like BATCircle, Boliden Harjavalta ensures and deepens its knowhow of processing battery metals. BATCircle also offers a unique network and viewpoint of the Finnish battery ecosystem.



*Petri Latostenmaa, R&D Manager  
Boliden Harjavalta*

During the last two and half years, the BATCircle consortium project has created a lot of new general information and detailed technical know-how about lithium-ion batteries, precursors, active cathode materials, applied minerals and metals, and refining and recycling technologies. The project was launched just at the right time because the battery business has really expanded from Asia to Europe and today it is growing fast. One of the main drivers for this growth is the electric vehicle industry (xEV), where all the major car manufacturers are developing several new xEV models for the market. Although the precursor plant of Umicore Finland Oy (member of the steering group of BATCircle) in Kokkola has been operating in the battery precursor business for more than 20 years, the BATCircle period has given new and excellent possibilities to improve and widen our battery precursor materials and technologies. We would like to thank all BATCircle participants, our close collaboration partners and the project organization. Together we have increased the overall battery knowhow in Finland.



*Timo Kankaanpää, Senior R&D Manager  
Umicore Finland Oy*

Fennoscandian Resources (Fennoscandian) would like to thank all the research and industry partners in BATCircle for a very well-implemented project. The project has led to great interest internationally and decisions on significant battery-related investments in Finland have already been made. This project proved that well-organized collaboration between academia, SMEs and industry can achieve great things and help Finland to a leading position in the European battery value chain. Within BATCircle, in collaboration with research institutions Fennoscandian has developed a process for further processing of natural graphite into anode precursor material for lithium-ion batteries. Fennoscandian will greatly benefit from the results of BATCircle in its ambition of building a sustainable integrated process for the production of anode precursor materials for the European battery market.



*Rasmus Blomqvist, Managing Director  
Fennoscandian Resources Oy*

Our company Latitude 66 Cobalt has been part of the two-year BATCircle1.0 program. The joint BATCircle project we had with GTK gave us excellent results and valuable information for our next stages of development. One of the key successes of the BATCircle program was the open and constructive dialogue between all the participants. In a rapidly growing and evolving market – like the batteries industry - it is of highest importance that national players, including academia and industry, have a forum where they can share information, challenge each other and ultimately create innovative products and business models. I am very happy with the outcomes we had with BATCircle1.0 and am looking forward to continuing the journey under the BATCircle2.0 program.



*Thomas Hoyer, CEO  
Latitude 66 Cobalt*

I have been on the Advisory Board of BATCircle. The project covers most of the Finnish battery-related industry and it is my impression that the project is well-managed. The program on the open seminars has been very good. It has also resulted in better cooperation between Norwegian and Finnish research programs. The BATCircle project has also strengthened the connections between Norwegian and Finnish metal industries, both commercially and within R&D. It takes time to build strong and good relationships, and the Covid-19 situation has not made it easier. It is my hope that BATCircle or similar programs can continue – and I think that would be good when we look at the Nordic countries as one region



*Oluf Bøckman, Senior R&D Specialist  
Glencore Nikkelverk*

## Public research in BATCircle

The open research in BATCircle was conducted in 5 work packages (WPs) supported by two non-technical WPs. The research was done at Aalto University, University of Oulu, LUT University, University of Eastern Finland (UEF), GTK (Geological Survey of Finland) and VTT with Aalto University coordinating the project. The topics of these WPs were chosen so that they support Finnish industry activities in the battery value chain:

- WP1 Sustainable primary resources
- WP2 Value addition in metals production
- WP3 Recycling of batteries
- WP4 Tailored precursors and active electrode materials
- WP5 Business potential
- WP6 Project management
- WP7 European network

Specific summaries of the results achieved by BATCircle research organizations in a single-page format are listed on the following pages. A publication list including works published thus far and expected outcomes are also listed at the end of this document.



Figure 6. Work packages in BATCircle.

**WP 1**
**Task 1.1 Analysis of potential resources and deposit types**
**D1.1.1 A database analysis of Finnish cobalt, lithium and graphite deposits as well as technical and economic profiles about different type of deposits**
**Main results**

Evaluation of different ore deposits as potential sources of critical metals, especially cobalt, including the side streams -> most important deposit type by resource. The most important Finnish cobalt deposits are Talvivaara-type black schist-hosted Zn-Ni-Cu-Co deposits and magmatic Ni-Cu-Co-PGE deposits, which contain 82% of all known cobalt.

Review of mineralogical hosts for cobalt and recovery to concentrates: past-producing mines, active mines, and tests done for potential future deposits. The most important Co-hosting minerals are pentlandite and cobaltpentlandite, Fe sulphides and Co-sulpharsenide minerals.

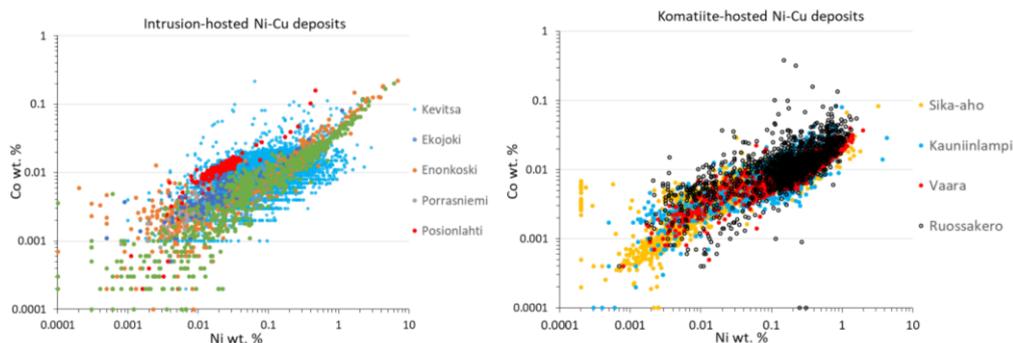


Figure 11. Ni-Co correlation in some Finnish intrusion-hosted and komatiite-hosted Ni-Cu deposits and occurrences.

**Highlights**

For the first time a comprehensive review of Finnish cobalt-nickel-copper deposits has been produced including analysis of cobalt grades and mineralogical hosts. The figure shows Ni-Co correlation for a few deposit types. Considering the processing options for these polymetallic deposits, the mineralogy is really the key factor to take into account.

**Possibility for future research and industrial potential**

Mineralogy and other specific features for each deposit can be studied using for example geometallurgical methods presented in other GTK project deliverables. These may provide new options and ideas for flowsheet development and better recoveries as well as project economics in the future.

<b>Contact person</b>	Tuomo Törmänen, <a href="mailto:tuomo.tormanen@gtk.fi">tuomo.tormanen@gtk.fi</a> , GTK
<b>Participants</b>	Pekka Tuomela
<b>Publications / Additional Information</b>	Törmänen, T., Tuomela, P., 2021, "Analysis of Finnish battery mineral deposits with special emphasis on cobalt", GTK Open File Research Report 29/2021, <a href="https://tupa.gtk.fi/raportti/arkisto/29_2021.pdf">https://tupa.gtk.fi/raportti/arkisto/29_2021.pdf</a>

<b>WP1</b>	<b>T1.2 Develop a more effective way of characterizing cobalt-bearing battery commodities in the context of process response, which leads to a more effective economic characterization</b>
<b>D1.2.1 A geometallurgical experimental and analytical procedure for cobalt-related battery minerals that allows for process characterization domaining of drill core scale samples to be validated with case studies</b>	
<p><b>Main results</b></p> <p>A battery minerals specific geometallurgy protocol was developed. The methodologies from several different technical areas were documented and integrated into one report.</p> <p><b>Highlights</b></p> <p>The experimental design process is split into 13 steps. Each step has been further quantified to the point where each step can be project managed.</p> <p><b>Possibility for future research and industrial potential</b></p> <p>This experimental protocol has been well received by the mining industry all over the world. Finland is now a world authority in geometallurgy (in conjunction with the two case studies). Further development could be the refinement of the procedure for specific mineral targets, and/or how to approach a polymetallic process path.</p>	
<b>Contact person</b>	Simon Michaux, <a href="mailto:simon.michaux@gtk.fi">simon.michaux@gtk.fi</a> , GTK
<b>Participants</b>	Simon Michaux, Alan Butcher, Quentin Dehaine, Tero Korhonen, Oleg Knauf
<b>Publications / Additional Information</b>	Report 01 Michaux, S.P., O'Connor, L., 2020, "How to Set Up and Develop a Geometallurgical Program", GTK Open Work File Report 72/2019, <a href="http://tupa.gtk.fi/raportti/arkisto/72_2019.pdf">http://tupa.gtk.fi/raportti/arkisto/72_2019.pdf</a> Michaux, S., 2019, "Oil from a Critical Raw Material Perspective", GTK Open File Work Report 70/2019, <a href="http://tupa.gtk.fi/raportti/arkisto/70_2019.pdf">http://tupa.gtk.fi/raportti/arkisto/70_2019.pdf</a>

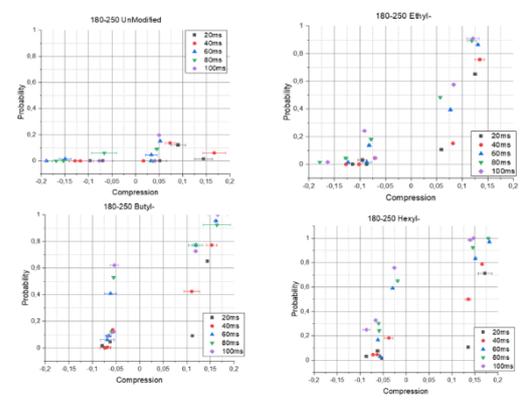
<b>WP 1</b>	<b>T1.2 Develop a more effective way of characterizing cobalt-bearing battery commodities in the context of process response, which leads to a more effective economic characterization</b>
<b>D1.2.2 A geometallurgical decision-making methodology based on case-study laboratory validation. This assists in the beneficiation process path development of cobalt-bearing battery minerals</b>	
<p><b>Main results</b></p> <p>A battery minerals specific geometallurgy protocol was developed (D1.2.1). This methodology was applied to two Finnish battery mineral deposit case studies (Konttijärvi Pd Pt Cu Ni Co and Rajapalot Au Co). The mineralogical influences that control various process separation methods were established. The efficiency of different processing methods for battery minerals was discussed.</p> <p><b>Highlights</b></p> <p>The use of mineralogy in a geometallurgy context proved valuable in this approach. In the Rajapalot case study, the mineralogical department of cobalt identified two different cobalt-bearing minerals (cobaltite and linnaeite), where the overall recovery of cobalt was quite poor when the ore was treated as a bulk stream. A series of process steps is proposed that will recover most of the cobalt. This will result in making cobalt extraction viable for future operations.</p> <p><b>Possibility for future research and industrial potential</b></p> <p>Methodology to fast track the feasibility development of battery mineral resources across the Nordic countries.</p>	
<b>Contact person</b>	Simon Michaux, <a href="mailto:simon.michaux@gtk.fi">simon.michaux@gtk.fi</a> , GTK
<b>Participants</b>	Simon Michaux, Alan Butcher, Quentin Dehaine, Tero Korhonen, Oleg Knauf
<b>Publications / Additional Information</b>	<p>Farajewicz, M., Cook, N., 2021, "Sample Selection for Geometallurgical Characterization in the Rajapalot Deposit", BATCircle Project Report 02, GTK Open File Work Report 9/2021. <a href="https://tupa.gtk.fi/raportti/arkisto/9_2021.pdf">https://tupa.gtk.fi/raportti/arkisto/9_2021.pdf</a></p> <p>Michaux, S., Butcher, A., Sardisco, L., Hughes, C., Morgan, L., Knauf, O., Dehaine, Q., 2020, "Characterization for Konttijärvi Geometallurgical Orientation Study Samples", BATCircle Project Report 03, GTK Open File Work Report 28/2020. <a href="https://tupa.gtk.fi/raportti/arkisto/28_2020.pdf">https://tupa.gtk.fi/raportti/arkisto/28_2020.pdf</a></p> <p>Dehaine, Q., Farajewicz, M., Michaux, S.P., Butcher, A.R., Cook, N., 2021, "Geometallurgical characterization of the Rajapalot Au-Co project", BATCircle Project Report 04, GTK Open File Work Report 5/2021, <a href="https://tupa.gtk.fi/raportti/arkisto/5_2021.pdf">https://tupa.gtk.fi/raportti/arkisto/5_2021.pdf</a></p> <p>Dehaine, Q., Michaux, S.P., Butcher, A.R., 2021, "Metallurgical testwork for the geometallurgical orientation study of the Mawson Gold's Rajapalot Au-Co project", BATCircle Project Report 05, GTK Open File Work Report 14/2021. <a href="https://tupa.gtk.fi/raportti/arkisto/14_2021.pdf">https://tupa.gtk.fi/raportti/arkisto/14_2021.pdf</a></p> <p>Michaux, S.P., Butcher, A.R., Dehaine, Q., Korhonen, T., Rivera, W., Bastin, D., Sardisco, L., Hughes, C., Morgan, L., Martin, J., Auranen, I., 2021, "Metallurgical testwork for the geometallurgical orientation study of the Konttijärvi Ni-Cu-PGE-(Au-Co) deposit", BATCircle Project Report 06, GTK Open File Work Report 15/2021. <a href="https://tupa.gtk.fi/raportti/arkisto/15_2021.pdf">https://tupa.gtk.fi/raportti/arkisto/15_2021.pdf</a></p>

**WP 1** Task 1.2.3 A novel characterization method to quantify hydrophobicity of microparticles

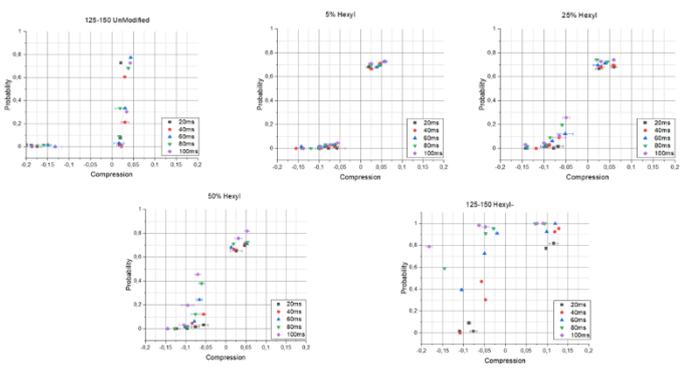
**D1.2.3 Report on Automated Contact Timer Apparatus (ACTA) as a characterization device**

**Main results**

Non-compressive attachment (NCA) is a phenomenon present in bubble-particle attachment when particles are adequately functionalized. It is directly proportional to material hydrophobicity. In addition to NCA, ACTA is capable of differentiating hydrophobicities and is sensitive to changes in hydrophobicity.



ACTA is selective and can distinguish between hydrophobic and non-hydrophobic particles. ACTA can also quantitatively detect varying degrees of hydrophobization and hydrophobic material abundance.



**Highlights**

The results show that it is possible to determine the wettability of particles using an automated contact time apparatus (ACTA). A reliable derivation of this quantification as a contact angle has been obtained. Results with different length alkyl coatings show that ACTA is capable of differentiating hydrophobicities in particles and subsequent dilutions show the quantitative sensitivity of the device.

**Possibility for future research and industrial potential**

Future research will involve investigation into: i) Effects of transport velocity on bubble-particle attachment, ii) Solution chemistry and how it affects bubble-particle attachment.

The industrial potential of the automated contact time apparatus (ACTA) is as a predictive flotation device where on-site flotation testing could even be an option. This would significantly reduce costs, environmental impact and the time used for pilot flotation tests.

<b>Contact person</b>	Rodrigo Serna, <a href="mailto:rodrigo.serna@aalto.fi">rodrigo.serna@aalto.fi</a> , Aalto University
<b>Participants</b>	Huggins Mkurazhizha, Robert Hartmann, Rodrigo Serna-Guerrero
<b>Publications / Additional Information</b>	Expatriation of Automated Contact Time Apparatus (ACTA) and its quantitative analysis of the wettability of microparticles in bubble-particle attachment.

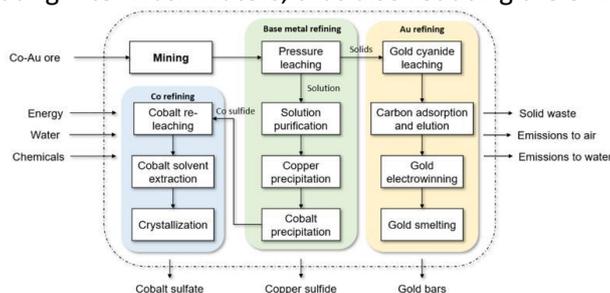
**WP 1** T1.2. Demonstrate a geometallurgical study concept, validated with selected case studies

**D1.2.4 Journal article on the simulation and LCA of prospective cobalt processing (Adjustable process model)**

**Main results**

A literature analysis was carried out to determine state-of-the-art processing options for the hydrometallurgical treatment of complex arsenical cobalt ores, which are found in Finland but are poorly utilized to date. A process flowsheet was proposed, and the process was simulated. The mineralogy of the prospective raw material was varied in the simulation and the effect of this variation on the environmental impacts, recovery rates, waste generation, and process heat balance was estimated.

It was shown that the environmental footprint of the hydrometallurgical process is high. In the evaluated process, the mineralogy of cobalt (in cobaltite, linnaeite or pentlandite) had very little effect. The environmental impacts were predicted to arise mainly from mining, beneficiation and concentrate pressure leaching. Oxygen consumption in pressure oxidation was the main hotspot in the hydrometallurgical process. It was also observed that the recovery rates of cobalt can be improved further by treating filter wash waters, thus also reducing the environmental impacts.



**Figure: Process model for Co-Au ore**

The global warming potential of the process was estimated to be 20–21 kg CO<sub>2</sub>-eq for 1 kg of produced cobalt sulphate, of which approximately 13 kg CO<sub>2</sub>-eq was attributed to the hydrometallurgical process.

**Highlights**

Highly detailed life cycle inventory data for the production of cobalt sulphate from future cobalt ores is presented, based on flowsheet simulation. Recommendations are made based on the predictive life cycle model.

**Possibility for future research and industrial potential**

The predictive life cycle model presented in the work can be improved greatly by specific inventory data on the mining and beneficiation steps. The hydrometallurgical process could be validated by experimental work, although some of the model parameters are difficult to measure accurately on laboratory scale. Other process options, such as chloride-based leaching processes, could be investigated for comparison.

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<b>Publications / Additional Info</b>	Scientific paper to be submitted by the end of the project. M. Rinne, H. Elomaa, M. Lundström, <i>Prospective life cycle assessment and process simulation of battery-grade cobalt sulfate production from Co-Au ores in Finland</i> , submitted April 2021.

**WP 1** Task 1.3 Strategic approach of battery mineral production in Finland

**D1.3.1 Strategic development plan for the development of Finnish mineral resources in a complete battery ecosystem**

**Scenario 1 (hydromet)**  
Central hydrometallurgical facilities & Terrafame/FBC downstream refining



**Main results**

Analysis of the Finnish battery ecosystem and strategic development plan to evaluate the options of Finnish battery mineral deposits exploitation (especially Ni-Co). Five mostly parallel value chain streams were identified. The ecosystem enables several options to exploit various types of Finnish battery mineral deposits -> three high-level scenarios were developed. Finnish primary nickel production could reach 50 000-60 000 tpa in the 2030s (currently approx. 40 000 tpa) if the key projects in the pipeline reach operational stage. Correspondingly cobalt production could be 2 500-3 000 tpa (approx. 2 200 tpa currently). This also enables an increase in domestic raw material refining in the ecosystem and hence promotion of a sustainable Finnish Battery Cluster.

**Highlights**

The existing Finnish industry ecosystem enables several production pathways to exploit the known advanced battery mineral deposits. These include three main options or scenarios of which two essentially consist of advanced hydrometallurgical processes (mixed hydroxide precipitate/MHP or mixed sulphide precipitate/MSP) and respective centralized processing facilities. These could feed the downstream refining facilities, partly in place already and partly being planned. The third option utilizes a pyrometallurgical process route which however would constrain midstream processing (in Finland) into one facility - the Boliden Harjavalta nickel smelter. Further downstream processing would also be partly more complicated and require more investments vs. the hydrometallurgical process options.

Option 1, Terrafame-Finnish Battery Chemicals, would be the most “domestic” option by far and possibly would enable the highest value chain benefits if the planned CAM plant materializes in the future.

**Possibility for future research and industrial potential**

The proposed strategic roadmap should be studied in detail and broken down into individual but connected project components run by the companies owning the assets and other commercial companies willing to develop the ecosystem. The technical and economic feasibility of these projects should then be properly evaluated and, based on the results, the necessary development measures undertaken at national level if need be and well justified. These actions require a new kind of national co-operation that could be undertaken as envisaged in the Finnish Battery Strategy launched in January 2021.

