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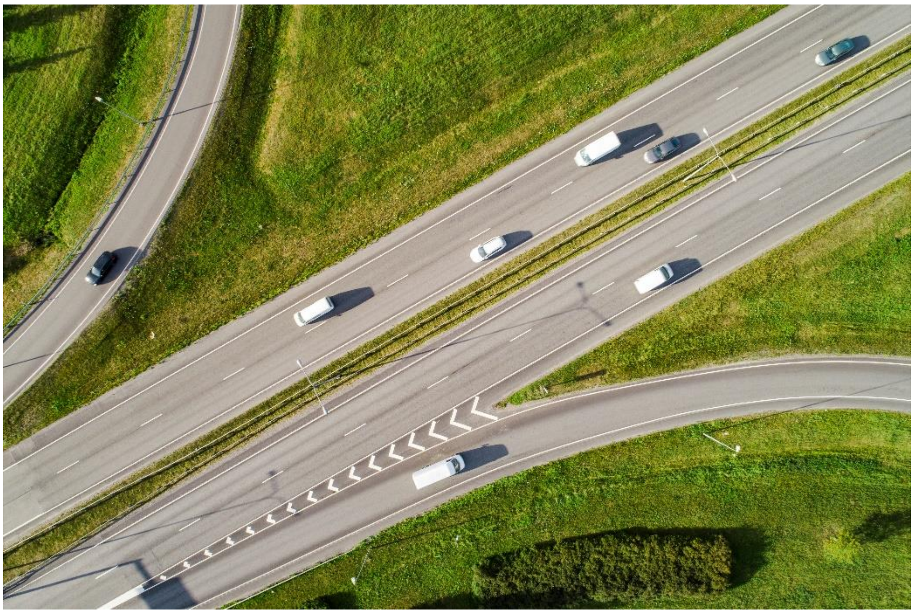

Assessment of environmental impacts and circularity of lithium-ion batteries

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beyond the obvious

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Summary

Lithium-ion batteries are complex products with numerous materials, and their life cycle is associated with various environmental impacts. There is a wide range of information available on the environmental impacts of the lithium-ion battery lifecycle from different LCA studies. However, the complexity of the lithium-ion battery value chain and a wide variation in the composition and design, as well as lack of primary data for industrial scale, amongst other, has caused a wide variety in the reported values for carbon footprint and other impacts. Nonetheless, there seems to be a consensus on where the most significant impacts arise: production of the cathode active materials and manufacturing of the battery cells. Also, various hotspots have been recognized related to specific materials and production pathways. While methods and tools are available for carrying out battery LCA studies, there is still a need for better and up-to-date primary data on an industrial scale.

For different environmental impacts, most attention has focused on GHG emissions, although in many studies, wider range of impact categories is included. To understand the sustainability of batteries in a more holistic way, it would be beneficial to include a wider set of indicators and not focus only on one indicator. PEF methodology for rechargeable batteries recommends a set of 15 different impact categories to be used in a calculation of the PEF profile, the most important ones being climate change, resource use (energy carriers, and minerals and metals) and respiratory inorganics. Currently, most battery LCA studies are focused on the impacts from manufacturing of battery materials and cells (i.e., cradle-to-gate studies). Less studies are available in which use and end-of-life stages are included. Adding use stage and end-of-life in the analysis adds another layer of complexity due to the difficulty of modelling battery behaviour and the lack of data from real-world applications and recycling. At the same time, excluding the use phase dismisses the effect of varying lifetime and performance on the lifetime environmental impacts.

LCA is an established methodology for evaluating wide range of environmental impacts of the products through its life cycle. However, alone it is not enough to assess all the necessary aspects for circular economy of batteries. For example, LCA do not provide information how materials stay in circulation for multiple cycles or their lifetime performance or required production assets, and therefore other CE indicators will be needed. Circularity assessment on the other hand is not as established as environmental impact assessment by LCA. However, ISO 59000 standard series for circular economy is currently under development which aims to give a framework to measure and assess circularity, amongst other. Numerous other indicators have been developed for evaluating circularity, which aim to recognize aspects related to e.g., durability, repairability and usage intensity, however currently there is very little information on their application to the battery value chain. The scope and purpose of different circularity indicators varies, therefore relevant indicators need to be chosen case by case, and for the specific purpose. In this report, three different circularity indicator tools (MCI, Circulytics and CTI) are presented shortly based on their capability to support or complement environmental impact assessment, with a focus on the data requirements for carrying out the assessment. Depending on the case, the results from the circularity assessment may be used to evaluate and compare circular strategies as well as to support sustainable design and decision making, therefore circularity indicators may be also suitable for increasing sustainability in the design phase rather than assessing circularity state of the art.

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Contents

List of abbreviations

ANL	Argonne National Laboratory
BMS	Battery management system
BOM	Bill of material
CAM	Cathode active material
CE	Circular Economy
CED	Cumulative energy demand
CFB-EV	Carbon Footprint of Electric Vehicle Batteries
CFF	Circular footprint formula
CMC	Carboxymethyl cellulose
CRM	Critical raw materials
CTI	Circular Transition Indicators
DRC	the Democratic Republic of the Congo
DEC	Diethyl carbonate
DMC	Dimethyl carbonate
DMSO	Dimethyl sulfoxide
EC	European Commission OR ethylene carbonate
EMF	Ellen MacArthur Foundation
EOL	End-of-life
ESRS	European Sustainability Reporting Standards
EV	Electric vehicle
FU	Functional unit
GBA	Global Battery Alliance
GHG	Greenhouse gases
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
GWP	Global warming potential
HPAL	high-pressure acid leaching
ICT	Information and Communications Technology
ISO	the international organization for standardization
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Analysis
LFP	Lithium iron phosphate, $LiFePO_4$
LIB	Lithium-ion battery
LMO	Lithium manganese oxide, $LiMn_2O_4$
LMT	Light means of transport
LTO	Lithium titanate, $Li_4Ti_5O_{12}$
MCI	Material Circularity Indicator
NCA	Lithium nickel cobalt aluminium oxide, $LiNi_xCo_yAl_zO_2$
NiMH	Nickel metal hydride battery
NMC	Lithium nickel manganese cobalt oxide, $LiNi_xMn_yCo_zO_2$
NMP	N-methyl-2-pyrrolidone
NPI	nickel pig iron
NVA	Net value added
OEM	Original equipment manufacturer
PC	Propylene carbonate
pCAM	Precursor to the cathode active material
PCI	Product Circularity Indicator
PE	Polyethylene

PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category rules
PHEV	Plug-in hybrid electric vehicle
PP	Polypropylene
PVDF	Polyvinylidene difluoride
SBR	Styrene butadiene rubber
SLI	Starting, lighting and ignition
SME	Small and medium-sized enterprises
SOC	State of charge
VC	Vinylene carbonate
WBCSD	World Business Council for Sustainable Development

1. Introduction

There is an urgent need to reduce CO_2 emissions and achieve climate neutrality. Lithium-ion batteries are one of the key technologies for the green transition; they are needed for the decarbonization of the transport sector, as well as for the storage of renewable energy. However, although being essential for the green transition, lithium-ion battery production also has significant impacts on the environment and the society. Producing batteries responsibly and sustainably means minimising emissions of greenhouse gases (GHG) and environmentally harmful substances throughout the value chain, eliminating human rights abuses, ensuring safe working conditions, and increasing reuse and recycling (Jürgens et al., 2021). A sustainable value chain for batteries is one which reduces environmental impacts and avoids the depletion of natural resources to maintain an environmental balance while promoting economic growth (Hill et al., 2019).

Sustainability is a multifaceted concept encompassing three key pillars: ecological or environmental sustainability, social sustainability, and economic sustainability. A sustainable value chain must address all three pillars throughout its entire life cycle. However, at times, industrial actions may come into conflict with sustainability aspects (environmental, social). Concerning environmental impacts, lithium-ion battery production, as well as the extraction and refining of the raw materials needed, is characterized by a relatively high energy and resource use. In addition to the global impacts, e.g., climate change and ozone depletion, the mining of raw materials may create environmental risks in the countries where extraction takes place, sometimes in countries with poor environmental legislation. Examples of such local environmental risks related to mining and processing of battery minerals are numerous. For example, mining of natural graphite, 67 % of the global production taking place in China (EC, 2023), generates local pollution of groundwater and soil, as well as health impacts from airborne graphite dust (Dolega et al., 2020). In the production of lithium from brine, concerns have been expressed on the high water consumption and consequences to the local communities as major part of the Li extraction takes place in countries associated with high water risk (IEA, 2021).

Social risks exist in the battery value chain and especially in the raw material extraction and processing, sourcing of cobalt being perhaps the most well-known issue. Today, more than half of all cobalt is mined in the Democratic Republic of the Congo (DRC), where a significant proportion originates from artisanal and small-scale mining operators and concerns related to human rights, child labour and life-threatening working conditions have been reported (Mancini et al., 2020). Environmental and social risks related to battery raw materials are addressed in the EU’s new battery regulation which poses due diligence requirements for economic operators sourcing battery minerals (EU, 2023). Global Battery Alliance (GBA) has recently published the Human Rights Index (GBA, 2022a) and Child Labour Index (GBA, 2022b) documents which aim to serve as key performance indicators for the GBA’s Battery Passport. These lists of indices serve as a self-reporting tool for companies and are precursors to more comprehensive indicator frameworks to be developed in 2023.

The strong increase in the battery demand will lead to a corresponding increase in the demand for raw materials, as well as an increase in the amount of waste, both the process-related waste and from batteries that have reached the end of their life. Furthermore, increasing demand of raw materials for lithium-ion batteries may lead to increased supply risks. Many of the materials used for active battery materials are classified as critical raw materials (CRMs) by the EU, e.g., cobalt, natural graphite and lithium (EC, 2023). There are geopolitical risks associated with highly concentrated production of CRMs, for example the majority of cobalt mining today is taking place in the DRC, and major share of cobalt refining facilities are located in China. Geographical concentration can lead to conflict, price instability, and artificial shortages as a result of the government policies or socio-political instabilities of these regions. (Porzio et al., 2021, Tao et al., 2021)

It is an open question if the availability of CRMs is sufficient to respond to the increasing consumption and whether scaling up battery manufacturing will deplete critical material reserves and/or drive-up prices. In addition to current CRMs, other materials may also face supply chain challenges in the near future due to limited feedstock and/or processing capacity (Porzio et al., 2021, Tao et al., 2021). For example, the increasing market share of nickel-rich cathodes increases the demand of Class 1 nickel needed for the cathode production, and a recent analysis predicts a deficit for suitable feedstock post-2027 (Fraser et al., 2021). In the latest EU's CRM assessment, nickel and copper have been listed as strategic raw materials, i.e., raw materials of high strategic importance, characterized by a potentially significant gap between global supply and projected demand, and materials for which an increase in production is relatively difficult (EC, 2023). However, there is a continuous development of the battery technologies. Role of substitution in battery chemistries is an open question and may change the need for certain CRMs in the future. However, also these new substitutes and their sustainability aspects need to be considered.

In order to produce batteries in a sustainable manner and to decrease and prevent harmful impacts to the environment and the society, methods are needed to evaluate the sustainability of batteries in a holistic manner. EU's new regulation on batteries brings new implications for evaluating and reporting environmental impacts, such as carbon footprint, of the batteries placed on the market in the EU. In addition, restrictions on the use of hazardous substances, mandatory recycled content targets and performance and durability parameters as well as requirements of end-of-life management, amongst other requirements, will be introduced in the next coming years.

In this report the focus is on environmental sustainability and circularity aspects of the battery value chain, with a focus on current lithium-ion batteries. Life cycle assessment (LCA) is a standardized and widely used method for evaluating the environmental impacts of products, such as impacts related to GHG emissions, eutrophication, and toxicity. Circularity assessment on the other hand is not as established yet, although wide range of indicators have been developed to assess circularity on different level. Increased circularity of battery minerals is needed to improve supply security of (critical) raw materials and to reduce the need for extraction of primary materials, which is also one of the key aims of the EU's battery regulation. Ideally, increased circularity also reduces the overall environmental impacts of the battery production with the proper recycling processes; however, this is not necessarily always the case if specific recycling operations have significant impacts. Therefore, it is necessary to understand potential trade-offs, and develop the processes in a way that minimizes the net environmental impacts.

2. Goal & methods

This report is carried out as a literature study. The objective of this deliverable 5.2.2 ”Framework to evaluate the circularity and environmental impacts of the battery” is to gather state-of-art knowledge on evaluation of environmental impacts and circularity of lithium ion batteries. Chapter 3 describes the key sustainability requirements in the EU's new Battery Regulation and what implications it creates for the battery value chain actors. Chapter 4 describes the evaluation of environmental impacts of batteries by LCA and reviews recent LCA studies on lithium-ion batteries with a focus on batteries for EVs. Chapter 5 provides an overview on circularity assessment and selected indicators. Also, recent development of ISO standardization on measuring and assessing circularity is described briefly.

3. Sustainability and circularity requirements for the battery value chain - EU's new battery regulation

EU's new battery regulation entered into force on August 2023 and will apply from February 2024 (EU, 2023). The new regulation modernized the previous battery directive (EU, 2006) with the overall aim to promote a circular economy, and to reduce environmental and social impacts throughout all stages of the battery life cycle, while strengthening the functioning of the internal market. The new regulation applies to all batteries placed on the EU market regardless of the battery chemistry, i.e., portable batteries, automotive batteries (SLI batteries, supplying power for starting, lighting or ignition of vehicles), electric vehicle batteries (EV), industrial batteries, and batteries for light means of transport (LMT batteries, supplying power in wheeled vehicles such as electric scooters and bikes).

The new battery regulation brings new requirements for the stakeholders in the battery value chain related to sustainability, safety and performance, as well as to labelling and information sharing. Sustainability requirements will be introduced gradually from 2024, while provisions on extended producer responsibility and management of waste batteries will start applying in mid-2025. Many technical aspects, such as format of labelling and rules for calculating recycled content, will require the adoption of secondary legislation (delegated and implementing acts) to be fully operational. In many articles, the regulation also takes into account future technological and market developments, and the Commission is empowered to adopt delegated acts to amend e.g., materials and targets for recycled content, recycling efficiency and recovery of materials.

The new regulation addresses all lifecycle stages of the batteries placed in the EU market. Key measures are presented in Figure 1.

