A Mixed-Methods Approach to Identify and Assess Sustainability Criteria for Battery Chemistries in Electric Vehicles

Master's thesis in Industrial Ecology

PERNILLA ANDERSSON
ELIN NILSSON

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
www.chalmers.se
Report No. E2023:27

REPORT NO. E2023:27

A Mixed-Methods Approach to Identify and Assess Sustainability Criteria for Battery Chemistries in Electric Vehicles

PERNILLA ANDERSSON
ELIN NILSSON

Department of Technology Management and Economics
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023

A Mixed-Methods Approach to Identify and Assess Sustainability Criteria for Battery Chemistries in Electric Vehicles
PERNILLA ANDERSSON
ELIN NILSSON

Supervisors: Mudit Chordia & Anders Nordelöf, Chalmers, Environmental Systems Analysis
Supervisors: Anna Hägg & Rei Palm, Volvo Cars
Examiner: Rickard Arvidsson, Chalmers, Environmental Systems Analysis

Report No. E2023:27
Department of Technology Management and Economics
Environmental Systems Analysis
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone +46 31 772 1000

Cover: Illustration depicting various components of the thesis.
Gothenburg, Sweden 2023

A Mixed-Methods Approach to Identify and Assess Sustainability Criteria for Battery Chemistries in Electric Vehicles

PERNILLA ANDERSSON
ELIN NILSSON

Department of Technology Management and Economics
Chalmers University of Technology

Abstract

The transport system is currently undergoing a transition, with car manufacturers shifting from producing conventional internal combustion engines to producing electric vehicles (EVs). One of those actors is Volvo Car Corporation, which has the ambition to become a fully electric car manufacturer by 2030, as well as climate neutral and circular by 2040. One important factor to assess in the transition to EVs is the choice of battery cell chemistry.

The aim of this study is to identify and assess sustainability criteria for multiple lithium-ion batteries (LIBs) and sodium-ion batteries (SIBs) chemistries for EV application. The LIB cell chemistries examined are nickel manganese cobalt - graphite (NMC811-Gr) and lithium iron phosphate - graphite (LFP-Gr), and SIB cell chemistries are nickel manganese magnesium titanium oxide - hard carbon (NaNMMT-HC) and nickel manganese cobalt oxide - hard carbon (NaNMC-HC).

Prior research within sustainability in battery cell chemistries for electric vehicles has often been covered through life cycle assessments (LCA) studies. However, LCA has been shown to only address limited aspects of sustainability. This thesis proposes a mixed-methods approach to assess sustainability, by combining an open space technology (OST) workshop, data from LCAs, expert interviews, and multi-criteria decision analysis (MCDA), in order to bring forward other aspects in the sustainability assessment.

The sustainability indicators identified in the OST workshop and used in this study are 'Responsible sourcing and social aspects', 'Human health', 'Raw material availability', 'Longevity of cell', 'Climate impact', and 'Recyclability'. Quantification of the indicators and the MCDA showed that the LFP-Gr cell is a promising chemistry amongst those assessed.

In conclusion, it is recommended to adopt additional stakeholder perspectives, and other tools, to complement the environmental and social assessments conducted using LCA studies, when assessing the sustainability of both current and emerging battery chemistries.

Keywords: Lithium-ion batteries, Sodium-ion batteries, Battery cell chemistries, Electric Vehicles, Sustainability assessment, Multi-criteria decision analysis, Mixed-methods approach, Open Space Technology

Acknowledgements

This project would not have been possible without our main supervisor Mudit Chordia. Thank you for all your invaluable input, guidance, and, above all, for always making time for us, even when it came to the smallest issues. We would also like to thank Anders Nordelöf for the valuable and confidence boosting meetings and inspirational talks on how to deal with everything from industry interactions to academic writing and assessments.

We are grateful to Volvo Cars for providing us with the opportunity to perform this thesis, and to all of the resources and support they provided. We are thankful to all the different people in different departments that took time for us to help us forward, but we would like to give a special thanks to our supervisors Anna Hägg and Rei Palm.

We also owe Tomas Ekvall a thank you for the support provided in guiding us on how to conduct our workshop and interpret the results. Furthermore, we want to thank all the participants in the workshop, for taking time to help us with their expertise. As well as other people that have supported us throughout the project, by guiding us, participating in surveys, and answering questions.

Pernilla Andersson would like to dedicate this work and extend a special thank you to her grandmother, Ann-Marie, who has always been very encouraging of her studies. Pernilla is also thankful for the never-ending support of her parents, Peter and Lotta.

Elin Nilsson would like to thank her parents, Kerstin and Peter, for their everlasting support and for always encouraging her to pursue her passions. She would also like to thank her partner, Christoffer, for all the love and support during her whole academic time.

Pernilla Andersson & Elin Nilsson, Gothenburg, May 2023

Table of Contents

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AAM	Anode Active Material
ACC	Anode Current Collector
BEV	Battery Electric Vehicle
BGS	British Geological Survey
CAM	Cathode Active Material
CCC	Cathode Current Collector
CF	Characterisation Factor
CSI	Crustal Scarcity Indicator
CSP	Crustal Scarcity Potential
CTU_h	Comparative Toxic Units for human toxicity
EoL	End-of-Life
EV	Electric Vehicle
FPIC	Free, Prior, and Informed Consent
Gr	Graphite
HC	Hard Carbon
HTP	Human Toxicity Potential
LCA	Life Cycle Assessment
LFP	Lithium Iron Phosphate
LIB	Lithium-ion Battery
MCDA	Multi-Criteria Decision Analysis
NaNMC	Sodium Nickel Manganese Cobalt
NaNMMT	Sodium Nickel Manganese Magnesium Titanium
NMC	Nickel Manganese Cobalt
NTA	Negative Terminal Assembly
OST	Open Space Technology
PTA	Positive Terminal Assembly
SIB	Sodium-ion Battery
USEtox	UNEP-SETAC toxicity model
WSM	Weighted Sum Model

List of Figures

List of Tables

1

Introduction

The first electrochemical cell was invented in 1800 by Alessandro Volta (Schumm, 2023). However, it was not until 1836, with the electrochemical cell invented by John Frederic Daniell, that a battery could be used as a source of electricity, as it unlike Volta's cell, could sustain continuous currents. Today, batteries are used for many different applications, one being the component that provides propulsion in vehicles. The field is ever growing and many types of electrochemical cells are available at more or less mature states, and all come with their own unique set of challenges - both technically and from a sustainability point of view.

The leading battery cell technologies for electric vehicles (EVs) are lithium-ion batteries (LIBs) (Houache et al., 2022). There are several Li-ion cathode chemistries available in the market today, such as lithium manganese oxide (LMO), lithium cobalt oxide (LCO), lithium titanate (LTO), lithium iron phosphate (LFP), nickel cobalt aluminium (NCA), and nickel manganese cobalt (NMC) (Warner, 2015).

One of the most common cathode chemistries is LFP, which is a chemistry that is known for its good cycle life, thermal and electrochemical stability, and low cost due to the use of iron (Houache et al., 2022). On the other hand, this cathode also has low energy density and low electronic conductivity resulting in high costs per kWh even with the use of the relatively cheap iron.

Currently, there is a search for LIBs with high energy density in the automotive industry due to an increasing energy crisis and because EVs are considered to be a step towards reduced carbon dioxide (CO_2) emission (Luo et al., 2022; Manthiram, 2017). One material that has been shown to increase energy density is nickel (Ni), and both NCA and NMC chemistries are considered to have superior structural properties and thermal stability compared to attempts with other elements such as magnesium (Mg) and manganese (Mn) among others (Luo et al., 2022). There are several types of NCA and NMC chemistries of the configurations $LiNi_xMn_yCo_zO_2$ and $LiNi_xCo_zAl_yO_2$, where $x+y+z=1$. Presently, these chemistries are gravitating towards higher shares of Ni (Houache et al., 2022), such as:

- $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ (NCA80)
- $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC622)
- $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811)

One Ni-rich cathode chemistry that is commercially used is NMC811 (Luo et al., 2022).

Another common driver for studies of Ni-rich LIBs are the reduced amount of Co, which, due to the questionable environmental impacts and working conditions in the mining phase, has been given a lot of attention (Luo et al., 2022; Sovacool, 2019). Furthermore, the use of Co also comes with a large financial cost, making it relevant to study alternative chemistries which are both Ni-rich and Co-free (Luo et al., 2022).

Sodium-ion batteries (SIBs) is a cell chemistry currently explored as an alternative to LIBs. Two reasons why SIBs are considered as alternatives to LIBs are: 1) Sodium (Na) is much more abundant than Li and costs less, and 2) the chemistry of SIBs is quite similar to that of LIBs (Delmas, 2018; Hwang et al., 2017). The main difference in chemistry is that LIBs use Li ions as charge carriers, and SIBs use Na ions (Hwang et al., 2017). Na ions have a radius $\sim$50% larger than the Li ions, which has an effect on anode materials (Walter et al., 2020). Graphite (Gr) is used in LIBs as anode but has very low capacities in SIBs. Instead carbonaceous materials like hard carbon (HC) can be used as alternative in SIBs (Walter et al., 2020).

SIBs have started being produced commercially only in a smaller scale so far, but CATL, one of the largest battery manufactures in the world, have plans to start mass-producing SIBs in the near future (Fichtner, 2022). There are a lot of different types of cathode chemistries currently being investigated for SIBs, and most can be placed in one of the three categories: layered transition metal oxides, Prussian blue and its analogues, and polyanionic compounds (Peters et al., 2021; Wang et al., 2020). Layered transition metal oxides include cathode chemistries such as nickel mangangese magnesium titanium oxide (NaNMMT), manganese magnesium oxide (NaMMO), and nickel manganese cobalt oxide (NaNMC) (Peters et al., 2021).

Volvo Car Corporation, commonly known as Volvo Cars, is a Swedish automotive manufacturer founded in 1927 that, in 2021, set out to be a fully electric car brand by 2030 as a step towards reduced life cycle carbon footprint of its products (Volvo Cars, 2021). Furthermore, one of the company's ambitions is that in 2040 their whole business should be climate-neutral (Volvo Car Group, 2023). They also have ambitions of going circular and becoming a recognised leader in ethical and responsible business. Currently, Volvo Cars communicate sustainability actions regarding use of cobalt (Co), Ni, and Li in their battery cathodes (Volvo Car Group, 2023). There are many technical solutions to choose from, just within the field of battery cell chemistries for EVs. However, which cell chemistry that is most sustainable is not yet clear (Amici et al., 2022). Considering this, the promising cell chemistries LFP-Gr, NMC811-Gr, NaNMMT-HC, and NaNMC-HC are assessed with a mixed-methods approach regarding their sustainability in this study.

1.1 Research gap

Multi-criteria decision analysis (MCDA) is decision-making tool, that can take both preferences and performance of different alternatives in to consideration through mathematical formulas (Linkov et al., 2021). MCDA has previously been used to assess LIBs for

EVs (Loganathan et al., 2021). Loganathan et al. (2021) discuss how EVs manufacturers often consider and deal with trade-offs, from performance factors such as energy density and specific power, but also safety, reliability, and cost, when selecting a LIB. This is a typical MCDA problem. Still, little research has been conducted on this decision problem using a multi-criteria approach.

An MCDA based framework for sustainable manufacturing in the automotive industry has been developed by Stoycheva et al. (2018). They discuss how the current sustainability frameworks often are qualitative and lack different components of sustainability. Some manufacturers focus is on economic factors and neglects environmental and social ones, while others heavily considers environmental issues. Stoycheva et al. (2018) emphasise that a focus material choices in the manufacturing process can be a first start for the automotive industry in its work for improved sustainability, as it affects both fuel efficiency in the final product as well as resource dependence, recyclability, and biodegradability. Traditionally, sustainability in manufacturing is assessed through LCAs (Stoycheva et al., 2018). However, the use of MCDAs in sustainability assessments are increasing as it provides a way to weight stakeholder preferences and performance in complex situations.

Domingues et al. (2015) discuss the use of MCDA as a complement to LCA for environmental assessments of vehicles to aid in decision making for both policy-makers and consumers. An LCA helps covering multiple dimensions of environmental impacts throughout the whole life cycle of different technologies (Domingues et al., 2015). However, they often only cover a few impact categories with a focus on global warming. An MCDA provides other aspects in environmental decision making as it makes it possible to compare alternatives in relation to, e.g., "technical information, stakeholder values, and non-monetary factors" (Domingues et al., 2015). Moreover, an MCDA allows for the inclusion of multiple perspectives in the weighting step. MCDA and LCA are good complements, but rarely seen used together.

A possible way to combine LCA and MCDA while including multiple aspects and perspectives is through a mixed-method approach. The mixed-method approach has been applied by, e.g., Gebhardt et al. (2022) with the purpose of addressing the lack of a comprehensive and accepted framework for sustainability assessments of the LIB supply chain. Currently, most studies on LIB supply chains are based on already defined frameworks such as LCAs, in which aspects specific for battery supply chains, e.g., circularity and child labour, are often lacking (Gebhardt et al., 2022).

1.2 Aim and research questions

The aim of this study is to compare and assess the sustainability of LIB and SIB cell chemistries used in EVs. A subgoal of the study, necessary to conduct the assessment, is to identify relevant sustainability indicators for assessing the LIB and SIB cell chemistries. The LIB battery chemistries selected for assessment are two of the most commercially used; NMC811-Gr and LFP-Gr. The SIB cell chemistries selected for assessment are

NaNMC-HC and NaNMMT-HC. NaNMC-HC has a cathode chemistry that has been used in LIBs for a long time and has advantageous properties such as high energy density. NaNMMT-HC is an alternative SIB, which has been studied more in depth in published articles (Peters et al., 2016; Peters et al., 2021). The focus is on these LIB and SIB cell chemistries as they were found relevant and of interest to Volvo Cars, who initiated and co-supervised this thesis work. Volvo Cars is a multinational car manufacturer with roughly 43'000 employees around the world, with its largest markets in Europe and Asia (Volvo Car Group, 2023). Sustainability is, together with safety, one of Volvo Cars' main values. Thus, increased understanding of sustainability aspects of today's and future cell chemistries is of high importance to Volvo Cars.

To fulfil the aim of the thesis, the following specified research questions are considered:

1. How do the battery cell chemistries LFP-Gr, NMC811-Gr, NaNMMT-HC, and NaNMC-HC compare in terms of the sustainability, according to chosen indicators?
2. What are the key sustainability indicators relevant to assess the above mentioned battery cell chemistries in automotive applications?

This study extends Volvo Cars' and other EV manufacturers' selection basis for propulsion batteries. This is done in accordance with the findings of Stoycheva et al. (2018), to include additional sustainability criteria, partly using the combination of sustainability assessment tools suggested by Domingues et al. (2015) through a mixed-methods approach.

1.3 Demarcation

This study focuses on the sustainability assessment of different battery cell chemistries, where the cathodes and anodes are of particular interest. The data is collected almost entirely from published studies, and the authors do not generate new raw data or perform additional LCAs.

As the study employs a mixed-method approach, various parts of the study adopt slightly different methodologies to gather data. When possible, the whole cell is taken into account, but for some indicators where data for each component in the cell is collected individually, the parts considered are cathode active material (CAM), anode active material (AAM), current collectors, terminals, and cell casing. Components not taken into account are electrolyte and additives.

2

Theory

In this section, the sustainability definition used in the study is defined. Next, an overview of the working principles of a battery cell, and the theories behind the studied cell chemistries are presented.

2.1 Definition of sustainable development

Sustainability is today seen everywhere, from newspapers and billboards, to job listings and children's books. Before using the word, one should clearly define the concept to be able to correctly understand what has been done in the context where it is used (Waseem & Kota, 2017). This assessment builds upon the Brundtland Commission's definition of sustainable development from 1987:

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*

While the Brundtland definition can be considered as general definition of sustainable development, one of the most common specific models in use are the three dimensions or pillars of sustainability (Hedenus et al., 2018; Waseem & Kota, 2017). The three dimensions; ecological, economic, and social, and potential interpretations can be seen in Figure 2.1.

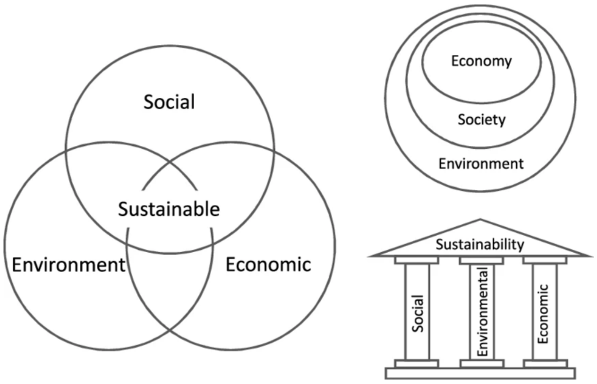


Figure 2.1: Different ways to depict the three dimensions of sustainable development. From Purvis et al. (2019), CC BY 4.0.

The ecological dimension focuses on the sustaining of natural systems to keep providing to human utility, and it includes both environmental production capacity and environmental assimilative capacity (Hedenus et al., 2018). In other words, the abilities to provide humans with natural goods and to manage pollution and environmental impacts.