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<b>Publications / Additional info</b>	Tuomela, P., Törmänen, T., Michaux, S., 2021, “Strategic roadmap for the development of Finnish battery mineral resources”, GTK Open File Work Report 31/2021. <a href="https://tupa.gtk.fi/raportti/arkisto/31_2021.pdf">https://tupa.gtk.fi/raportti/arkisto/31_2021.pdf</a>

**WP 2** T2.1 Metallurgical processes for new battery metal concentrates from new mine sites

**D2.1.1 Scientific paper on hydrometallurgical treatment of raw material of future mines**

**Main results**

Ni- and Cu-rich concentrate was investigated from a new site in Suhanko, Finland.

A so-called “ripening process” liberated the associated Ni due to the oxidation of chalcopyrite and pyrrhotite. This liberation effect was found to enhance Ni extraction, whilst simultaneously inhibiting the dissolution of Si in the subsequent leaching stage.

Sulphuric acid leaching solution with Fe(III) as oxidant and Cl<sup>-</sup> as lixiviant was shown to be effective at leaching Ni (97%), Cu (62%) and Ag (89%), whilst simultaneously enriching the PMs Pd, Pt and Au in the residue.

A feasible flowsheet including: 1) sulphuric acid ripening, 2) recovery of Ni and Cu and enrichment of PMs, and 3) recovery of PMs was proposed for the recovery of target metals from the AHM concentrate.

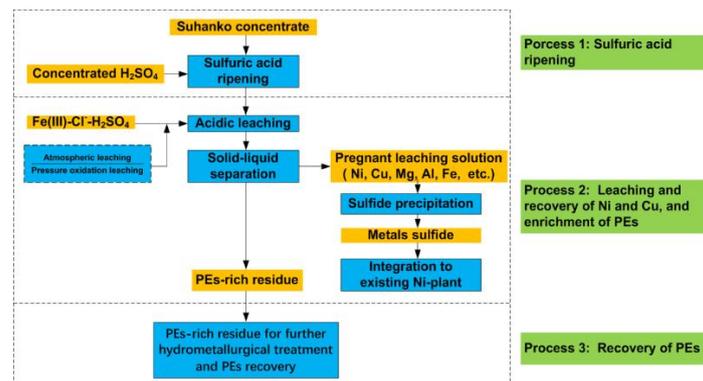


Figure: Flowsheet for the recovery of Ni, Cu and PMs.

**Highlights**

- (1) Extraction of a Ni- and Cu-rich concentrate from a new site in Suhanko, Finland.
- (2) Ripening process was used to restrain Si leaching and facilitate Ni leaching.
- (3) Ni and Cu were efficiently leached in the Fe(III)-Cl<sup>-</sup>-H<sub>2</sub>SO<sub>4</sub> system.
- (4) Pd, Pt and Au were enriched during the leaching process.

**Possibility for future research and industrial potential**

A preliminary flowsheet for the efficient recovery of the Ni, Cu and PM/PGMs in the Suhanko concentrate was proposed, which provides a potential process for future industrial-scale extraction of battery and precious metals from the concentrate.

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<b>Publications / Additional Information</b>	Ke, P., Rinne, M., Kalliomäki, T., Wang, Z., Hannula, P., Liu, Z., Wilson, B., Lundström, M., Ripening and leaching behavior of Ni- and Cu-rich Suhanko Ahmavaara concentrate in Fe(III)-Cl <sup>-</sup> -H <sub>2</sub> SO <sub>4</sub> system, Hydrometallurgy, 2021. (under review).

**WP 2** T2.2 Improved Co and Ni recovery in primary production

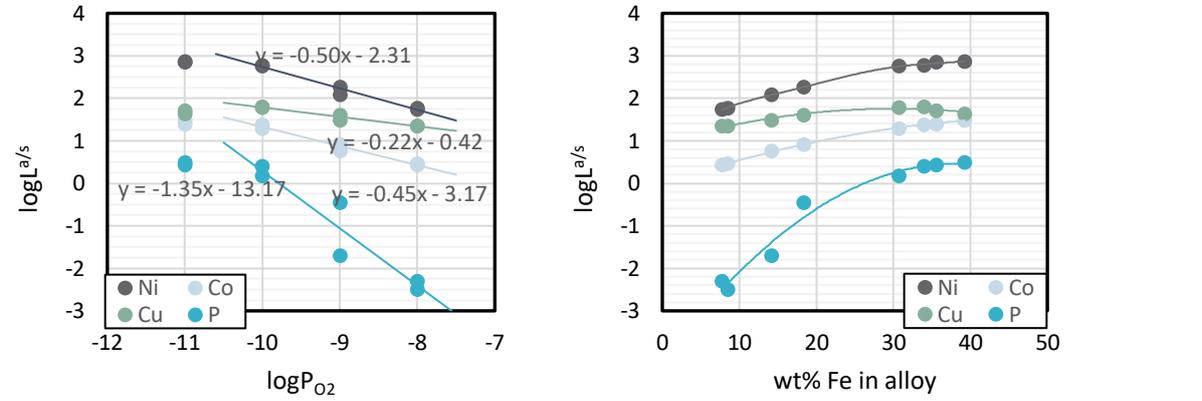
**D2.2.1 Scientific paper(s) on Co reduction equilibria and kinetics**

**D2.2.2 Scientific paper(s) on Ni slag cleaning element distributions and kinetics**

**Main results**

The equilibrium distribution behaviour of Ni, Co, Cu and P in Ni slag cleaning conditions (1400 °C and  $p_{O_2}$ :  $10^{-11}$ – $10^{-7}$  atm) was determined by using the sensitive analytical techniques of an electron X-ray microprobe and laser ablation high resolution inductively coupled mass spectrometer.

At  $10^{-7}$  atm, the metal alloy did not form and all elements were in slag and/or gas phases. At the lower partial pressures of oxygen, metal alloy formed and the distribution coefficients increased as a function of decreasing partial pressure and increasing iron concentration in the alloy. Copper concentration was low in the alloy (< 0.5 wt%) and slag (<500 ppmw) phases in all conditions, indicating high vaporization during the experiments.



**Highlights**

This study clarified the behaviour and chemical properties of typical battery metals in nickel slag cleaning conditions. The oxidation states of Ni, Cu, Co and P were determined as NiO, Cu<sub>2</sub>O, CoO and P<sub>2</sub>O<sub>5</sub>, respectively; additionally their activity coefficients were evaluated.

Phosphorus distribution behaviour was investigated for the first time in the aforementioned conditions. The study also elaborated on the reduction path of the main valuable metals in the process as a function of partial pressure of oxygen.

**Possibility for future research and industrial potential**

This data can be employed further by academia for the database development of process simulation and modelling programs. Industry can use this data as guidelines for process operation, such as the end point evaluation/optimization of the Ni slag cleaning process.

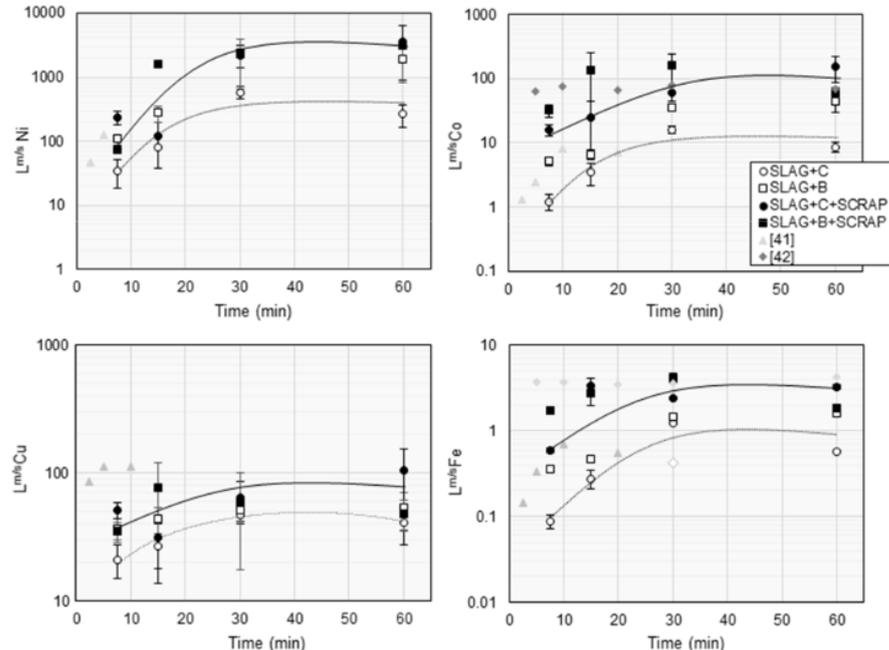
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<b>Publications / Additional Information</b>	Avarmaa, K., Taskinen, P., Klemettinen, L., O'Brien, H., Lindberg, D., 2021. Ni-Fe-Co alloy – magnesia-iron-silicate slag equilibria and the behavior of minor elements Cu and P in nickel slag cleaning. Journal of Materials Research and Technology. <a href="https://doi.org/10.1016/j.jmrt.2021.07.112">https://doi.org/10.1016/j.jmrt.2021.07.112</a>

**WP 2** T2.2 Improved Co and Ni recovery in primary production

**D2.2.1 Scientific paper(s) on Co reduction equilibria and kinetics**  
**D2.2.2 Scientific paper(s) on Ni slag cleaning element distributions and kinetics**

**Main results**

The reduction kinetics and recoveries of Co, Cu and Ni were investigated in nickel slag cleaning conditions (1400 °C) by using traditional fossil-based coke and a more sustainable option, biochar, as reductants. A cobalt-rich fraction of battery scrap (25.5 wt% Co) was also used as a secondary feed.



The distribution coefficients of Ni, Co, Cu and Fe between matte and slag increased as a function of time, biochar results being on the higher side compared to coke. Moreover, the addition of scrap notably increased the distribution coefficients of the valuable metals but consequently also the iron concentration in matte.

**Highlights**  
 The use of biochar results in faster reaction kinetics in the reduction process, compared to coke. The presence of battery scrap has a clear positive impact on the behaviour and reduction kinetics of the elements and/or enhanced settling and separation of matte and slag. The mass balance calculations were executed and presented in a manuscript published in the journal *Batteries*.

**Possibility for future research and industrial potential**  
 Results provide strong evidence that biochar would be a suitable reductant for an industrial slag cleaning process and that Co-rich battery scrap can improve the recoveries and process kinetics. Nevertheless, more research concerning biochar usage in nickel slag cleaning is needed, such as testing different biochars, different reductant/slag and biochar/coke ratios on laboratory and industry scale.

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<b>Publications / Additional Information</b>	Master's thesis by Marko Järvenpää, finished 1/2020. Journal article: 'Battery Scrap and Biochar Utilization for Improved Metal Recoveries in Nickel Slag Cleaning Conditions', <i>Batteries</i> , 6, 58, doi:10.3390/batteries6040058

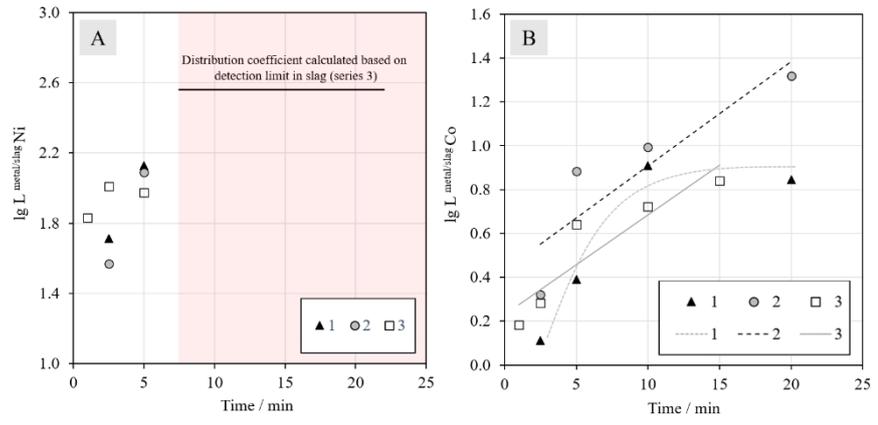
**WP 2** T2.2 Improved Co and Ni recovery in primary production

**D2.2.1 Scientific paper(s) on Co reduction equilibria and kinetics**  
**D2.2.2 Scientific paper(s) on Ni slag cleaning element distributions and kinetics**

**Main results**

The possibility of integrating battery scrap recycling and nickel slag cleaning by reduction with methane was investigated experimentally. Industrial nickel slag from the direct Outotec nickel flash smelting (DON) process was mixed with both synthetic and industrial battery scrap. The end products of the slag-scrap mixtures after reduction at 1400 °C in a (5 vol %) CH<sub>4</sub>-N<sub>2</sub> atmosphere were a Ni-Co-Cu-Fe metal alloy and FeO<sub>x</sub>-SiO<sub>2</sub> slag.

The distribution coefficients of Ni and Co between metal and slag are shown in Figures A and B, respectively.



It was observed that the reduction of nickel oxide started almost as soon as the molten slag came into contact with the CH<sub>4</sub>-N<sub>2</sub> atmosphere. The value of the distribution coefficient of Ni is only presented for the two shortest reduction times, since the Ni concentrations in the slag were below the detection limits of EDS after longer periods of time. This indicated that it is beneficial to add a battery scrap fraction rich in Co (Series 2 in Figure B) as it has a strongly increasing effect on cobalt recovery from the beginning of the reduction stage.

**Highlights**

The results clearly show that methane can be used as an effective reductant in the nickel slag cleaning process on a laboratory scale. Replacing conventional coke with an alternative reductant offers possibilities for smelters to reduce their environmental footprint and combat climate change.

**Possibility for future research and industrial potential**

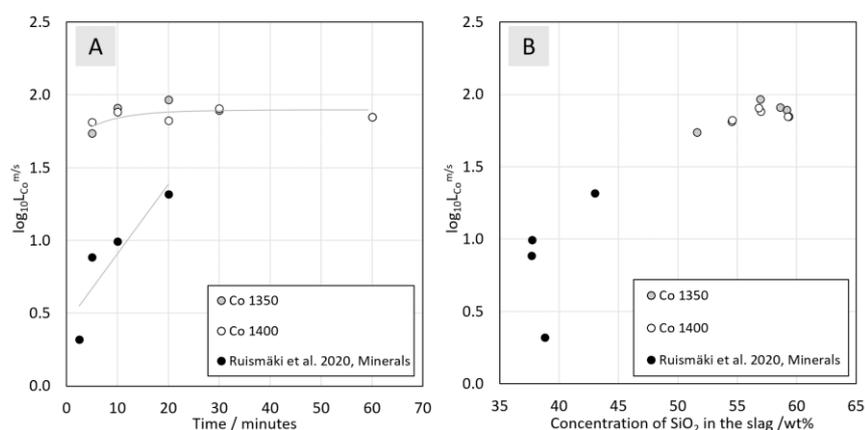
The use of methane in an electric arc furnace definitely requires further development and modifications to the present furnace design. Moreover, the optimal ratio between slag and added secondary material and the physical form of the scrap must be determined. The rate controlling steps should also be determined to enhance the process efficiency. The reaction rate can be affected by e.g. soot formation that may be blocking the reaction sites or gas flow. Additionally, other alternative reducing agents should be considered.

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<b>Publications / Additional Information</b>	Master's thesis by Otso Matikainen, 2020 <a href="http://urn.fi/URN:NBN:fi:aalto-202005243286">http://urn.fi/URN:NBN:fi:aalto-202005243286</a> Journal article: 'Integrated Battery Scrap Recycling and Nickel Slag Cleaning with Methane Reduction', Minerals 2020, 10, 435 doi: <a href="https://doi.org/10.3390/min10050435">10.3390/min10050435</a>

**WP 2**
**T2.2 Improved Co and Ni recovery in primary production**
**D2.2.1 Scientific paper(s) on Co reduction equilibria and kinetics**
**D2.2.2 Scientific paper(s) on Ni slag cleaning element distributions and kinetics**
**Main results**

The possibility of integrating froth flotation as a mechanical treatment to optimize the recovery of valuable metals from LIB scrap and minimize their losses in the nickel slag cleaning process. The conventional reducing agent in slag cleaning, coke, was replaced with graphite contained in the LIB waste flotation products. The industrial Ni-slag and flotation fraction were mixed in a 4:1 ratio. The experiments were conducted in temperatures of 1350 °C and 1400 °C in an argon atmosphere with different contact times.

The presented figure shows the distribution of Co between the metal alloy and the slag as a function of contact time (A) and as a function of silica concentration in the slag (B). The results showed that temperature (1350 or 1400 °C) does not have an impact on the



cobalt distribution coefficient. Moreover, it was indicated that the distribution coefficient of cobalt already reached its maximum value during the first 10 minutes. It was observed that an increasing silica concentration in the slag has an increasing effect on the cobalt distribution coefficient. The obtained results were compared to an earlier study published in the Minerals journal.

**Highlights**

The experimental results indicated that the integration of industrial nickel slag cleaning and LIB recycling was successful. Froth flotation can be introduced as a mechanical pre-treatment for pyrometallurgical battery recycling. Additionally, graphite in the flotation fraction can be utilized to replace coke at least partially in the nickel slag cleaning process.

**Possibility for future research and industrial potential**

A proof-of-concept for integrating froth flotation and a high-temperature pyrometallurgical process for recovering valuable metals from lithium-ion batteries was investigated for the first time. Further research on the optimal charging procedure and ratio of Ni-slag and battery scrap should be conducted.

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<b>Publications / Additional Information</b>	Journal article: 'Integrating Flotation and Pyrometallurgy for Recovering Graphite and Valuable Metals from Battery Scrap', Metals, 2020, 10(5), 680 doi: <a href="https://doi.org/10.3390/met10050680">10.3390/met10050680</a>

**WP 2** T2.2 Improved Co and Ni recovery in primary production: The effect of increased Ni concentration in Cu-ER electrolyte

**D2.2.3 Scientific paper on the modelling of the effect of battery metals and impurities on the physicochemical properties of the electrolyte**

**Main results**

The regression models for the physico-chemical properties of Cu electrolytes, built as a function of composition and temperature, were combined into an optimization model. These separate models (for conductivity, viscosity, diffusion coefficient of Cu(II) and limiting current density) were also validated by measurements of industrial Cu electrolytes. One optimization example with varying [Ni] and T is presented in Figure 1, in which the highest desirability means the most optimal conditions.

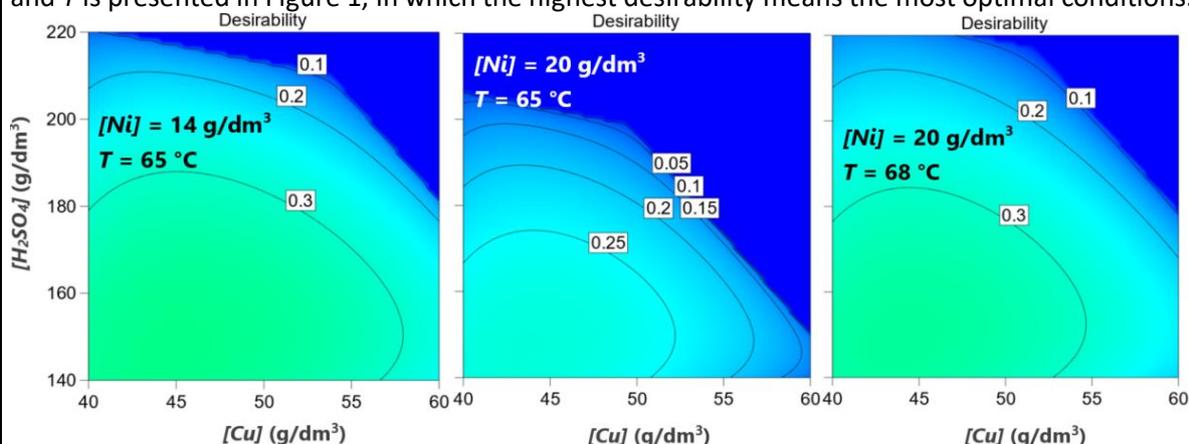


Figure 1. Example of optimization plots. [As] = 7.5 g/dm³ and Σ[Minor impurities] = 0.5 g/dm³.

**Highlights**

Cu-ER electrolytes in industry can be optimized further by utilizing the regression models built during this research for physico-chemical properties.

**Possibility for future research and industrial potential**

This topic is closely related to the industrial Cu-ER process. Thus, the further research of the effects of Ni on Cu-ER electrolyte is crucial.