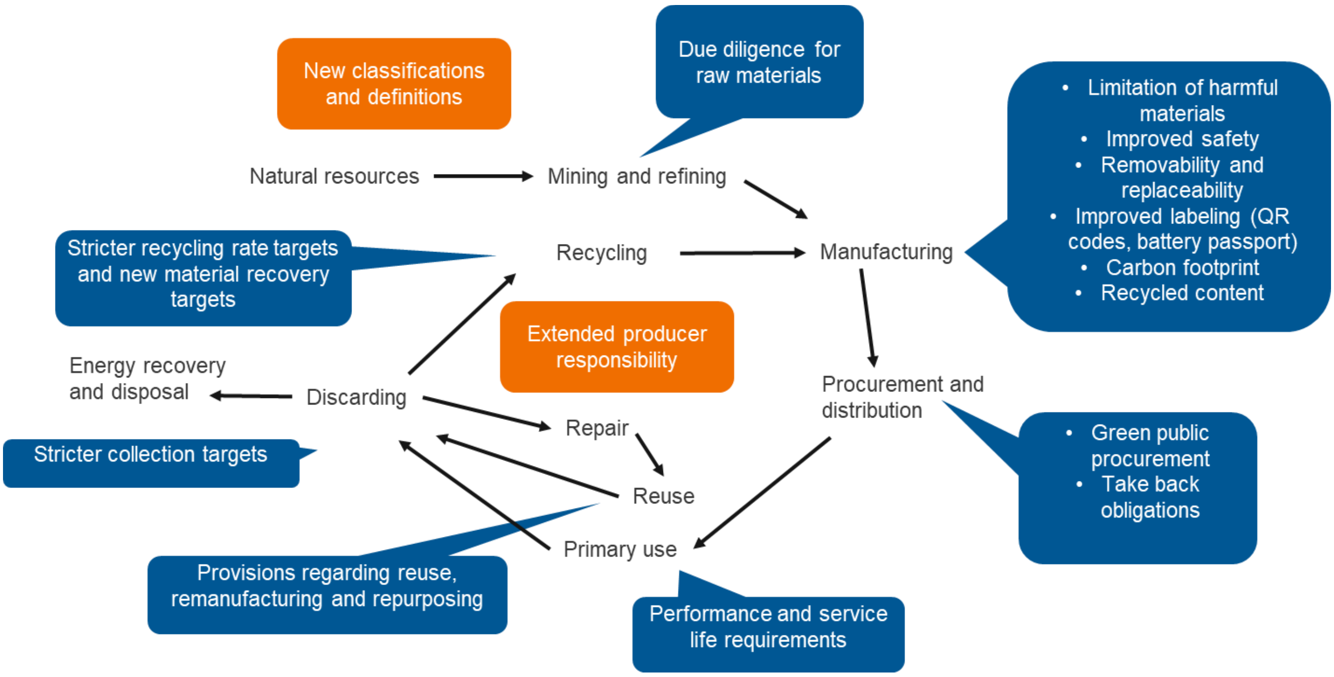

Figure 1 Key measures in the EU battery regulation. (Adapted from Recser, 2023)

Increasing circularity of battery materials is one of the key aims in the battery regulation. The regulation sets new (or increased) targets for the **collection of waste batteries** (Articles 59-61), targets for the **recycling efficiency** of different battery chemistries and **recovery** of specific materials (Article 71), as well as the mandatory **recycled content** of Co, Pb, Li, and Ni in industrial batteries, EV batteries and SLI batteries (Article 8). The timeline for introducing these targets is presented in Figure 2 as well as the required levels.

Concerning the recycled content, in the first phase documentation of **information about the share of recycled content** is required, whereas in the second phase **minimum share of recycled content** is set. The requirement for the recycled content concerns cobalt, lithium or nickel that is present in active materials and that has been recovered from battery manufacturing waste or post-consumer waste, and lead that is present in the battery and that has been recovered from waste. It is estimated that in the near future, major part of the input for lithium-ion battery recycling comes from the manufacturing waste due to the long lifetime of EV batteries (IEA, 2023). There has been debate if recycled content targets are reachable for the battery manufacturers due to the limited availability of recycled feedstock from battery recycling in the EU (Benchmark Minerals, 2023). The regulation states that the Commission shall assess whether, due to the existing and forecasted availability for 2030 and 2035 of cobalt, lead, lithium or nickel recovered from waste, or lack thereof, and in view of technical and scientific progress, it is appropriate to revise the targets.

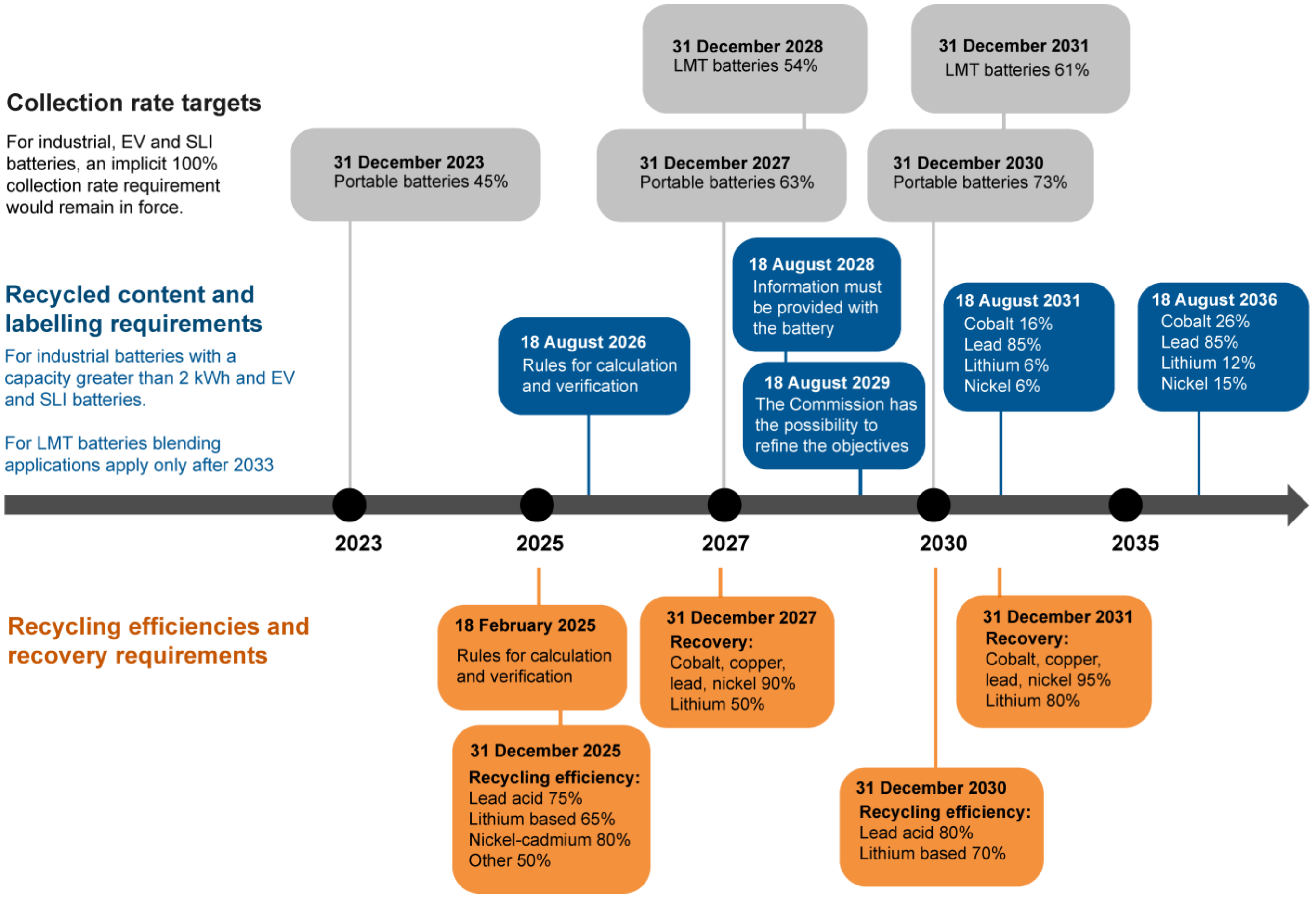

Figure 2 Timeline for the targets on collection rate, recycling efficiency, recovery requirements and recycled content. Abbreviations: EV = electric vehicle, LMT = light means of transport, SLI = starting, lighting and ignition.

To better inform consumers, as well as professionals in the battery value chain, and to facilitate the circular economy (e.g., repair, repurposing and recycling activities), improved **labelling and marking** requirements are introduced for all battery types, including QR codes with access to necessary information (Article 13). A **digital battery passport**, also accessible through the QR code, is required for LMT battery, industrial battery with a capacity above 2 kilowatt-hours (kWh) and each EV battery placed on the market (Article 77-78, and Annex XIII). Timeline for the requirements related to the labelling and battery passport, as well as due diligence and carbon footprint is presented in Figure 3.

Mandatory carbon footprint declaration (Article 7) is required for rechargeable industrial batteries with a capacity above 2 kWh, LMT batteries and EV batteries. In the second step, **carbon footprint performance classes** will be introduced, and in the third step, **maximum life cycle carbon footprint thresholds** will be established. Figure 3 presents the timeline for the carbon footprint requirements for different battery types. The carbon footprint of the battery is expressed as kilograms (kg) of carbon dioxide equivalent per one kWh of the total energy provided by the battery over its expected service life, and it is specific to a model battery produced in a defined production site. Furthermore, the carbon footprint of the battery shall be differentiated according to life cycle stage. Annex II of the regulation defines the scope, functional units and reference flows, system boundaries, and use of datasets for the carbon footprint calculation. Calculation rules shall be in compliance with the latest version of the Commission Product Environmental Footprint (PEF) method and relevant Product Environmental

Footprint Category Rules (PEFCRs) and reflect the international agreements and technical/scientific progress in the area of life cycle assessment. Lifecycle stages included in the calculation are raw material acquisition and pre-processing (from mining up to battery cells, components and electronic parts), main product production, distribution (transport to the point of sale) and end-of-life and recycling (collection, dismantling, and recycling). The use phase is excluded from the lifecycle carbon footprint calculations as well as manufacturing of equipment for the assembly and recycling. The calculation of the life cycle carbon footprint shall be based on the bill of material, the energy, and auxiliary materials used in a specific plant to produce a specific battery model. In particular, the electronic components (e.g., battery management units, safety units) and the cathode materials have been identified as the main contributors for the carbon footprint, and therefore have to be accurately identified for the carbon footprint calculation. More detailed methodology for the calculation of the carbon footprint, carbon footprint performance classes and carbon footprint thresholds will be established later in delegated and implementing acts. JRC has published “Rules for the calculation of the Carbon Footprint of Electric Vehicle Batteries (CFB-EV)” which aims to serve as the technical basis for the carbon footprint methodology (Andreasi Bassi et al., 2023).

Due diligence obligations are imposed for economic operators who must verify the source of raw materials used for batteries placed on the market. Economic operators include manufacturers, importers, and distributors, as well as companies that import batteries for use in their own products or operations, exception are SMEs with a net turnover of less than EUR 40 million in the financial year. Due diligence obligations aim for the identification and mitigation of social and environmental risks associated with raw materials used in battery manufacturing. Materials listed in the Annex X of the regulation include cobalt, natural graphite, lithium, and nickel. Economic operators thus need to establish company due diligence policy, and management system to support the due diligence policy and risk management.

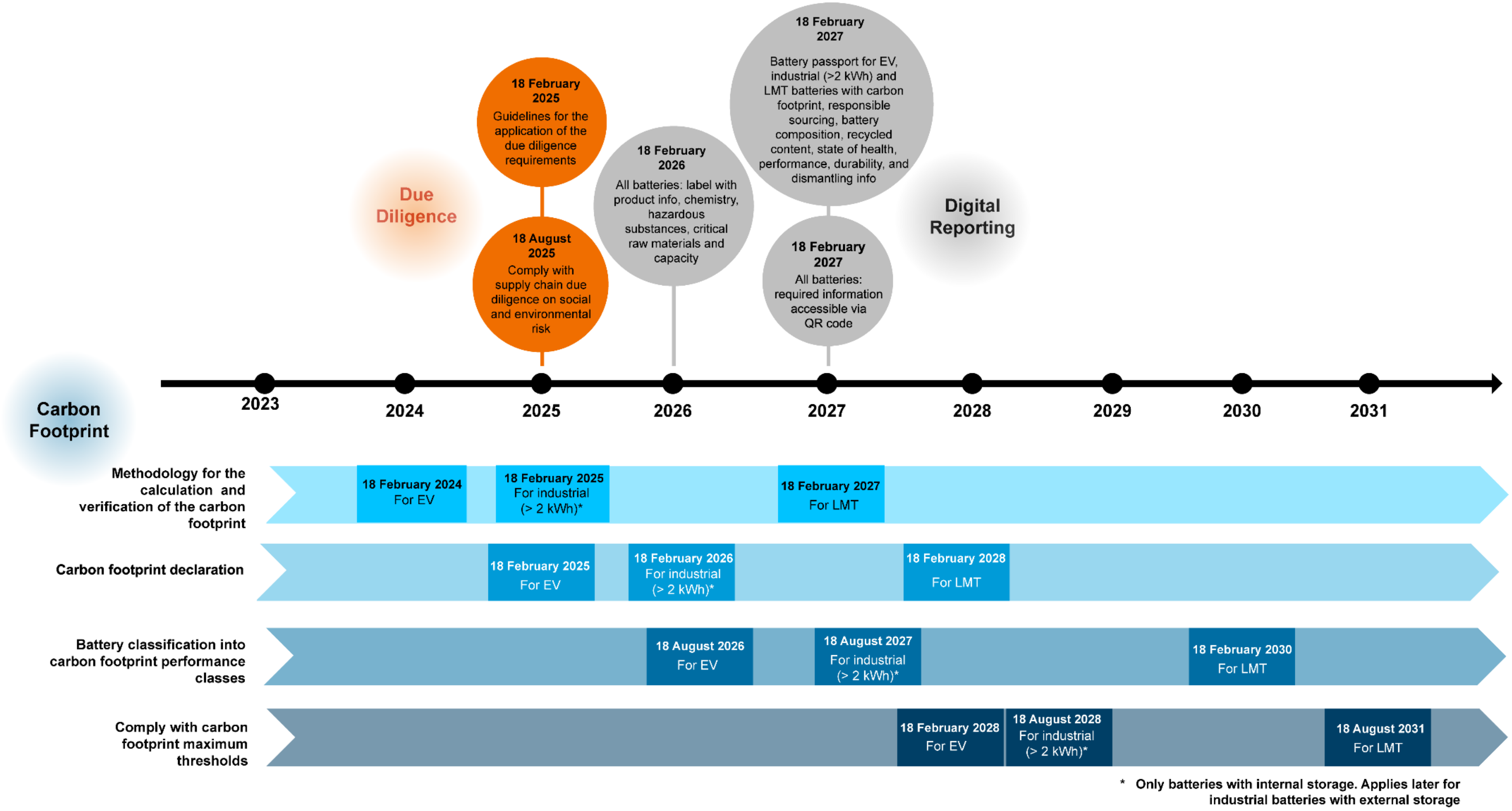

Figure 3 Timeline for the requirements related to labelling and battery passport, due diligence and carbon footprint. Abbreviations: EV = electric vehicle, LMT = light means of transport. It should be noted that for many articles, the entry into force depends on the delegated/implementing acts. As a result, these articles may enter into force later compared to the presented timeline if delegated/implementing acts are adopted later than foreseen.