Hedenus et al. (2018) further describe that the economic dimension focus on resource management with the aim to meet current and future human needs. Here, both finite natural resource such as fossil fuels and minerals are included, as well as man-made capital of different kinds e.g. buildings and knowledge capital.

The social dimension of sustainable development is the least covered topic in the scientific literature, and often the most controversial (Hedenus et al., 2018). It commonly covers topics such as health, social context and human rights. However, Hedenus et al. (2018) argues that these are means or ends of sustainable development, rather than preconditions to meet human needs, as in the ecological and economic dimension. Instead, they state that horizontal and vertical social relations should be considered as the preconditions for social sustainability.

Horizontal relations are the networks consisting of humans and organisations, and good horizontal relations lead to increased trust, correlating with economic growth, higher democracy, and less corruption and crime (Hedenus et al., 2018). The vertical relations refer to formal institutions with rules and hierarchical structure e.g., judicial systems, and social security systems (Hedenus et al., 2018). Furthermore, for a well-functioning nation the three parts; state, judicial system, and accountability, are required. In such a nation collective decision-making is possible, therefore managing crises while still supporting autonomy. Although described as separate, vertical and horizontal relations are interconnected.

The connections between the three dimensions are strong, and the boundaries not always clear. Dimensions can also be conflicting, forcing one to make a compromises regarding what will have the greatest utility for human needs.

2.2 Working principle of a battery cell

The three main components of a battery cell are the anode, cathode and the electrolyte (Beard, 2019). The anode and cathode together create a flow of electrons, which can power devices. Between the anode and cathode, the electrolyte is located, which is usually a solution of salt(s) dissolved in solvent(s) (Berg, 2015a).

During discharge of the battery, the anode undergoes oxidation (Berg, 2015a). This means that electrons are released, causing the anode to become positively charged. The electrons flow through a circuit to the cathode, thereby causing the electric current that can operate devices. As the electrons arrive at the cathode, it undergoes reduction, meaning it receives electrons and thereby becomes negatively charged. At the same time as the electrons move in the external circuit, where ions - Li ions in LIBs and Na ions in SIBs - are released from the anode and move through the electrolyte to the cathode. There they react with the electrons, ensuring that the reaction can continue until the battery is discharged. When the battery is instead being charged, an external power source forces the electrons to go back from the cathode to the anode. A schematic overview of a battery can be seen in Figure 2.2.

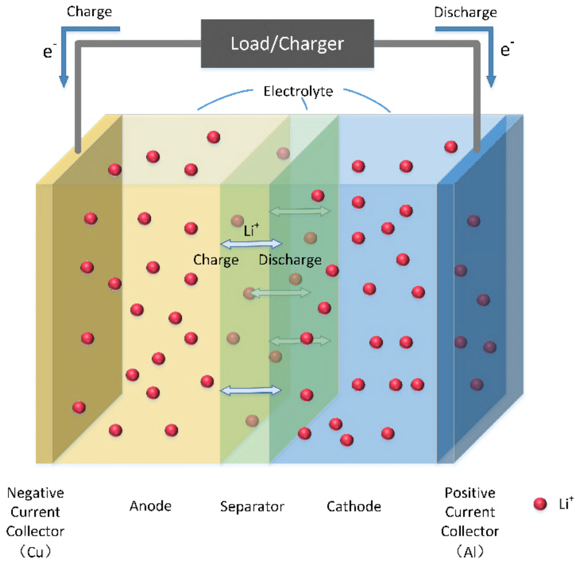


Figure 2.2: Schematic picture of a battery with Li ions as charge carriers. From Zhang et al. (2018), CC BY 4.0.

In addition to the electrolyte, anode, and cathode, a battery also contains a negative current collector, positive current collector and a separator (Berg, 2015a). The separator prevents direct contact of the electrodes, which can lead to internal short circuit (Beard, 2019). On each side of the battery, current collectors are located, composed of materials with high electrical conductivity such as aluminium (Al) or copper (Cu). The collectors help transferring the electrons to and from the external circuit as efficiently as possible, and make the cell more stable (Berg, 2015a). The cell is finally enclosed in a casing, to add mechanical stability and protection (Berg, 2015a).

2.3 Lithium-ion battery cell chemistries

Here, the LIB cell chemistries LFP-Gr and NMC811-Gr are described in more detail.

2.3.1 Lithium iron phosphate cathode and graphite anode

The LFP-Gr cathode has the chemical structure $LiFePO_4$, a theoretical capacity at 170 mAh/g, and an energy density at 190 Wh/kg at cell level (Berg, 2015b; Houache et al., 2022). The cell has good cycle life, thermal and electrochemical stability, and safety, due to strong bonds in the PO_4 anion (Houache et al., 2022).

The most common anode materials for LIBs are carbon-based, especially common is graphite (Berg, 2015b). Graphite has a crystalline structure made up of graphene layers connected by weak van der Waal bonds, and between the layers Li ions can be inserted. During charge and discharge, the graphite undergoes redox, which is highly dependent on factors such as particles size, surface chemistry, morphology, crystallinity, and orientation of the crystallites.

2.3.2 Nickel manganese cobalt oxide cathode and graphite anode

NMC811-Gr is a high-power layered oxide LIB, with the chemical structure $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$. It has high theoretical capacity (200 mAh/g) and energy density (e.g. 244 Wh/kg, 227 Wh/kg) (Campagnol et al., 2021; Houache et al., 2022; Julien & Mauger, 2017). The more Ni in the NMC chemistry, the higher capacity and energy density, but at the cost of thermal stability and short calendar life (Houache et al., 2022). Moreover, the manganese (Mn) reduces internal resistance at the cost of lower specific energy while Co improves electric conductivity but increases material costs. This chemistry does also, most commonly, have a graphite anode.

The NMC811 cathode chemistry has its own set of shortcomings. For example, due to the Ni ions' instability there is high surface reactivity with the liquid organic electrolyte while charged. It is also structurally unstable, causing thermal safety issues (Houache et al., 2022). Despite this, the NMC811-Gr cell is commercially available and is soon expected to be highly implemented among EV original equipment manufacturers (OEMs) (Houache et al., 2022; Luo et al., 2022).

2.4 Sodium ion batteries

In this section, the SIB cell chemistries NaNMMT-HC and NaNMC-HC, are described in more detail.

2.4.1 Nickel manganese cobalt oxide cathode and hard carbon anode

NaNMC ($Na(Ni_{0.33}Mn_{0.33}Co_{0.33})O_2$) is a layered oxide cathode (Peters et al., 2021). As can be seen from the composition, the ratio of elements in the NMC cathode is 1:1:1, meaning the same amounts of Ni, Mn and Co are used. HC is the most commonly used material for the anode in SIBs, and it is a carbon material that does not graphitise even at very high temperatures (del Mar Saavedra Rios et al., 2021). The reason HC is used instead of Gr is because the Na ions are larger than the Li ions, and so they cannot fit in between the graphene layers of the Gr (Hwang et al., 2017).

2.4.2 Nickel manganese magnesium titanium oxide cathode and hard carbon anode

NaNMMT ($Na_{1.1}(Ni_{0.3}Mn_{0.5}Mg_{0.05}Ti_{0.05})O_2$) is a layered transition metal oxide cathode as well (Peters et al., 2021). Mg and Ti are used in the cell as doping agents, in order to improve cycling stability, maximise specific energy and reduce cost (Rudola et al., 2021). The anode material in this SIB is HC as well, for the same reason it is used in the NaNMC-HC cell chemistry.

3

Methods

The section describes the different methods that are combined in a mixed-methods approach to assess the sustainability of EV battery cell chemistries.

3.1 Mixed-methods approach

A mixed-methods approach is a multi-phase research method, in one phase, quantitative methods are used, while the second consists of qualitative research, in order to understand a problem to a greater extent (Migiro & Magangi, 2011). The quantitative and qualitative methods are complementary, rather than competing.

The mixed-methods approach used in this sustainability assessment started, as depicted in Figure 3.1, with an OST workshop, where relevant criteria (sustainability indicators) for the MCDA were identified. Then, a literature review was conducted, where quantitative methods were identified and data collection was conducted. The indicators were then separately weighted by stakeholders, while the quantitative methods and collected data were used to rank the different cell chemistries. Lastly, the weights and ranked cell chemistries were combined in an MCDA.

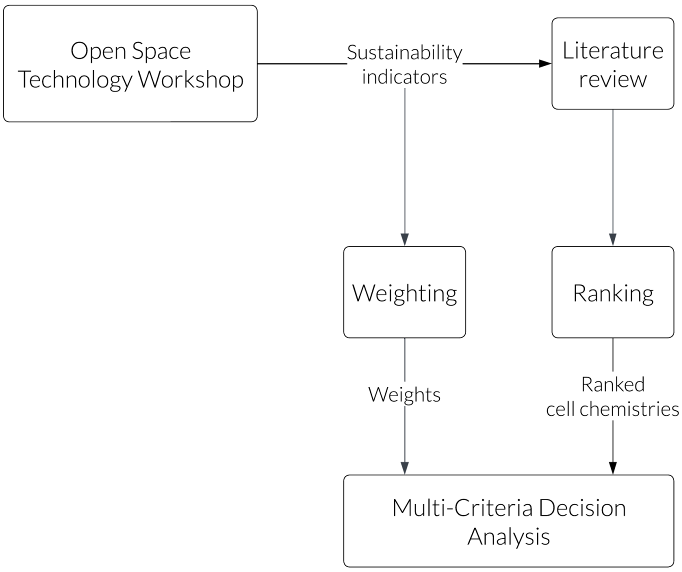


Figure 3.1: Flowchart showing the mixed-methods approach.

3.2 Open Space Technology

The Open Space Technology (OST) workshop is a method for organising group discussions and meetings (Owen, 2008). It is inspired by the idea that spontaneous discussions between stakeholders (like the ones around a coffee machine), often lead to better outcomes in terms of quality of discussions and agreements as compared to strictly agenda-driven meetings. A key element of an OST workshop is that the participants actively set the agenda during the workshop and are encouraged to participate only if the topic being discussed interests them (Owen, 2008). This paves the way for more deliberate discussion. The OST workshop was used in this work as a step towards defining and weighing the sustainability indicators that were then used in the MCDA. The approach to the OST workshop is inspired by the report on *Participatory Life Cycle Sustainability Analysis* by Ekvall et al. (2016).

3.2.1 Identifying stakeholders and conducting the OST workshop

The OST workshop consisted of two main phases. First, stakeholders relevant to the research topic were identified and invited to the workshop. Next, the workshop was conducted, at which participants had to work together through a multi-step group discussion and vote on the sustainability aspects they deemed most critical for assessing battery chemistries.

In the first phase, people with expertise in battery and electric vehicle technology development and sustainability assessments of battery production, recycling and material supply chain were invited to the workshop. The list of attendees was also limited due to geographical and logistical constraints, as online participation was not considered. In total, 38 people with battery or sustainability backgrounds within academia, industry, consulting, and media were contacted, 17 intended to attend the workshop but on the actually day 14 people participated. An anonymised list of attendees can be seen in Appendix A.

The second phase was the execution of the OST workshop. Firstly, the attendees were asked to think of the most important indicators for assessing battery cell chemistries for five minutes. The participants were then told to find two other people, whom they did not know beforehand, to decide on the top three combined indicators. In total, there were four groups of three and one group with two participants. The groups were then asked to present their three indicators, which were written down on the wall. Any overlapping indicators were collectively decided to be one joint topic.

At this point, the participants were asked to write their names on any topics they were interested in discussing during the day. They were explicitly told that they did not have to choose the indicators they thought were the most important ones, just the ones they wanted to discuss the most. They were also asked to indicate if they were willing to lead the discussion on one topic. After that, four parallel discussions in two sessions were set up, with as few scheduling collisions for all participants as possible.

The two sessions were carried out consecutively. For all topics, the participants were asked to discuss the following questions and fill out prepared sheets for documentation purposes, see Figure 3.2.

- Why is the indicator important?
- What aspects and facts should be considered and accounted for when including the indicator in a sustainability assessment of battery cell chemistries?

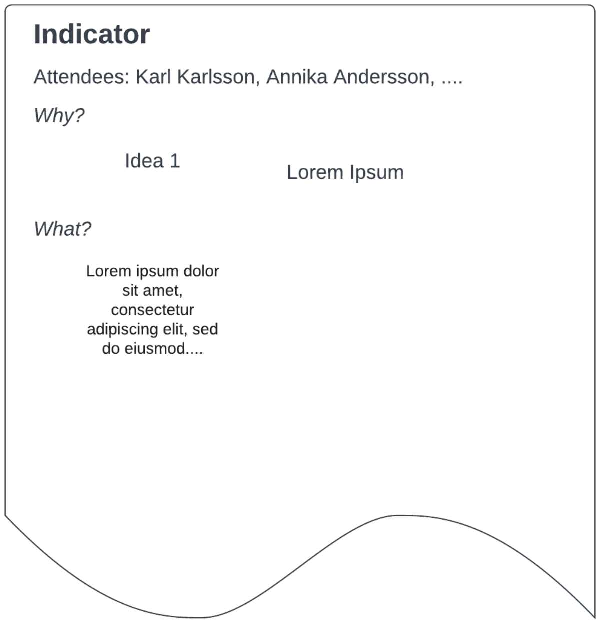


Figure 3.2: Graphic representation of the prepared sheets at the Open Space Technology workshop.

During the workshop, the participants were free to leave and join a different discussion at any point in time. The names of everyone that contributed to the final output were noted down on the sheets. Once both sessions had been completed, all participants were assembled and a member of each group briefly presented what had been written down.

In the last part of the OST workshop, the participants were asked to vote on the importance of the discussed indicators. Two of the presented indicators were not discussed, as the participants chose to stay in other discussions during the whole session. These indicators were still presented as possible to vote for. Each person was given five green dots and three red dots, and was instructed to place a dot by the indicator if they agreed (green) or disagreed (red) with most of the contents. If they only agreed or disagreed with certain parts they could place their dots by that section. A few participants had to leave early and were either asked to vote before the presentation or in an email afterwards. After the workshop, the indicators were summarised, and due to overlapping discussions some were combined to one indicator.

3.3 Quantifying the sustainability indicators

Based on the indicators discussed and chosen in the OST workshop, a literature review was conducted with the aim to identify quantitative methods for the sustainability indicators and quantify them. Furthermore, a literature review was also used for qualitative discussion of the non-quantifiable indicators. The main databases used were available through Chalmers Library and Google Scholar, e.g., ScienceDirect, Scopus, and Knovel. For more details, see Section 4.3.

In the quantifying methods, the different battery cell chemistries were compared within each indicator, by looking at the impacts per kilowatt hour (kWh). This unit is chosen as the kWh relates to the propulsion of the vehicle, and as the different cells have different energy density, using a unit such as per kilogram (kg) could be misleading.

For the indicators where only specific components of the cells were considered, the materials and parts presented in Table 3.1 was assessed.

Table 3.1: Component and material overview of the cell chemistries.

	Cell component						
Cell chemistry	**CAM**	**AAM**	**CCC**	**ACC**	**PTA**	**NTA**	**Cell container**
LFP-Gr	Li, Fe, P	Gr	Al	Cu	Al	Cu	Al
NMC811-Gr	Li, Ni, Mn, Co	Gr	Al	Cu	Al	Cu	Al
NaNMMT-HC	Na, Ni, Mn, Mg, Ti	HC	Al	Al	Al	Al	Al
NaNMC-HC	Na, Ni, Mn, Co	HC	Al	Al	Al	Al	Al

Note: CAM - cathode active material, AAM - anode active material, CCC - cathode current collector, ACC - anode current collector, PTA - positive terminal assembly, NTA - negative terminal assembly.

3.4 Weighting of the sustainability indicators

In order to assign importance to the finalised sustainability indicators, an online survey was sent out to stakeholders who had been contacted regarding attendance in the OST workshop. Both people who had attended the workshop and those who had declined were invited to participate in the weighting. In the survey, they weighted the importance of the identified sustainability indicators by assigning a percentage of importance to them. In total, the percentages had to add up to 100%.

3.5 Multi-criteria decision analysis

MCDA is a group of mathematical tools aiming to incorporate perspectives from various stakeholders combined with technical information to inform a decision-making process (Linkov & Moberg, 2012). Moreover, decision-making in relation to environmental impacts are complex and the use of multiple criteria and perspectives as in MCDAs provides aid in that process. According to Linkov and Moberg (2012), a basic MCDA is structured in the following way:

1. Problem identification
2. Problem structuring
3. Model assessment and building
4. Model application
5. Planning and extension

Initially, the problem is identified, then the problem is structured using alternatives and criteria (Linkov & Moberg, 2012). In the modelling and building step the alternatives and criteria are given numeric values. Weights are added to the criteria, giving the alternatives a value of performance in relation to the criteria (Linkov & Moberg, 2012). Once the weights have been added, the model is applied, and the output depends on which specific MCDA method used. Based on that a decision can be made and inform the plans.