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<b>Publications / Additional Information</b>	<p>Helin, S. A. P., Extraction of manganese from mining process and battery waste solutions via carbonate precipitation. Master’s thesis, 2020. <a href="http://urn.fi/URN:NBN:fi:aalto-202101311754">http://urn.fi/URN:NBN:fi:aalto-202101311754</a></p> <p>Kalliomäki, T., Aji, A.T., Jafari, S., Leskinen, W., Wilson, B.P., Aromaa, J., Lundström, M., 2021, Industrial Validation of Conductivity and Viscosity Models for Copper Electrolysis Processes. Minerals Engineering 171, 107069, <a href="https://doi.org/10.1016/j.mineng.2021.107069">https://doi.org/10.1016/j.mineng.2021.107069</a></p>

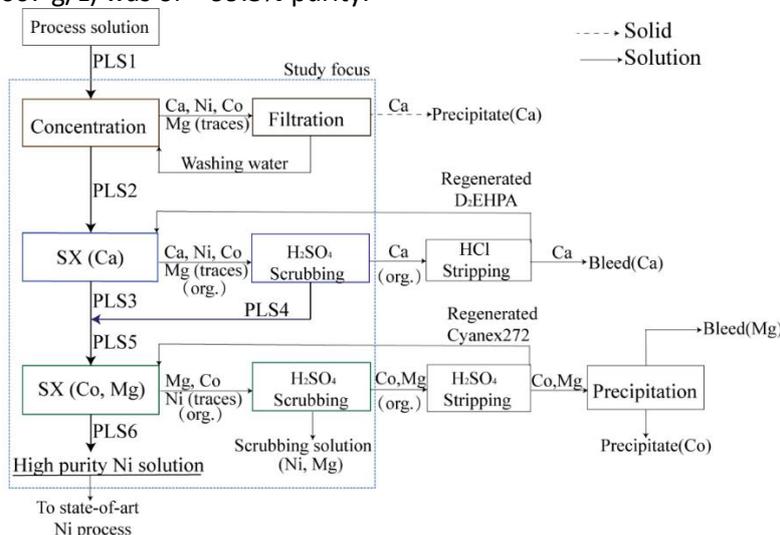
**WP 2** T2.3 Value addition of produced Ni- and Co-rich solutions

**D2.3.1 Towards high purity for nickel recovery from industrial side stream by the use of concentration and liquid-liquid extraction**

**Main results**

A multi-metal industrial side stream (16.3 g/L Ni, 0.7 g/L Co, 0.6 g/L Ca and 1.6 g/L Mg) was purified by using a methodology which comprises initial evaporation and two-step solvent extraction with organophosphorus extractants (shown in Figure 1).

It was found that over 80% of Ca was selectively removed as  $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$  by evaporation. In the  $\text{Na-D}_2\text{EHPA}$  treatment, ~90% of residual Ca (0.6 g/L) can be selectively extracted. Co (>99%) and Mg (>95%) were separated with Na-Cyanex 272. The resultant nickel sulphate solution (61.7 g/L Ni, 0.3 g/L Mg and Co 0.007 g/L) was of > 99.5% purity.



**Figure 1. Schematic flowsheet for the purification of industrial sidestream.**

**Highlights**

The separation of Ca, Mg, Co and Ni by means of evaporation and solvent extraction was explored. The concentration behaviour of the metal ions during evaporation was observed. The effect of the process parameters was determined. Finally, purified nickel sulphate solution was obtained.

**Possibility for future research and industrial potential**

The industrial potential for future research in this topic is high as the process can be used to treat an industrial side stream, thus producing nickel sulphate solution with high purity.

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<b>Publications / Additional Information</b>	Hu F., Wilson, B. P., Han B., et al. High Purity Nickel Recovery from an Industrial Sidestream Using Concentration and Liquid–Liquid Extraction Techniques[J]. JOM: the journal of the Minerals, Metals & Materials Society, 2019, 72(8). DOI: <a href="https://doi.org/10.1007/s11837-019-03928-4">10.1007/s11837-019-03928-4</a>

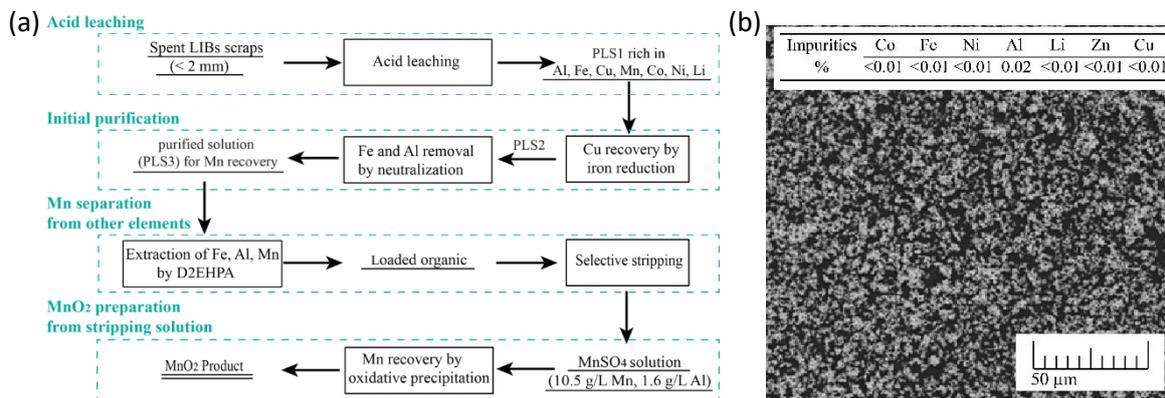
**WP 2**

**T2.4 Mn recovery from currently underutilized process streams**

**D2.4.1 Process description for a potential Mn recovery route**

**Main results**

The current study investigated in detail the recovery of Mn from industrially produced LIBs waste that is rich in valuable metals (Co, Ni, Mn, Li) and impurities (Fe, Al, Cu). High-purity MnO<sub>2</sub> (purity > 99.5%) product can be produced via a multi-step process based on solvent extraction with D2EHPA, scrubbing, stripping and oxidative Mn precipitation. In addition, the behaviour of other elements (Co, Ni, Fe, Al, etc.) was also investigated throughout the whole process.



**Figure1. (a) Proposed flow sheet for the recovery of Mn from spent LIBs. (b) SEM of the MnO<sub>2</sub> product including associated impurity values.**

**Highlights**

Co and Fe are the two main detrimental elements that can contaminate the prepared MnO<sub>2</sub> product via oxidative precipitation.

The separation of Mn from Co/Ni/Li and Fe can be achieved by solvent extraction with D2EHPA (A/O = 1:2, D2EHPA = 0.4 M, pH 3.2, t = 15 min) and a selective stripping process (H<sub>2</sub>SO<sub>4</sub> = 0.5 mol/L, A/O = 1:8, t = 10 min), respectively.

The presented approach produces MnO<sub>2</sub> with a purity of above 99.5%.

**Possibility for future research and industrial potential**

The presented flowsheet allows the high recovery of Mn with limited loss of other target metals (e.g. Co), and has the potential for large-scale applications since all the selected operations are based upon known unit processes.

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<b>Publications / Additional Information</b>	Peng C., Chang C., Wang Z. L., Wilson B. P., Liu F. P., Lundström, M., Recovery of High-Purity MnO <sub>2</sub> from the Acid Leaching Solution of Spent Li-Ion Batteries, JOM, 72 (2020): 790-799. DOI: <a href="https://doi.org/10.1007/s11837-019-03785-1">https://doi.org/10.1007/s11837-019-03785-1</a>

**WP 2**
**T2.4 Mn recovery from currently underutilized process streams**
**Extraction of manganese from mining process and battery waste solutions via carbonate precipitation**
**Main results**

Full extraction of manganese from the two studied synthetic solutions presented in Table 1 was possible using 200 g/l Na<sub>2</sub>CO<sub>3</sub> solution. Case I solution was modelled after a primary production PLS and Case II solution was a high-Mn waste LIB leaching solution PLS. In both cases, it was assumed that the more valuable metals (Ni, Co, Cu, Zn) had already been extracted from the solutions.

**Table 1. Compositions (g/l) of studied solutions.**

Solution	Mn	Fe	Li	Mg	Na
Case I	7	12	-	5	1
Case II	10	3.2	1.5	-	-

Full extraction of Mn was obtained from Case I solution by raising the pH to 7.2 for 4 hours. However, 100% of Fe was co-precipitated. To selectively precipitate Mn, a pH range between 6.0 and 6.4 was found where selective Mn precipitation could be possible with careful pH regulation, resulting in 100% Mn precipitation and 30% Fe precipitation. In Case II solution, full extraction of Mn was possible by raising the pH to 7.6 for 4 hours, again resulting in 100% Fe co-precipitation in addition to 30% Li co-precipitation. Selective extraction of Mn would need 100% Fe extraction in pH 6.0 to 6.4 for over 4 hours, after which the pH could be raised to 6.8, where 100% of Mn would precipitate. This would also result in 30% Li co-precipitation.

**Highlights**

A narrow range of selectivity found for both solutions, which allows for further studies. Li co-precipitation approx. 30% when Mn and Fe fully precipitated from Case II solution. Precipitate contents might allow use in steelmaking processes as high-grade (>40 wt.%, Case II) and low-grade (<40 wt.%, Case I) Mn-containing materials.

**Possibility for future research and industrial potential**

Potential for future research to ascertain the possibility of selective precipitation of Mn and Fe from each solution. Possibility of studying Li co-precipitation phenomenon in more detail from Case II solution. Industrial potential to provide materials for the steelmaking industry through the precipitates.

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<b>Publications / Additional Information</b>	Helin, S. (2020) <i>Extraction of manganese from mining process and battery waste solutions via carbonate precipitation</i> . Master's thesis. Aalto University. <a href="http://urn.fi/URN:NBN:fi:aalto-202101311754">http://urn.fi/URN:NBN:fi:aalto-202101311754</a>

**WP2**
**T2.5 Performance of different oleic acid sources and the effect of temperature on flotation**
**D2.5.1 Report on the performance of different oleic acid sources**
**D2.5.2 Report on the effect of temperature on flotation**
**Main results**

The performance and behaviour of alternative fatty acid sources and the effect of increased temperature in spodumene ( $\text{Li}_2\text{O}$ ) flotation were studied with Keliber Rapasaari spodumene ore on bench scale and mini-pilot scale.

It was found that it could be possible to reduce the collector dosages depending on the collector type if elevated temperatures were applied.

In the bench-scale flotation tests, the elevated temperature improved the  $\text{Li}_2\text{O}$  recoveries significantly with distilled rapeseed fatty acid (Prifac) and oleic acid (Olefat-11) in rougher spodumene flotation. In contrast, with distilled rapeseed oil fatty acid (Colza) the  $\text{Li}_2\text{O}$  recoveries were slightly lower at elevated temperature in comparison to room temperature. The results with tall oil fatty acid were modest; the rougher flotation seemed to work rather well, but in the cleaning spodumene was depressed heavily.

Elevated temperatures in pre-flotation cause high spodumene losses. If elevated temperatures are applied in this stage the collector dosages should be decreased and optimized. The recoveries with rapeseed oil fatty acid (Colza) and oleic acid were slightly better in comparison to the reference collector, distilled rapeseed fatty acid (Prifac).

In the mini-pilot flotation tests the spodumene recovery and grade in the final concentrate were higher in elevated temperatures than in the reference test points but also  $\text{P}_2\text{O}_5$  recoveries were slightly higher in elevated temperatures whilst the grade remained at the same level.

**Highlights**

Overall, it was confirmed that elevated temperatures improve spodumene recovery with rapeseed fatty acid (Prifac).

**Possibility for future research and industrial potential**

The potential for future research in this topic is great as alternative fatty acid sources could be applied in spodumene flotation. When elevated temperatures are used it could be possible to reduce the chemical dosages and, therefore reduce costs.

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<b>Participants</b>	Pekka Tuomela, Pirjo Seppälä, Tero Korhonen
<b>Publications / Additional Information</b>	Seppälä P., Korhonen T. (2020) The Performance and Behavior of Alternative Collectors and the Effect of Temperature in Spodumene Flotation, GTK Report 18/2020.

**WP 3**
**T3.1 Mechanical Treatment of Waste EV Batteries**
**D3.1.1 Report on the characteristics of crushed battery waste and mechanical pretreatment on laboratory scale**
**Main results**

The study aimed at investigating the characteristics and mechanical processability of primary crushed e-bike and power tool batteries. Both samples, i.e. the e-bike and power tool batteries were sieved into 12 fractions (sieve sizes of 0.5 – 63 mm) with a similar size distribution. Gas emissions from all the fractions were also monitored by FTIR, and an HF detector was used to identify HF. No HF was detected, but carbon emissions (e.g. CO<sub>2</sub>) were detected from the sample fractions. After the emission tests, the power tool sample was discarded, and the study was refocused on the e-bike sample which was divided into two parts (each composed of an individual size fraction) and inspected further. The < 4 mm fractions were analysed separately by XRF, and the aggregated results indicated the presence of NMC-111 type cathode materials. The size fractions > 4 mm were visually inspected for classification as well as liberation purposes. Significantly, undamaged cells were detected due to primary crushing. In particular, poor liberation was identified in the Al cathode foils, which is expected because of the polymeric binders. The mechanical treatment experiments showed that a significant proportion of damaged battery cells was removed by magnetic separation, whereas cathodes and anodes as well as plastics continued to eddy current separation. Eddy current enriched anode and cathode particles to splitter fraction, the recoveries of enriched anode and cathode particles were 32 and 28 wt.%, respectively. This study concentrated on the preliminary suitability of eddy current separation on crushed battery wastes. Despite the rather low recoveries, we observed the separation characteristics of anode and cathode particles with eddy current. In this task, the raw material was only primary crushed; the foils were not fully liberated, which decreases the recovery levels.

**Highlights**

Gas emissions from the primary crushed materials measured with an FTIR and HF detector. No HF detected.

Most of the Al foils throughout size classes larger than 4 mm still contaminated, i.e. not liberated. Similarly, the anode Cu foils show contamination.

Separation characteristics of anode and cathode particles observed with eddy current.

**Possibility for future research and industrial potential**

Further investigation with other battery designs, such as pouch and prismatic would be valuable. In addition, the crushability of different batteries as well as further refinement of the materials would be important research topics. Moreover, research with secondary crushed feed, in which the anode and cathode are liberated, would lead to more accurate results on separation. Additionally, future studies should cover the possibilities to separate anode and cathode components into distinct fractions via eddy current.

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<b>Participants</b>	John Bachér, Tuomo Mäkelä, Antti Porvali, Lotta Rintala
<b>Publications / Additional Information</b>	Characteristics of crushed battery waste and mechanical pretreatment at laboratory scale, VTT Research Report (VTT-R-01091-20)

**WP 3****T3.1 Froth Flotation for the Recovery of Metals and Active Materials in Waste LIBs****D3.1.2 Academic report on froth flotation for the recovery of metals and active materials in waste LIBs****Main results**

A dedicated research laboratory for the study of LIB recycling was established at Aalto University following strict safety measures and protocols for handling waste LIB samples.

Dry sieving of the mechanically crushed end-of-life (EoL) battery waste results in most of the Cu and Al particles being retained in a coarse (> 400 $\mu$ m) fraction, while the majority of the black mass (BM) is concentrated in the fine fraction. However, the coarse fraction still contains a significant amount (~30 wt.-%) of non-liberated BM.

When not treated for the removal of the PVDF binder, both the anode and the cathode components behave hydrophobically, and are therefore predominantly extracted in the froth phase of the flotation process. Therefore, flotation is a potential method for the selective recovery of the non-liberated BM in a Cu/Al-rich coarse fraction. Milling allows for increased liberation of the BM and can be applied as a pre-treatment for flotation.

The froth concentrate was demonstrated to be suitable as a feed for industrial Ni slag cleaning. A high-temperature treatment of a 1:4 mixture of froth fraction-Ni slag resulted in the recovery of Co, Ni and Cu as a matte phase, and utilized the recovered graphite as a reducing agent, eliminating the need for an additional reductant. This study was the first reported case in which BM recycling was integrated with an existing industrial process.

**Highlights**

A compilation of safety practices and protocols for handling and experimentation with EoL LIBs.

Flotation recoveries with the optimal 20 min milling time for Co, Ni, Mn and Cu reported to be 81.3%, 67.6%, 78.4% and 10%, respectively. Very fast reaction kinetics recorded when mixed with Ni slag and fed to a high-temperature slag cleaning process, as the distribution coefficient of valuable metals reached its maximum in just 5 min of reduction time. This is hypothesized to be due to the small particle size of the recovered graphite.

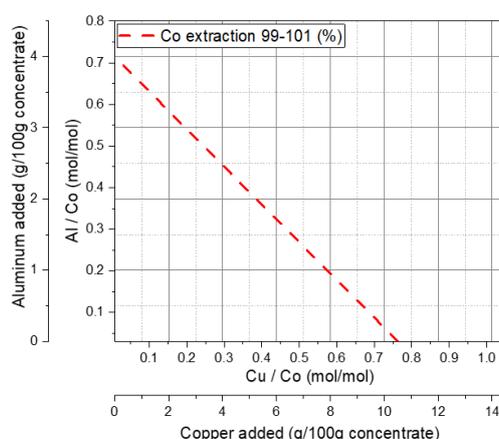
**Possibility for future research and industrial potential**

Flotation was demonstrated to be a suitable unit operation for the selective recovery of industrially prepared BM in Cu/Al-rich coarse sieve fractions. Furthermore, the applicability of the froth fraction as a feed for the existing industrial process of Ni slag cleaning was demonstrated for the first time. Future research is still needed for the optimization of the Ni slag cleaning process parameters.

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<b>Publications / Additional Information</b>	Ruismäki, R.; Rinne, T.; Danczak, A.; Taskinen, P.; Serna Guerrero, R.; Jokilaakso, A. Integrating Flotation and Pyrometallurgy for Recovering Graphite and Valuable Metals from Battery Scrap. <i>Metals</i> 2020, 10, 680. DOI: <a href="https://doi.org/10.3390/met10050680">10.3390/met10050680</a> Nissi, J. Development of Safety Protocols in Aalto University LIB Recycling Laboratory, Aalto University Master's thesis, 2019

**WP 3**
**T3.2 Leaching of selected waste EV battery fractions**
**D3.2.1 Academic report on leaching selected EV battery waste fractions**
**Main results**

It was found that Cu and Al can effectively reduce the active materials in the presence of iron originating from black mass. Cu was shown to be a more efficient reductant than Al. The concentration of aqueous  $\text{Cu}^{2+}$  in the solution decreased when Al was added. This indicated the cementation of Cu on the Al surface as Cu re-dissolved into the solution by acting as a reductant for  $\text{LiCoO}_2$ . The built model predicts that either 11 g of Cu or 4 g of Al or a combination of both are required for full Co extraction and ~90% extraction of Ni, Mn and Li from 100 g of sieved industrial battery waste concentrate containing 26 g of Co, 2.5 g of Ni, 2.7 g of Mn and 3.8 g of Li.



**Figure: Adjusted Al-Cu ratio required for maximum cobalt extraction.**

The effects of Cu and Al were found to be linear, and the  $\text{Cu} \cdot \text{Al}$  interaction term was not significant. Al may be dependent on the presence of  $\text{Cu}^{2+}$  to be an effective reductant.

**Highlights**

The effects of individually added Al and Cu scrap current collectors (crushed and sieved with two sieves) were investigated in  $\text{LiCoO}_2$ -rich black mass leaching in sulphate media ( $T = 60^\circ\text{C}$ ,  $[\text{H}_2\text{SO}_4] = 2\text{M}$ ,  $S/L = 200 \text{ g/L}$ ) using regression modelling.

**Possibility for future research and industrial potential**

The reaction mechanism of Al should be investigated with active material and its feasibility as a reductant estimated. The interaction of the common reductant  $\text{H}_2\text{O}_2$  with Cu, Fe, Al and other components in battery waste and how their concurrent presence can impact the metal extraction should also be investigated.