Digital battery passport will be mandatory for the industrial, EV, and LMT batteries in 2027 according to the battery regulation. The battery passport will contain a wide range of information categorized by the availability of information (access rights). Information required in the digital battery passport is presented in Table 1. While part of the information in battery passport will be publicly available to all users, such as carbon footprint information and recycled content, part of the information is restricted to “persons with legitimate interest”, and/or the European Commission, notified bodies and market surveillance authorities. This means for example repairers, remanufacturers, second-life operators and recyclers who need information about dismantling of the battery, including safety measures to be taken during the dismantling, and the detailed composition of the battery model to conduct their respective economic activities.

Table 1. Information requirements in digital battery passport and availability on information

Publicly accessible information	Information relating to the battery model accessible only to persons with legitimate interest and the Commission	Information and data relating to an individual battery accessible only to persons with legitimate interest	Information relating to the battery model accessible only to notified bodies, market surveillance authorities and the Commission
- the manufacturer’s identification - the battery category - manufacturing place (geographical location of a battery manufacturing facility) - manufacturing date (month and year) - weight - capacity - usable extinguishing agent - Material composition of the battery, including its chemistry, hazardous substances contained in the battery other than mercury, cadmium or lead, and critical raw materials contained in the battery - Carbon footprint information - Information on responsible sourcing - Recycled content, The share of renewable content - Performance parameters (including expected lifetime)	- Detailed composition, including materials used in the cathode, anode and electrolyte - Part numbers for components and contact details of sources for replacement spares - Dismantling information - Safety measures	- the values for performance and durability parameters when the battery is placed on the market and when it is subject to changes in its status - information on the state of health of the battery; - information on the status of the battery, defined as 'original’, ‘repurposed’, ‘reused’, 'remanufactured' or ‘waste’ - information and data as a result of its use, including the number of charging and discharging cycles and negative events, such as accidents, as well as periodically recorded information on the operating environmental conditions, including temperature, and on the state of charge	- Results of tests reports proving compliance with the requirements set out in this Regulation or any implementing or delegated act adopted on its basis

4. Environmental impact assessment

4.1 Introduction to environmental impact assessment of batteries by LCA

Life cycle assessment (LCA) is a methodology used to evaluate the inputs, outputs, and the environmental impacts of products and systems in all stages of the life cycle. LCA is standardised by ISO 14040:2006 and 14044:2006 standards. LCA consists of several building blocks illustrated in Figure 4. Implementation of LCA requires harmonised calculation rules (standards and methodologies), reliable data from multiple sources and a tool to manage large amounts of data.

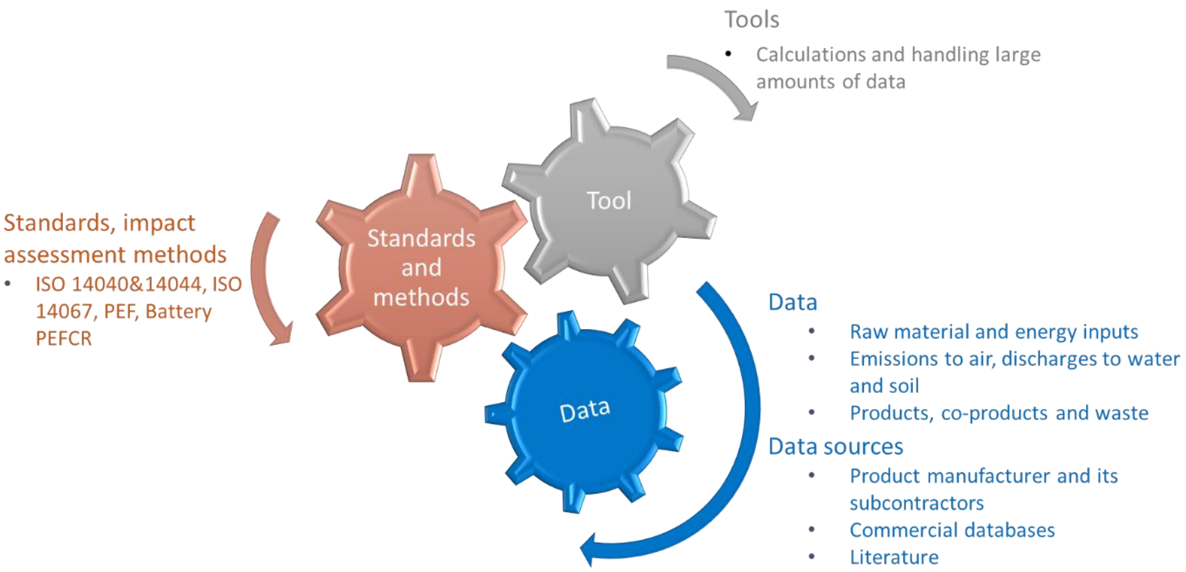

Figure 4 Building blocks in LCA

Product Environmental Footprint (PEF) is an environmental impact assessment method for products based on LCA and developed by the European Commission's Joint Research Center (JRC). While PEF guidelines follow the main principles of the leading international ISO-standards for LCA, the PEF guidance aims to further harmonise the LCA practice by providing more detailed and strict requirements compared to current LCA standards. For example, the PEF includes pre-defined environmental impact categories and specifies the impact assessment methods to use for each impact category. **Product Environmental Footprint Category Rules (PEFCRs)** complement the PEF methodology and provide more detailed guidelines for making a PEF study for pre-defined product categories that fulfil the same function. The PEFCR guidance documents provide instructions for defining the product category rules for specific product groups.

PEFCR for high specific energy rechargeable batteries for mobile applications have been published in 2018, and it is applicable to cells/batteries used in e-mobility (e.g. e-bikes, EV/PHEV, bus/truck etc.), ICT (e.g. tablets, phones, computers, cameras games etc.) and cordless power tools (e.g. drills etc.) as well as lithium-ion (various chemistries) and nickel-metal hydride (NiMH) battery technologies (Recharge, 2018). The PEFCR defines how to calculate a number of impact categories, including climate change, for the main battery chemistries currently found in the market. EU's Battery regulation refers to the PEF method and PEFCR in the calculation methodology for the carbon footprint (Annex II in the Regulation).

In general, LCA consists of four main phases (ISO 14040:2006/ISO 14044:2006):

1. In the **Goal and scope definition phase**, the aim of the LCA is defined and the assumptions and system choices in the assessment are described, including definition of the functional unit, the

identification of the system boundaries, the identification of the allocation procedures, the studied impact categories and the Life Cycle Impact Assessment (LCIA) models used, and the identification of data quality requirements.

2. In the **Life Cycle Inventory (LCI) phase**, the data collection and the calculation procedure for the quantification of inputs and outputs of the studied system is carried out. Inputs and outputs concern energy and material inputs, waste, emissions and other environmental aspects.

3. In the **Life Cycle Impact Assessment (LCIA) phase**, LCI data are translated into indicators that reflect environment and health pressures as well as resource scarcity. This is done through LCIA methods which classify emissions into impact categories and then characterize them to common units.

4. In the **Interpretation phase**, the outcome of LCI and LCIA are interpreted in accordance with the aim defined in the goal and scope of the study.

4.1.1 Goal and scope

Methodological choices concerning system boundary, allocation method, and functional unit are important steps in the LCA study and affect the comparability of different studies. Various **system boundaries** have been used in battery LCAs, but majority of the studies are made cradle-to-gate. This means analysing the environmental impact from material extraction to when the battery is ready for sale and excluding the use stage and end-of-life. Less studies are available that have been made cradle-to-grave, thus including the use stage and end-of-life. Figure 5 illustrates cradle-to-gate and cradle-to-grave system boundaries, starting from the raw material extraction and refining, followed by battery material and component production, cell manufacturing and battery pack assembly, distribution to customers, use stage and finally end-of-life treatment. Material and/or energy input is needed for all life cycle stages, and outputs include all types of environmental releases including emissions to air, water and soil, ad generation of products, co-products and waste. In the EU battery regulation, the use phase is excluded from the calculation of the carbon footprint whereas distribution and end-of-life and recycling stages are included. PERCR for rechargeable batteries on the other hand includes use phase, but the description states that “the use stage of the battery is defined by the energy losses due to the battery and charger efficiency”.

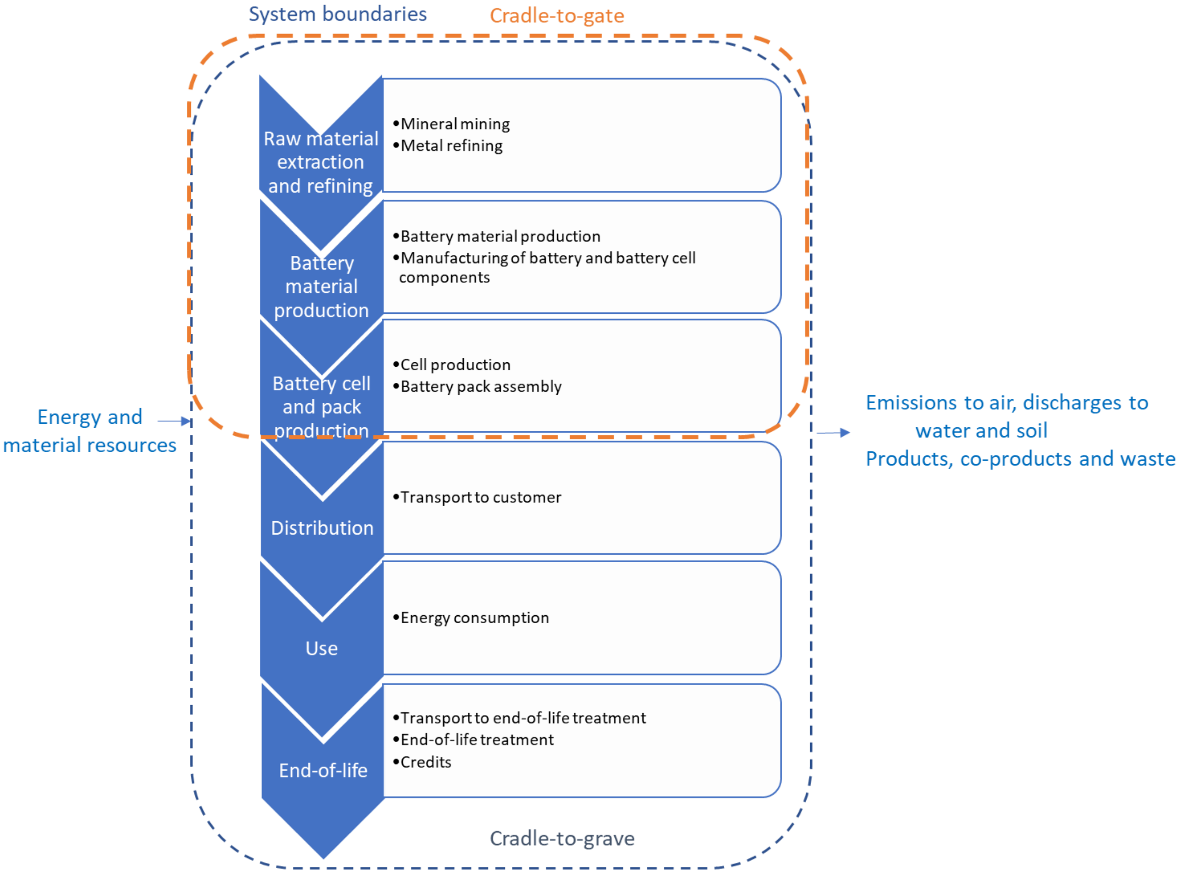

Figure 5 System boundaries of life cycle of a battery system (cradle-to-gate and cradle-to-grave).

The majority of battery LCAs are tied to a particular **use case** because performance differences (e.g., roundtrip efficiency and cycle life) are important to the definition of a common functional unit across which different alternatives can be compared (Porzio & Scown, 2021). The majority of studies focus on current Li-ion battery chemistries for electrified/electric passenger cars (i.e. HEV, PHEV and BEV) but there are also some studies that consider applications for stationary storage and for new battery chemistries (such as Li-S, solid-state and Na-ion batteries) (Hill et al., 2019). For other vehicle types that passenger cars, there are very few studies available although electrification of for example heavy duty vehicles, motorcycles, and light duty lorries has commenced and can be expected to continue in future (Accardo et al., 2021). It should be noted that not all studies are tied to a specific application, especially in case of more advanced, pre-commercialization battery technologies where reliable data on use stage performance and battery characteristics may not be available.

There are several alternatives for the **functional unit** (FU) which is defined in the ISO 14040:2006 standard as the “quantified performance of a product system for use as a reference unit”. Functional units used in different battery LCA studies include for example battery or material mass (kg), individual battery pack, energy capacity (kWh of battery capacity), energy throughput (kWh passed through the system over the battery lifetime), and distance driven (km) for battery electric vehicles (Porzio & Scown, 2021). In case of GHG emissions, the most commonly used functional unit in battery LCAs is $kgCO_{2e}$/kWh (per storage capacity) or $kgCO_{2e}$/kg (per battery mass) (Zhao et al. 2021). The functional unit defined in the PEFCR for rechargeable batteries, as well as in the carbon footprint calculation method in the battery Regulation, is **1 kWh of the total energy provided over the service life by the battery system** (measured in kWh). **The reference flow** in PEFCR is defined as the amount of product needed to fulfil the defined function and shall be measured in kg of battery per kWh of the total energy required by the application over its service life.

Allocation is procedure, where environmental impacts of input or output flows can be partitioned between product systems. ISO 14044 states that whenever possible, allocation should be avoided either by dividing unit process to be allocated into two or more sub-processes, or by expanding the product system to include additional functions. PEFCR for batteries do not provide specific guidance on allocation, since there are no identified cases of co-products in the batteries manufacturing process. However, it states **that modelling of waste and recycled content should be according to Circular Footprint Formula (CFF)**. It includes material, energy recovery and disposal aspects, and defines how environmental burdens and benefits should be allocated between the product systems. Typically recycling credits are given based on recycled content in material production stage, where recycled content can contribute to lower impacts for the material. CFF enables to assess also the recycled content at the end of product's life cycle. Since EU's battery regulation defines requirements for both production and end-of-life sides, it is important that environmental impacts can be evaluated at both ends of the product's life cycle.