The specific MCDA model applied in this work is the weighted sum model (WSM), where m alternatives and n criteria were used to structure the MCDA problem (Triantaphyllou, 2000). Furthermore, w_j denotes the weight of the j^{th} criterion and a_{ij} the value/rank of the i^{th} alternative in relation to the j^{th} criterion, giving Equation 3.1, where Q_i is the WSM score for alternative i.

$$Q_i = \sum_{j=1}^{n} a_{ij} w_j, \text{ for } i = 1, 2, 3, ..., m \tag{3.1}$$

In the present assessment, the alternatives were the different battery cell chemistries NMC811-Gr, LFP-Gr, NaNMMT-HC, and NaNMC-HC, while the criteria were the sustainability indicators defined at the OST workshop. After modification of the sustainability indicators, weights were assigned by the stakeholders invited to the OST workshop.

The ranking of the chemistries was based on data collection and the quantification of the indicators. Depending on how well each chemistry performed within an indicator compared to the others, it received a rank from 1 to 4, where 1 is the best and 4 the worst. The ranks were assigned as in a runner's competition, meaning that if two or more alternatives got the same results (or score) they were given the same rank, thus implying that multiple chemistries performed similarly on a particular sustainability indicator. In such an instance, the next subsequent rank was assigned based on the number of higher ranked chemistries. For example, if two cell chemistries received rank 1 for an indicator, then the subsequent rank assigned would be 3 instead of 2.

4

Quantifying the sustainability indicators

This section presents the output from the OST workshop and the identified sustainability indicators, as well as how they were interpreted for quantification. Furthermore, a literature overview of each indicator and their chosen quantification method(s) is presented.

4.1 Identifying indicators from the workshop output

After the OST workshop was performed, the indicators and the total number of votes they received were summarised, see Table 4.1. Green votes represent that the participants found the indicator highly relevant/important for the sustainability assessment of battery cell chemistries, while red meant that they found it to not be relevant/important. For a more detailed overview see Appendix B.

Table 4.1: The indicators and their total number of votes from the OST workshop.

Sustainability indicator	**Green dots [total]**	**Red dots [total]**
Responsible sourcing incl. traceability	15	0
Geopolitics/Control of value chain	13	2
Raw material availability	10	1
Longevity of cell	9	3
Climate impact	8	3
Recyclability	6	0
Human health	1	0
Sufficient supply of technical expertise and standards	0	0

The indicator ’Human health of all workers and inhabitants’ was not discussed and got only one vote. However, the group that set out to discuss it instead merged into the discussion group for ’Responsible sourcing and traceability’. Furthermore, there was some overlap of discussion in ’Geopolitics/Control of the value chain’ and ’Responsible sourcing and traceability’. For example, traceability was mentioned in both indicator discussions. After several discussions and consultations, it was decided that three of the indicators should be merged. ’Geopolitics/Control of the value chain’, ’Responsible sourcing and traceability’, and ’Human Health of all workers and inhabitants’ were merged into the two indicators ’Responsible sourcing and social aspects’ and ’Human health’. This division was partly motivated by the first-mentioned indicator being of a more qualitative nature, while the last-mentioned could be more easily quantified. The resulting indicators and their number of votes in total, i.e., including votes on specific parts on the sheet, is presented in Table 4.2.

As climate impact is a measure related to the assimilative capacity of the environment, it was categorised into the ecological dimension. Raw material availability, longevity of cell, and recyclability all focus on resource management, thus placing them mainly in the economic dimension. Lastly, human health and responsible sourcing and social aspects were categorised in the social dimension. However, there are some overlaps between the categories as the responsible sourcing indicator also contains a few environmental elements.

Table 4.2: The final number of green votes (representing the attendees choice of importance) for the different indicators.

Sustainability indicator	**Green dots** [**total**]
Responsible sourcing and social aspects Human health	28[1]
Raw material availability	10
Longevity of cell	9
Climate impact	8
Recyclability	6

[1] Note that these indicators were merged and altered.

4.2 Summary of OST workshop output

This is a brief overview of the resulting output from discussions regarding sustainability indicators in the OST workshop - why they where deemed important and what to take into account when assessing them, according to the participants of the workshop. For more details, see Appendix B.

The use of indicators for *raw material availability* was motivated in OST workshop with keywords such as risk management, economic importance, scarcity, long-term possibilities to maintain the availability, and bottlenecks in production capacity. The workshop participants saw that ’physical availability in the crust’, ’criticality’, ’market demands for the raw material’, ’supply chain risks’, and ’local governance at the extraction site’ should be included when assessing the raw material availability. Notably, this includes both long-term geochemical resource availability (Gordon et al., 2007) and more near-term resource criticality (Blengini et al., 2020).

Longevity of cell was motivated as an important indicator during the OST workshop since the longer the battery can be used, the less mineral extraction and environmental impacts of production per battery occur. Regarding what to consider and account for when assessing this indicator, the prioritising of longevity over fast charge and energy density were mentioned, as well as optimisation of battery usage.

During the discussions on *climate impact* in the workshop, aspects mentioned to consider and include in the assessment were, e.g., such as the full life cycle (production, use of vehicle, and end-of-life), conservative assumptions regarding future recycling, as well as the importance to have a common methodology for all options compared.

Recyclability was motivated as an indicator during the workshop since a better recyclability can reduce future mining, carbon footprint, and environmental impact. When defining what to consider and account for in the sustainability assessments, key words mentioned was 'technically possible', 'economically feasible', 'battery grade quality', 'energy and chemicals used in recycling', and that 'critical batteries require higher grade of recyclability'.

In the OST workshop, *human health of all workers and inhabitants involved* were given its own time slot for discussion due to large interest, but this indicator ended up not being discussed on its own. Instead, the topic was mentioned and written down on sheets from multiple of the other discussions. The indicators itself were only given one vote, but keywords such as 'working conditions' and 'workers health' were given both individual votes and votes on whole sheets on some of the other indicator sheets. Therefore, an indicator of human health deemed important to include in the assessment.

To summarise what an indicator for *responsible sourcing* should include, the workshop attendees used a wide range of keywords, such as 'workers rights and working conditions/health', 'preservation of ecosystems incl. biodiversity', 'indigenous peoples rights', 'free, prior and informed consent (FPIC)', 'ensuring value to the area of extraction', 'corruption', and 'supporting local development with financial tools'.

4.3 Choice of quantification methods

In this section, the theory behind each quantification method of the indicators from the OST workshop output are presented.

4.3.1 Raw material availability

Minerals are fundamental for a functioning society where economic development and good quality of life is maintained (Graedel et al., 2014). However, factors such as globalisation, increased consumption, and growing economies are responsible for a rising concern regarding the availability of minerals (Careddu et al., 2018; de Groot et al., 2012).

With regards to more near-term risk management, criticality, market demands, supply chain risks and short-term availability the quantification method ’Diversity of supply’ is chosen. To address long-term global geochemical scarcity the ’Crustal scarcity indicator’ (CSI) is chosen as a complimentary method for assessment of raw material availability. In the assessment of raw material availability, only material use for the CAM, AAM, collectors, and cell container are taken into account.

High dependency on few suppliers leads to uncertainties on the market due to the competition for the material, while giving the suppliers the possibility to set the price (de Groot et al., 2012). A simple method for assessing the diversity in supply chains are the number of producing countries, where ’production’ is used as a proxy for the ’supply’ (Brown, 2018). To quantify the diversity of supply for specific battery chemistries, a number of steps are proposed. First, production and, when necessary (due to lack of data on production), export rates of minerals will be used to identify the diversity of material supply. A cut-off criteria of 5% of the total world production (or export, where applicable) is used to identify the regions supplying the relevant materials used in the batteries. Regions supplying battery materials that are below the cut off criteria of 5% of the global production are summed as “Others”. These regions are deemed to be less relevant in the supply chain of the battery materials.

A second cut-off criteria is then implemented, where the limiting factor is the one material where the relevant suppliers add up to the lowest share of world production, compared to the other materials. The second cut-off is applied to each material and the number of countries required to supply that share of the world production are counted. Thereafter, for each battery chemistry, all relevant materials are listed along with the number of countries that supply up to the second cut-off criteria. Finally, to quantify the (lack of) diversity of supply, the chemistries are ranked according to the material supplied by the least number of regions. This essentially means that, if a specific battery material is supplied by a fewer number of countries or regions, it would affect the ranking of that chemistry towards a lower ranking, as the lack of availability of the material would affect whether the battery chemistry can be produced or not.

Long-term geochemical scarcity is another factor to consider when assessing raw material availability. Suppliers rarely include the current assessments of reserves and reserve bases in the pricing, as higher prices, yields high incomes in the short-term when few alternative suppliers are available (de Groot et al., 2012). According to findings by Arvidsson et al. (2020b), it is important to separate short-term and long-term availability, as well as local and global, when assessing mineral resource impacts. Arvidsson et al. (2020b) saw that multiple studies have found relatively abundant materials, e.g., manganese and sulphur, to have high effects on life-cycle impact categories such as mineral resource impact and abiotic resource depletion, compared to rarer elements like lithium. The authors propose a new indicator, the crustal scarcity indicator (CSI), which is based on average crustal concentration of elements as proxy for long-term global elementary scarcity.

The CSI is calculated according to Equation 4.1, with the characterisation factor (CF) crustal scarcity potential (CSP), where m_i is the mass of element i extracted from the crust (in kg).

$$CSI = \sum_i m_i \times CSP_i \tag{4.1}$$

The CSP for materials relevant in the batteries under assessment is presented in Table 4.3.

Table 4.3: Crustal depletion potentials.

Material	**CSP** [**kg Si eq./kg**]
Li	14’000
Co	11’000
Ni	4800
Mn	370
Fe	5.4
P	650
Na	12
Mg	10
Ti	67
Al	3.4
Cu	10’000
Gr	140
HC	140

Note: The CSP for carbon is used as a proxy for hard carbon and graphite. From Arvidsson et al. (2020a), CC BY-SA 4.0.

4.3.2 Longevity of cells

The ageing of a battery takes place during all operation modes - driving, charging and inactivity - and is dependent on several different mechanisms that often interconnect (Keil et al., 2015). Examples of factors that affect the ageing are temperature, how often the battery is charged, and to which level it is charged and discharged (Xiong et al., 2020).

Two common types of measurements used for batteries are calendar life and cycle life. The calendar life is of high importance when the battery is inactive, and the cycle life is of high importance during the discharge and recharge of the batteries (Azaïs & Kuntz, 2022). For the most accurate prediction of a battery’s lifespan, all possible parameters should be modelled, together with expected usage of the battery (Peters et al., 2021). This report primarily focuses on the cycle life parameter, given its significance and the availability of relevant data.

4.3.3 Climate impact

Climate impact can be measured in several different ways, and can have both local and global consequences. In this study, the indicator is quantified using global warming, measured in CO_2-equivalents. This was chosen as it is one of the most widely used for climate impact assessments in an LCA context (Life Cycle Initiative, 2022), and it can compare the relative radiative forcing of several greenhouse gases. In the assessment, only the production phase will be considered, partly because of data availability and partly because the EoL phase will be covered in the recyclability indicator. One parameter that effects the energy use in production is the electricity mix, and the influence of this is examined in this study.

4.3.4 Recycling

Based on the discussion from the workshop, it was deemed important for the cell chemistries to have a high recyclability, i.e., for the materials to be both technically and economically feasible to recycle. Technical feasibility refers to the practical possibilities for recycling, i.e., if there are methods and techniques to dismantle the battery cell and separate the materials. The economic feasibility refers to the economic incentives for recycling the different cell chemistries. In the beginning, the technical and economic feasibility was intended to be ranked separately. However, as they are closely interlinked, a decision was made to rank them together.

During the literature review of the chemistries, most published articles that were found took into account the current situation, and not future possibilities. In order to get a more prospective perspective, the recycling feasibility was ranked by an expert in the area - Martina Petranikova, who is an associate professor at Industrial Materials Recycling and Nuclear Chemistry at Chalmers University of Technology, researching recovery of valuables metals, based on hydrometallurgical processes ("Chalmers Research: Martina Petranikova", n.d.). She has co-published several papers on the recycling of EV batteries that consider both technical and economic perspectives (Armand et al., 2020; Neumann et al., 2022).

Recycling of spent EV batteries cells can be performed in several different ways, with the major stages being pretreatment, metal extraction and product preparation, all often containing several minor steps (Romare & Dahllöf, 2017). The pretreatment usually involves mechanical crushing, and sometimes thermal pre-treatment. Two of the currently most commonly used processes for metal extraction are hydrometallurgy and pyrometallurgy (Meshram et al., 2020).

The pyrometallurgical process involves breaking down spent LIBs using high temperature (Chitre et al., 2020). The only materials that are currently recovered from this step are Co, Ni, Cu and Fe, which end up in an alloy that needs hydrometallurgy in order to be separated. The rest of the materials such as Li, Al, Mg, and graphite are burnt and/or end up in a slag, which is commonly used as construction material (Mousa et al., 2022).

Hydrometallurgy uses aqueous solutions to recover metals, with techniques such as leaching, solvent extraction and precipitation (Chitre et al., 2020). Hydrometallurgy can theoretically separate the materials up to 100%. However, materials such as graphite would still need further purification and/or regeneration in order to be reused in batteries.

Another alternative is ’direct recycling’, which is the process of using the batteries in a more preserved state, on component basis (Chitre et al., 2020). For example, carbonaceous material can be used in new anodes in LIBs, in order to increase higher density. Most direct recycling is so far only conducted on a lab scale, and the research is focused mainly on cathode materials, as these are the most expensive.

4.3.5 Human health

A method developed by Rosenbaum et al. (2008) for comparison of human health impacts is the UNEP-SETAC toxicity model (USEtox). It is a model that can calculate CFs for both human toxicity and freshwater ecotoxicity which is used as a life cycle midpoint indicator in the ILCD impact assessment method (European Commission, 2011; Rosenbaum et al., 2008). The CFs for the toxicological impacts, specifically for human toxicity, are calculated based on the three factors: environmental fate FF in a day, exposure XF per day, and effects EF in cases/kg$_{\text{intake}}$, see Equation 4.2.

$$CF = EF \times XF \times FF \tag{4.2}$$

Two spatial scales are used in USEtox, the continental and the global, both consist of multiple environmental compartments: rural air, agricultural soil, industrial soil, freshwater, and coastal marine water, while the continental scale also includes urban air (Rosenbaum et al., 2008). The fate model accounts for the mass increase (kg) in a given medium due to emissions (kg/day). The human exposure model is based on the increased concentration in different media leading to increased amounts of a compound in the human population. The human effect factors connect the potential risk of adverse effects caused by a chemical, to the quantity ingested and/or inhaled through different exposure routes. The effect factors are based on toxicity data for cancer and non-cancer effects, and measured in disease cases per kilogram intake (Rosenbaum et al., 2008).

Furthermore, the CF for human toxicity is measured in comparative toxic units (CTU$_{\text{h}}$), which is an estimate of increased morbidity in the total human population per unit of mass of a chemical emitted (Rosenbaum et al., 2008). Cancerous and non-cancerous effects are given the same weight.

4.3.6 Responsible sourcing and social aspects

As the contents of the keywords discussed during the OST workshop for responsible sourcing are broad and diverse, a similar approach to responsible and sustainable sourcing as Mancini et al. (2020) was chosen for a qualitative assessment of this indicator. Here, responsible sourcing is rooted in the risk categories as presented in *OECD Due Diligence Guidiance for Responsible Business Conduct* (2018), mainly focusing on human rights abuses, corruption, money laundering, tax evasion, and other risks related to mineral supply. This assessment further uses the Mancini et al. (2020) approach to sustainable sourcing, meaning that both environmental and social dimensions are considered, mainly focused on social sustainability. For this indicator, the following topics will be used to complete the assessment:

- Risk of child labour and forced labour
- Local social and environmental impacts
- Corruption
- Indigenous people's rights

Co, Li, and Ni are materials that are often seen in sustainability assessments of batteries, and are looked deeper into. However, there are many more materials used in the batteries in question, as listed below:

- Aluminium (Bauxite)
- Copper
- Hard carbon
- Iron
- Magnesium (Magnesite)
- Manganese
- Natural graphite
- Phosphate
- Sodium carbonate
- Titanium

To identify any major violations related to responsible sourcing and social impacts for the remaining materials, the material in question are used along with the following search terms: *child labour*, *conflict mineral*, *responsible sourcing*, *corruption*, and *indigenous people's rights*.

5

Results and discussion

In this section, the result of the different indicators are laid forward, along with their quantification, ranking, and discussion. then, the MCDA is presented and discussed, including a summary of the ranking and weighting of the indicators.

5.1 Raw material availability

In this section, the results from the assessment of raw material availability with the two quantification methods Diversity of supply and Crustal scarcity indicator are presented.

5.1.1 Diversity of supply (short-term raw material availability)

For this indicator, the largest producing country of cathode and anode materials in 2020 was calculated based on the share of annual world production, with a cut-off criteria at 5% of the total world production in 2020. Most data were collected from the British Geological Survey (BGS) report *World Mineral Production 2016-2020*. However, exceptions were for natural sodium carbonate and synthetic graphite, as seen in Table 5.1. For synthetic graphite, which is mostly synthesised from petroleum needle coke (Surovtseva et al., 2022), exports of the material were used as a proxy for production. Most data from BGS were used as presented. However, the lithium minerals were modified with supplementary data from the BGS, as the world total was presented in Li content while the country-specific data was presented as mineral mined. The presented data for titanium only considers the minerals ilmenite and rutile, which are the two most important titanium minerals

Table 5.1: References for extraction and export rates per material.