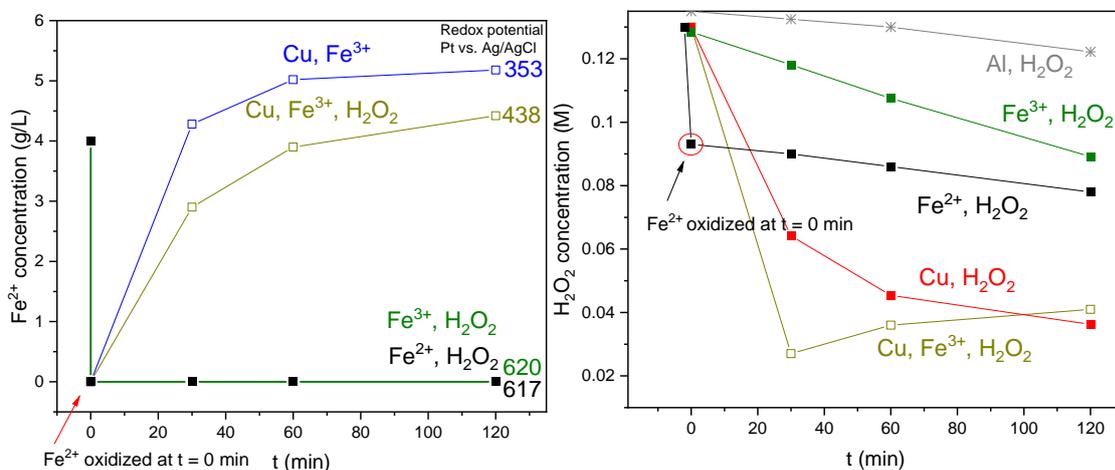
<b>Contact person</b>	Mari Lundström, <a href="mailto:mari.lundstrom@aalto.fi">mari.lundstrom@aalto.fi</a> , Aalto University
<b>Participants</b>	Alexander Chernyaev, Jere Partinen, Mari Lundström
<b>Publications / Additional Information</b>	Chernyaev, A., Partinen, J., Klemettinen, L., Wilson, B.P., Jokilaakso, A., & Lundström, M., 2021, The efficiency of scrap Cu and Al current collectors materials as reductants in LIB waste leaching, <i>Hydrometallurgy</i> 203, 105608, <a href="https://doi.org/10.1016/j.hydromet.2021.105608">https://doi.org/10.1016/j.hydromet.2021.105608</a>

**WP 3**
**T3.2 Leaching of selected waste EV battery fractions**
**D3.2.1 Academic report of leaching selected EV battery waste fractions**
**Main results**

The interaction of the commonly utilized  $H_2O_2$  reductant with metallic Cu, Fe and Al in the absence of active material was studied analytically in an agitated reactor ( $T = 30^\circ C$  and 400 ml of lixiviant  $[H_2SO_4] = 2M$ ). The amounts of reductant added were as follows:  $[Cu] = 5 \text{ g/L}$ ,  $[Al] = 7.5 \text{ g/L}$ ,  $[H_2O_2] = 0.13 \text{ M}$  (7.5 ml/L of 50% conc.),  $[Fe(III)] = 6 \text{ g/L}$  of and  $[Fe(II)] = 4 \text{ g/L}$  as sulphate salts. Similar phenomena also investigated briefly in the presence of chlorides.

**Highlights**

The possibility of  $H_2O_2$  overconsumption for the oxidation of Cu, Fe and Al was confirmed in the absence of active material.



**Figure:  $Fe^{2+}$  ions and  $H_2O_2$  concentration.**

$H_2O_2$  was consumed for the rapid oxidation of  $Fe^{2+}$  and Cu. This resulted in the simultaneous consumption of all reducing agents which reacted with each other. Al had a minimal impact on  $H_2O_2$  consumption.

**Possibility for future research and industrial potential**

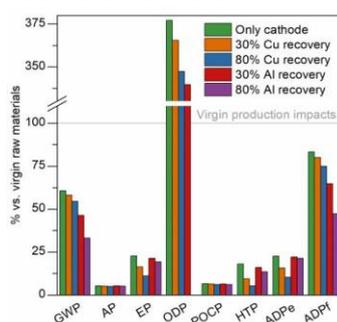
The applicability of these reductants in  $LiNi_xMn_yCo_zO_2$  leaching should be investigated. Research is needed on their interactions, i.e. whether the presence of Cu, Fe or Al would negatively affect metal extraction using  $H_2O_2$  as the main reducing agent. The study can help highlight the importance of using either only metallic components from battery production scrap or waste black mass, or only  $H_2O_2$  in the absence of metallic components in the waste. This will help to avoid the unwanted consumption of  $H_2O_2$  for the oxidation of metallic components, which are also effective reductants.

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<b>Participants</b>	Alexander Chernyaev, Yuanmin Zou, Jere Partinen, Mari Lundström
<b>Publications / Additional Information</b>	Analytical study being prepared on the interaction of $H_2O_2$ with Cu, Fe and Al in 2M $H_2SO_4$ Study to be continued with NMC active material

**WP 3**
**T 3.3 Solution purification and metal recovery from PLS originating from EV**
**D3.3.1 Scientific paper on hydrometallurgical processing of EV battery waste**
**Main results**

The synergistic battery recycling process presented by Liu et al. (2019) in the project was critically evaluated by simulation and life cycle assessment. Scenario analysis was conducted to estimate the feasibility of sodium circulation in the process: crystallization, in solution, or not at all.

Sodium sulphate crystallization was shown to be the most beneficial way to recycle sodium in the process (3.7 kg CO<sub>2</sub>-eq global warming potential for treating 1 kg batteries), while recycling it in solution increased chemicals consumption the most and resulted in the highest GWP (3.9 kg CO<sub>2</sub>-eq). It was estimated that the recycling process would result in approximately 36% less greenhouse gas emissions than equivalent primary processes to produce nickel and cobalt sulphate, lithium chemicals, manganese oxide and rare earths from ores with the system boundaries used.



**Figure: The effect of including mechanical processing (Cu and Al recovery) inside the studied system boundaries on the environmental impacts of the process**

It was shown that the consumption of acid and neutralizing chemicals (NaOH), particularly in Ni and Co solvent extraction, contributed the most to environmental impacts. Calcium-based neutralizing chemicals should be considered, although this reduces the amount of recyclable Na in the process and necessitates additional gypsum removal steps.

The scalability of the process is limited by the low availability of waste NiMH batteries in comparison to Li-ion batteries in the estimated time scale (2030), which also affects the amount of recoverable rare earth elements (REEs) in the process and the consumption of external reductants in the leaching of active materials from Li-ion batteries.

**Highlights**

A detailed process-level life cycle assessment of a prospective battery recycling process and analysis of the strengths and problem areas of the process. The scalability of the process is also evaluated based on the process simulation.

**Possibility for future research and industrial potential**

The methodology used in the study was shown to have great potential in evaluating the impacts of prospective battery recycling processes, considering the lack of facility-level data so far. This is invaluable in developing sustainable processes.

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<b>Participants</b>	Marja Rinne, Heini Elomaa, Antti Porvali, Mari Lundström
<b>Publications / Additional Information</b>	<p>F. Liu, C. Peng, A. Porvali, Z. Wang, B.P. Wilson, M. Lundström, <i>Synergistic Recovery of Valuable Metals from Spent Nickel–Metal Hydride Batteries and Lithium-Ion Batteries</i>, ACS Sustainable Chem. Eng. 2019, 7, 16103-16111. DOI: <a href="https://doi.org/10.1021/acssuschemeng.9b02863">10.1021/acssuschemeng.9b02863</a></p> <p>M. Rinne, H. Elomaa, A. Porvali, M. Lundström, <i>Simulation-based life cycle assessment for hydrometallurgical recycling of mixed LIB and NiMH waste</i>, Resources, Conservation and Recycling, 2021, 170, 105586. DOI: <a href="https://doi.org/10.1016/j.resconrec.2021.105586">10.1016/j.resconrec.2021.105586</a></p> <p>Press release – over 5M views from ~20 websites internationally by April 2021, e.g. <a href="https://www.mining.com/raw-materials-from-ev-battery-recycling-have-smaller-carbon-footprint-study">https://www.mining.com/raw-materials-from-ev-battery-recycling-have-smaller-carbon-footprint-study</a></p>

**WP 3**
**T 3.3 Solution purification and metal recovery from PLS originating from EV**
**Master's thesis on battery metals and oxides recovery from hydrometallurgically treated waste LIBs**
**Main results**

Currently operational recycling processes were studied and summarized in detail. Based on these processes, a simulation of a new recycling process was created. The simulation provided information on the scale of chemical consumption in a continuous industrial recycling process, as well as the concentrations of leach solutions after purification.

It was concluded that the reactions occurring on the electrode are complex and highly dependent on the applied operating parameters. Under certain conditions, the anodic deposit of oxides tended to detach from the surface of the electrode, which limited the amount of information that could be obtained from the experiments. In solutions containing cobalt, a reversible oxidation reaction could be observed at 50 °C and pH 6-7. However, no reversible oxidation reaction could be observed for nickel, which conflicted with the literature. At 25 °C, both cobalt and nickel were oxidised irreversibly. Probable species were determined based on thermodynamics and earlier literature.



*Figure: GC electrode with black precipitate. The result of a CV experiment carried out in cobalt-lithium solution at 25 °C and pH 5, sweep rate 5 mV s<sup>-1</sup>, potential range 2.3 V to -1.4 V vs. SCE.*

**Highlights**

A new LIB recycling process was created and simulated. The composition of the raw material feed used in the simulation was varied, and the resulting solution compositions were tabulated.

Solutions containing nickel, cobalt and lithium were subjected to cyclic voltammetry under varying conditions. A series of cyclic voltammograms were drawn and presented in the work. Challenges of anodic deposition of battery metals on an industrial scale were discussed.

**Possibility for future research and industrial potential**

In future research, the compositions of the anodic deposits could be determined by SEM-EDS, XRD or other techniques. This could prove useful if the formation of LiCoO<sub>2</sub> or LiNiO<sub>2</sub> can be verified. Determining the composition could provide some insight into the anode slimes formed in the electrowinning stage of recycling processes. More research could even include EQCM measurements, which would further illuminate the electrochemical processes occurring on the electrodes. EQCM results could prove useful in providing elementary knowledge on cloudy electrodeposition processes.

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<b>Publications / Additional Information</b>	Palomäki, H., 2020, "Electrochemical Methods for the Recovery of Battery Metals from Lithium-ion Battery Waste Leach Solutions", MSc Thesis, Aalto University. <a href="http://urn.fi/URN:NBN:fi:aalto-202101311734">http://urn.fi/URN:NBN:fi:aalto-202101311734</a>

**WP 3**

**T 3.4 Removal of trace and harmful impurities**

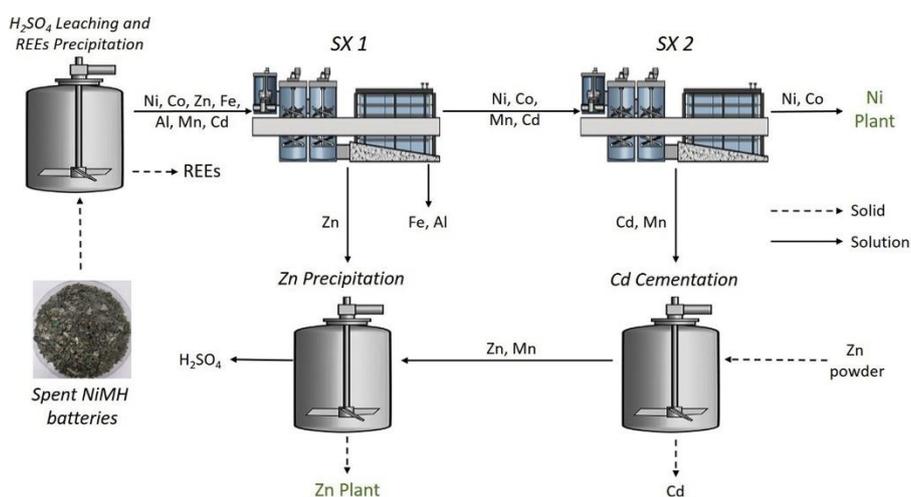
**D3.4.1 Scientific paper on the removal of impurity elements from battery waste**

**Main results**

A two-step solvent extraction process using Di-2-ethylhexyl phosphoric acid (D2EHPA) was developed. In the first step, Zn, Al and Fe were removed at pH 1.5, whereas in the second step Cd and Mn were removed at pH 2.3. The extraction of Cd contamination from NiMH waste process solution removes a detrimental element that would challenge its use in primary plant operations. Different process parameters (pH, O/A ratio, temperature, extractant concentration, kinetics) were optimized at each step of the solvent extraction. The purified and fully integrable PLS was found to contain Ni ~28 g/L and Co ~3.7 g/L.

**Highlights**

A new flowsheet for integration of end-of-life nickel metal hydride (NiMH) batteries into a primary nickel production plant was proposed. The process consists of leaching in sulphuric acid and precipitation of REEs, followed by two-step solvent extraction to remove Zn, Fe, Al, Mn and Cd to produce a solution with Ni and Co for integration into nickel production.



**Figure: Proposed flowsheet for Ni recovery from NiMH via integration into Ni plant**

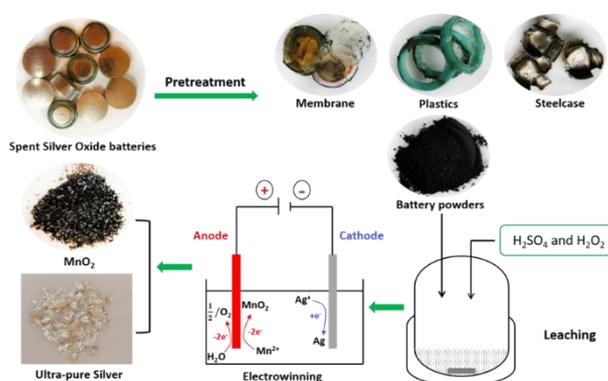
**Possibility for future research and industrial potential**

The development of such a new recycling process may accelerate or allow smaller scale operations to be undertaken, as only a relatively straightforward hydrometallurgical pre-treatment is required prior to integration into the existing process.

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<b>Participants</b>	Vivek Agarwal, Muhammad K.Khalid, Antti Porvali, Benjamin P.Wilson, Mari Lundström
<b>Publications / Additional Information</b>	“Recycling of spent NiMH batteries: Integration of battery leach solution into primary Ni production using solvent extraction” Sustainable Materials and Technologies. 2019. <a href="https://doi.org/10.1016/j.susmat.2019.e00121">https://doi.org/10.1016/j.susmat.2019.e00121</a>

**WP 3**
**Task 3.4 Removal of trace and harmful impurities**
**Recovery of High-Purity Silver from Spent Silver Oxide Batteries by Sulphuric Acid Leaching and Electrowinning**
**Main results**

A sustainable and effective sulphuric acid-based process with the combination of straightforward acid leaching and electrowinning has been developed for the recovery of valuable elements from spent silver oxide batteries. In the leaching step, 97% of silver as well as just over 99% of Mn and Zn could be extracted under the optimal conditions: 1 mol/L  $\text{H}_2\text{SO}_4$ , a leaching temperature of 70 °C, an S/L ratio of 50 g/L, addition of 3 v/v %  $\text{H}_2\text{O}_2$  at 240 min and a total leaching time of 270 min. Ultra-pure silver (Ag w/w%  $\geq 99.98$  %) was further recovered from the pregnant leaching solution (PLS) by potentiostatic electrowinning. Under the optimal deposition potential of -0.10 V and after 4 h of electrowinning, silver recovery reached 98.5% with a high energy efficiency of 98.7%. Simultaneously, 5.6% Mn was recovered on the anode in the form of  $\text{MnO}_2$ .



**Figure: Leaching and electrowinning route for the recovery of ultra-pure silver from used silver oxide batteries**

**Highlights**

Silver extracted using  $\text{H}_2\text{SO}_4$  solution instead of aggressive  $\text{HNO}_3$ .

High-purity silver obtained with the simultaneous recovery of  $\text{MnO}_2$ .

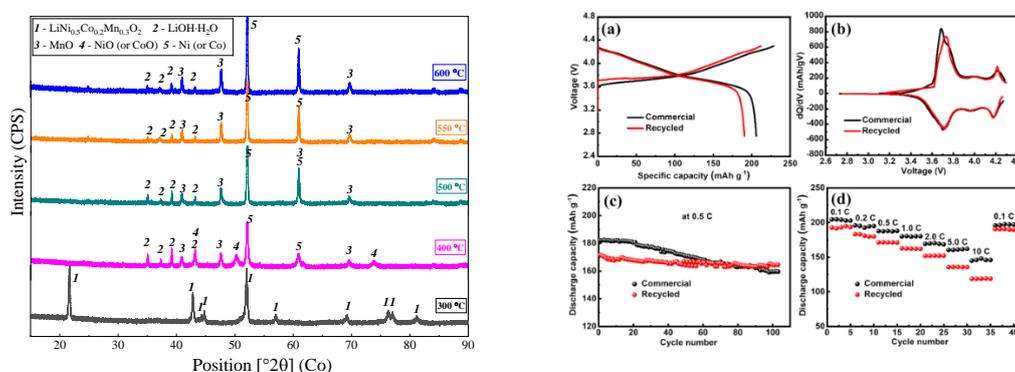
**Possibility for future research and industrial potential**

This research suggests the feasibility of recycling silver oxide batteries in sulphuric acid media, which avoids the usage of nitric acid and thus reduces the environmental challenge of  $\text{NO}_x$  emission and costs of corrosion protection.

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<b>Publications / Additional Information</b>	Wang, Z., Peng, C., Yliniemi, K., Lundström, M., 2020, Recovery of High-Purity Silver from Spent Silver Oxide Batteries by Sulfuric Acid Leaching and Electrowinning [J]. ACS Sustainable Chemistry & Engineering 8(41): 15573-15583. DOI: <a href="https://doi.org/10.1021/acssuschemeng.0c04701">10.1021/acssuschemeng.0c04701</a>

**WP3**
**T3.5 Integration of secondary process into primary production**
**D3.5.1 Scientific paper on battery metals integration into primary production**
**Main results**

About 98% of Li was transformed into soluble LiOH·H<sub>2</sub>O with H<sub>2</sub> reduction at 500 °C within 15 min, while Ni, Co, Mn all transformed into their corresponding insoluble metals or their oxides. Consequently, almost all of the Li present in the roasted material was effectively separated from other impurities by 10 minutes of water leaching at 25 °C at a liquid-solid (L/S) ratio of 2, so that the extraction of other metals like Ni, Co, Mn was < 0.1%. Subsequent stages allowed high purity LiOH·H<sub>2</sub>O (99.92%) to be obtained directly through evaporation and crystallization. In addition, high nickel battery cathode materials (LiNi<sub>0.8</sub>Co<sub>0.1</sub>Mn<sub>0.1</sub>O<sub>2</sub>) were prepared from the recycled LiOH·H<sub>2</sub>O products and demonstrated good electrochemical performance.


**Highlights**

Battery grade LiOH·H<sub>2</sub>O can be produced by ‘hydrogen reduction-water leaching’ followed by an evaporative crystallization process.

The recovery rate of lithium is high and > 97% of Li can be selectively separated from the other metals present very quickly – reduction roasting for 15 min.

Compared with other roasting processes (nitrication, carbon reduction and sulphate-based), the hydrogen route is free from harmful gases such as SO<sub>2</sub>, CO, NO<sub>x</sub>, etc.

**Possibility for future research and industrial potential**

This newly developed hydrogen reduction-based process may provide a more simple, efficient and environmentally friendly method for the recovery of valuable metals from spent LIBs, as well as offering great potential for straightforward industrial-scale recycling.

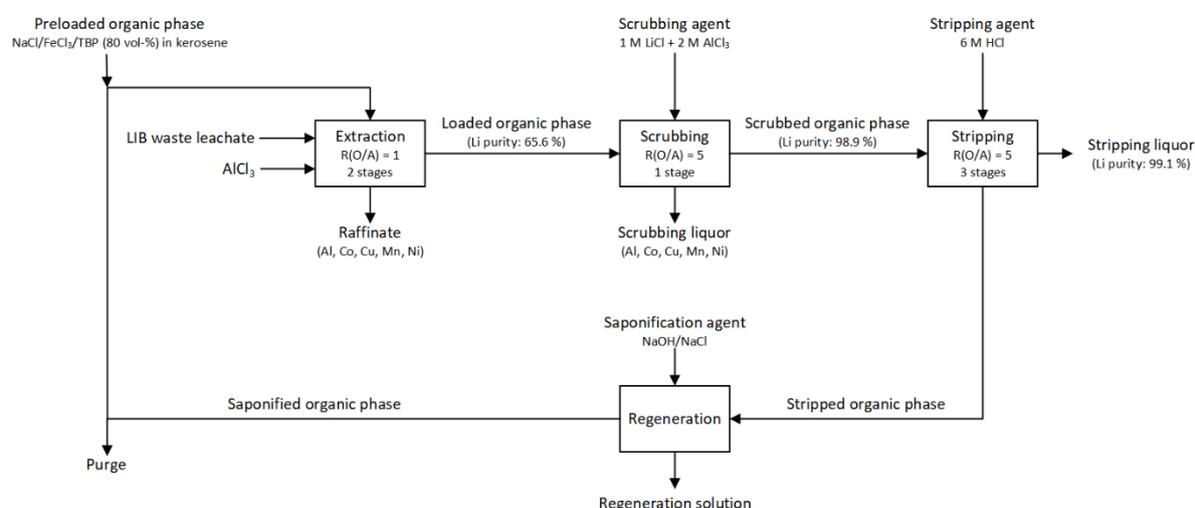
<b>Contact person</b>	Mari Lundström, <a href="mailto:mari.lundstrom@aalto.fi">mari.lundstrom@aalto.fi</a> , Aalto University
<b>Participants</b>	Fupeng Liu, Mari Lundström
<b>Publications / Additional Information</b>	Fupeng Liu, Chao Peng, Quanxin Ma, Jinliang Wang, Songlin Zhou, Zaoming Chen, Benjamin P. Wilson, Mari Lundström. Selective lithium recovery and integrated preparation of high-purity lithium hydroxide products from spent lithium-ion batteries, Separation and Purification Technology (2021). DOI: <a href="https://doi.org/10.1016/j.seppur.2020.118181">10.1016/j.seppur.2020.118181</a>

**WP 3**
**T3.7 Direct solvent extraction recovery of Li from battery waste leachate**
**D3.7.1 Scientific publication on direct Li solvent extraction**
**Main results**

Lithium was recovered from synthetic LIB waste leachate using TBP as an extractant and FeCl<sub>3</sub> as co-extractant (according to (1)) in kerosene.