4.1.2 LCI

Life cycle inventory (LCI) phase, involving the compilation and quantification of inputs and outputs for a product throughout its life cycle, is often the most laborious phase in the LCA. Compiled data can be divided into **primary data and secondary data**. Primary data is site-specific, company-specific (if multiple sites for a same product) or supply-chain-specific data which may be obtained through meter readings, purchase records, utility bills, engineering models, direct monitoring, material/product balances, stoichiometry, or other methods for obtaining data from specific processes in the value chain. Secondary data means data that is not directly collected, measured, or estimated by the company, but sourced from a third-party life cycle inventory database or other sources. Secondary data includes industry average data (e.g., from published production data, government statistics, and industry associations), literature studies, engineering studies and patents, and can also be based on financial data, and contain proxy data, and other generic data (Recharge, 2018). EU's battery regulation emphasizes that the calculation of the life cycle carbon footprint shall be based on the bill of materials, the energy and the auxiliary materials used in a specific manufacturing plant to produce a specific battery model, and in particular, all activity data related to the battery's anode, cathode, electrolyte, separator and cell-casing shall refer to a specific battery model produced in a specific production plant.

Due to the difficulty to obtain the primary data of battery production from industry, many LCA studies use secondary data. The generic LCI databases are often used to determine the impacts battery materials and components, additionally some databases also provide data for the battery manufacturing and recycling processes. The choice of the LCI database can influence e.g., resulting impacts of materials, due to different processing steps, assumed shares of virgin and recycled material, and production location (Aichberger & Jungmeier, 2020). In addition, data is needed for unit processes throughout the value chain. Usually there is specific data available for only some of the processes and the data gaps must be filled with generic data from databases. Often used databases for battery LCI data include:

- EcoInvent database contains various data on for example energy supply, resource extraction, material supply, chemicals, metals, and transport services. Latest update v3.9.1 includes new datasets on the LFP battery technology (to complement the previous datasets for NCA, NMC111, NMC811 and LMO), and updated datasets for battery separator and electrolyte. (EcoInvent, 2022)
- GaBi is a commercial LCA tool with own database that covers about 15 000 different datasets for various industry sectors. It is mainly used in industry by OEM clients such as Volkswagen, Daimler, BMW, Volvo, Polestar, Scania for their own LCA projects (Engels et al., 2022).
- GREET model (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) is a full life cycle model developed by the Argonne National Laboratory (US) for evaluating energy and emission impacts of batteries (or other vehicle and fuel combinations). Since 2018 Argonne National Laboratory (ANL) has conducted several studies in which primary and secondary industry data have been retrieved and used as new inventory for the life cycle database GREET.

BatPaC (Battery performance and cost) model by ANL is also frequently used data source for battery materials and composition data (Nelson et al., 2019).

In addition, there are several other databases available which can be used for battery LCA as well, for example, ELCD (ILCD database, EU – Joint Research Center), PlasticsEurope (Association of the European Plastics Manufacturers), World Steel, and EAA (the European Aluminium Industry).

Global Battery Alliance (GBA) has published Greenhouse Gas (GHG) Rulebook which is a document providing detailed guidelines for the calculation of comparable greenhouse gas footprints of lithium-ion batteries (LIB) for electric vehicles (EV) by users of the (GBA) Battery Passport (GBA, 2023). The GHG Rulebook describes the lifecycle stages of lithium-ion battery using NMC as an example chemistry, and provides detailed instructions for the data collection in order to calculate the carbon footprint of the battery in a harmonized and transparent manner. Furthermore, the document identifies the main processes and contains generic data collection templates for the associated input and output material parameters. Latest version of the GHG Rulebook (v1.5) includes cluster specific rules for lifecycle stages mining and refining; pCAM and CAM manufacturing; anode materials; electrode, cell and module manufacturing; battery assembly; and recycling. Use phase is thus excluded, as well as advanced chemistries such as solid-state batteries, but may be covered in the future updates of the GHG Rulebook.

4.1.3 LCIA

When calculating the impacts of an LCA, many different **impact assessment methods** can be used. Although these methods vary in several aspects, one main distinction is between midpoint and endpoint methods. These methods use different stages in the cause-effect chain to calculate the impact. Usually, environmental impacts are calculated and reported at midpoint level.

Some impact categories cover impacts that are distributed across the world, independently from the place of extraction or emission. Therefore, they only contain global characterisation factors. This is the case for climate change, ozone depletion, and resource use. Some impact categories describe impacts that are limited to the local scale and thus vary widely depending on where the intervention extraction and emissions takes place and the associated local environmental conditions.

PEFCR for batteries recommends the following 15 impact categories to be used in calculation of the PEF profile, the most important for batteries categories shown in bold[1] (Recharge, 2018):

- **Climate change**
- Ozone depletion
- Human toxicity (cancer, non-cancer)
- **Particulate matter/respiratory inorganics**
- Ionising radiation
- Photochemical ozone formation
- Acidification
- Eutrophication, terrestrial
- Eutrophication, freshwater
- Eutrophication, marine
- Ecotoxicity, freshwater
- Land use

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[1] Most important for the representative product(s) defined in the PEFCR (the average product(s) sold in Europe, during the time of the development of the PEFCR). For emerging technologies, different impact categories may be relevant, and PEFCR recommends all 15 impact categories to be included for the calculation of the PEF profile.
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- Water use
- **Resource use, minerals and metals**
- **Resource use, fossils**

4.2 Assessing environmental impacts of lithium-ion batteries – current knowledge

LIBs are complex products and large variability is observed in the reported impacts in different LCA studies.

There is a large amount of information on the environmental impacts of lithium-ion batteries from different LCA studies. However, the results from these studies can vary significantly even though LCA method is based on ISO standards and more detailed guidelines (e.g., PEFCR for rechargeable batteries) have also been published in recent years. This variation is due to several factors including at least production energy demand and location, the amount and composition of cell materials and other components, use of primary versus secondary data, the details of production processes included in the analysis, treatment of recycling, and the LCI databases used (Hill et al., 2019).

Furthermore, the selected system boundaries have crucial effect on the outcomes of the evaluation. Most of the battery LCA studies are cradle to gate, whereas less studies are available which consider use stage and end-of-life, although LCA studies concerning battery recycling have been increasingly published recently. Cradle to grave battery LCA studies tied to a particular use case, such as studies assessing batteries in EV application in comparison with conventional or other alternative powertrains, are typically more variable, due to the additional degrees of freedom available for assumptions for operational impacts (in particular the source of electricity and lifetime km) and on the treatment of end-of-life impacts (e.g. assuming a recycled content or avoided burden approach to account for recycling) (Hill et al., 2019).

The LCA study is based on the bill of material, the energy, and auxiliary materials used in a specific plant to produce a specific battery model. Lithium-ion batteries are complex products with numerous materials and components. In addition, battery value chain is complex and can be organized in many ways. Mining and refining of the battery metals often occur in separate locations and the material refining for one material can be done in several smaller refining steps. Furthermore, there are often several possible process pathways to obtain the desired chemical product from different types of resources (e.g., lithium may be extracted from spodumene ore or brine, which fundamentally different process pathways). Battery cell production takes place in a facility that needs strict controls on humidity, temperature, and cleanliness. Subsequent battery pack assembly can be done by the cell manufacturer, or the battery pack components can be assembled by different operator or by the automobile manufacturers. Currently, large part of the battery materials refining, and cell manufacturing takes place in Asia. (Emilsson & Dahllöf, 2019)

The main Li-ion battery material chemistries used in electric vehicles cathodes are lithium nickel manganese cobalt oxides (NMC, $LiNi_xMn_yCo_zO_2$), lithium iron phosphate (LFP, $LiFePO_4$), lithium nickel cobalt aluminium oxide (NCA, $LiNi_xCo_yAl_zO_2$), and lithium manganese oxide (LMO, $LiMn_2O_4$). Cathodes consist of these electrochemically active powders mixed with carbon black and glued to aluminium foil as electric current collector with a polymeric binder, typically with polyvinylidene difluoride (PVDF). PVDF typically requires the use of organic solvents like NMP (N-methyl-2-pyrrolidone) in electrode coating process. Graphite (natural or synthetic) and lithium titanate LTO ($Li_4Ti_5O_{12}$) are commonly used as anode materials and copper foils are used as electric current collectors in anodes. Anodes are typically coated using water as solvent and carboxymethyl cellulose (CMC) and styrene butadiene rubber (SBR) as binders. Silicon is increasingly used in anodes to increase the energy density, typically in small amounts together with graphite (less than 5-10 % of the anode active mass). Polypropylene (PP) or polyethylene (PE) membranes are used as separators. Solutions of $LiPF_6$, $LiBF_4$, $LiClO_4$, or $LiSO_2$ dissolved in a mixture of propylene carbonate (PC), ethylene carbonate (EC), dimethyl carbonate (DMC), diethyl carbonate (DEC) or dimethyl sulfoxide (DMSO) with various additives such as vinylene carbonate (VC) are used as electrolyte. These battery components cathode, anode, separator, and electrolyte form battery cells with different designs (cylindrical batteries, prismatic cells and pouch cells). Steel and aluminium are typically used in casing materials (Hill et al., 2019).

LCA studies for various battery chemistries are available, with NMC, LMO and LFP the most often studied lithium-ion battery chemistries (Aichberger & Jungmeier, 2020). Table 2 shows Li-ion battery cell, module and pack components and materials, as well as auxiliary materials (solvents) included in the cell manufacturing. Electric vehicle contains cells grouped into modules and EV battery pack consist of multiple interconnected modules, and each module is made up of hundreds of individual cells. In battery packs battery management systems (BMS) are also integrated including sensors, safety devices and circuits that control battery operation and monitor its use.

Table 2 Li-ion battery cell, module and pack components and materials (Crenna et al., 2021, Hill et al., 2019)

Cell					
Cathode	**Anode**	**Electric current collectors**	**Separator**	**Electrolyte**	**Casing**
Cathode active materials: - NMC - LFP - NCA - LMO	Anode active materials: - synthetic graphite - natural graphite - LTO - (Si)	- copper foil (anode) - aluminium foil (cathode)	- PP - PE	Lithium salt: - $LiPF_6$ - $LiBF_4$ - $LiClO_4$ - $LiSO_2$	Plastic components
Additive: - carbon black	Additive: - carbon black			Additive: - VC	Aluminium components
Binder: - PVDF	Binder: - SBR - CMC			Solvent: - PC - EC - DMSO - DMC - DEC	
Solvent: - NMP	Solvent: - water				
Module					
External box (aluminium)	Insulation (plastic)	Electronic parts	Terminals, connectors		
Pack					
External box (aluminium)	Internal fasteners (steel)	Insulation (plastic)	BMS	Electronic pack heater	cooling liquid
Terminals, connectors					

Although the selection of materials and compositions in LCA (bill of material) is highly important, there is a considerable variety in the transparency of the LCI presented in battery LCA studies. In order to compare the results of different LCA studies, LCI should be reported transparently. Furthermore, it is highly important to divide the studied system in as small modules as possible. This allows for more detailed analysis of which materials and processing steps are hot spots of environmental impacts. In addition, high degree of modularity increases the traceability of data sources and make it easier to compare different LCA studies. A detailed inventory for current and near future lithium-ion battery chemistries, NMC111, NMC811 and NCA, is presented in a recent study by Crenna et al. (2021) with an example of a modular and flexible life cycle inventory.

It is also important to note that a large part of the LCA studies, and especially those studies most frequently cited and used as data sources in other studies, appear to be based upon analyses of now older battery chemistries and formulations that were introduced 5-10 years ago (Hill et a., 2019). Furthermore, databases, such as EcoInvent, are being constantly updated, and the datasets derived from the previous EcoInvent versions may not be representative of the current production routes or battery compositions, and associated impacts.

Carbon footprint of the battery: LIB manufacturing is energy intensive, thus production location and scale of production is important.

Different variants of NMC have been the major cathode chemistries in the EVs representing over 50 % of the market share, although in recent years also LFP batteries have been gaining market share (IEA, 2023). Therefore, the impacts of NMC production are discussed more in detail in the following chapters.

The focus of the environmental impacts in battery LCAs is typically on GHG emissions and cumulative energy demand (CED), and a wide range of numbers have been reported for these impacts. Several studies published in recent years focused on NMC batteries for light duty vehicles report GHG emissions for the battery production (cradle to gate) to be around 100 ($kgCO_{2e}$/kWh), and for the production with a European electricity mix even close to 50 ($kgCO_{2e}$/kWh). Table 3 presents reported GHG emissions for the battery production as presented in selected LCA studies, with a focus on studies published <5 years ago and comparing the regional variability of the GHG emissions due to different energy mixes. Several comprehensive review articles have been published on the existing LCA studies on lithium-ion batteries. For further information the interested reader is referred to reviews by Zhao et al. (2021), Peters et al. (2017), Aichberger and Jungmeier (2020), and Emilsson and Dahllöf (2019).

Since the manufacturing of battery materials and cells is energy intensive, the location of the battery manufacturing is highly important for the environmental impact assessment. It is evident that GWP impacts of battery manufacturing vary significantly amongst different countries and regions due to the variable GHG intensity of the energy source used in manufacturing and in the production of key materials. Today, China continues to dominate the LIB supply chain, where the grid mix is highly carbon-intense as a result of high shares of coal use. In contrast to this, cell manufacturing in countries with low carbon-intense grid-mixes (such as Sweden) reduces the GHG emissions of the production significantly and shifts the GWP and CED impact onto upstream materials production instead (Zhao et al., 2021). It should be noted that the grid mix varies between countries and regions, but there is also a rapid decarbonization of the electricity occurring in many countries.

Furthermore, results from more recent studies tend to have lower impacts, especially for the environmental impact of cell manufacturing, due to the assessments of relatively small or underutilized production facilities in prior studies (Aichberger & Jungmeier, 2020). For example, a recent study by Chordia et al. (2021) compares the energy demand per kWh of large-scale battery production to that of a small-scale battery production, and reports a significant reduction in the electricity demand per kWh cell storage capacity in the giga-factory. As a result of the reduced impacts from cell manufacturing (per kWh), the share of environmental burdens shifts upstream to material extraction and production. This means that further reductions in the climate impacts from LIB production require reduction of impacts in the upstream LIB supply chain.

Table 3 GHG emissions reported in selected LCA studies for battery manufacturing (cradle-to-gate), kgCO$_2$e/kWh

Reference	Battery chemistry	Geographical scope	GHG emissions (kgCO$_{2e}$/kWh)
Kelly et al., 2020	NMC111	European supply chain Chinese supply chain	65 100
Chordia et al., 2021	NMC111, NMC811	South Korean energy mix, reference scenario Swedish energy mix, low carbon scenario	188 (small scale factory, NMC111), 104 (giga factory, NMC811) 50 (giga factory, NMC811)
Crenna et al., 2021	NMC111, NMC811, NCA	Chinese based value chain European based value chain	approx.117 (NMC811) approx. 99 (NMC811)
Winjobi et al., 2022	NMC111, NMC532, NMC622, NMC811	Production regions: GREET baseline, US, China, Japan, Korea, Europe	60 (NMC111, GREET baseline) 55 (NMC811, GREET baseline) 51 (NMC811, Europe) approx. 112 (NMC811, worst case)

Most significant impacts arise from the production of cathode materials and cell manufacturing.