Material	Reference
Cobalt	Idoine et al. (2022)
Copper	Idoine et al. (2022)
Graphite (natural)	Idoine et al. (2022)
Graphite (synthetic)	Observatory of Economic Complexity (n.d.)
Iron ore	Idoine et al. (2022)
Lithium minerals	Idoine et al. (2022)
Manganese ore	Idoine et al. (2022)

Continued on next page

Material	**Reference**
Natural sodium carbonate	Bolen (2022)
Nickel	Idoine et al. (2022)
Phosphate rock	Idoine et al. (2022)
Bauxite	Idoine et al. (2022)
Magnesite	Idoine et al. (2022)
Titanium minerals	Idoine et al. (2022)

The origin of materials for anodes, cathodes, cell casing, and collectors are limited to 27 countries, when the cut-off is 5% of world production, which is presented in Figure 5.1.

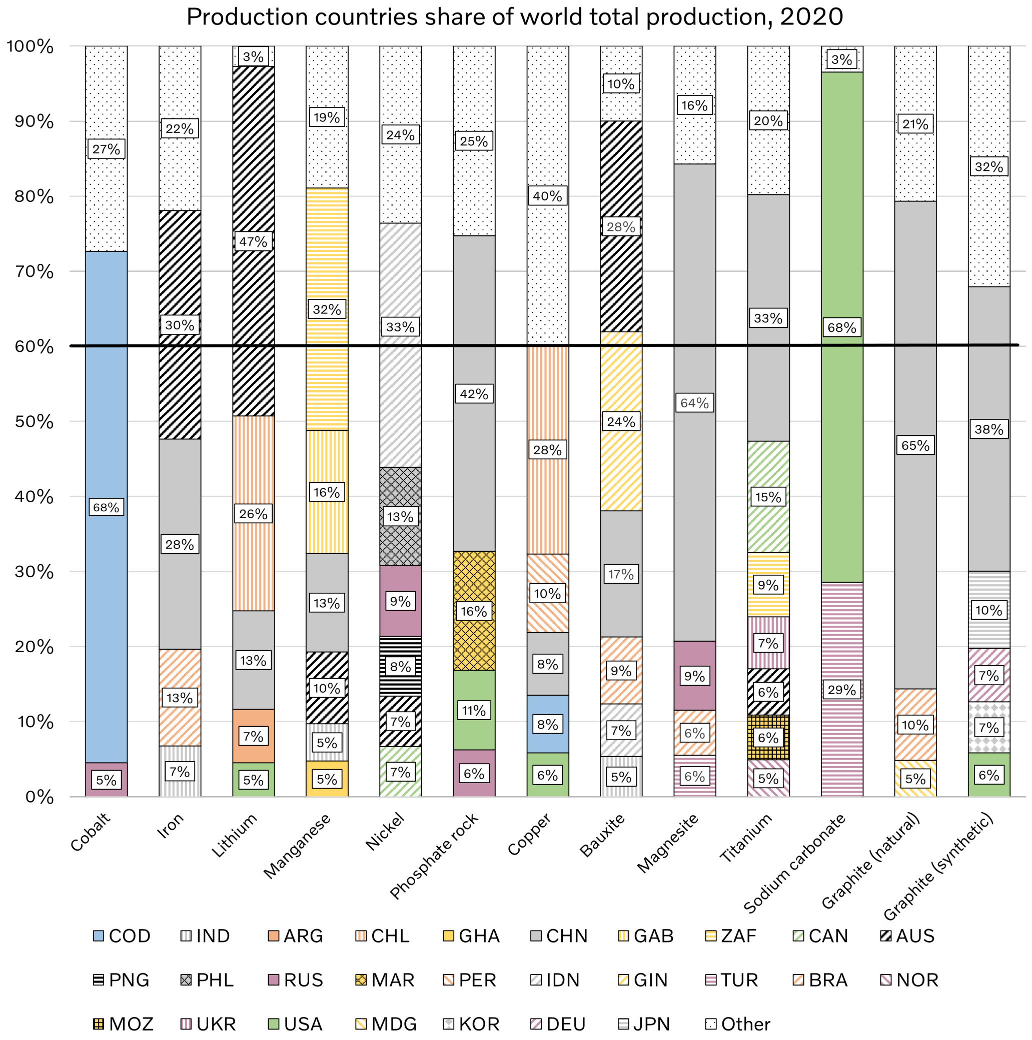


Figure 5.1: Countries that produce battery critical materials and their share of world production. The cut-off for being counted as an individual producing region is 5%. The second cut-off is identified based on Cu, and marked with a line at 60%.

As can be seen in Figure 5.1, only 60% of the total world supply of Cu is covered by the countries that produce 5% or more of world production. Therefore, the second cut-off for the number of supplying countries of each material is set to 60%. The number of producing countries for each material within the limit of 60% is presented in Figure 5.2. Consequently, NMC, NaNMMT, and NaNMC with only two countries supplying Co or Na rank 2, while LFP, where all materials are supplied by at least three countries, get rank 1 as the most diverse chemistry, see Table 5.2.

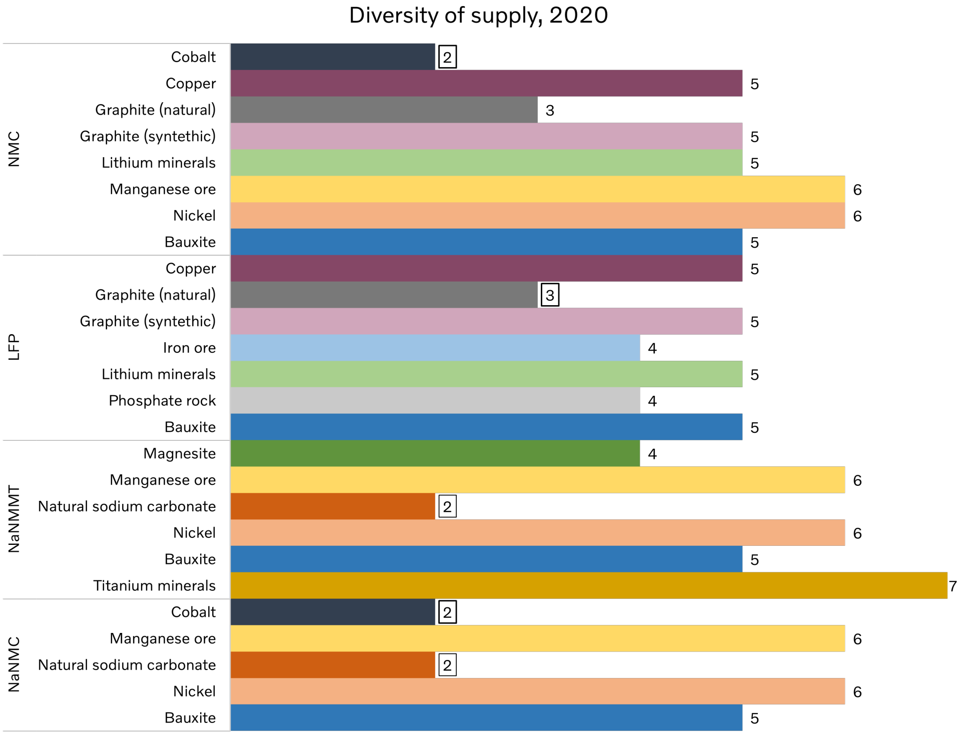


Figure 5.2: The number of countries producing 60% technology critical materials use for batteries. The cut-off for being counted as an individual producing region is 5%, presented is the highest numbers of countries that can achieve 60%. The limiting material(s) in each chemistry is marked with a black box.

Table 5.2: Quantification of diversity of supply and resulting rank.

Cell chemistry	Limiting number of countries	Rank
LFP-Gr	3	1
NMC811-Gr	2	2
NaNMMT-HC	2	2
NaNMC-HC	2	2

One uncertainty in this assessment is that the batteries in question are sometimes produced using other precursors than those presented, e.g., other mineral forms for metals. As much of the data presented by BGS have been modified to present metal content rather than the mineral form, the percentages may not always be entirely representative.

A measure that could have been used to achieve a similar overview of the current diversity of supply is estimated reserve sizes. However, both reserve size and production as proxy for diversity of supply have a major uncertainty as not all material processing occurs in the same countries that have the reserves or extract the raw materials. Hence, bottlenecks could in fact be in the regions that process the raw materials to produce the battery-relevant precursors, no matter where the reserves and current production are. This is a limitation of this indicator and can be addressed by gathering supply chain-specific data for various battery materials.

One clear example of how the diversity of supply not only depends on the country of origin is China's dominance in the processing of the required minerals, as seen in Figure 5.3 (International Energy Agency, 2021). The impacts on the ranking caused by inclusion of processing and remaining steps until a final cell, are difficult to estimate, but it would most likely lower the diversity for all chemistries, thus potentially giving all of them the same rank.

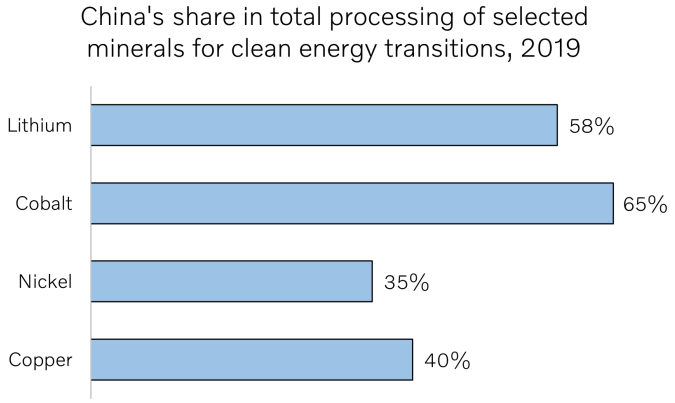


Figure 5.3: China's share in processing in minerals critical for a clean energy transition. From International Energy Agency (2019), CC BY 4.0.

Another uncertainty of this assessment is the use of production by countries as a proxy for diversity. As suggested by Brown (2018), studies that claim to assess 'supply risk' or 'risk of supply disruption' commonly includes 'supply concentration' based on the assumption that if supply is limited to a few countries there is a risk. However, the situation is more complex in reality, where companies, countries, and external factors creates a complicated situation. One major risk with supply concentration is the potential price volatility due to competition for materials and concern for supply (Brown, 2018). Brown (2018) further argues that it is not the production concentration that is the issue when assessing the criticality of a mineral, but rather the geopolitic situation.

This assessment gives an indication on acute access to the material required for each of the studied chemistries. If one of the countries for some reason are unable to produce the required material, the production of the batteries chemistries will be hard. Currently, the Russian invasion of Ukraine affects world trade, but also other factors such as disasters, industrial accidents, and strikes are potential threats to the supply of materials.

HC is an exception in this assessment as there are only 17 manufacturers of the material worldwide, out of which at least six are only pilot scale, and all commercial HC is produced in China (Liu et al., 2022). As this technology is currently emerging, this material is excluded from the assessment.

One shortcoming of this indicator is that it does not include the actual amounts used for each chemistry, but only considers whether it contains a certain material or not. A smaller mass used means less dependence on one country compared to a chemistry that uses more of the same material.

5.1.2 Crustal scarcity indicator (long-term raw material availability)

The CSI for LFP-Gr and NMC811-Gr was based on the inventory data from Porzio and Scown (2021), while Peters et al. (2021) was used for NaNMMT-HC and NaNMC-HC. To find the CSI, the total content of the different metals used in the battery chemistries assessed were calculated per kWh of storage capacity and multiplied by their respective CSP values obtained from Arvidsson et al. (2020a). The results of this CSI assessment are shown in Table 5.3.

Table 5.3: Quantification of CSI and resulting rank.

Cell chemistry	CSI [kg Si eq./kWh]	Rank
NaNMMT-HC	2077	1
LFP-Gr	6488	2
NMC811-Gr	7781	3
NaNMC-HC	8398	4

The highest CSPs are Li, Co, and Cu ($\geq$ 10’000 kg Si eq./kg). Ni is also high at 4800 kg Si eq./kg, meaning that the drivers for this indicator are these three, or potentially four materials.

A limitation of the CSI calculations is that only the AAM, CAM, current collectors, cell terminals, and cell casing were considered. It is also worth noting that the cathode NaNMC is of the NMC configuration 1:1:1, and as the CSP for Co is one of the highest, even lack of Cu in the collectors and the low CSP of Na (12 kg Si eq./kg) compared to Li, do not compensate for the impacts caused by the the high levels of Co.

One major difference between the SIBs and LIBs is that 91% and 98% of the contributions to this indicator comes from the CAM for NaNMMT-HC and NaNMC-HC, respectively, while the corresponding numbers for NMC811-Gr and LFP-Gr are 65% and 23%. For NMC811-Gr and LFP-Gr, other cell parts play a larger roll with contributions at 34% and 75%, where the main contributor is the Cu in the collectors. This means that, according with this indicator, it is preferable to substitute Ni and Co SIBs for more abundant materials.

One uncertainty in this assessment is the mass compositions of the cells as they are either modelled (for NMC811-Gr and LFP-Gr) or based on the only available data (for NaNMMT-HC and NaNMC-HC). A more complete analysis would include ranges of each material.

As discussed by Arvidsson et al. (2020b), the CSI is a midpoint indicator for long-term global scarcity, and does thus not cover all aspects related to the use of mineral resources. This means that CSI should be combined with other methods for assessment of resources use to gain a more complete picture. Arvidsson et al. (2020b) also point out the lack of consideration of the form of the element in the CSI. While equally abundant on an element basis, different forms of elements might be differently desirable in the short term - compare, e.g., diamond and graphite. The CSI also neglects that some materials could be extracted from other sources than the crust. One relevant example is Na, as NaCl from the ocean might be an important future raw material, another is the use of biomass as HC precursor (Liu et al., 2022; Nurohmah et al., 2022).

5.2 Longevity of cell

In Table 5.4, a range of estimated cycle life for four different battery cell chemistries are presented, along with their ranking. Values for cycle life for NMC811-Gr and LFP-Gr with 100% depth of discharge were collected from Mitchel and Waters (2017): >2000 for NMC811-Gr and >3000 for LFP-Gr. From Peters et al. (2021), cycle life values for LFP-Gr (7000), NaNMMT-HC (4000) and NaNMC-HC (4000) were collected. Warner (2019) estimated a cycle life of 3000-4000 for NMC811-Gr and 5000-6000 for LFP-Gr. Finally, Yoshio et al. (2009) estimated a cycle life of 2000-3000 for NMC811-Gr and 5000-10000 for LFP-Gr.

Table 5.4: Quantification of longevity of cell and the resulting rank. From Mitchel and Waters (2017), Peters et al. (2021), Warner (2015), and Yoshio et al. (2009)

Cell chemistry	Cycle life	Rank
LFP-Gr	3000-10000	1
NMC811-Gr	2000-4000	2
NaNMMT-HC	4000	2
NaNMC-HC	4000	2

LFP-Gr receives rank 1, due to a higher average cycle life than the other cell chemistries, according to the literature review. NMC811-Gr, NaNMMT-HC and NaNMC-HC all receive rank 2. As NMC811-Gr has a range between 2000-4000, it could have been argued that it should get a lower rank than the SIBs, which both have a value of 4000. However, as the SIB cell chemistries are novel technologies, and the data is scarce, it only consists of two data points, both from Peters et al. (2021). In that same article, there was a cycle life for NMC622-Gr listed as well, with the same cycle life as the SIB cells. As the composition of an NMC622 cathode is similar to an NMC811, it is concluded that the cycle life of NMC811-Gr would likely be approximately the same as that of the SIB cells.

As a complement to the literature review, simulations were conducted internally by Volvo Cars, where the longevity of NMC-Gr and LFP-Gr battery cell chemistries was estimated for some different customers in different climates. Based on an initial data review, it was assumed that the cycle life of the LFP-Gr battery cell was twice that of the NMC-Gr cell. The calendar life was assumed to be the same as that of the NMC-Gr cell. For an average customer, this assumption resulted in an increased simulated battery life of around 10–20% for the LFP-Gr battery compared to the NMC-Gr battery (L. Lundberg, personal communication, 2023). This is consistent with the results that the literature review and ranking showed. The modelling further showed that the way the car is used by the customer can affect the impact of the cell chemistry on the lifetime. In the most extreme case, when the battery is cycled almost continuously (e.g., a taxi customer), the simulated battery life was almost twice as long for the LFP-Gr cell compared to the NMC-Gr cell. However, the difference in lifetime shown in this work is highly dependent on the assumption that the cycle life of the LFP-Gr cell is double that of the NMC-Gr cell, as well as the assumption that the calendar life is the same for the two cells.

It is important to note that the battery life depends on several design choices, as well as the way the user is assumed to be using the car. There is also a high uncertainty regarding the cycle life of the SIB cells, as there is not as much data available yet, and the cells remain to be optimised. In order to get an improved result more data points are needed, especially for the SIB cells, but this data is often difficult to find or not publicly available. To get an as accurate result as possible for a specific battery cell, simulations based on the actual cell data (both calendar and cycling) are needed. Several different scenarios should be considered, such the use of cars in different climates and with different charging patterns.