It was found that Li can be selectively separated over divalent LIB metals (Mn, Cu, Co, Ni) and Al(III) from a multicomponent mixture according to the flowsheet below.


**Highlights**

The application of the system to recover Li from LIB waste leachate is reported for the first time. The extraction ability of the system is  $H^+ > Li^+ \gg$  LIB metals. Substitution of MgCl<sub>2</sub> by AlCl<sub>3</sub> as chloride source promoted Li extraction ( $E(Li) = 87.7\%$  for  $R(O/A) = 1$ ) due to its strong salting out effect. This resulted in enhanced separation factors ( $\beta(Li/Ni) = 2825$  and  $\beta(Li/Co) = 854$  for  $R(O/A) = 1$ ).

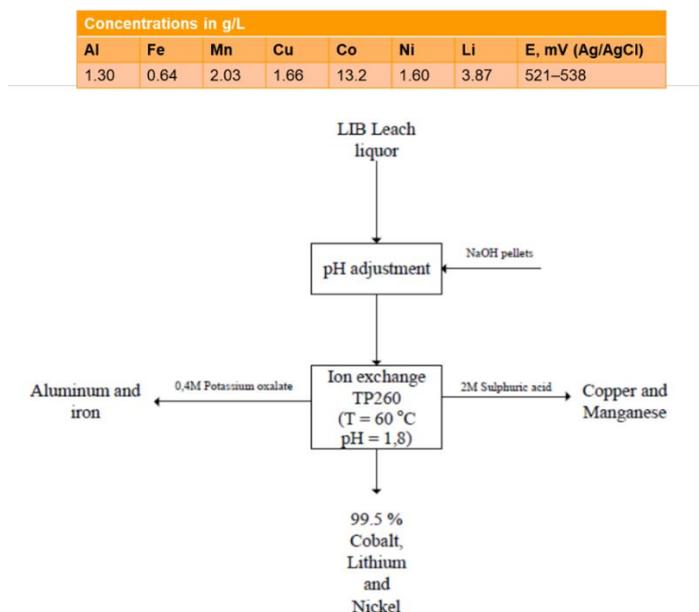
**Possibility for future research and industrial potential**

The potential for future research in this topic is great as the presented system could be used to avoid Li losses during LIB recycling. Research on the recovery of valuable LIB metals (especially Ni and Co) from chloride media also needs to be conducted.

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<b>Publications / Additional Information</b>	Wesselborg, T., Virolainen, S., Sainio, T., 2021 "Recovery of lithium from leach solutions of battery waste using direct solvent extraction with TBP and FeCl <sub>3</sub> ". Hydrometallurgy, vol. 202, 105593, <a href="https://doi.org/10.1016/j.hydromet.2021.105593">https://doi.org/10.1016/j.hydromet.2021.105593</a> . Conference abstract for ISEC 2021 was submitted to 2022 (postponed due to Covid-19)

**WP 3**
**T3.8 Solvent extraction process for producing a controlled mixture of battery chemicals**
**D3.8.1 Scientific publication about the battery chemical mixture**
**Main results**

The main result was the experimental demonstration that a high-purity (99.5%) Ni/Co/Li product mixture, with only 1.1% Co losses, can be produced in a single step using ion exchange starting from a synthetic leachate containing Al, Fe, Mn and Cu as impurities. From the impurity-loaded chelating resin, Al and Fe were eluted with potassium oxalate, and Cu and Mn were eluted with sulphuric acid.


**Highlights**

Ion exchange is used for the first time for LIB waste leachate fractionation. Typically, in hydrometallurgical fractionation, impurity (Fe, Al, Mn, Cu) removal has been very challenging. Several precipitation and/or solvent extraction stages are needed and the losses of valuable Co have also been high. Therefore, the presented ion exchange method seems to be a very viable option for this process step, and it also predicts that ion exchange with known potential for high selectivities could be useful for the subsequent Co/Ni/Li fractionation.

**Possibility for future research and industrial potential**

The potential for future research in this topic is very great as, based on the results, the amount of process steps could be reduced, recoveries of target metals could be improved and their losses could be reduced. All in all, more efficient separation and purification performance compared to the conventionally used precipitation and solvent extraction could be obtained. These results also present a very significant potential for industrial utilization.

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<b>Participants</b>	Sami Virolainen, Arttu Kaukinen, Tobias Wesselborg, Tuomo Sainio
<b>Publications /</b>	Virolainen, S., Wesselborg, T., Kaukinen, A., Sainio, T., 2021, "Removal of iron, aluminum, manganese and copper from leach solutions of lithium-ion battery waste using ion exchange". <i>Hydrometallurgy</i> , vol. 202, 105602, <a href="https://doi.org/10.1016/j.hydromet.2021.105602">https://doi.org/10.1016/j.hydromet.2021.105602</a> . Conference abstract for <i>IEX2020 - A Vision for the Future</i> was accepted, but the conference was postponed to 2022 due to Covid-19.

## WP 4

## T4.1 Synthesis of cathode materials

## D4.1.1 Scientific publication related to LNO

## Main results

$\text{Ni}(\text{OH})_2$  precipitation was performed by applying different temperatures between 40 and 60 °C, and lithiated at 650, 670 or 690 °C. Results showed that it is possible to change the precursor particle morphology and tap density by changing the precipitation temperature within this temperature range.

Lithiated  $\text{LiNiO}_2$  samples showed high capacities according to electrochemical studies. The optimal lithiation temperature to achieve high capacity and good capacity retention was found to be 670 °C.

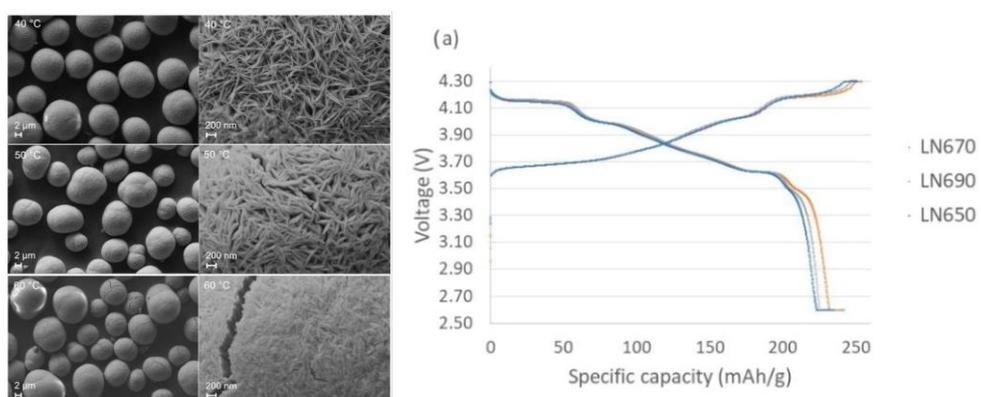


Figure: Precipitated and lithiated LNO particles (left) and the specific capacities of LNO (right).

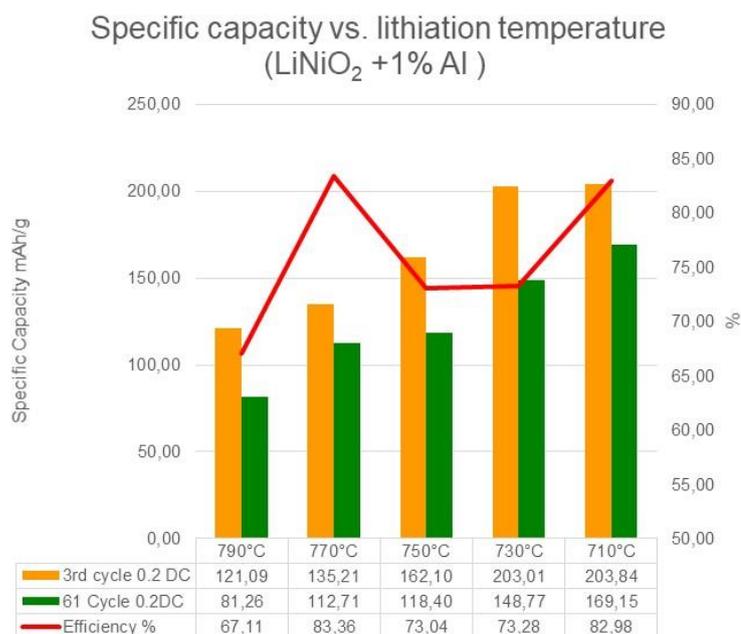
## Highlights

$\text{LiNiO}_2$  calcination temperature optimized to achieve a high initial discharge capacity of 231.7 mAh/g (0.1 C/2.6 V) with a first cycle efficiency of 91.3% and retaining capacity of 135 mAh/g after 400 cycles. These are among the best results reported so far for pure  $\text{LiNiO}_2$  cathode material.

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<b>Publications / Additional Information</b>	Välikangas, Juho; Laine, Petteri; Hietaniemi, Marianna; Hu, Tao; Tynjälä, Pekka; Lassi, Ulla (2020) Precipitation and Calcination of High-Capacity $\text{LiNiO}_2$ Cathode Material for Lithium-Ion Batteries. Applied Sciences 10 (24), 8988. DOI: <a href="https://doi.org/10.3390/app10248988">10.3390/app10248988</a>

**WP 4**
**T4.1 Synthesis of cathode materials**
**D4.1.1 Scientific publication related to coating of LiNiO<sub>2</sub>**
**Main results**

LiNiO<sub>2</sub> (LNO) was coated with 1-5 wt.% Al<sub>2</sub>O<sub>3</sub> (and other coatings). Coating improved the stability and cyclability of LNO. Results showed that high nickel material cyclability can be improved by optimization of the lithiation process (temperature), which can be done at far lower temperatures.



**Figure: Effect of Al-coating (1 wt%) and lithiation temperature on the specific capacity and efficiency of LNO.**

**Highlights**

Al-coated LiNiO<sub>2</sub> calcination temperature optimized. Significantly lower temperatures for lithiation can be used

**Possibility for future research and industrial potential**

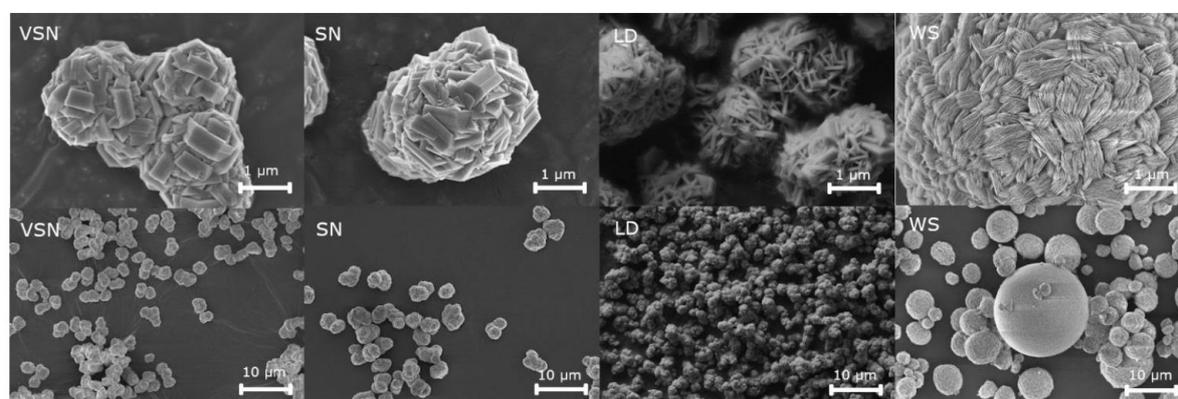
Coated, cobalt-free LNO is one of the most potential cathode materials for future LIBs, and it can be produced on industrial scale.

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<b>Publications / Additional Information</b>	Välikangas, J., Laine, P., Tanskanen, P., Hu, T., Tynjälä, P., Lassi, U., 2021, "Effect of coating (Al, etc.) on the capacity and cyclability of LNO", manuscript to be submitted

**WP 4**
**T4.1 Synthesis of cathode materials**
**D4.1.1 Scientific publication related to lithiation of NMC622 precursors**
**Main results**

Effect of precursor particle size and morphology on lithiation of NMC622 was studied. Key issue affecting the capacity and cyclability of NMC622 is the Li/Me ratio during the lithiation.

Based on the results, a low density precursor (tap density  $1.1 \text{ g/cm}^3$ ) does not lower the capacity if sufficiently lithiated. A highly porous precursor can be lithiated with shorter lithiation times than traditional large wide-span materials. A highly porous precursor also has low cation mixing and good crystallinity. However, the volumetric energy density of the porous material after lithiation was low.



**Figure:** FESEM images of very small and narrow (VSN), small and narrow (SN), low density (LD) and wide-span (WS) precursors with 50 000x magnification and 5 000x magnification.

**Highlights**

New fundamental understanding of lithiation of NMC622 precursors. Li/Me ratio is the most important parameter affecting the capacity and cyclability of NMC622. Low tap density of precursor does not affect capacity or cyclability if successfully lithiated.

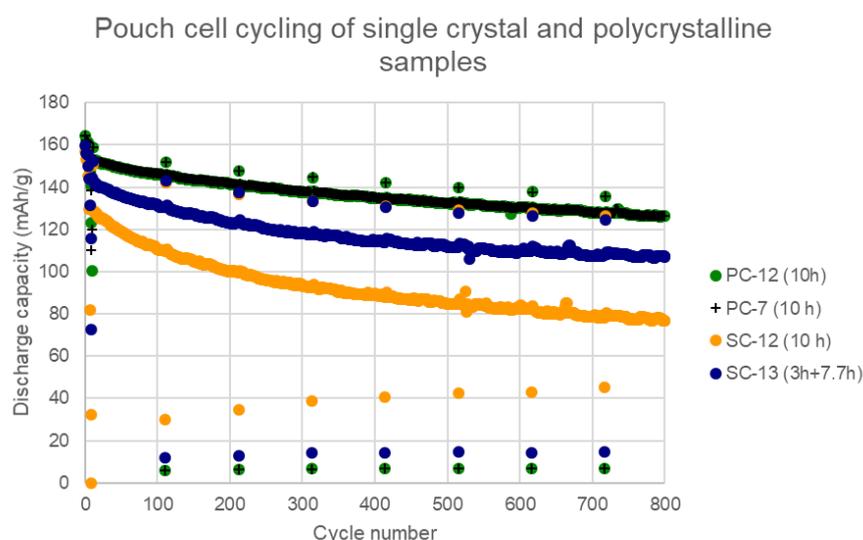
<b>Contact person</b>	Ulla Lassi, <a href="mailto:ulla.lassi@oulu.fi">ulla.lassi@oulu.fi</a> , University of Oulu
<b>Participants</b>	Marianna Hietaniemi, Tao Hu, Juho Välikangas, Janne Niittykoski, Ulla Lassi
<b>Publications / Additional Information</b>	Hietaniemi, M., Hu, T., Välikangas, J., Niittykoski, J., Lassi, U. (2020) Effect of precursor particle size and morphology on lithiation of $\text{Ni}_{0.6}\text{Mn}_{0.2}\text{Co}_{0.2}(\text{OH})_2$ , submitted

**WP 4**
**T4.1 Synthesis of cathode materials**
**D4.1.1 Scientific publication related to single vs polycrystalline NMC622**
**Main results**

Single crystal and polycrystalline NMC622 materials were compared. Several precursors were successfully lithiated (one-step or two-step) to single crystal morphology, which has been claimed in the literature to improve the capacity of NMC. The effect of washing was also studied.

Based on the results, polycrystalline NMC622 has a higher initial capacity. Both polycrystalline and single crystal materials showed similar cyclability in coin cell testing. Electrode density was better for single crystals except for large wide-span precursors.

Washing dramatically decreased the Li concentration at the surface. There is a precursor effect in single crystal lithiation. Two-step heating is only beneficial for low-density precursors.



**Figure: Cyclability of single crystal (SC) and polycrystalline (PC) NMC622 cathodes.**

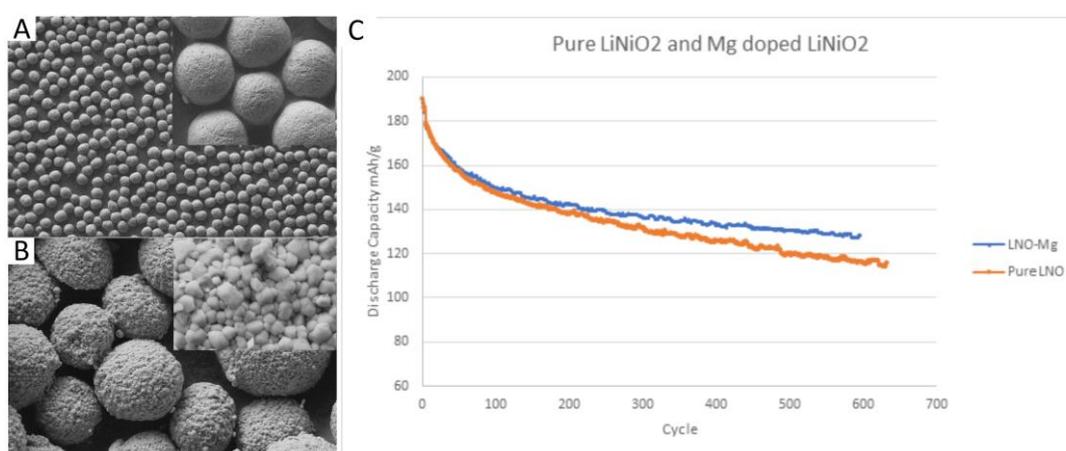
**Highlights**

Contrary to earlier literature observations, single crystal lithiation does not seem to improve the capacity or cyclability of NMC622. Washing has a clear effect on the electrochemical properties of NMC622.

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<b>Publications / Additional Information</b>	Hietaniemi, M., Hu, T., Välikangas, J., Niittykoski, J., Singh, H., Lassi, U. (2021) Effect of precursor in NMC622 single crystal lithiation, manuscript

**WP 4**
**T4.1 Synthesis of cathode materials**
**D4.1.1 Scientific publications (2) related to doping of LiNiO<sub>2</sub>**
**Main results**

Precipitation experiments on spherical Ni(OH)<sub>2</sub> precursor material containing low levels of aluminium, magnesium, fluorine, tin, manganese, titanium, zirconium, chromium, as well as combinations thereof were carried out. Precipitation behaviour was significantly influenced by dopant concentration as well as slight alterations in precipitation conditions. The influence of low-level doping of the precursor material on the electrochemical performance of LiNiO<sub>2</sub> material was also studied. Furthermore, the synergistic effects of bimetallic doping, such as Mg-Ti, Mg-Zr, Mn-Ti, Mn-Zr, Mg-Mn, Ti-Zr and Mg-Cr was explored. Additionally, Ti and Zr were precipitated separately from isopropoxide/propoxide solutions onto the surface of the Ni(OH)<sub>2</sub> precursor to ascertain the possible effects of bulk structure doping and surface-introduced coating.



**Figure 1:** A. Precursor material containing 1 mol% and 2 mol% Mn, B. Lithiated 1 mol% Ti-coated sample, C. Electrochemical performance of washed pristine LiNiO<sub>2</sub> and LiNiO<sub>2</sub> doped with 1 mol% Mg.

**Highlights**

Highly homogeneous spherical precursor material with good electrochemical performance synthesized. Low-level coating has a greater influence on battery cell performance than low-level doping.