PEFCR for rechargeable batteries identifies most relevant impact categories, life cycle stages and processes for lithium-ion batteries for mobility. The share of climate change, resources use (energy carriers, minerals and metals) and respiratory inorganics impact categories of different life cycle stages are presented in Table 4. The most relevant life cycle stages are identified in blue; whereas for the climate impact and energy use the highest impacts arise from the raw material extraction and battery manufacturing, for the resource use (minerals and metals) and respiratory inorganics categories the end-of-life stage is also significant. (Recharge, 2018)

Table 4 Most important impact categories for lithium-ion batteries for mobility (NMC) according to PEFCR. Modified from (Recharge, 2018)

Impact category	Raw material acquisition	Battery production	Distribution	Use	End-of-life
Climate change (fossil) [kg CO_2 eq.]	45 %	26 %	0 %	17 %	12 %
Resource use, energy carriers [MJ]	43 %	29 %	0 %	18 %	10 %
Resource use, minerals and metals [kg Sb eq.]	65 %	1 %	0 %	0 %	34 %
Respiratory inorganics [kg $PM_{2.5}$ eq.]	66 %	13 %	0 %	6 %	41 %

Based on the current information, most significant environmental impacts arise from the production of cathode active materials as well as cell manufacturing for most impact categories. A review by Aichberger & Jungmeier (2020) concludes that the most significant environmental contributor mainly depends on two aspects: 1) the choice of the modeling approach (top-down or bottom-up) for the energy demand of cell production, 2) the capacity and utilization of the cell production facility. In a top-down approach energy consumption for a typical plant is allocated to the different production steps and divided by the manufacturing output, whereas in a bottom-up approach the energy use for each process is calculated or estimated and distributed per battery (Melin, 2019). Typically, top-down approach results in higher energy consumption for cell production and as a result, top-down LCAs typically mention cell manufacturing as the most significant environmental contributor, while bottom-up studies are highlighting the environmental impacts of the cathode production (Aichberger & Jungmeier, 2020).

Especially the production of nickel and cobalt sulphates, raw materials used in the precursor (pCAM) production, and co-precipitation and calcination steps in the production of the cathode active material (CAM) are the most significant contributors to the carbon footprint of NMC cathode materials (Dai et al., 2019; Winjobi et al., 2022). The energy demand of both co-precipitation and calcination is largely due to the heat required. Especially the energy required to the calcination kiln is a major contributor to the energy need; according to Dai et al. (2018) the process can last up to twelve hours at temperatures over 1 000 ° C based on information on the production of NMC622 at Chinese manufacturing facility. It is also noted that the high-quality cathode materials for automotive LIB applications need multiple stages of calcination instead of the single stage calcination. For the co-precipitation step, the majority of energy demand is attributable to wastewater treatment, according to Dai et al. (2019) up to 45 percent of the heat demand of the NMC production facility.

Trend in cathode materials is to shift to higher nickel content (both for NMC and NCA). Conflicting results have been published on how this gradual shift affects the environmental impacts of the NMC/NCA production. Studies by Winjobi et al., (2022) and Accardo et al. (2021) finds NMC111 the most GHG intensive battery chemistry compared to the nickel rich NMC (in $kgCO_{2e}/kWh$). In contrast to this, Crenna et al. (2021) report that the production of an NMC111 battery pack shows lower impacts than more advanced technologies NMC811 and NCA. Rationale behind the difference between nickel rich and nickel low NMC include: (1) calcination of Ni rich cathode materials consumes more electricity (multiple steps required); (2) more carbon- and energy-intensive lithium source LiOH instead of Li_2CO_3 is used; (3) the increasing nickel content does not only replace cobalt content, but also replaces the relatively abundant and environmentally benign manganese content (Tao et al., 2021, Dai et al., 2018).

Regarding cell manufacturing, there are two factors that have major impact on the energy use: the dry room operation and NMP drying in electrode manufacturing are substantial in comparison to other sources of energy use in the cell production (Dai et al., 2019). Since moisture is detrimental to the performance of lithium-ion batteries with $LiPF_6$ based electrolyte, the cell assembly needs to take place in a dry room, in which the moisture content of the air is below 100 parts per million by volume (ppmv) (Dai et al., 2017). Another energy intensive step is the NMP evaporation in cathode manufacturing after coating of the electrodes and before the cells are assembled. The choice of the solvent is crucial for the energy consumption, due to the large quantity of heated air that is needed for the electrode drying process to keep the NMP vapor concentration well below its flammability limit. There is a will to replace NMP in the processing due to the cost and toxicity of the solvent, but so far, the current industry practise is to utilize NMP based coating for cathodes and water-based coating process for anodes. However, there are several LCA studies where different assumptions have been made for the solvent use (Porzio & Scown, 2021).

In addition, aluminium, copper, and electronic components have significant impacts. EU battery regulation highlights the importance of accurately identifying electronic components in addition to cathode materials, as potential main contributor for carbon footprint. In case of aluminium, the share of material in the current collectors and cell and pack casing is significant and may represent ¼ of the total mass of NMC battery. Furthermore, aluminium production is very energy intensive and alumina reduction can also be associated with the production of other potent greenhouse gases such as CF_4 and C_2F_6 (Kelly et al. 2020).

Although other materials have been estimated to have minor impacts in many prior studies, recent articles on impacts from graphite (Engels et al., 2022) and lithium (Kelly et al., 2021) production suggest that for example associated GHG emissions may be higher than previously has been estimated. As an example, LCA study by Engels et al. (2022) on natural graphite production based on industrial primary data concludes that the carbon footprint of natural graphite is more than four times higher than the value reported in EcoInvent (v3.7.1). This highlights the importance of accurate identification of all materials and production steps, as well as verification of representatives of the used datasets for the LCA case.

Impacts of battery materials are dependent on the production pathway.

In addition to the variation in electricity mix in the location of the production facilities, the origins of the battery materials and the varying industrial practices can also significantly affect the energy demand and environmental impacts of lithium-ion batteries. Figure 6 illustrates how significantly the resource type and the processing route affects the GHG emissions for lithium and nickel chemicals used for the battery production.

There are key differences in environmental impacts between brine- and ore-based lithium chemicals which mainly arise from the different energy sources used in these production pathways. The current brine-based pathway (i.e. production from Chilean brines) predominantly uses solar energy, while the dominant ore-based pathway (i.e. extraction of spodumene in western Australia followed by further refining of battery grade lithium in China) relies heavily on fossil fuels (Kelly et al., 2021). In case of nickel chemicals, class 1 nickel used for the battery chemicals has traditionally originated from sulphide ores. New production routes for class 1 nickel have been explored such as production from laterite via HPAL (high-pressure acid leaching) and conversion of nickel pig iron (NPI) via matte. These could diversify the supply of nickel chemicals, but also increase the carbon footprint (IEA, 2021).

In addition to GHG emissions, there are significant regional differences for local pollutants in the refining of battery chemicals, for example, SO_x emissions related to nickel production are highlighted by Kelly et al. (2020). The SO_x emissions from nickel refining can vary to a great degree based on the ore type (sulphide ores as opposed to laterite ores) and nickel refining practices (i.e., whether SO_2 is captured and turned into sulfuric acid) (Kelly et al., 2020).

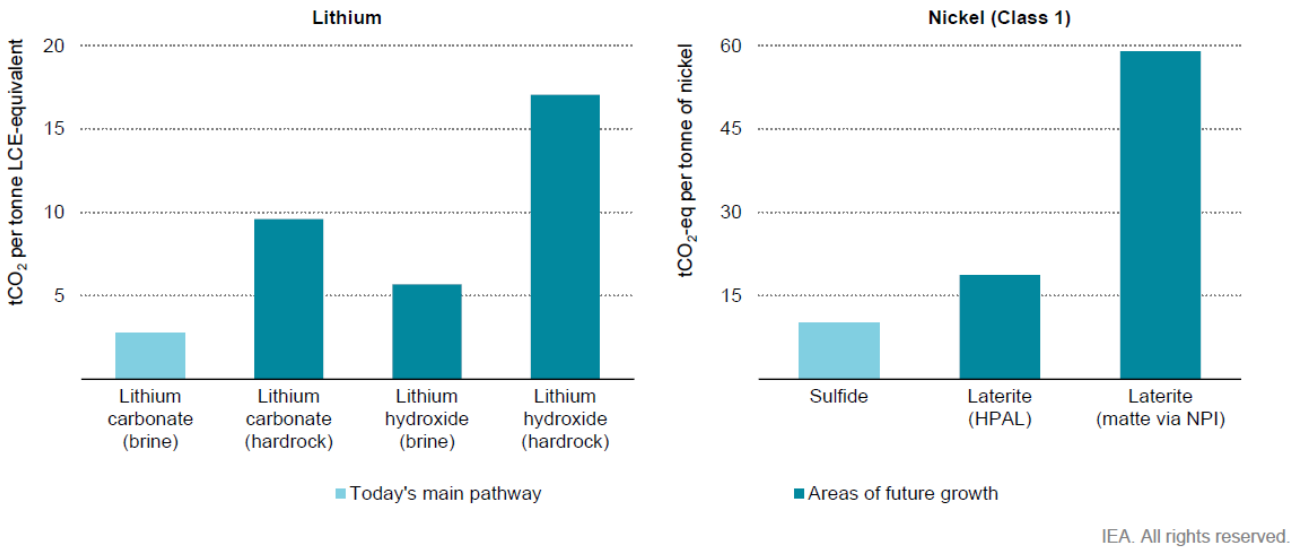

Figure 6 GHG emissions intensity for lithium and nickel chemicals for battery production by resource type and processing route. Figure from IEA (2021), Licence: CC BY 4.0

Furthermore, mineral extraction depends on various process parameters and factors, and changes in material and resource quality (such as ore grade, ore hardness, and mine depth) can therefore have significant impact on the LCA results (Manjong et al., 2021). The evolution of the ore grade can impact the energy use in mining, as the ore grades decrease with time due to the depletion of best quality ores, leading to higher footprints. For example, according to Chordia et al. (2022) low-lithium content brines show higher climate change, water use, and freshwater ecotoxicity impacts compared to high-lithium content brines. This may imply that in future impacts may increase if brines with lower lithium concentration are to be extracted.

The impacts from mining of battery minerals depends on the location and local practices and regulations. Artisanal cobalt mining, which is estimated to represent 15–20 % of total DRC production or 9–12 % of global supply, may have significantly increased human health impacts from heavy metals due to proximity to populated areas and unsafe practices, and can be responsible for an outsized share of the sector's overall health impacts.

These examples highlight the importance of understanding the materials supply chains in the environmental impact assessment. Dai et al. (2019) recommend that battery LCA studies could explore the temporal and spatial variations of the production processes of battery materials and cells to provide a more comprehensive picture of the sustainability of the global LIB industry. Furthermore, Porzio and Scown (2021) suggest that future studies should account for extraction and processing operations that deviate from industry best-practices and may be responsible for an outsized share of sector wide impacts.

Environmental benefits of recycling depend on the battery chemistry and recycling technology.

End-of-life treatment of batteries includes collection and pre-treatment (which can include sorting, discharging, and dismantling of the battery packs/modules), followed by different recovery processes. Currently, mechanical, pyrometallurgical and hydrometallurgical processes and their combinations are implemented at the commercial scale to recycle raw materials from lithium-ion batteries. In addition, direct recovery technologies (for cathode materials) have been increasingly studied in the recent years (Ciez & Whitacre, 2019). Recycling of materials from waste batteries has high potential to reduce environmental impacts by reducing the need for primary resources and reduce supply risks related to certain key metals. However, the impacts from the high energy need and use of chemicals in the current recycling processes may in some cases hamper the environmental benefits obtained.

The environmental impacts of the recycling are specific to the used recycling processes, and recycling benefits are highly dependent on recovering efficiency and electricity mix used in the process. In the case of pyrometallurgical recovery, impacts especially arise from the high energy consumption of the high temperature processing and the loss of aluminium, lithium, and other materials into the slag (Mohr et al., 2020; Abdelbaky et al., 2021). For the hydrometallurgical recovery, environmental impacts arise from e.g., the use of extraction solvents, and therefore the degree of reusing solvents is important for the assessment. In addition, wastewater treatment and emissions to water are hotspots for significant impacts (Abdelbaky et al., 2021). Especially direct recycling methods, in which cathode and anode materials are recovered in their original composition, are considered most beneficial from environmental perspective (Ciez & Whitacre, 2019; Tao et al., 2021). It is however uncertain if and when these methods will be implemented in large scale. In general, there still appears to be significant uncertainty on the net impacts of the various recycling processes due to the high energy intensity of the processing (Hill et al., 2019). It is evident that recycling processes will evolve and scale up in the future when more and more batteries will reach their end-of-life, and optimisation of recycling for EV batteries specifically can be expected. Furthermore, EU's battery regulation will set increased targets for the recycling efficiency and recovery of lithium. This will likely promote hydrometallurgical processes, combined technologies, or other advanced recovery technologies, rather than relying solely on pyrometallurgy.

Research gaps, and what needs to be improved in order to understand the impacts better.

Majority of the LCA studies rely on secondary data for their LCI, and only few studies are based on primary data from industry. While methods and tools are available for carrying out LCA studies, better data is needed especially for the raw material extraction, and for several materials such as binders, and electronic components. Concerning recycling stage, there is still lack of primary data and battery recycling LCAs rely largely on estimated or simulated mass and energy balances because of the limited number of LIBs being recycled. Due to the large uncertainty associated with the use of materials (e.g., solvents) and energy, there is also a significant uncertainty associated with the reported results (Ellingsen at el., 2017). It is speculated that the environmental benefits of recycling could be overestimated because of missing critical steps and essential materials in existing LCA studies (Tao et al., 2021).