5.3 Climate impact

Throughout published studies, values found for global warming for different battery cell chemistries vary substantially. Several review articles have aimed to summarise the results from LCAs performed on EV batteries, such as Ellingsen et al. (2017), Peters and Weil (2018), Xia and Li (2022), and Gutsch and Leker (2022). However, as pointed out by Porzio and Scown (2021), even among the review articles, there is a lack of consensus regarding the findings. There are also many different parameters in the modelling that can be the cause of variation in results, such as assumptions regarding electricity mix, supply chain and design of cell.

In this study, values for CO_2-eq./kWh for different battery cell chemistries have been collected from previously published studies. All articles chosen were published 2019 or later. The results were grouped depending on if they had a low, medium, or high carbon intense electricity mix used to model the production, in order to show the effect this has on the results. In the low-medium carbon-intense electricity mix, results using electricity mixes from countries such as Sweden and Europe have been categorised together. In the high carbon intensity electricity mix, results based on electricity from countries such as China and South Korea are found. The results from the post-2018 studies assessing the emission of CO_2-eq./kWh for batteries were summarised in Table 5.5.

Table 5.5: Quantification of climate impact and resulting rank. From Chordia et al. (2021), Ciez and Whitacre (2019), Crenna et al. (2021), Lai et al. (2022), and Peters et al. (2021).

	Climate impact [kg CO_2-eq./kWh]		
Cell chemistry	**Low-medium carbon intensity electricity mix**	**High carbon intensity electricity mix**	**Rank**
LFP-Gr	31-66	40-88	1
NaNMMT-HC	51		1
NMC811-Gr	50-99	87-120	3
NaNMC-HC	87		3

As can be seen in Table 5.5, LFP-Gr and NaNMMT-HC are both ranked highest, while NMC811-Gr and NaNMC-HC are ranked third. The reason for two chemistries getting the same ranking, is because the results are so close it is difficult to conclude that the difference is significant. Furthermore, there is only one data point for each sodium-ion chemistry, making them difficult to compare with the two other chemistries that have a range of data points.

The results for both LFP-Gr and NMC811-Gr vary considerably between studies, with the result for LFP-Gr spanning from 31 to 88 kg CO_2-eq./kWh and NMC811-Gr spanning from 50 to 120. As previously mentioned, the variation in results is most likely due to differences in modelling, such as design of cell, chosen supply change, and choice of database (Chordia et al., 2021).

One reason for why both cell chemistries containing NMC have a higher climate impact is that production of Co and Ni are linked to higher emissions than most other minerals per kg (Romare & Dahllöf, 2017; Sharma & Manthiram, 2020). One factor contributing to this is that abundant materials generally require less energy during mining and production compared to rarer ones (Sharma & Manthiram, 2020). At the same time, Co and Ni have a high energy density, so the effect per kWh is somewhat mitigated (Romare & Dahllöf, 2017). Overall, there is still uncertainty on whether LFP chemistries actually have a lower climate impact than NMC, as some reviews have shown them to be almost the same, or NMC being even slightly lower (Gutsch & Leker, 2022; Peters & Weil, 2018).

The difficulty in determining which chemistry and material has the lowest climate impact can also be observed when looking into the different possible compositions of NMC cathodes. In an article by Winjobi et al. (2022), the environmental impacts of different Ni contents in NMC-batteries were studied, following the trend of moving towards cathodes with higher Ni content and lower Mn and Co contents. The results showed that a higher Ni content was associated with lower GHG emissions, but higher SO_x emissions. Ni raw material is associated with a lower kg CO_2-eq./kg than Co - around 7.9 for Ni sulphate and around 23.3 for Co sulphate (Chordia, 2022). Furthermore, Gutsch and Leker (2022) mention that increasing the Ni content leads to a slightly higher energy density, which in turn should lead to less material being used per kWh. For example, in a study by Peters and Weil (2018), a battery with configuration NMC442 was shown to have higher GHG emissions than NMC111. However, there is uncertainty regarding whether Ni has lower climate impact in practice, as increasing the Ni content is associated with lower chemical stability, which can cause higher energy requirements in the production and in turn can lead to a higher global warming (Gutsch & Leker, 2022). It is worth mentioning that the composition between Mn and Co also matters, as Mn have a significantly lower climate impact, with around 0.75 CO_2-eq./kg per kg Mn sulphate (Chordia, 2022).

5.4 Recyclability

At the moment, large-scale EV technology is still so new that the recycling is not optimised yet, the recycling done is driven by economic incentives, where the most valuable materials to recycle are Ni and Co (Romare & Dahllöf, 2017). However, there is coming legislation, that will likely further push actors towards recycling of batteries. One such regulation is the implementation of the EU Battery Regulation in the EU, which will require new batteries to contain certain percentages of recycled material of specified materials, such as Li, Ni and Co, by early 2030's (European Commission, 2020).

In Table 5.6, the expert assessment performed by M. Petranikova (personal communication, April 21, 2023) of the technical and economic feasibility of recycling the four battery cell chemistries is presented, together with the resulting ranking. M. Petranikova was asked to give the different cell chemistries scores from 1 to 5, with 1 having low technical and economic feasibility to recycle, and 5 having high feasibility. This was translated to ranking to be used in the MCDA, from 1 to 4.

Table 5.6: Quantification of recyclability and resulting rank.

Cell chemistry	Technical and economic feasibility of recycling [1-5]	Rank
NMC811-Gr	5	1
LFP-Gr	3	2
NaNMC-HC	2	3
NaNMMT-HC	1	4

As can be seen in Table 5.6, NMC811-Gr is ranked 1. According to M. Petranikova, this is because recycling of NMC-Gr chemistries is already carried out in industry, due to high-value metals such as Ni, Co, and Li present, i.e., it is both economically and technically feasible to recycle (personal communication, April 21, 2023)

According to M. Petranikova (personal communication, April 21, 2023), LFP-Gr ranks second, as similar technical processes are employed to recover metals like the ones in the NMC-Gr chemistry. However, it contains fewer high-value metals compared to an NMC chemistry, thus the purification of the black mass in LFP-Gr is not commonly performed in industry. It is usually the Al and Cu that are recovered from the current collectors in the cells. However, it is likely that with the implementation of the EU Battery Regulation, there will be more incentive to recover other materials as well (European Commission, 2020). Li and P might also become more valuable as demands seem to be increasing (M. Petranikova, personal communication, April 21, 2023).

As both SIB cell chemistries are not technologically mature yet, M. Petranikova (personal communication, April 21, 2023) noted that they were difficult to compare to the more technologically mature ones. The NaNMC-HC is ranked as third best, since it contains the high value metals Ni and Co. However, by using Na ions instead of Li ions, the revenue would likely decrease, as Na is considerably more abundant and less valuable than Li. The NaNMMT-HC was ranked as the least feasible to recycle, partly because it lacks more valuable and critical materials, and partly because the Ti might complicate the recycling process.

As has been the case in most of the quantification methods for the indicators, there are uncertainties regarding newer chemistries, in this case the SIB cell chemistries. The difference in technology maturity makes these difficult to compare to LIB cell chemistries. Another thing that makes the future of recyclability difficult to anticipate is that it depends on which different directives will be implemented.

The expert interview with M. Petranikova was conducted as method of quantification for this interview, and despite the absence of any conflict of interest, the view of recyclability is still somewhat subjective. Other potential ways to quantify the indicator could be recycling rate, i.e., how much of a product that is recycled (Hotta et al., 2016). However, the data for recycling rate is limited, as the majority of EV batteries are not yet being recycled. It might also not give the correct picture for future recycling possibilities. Di Maio, Rem, et al. (2015) propose another measure for recyclability - the Circular Economy Index. This would capture the economic feasibility, as the index is a ratio between "material value produced by the recycler (market value) by the intrinsic material value entering the recycling facility" (Di Maio, Rem, et al., 2015). However, an assessment such as this would require more data than was available for this study.

In the future, investing in hydrometallurgy over pyrometallurgy would be recommended, as this can recover more of the materials. Overall, more investment in recycling, as well as repurposing of batteries, is needed. Lastly, it is important to mention that the rarer materials a cell chemistry contains, the more crucial is high recyclability. For example, Na is a lot more abundant in nature than Li, so even if it would be less feasible to recycle, it would also not be as crucial to do so.

5.5 Human health

Data for human toxicity potential modelled in ILCD was collected from Peters et al. (2021) for LFP-Gr, NaNMMT-HC, and NaNMC-HC. For NMC811-Gr the ReCiPe midpoint indicator for their Gigafactory model from Chordia et al. (2021) was reassessed using the ILCD midpoint impact assessment method to achieve comparability with the data from Peters et al. (2021).

As can be seen in Table 5.7, the chemistries NMC811-Gr, LFP-Gr, NaNMMT-HC, and NaNMC-HC were all given the rank 1. The reason for this is that NMC811-Gr, LFP-Gr, and NaNMC-HC all are of the same magnitude, while NaNMMT-HC is slightly lower compared to the other chemistries, this difference is deemed insignificant in the assessment as the CFs for toxicity have an uncertainty of several orders of magnitude (Rosenbaum et al., 2008).

Table 5.7: Quantification of human health and resulting rank.

Cell chemistry	**Human toxicity potential [mCTUh/kWh]**	**Rank**
NMC811-Gr	0.1424	1
LFP-Gr	0.0999	1
NaNMMT-HC	0.0295	1
NaNMC-HC	0.1159	1

One large uncertainty is relying on only one study for three values, and one reassessed data point for the fourth. The system boundaries are all cradle-to-gate, but the use of disparate LCAs with different modelling setups makes comparison between the chemistries challenging.

5.6 Responsible sourcing and social aspects

In this section social sustainability aspects is assessed using a literature review.

5.6.1 Cobalt

Co is largely dominated by production from from Democratic Republic of Congo (DRC) (Sharma & Manthiram, 2020). The DRC is seen as a high-risk country - for example it is the 15th most corrupt (Transparency International, 2023) in the world and the 6th most fragile (The Fund for Peace, 2022). Fragility measures the vulnerability of countries to conflict and stability to assess the risk of state failure (The Fund for Peace, n.d.).

In a hotspot analysis by Mancini et al. (2020), where responsible sourcing of battery raw materials is examined using a social view, Co from DRC gets the highest average risk score of all materials, scoring a 'very high risk' in indices concerning child labour, slavery, governance, and conflicts. Child labour and dangerous working conditions have been observed by several sources (Amnesty International, 2016). Moreover, there are reports of toxic pollution causing birth defects and other health issues to local communities (Sharma & Manthiram, 2020).

5.6.2 Nickel

Extraction of Ni is not as dominated by production from one country as Co. The largest producer is Indonesia (33%) followed by the Philippines (13%), Russia (9%), Papua New Guinea (8%), Australia (7%), and Canada (7%) (Idoine et al., 2022).

In the hotspot analysis by Mancini et al. (2020), Ni from the Philippines obtained the second worst score, after Co from the DRC. The production in the Philippines is especially prone to high risk of water scarcity and internal conflicts. The conflicts seem to often be concerning environmental degradation, land competition and use of ancestral lands (Holden et al., 2011; Mancini et al., 2020). Mining in both Indonesia and the Philippines seem to be connected to conflicts between the local communities and mining companies (Agence France-Presse, 2023; Hudayana et al., 2020; Mancini et al., 2020).

Both Australia and Canada have a much lower overall risk scores within governance, conflicts, and human and social rights, than Indonesia and the Philippines (Mancini et al., 2020). However, as Sharma and Manthiram (2020) mention in their study, even when a more low-risk mining of Ni is employed, it can still cause emissions that lead to pollution of the local environment, and can for example cause respiratory problems for near-by inhabitants.

5.6.3 Lithium

Li is mainly extracted in two different forms - ore-based or brine-based (Kelly et al., 2021). Ore-based Li is extracted by hard-rock mining. When extracting Li from brine, the solution is pumped up from under salt flats into large pools, where it evaporates for about 12-24 months before the solution can be further processed (Dorn & Huber, 2020). The majority of Li from Australia are in the form of minerals - mainly spodumene (Bae & Kim, 2021). The majority of Li in brine comes from the so called South American lithium triangle in the Atacama Desert between Argentina, Bolivia and Chile (Bae & Kim, 2021).

Extracting Li from brines is usually less energy-intensive than extracting from ores, even though the ores usually have a higher concentration of Li (Dorn & Huber, 2020). This can make it environmentally beneficial to extract Li from brines in South America over the extraction of spodumene ore in Australia, depending on which energy source is used in the extraction. However, extraction from brine is not without issues, as it consumes much water (Harper et al., 2019). There are indications that freshwater seeps into reservoirs from which the brine is extracted, which could lead to water scarcity for the local community (Chordia et al., 2022). It would also imply reduced Li concentrations in the brines, whereby more brine needs to be extracted to get the same amount of Li (Chordia et al., 2022).

Because of the high water consumption of brine extraction, there are several conflicts related to water access and control in these areas (Church & Crawford, 2018). There have also been conflicts over mining companies alleged intrusion of land that is protected and/or belongs to indigenous populations (Church & Crawford, 2018). Productions in Australia has been shown to have a lower risk regarding social issues, compared to production in South America (Mancini et al., 2020). However, this is a trade off with other indicators, as brine extraction has been shown to have environmental advantages (Thies et al., 2019).

5.6.4 Other materials

As a reminder, the remaining materials of relevance in this assessment are: aluminium (bauxite), copper, hard carbon, iron, magnesium (Magnesite), manganese, natural graphite, phosphate, sodium carbonate, and titanium.

There are often issues related to responsible sourcing and social impacts in mineral extraction and treatment, some examples of this are given below. However, none of the remaining materials assessed have issues of seemingly the same magnitude as of Co, Ni, and Li, therefore they will be excluded from further assessment. It is worth noting that this is a brief assessment, and as there are reports on impacts in socio-environmental sustainability aspects, there is a need for further research on the topic.

Aluminium (Bauxite)

Agusdinata and Liu (2023) found reports on halted bauxite mines in Jamaica due to protest by indigenous people's descendants related to fresh drinking water availability, impacts on rainforest and on endemic species. In the same areas there are also issues with dust, chemical spills in rivers and other water sources, affecting those living close to the Chinese-built aluminium refineries.

Iron

One example of violations of indigenous people's rights in iron mining is Sweden, which provides 90% of EU's domestic iron production (Lawrence & Kløcker Larsen, 2017). The material is extracted in Sami traditional territories, yet the Sami people have very little influence in the process (Lawrence & Kløcker Larsen, 2017).

Manganese

Concerning examples of violations of indigenous people's rights was also identified in manganese ore mining. There are examples of breaches of Australia's *Norther Territory*

Aboriginal Sacred Sites Act 1989, where mine operators were fined for having mined manganese at a sacred site (Lewis & Scambary, 2016).

Copper

Issues related to large water use in Cu mining was identified. In the Antofagasta region in Chile, Cu mining accounts for 64.1% of total water use (Gilsbach et al., 2019). In USA, multiple issues related to Cu mining have been identified e.g. concerns over cultural heritage of indigenous people, corruption, and environmental impacts (Agusdinata & Liu, 2023).

Graphite, magnesium, phosphate, titanium, sodium, and HC

No reports or articles about violations in graphite, magnesium, phosphate, titanium, or natural sodium carbonate extraction were identified. As previously discussed, HC is an exception in this assessment as there are only 17, mainly non-commercialised, manufacturers of the material worldwide, and is therefore not included in this criterion.

Fragility and corruption

Lastly, most titanium, manganese, aluminium minerals, copper, graphite, and iron reserves are located in fragile or corrupt states, see Table 5.8 (Church & Crawford, 2018). This means that there could be concerns regarding responsible sourcing and social impacts.

Table 5.8: Mineral reserves in states with fragile and corrupt states. Adapted from Church and Crawford (2018).

	Fragility		**Corruption**	
Mineral	**Located in very fragile states**	**Located in fragile or very fragile states**	**Located in states perceived as very corrupt**	**Located in states perceived as corrupt or very corrupt**
Bauxite & Alumina	28%	44%	0%	68%
Copper	4%	41%	4%	41%
Graphite	1%	73%	7%	100%
Iron	0%	42%	0%	60%
Manganese	0%	66%	0%	86%
Titanium	12%	57%	6%	62%

5.6.5 Ranking and discussion

As concluded above, the materials with largest well documented impact in relation to responsible sourcing and social impacts are Co, Ni, and Li. If a cell contains any of those, there is a risk that that the materials have been produced under irresponsible conditions, either to individuals, environment, or vulnerable groups. Therefore, the ranking of battery cell chemistries is performed based on the presence of either of these metals in its chemistry.As both LFP and NaNMMT only contains one of the metals of concern, they were both given rank 1. The NaNMC cathode contains both Co and Ni and was therefore given rank 3, while NMC-811, which additionally also contains Li, was given rank 4. The summarised results and the associated ranking of the cell chemistries is presented in Table 5.9.

Table 5.9: Resulting ranking of responsible sourcing and social impacts.