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<b>Publications / Additional Information</b>	Laine, Petteri; Välikangas, Juho; Kauppinen, Toni; Hu, Tao Tynjälä, Pekka; Lassi, Ulla (2021) Synergistic effects of low-level magnesium and chromium doping on the electrochemical performance of LiNiO <sub>2</sub> material, manuscript.  Laine, Petteri; Välikangas, Juho; Kauppinen, Toni; Hu, Tao Tynjälä, Pekka; Lassi, Ulla (2021) The influence of titanium and zirconium doping methods on the electrochemical performance of LiNiO <sub>2</sub> , manuscript.

**WP 4**
**T4.1 Synthesis of cathode material**
**D4.1.2 Laboratory-scale test results**
**Main results**

NMC622 material solution was received from Umicore Finland Oy. TGA (Thermal Gravimetric Analysis) studies were first carried out. The water mass loss observed below 250 °C was 35.98%, between 250 and 500 °C the crystalline water loss was 6.44% and between 500 and 900 °C the sulphur mass loss was 28.37%. The observed water plus sulphur mass loss was 49.27% when the theoretical value was 49.72%. Between 500 and 900 °C during sulphur mass loss, the phase changed from metal sulphate to metal oxide. The phase transformation was analysed more carefully using powder XRD. In collaboration with Aalto University and Prof. Daniel Lindberg, thermochemical analysis was carried out using Factsage 7.3 software. The results of the calculation agreed quite well with the observed TGA results and conversion from metal sulphate to metal oxide phase was obtained at 850–900 °C.

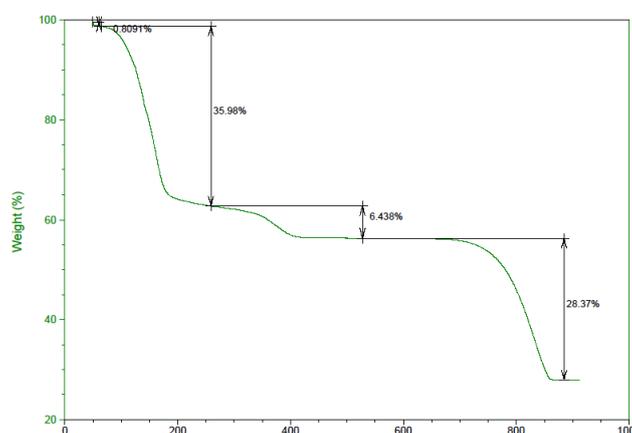


Figure. TGA results of NMC 6-2-2 sulphate at different temperatures.

**Highlights**

The experimental TGA and theoretical thermochemical calculation results of the NMC622 water solution mass losses and phase transformation agree quite well. From the results of X-ray diffractometry it can be deduced that unlihtiated NMC622 particles heated up to 1000 °C in TGA consist mostly of Co<sub>3</sub>O<sub>4</sub>-type spinel phase.

**Possibility for future research and industrial potential**

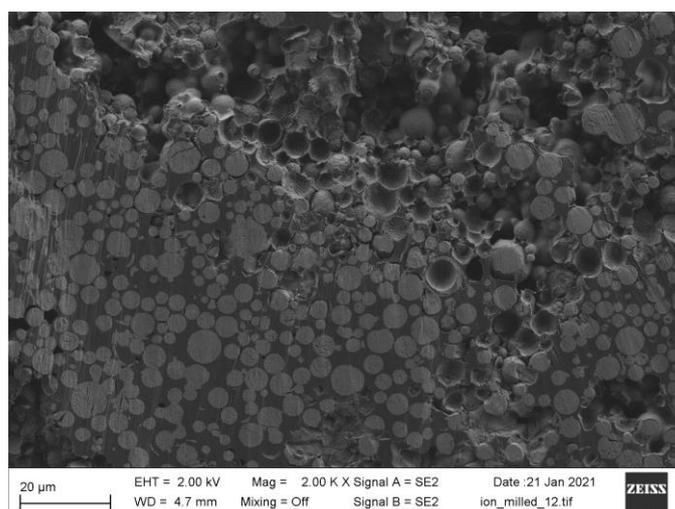
These results were later used to guide spray drying (SD) and spray prolysis (SP) experiments. The SD and SP processing of NMC622 water solution aims at obtaining solid, dense NMC622 precursor particles.

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<b>Publications / Additional Information</b>	Under preparation.

**WP 4**
**T4.1 Synthesis of cathode materials**
**D4.1.3 Pilot-scale test results**
**Main results**

NMC622 material solution was received from Umicore Finland Oy. Spray drying (SD) and spray pyrolysis (SP) processes were studied to obtain spherical dense NMC particles. If the process works, its advantage over existing commercial methods to produce cathode precursor and active materials will be its simplicity and cost reduction. One-step spray pyrolysis had been studied earlier, which resulted each time in hollow particles being obtained, which is not the desired result.

In this work the focus was on a two-step process to make spherical dense NMC precursor particles. In the first step, NMC622 water solution is atomised into 10-40  $\mu\text{m}$  size droplets, which are then dried gently to obtain solid dense 5-10  $\mu\text{m}$  particles. The morphology of the final particles is controlled by several parameters like the drying gas temperature, dispersion gas pressure, solution concentration, carrier gas flow rate and liquid flow rate. By the ion milling technique, we were able to study the particle morphology in various conditions. Below is a SEM picture of the NMC622 particles obtained.



**Figure. SEM image of NMC622 obtained by ion milling.**

**Highlights**

Fairly solid, mostly non-hollow particles obtained by spray drying, as determined by ion milling and SEM imaging techniques.

**Possibility for future research and industrial potential**

We found that it is possible to produce solid NMC622 precursor particles using the spray drying (SD) process. Future work is needed to scale up the spray drying process to industrial scale by modelling the droplet drying processes.

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<b>Publications / Additional Information</b>	Under preparation.

**WP 4**
**T4.2 Synthesis of anode materials**
**D4.2.1 LTO precursor fuel combination**
**Main results**

Nanostructured LTO from affordable precursors was synthesized by flame methods at UEF. A laboratory-scale flame spray pyrolysis reactor was used to determine the best combinations of precursors and fuel to obtain doped LTO anode material.

So far in the flame synthesis of oxide materials, mainly organometallic precursors like acetylacetonates and ethylhexanoates have been used as metal precursor materials. Oxygen has been used as dispersion and combustion gas. However, these are too expensive for commercial applications. In this task we used affordable sources for lithium and titanium and used air as combustion gas. The precursor solution was produced by adding 30.64 g of Li-nitrate to 835.5 mL of ethanol while vigorously mixing with a magnetic stirrer. Once all solids had fully dissolved, the magnetic stirrer was set to a low speed and 164.5 mL of Ti-tetraisopropoxide was added to the solution. The total metal ion concentration of the solution was 1 mol/L. The solution was used within two hours of TTIP addition; during this time no precipitation was observed.

**Highlights**

The precursors and air used in the flame synthesis of anode lithium titanate (LTO) active material. Successful combustion experiments produced LTO powder of the desired phase, as determined by XRD.

**Possibility for future research and industrial potential**

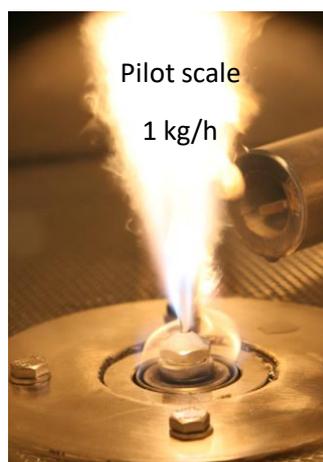
Pilot-scale production of LTO should be possible with these affordable starting materials.

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<b>Publications / Additional Information</b>	T. Karhunen, J. Jokiniemi, A. Lähde, 2020, "Inorganic precursors for flame synthesis of LTO." 4 <sup>th</sup> International Symposium Gas-Phase Synthesis of Functional Nanomaterials, October 6-9, 2020, Fraunhofer-inHaus-Center, 47057 Duisburg, Germany.

**WP 4**
**T4.2 Synthesis of anode materials**
**D4.2.2 LTO pilot-scale results**
**Main results**

Nanostructured LTO from affordable precursors were synthesized by flame methods at UEF.

A pilot-scale flame spray pyrolysis reactor was used to determine the best combinations of precursors and fuel to obtain doped LTO anode material. A new bag filter system was installed in the UEF pilot-scale flame synthesis environment to collect the LTO material.


**Highlights**

Successful pilot-scale production of LTO anode active material, at about 1 kg/h production rate.

**Possibility for future research and industrial potential**

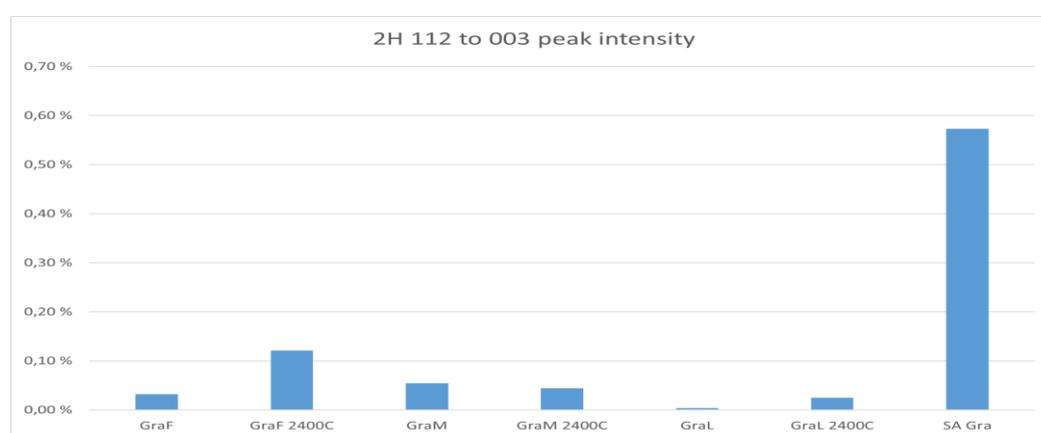
Industrial-scale production of LTO should be possible with affordable starting materials and commercial burners.

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<b>Publications / Additional Information</b>	Murashko, K., Karhunen, T., Lähde, A., Jokiniemi, J., "Pilot-scale flame synthesis and electrochemical performance of silver doped LTO", to be submitted

**WP 4**
**T4.2 Synthesis of anode materials**
**D4.2.3 Graphite purification**
**Main results**

Natural graphite was purified by thermal treatments in an induction furnace at UEF. The electrochemical results were compared with a commercial reference material.

After induction annealing at 2400 °C and 10 min holding time, the main impurities in the pristine and floated Aitolampi natural graphite were Si, Al, Mg, Fe, K, Na. Based on ICP-MS results the purity was 99.811% for LargeFlakes, 99.662% for MediumFlakes and 99.792% for FineFlakes based on elemental concentrations.



**Figure.** XRD 2H graphite 112 and 3R 003 peak intensity ratios describing best the graphitization of the sample. As can be seen, the most graphitized sample compared to the commercial synthetic graphite (SA Gra) is the fine flake synthesized at 2400 °C (GraF 2400C). The graphitization level also explains well the electrochemical results obtained.

**Highlights**

Graphitization results (XRD and Raman) correspond well with the obtained electrochemical results of natural graphite heat treated by induction annealing at 2400 °C.

**Possibility for future research and industrial potential**

Induction annealing seems to be a viable method for natural graphite purification and graphitization. Optimization of heat treatment conditions, coating and upscaling are needed for industrial applications.

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<b>Publications / Additional Information</b>	Manuscript for scientific publication is under preparation with OU and GTK.

**WP4**
**T4.2 Synthesis of anode materials**
**D4.2.3 Report on graphite purification tests by alkaline and acid leaching**
**Main results**

The purification scheme by alkaline roasting followed by acid leaching proved to be capable of producing high-purity graphite concentrates, with over 99% purity. The highest C grade of 99.6% was obtained by alkaline roasting at a temperature of 500 °C, followed by acid leaching with H<sub>2</sub>SO<sub>4</sub> at a concentration of 3.9%.

**Highlights**

The roasting temperature is a key factor as far as purity is concerned, while roasting time does not seem to be critical. Low H<sub>2</sub>SO<sub>4</sub> concentration was enough for efficient acid leaching, as increasing the concentration did not lead to higher purity.

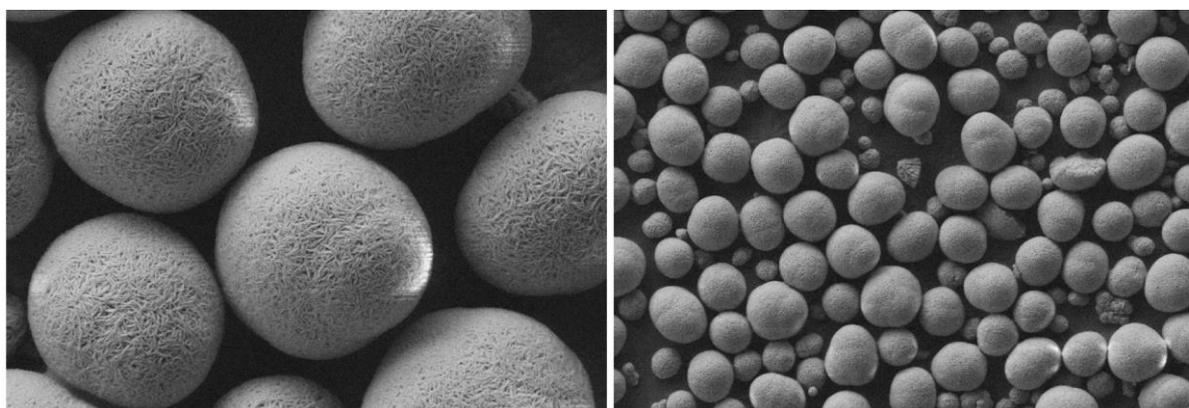
**Possibility for future research and industrial potential**

For future test work, it is recommended to aim for lower NaOH concentrations in alkaline roasting.

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<b>Participants</b>	Dandara Salvador, Jason Yang, Oleg Knauf, Arno-Matti Kirpala
<b>Publications / Additional Information</b>	Salvador, D., Yang, J., 2020. Purification Tests on Graphite Flotation Concentrates, GTK Research Report C/MT/2020/21.

**WP 4**
**T4.3 Use of secondary raw materials**
**D4.3.1 Report on co-precipitation of NMC811 from battery recycling solution**
**Main results**

Metal sulphate solutions with a known amount of impurities were used in  $(\text{Ni}_{0.8}\text{Co}_{0.1}\text{Mn}_{0.1})\text{OH}_2$  (NMC811) precursor co-precipitation. Commercial pure manganese and nickel sulphates were used as reference samples. Key impurities in the solutions were zinc, iron, calcium, potassium, lithium and magnesium. Based on the results, co-precipitation of impurities on the NMC particles was in line with the thermodynamic calculations. As expected, iron, zinc, magnesium and calcium co-precipitated in NMC811 to a large extent, but potassium and lithium remained in the mother liquor. The presence of impurities was confirmed by several characterizations. Impurities did not affect the particle morphology or tap density of NMC811. Surprisingly, the effect of impurities on cell performance was also minor. During cycling, these cells provided good cyclability and high retention (>80%) after 1100 cycles compared to the reference samples.



*Figure: Co-precipitated impure NMC811 precursors, lithiated sample (left) and precursor (right).*

**Highlights**

Successful co-precipitation of NMC811 using impure battery recycling solution.

No effect on the particle morphology or tap density of NMC811 due to the presence of impurities. Surprisingly, the effect of impurities on cell performance is also minor.

**Possibility for future research and industrial potential**

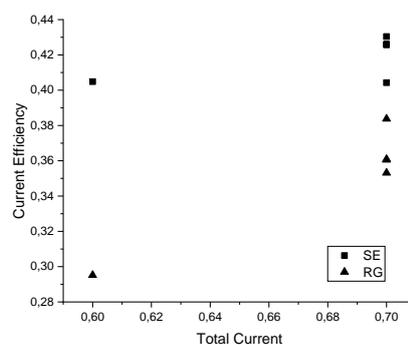
Recycling solutions seem to be a potential raw material for NMC precipitation, thus reducing dependence on primary raw materials.

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<b>Publications / Additional Information</b>	Tynjälä, Pekka, et al. Use of Secondary Materials in NMC Co-Precipitation: Effect of Impurities on the Cell Performance, ECS meeting, 2021 (invited presentation).

**WP 4**
**T4.3 Use of secondary raw materials**
**D4.3.1 Report on the reuse of residue sodium sulphate from co-precipitation**
**Main results**

Battery chemical production is limited by environmental strain caused by sulphate effluent in wastewaters. It can be estimated that one metric ton of NMC precursor production yields 1.1 metric ton of sulphates. Here, residue sodium sulphate (8 wt%) from NMC precursor co-precipitation (SE) was used in neutral electrolytic pickling for scale removal. The sulphate solution also contained small quantities of transition metals (Co, Ni, Mn) and ammonia ions.

The obtained results, ICP-OES analysis from electrolyte, current efficiency comparison and FESEM-EDS image comparison, all suggested a slight improvement in pickling efficiency when the residual sodium sulphate solution was compared with an electrolyte solution of similar conductivity dissolved from reagent grade sodium sulphate (RG).



**Figure: Pickling current efficiency comparison of reused sodium sulphate solution (SE) and reagent grade (RG) sodium sulphate.**

**Highlights**

Successful use of residual sodium sulphate solution for neutral electrolytic pickling.

Slight increase in pickling efficiency demonstrated by an increase in dissolved chromium (0.13 mg/L) and current efficiency (7 %) when pickled in reused sodium sulphate. Increase is probably caused by residue ammonia.

**Possibility for future research and industrial potential**

Industrial use of secondary sodium sulphate solution seems to have potential in electrolytic neutral pickling.

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<b>Publications / Additional Information</b>	Tuovinen Teemu, Tynjälä Pekka, Vielma Tuomas, Lassi Ulla et al. (2021) "Utilization of waste sodium sulphate from battery chemical production in the neutral electrolytic pickling", manuscript

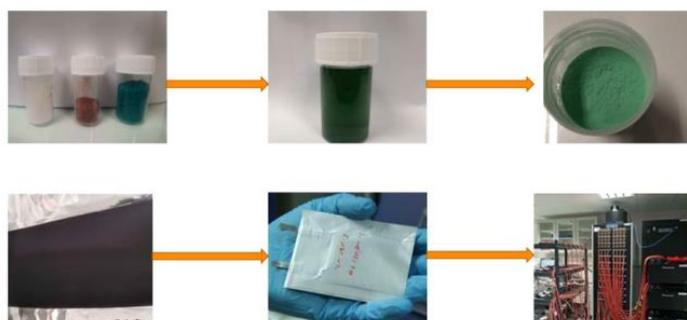
**WP 4**

**T4.3 Use of secondary raw materials**

**D4.3.1 Publication related to NMC811 co-precipitation from secondary materials**

**Main results**

The applicability of recycled manganese solutions for co-precipitation of NCM811 was studied. Three different sources of manganese sulphate were used in NCM811 precursor co-precipitation. Key impurities were Ca, Mg, K, Fe and Zn. As expected, based on the thermodynamic calculations, these impurities (except K) were co-precipitated in the precursor.



*Figure: Synthesis of NMC811 from impure raw materials.*

**Highlights**

Successful co-precipitation of NMC811 using impure industrial Mn solutions.

Initial discharge capacities equal to reference sample, and after 1100 cycles still over 80% capacity retention observed.

**Possibility for future research and industrial potential**

Manganese from anode sludge is a potential raw material for NMC precipitation, thus reducing dependence on primary raw materials.

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<b>Publications / Additional Information</b>	Kauppinen, Toni; Vielma, Tuomas; Salminen, Justin; Lassi, Ulla (2020) ChemEngineering 4 (2), 40. <a href="https://doi.org/10.3390/chemengineering4020040">https://doi.org/10.3390/chemengineering4020040</a> Kauppinen T., Laine, P., Välikangas, J., Salminen, J., Lassi, U. (2021), Co-precipitation of NCM 811 from manganese sulfate obtained from anode sludge: Effect of impurities on the battery cell performance, manuscript

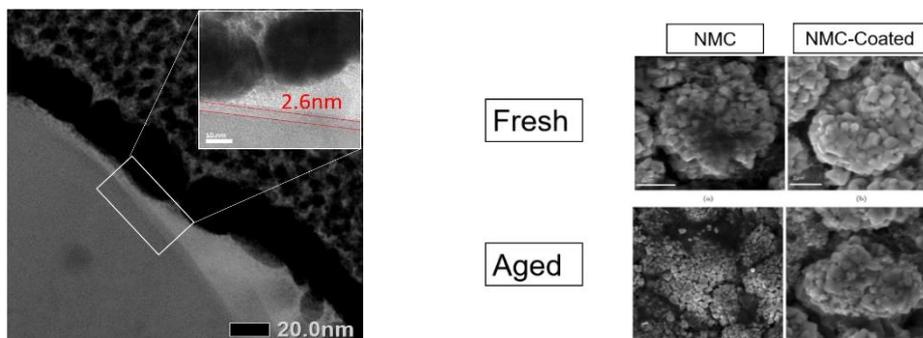
**WP 4**

**T4.4 Structural and electrochemical characterization**

**D4.4.1 Initial results on LCO/NMC**

**Main results**

NMC622 positive electrode material was coated with lithium titanate (LTO) via the ALD technique. The thickness of coating was around 2nm (TEM image) and it enhanced the stability of the electrode material.