The rapid development of lithium-ion batteries (material compositions, design and performance) is also to be considered as the LCI data presented in many older studies may not be representative of the industry practices today. Thus, there is a need for better and up-to-date primary data, especially for the production process (on an industrial scale), the main raw materials used to prepare the battery precursor chemicals for the active cathode materials (e.g., metal sulphates, etc.) and anode materials (e.g., graphite) and the different recycling processes. In addition, for the raw materials extraction stage, there is also a need for regionalised LCI data for mining, such as water consumption and harmonised energy source declarations from exploration to products. (BATT4EU / SRIA, 2021)

To understand the environmental impacts of batteries, it is important to consider all life cycle stages from raw material extraction to the end-of-life. Currently, most battery LCA studies are focused on impacts from manufacturing of battery material and cells, i.e., cradle-to-gate studies with system boundaries starting from raw material extraction and ending at the factory gate. Less studies are available in which system boundary is cradle-to-grave including also use and end-of-life stages, partly because of the complexity of the assessment and lack of data, but also because the battery manufacturer does not have control over the use stage. Therefore, results from the use stage also vary significantly due to uncertainty and complexity of battery performance and lifetime, and in case of EV batteries, due to assumptions for vehicle efficiency, lifetime mileage and electricity mix (Porzio & Scown, 2021; Hill et al., 2019). Including the use and end-of-life stages would result in the most complete assessment of the net environmental impacts and capture the effect of different efficiencies and lifetimes when comparing different battery technologies. However, modelling of the battery behaviour during use stage is complex and would benefit from a set of standardized scenarios that capture variations in charge rate, operating temperatures, SOC (state of charge), and the expected impacts on capacity fade, battery lifetime, and efficiency (Porzio & Scown, 2021). In the case of recycling, the long lifetime of the EV batteries increases of challenges of evaluating environmental impacts. As the battery recycling technologies are continuously evolving and more treatment capacity is built, it is not straightforward to estimate the process parameters when recycling takes place in 10-15 years.

Defining the system boundaries and functional unit is a balance between comprehensiveness and accuracy due to the number of assumptions needed. Studies that include the use and end-of-life stages will result in the most complete assessment of the net environmental impacts, but at the same time carrying out the LCI phase becomes more demanding. Adding use stage and end-of-life in the analysis adds another layer of complexity due to the difficulty of modelling battery behaviour and the lack of data from real-world applications and recycling. Therefore, it is not surprising that many battery LCAs do not incorporate these life cycle stages. Although more laborious and more assumptions needed, inclusion of use and end-of-life stages can sometimes alter the conclusions of battery technology LCA comparisons. As an example, a less resource-intensive battery technology or use of recycled content may show beneficial in cradle-to-gate analysis using per kWh battery capacity as functional unit, but if these materials result in reduced battery cycle life, only a cradle-to-grave analysis with different functional unit may capture the effect of the reduced use stage performance. (Porzio & Scown, 2021) Thus, cradle-to-gate analysis can incentivize use of materials with low carbon footprint and recycled content as well as production of batteries in an energy efficient way, but not the manufacturing of batteries that last longer in use and retains the performance, or batteries that are easier to recycle.

5. Circularity assessment and indicators

Circular economy (CE) is a concept that aims to keep materials in use at their highest value. The aim of CE is to accomplish sustainable development, while simultaneously creating environmental quality, economic prosperity, and social equity, to the benefit of current and future generations. (Kirchherr et al. 2017) In circular economy, indicators (measurable metrics) can provide quantitative or qualitative illustrations on the effects of changing from linear to more circular systems.

World Business Council for Sustainable Development (WBCSD) has published a global landscape analysis that describes the current benefits and motivations for companies utilizing CE indicators. (WBCSD 2018) The interest in measuring circularity originated mainly from 5 aspects: drivers for business performance or strategy, to justify achievements externally, integration of circularity to business, manage risks associated with the existing linear business model, and to know the impact of their circular activities. Therefore, CE indicators can be utilized in achieving knowledge, communication, guiding decision-making or driving business strategies.

Circular economy is a multidimensional concept; therefore, the evaluation of circularity occurs in different levels. Additionally, circularity indicators can be characterized according to the scope, life cycle factors or circularity strategies the method assesses. Saidani et al. (2019) and Moraga et al. (2019) referred to a system for characterizing CE indicators according to studied system level, resulting in three levels: macro, meso and micro. WBCSD and de Oliveira et al. (2021) added fourth, nano-level, dividing the micro category to two levels. The indicator levels are presented in Figure 7.

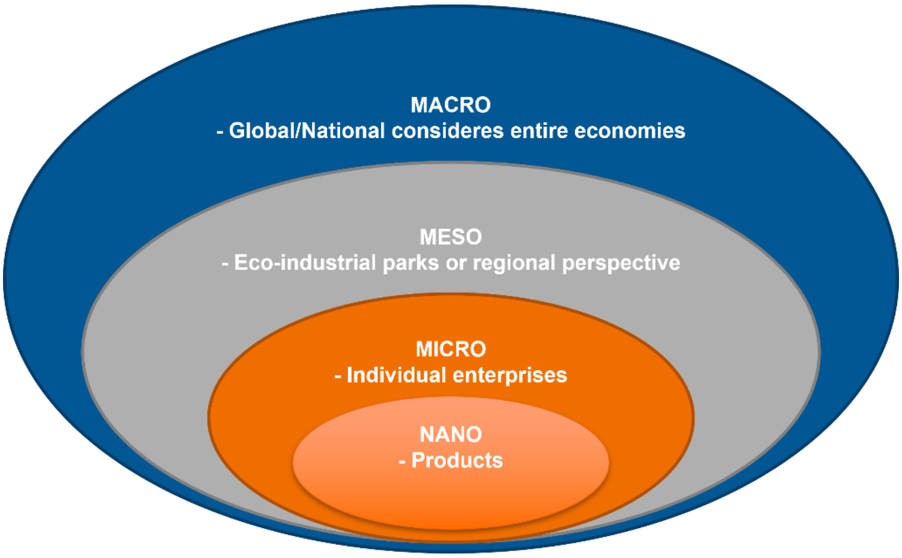

Figure 7 Circular economy evaluation levels. Own illustration based on Oliveira et al. (2021).

This report focuses on micro or nano level indicators as they are the tools of interest in companies, and which might provide metrics for company and product levels. The number of available CE indicators is extensive. As an example, Picatoste et al. (2023) identified 127 different CE indicators.

Research in the field of circular economy is continuously evolving. Recently, the international organization for standardization (ISO) is actively engaged in the development of a series of standards for the circular economy. Overall, the reporting landscape is changing. From 2024, the European Commission will require businesses to adopt the European Sustainability Reporting Standards (ESRS), which includes reporting related to circular economy.

5.1 ISO Standardization work for measuring and assessing circularity

To evaluate the circularity of a battery, or any other product or system, indicators are needed. These indicators define what aspects of circularity are considered, and how those can be measured and assessed. One way to do that is presented in standard ISO/DIS 59020, *Circular economy – Measuring and assessing circularity*. It is part of the ISO 59000 standard series, which includes total of five different documents addressing circular economy from different perspective. ISO 59004, *Terminology, Principles and Guidance for implementation* and ISO 59010, *Guidance on business models and value networks* are interconnected with ISO/DIS 59020 and provide additional information how circularity measurement and assessment should be done. The standard does not set requirements for the value chain but guides and instructs on how circularity is assessed according to it. Entire standard series is still under development, and none of them is finalized yet. Publication dates for the final versions are assumed to be in the beginning of 2024. Therefore, in this document ISO/DIS 59020 version is introduced.

Scope of ISO DIS 59020 is to give a framework to measure and assess circularity of a certain system at a specific time. It can be applied to regional, interorganizational, organizational or the product level, and provides guidance and requirements how circularity performance should be measured and assessed objectively, comprehensively and reliably. The goal of the standard is to assist in the gathering of necessary data, and calculation of the results based on collected data. Standard has three main principles: It should consider principles defined in ISO 59004, ensure appropriate spatial and temporal boundaries and ensure meaningful outcome. When these principles are followed, reliable, transparent and understandable results can be achieved.

Framework provided by ISO DIS 59020 for circularity measurement and assessment is presented in Figure 8. First step is to define the context of application, where framework for the study is determined. It creates the foundation for the study and gives overview of the most important circularity aspects of the studied system. Context of application definition gives input and works as a basis for the boundary setting phase, where the system in focus is defined. It also includes definition of the most important circularity aspects, data quality requirements and pre-selecting complementary methods to be used. These two phases create the starting point for the study and guides the work in the following phases.

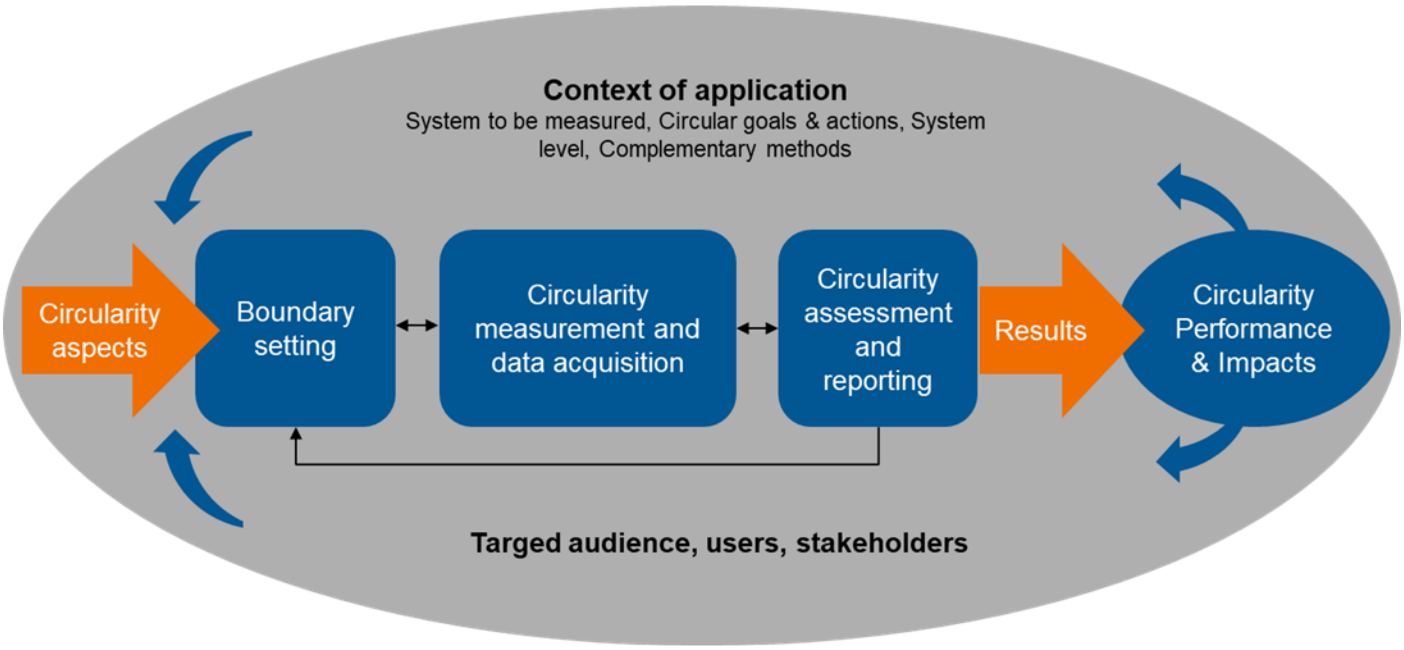

Figure 8 Framework for circularity measurement and assessment according to ISO DIS 59020.

In the circularity measurement phase data for the study is acquired and circularity indicator results are calculated for selected circularity indicators according to the available data. Indicators are divided into two groups, core indicators and additional indicators. Core indicators, presented in Table 5, include total of 14 indicators considering five different categories: resource inflows, resource outflows, energy, water and economic. Resource inflows and outflows are considered to be the minimum requirement for the circularity measurement and assessment, and those shall be quantified and fully balanced. These are also the categories, where links to the battery regulation can be noticed.

Table 5 Core circularity indicators and link to requirements in the EU battery regulation

Indicator category	Circularity indicator	Description	Link to battery regulation
Resource inflows	A.2 Resource inflows		
	A.2.2 Average percent reused content of an inflow	Fraction of input material resources that is reused content.	
	A.2.3 Average percent recycled content of an inflow	Fraction of input material resources that is recycled content	Information and minimum share for recycled content for specific elements (Co, Pb, Li, Ni)
	A.2.4 Average percent renewable content of an inflow	Fraction of material resources inflow that is sustainably produced renewable content	Information on the share of renewable content (battery passport)
Resource outflows	A.3 Resource outflows		
	A.3.2 Average lifetime of product or material relative to industry average	Indicator of time that an output resource (e.g., product) will remain in use compared to an industry average	Minimum durability parameters for some battery categories, expected lifetime in cycles (battery passport)
	A.3.3 Percent actual reused content derived from outflow	Fraction of outflow that is reused.	
	A.3.4 Actual % recycling rate of outflow	Fraction of outflow that is recycled	Minimum collection target, recycling efficiency (by battery category) and recovery target (by material)
	A.3.5 Percent actual recirculation of outflow in the biological cycle	Fraction of outflow content that is recirculated at end of life for safe return to the biosphere and meets the qualifying conditions for recirculation	
Energy	A.4 Energy		
	A.4.2 Average percent of energy consumed that is renewable energy	Fraction of net consumed energy that qualifies as renewable energy, taking into account both energy inflows and energy outflows	
Water	A.5 Water circularity indicators		
	A.5.2 Percent water withdrawal from circular sources	Percent of annual water demand that is derived from circular sources	
	A.5.3 Percent water discharged in accordance with quality requirements	Percent (by volume) of total water withdrawn that is discharged in accordance with circularity principles	
	A.5.4 Ratio (onsite or internal) water reuse or recirculation	Reuse cycles of onsite water	
Economic	A.6 Economic		
	A.6.2 Revenue share of circular resources (or products) (RSCR)	Percent of total revenue generated per year by use of circular (and/or) non-circular resources	

	A.6.3 Material productivity (MP)	Ratio of revenue generated by total mass of all linear resource inflows	
	A.6.4 Resource intensity index (RII)	Quantitative measure of economic growth versus total resource use	

Resource inflow indicators acknowledge three sources of inflow: reused content, recycled content, and renewable content. On the outflow side indicators are focusing on the similar topics: reused content derived, actual recycling rate and recirculation in the biological cycle. In addition, lifetime of the product is assessed compared to industry average product. These two categories can be linked to the battery regulation, where the requirements focus specifically on the recycling of input and output materials, and lifetime of the battery. With standard's indicators it is possible to measure whether minimum requirements are fulfilled. In case of other core indicator categories, topics measured are totally different. For energy, the only indicator considers usage of renewable energy compared to overall energy consumption. Water and economic core indicator categories both include three indicators, which include aspects regarding of water withdrawal and discharge while economic indicators measure revenue and economic growth compared to resource usage.

While core indicators offer the foundation for circularity measurement, it can be expanded with additional indicators. Goal of the additional indicators is to give more specified information regarding the system. These indicators may not be directly focused on the circularity but can still provide useful insight, when transition from linear economy is pursued. For resource inflows and outflows no additional indicators are provided, but for other categories, additional indicators have been defined, presented in Table 6, considering issues such as energy intensity, nutrient extraction from water or net value added (NVA). In addition to indicators, different complementary methods are suggested, that can be used together with the standard to get deeper view on the system. Examples of complementary methods are environmental or social life cycle assessment (LCA, SLCA), Material Flow Analysis and life cycle costing (LCC) studies. Standard do not include or duplicate these complementary methods but encourages their usage in order to avoid negative trade-offs while performing circular actions.