	Material content			
Cell chemistry	**Cobalt**	**Lithium**	**Nickel**	**Rank**
LFP-Gr		×		1
NaNMMT-Gr			×	1
NaNMC-Gr	×		×	3
NMC811-Gr	×	×	×	4

One shortcoming of the ranking of this indicator is that it disregards the actual amount of the concerning material used in each cell chemistry. One clear example is that the NMC811-Gr contains 0.074 kg Co/kWh, while the Ni, Mn, and Co in the NaNMC-HC is a 1:1:1 configuration and contains 0.507 kg Co/kWh, but any content is still considered equally problematic here.

5.7 Multi-criteria decision analysis

First, Table 5.10 provides an an overview of the ranking of all cell chemistries, for all indicators.

Table 5.10: Overview of all resulting ranks.

Indicator	**Quantification method**	**NMC811 Gr**	**LFP Gr**	**NaNMMT HC**	**NaNMC HC**
Raw material availability	Diversity of supply	2	1	2	2
Raw material availability	Crustal scarcity indicator	3	2	1	4
Longevity of cell	Cycle life	2	1	2	2
Climate impact	Global warming potential	3	1	1	3

Continued on next page

Indicator	Quantification method	NMC811 Gr	LFP Gr	NaNMMT HC	NaNMC HC
Recyclability	Recyclability	1	2	4	3
Human health	Human toxicity potential	1	1	1	1
Responsible sourcing and social aspects	Ni, Co, Li content	4	1	1	3

In Table 5.11, the weighting of the indicators, collected via survey sent out to experts invited to the OST workshop, is presented. The importance of the indicators was expressed by the respondents by assigning a percentage to each indicator, which in total had to add up to 100%. In total, 21 responses were collected, where 11 had an 'industry' perspective, 6 had an 'academic' perspective, 3 had a 'consultancy' perspective and 1 had a 'media and communications' perspective. In Table 5.11, the first column shows the aggregated weighting results from all respondents, the second shows the industry perspective and the last shows the academia perspective.

Table 5.11: Weighting of indicators with regards to perspectives.

Sustainability indicator	Perspective		
	All (21 respondents)	**Industry (11 respondents)**	**Academia (6 respondents)**
Raw material availability	16%	12%	24%
Longevity of cell	13%	12%	16%
Climate impact	19%	20%	15%
Recyclability	22%	26%	14%
Human health	15%	15%	15%
Responsible sourcing and social aspects	16%	15%	16%

Note: Due to rounding not all percentages add up exactly to 100%.

Certain differences can be seen between the two perspectives presented. The most notable difference was that respondents with an academic background valued raw material availability higher than industry respondents, while industry respondents valued recyclability higher. It is important to note that the number of respondents in the weighting is too small to be representative of the industry and academia at large.

In Table 5.12, the ranking and weighting of the indicators is combined into the final MCDA. In the MCDA, the weighting from all respondents is taken into account. As can be seen, LFP-Gr obtains the lowest overall result, meaning it is the preferable alternative according to the sustainability assessment in this study. NaNMMT-HC is second best, NMC811-Gr third, and finally NaNMC-HC fourth. As the LIBs and SIBs have been assessed using the same scale, even though the technology maturity for them are on different levels, the results should be seen as preliminary estimations and should therefore be interpreted with caution. For example, when the SIB technology becomes mature, the longevity of cells and recyclability might increase. Similarly, supply routes for existing cell chemistries are there because of demand, and the diversity of supply mirrors this. For example, if NaNMMT-HC were to be commercialised, this might drive more supply routes for Mg to open up, which would improve the cell chemistry's rank regarding diversity of supply.

Table 5.12: The MCDA of the indicators, including ranking and weighting.

	Perspective		
Cell chemistry	**All**	**Industry**	**Academia**
LFP-Gr	1.30	1.32	1.26
NaNMMT-HC	1.85	1.96	1.70
NMC811-Gr	2.22	2.15	2.30
NaNMC-HC	2.57	2.58	2.54

6

Conclusion

This study set out to assess the sustainability of current and upcoming battery cell chemistries for EVs, specifically NMC811-Gr, LFP-Gr, NaNMMT-HC, and NaNMMT-HC. This topic was explored in the study by using a mixed-methods approach, comprised of an indicator generating OST workshop, different quantification methods and an MCDA. The identified key indicators for the sustainability assessment of the cell batteries are: 'responsible sourcing including social aspects', 'human health', 'raw material availability', 'longevity of cell', 'climate impact', and 'recyclability'.

According to the resulting MCDA, the LFP-Gr is the most sustainable cell chemistry out of the four assessed, based on the indicators and quantification methods used in the study, followed by NaNMMT-HC, NMC811-Gr and NaNMC-HC. A possible explanation of LFP-Gr being ranked better could be because it does not contain the minerals Co and Ni. These minerals contributed to a low rank in indicators such as 'raw material availability' and 'responsible sourcing and social aspects'. However, it is important to exercise caution when interpreting these results due to several limiting factors, especially in the data collection, that can influence their reliability. The results are also partly specific to the set of participants at the OST workshop, and might not be generalisable.

One key takeaway from this study is that what is deemed important to consider in sustainability assessment is not necessarily what is measured. As an example, the indicators voted most important during the discussions in the OST workshop were 'responsible sourcing including traceability' and 'geopolitics/control of the value chain' (later combined into the indicators 'Responsible sourcing and social aspects' and 'Human health'). These are broad topics, which are difficult to quantify and analyse. Nevertheless, this does not mean they should not be pursued. Often, sustainability assessments opt for LCAs (European Commission et al., 2022), as it is a well-known assessment method, but it only covers certain sustainability issues. In this study, several types of assessments and indicators are instead combined in order to get a more comprehensive picture, also including indicators rarely considered in LCA. By doing this, and combining LCA and MCDA, more aspects of sustainability are covered in the assessment.

In the assessment, it became clear that the difference in technology maturity made it difficult to compare the more established LIB cell chemistries with less mature SIB cell chemistries. This was partly due to lack of data for the SIBs, but also because the less mature chemistries have not had as much investment and time to be developed yet.

The authors recommend to study more of both mature and novel cell chemistries, using more methods than only LCAs, to capture multiple perspectives and aspects of sustainability. It is also recommended to, in future MCDAs for battery selection, have a larger sample of stakeholders to weight the assessed indicators, in order to identify more representative perspectives.

To summarise, with the many technical solutions and supply routes to choose from in EV battery development, it is important to emphasise the complexity of sustainability assessments on the topic. The inclusion of multiple aspects and perspectives, going beyond LCA results, helps shining light upon this complexity. A shift towards more sustainable battery cell chemistries goes further than material selection, as each phase, from cradle-to-grave, has its own set of challenges for all three pillars of sustainability.

References

Agence France-Presse. (2023). Indonesian farmers fight for their land in nickel mining boom. https://www.france24.com/en/live-news/20230313-indonesian-farmers-fight-for-their-land-in-nickel-mining-boom

Agusdinata, D. B., & Liu, W. (2023). Global sustainability of electric vehicles minerals: A critical review of news media. *The Extractive Industries and Society*, *13*. https://doi.org/10.1016/j.exis.2023.101231

Amici, J., Asinari, P., Ayerbe, E., Barboux, P., Bayle-Guillemaud, P., Behm, R. J., Berecibar, M., Berg, E., Bhowmik, A., Bodoardo, S., Castelli, I. E., Cekic-Laskovic, I., Christensen, R., Clark, S., Diehm, R., Dominko, R., Fichtner, M., Franco, A. A., Grimaud, A., & Guillet, N. (2022). A roadmap for transforming research to invent the batteries of the future designed within the european large scale research initiative battery 2030+. *Advanced Energy Materials*, *12*(17), 1–42. https://doi.org/10.1088/2515-7655/acaa57

Amnesty International. (2016). *"This is what we die for": Human rights abuses in the Democratic Republic of the Congo power the global trade in cobalt*. https://www.amnesty.org/en/documents/afr62/3183/2016/en/

Armand, M., Axmann, P., Bresser, D., Copley, M., Edström, K., Ekberg, C., Guyomard, D., Lestriez, B., Novák, P., Petranikova, M., Porcher, W., Trabesinger, S., Wohlfahrt-Mehrens, M., & Zhang, H. (2020). Lithium-ion batteries – Current state of the art and anticipated developments. *Journal of Power Sources*, *479*, 228708. https://doi.org/10.1016/j.jpowsour.2020.228708

Arvidsson, R., Chordia, M., Wickerts, S., & Nordelöf, A. (2020a). *Implementation of the crustal scarcity indicator into life cycle assessment software (2020:05)*. Chalmers University of Technology. https://research.chalmers.se/en/publication/519861

Arvidsson, R., Söderman, M., Sandén, B. A., Nordelöf, A., André, H., & Tillman, A. M. (2020b). A crustal scarcity indicator for long-term global elemental resource assessment in LCA. *International Journal of Life Cycle Assessment*, *25*(9), 1805–1817. https://doi.org/10.1007/s11367-020-01781-1

Azaïs, P., & Kuntz, P. (2022). Standards and Safety. In *Li-ion batteries* (pp. 317–350). EDP Sciences. https://doi.org/10.1051/978-2-7598-2567-7.C017/HTML

Bae, H., & Kim, Y. (2021). Technologies of lithium recycling from waste lithium ion batteries: a review. *Materials Advances*, *2*(10), 3234–3250. https://doi.org/10.1039/D1MA00216C

Beard, K. W. (2019). *Linden's handbook of batteries* (5th ed.). McGraw-Hill Education.

Berg, H. (2015a). The electrochemical cell. In *Batteries for electric vehicles* (pp. 7–46). Cambridge University Press. https://doi.org/10.1017/CBO9781316090978.004

Berg, H. (2015b). Lithium battery materials. In *Batteries for electric vehicles* (pp. 83–125). Cambridge University Press. https://doi.org/10.1017/CBO9781316090978.006

Blengini, G. A., Latunussa, C. E., Eynard, U., Torres de Matos, C., Wittmer, D., Georgitzikis, K., Pavel, C., Carrara, S., Mancini, L., Unguru, M., Blagoeva, D., Mathieux, F., & Pennington, D. (2020). *Study on the EU's list of Critical Raw Materials Final Report*. European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. Publications Office of the European Union. https://doi.org/10.2873/904613

Bolen, W. P. (2022). Soda Ash. In *Mineral commodity summaries 2022*. U.S. Geological Survey. https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-soda-ash.pdf

Brown, T. (2018). Measurement of mineral supply diversity and its importance in assessing risk and criticality. *Resources Policy*, *58*, 202–218. https://doi.org/10.1016/j.resourpol.2018.05.007

Campagnol, N., Erriquez, M., Schwedhelm, D., Wu, J., & Wu, t. (2021). Building better electric batteries for battery electric vehicles. *McKinsey*. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/building-better-batteries-insights-on-chemistry-and-design-from-china

Careddu, N., Dino, G. A., Danielsen, S. W., & Přikryl, R. (2018). Raw materials associated with extractive industry: An overview. *Resources Policy*, *59*, 1–6. https://doi.org/10.1016/j.resourpol.2018.09.014

Chalmers Research: Martina Petranikova. (n.d.). https://research.chalmers.se/en/person/?cid=marpetr

Chitre, A., Freake, D., Lander, L., Edge, J., Titirici, M.-M., Batteries,] & Reviews, S. (2020). Towards a More Sustainable Lithium-Ion Battery Future: Recycling LIBs from Electric Vehicles. *Batteries & Supercaps*, *3*(11), 1126–1136. https://doi.org/10.1002/BATT.202000146

Chordia, M. (2022). *Taking stock of large-scale-lithium-ion battery production using life cycle assessment* (Licentiate Thesis). Chalmers University of Technology, Göteborg, Sweden.

Chordia, M., Nordelöf, A., & Ellingsen, L. A. W. (2021). Environmental life cycle implications of upscaling lithium-ion battery production. *International Journal of Life Cycle Assessment*, *26*(10), 2024–2039. https://doi.org/10.1007/s11367-021-01976-0

Chordia, M., Wickerts, S., Nordelöf, A., & Arvidsson, R. (2022). Life cycle environmental impacts of current and future battery-grade lithium supply from brine and spodumene. *Resources, Conservation and Recycling*, *187*, 106634. https://doi.org/10.1016/J.RESCONREC.2022.106634

Church, C., & Crawford, A. (2018). *Green Conflict Minerals: The fuels of conflict in the transition to a low-carbon economy IISD REPORT*. International Institute for Sustainable Development. Winnipeg, Maintoba.

Ciez, R. E., & Whitacre, J. F. (2019). Examining different recycling processes for lithium-ion batteries. *Nature Sustainability 2019 2:2*, *2*(2), 148–156. https://doi.org/10.1038/s41893-019-0222-5

Crenna, E., Gauch, M., Widmer, R., Wäger, P., & Hischier, R. (2021). Towards more flexibility and transparency in life cycle inventories for Lithium-ion batteries. *Re-*

sources, Conservation and Recycling, *170*, 105619. https://doi.org/10.1016/j.resconrec.2021.105619

de Groot, H. L., Rademaekers, K., Smith, M., Svatikova, K., Widerberg, O., Obersteiner, M., Marcarini, A., Dumollard, G., Strosser, P., de Paoli, G., Lise, W., & Klaassens, E. (2012). *Mapping resource prices: the past and the future - Final report*. European Economic and Social Committee. Belgium. https://policycommons.net/artifacts/3347942/mapping-resource-prices/4146842/

del Mar Saavedra Rios, C., Beda, A., Simonin, L., & Matei Ghimbeu, C. (2021). Hard carbon for na-ion batteries: From synthesis to performance and storage mechanism. In *Na-ion batteries* (pp. 101–146). John Wiley & Sons, Ltd. https://doi.org/https://doi.org/10.1002/9781119818069.ch3

Delmas, C. (2018). Sodium and Sodium-Ion Batteries: 50 Years of Research. *Advanced Energy Materials*, *8*(17), 1703137. https://doi.org/10.1002/AENM.201703137

Di Maio, F., Rem, P. C., et al. (2015). A robust indicator for promoting circular economy through recycling. *Journal of Environmental Protection*, *6*(10), 1095. https://doi.org/10.4236/jep.2015.610096

Domingues, A. R., Marques, P., Garcia, R., Freire, F., & Dias, L. C. (2015). Applying Multi-Criteria Decision Analysis to the Life-Cycle Assessment of vehicles. *Journal of Cleaner Production*, *107*, 749–759. https://doi.org/10.1016/J.JCLEPRO.2015.05.086

Dorn, F. M., & Huber, C. (2020). Global production networks and natural resource extraction: Adding a political ecology perspective. *Geographica Helvetica*, *75*(2), 183–193. https://doi.org/10.5194/GH-75-183-2020

Ekvall, T., Ljungkvist, H., Sandvall, A. F., & Ahlgren, E. O. (2016). *Participatory life cycle sustainability analysis*. SETAC Europe 26th Annual Meeting, Nantes, France. IVL Swedish Environmental Research Institute. https://www.ivl.se/english/ivl/publications/publications/participatory-life-cycle-sustainability-analysis.html

Ellingsen, L. A. W., Hung, C. R., & Strømman, A. H. (2017). Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. *Transportation Research Part D: Transport and Environment*, *55*, 82–90. https://doi.org/10.1016/J.TRD.2017.06.028

European Commission. (2011). *International Reference Life Cycle Data System (ILCD) Handbook: Recommendations for Life Cycle Impact Assessment in the European context*. Publications Office of the European Union.

European Commission. (2020). Proposal for a regulation of the european parliament and of the council concerning batteries and waste batteries, repealing directive 2006/66/ec and amending regulation (eu) no 2019/1020.

European Commission, Joint Research Centre, Caldeira, C., Farcal, L., Garmendia Aguirre, I., Mancini, L., Tosches, D., Amelio, A., Rasmussen, K., Rauscher, H., Riego Sintes, J., & Sala, S. (2022). *Safe and sustainable by design chemicals and materials : Framework for the definition of criteria and evaluation procedure for chemicals and materials*. Publications Office of the European Union. https://doi.org/10.2760/487955

Fichtner, M. (2022). Recent research and progress in batteries for electric vehicles. *Batteries & Supercaps*, *5*(2), 1–9. https://doi.org/10.1002/batt.202100224

Gebhardt, M., Beck, J., Kopyto, M., & Spieske, A. (2022). Determining requirements and challenges for a sustainable and circular electric vehicle battery supply chain: A mixed-methods approach. *Sustainable Production and Consumption*, *33*, 203–217. https://doi.org/10.1016/j.spc.2022.06.024

Gilsbach, L., Schütte, P., & Franken, G. (2019). Applying water risk assessment methods in mining: Current challenges and opportunities. *Water Resources and Industry*, *22*. https://doi.org/10.1016/J.WRI.2019.100118

Gordon, R. B., Bertram, M., & Graedel, T. E. (2007). On the sustainability of metal supplies: A response to Tilton and Lagos. *Resources Policy*, *32*(1-2), 24–28. https://doi.org/10.1016/J.RESOURPOL.2007.04.002

Graedel, T., Gunn, G., & Tercero Espinoza, L. (2014). Metal Resources, Use and Criticality. In G. Gunn (Ed.), *Critical metals handbook*. American Geophysical Union.