**Figure: A TEM image of NMC coated with LTO (left) and SEM images (right) of the fresh and aged samples (100 cycles at 1C).**

Based on the SEM analysis, it was found that the NMC electrode degraded after 100 cycles of charging and discharging at 1C rate, whereas the NMC-coated sample retained its own shape and no major microcracks were detected. In the same trend, the electrochemical performance for the NMC-coated samples was enhanced significantly in comparison to the pristine samples.

**Highlights**

Chemical modification of NMC electrode surfaces via ALD technique. Suppression of parasitic reactions effectively reduces dissolution rate of transition metals and mitigates particle fragmentation of NMC electrodes. Surface modification may well improve the cycling stability of NMC in half cell and full cell configurations.

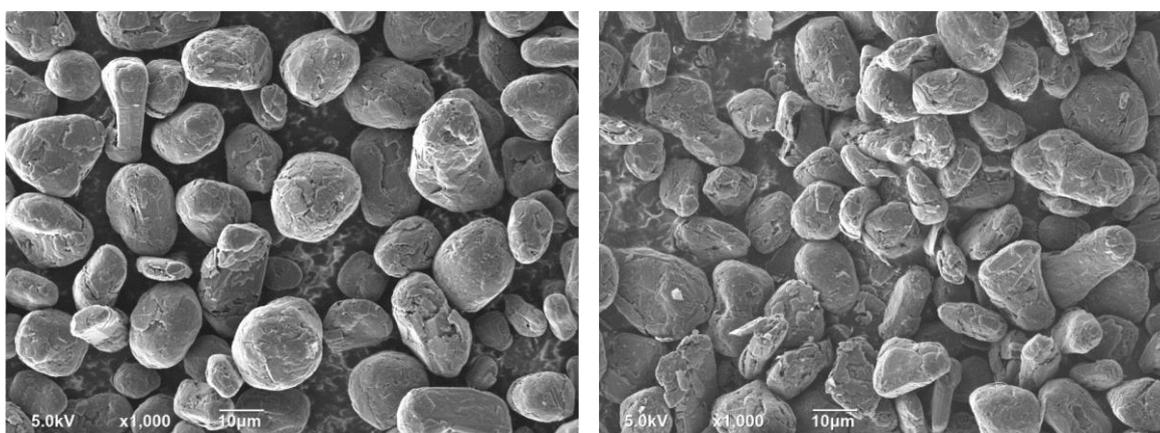
**Possibility for future research and industrial potential**

Surface modification of the electrode material is a promising technique to provide a highly stable interface for electrode material inside lithium ion batteries. This can enhance the electrochemical properties of the batteries. Besides, there are several methods and materials which could be used to improve the electrode chemistry. As such, this project has great potential to be continued in the future.

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<b>Participants</b>	Tanja Kallio, Zahra Ahaliabadeh
<b>Publications / Additional Information</b>	Initial results achieved.

**WP 4**
**T4.4 Structural and electrochemical characterization**
**D4.4.2 Master's thesis on Aitolampi graphite**
**Main results**

A comparison was made of the structure and performance of lithium ion battery negative electrodes made of Aitolampi natural graphite and commercial Imerys synthetic graphite. The latter showed notable higher rate capability when cycled up to 5C rates. The electrochemical performance and structural analysis revealed crack formation in the structure of the commercial graphite during cycling but not for the natural graphite. These results suggest that the natural graphite has a longer cycle life when serving as a negative electrode in a lithium ion battery.



*Figure: SEM images of pristine A) natural graphite and B) synthetic graphite powder particles.*

**Highlights**

Mechanochemical properties of Aitolampi natural graphite appear to be more suitable for a lithium ion battery negative electrode than those of a commercial reference material. Hence, these preliminary results suggest a longer cycle life for natural graphite.

**Possibility for future research and industrial potential**

The ageing of the Aitolampi natural graphite should be verified in long-term cycling experiments.

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<b>Publications / Additional Information</b>	Emilia Jansson, Investigation of Natural Graphite as an Active Material for the Negative Electrode of Lithium Ion Batteries, MSc thesis, Aalto University 2020 <a href="http://urn.fi/URN:NBN:fi:aalto-202008245110">http://urn.fi/URN:NBN:fi:aalto-202008245110</a>

## WP 4

## T4.4 Structural and electrochemical characterization

## D4.4.3. Scientific publication on LCO/NMC

## Main results

Conformal nanoscale (<5 nm) coating layers of TiO<sub>x</sub> (TO) and Li<sub>x</sub>Ti<sub>y</sub>O<sub>z</sub> (LTO) were deposited over a NMC622 positive electrode (TEM image) to reduce the side reactions at the interfacial zone and increase structural stability. Atomic layer deposition (ALD) was used to deposit the LTO and TO coating layers onto the NMC electrode. Both coating layers provided a protective surface and reinforced the electrode structure by incorporating Ti into the bulk of NMC, which was determined by XRD analysis (Figure 2a-b).

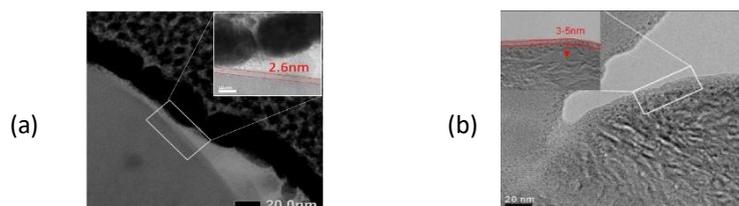


Figure 1. HRTEM image of cross-sectioned NMC-TO (a) electrode and NMC-LTO (b).

The coating layers enable enhanced electrochemical behaviour of NMC with better cyclability and higher capacity retention (Figure 2c). Furthermore, NMC-LTO provided better Li ion diffusion and significantly enhanced the rate capability of NMC in comparison to NMC-TO and uncoated NMC.

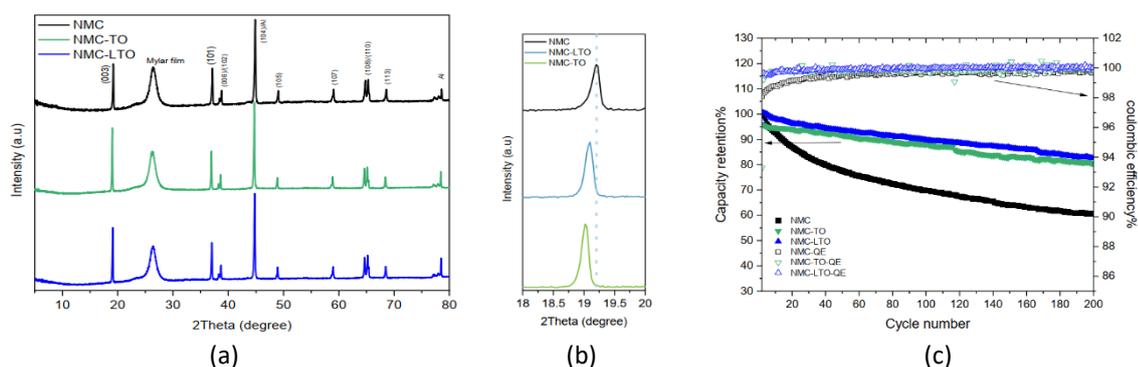


Figure 2. X-ray diffraction patterns of the electrodes (a) enlarged region of the (003) peak (b) and Full cell long term cycling for NMC-TO, and NMC-LTO, NMC at 1C for 200 cycles

## Highlights

The electrochemical behaviour of the NMC-coated sample is notably enhanced in NMC-TO and NMC-LTO. NMC-LTO provides higher capacity than NMC-TO, which can be attributed to the lithium-containing coating layer and higher Li diffusivity. Both coating layers improve structural stability by suppressing chemical reactions with electrolyte, reducing the dissolution rate of transition metals and mitigating the particle fragmentation of NMC electrodes.

## Possibility for future research and industrial potential

Atomic layer deposition (ALD) has attracted increasing attention in the development of next-generation LIBs in recent years. It can provide a nanoscale and highly stable interface for electrode material which can greatly improve the specific capacity, cycling stability and rate capability. New coating materials using ALD may emerge as a promising coating layer which could be used to improve the electrode chemistry. Furthermore, the possibility of controlling coating layer quality and the coating process promise ALD great potential for industry-level applications in the future.

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<b>Publications / Additional Information</b>	Ahaliabadeh, Z., Miikkulainen, V., Mäntymäki, M., Mousavi, S., Lahtinen, J., Lide, Y., Jiang, H., Mizohata, K., Kallio, T., 2021. Atomic Layer Deposition of Metal oxide and Li-metal oxide Coatings for Stabilizing Ni-rich Cathode Material in Lithium Ion Batteries. Manuscript submitted.

**WP 4**
**T4.4 Structural and electrochemical characterization**
**D4.4.5 Scientific publication related to modification of layered cathode oxides**
**Main results**

Layered cathode materials for EV applications and portable electronics are the only cathodes that currently fulfil the requirements of battery manufacturers. In order to overcome some challenges, especially in the case of high-nickel cathodes, these materials should be further modified by doping and coating. Modification enables enhanced stability and cyclability of the battery cells, achieving high voltage and high power at moderate cost.

**Table 1. Theoretical and practical capacities of selected positive electrode materials.**

Material	Theoretical capacity (mAh/g)	Practical capacity (mAh/g)	% of Li reversibly removed
LiCoO <sub>2</sub>	274	142	52
LiNiO <sub>2</sub>	275	145	53
LiMnO <sub>2</sub> (layered), LMO	286	Converts to spinel during cycling	
LiMn <sub>2</sub> O <sub>4</sub> (spinel), LMO	148	120	81
LiNi <sub>0,8</sub> Co <sub>0,2</sub> O <sub>2</sub>	274	180	66
LiNi <sub>0,8</sub> Co <sub>0,15</sub> Al <sub>0,05</sub> O <sub>2</sub>	279	180-200	65-72
LiNi <sub>1/3</sub> Co <sub>1/3</sub> Mn <sub>1/3</sub> O <sub>2</sub>	278	160-170	56-61
LiFePO <sub>4</sub> (LFP)	170	170	100
NCM333	278	154	55
NCM523	278	164	59
NCM424	279	155	56
NCM622	277	178	64
NCM811	276	>185	>67

**Highlights**

Cathode modification is needed to improve battery cell performance, which also requires consideration of other cell components, such as the electrolyte at higher cell voltages.

Cobalt is essential in layered oxide materials from the stability viewpoint. There is no universal cathode chemistry, but it is selected based on application. Less energy-dense materials (LFP, LMO) are used for stationary applications, whereas layered mixed metal oxides are suitable for volume- and weight-sensitive applications.

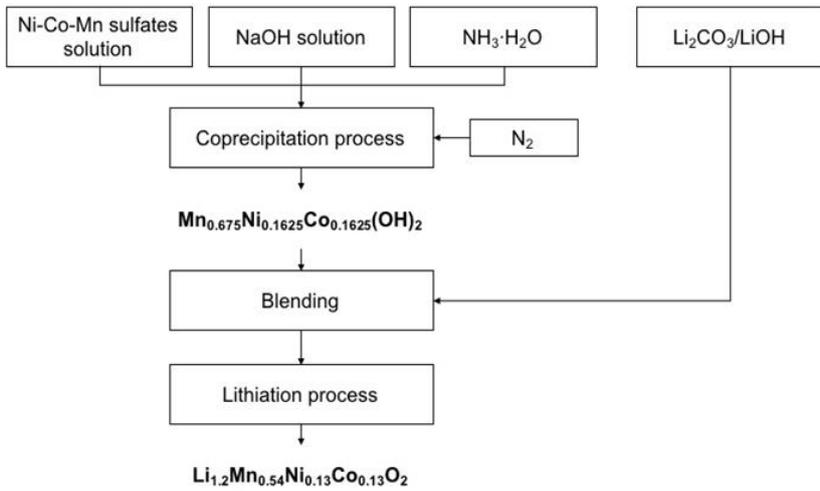
<b>Contact person</b>	Ulla Lassi, <a href="mailto:ulla.lassi@oulu.fi">ulla.lassi@oulu.fi</a> , University of Oulu
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<b>Publications / Additional Information</b>	Dong, J., Hietaniemi, M., Välikangas, J., Hu, T., Lassi, U. 2019, "Modification of Layered Oxide Cathode Materials. In: Future Lithium-ion Batteries", (Ed. Eftekhari, Ali), RSC publications, London. 44-71. <a href="http://dx.doi.org/10.1039/9781788016124-00044">http://dx.doi.org/10.1039/9781788016124-00044</a>

**WP 4** T4.4 Structural and electrochemical characterization

**D4.4.5 MSc thesis on layer-structured lithium-rich cathodes**

**Main results**

Layer-structured, Li-rich Mn-based cathode material (LLO) was synthesized by two-step coprecipitation. The benefits of LLOs compared with traditional high-nickel NMCs are their high chemical potential and high discharge capacity. Further, these materials are less toxic and more cost-efficient due to the lower nickel and cobalt content. However, there are still some challenges to overcome prior to commercialization, e.g. initial irreversible capacity loss, voltage fading and poor rate capability.



*Figure: Synthesis of Li-rich  $Li_{1.2}Mn_{0.54}Ni_{0.13}Co_{0.13}O_2$  cathode.*

**Highlights**

- Layered  $Li_{1.2}Mn_{0.54}Ni_{0.13}Co_{0.13}O_2$  cathode successfully synthesized.
- High specific capacity of  $279 \text{ mAh g}^{-1}$ , and Coulombic efficiency of 82.8% at 2.0-4.8V.
- After 30 cycles, capacity retention of 82.9% ( $232 \text{ mAh g}^{-1}$  at 0.1C) at 2.0-4.8V

**Possibility for future research and industrial potential**

Layered lithium-rich oxides are one of the most potential cathode materials for future LIBs if synthesis can be done on industrial scale.

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<b>Publications / Additional Information</b>	Yufan Wang, Co-precipitation of lithium-rich layered oxide materials, MSc thesis, University of Oulu, 2021

**WP 5** T5.1 Exploring untapped business potential in the battery ecosystem

**D5.1.1 Tools for business model design in the battery ecosystem**

**Main results**

The research by Aalto DIEM produced evidence of significant untapped business potential in the battery ecosystem. Several research highlights were identified; more work is required.

**Highlights**

Gao & Hakanen (in press) note how failures to capture business potential is often hindered by the misalignment between (new) technological competences and prevailing business models in the industry. Novel opportunities often call for reconsideration of the roles, responsibilities and activities among industry actors. These changes are non-trivial and usually require new approaches. Hänninen’s (2020) work presents a roadmap for value-based pricing. Turunen & Töytäri (2020) further discuss the underlying reasons behind the slow transformation of business models and pointed out how innovative approaches often come from new entrants to the industry.

Roadmap to value-based pricing



*Figure: Roadmap to value-based pricing (Hänninen, 2020).*

**Possibility for future research and industrial potential**

Considerable need for future work remains. Firms need support in their business transformation journey. New forms of collaboration need to be established to move from dyadic agreements and unidirectional supply chains to multilateral, networked business models.

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<b>Publications / Additional Information</b>	Gao, S. & Hakanen, E. (in press), “Technical capabilities are not enough: Deploying Internet of Things in the metals and mining industry”, International Journal of Information Technology and Management. Hänninen, H. 2020. “Practices of value-based pricing in industrial services”, MSc Thesis, Aalto University. Turunen, T. & Töytäri, P. 2020, “Business Models as Artefacts Driving Temporal Segmentation and Logic Consolidation”, Academy of Management Proceedings 2020. <a href="http://doi.org/10.5465/AMBPP.2020.16942abstract">http://doi.org/10.5465/AMBPP.2020.16942abstract</a>

**WP 5**
**T5.1 Exploring untapped business potential in the battery ecosystem**
**D5.2.1 Analysis of the key criteria for sustainable business models in the Finnish battery ecosystem**
**Main results**

The research identified many current business practices that were considered less than optimal. In particular, information and data management were inefficient. Improvements are needed to facilitate closed-loop material flows and information-based services across the battery ecosystem.

**Highlights**

Our study highlights the potential of data management for the circular economy. The main argument in Hakanen's (2018) thesis is that firms can benefit by opening up the data that they accumulate as part of a manufacturing value chain. This line of thought is extended in Seppälä et al. (2019) by suggesting guidelines for sharing operational and process data. Since data analysis also requires abilities beyond the core competences of manufacturing firms, Gao et al. (2020) suggest gathering support from external collaborators to extend and enrich the capability development of the focal firm.

Data categorization	Primary flow	Secondary flow (own re-use)	Secondary flow (shared)	Waste	Hazardous waste/ emissions	Model terms of data sharing
Proprietary data	X	(X)			X	Proprietary information
Confidential data		X	X		X	Confidential information
Distributed data			X			Decentralized information
Open data				X	(X)	Open information
	Value added of internal resources			Value added of external resources		

**Table: Suggested approaches for sharing manufacturing data (Seppälä et al., 2020).**

**Possibility for future research and industrial potential**

Support for implementing more collaborative practices for data and information management is needed. Research should investigate models to incentivize participants to take actions that enable direct or indirect value creation by other ecosystem participants.

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<b>Publications / Additional Information</b>	Hakanen, E. 2018. "Platform-based exchange: New business models in technology industries." DSc thesis, Aalto University. (Available at: <a href="https://aaltodoc.aalto.fi/handle/123456789/35601">https://aaltodoc.aalto.fi/handle/123456789/35601</a> ) Gao, S., Hakanen, E., & Rajala, R. 2020, "Digital Transformation: The Interplay of Explorative and Exploitative Capability Development", Proceedings of the 53rd Hawaii International Conference on System Sciences, 4306-4315. <a href="https://doi.org/10.24251/HICSS.2020.527">https://doi.org/10.24251/HICSS.2020.527</a> Seppälä, T., Hakanen, E., Lähteenmäki, I., Mattila, J. & Niemi, R. (2019) "The resource dependency of data: A perspective on data sharing in supply chains" (Available at SSRN: <a href="https://ssrn.com/abstract=3493650">https://ssrn.com/abstract=3493650</a> )

**WP 5** T5.2 Determinants of sustainable business in the battery ecosystem

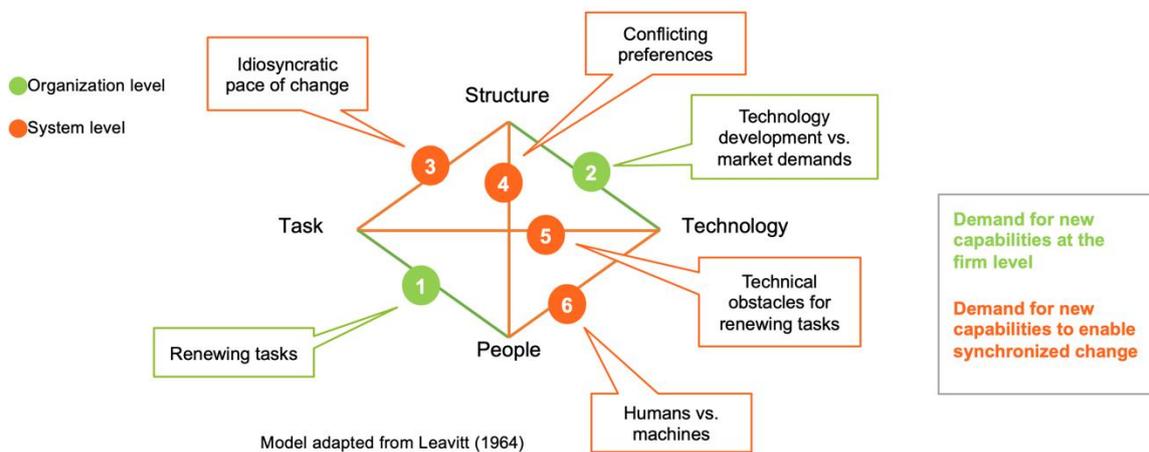
**D5.1.1 Tools for business model design in the battery ecosystem**

**Main results**

Our studies provided evidence in favour of networked business models. This was considered as the key insight in facilitating sustainable business in the battery ecosystem.