Table 6 Additional Circularity indicators

Indicator category	Circularity indicator	Description	Link to battery regulation
B.4 Additional energy indicators	4.2 Percent energy recovered from residual, non-renewable and non-recoverable resource outflows	Percent energy recovered from residual, non-renewable and non-recoverable resource outflows	
	4.3 Energy intensity	The amount of energy used to produce a given level of output or activity	Carbon footprint (declaration, performance classes, and minimum thresholds)
B.5 Additional water indicators	5.2 Nutrient extraction from discharged water	Extraction of nutrients from water before discharge	
B.6 Additional economic indicators	6.2 Net value added (NVA)	Value of a product minus negative economic factor costs	
	6.3 Value per mass	Value per unit mass of resource	
	6.4 Resource productivity	Ratio of gross domestic product (GDP and domestic material consumption (DMC) or raw material consumption (RMC)	
	6.5 Genuine progress indicator (GPI)	Measures GDP after removing negative impact costs	

Last phase of the framework is circularity assessment and reporting, where achieved results from the measurement phase are evaluated. Based on the results, a comprehensive statement about the system's circularity performance is provided, which is consistent with the scope established in the boundary setting phase. In addition to assessment of circularity indicators, also measurement of other selected sustainability aspects via complementary methods is included into assessment phase. Achieved results from the assessment are reported comprehensively, including all the measurements done in the study. Final report can then be communicated to target audience, users, and stakeholders, which leads to increased knowledge regarding the system under evaluation.

5.2 Evaluating circularity using selected indicators

As stated earlier, there is a wide amount of available CE indicators, each operating at different levels. Consequently, the data required for these metrics can be extensive and varies based on the indicator's scope. Vinante et al. (2021) reviewed that data related to material flows such as resource consumption and recovery of materials and energy, and waste management was often utilized in CE indicators. On the other hand, data related to governance such as strategy, business model and environmental management was identified as relevant data sources in company level indicators. Depending on the indicator and its scope it might require data related to material flows, environmental impacts, economics, strategy and management, circular strategy options and design parameters. CE Indicators can utilize quantitative, semiquantitative or qualitative data.

Although a wide variety of CE indicators have been developed in general, there is very little information on their application and suitability for evaluating batteries as products or companies in the battery value chain. In the next chapters, three circularity indicators are presented on general level, followed by short discussion on other potential indicators to support the design process of batteries, as well as the potential of circularity indicators to complement and support the environmental assessment of batteries by LCA.

Three indicators presented in the next chapters, Material Circularity Indicator (MCI), WBCSD Circular Transition (CTI) and Circulytics, are perhaps the best known outside research community, and for example in Orienting project (2022a), expert interviews stated that these three circularity tools appear to be most in use by companies. All three tools include a series of indicators and metrics, that have company and product specific indicators. These tools will be presented next, with a specific emphasis on the required data for their application.

5.2.1 Material Circularity Indicator (MCI)

Material Circularity Indicator (MCI) is a quantitative indicator developed by the Ellen MacArthur Foundation (EMF) and Ansys Granta. (EMF&Granta, 2019) The initial version of the method was published in 2015, with the most recent revision dated in 2019. MCI asses the circularity of companies' flows of products and materials. The method consists of two indicators: product-level MCI and company-level MCI. As presented in Figure 9, the MCI evaluates the degree to which the material resources follow a circular model, aiming to minimize linear material flows and maximize regenerative material cycles. It also considers the duration and intensity of material utilization in comparison to a similar industry-average product. The indicator produces a single value between 0 and 1, where higher values indicate higher circularity.

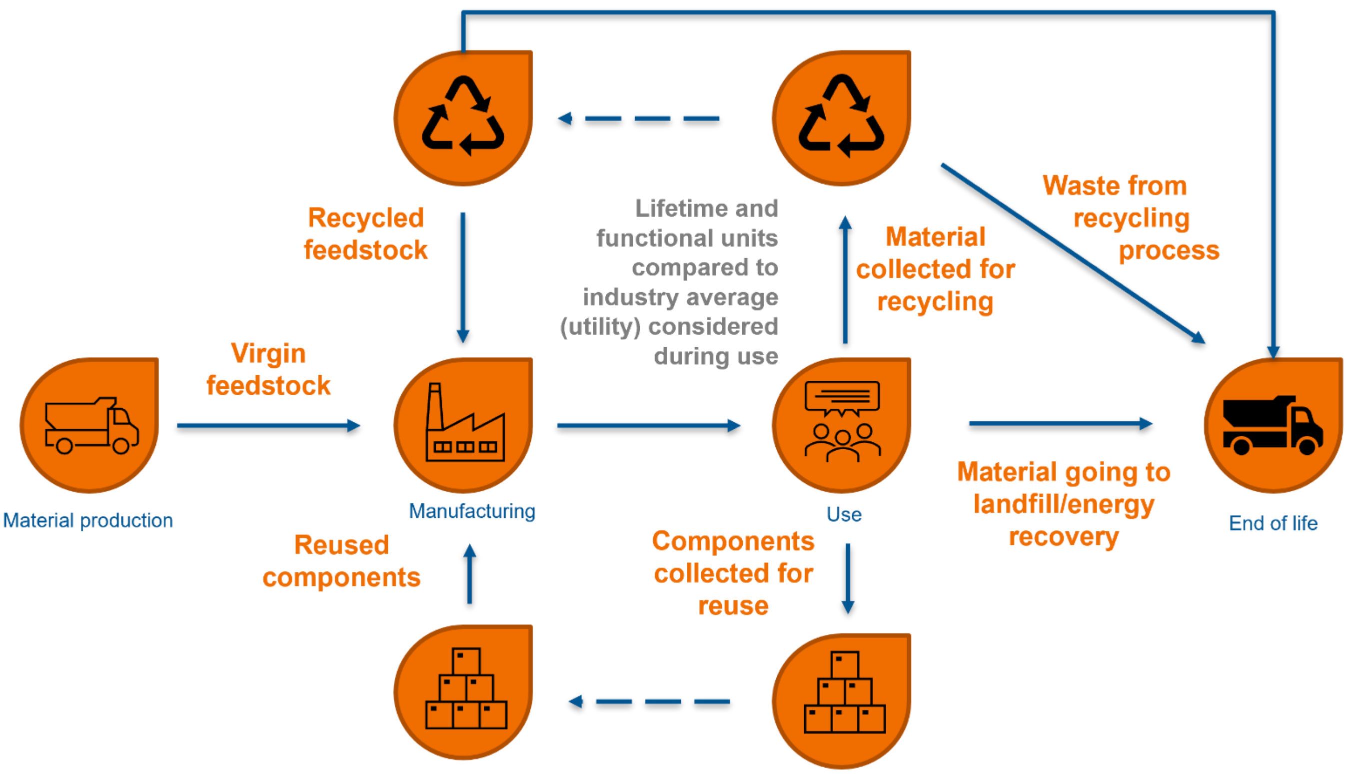

Figure 9 Material flows included in the MCI method adapted from EMF&Granta (2019).

The MCI requires data related to material flows presented in Figure 9, specifically focusing on the mass inflow fractions of virgin, recycled, reused or biological materials. For outflow, the focus is on the fraction of waste and how that fraction is collected for reuse, recycling, energy recovery or in biological materials case for composting. The duration and intensity of the product use is evaluated with utility factor, that requires data related to the products lifetime and functional units that measure the products use compared to industry average. For example, the functional unit for car's or batteries' use could be one driven kilometre.

With utility and linear flow index that is calculated based on the material flows, the product's (for example battery's) MCI score can be determined. The company level MCI is obtained as a weighted average of product level MCIs, indicating that the material circularity of a company can be built up from the material circularity of company's products.

The MCI has limitations. It does not assess efficacy of a closed loop, for example, favouring reuse over recycling. Additionally, it does not take into consideration the potential material quality losses occurred during secondary processing. Therefore, Bracquene et al. (2020) proposed a product circularity indicator (PCI) which aimed to overcome some of the limitations in MCI by further developing the MCI method. The PCI is a slightly more complex indicator that requires additive data compared to MCI, but it produces estimates on the effectiveness of different circularity strategies.

5.2.2 Circulytics

Circulytics is a framework created by the Ellen MacArthur Foundation (EMF) that was launched in 2020. (EMF, 2022) It is a company-level measuring tool that assess circularity within business' operations. The tool is suitable across industries and modifiable to suit multiple business models. The method includes a set of 37 different qualitative and quantitative indicators that collectively capture the company's CE performance inside their entire operations. The method is divided into two indicator categories: enablers and outcomes, which in total have 11 themes. The overall Circulytics score is the equal weight of the two categories with score results being from 0 to 100. The number of indicators that is applied from the method is dependent on the industry and business, for example if the industry is water intensive, the company answers to theme 9 indicators related to water. The Circulytics method and themes are illustrated in Figure 10.

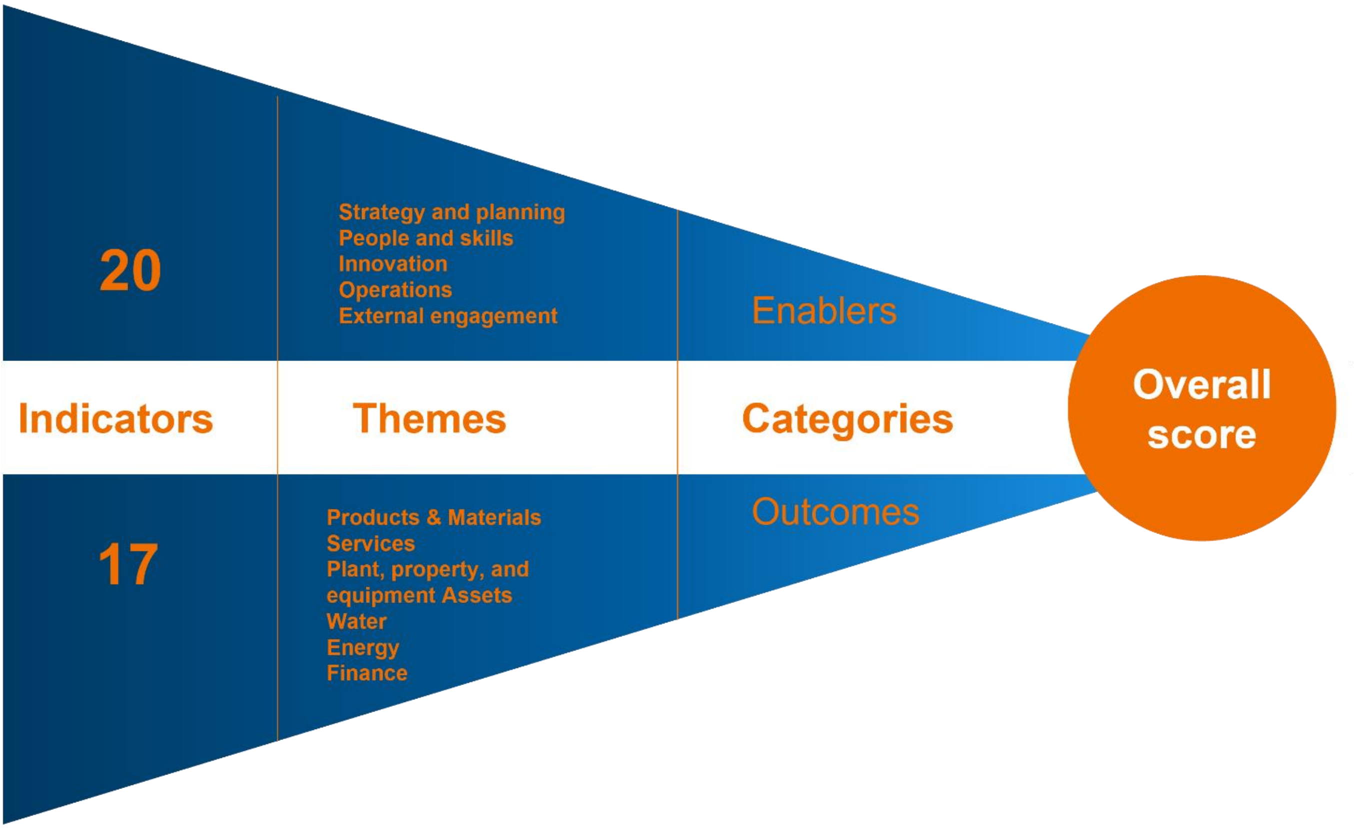

Figure 10 Circulytics method, adapted from EMF (2022).

The Circulytics tools rely heavily on qualitative and semi-quantitative question-based indicators. (EMF-Indicators, 2022) In the enablers category, the strategical and operational aspects of the business are evaluated through questions with answer options, and the score is received based on the answer. The required data to address these questions relate to company's comprehensiveness and measurability of CE plans and targets, their public accessibility, and the effectiveness of internal communication regarding these plans and targets. Additionally, it evaluates the company's utilization of assets to support circular development within its operations. On the external management front, the questions revolve around engaging CE topics among customers, investors, networks, and policy makers.

On the other hand, the outcomes category incorporates more quantitative data, while also utilizing question-based metrics. (EMF-Indicators, 2022) In products & materials theme, the data relates to inflows and outflows of product and material masses. Relating to inflow, the percentual amount of virgin or non-virgin sources, the usage of renewable, regenerative, or sustainably produced percentual masses data is required. In outflows, the interest is in the produced waste, how much of it is landfilled or incinerated and how well the product and materials are recirculated. Also, the material outflows and how well it complies with chemical restrictions list is inquired. The services theme requires data related to annual revenue that is obtained from services and how big of a percentual portion of that is from circular services. Plant, property & equipment assets require data related to procured assets that the company has, and whether these assets have been circularly procured by e.g., utilizing second hand assets or leasing. In water theme the required data relates to inflows of water and its origin and to outflows and whether the outflow water is purified from toxins. In energy, the annual energy usage and potential production data is required. Lastly, the tool requires economic data related to company's finances such as equities and incomes.

According to EMF website, over 2000 companies have signed up to Circulytics, although from the end of August 2023 EMF has no longer accepted submission to the tool due to the overlapping of Circulytics and the incoming ESRS reporting. The methodology is still publicly available at the EMF website and the foundation is currently exploring opportunities to enhance the tools value in the rapidly changing reporting landscape.

5.2.3 Circular Transition Indicators (CTI 4.0)

Circular Transition Indicators (CTI) is a set of quantitative indicators shaped by the World Business Council for Sustainable Development (WBCSD). (WBCSD, 2023) The first version of CTI was published in 2020, and since it has been updated and developed four times, the most recent version being 4.0. WBCSD state that CTI is a simple tool that is applicable across industries and value chains. The CTI was developed based on the results from the WBCSD landscape analysis, that indicated a need for inward facing, quantitative indicators that measure circularity for the whole company, business unit or product (group) within a same framework. The method consists of four modules, presented in Figure 11, that have in total 11 individual main indicators. Inside the main indicators, there are internal indicators. Portion of the indicators are optional.

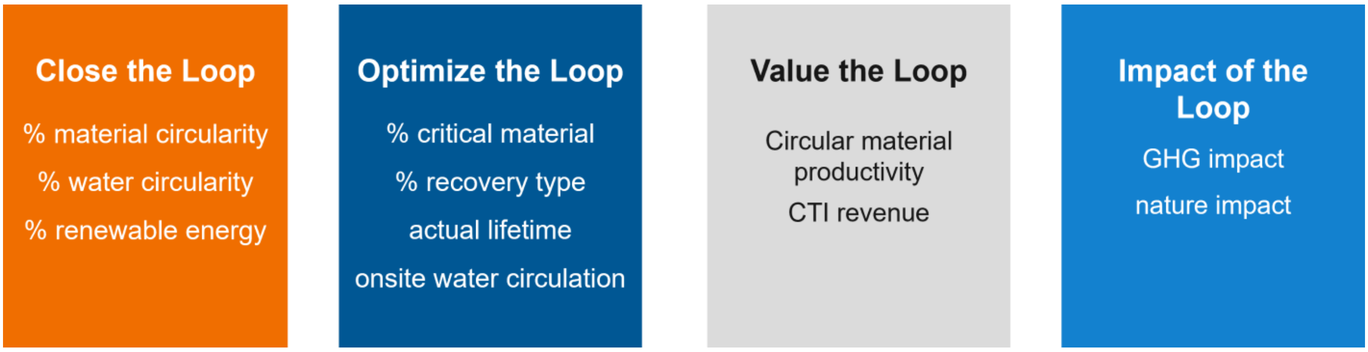

Figure 11 CTI modules and indicators adapted from WBCSD (2023).

The data requirements for the indicators in the close the loop module focus on material, water, and energy flows. (WBCSD, 2023) For inflows, the percentual amount of renewable content and masses, volumes or consumption is required. For the outflows, the percentual recovery potential, recovery rates are of interest. For water related parameters, the quality and source vulnerability are in scope. Optimize the loop indicators require data related to critical materials used in the company or a product and up to date national or regional critical raw material lists (e.g., European Commissions critical raw materials list). For separate outflows the recovery type should be defined e.g., is the product reused or repaired. For actual lifetime data related to industry reference and actual lifetime is required.

Value the loop module takes economic aspects to consideration in the assessment (WBCSD, 2023). Therefore, economic data related to revenue from the assessed part of the business, revenue per product and level of circularity per product based on the result from Close the Loop indicators. Impact of the Loop assess the environmental impacts of the studied process. These indicators are bit more complex and require data from the close the loop indicators and, data related to CO_2 emissions of the sourced virgin and secondary materials, CO_2 emissions of recycling processes and preparation for reuse, land-use types, intensity, and sourcing locations. The GHG emissions are calculated based on the emission factor and weight of the material. The land use evaluates the biodiversity loss and nature impact produced by changes in land-use.

The CTI methodology is freely accessible, although their web-based tool is commercialized to companies. The CTI tool has currently over 2000 different organization accounts from 94 different countries. The challenge and advantage of the method is that it simplifies metrics, therefore aspects or

CE strategies such as reuse are not considered in the method. At the same time, it provides clear metrics for CE evaluation.

5.2.4 Data requirements and differences in CE indicators

The three indicator sets (MCI, Circulytics and CTI) have similarities in the data requirements. The comparison of quantitative data requirements for these indicators is presented in Table 7.

Table 7 Comparison of quantitative data requirements for MCI, CTI and Circulytics indicators.

Quantitative data required for circularity assessment				
Data type	Quantitative data	Indicators		
		MCI	CTI	Circulytics
Inflow	Quantity	x	x	x
	Primary	x	x	x
	Secondary	x	x	x
	Biological	x		
	Criticality		x	x
Outflow	Quantity	x	x	x
	Recovery potential		x	
	Actual recovery	x	x	x
	Energy recovery	x		
Lifetime	Product actual lifetime	x	x	x
	Average product lifetime	x	x	
	Utility	x		
Energy	Annual usage		x	x
	Annual production			x
	Renewable		x	x
Water	Inflow volume		x	x
	Inflow circular		x	x
	Outflow volume		x	x
	Outflow circular		x	x
Impacts	GHG emissions		x	
	Land use, biodiversity		x	
Plant, property, Equipment	Procured following CE principles			x
Finances	Revenue		x	x
	Revenue from services			x

Circulytics has the highest number of internal indicators, while the quantitative data needs are at a same level with CTI. Still, it could be stated that Circulytics requires the widest knowledge on the business and it's CE strategies, which is not totally visible in Table 7 presenting quantitative data requirements due to half of the questions in the method being qualitative or semi-quantitative. MCI requires the lowest amount of quantitative data due to its focus solely on material flows, whereas CTI and Circulytics address circularity in a wider scope of energy, water, impacts and finances. Another major difference in MCI is that it does not have economic indicators, or economic evaluation in the method, which marks the history of the method being designed as a product level-metric. Therefore, especially Circulytics addresses the company level assessment better compared to MCI through several internal indicators, considering wider scope than just material flows. On the other hand, CTI is designed for both company and product level assessment, and in that sense as a method locates between MCI and Circulytics. CTI is the only method that evaluates environmental impacts through two indicators GHG and land use. It should be noted that CTI consists of four indicator modules, and the guidance document states that some of the indicators are optional. For example, Close the Loop module mainly requires resource inflow and outflow data for calculating the indicators. The selection of the suitable indicator set depends on the objectives of the assessment.

Another difference between the indicators is that both MCI and Circulytics methods result in an overall score for the circular performance, while CTI framework consists of a set of different indicators evaluating different aspects of CE performance. As a result, CTI provides results in a more scattered format, covering only a specific aspect of circularity, but they are also easier to interpret. MCI and Circulytics, on the other hand, give a single number for product's overall circularity, but a deeper interpretation of the results requires an understanding of the variables behind the indicators.

All three methods require data related to material inflows and outflows. This quantitative data could be collected or supported with a separate assessment of material flows, referred to as the material flow analysis. The most suitable CE evaluation method is dependent on the studied subject and the specific metrics of interest. Therefore, the suitability of the method to the studied case should be always evaluated in advance.

5.2.5 Circularity indicators in the context of sustainable battery design

The results obtained from circularity assessment can be utilized for multiple purposes, such as in decision-making or product development. Therefore, CE indicators can be utilized in circular design or redesign of products. Picatoste et al. (2023) evaluated the relevance of CE indicators to design more sustainable batteries for electric vehicles. Based on the criteria (quantitative, product level indicators applicable to Li-ion batteries), 15 different indicators were analyzed based on answers from ten stakeholders of the European EV battery industries. According to Picatoste et al. (2023) the three most suitable indicators (based on importance and viability) to support decision-making processes for the circular design and sustainability management of EV batteries were End of Life indices (EoLi), Product Circularity Indicator (PCI), and Circularity Index (CI). EoLi is an indicator that focuses on the end-of-life strategies and their comparison. The PCI is a similar method to MCI as stated before. The CI evaluates circularity based on recovered materials and energy demand required for recovering materials.

Overall, circularity indicators can assist companies in identifying hotspots in their value chains, after which they can focus their product development on those. Depending on the used indicator, the value can be achieved in different ways. For example Circulytics results scorecard, which tells the overall circularity score, and breaks it down into theme scores. From there user can easily recognize where their performance needs the most development. (EMF 2022b) Similarly also other indicators can provide additional value about product when interpreted correctly. In some cases, like for CTI 4.0, interpretation is easier because each indicator includes only one aspect of the circularity. From there it is easy to see which aspects needs to be focused on. In different applications, there may be a desire to emphasize different aspects, and therefore relevance should be defined on a case-by-case basis. When possible, also industry-specific benchmark values are a good way to provide depth for interpreting the results and facilitate the identification of major areas for improvements.

5.2.6 Circularity indicators to complement LCA

As stated in chapter 3, the new battery regulation demands carbon footprint assessment for certain battery types. Carbon footprint calculation is part of the LCA but includes only one environmental impact category of greenhouse gas emissions. The Orienting project (2022b) studied product-related stand-alone CE indicators that were the most suitable to complement Life Cycle Sustainability Assessment (LCSA) framework, where products overall sustainability is assessed. According to Orienting project findings, the most suitable indicators to evaluate circularity, which also complement overall sustainability assessment calculations, were MCI and % Circularity indicator from the CTI tool. MCI was seen suitable for advanced level assessment, where the whole scope of the life cycle is considered. The Orienting project stated that the % Circularity indicator (% material indicator in version 4.0) is suitable for intermediate level circularity assessment, meaning the scope of the assessment is narrower considering only information regarding to manufacturing of the product or it's bill of materials (BOM). Therefore, it could be stated that MCI and % material indicators are potential indicators to complement the carbon footprint calculations as the indicators can be mostly calculated based on the same data that is collected for the environmental life cycle inventory.

Even if only carbon footprint is the only impact category that is demanded in the battery regulation, also other impact categories can be assessed, and it is even desirable. Full LCA requires more data and time, but it provides a better overall insight of battery's sustainability. It can also recognize possible trade-offs, that might be caused due to changes in the value chain. Even when full LCA is performed, it only assesses the emissions and impacts caused in the production, and for example share of recycled material or renewable energy are not reported. Conversely, circularity indicators assess only the product's circularity and therefore do not tell anything about sustainability in general. Hence, it is important to inspect the value chain from both perspectives.

6. Summary and conclusions

There is an increasing demand for lithium-ion batteries and as a result, the raw materials used in their manufacturing. The production and end-of-life operations of the batteries are associated with various impacts on the environment and the society. Therefore, better understanding of the impacts from the battery life cycle is needed to mitigate the negative consequences. Furthermore, increased circularity of battery materials may reduce supply risks related to the (critical) raw materials, increase supply security of battery materials and secure European production. EU's battery regulation is envisaged to improve the sustainability of the batteries placed on the market in the EU by e.g., placing tightened requirements for the management of end-of-life batteries. Furthermore, manufacturers are obligated to share information on their products in order to facilitate circular economy, for example battery second life activities. Finally, the regulation requires carbon footprint declaration for certain battery types, and later also sets carbon footprint performance classes and minimum thresholds to comply with. The mandatory carbon footprint will require the battery manufacturers to gather data on their supply chain, specific to their battery model produced in a specific plant.

LCA is a standardized method for evaluating the environmental impacts of products and it has been widely applied to lithium-ion batteries as well. Thus, plenty of information on the environmental impacts of the lithium-ion battery lifecycle is available. Complexity of the lithium-ion battery value chain and a wide variation in the composition and design, as well as lack of primary data for industrial scale, amongst other, has caused a wide variety in the reported values for carbon footprint and other impacts. However, there seems to be a consensus on where the most significant impacts arise: production of the cathode active materials and manufacturing of the battery cells. Also, various hotspots have been recognized related to specific materials and production pathways, such as SO_x emissions from the refining of nickel chemicals from sulphide ores. While methods and tools are available for carrying out battery LCA studies, there is still a need for better and up-to-date primary data, especially for the production process on an industrial scale, the main raw materials used to prepare the battery precursor chemicals for the active cathode materials, and the different recycling processes. In addition, for the raw materials extraction stage, there is also a need for regionalised LCI data for mining.

For different environmental impacts, most attention has focused on GHG emissions, although in many studies, wider range of impact categories is included. To understand the sustainability of batteries in a more holistic way, it would be beneficial to include a wider set of indicators and not focus only on one indicator. PEF methodology for rechargeable batteries recommends a set of 15 different impact categories to be used in a calculation of the PEF profile, the most important ones being climate change, resource use (energy carriers, and minerals and metals) and respiratory inorganics.

Currently, most battery LCA studies are focused on the impacts from manufacturing of battery materials and cells (i.e., cradle-to-gate studies). Less studies are available in which use and end-of-life stages are included. Adding use stage and end-of-life in the analysis adds another layer of complexity due to the difficulty of modelling battery behaviour and the lack of data from real-world applications and recycling. The use stage is also excluded from the carbon footprint calculation in the EU's battery regulation. Including the use phase and recycling in the system boundary (cradle-to-grave) increases the complexity of the assessment and uncertainty due to large number of assumptions required to model the use phase performance. At the same time, excluding the use phase dismisses the effect of varying lifetime and performance on the lifetime environmental impacts.

LCA is an established methodology for evaluating wide range of environmental impacts of the products through its life cycle. However, alone it is not enough to assess all the necessary aspects for circular economy of batteries. For example, LCA has shortcomings in capturing the supply chain risks associated with geographically-concentrated extraction and processing, as well as dynamics of demand, reserves, and annual trends in production. For example, as a result of the resource depletion, there may be a long-term shift toward more costly and energy-intensive extraction methods. Currently, the lithium-ion batteries on the market contain several materials classified as critical or strategical.

Furthermore, LCA do not provide any information how materials stay in circulation for multiple cycles or their lifetime performance or required production assets, and therefore other CE indicators will be needed. In general, circularity assessment is not as established as environmental impact assessment by LCA. However, ISO 59000 standard series for circular economy is currently under development. Especially the forthcoming ISO 59020 aims to give a framework to measure and assess circularity. Numerous other indicators have been also developed for evaluating circularity, which aim to recognize aspects related to e.g., durability, repairability and usage intensity, however currently there are quite a few examples in scientific literature on their application to the battery value chain. The scope and purpose of different indicators varies, therefore relevant indicators need to be chosen case by case, and for the specific purpose. In this report, three different circularity indicator tools (MCI, Circulytics and CTI) are presented shortly based on their capability to support or complement environmental impact assessment, with a focus on the data requirements for carrying out the assessment.

Circularity indicators presented in this report may be considered as complementary methods also for evaluating environmental sustainability of a product/unit/facility/company, as these indicators typically include aspects/targets, such as supply security and economic sustainability, instead of strictly environmental targets, although environmental benefits may arise from enhanced circularity. As the carbon footprint declaration will become mandatory for several battery types, the LCI data required for the carbon footprint calculation may potentially be utilized for the circularity assessment as well, as many of these are based on material flow data. Depending on the chosen circularity indicator, data on lifetime, utility or economic aspects may also be required. LCA's shortcomings may include lack of the lifetime (in cradle-to-gate assessment), utility and economic aspects as well as system boundaries, if excluding for example production assets in the battery manufacturing. Depending on the case, the results from the circularity assessment may be used to evaluate and compare circular strategies as well as to support sustainable design and decision making, therefore circularity indicators may be also suitable for increasing sustainability in the design phase rather than assessing circularity state of the art. For holistic assessment of circular economy of batteries also economic and social impact indicators may be needed, and some of the circularity indicators consider economic and criticality aspects in certain level.

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