Gutsch, M., & Leker, J. (2022). Global warming potential of lithium-ion battery energy storage systems: A review. *Journal of Energy Storage*, *52*, 105030. https://doi.org/10.1016/J.EST.2022.105030

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., & Anderson, P. (2019). Recycling lithium-ion batteries from electric vehicles. *Nature 2019 575:7781*, *575*(7781), 75–86. https://doi.org/10.1038/s41586-019-1682-5

Hedenus, F., Persson, M., & Sprei, F. (2018). *Sustainable Development - Nuances and Perspectives*. Studentlitteratur.

Holden, W., Nadeau, K., & Jacobson, R. D. (2011). Exemplifying accumulation by dispossession: Mining and indigenous peoples in the philippines. *Geografiska Annaler: Series B, Human Geography*, *93*(2), 141–161. https://doi.org/10.1111/j.1468-0467.2011.00366.x

Hotta, Y., Visvanathan, C., & Kojima, M. (2016). Recycling rate and target setting: Challenges for standardized measurement. *Journal of Material Cycles and Waste Management*, *18*, 14–21. https://doi.org/10.1007/s10163-015-0361-3

Houache, M. S. E., Yim, C.-H., Karkar, Z., & Abu-Lebdeh, Y. (2022). On the Current and Future Outlook of Battery Chemistries for Electric Vehicles-Mini Review. *Batteries*, *8*(70). https://doi.org/10.3390/batteries8070070

Hudayana, B., Suharko, & Widyanta, A. B. (2020). Communal violence as a strategy for negotiation: Community responses to nickel mining industry in Central Sulawesi, Indonesia. *The Extractive Industries and Society*, *7*(4), 1547–1556. https://doi.org/10.1016/J.EXIS.2020.08.012

Hwang, J. Y., Myung, S. T., & Sun, Y. K. (2017). Sodium-ion batteries: present and future. *Chemical Society Reviews*, *46*(12), 3529–3614. https://doi.org/10.1039/C6CS00776G

Idoine, N. E., Raycraft, E. R., Shaw, R. A., Hobbs, S. F., Deady, E. A., Everett, P., Evans, E. J., & Mills, A. J. (2022). *World Mineral Production 2016-2020*. British Geological Survey.

International Energy Agency. (2019). Share of top producing countries in total processing of selected minerals and fossil fuels, 2019. https://www.iea.org/data-and-statistics/charts/share-of-top-producing-countries-in-total-processing-of-selected-minerals-and-fossil-fuels-2019

International Energy Agency. (2021). *The Role of Critical World Energy Outlook Special Report Minerals in Clean Energy Transitions*. www.iea.org/t&c/

Julien, C. M., & Mauger, A. (2017). NCA, NCM811, and the Route to Ni-Richer Lithium-Ion Batteries. *Energies*, *13*(23). https://doi.org/10.3390/en13236363

Keil, P., Schuster, S. F., Lüders, C., Hesse, H., Arunachala, A., & Jossen, A. (2015). Lifetime analyses of lithium-ion ev batteries. *3rd Electromobility Challenging Issues conference (ECI), Singapore, 1st–4th December*.

Kelly, J. C., Wang, M., Dai, Q., & Winjobi, O. (2021). Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries. *Resources, Conservation and Recycling*, *174*. https://doi.org/10.1016/J.RESCONREC.2021.105762

Lai, X., Chen, Q., Tang, X., Zhou, Y., Gao, F., Guo, Y., Bhagat, R., & Zheng, Y. (2022). Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: A lifespan perspective. *eTransportation*, *12*, 100169. https://doi.org/10.1016/J.ETRAN.2022.100169

Lawrence, R., & Kløcker Larsen, R. (2017). Third World Quarterly The politics of planning: assessing the impacts of mining on Sami lands The politics of planning: assessing the impacts of mining on Sami lands. *Third World QuarTerly*, *38*(5), 1164–1180. https://doi.org/10.1080/01436597.2016.1257909

Lewis, G., & Scambary, B. (2016). Sacred bodies and ore bodies: conflicting commodification of landscape by Indigenous peoples and miners in Australia's Northern Territory. In P. F. Mcgrath (Ed.), *The right to protected sites: Indigenous heritage management in the era of native title*. AIATSIS Research Publications.

Life Cycle Initiative. (2022). *Life Cycle Initiative Progress Report 2022*. https://www.lifecycleinitiative.org/library/life-cycle-initiative-progress-report-2022/

Linkov, I., & Moberg, E. (2012). *Multi-Criteria Decision Analysis: Environmental Applications and Case Studies* (D. G. W. Suter II, Ed.). CRC Press.

Linkov, I., Moberg, E., Trump, B. D., Yatsalo, B., & Keisler, J. M. (2021). *Multi-Criteria Decision Analysis; Case Studies in Engineering and the Environment* (D. G. W. Suter II, Ed.; 2nd ed.). CRC Press. https://www.crcpress.com/

Liu, H., Baumann, M., Dou, X., Klemens, J., Schneider, L., Wurba, A. K., Häringer, M., Scharfer, P., Ehrenberg, H., Schabel, W., Fleischer, J., von der Aßen, N., & Weil, M. (2022). Tracing the technology development and trends of hard carbon anode materials - A market and patent analysis. *Journal of Energy Storage*, *56*, 105964. https://doi.org/10.1016/J.EST.2022.105964

Loganathan, M. K., Mishra, B., Tan, C. M., Kongsvik, T., & Rai, R. N. (2021). Multi-criteria decision making (MCDM) for the selection of Li-ion batteries used in electric vehicles (EVs). *Materials Today: Proceedings*, *41*(5), 1073–1077. https://doi.org/10.1016/J.MATPR.2020.07.179

Luo, Y.-H., Wei, H.-X., Tang, L.-B., Huang, Y.-D., Wang, Z.-Y., He, Z.-J., Yan, C., Mao, J., Dai, K., & Zheng, J.-C. (2022). Nickel-rich and cobalt-free layered oxide cathode materials for lithium ion batteries. *Energy Storage Materials*, *50*, 274–307. https://doi.org/10.1016/j.ensm.2022.05.019

Mancini, L., Eslava, N. A., Traverso, M., Mathieux, F., & European Commission. Joint Research Centre. (2020). *Responsible and sustainable sourcing of batteries raw* *materials : insights from hotspot analysis, corporate disclosures and field research.* Publications Office of the European Union. Luxembourg. https://doi.org/10.2760/562951

Manthiram, A. (2017). An Outlook on Lithium Ion Battery Technology. *ACS Central Science*, *3*(10), 1063–1069. https://doi.org/10.1021/acscentsci.7b00288

Meshram, P., Mishra, A., Abhilash, & Sahu, R. (2020). Environmental impact of spent lithium ion batteries and green recycling perspectives by organic acids – A review. *Chemosphere*, *242*, 125291. https://doi.org/10.1016/J.CHEMOSPHERE.2019.125291

Migiro, S. O., & Magangi, B. A. (2011). Mixed methods: A review of literature and the future of the new research paradigm. *African Journal of Business Management*, *5*(10), 3757–3764. https://doi.org/10.5897/AJBM09.082

Mitchel, P., & Waters, J. (2017). *Energy storage roadmap report*. Energy Systems Network.

Mousa, E., Hu, X., & Ye, G. (2022). Effect of Graphite on the Recovery of Valuable Metals from Spent Li-Ion Batteries in Baths of Hot Metal and Steel. *Recycling*, *7*(1), 5. https://doi.org/10.3390/RECYCLING7010005

Neumann, J., Petranikova, M., Meeus, M., Gamarra, J. D., Younesi, R., Winter, M., & Nowak, S. (2022). Recycling of Lithium-Ion Batteries—Current State of the Art, Circular Economy, and Next Generation Recycling. *Advanced Energy Materials*, *12*(17), 2102917. https://doi.org/10.1002/AENM.202102917

Nurohmah, A. R., Nisa, S. S., Stulasti, K. N. R., Yudha, C. S., Suci, W. G., Aliwarga, K., Widiyandari, H., & Purwanto, A. (2022). Sodium-ion battery from sea salt: a review. *Materials for Renewable and Sustainable Energy*, *11*(1), 71–89. https://doi.org/10.1007/S40243-022-00208-1

Observatory of Economic Complexity. (n.d.). Artificial Graphite. https://oec.world/en/profile/hs/artificial-graphite?yearSelector1=2020

Organisation for Economic Co-operation and Development. (2018). *OECD Due Diligence Guidiance for Responsible Business Conduct.*

Owen, H. (2008). *Open Space Technology: A User's Guide* (3rd ed.). Berrett-Koehler Publishers, Incorporated.

Peters, J., Buchholz, D., Passerini, S., & Weil, M. (2016). Life cycle assessment of sodium-ion batteries. *Energy & Environmental Science*, *9*(5), 1744–1751. https://doi.org/10.1039/C6EE00640J

Peters, J. F., Baumann, M., Binder, J. R., & Weil, M. (2021). On the environmental competitiveness of sodium-ion batteries under a full life cycle perspective-a cell-chemistry specific modelling approach. *Sustainable Energy Fuels*, *5*(24), 6414–6429. https://doi.org/https://doi.org/10.1039/D1SE01292D

Peters, J. F., & Weil, M. (2018). Providing a common base for life cycle assessments of Li-Ion batteries. *Journal of Cleaner Production*, *171*, 704–713. https://doi.org/10.1016/J.JCLEPRO.2017.10.016

Porzio, J., & Scown, C. D. (2021). Life-Cycle Assessment Considerations for Batteries and Battery Materials. *Advanced Energy Materials*, *11*(33). https://doi.org/10.1002/AENM.202100771

Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*, *14*(2), 681–695. https://doi.org/10.1007/s11625-018-0627-5

Romare, M., & Dahllöf, L. (2017). *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries A Study with Focus on Current Technology and Batteries for light-duty vehicles*. IVL Swedish Environmental Research Institute.

Rosenbaum, R. K., Bachmann, T. M., Gold, L. S., Huijbregts, M. A., Jolliet, O., Juraske, R., Koehler, A., Larsen, H. F., MacLeod, M., Margni, M., McKone, T. E., Payet, J., Schuhmacher, M., Van De Meent, D., & Hauschild, M. Z. (2008). USEtox - The UNEP-SETAC toxicity model: Recommended characterisation factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment. *International Journal of Life Cycle Assessment*, *13*(7), 532–546. https://doi.org/10.1007/s11367-008-0038-4

Rudola, A., Rennie, A. J., Heap, R., Meysami, S. S., Lowbridge, A., Mazzali, F., Sayers, R., Wright, C. J., & Barker, J. (2021). Commercialisation of high energy density sodium-ion batteries: Faradion's journey and outlook. *Journal of Materials Chemistry A*, *9*(13), 8279–8302. https://doi.org/10.1039/D1TA00376C

Schumm, B. (2023). Battery. https://www.britannica.com/technology/battery-electronics

Sharma, S. S., & Manthiram, A. (2020). Towards more environmentally and socially responsible batteries. *Energy & Environmental Science*, *13*(11), 4087–4097. https://doi.org/10.1039/D0EE02511A

Sovacool, B. K. (2019). The precarious political economy of cobalt: Balancing prosperity, poverty, and brutality in artisanal and industrial mining in the Democratic Republic of the Congo. *Extractive Industries and Society*, *6*(3), 915–939. https://doi.org/10.1016/J.EXIS.2019.05.018

Stoycheva, S., Marchese, D., Paul, C., Padoan, S., Juhmani, A. s., & Linkov, I. (2018). Multi-criteria decision analysis framework for sustainable manufacturing in automotive industry. *Journal of Cleaner Production*, *187*, 257–272. https://doi.org/10.1016/j.jclepro.2018.03.133

Surovtseva, D., Crossin, E., Pell, R., & Stamford, L. (2022). Toward a life cycle inventory for graphite production. *Journal of Industrial Ecology*, *26*(3), 964–979. https://doi.org/10.1111/JIEC.13234

The Fund for Peace. (n.d.). What Does State Fragility Mean? https://fragilestatesindex.org/frequently-asked-questions/what-does-state-fragility-mean/

The Fund for Peace. (2022). *Fragile States Index 2022 – Annual Report*. https://fragilestatesindex.org/2022/07/13/fragile-states-index-2022-annual-report/

Thies, C., Kieckhäfer, K., Spengler, T. S., & Sodhi, M. S. (2019). Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries. *Procedia CIRP*, *80*, 292–297. https://doi.org/10.1016/J.PROCIR.2018.12.009

Transparency International. (2023). *Corruption Perception Index 2022*. https://www.transparency.org/en/cpi/2022

Triantaphyllou, E. (2000). *Multi-criteria Decision Making Methods: A Comparative Study* (P. M. Pardalos & D. Hearn, Eds.). Springer US. https://doi.org/10.1007/978-1-4757-3157-6

Volvo Car Group. (2023). Annual and Sustainability Report 2022.

Volvo Cars. (2021). Volvo Cars to be fully electric by 2030. https://www.media.volvocars.com/global/en-gb/media/pressreleases/277409/volvo-cars-to-be-fully-electric-by-2030

Walter, M., Kovalenko, M. V., & Kravchyk, K. V. (2020). Challenges and benefits of post-lithium-ion batteries. *New Journal of Chemistry*, *44*(5), 1677–1683. https://doi.org/10.1039/C9NJ05682C

Wang, W., Gang, Y., Hu, Z., Yan, Z., Li, W., Li, Y., Gu, Q.-F., Wang, Z., Chou, S.-L., Liu, H.-K., et al. (2020). Reversible structural evolution of sodium-rich rhombohedral prussian blue for sodium-ion batteries. *Nature Communications*, *11*(1), 1–9.

Warner, J. T. (2015). *The handbook of lithium-ion battery pack design: Chemistry, components, types and terminology*. Elsevier.

Warner, J. T. (2019). Chapter 4: Overview and comparison of different lithium-ion chemistries. In *Lithium-ion battery chemistries: A primer* (pp. 79–97). Elsevier. https://doi.org/10.1016/B978-0-12-814778-8.00004-1

Waseem, N., & Kota, S. (2017). Sustainability Definitions - An Analysis. In *Smart innovation, systems and technologies* (pp. 361–371). Springer Science; Business Media Deutschland GmbH. https://doi.org/10.1007/978-981-10-3521-0{_}31

Winjobi, O., Kelly, J. C., & Dai, Q. (2022). Life-cycle analysis, by global region, of automotive lithium-ion nickel manganese cobalt batteries of varying nickel content. *Sustainable Materials and Technologies*, *32*, e00415. https://doi.org/10.1016/J.SUSMAT.2022.E00415

Xia, X., & Li, P. (2022). A review of the life cycle assessment of electric vehicles: Considering the influence of batteries. *Science of The Total Environment*, *814*, 152870. https://doi.org/10.1016/J.SCITOTENV.2021.152870

Xiong, R., Pan, Y., Shen, W., Li, H., & Sun, F. (2020). Lithium-ion battery aging mechanisms and diagnosis method for automotive applications: Recent advances and perspectives. *Renewable and Sustainable Energy Reviews*, *131*, 110048. https://doi.org/10.1016/J.RSER.2020.110048

Yoshio, M., Brodd, R. J., & Kozawa, A. (2009). *Lithium-Ion Batteries* (M. Yoshio, R. J. Brodd, & A. Kozawa, Eds.). Springer New York. https://doi.org/10.1007/978-0-387-34445-4

Zhang, J., Zhang, L., Sun, F., & Wang, Z. (2018). An Overview on Thermal Safety Issues of Lithium-ion Batteries for Electric Vehicle Application. *IEEE Access*, *6*, 23849. https://doi.org/10.1109/ACCESS.2018.2824838

Appendix A

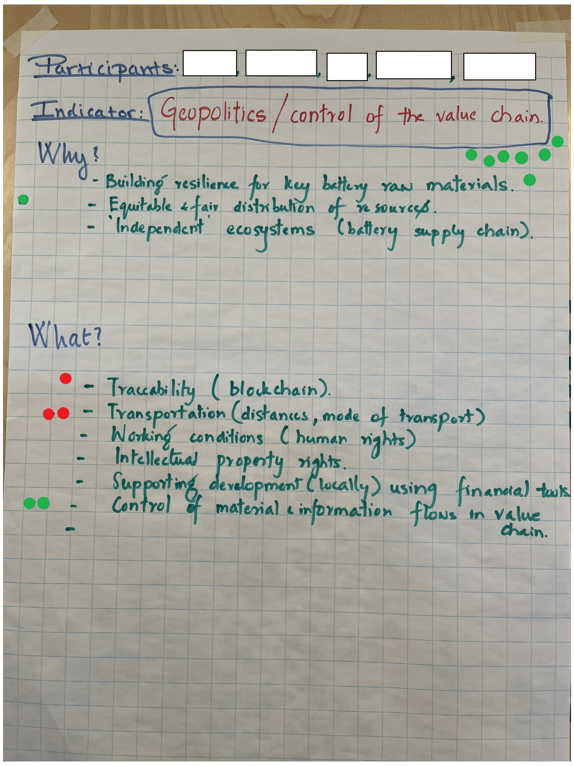
Table A.1: List of OST workshop attendees. Names have been anonymised

Attendee	**Organisation**
Academia 1	Chalmers University of Technology
Academia 2	Chalmers University of Technology
Academia 3	Chalmers University of Technology
Academia 4	Chalmers University of Technology
Industry 1	Stena Recycling
Industry 2	Volvo Cars (Battery R&D)
Industry 3	Northvolt
Industry 4	CEVT
Industry 5	Volvo Cars (Sustainability Centre)
Industry 6	Volvo Cars (Sustainability Centre)
Industry 7	Volvo Cars (Global Procurement Sustainability)
Consultancy 1	Swedish Environmental Research Institute (IVL)
Consultancy 2	Triathlon Group (Greentech)
Consultancy 3	Industry Senior Advisors (ISEA)

Appendix B

Table B.1: Summary of workshop output for Geopolitics/Control of the value chain.