**Highlights**

Increasingly few companies can succeed solely on internal resources and capabilities, as business models are becoming increasingly networked. Our research provides several examples that both vindicate and explain this trend. Hakanen (2019) examines how interfirm collaboration provides innovation benefits. Yet, as Hämäläinen (2020) points out, how can networked value creation influence the existing organizational boundaries and how are the firm boundaries understood? Gao (2020) explains why such changes can pose new systemic constraints and, in particular, call for synchronized change across the industry.



**Figure: Business model development demands new capabilities that span organizational boundaries, build on network of actors, and facilitate synchronized change across the industry (Gao, 2020).**

**Possibility for future research and industrial potential**

More work is needed to understand the nature and impact of the sociotechnical change in the business models of battery industry firms, including models for sharing jointly created value.

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<b>Publications / Additional Information</b>	Gao, S. 2020. "Digital transformation in asset-intensive industries: Systemic Constraints and Synchronized Change" DSc thesis, Aalto University. (Available at: <a href="https://aalto.doc.aalto.fi/handle/123456789/45440">https://aalto.doc.aalto.fi/handle/123456789/45440</a> ) Hakanen, E. 2019, "Why to collaborate? Three approaches to innovation behind the transition from firms to ecosystems", Academy of Management Proceedings 2019. <a href="https://doi.org/10.5465/AMBPP.2019.16859abstract">https://doi.org/10.5465/AMBPP.2019.16859abstract</a> Hämäläinen, H. 2020. "The effect of digital servitization to the boundaries of firms", MSc thesis, Aalto University.

**WP 5**
**T5.2 Determinants of sustainable business in the battery ecosystem**
**D5.2.1 Analysis of the key criteria for sustainable business models in the Finnish battery ecosystem**
**Main results**

In addition to new capability demands for the battery ecosystem, the research highlighted the need to reconsider the premises of conducting business. In particular, many institutionalized beliefs impact decision making and hinder the renewal of business models across the industry.

**Highlights**

Our research indicates that many of the challenges caused by shared beliefs (i.e. institutional logic) can be alleviated by adopting a value-based approach among firms (see Pitkänen, 2020). In other words, in such arrangements where the supplier's compensation is tied to the customer's realized benefits, both parties will inevitably develop new means that support a more sustainable business ecosystem. Gao et al. (2019) note several typical hindrances to ecosystem growth, whereas Siltaloppi et al. (2020) suggest means for navigating the tensions of misaligned expectations.

Institutional logic	Institutional challenge	Service transformation opportunity
Geological logic	Pre-existing idea of legitimate services	Value-based selling / systematic purchasing of value-adding solutions
	Institutionalised structures	
Risk-averse logic	Collective identity prevents from questioning status quo	
	Organisational attention on the costs of sub-processes	
	Centralised funding determining acceptable problems and solutions	
	Resource imitation driven by uncertainty	
	Need for secrecy	Buyer-seller integration
New ventures lacking credibility	Customer segmentation based on use value	

*Figure: Institutional challenges often related to industry-specific (geological) and risk-averse beliefs (Pitkänen, 2020).*

**Possibility for future research and industrial potential**

This research identified many institutional challenges; more work is required to resolve them.

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<b>Publications / Additional Information</b>	Gao, S., Hakanen, E., Töytäri, P., & Rajala, R. 2019, "Digital transformation in asset-intensive businesses: Lessons learned from the metals and mining industry", Proceedings of the 52nd Hawaii International Conference on System Sciences, 4927–4936. <a href="https://doi.org/10.24251/HICSS.2019.593">https://doi.org/10.24251/HICSS.2019.593</a> Pitkänen, K. 2020. "The institutional challenge of service transformation in a battery ecosystem", MSc thesis, Aalto University Siltaloppi, J., Rajala, R. & Hietala, H. 2020, "Integrating CSR with business strategy: A tension management perspective." Journal of Business Ethics. Doi: <a href="https://doi.org/10.1007/s10551-020-04569-3">https://doi.org/10.1007/s10551-020-04569-3</a>

**WP 5** T5.3 System-level influences

**D5.1.1 Tools for business model design in the battery ecosystem**

**Main results**

Our research provided insights to business model design that address the system-level factors in the battery ecosystem. We described the demand for the alignment of actions and incentives between firms and the ecosystem, and provided tools to support development efforts.

**Highlights**

Firstly, the study highlights how value creation and value capture has been decoupled in the ecosystem debate (see Eloranta et al., 2019). The potential for value creation is often appraised at the ecosystem level, while mechanisms for value capture are evaluated at the firm level. Secondly, to address this decoupling, the toolkit for ecosystem design focuses on understanding the interplay of different ecosystem participants and emphasizes the role of incentives for each participant.

*Ideology-free toolkit for*  
**DIGITAL ECOSYSTEM DESIGN**  
 v0.2.5 (July 2020)  
 CC BY-SA, Ville Eloranta, Aalto University (IDBM) & Esko Hakanen, Aalto University (IDEM)  
 The toolkit is largely based on and inspired by Simone Cicero's Platform Design Toolkit (CC 4.0 BY-SA).  
**Changelog**  
 v0.2.5: New Canvas 5: Ecosystem interaction profiles (moved Canvas 5 to Canvas 6)  
 v0.2: New Canvas 4: Ecosystem activities and interactions map (moved Canvas 4 to Canvas 5)  
 v0.1: Changes and additions to Cicero's work:  
 - Canvas 1: Simplifications and generalizations  
 - Canvas 2: New contribution inspired by Cicero  
 - Canvas 3: Simplifications and generalizations  
 - New Canvas 4: Ecosystem governance (new contribution)

**5. Map the key activities and interactions in the**  
**4. Identify the motivations for interacting**  
**3. Build platform member profiles**  
**2. Map the members of your ecosystem**  
**1. Identify the mission of your ecosystem**

Canvas 1: Define the purpose/mission of the platform. Why does it exist? Who does it benefit?  
 • For existing cases: How does the platform describe the reason of its existence?  
 • For new platforms: formulate a short statement describing the reason of existence for the platform.

When you are ready, write the mission statement to the canvas

IBM, 3M, BM

**Figure: Toolkit for ecosystem design offers practical tools to plan and evaluate a shared value proposition.**

**Possibility for future research and industrial potential**

While the research offered insights and tools for business model design, much more remains to be done. Further work is needed to understand the system-level influences and the best practices of seizing the identified business opportunities. Little research exists on situations in which a group of firms are jointly renewing their business approach to be more collaborative, without clear agreements that define the desired end state or the division of tasks and responsibilities.

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<b>Publications / Additional Information</b>	Eloranta, V., Hakanen, E., Töytäri, P., & Turunen, T. 2019, "Aligning multilateral value creation and value capture in ecosystem-level business models", Academy of Management Proceedings 2019. <a href="https://doi.org/10.5465/AMBPP.2019.18966abstract">https://doi.org/10.5465/AMBPP.2019.18966abstract</a> Eloranta, V. & Hakanen, E. Ideology-free Toolkit for Digital Ecosystem Design.

**WP 5**

**T5.3 System-level influences**

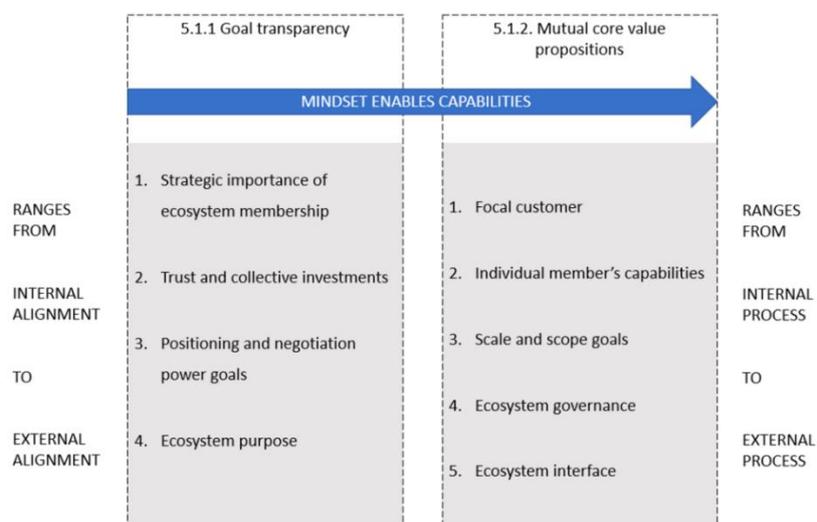
**D5.2.1 Analysis of the key criteria for sustainable business models in the Finnish battery ecosystem**

**Main results**

A key insight related to the system-level influences on creating sustainable business models in the battery ecosystem stressed the importance of goal transparency between the participants. Ecosystem growth requires alignment and processes to combine internal and external resources.

**Highlights**

Heliö (2020) has uncovered how goal transparency decreases information asymmetry and facilitates actions that rely on multiple, disconnected parties. The comparison of two ecosystems at different levels of maturity indicates that the more developed one was built on higher openness. The ecosystem members feel this transparency is particularly important for ecosystem prosperity.



*Figure: Ecosystem development was seen to be viable when the members were willing to disclose their individual goals, helping them to understand their role and the opportunities created by other ecosystem members (Heliö, 2020).*

**Possibility for future research and industrial potential**

The research on the system-level influences of ecosystem development is still at a nascent stage. Firms need alignment both internally and externally on their goals and activities. The more new, collaborative actions become established in the industry, the more defining the impact these structures will have on the rest of the industry, igniting new system-level influences.

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<b>Publications / Additional Information</b>	Heliö, H. 2020, "Role of transparency and value communication in ecosystems", MSc thesis, Aalto University Seppälä, T., Mattila, J., & Rajala, R. 2019, "Is the Digital Future Sustainable?" ETLA Brief (No. 80). The Research Institute of the Finnish Economy. <a href="https://ideas.repec.org/p/rif/briefs/80.html">https://ideas.repec.org/p/rif/briefs/80.html</a>

**WP 6**
**Project Management**
**D6.1.1. Consortium Agreement**
**D6.2.1. Periodic reports (4 periodic reports 30.9.2019, 31.1.2020, 31.5.2020, 30.9.2020)**
**D6.2.2. Final report (this document)**
**D6.3.1. Public workshops (8 steering group meetings and 2 open seminars)**
**Main results**

The project management was focused on facilitation to achieve project goals, monitoring and execution of the project, including reporting, communication, organizing of consortium meetings and workshops, managing relationships with stakeholders, showcasing the project to interested parties, producing promotional material and coordinating the application for the follow-up BATCircle2.0 project.



*Steering group in Pori, Finland. September 2019.*

**Highlights**

Bringing together all the key actors from the Finnish battery metals value chain. Promotion of the project and Finnish battery activities in over 40 talks and interviews as well as dozens of presentations given at various conferences, seminars, workshops and other battery-related events.

Seven seminars and steering group meetings organized with three seminars open to invited guests including international keynote speakers and > 100 participants. Five periodic reports on project progress, including this final report.

Facilitation of the BATCircle2.0 application, submitted in December 2020.

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<b>Participants</b>	Pyry-Mikko Hannula, Mari Lundström
<b>Publications / Additional Information</b>	BATCircle Final report, available at <a href="http://batcircle.aalto.fi">batcircle.aalto.fi</a> Periodic reports (only available to steering group)

**WP 7** T7.2 European battery recycling

**D7.2.1 Sub-group established**

**Main results**

BATCircle has built wide network with European research organizations working in the field of battery metals and recycling. SET Plan Action 7 Implementation Working Group (IWG): Recycling sub-group was initiated in a workshop on 15 January 2019 in Espoo, Finland, and was converted into the Batteries Europe Working Group 2 (WG2) on Raw Materials and Recycling in another workshop on 13-14 June 2019 in Milan, Italy. BATCircle was active in both of these gatherings to meet European research organization and to discuss and plan research in the field of battery metals and recycling. In addition, several teleconferences in identification of R&D needs as well as in the planning of several EU applications were arranged. Physical meetings were limited due to the Covid-19 pandemic.

**Highlights**

Notable amount of European research organizations and actors were met and a strong research network in the field of battery raw materials and recycling built. Research needs and collaboration possibilities were discussed in two physical workshops (85 participants representing 46 different organizations and 12 European countries as well as the EU Commission) and in several smaller occasions.



*Figure: Identifying collaboration needs and possibilities in Espoo (left) and Workshop in Milan (right).*

**Possibility for future research and industrial potential**

BATCircle network is strong and wide, and several EU proposals have been submitted and granted. Collaboration with European research organizations will continue, and several key stakeholders will be met e.g. along Batteries Europe WG2 and Batteries European Partnership Association (BEPA) events.

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<b>Participants</b>	Pertti Kauranen, Mari Lundström, Aalto University Ilkka Kojo, Outotec Finland Oy
<b>Publications / Additional Information</b>	Batteries Europe Working groups: <a href="https://www.energy.eu/en/working-groups">Working groups   Energy (europa.eu)</a>

**WP 7**
**T7.3 Mapping of interests, competences, activities and financial resources**
**D7.3.1 Report on interests, activities and finances**
**Main results**

The BATCircle project involved knowledge exchange with a wide variety of European research partners. As a result, research and development interests, competences and ongoing activities in the field of battery raw materials and recycling were extensively mapped. This supports the future research activities and planning of the BATCircle project participants in the battery sector.

Collaborative research organizations included University of Agder, Chalmers University of Technology, IVL The Swedish Environmental Institute, Politecnico di Milano, the National Research Council of Italy, VTT Technical Research Centre of Finland, SINTEF and many others.

Along with this work, BATCircle participated in two workshops on 15 January 2019 in Espoo, Finland, and 13-14 June 2019 in Milan, Italy. As a result, a summary report was compiled and distributed to the stakeholders.

**Highlights**

Two workshops attracted 85 participants representing 46 different organizations and 12 European countries as well as the EU Commission. Identification of 46 relevant recent and ongoing European projects and more than 100 stakeholders in the fields of battery raw materials and recycling. All of this has allowed BATCircle to gain considerable visibility and international contacts for future projects and research collaboration.

**Possibility for future research and industrial potential**

The collaboration activities are foreseen to continue. The BATCircle project has been actively participating in upcoming Horizon Europe funding calls.

<b>Contact person</b>	Mari Lundström, <a href="mailto:mari.lundstrom@aalto.fi">mari.lundstrom@aalto.fi</a> , Aalto University
<b>Participants</b>	Pertti Kauranen, Mari Lundström, Aalto University Ilkka Kojo, Outotec Finland Oy
<b>Publications / Additional Information</b>	P. Kauranen, M.Lundström, I. Kojo, O. Salmi, SET Plan Action 7 IWG Sub-group Recycling Meeting, 15 January 2019, Aalto University, Espoo, Finland, and ETIP Batteries Europe Raw Materials and Recycling Workshop, 13-14 June 2019. Aalto University, 10 September 2019.

**WP 7**
**T7.5 European R&I needs**
**D7.5.1 Report on R&I needs**
**Main results**

The R&I needs in European battery raw materials and recycling were identified in detail. The BATCircle project has collaborated with a wide variety of European research partners. Working together with the group we were able to identify the following important topics:

- Collection, reverse logistics, sorting and dismantling
- Safety in recycling
- Sustainable processing of Li, Ni, Co and graphite
- Raw Material LCA and Material Flow Analysis
- Metallurgical recycling processes, industrial integration and secondary material-based precursors
- Circular economy-based business models
- Second life of batteries

These topics are essential for BATCircle collaboration in EU research projects and will provide a solid basis for several new research openings.

The work has been documented in Batteries Europe (ETIP) WG2 Raw Materials and Recycling Roadmap and a Strategic Research Agenda (SRA) as well as drafted topics for the Horizon Europe Cluster 5 (Climate, Energy, Mobility) 2021-2022 funding calls for battery raw materials and recycling. In addition, Ilkka Kojo and Tuomas van der Meer (Outotec) were invited to a temporary Shadow Group of the Batteries European Partnership Association (BEPA) to initiate the strategy work of the association and to finalize the Horizon Europe funding calls with the Commission, as drafted by the ETIP Europe WG2.

**Highlights**

Identification of several important topics within raw materials and recycling R&I together with European research organizations. These topics will provide a strong basis for further collaboration between the research organizations, such as WG2 roadmap organizations. Key messages from the ETIP SRA have been adopted in the BEPA SRIA. Two raw material and two recycling topics have been implemented in the Horizon Europe Cluster 5 2021-2022 funding call document.

**Possibility for future research and industrial potential**

European funding will be available for primary processing of battery metals (Li, Ni, Co, Mn) and graphite as well as the collection, sorting, dismantling and recycling of end-of-life electric vehicle batteries.

<b>Contact person</b>	Mari Lundström, <a href="mailto:mari.lundstrom@aalto.fi">mari.lundstrom@aalto.fi</a> , Aalto University
<b>Participants</b>	Mari Lundström, Pertti Kauranen, Aalto University Ilkka Kojo, Tuomas van der Meer, Outotec (Finland Oy)
<b>Publications / Additional Information</b>	ETIP SRA: <a href="https://ec.europa.eu/energy/topics/technology-and-innovation/batteries-europe/news-articles-and-publications/sra_en">https://ec.europa.eu/energy/topics/technology-and-innovation/batteries-europe/news-articles-and-publications/sra_en</a> R&I topics: <a href="https://ec.europa.eu/energy/sites/ener/files/batterieseuropeereseearchandinnovationpriorities-detailedsummary.pdf">https://ec.europa.eu/energy/sites/ener/files/batterieseuropeereseearchandinnovationpriorities-detailedsummary.pdf</a> Roadmap: <a href="https://ec.europa.eu/energy/sites/ener/files/batterieseuropeereseearchandinnovationpriorities-detailedsummary.pdf">Batteries Europe Raw Materials and Recycling Roadmap   Energy (europa.eu)</a>

## Publications

### Aalto University

#### Peer-reviewed publications

Ahaliabadeh, Z., Federovskaya, E., Kong, X., Kallio, T., “Modifying NMC811 structure – review publication”, to be submitted

Kalliomäki, T., Aji, A.T., Wilson, B.P., Aromaa, J., Lundström, M., “Optimization of copper electrorefining electrolytes”, to be submitted

Mkurazhizha, H., Hartmann, R., Serna-Guerrero, R., “Automated Contact Timer Apparatus (ACTA) as a predictive flotation device: A pyrrhotite study”, to be submitted

Mkurazhizha, H., Hartmann, R., Serna-Guerrero, R., “Qualitative analysis to determine the wettability of microparticles towards predictive flotation modelling: An Automated Contact Timer Apparatus (ACTA) approach”, to be submitted

Rinne, T., Ruismäki, R., Dańczak, A., Serna Guerrero, R., Jokilaakso, A., “Applying a Cu/Al-rich Material Stream Recovered by Waste LIB Flotation in a Pyrometallurgical Cu Slag Cleaning Process”, to be submitted

Rinne, T., Ruismäki, R., Dańczak, A., Serna Guerrero, R., Jokilaakso, A., “Integrating Flotation and Pyrometallurgy for Recovering Graphite and Valuable Metals from Battery Scrap part II: Optimization of Ni Slag Cleaning Process Parameters”, to be submitted

Töytäri, P., Hakanen, E., Turunen, T., “Servitization as an activity-to-governance allocation: Multi-stakeholder perspective on shared goals, joint activity system, and distributed governance “, to be submitted

Ahaliabadeh, Z., Miikkulainen, V., Mäntymäki, M., Mousavi, S., Lahtinen, J., Lide, Y., Jiang, H., Mizohata, K., Kallio, T., 2021, “Atomic Layer Deposition of Metal oxide and Li-metal oxide Coatings for Stabilizing Ni-rich Cathode Material in Lithium Ion Batteries”, manuscript submitted

Ahaliabadeh, Z., Miikkulainen, V., Mäntymäki, M., Mousavihashemi, S., Lahtinen, J., Lide, Y., Jiang, H., Mizohata, K., Kankaanpää, T., Kallio, T., 2021, “Understanding stabilizing effects of nano scale metal oxide and Li-metal oxide coatings on lithium ion battery positive electrode materials”, manuscript submitted

Chernyaev, A., Wilson, B.P., Lundström, M., “Study on valuable metal incorporation in the Fe-Al precipitate during neutralization of LIB leach solution”, manuscript submitted

Chernyaev, A., Zou, Y., Wilson, B.P., Lundström, M., “The interference of copper, iron and aluminum with hydrogen peroxide and its effects on reductive leaching of  $\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$ ”, manuscript submitted

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## Theses

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## Conferences

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