Indicator: Geopolitics/Control of the value chain (7 green dots)	
Participants: Academia 3, Industry 3, Industry 5, Industry 7, Consultancy 2	
Why? (1 green dot)	**What?**
- Building resilience for key battery raw materials - Equitable and fair distribution of resource - Independent ecosystems (battery supply chain)	- Traceability (blockchain) (1 green dot) - Transportation (distances, mode of transport) (2 red dots) - Working conditions (human rights) - Intellectual property rights - Supporting development (locally) using financial tools - Control of material and information flows in value chain (2 green dots)
Total No. of green dots: 10	**Total No. of red dots:** 3



Participants: [redacted], [redacted], [redacted], [redacted], [redacted]

Indicator: Geopolitics / control of the value chain. ●●●●●●

Why? ●

- Building resilience for key battery raw materials. ●
- Equitable & fair distribution of resources.
- 'Independent' ecosystems (battery supply chain).

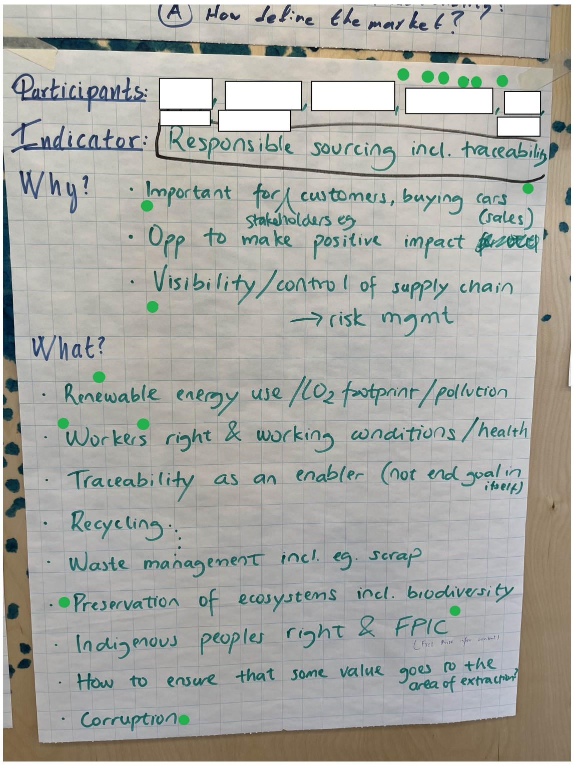
What?

- ● - Traceability (blockchain).
- ●● - Transportation (distances, mode of transport)
- Working conditions (human rights)
- Intellectual property rights.
- Supporting development (locally) using financial tools
- ●● - Control of material & information flows in value chain.
-

Figure B.1: Output from workshop: Geopolitics/Control of value chain

Table B.2: Summary of workshop output for Responsible sourcing incl. traceability.

Indicator:	Responsible sourcing incl. traceability (7 green dots)
Participants:	Academia 3, Industry 4, Industry 5, Industry 6, Industry 7, Consultancy 1, Consultancy 2, Consultancy 3
Why?	**What?**
- Important for stakeholders e.g., customers, buying cars (sales) (1 green dot) - Opportunity to make a positive impact - Visibility/Control of supply chain a risk management (1 green dot)	- Renewable energy use, CO_2 footprint, pollution (1 green dot) - Workers' rights, and working conditions and health (2 green dots) - Traceability as an enabler (not end goal) - Recycling - Waste management incl. e.g., scrap - Preservation of ecosystems including biodiversity (1 green dot) - Indigenous people's rights and FPIC (1 green dot) - How to ensure that some value goes to the area of extraction? - Corruption (1 green dot)
Total No. of green dots: 15	**Total No. of red dots:** 0



Ⓐ How define the market?

Participants: [redacted], [redacted], [redacted], [redacted], [redacted], [redacted] [redacted] [redacted]

Indicator: Responsible sourcing incl. traceability

Why?

- Important for stakeholders eg customers, buying cars (sales)
- Opp to make positive impact
- Visibility/control of supply chain → risk mgmt

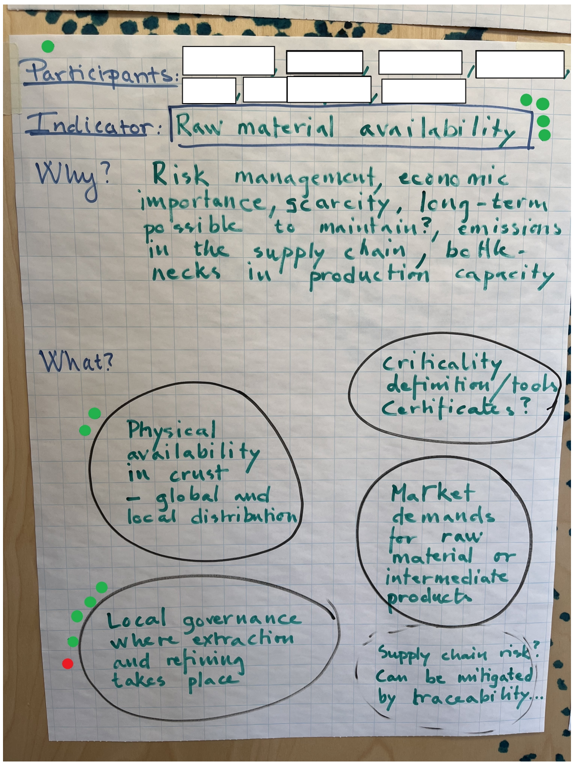
What?

- Renewable energy use/CO_2 footprint/pollution
- Workers right & working conditions/health
- Traceability as an enabler (not end goal in itself)
- Recycling
- Waste management incl. eg. scrap
- Preservation of ecosystems incl. biodiversity
- Indigenous peoples right & FPIC (Free Prior infor consent)
- How to ensure that some value goes to the area of extraction?
- Corruption

Figure B.2: Output from workshop: Responsible sourcing.

Table B.3: Summary of workshop output for Raw material availability.

Indicator: Raw material availability (4 green dots)	
Participants: Academia 1, Academia 2, Industry 1, Industry 5, Industry 6, Industry 7, Consultancy 1, Consultancy 3	
Why?	**What?**
- Risk management - Economic importance - Scarcity - Long-term possible to maintain? - Emissions in the supply chain - Bottlenecks in production capacity	- Physical availability in crust – global and local distribution (2 green dots) - Local governance where extraction and refining takes place (4 green dots, 1 red dot) - Criticality definitions/tools. Certificates? - Market demands for raw material or intermediate products - Supply chain risk? Can be mitigated by traceability. . .
Total No. of green dots: 10	**Total No. of red dots:** 1



Participants: [redacted], [redacted], [redacted], [redacted], [redacted], [redacted], [redacted], [redacted]

Indicator: Raw material availability

Why? Risk management, economic importance, scarcity, long-term possible to maintain?, emissions in the supply chain, bottle-necks in production capacity

What?

Criticality definition/tools Certificates?

Physical availability in crust – global and local distribution

Market demands for raw material or intermediate products

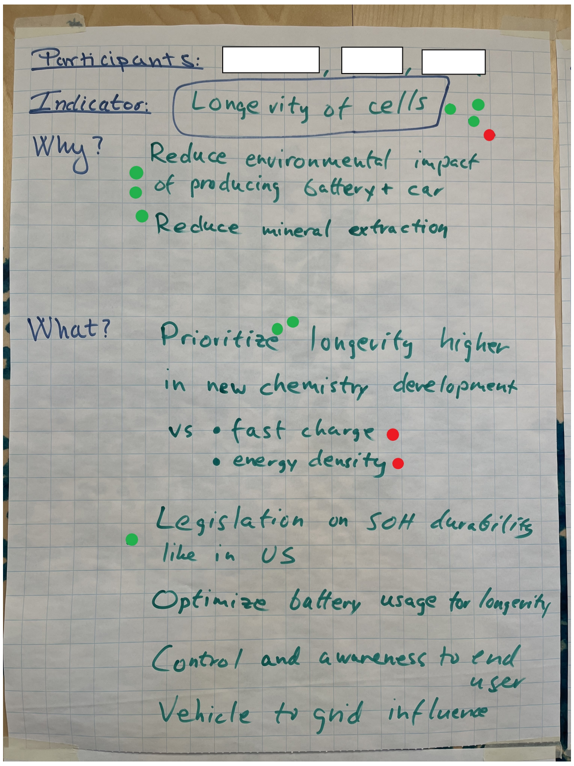
Local governance where extraction and refining takes place

Supply chain risk? Can be mitigated by traceability...

Figure B.3: Output from workshop: Raw material availability

Table B.4: Summary of workshop output for Longevity of cell.

Indicator: Longevity of cell (3 green dots, 1 red dot)	
Participants: Academia 1, Industry 2, Industry 4	
Why?	**What?**
- Reduce environmental impact of producing battery + car (2 green dots) -Reduce mineral extraction (1 green dot)	- Prioritise longevity higher in new chemistry development vs (2 green dots) - Fast charge (1 red dot) - Energy density (1 red dot) - Legislation on SOH durability like in US (1 green dot) - Optimise battery usage for longevity - Control and awareness to end user - Vehicle to grid influence
Total No. of green dots: 9	**Total No. of red dots:** 3



Participants: [redacted], [redacted], [redacted]

Indicator: Longevity of cells 🟢🟢🟢🔴

Why? 🟢🟢 Reduce environmental impact of producing battery + car

🟢 Reduce mineral extraction

What? Prioritize🟢🟢 longevity higher in new chemistry development

vs • fast charge 🔴

• energy density 🔴

🟢 Legislation on SOH durability like in US

Optimize battery usage for longevity

Control and awareness to end user

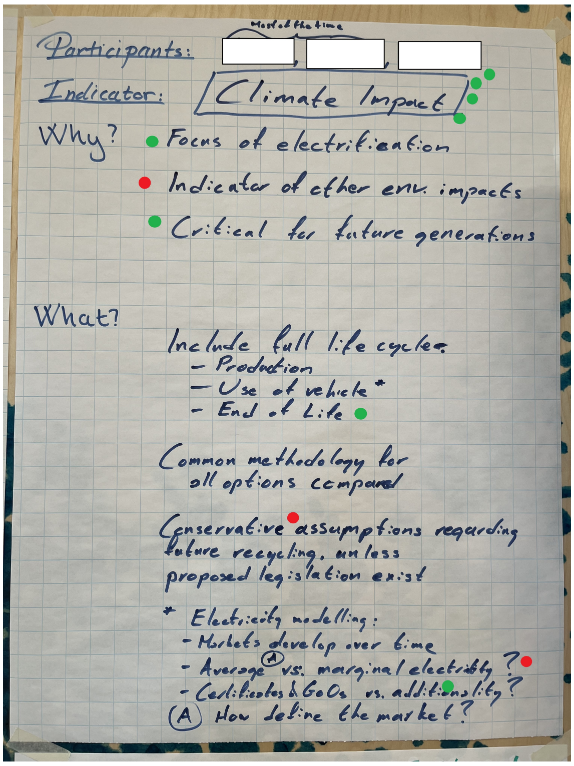
Vehicle to grid influence

Figure B.4: Output from workshop: Longevity of cell

Table B.5: Summary of workshop output for Climate impact.

Indicator: Climate impact (4 green dots)	
Participants : Academia 4, Industry 2, Industry 4	
Why?	**What?**
- Focus of electrification (1 green dot) - Indicator of other environmental impacts (1 red dot) - Critical for future generations (1 green dot)	- Include full life cycle - Production - Use of vehicle[1] - End-of-life (1 green dot) - Common methodology for all options compared - Conservative assumption regarding future recycling, unless proposed legislation exist (1 red dot)
Total No. of green dots: 8	**Total No. of red dots:** 3

[1] Electricity modelling:
- Markets develop over time
- Average vs. marginal electricity? (1 red dot)
    - How define the market?
- Certificates and Guarantee of Origin vs additionality (1 green dot on top of the word additionality)



Most of the time

Participants: [redacted], [redacted], [redacted]

Indicator: Climate Impact ● ● ● ●

Why? ● Focus of electrification

● Indicator of other env. impacts

● Critical for future generations

What?

Include full life cycle:
- Production
- Use of vehicle*
- End of Life ●

Common methodology for all options compared

Conservative ● assumptions regarding future recycling, unless proposed legislation exist

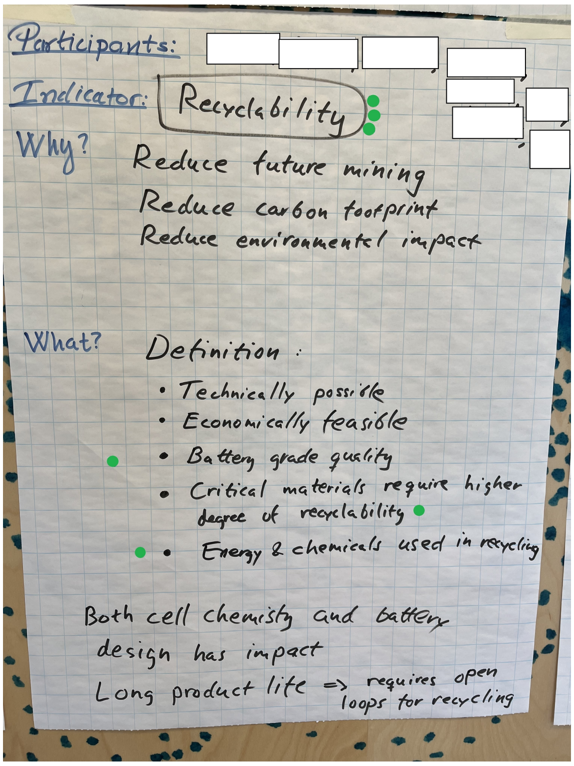
* Electricity modelling:
- Markets develop over time
- Average Ⓐ vs. marginal electricity? ●
- Certificates & GoOs vs. additi●onality?

Ⓐ How define the market?

Figure B.5: Output from workshop: Climate impact

Table B.6: Summary of workshop output for Recyclability.

Indicator: Recyclability (3 green dots)	
Participants:	Academia 1, Academia 2, Academia 3, Academia 4, Industry 1, Industry 2, Industry 3, Industry 4
Why?	**What?**
- Reduce future mining - Reduce carbon footprint - Reduce environmental impact	- Definition: - Technically possible - Economically feasible - Battery grade quality (1 green dot) - Critical batteries require higher grade of recyclability (1 green dot) - Energy and chemicals used in recycling (1 green dot) - Both cell chemistry and battery design has impact - Long product life → requires open loops for recycling
Total No. of green dots: 6	**Total No. of red dots:** 0



Participants: [redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted] [redacted]

Indicator: Recyclability ● ● ●

Why? Reduce future mining
Reduce carbon footprint
Reduce environmentel impact

What? Definition :
- Technically possible
- Economically feasible
- ● Battery grade quality
- Critical materials require higher degree of recyclability ●
- ● Energy & chemicals used in recycling

Both cell chemisty and battery design has impact
Long product life => requires open loops for recycling

Figure B.6: Output from workshop: Recyclability

The indicators 'Human health' and 'Supply of technical expertise' were not discussed individually but were still available for voting. The outcome is summarised below:

- Human health – of all workers and habitants involved (1 green dot)
- Sufficient Supply of technical expertise – standards

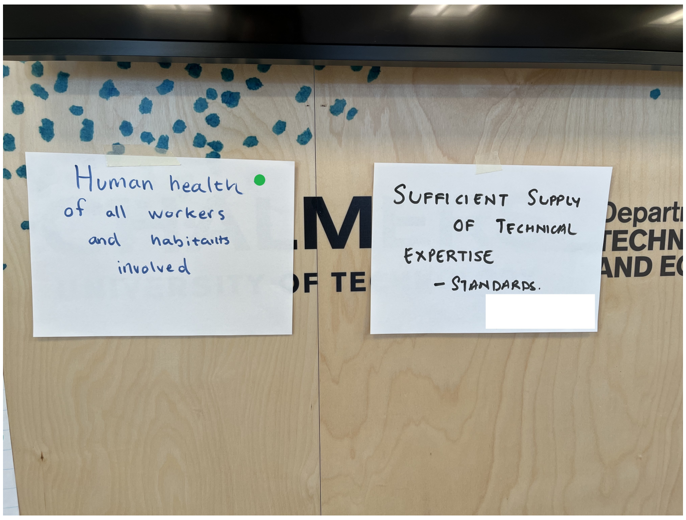


Figure B.7: Output from workshop: Human health & Sufficient supply of technical expertise and standards

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY