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TwinVECTOR

Twinning for Development of World-Class Next Generation Batteries

Project Number: 101078935

Teaching roadmap and materials required for further activities

Activity: WP4 – Boosting research capacity in sustainability assessments

Submission 31.10.2023

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Comment*: The final text version V3 differs from version V2 in that the links/filenames of the learning materials received from TBU are without the link to TBU's server sharepoint.

Imprint

This document is elaborated by KIT together with TBU. This document is issued for public use by the consortium formed for the implementation of the TwinVECTOR project as followed:

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3	BAYERISCHE FORSCHUNGSALLIANZ BAVARIAN RESEARCH ALLIANCE GMBH	BayFOR	Germany
4	KARLSRUHER INSTITUT FUER TECHNOLOGIE	KIT	Germany
5	TEKNOLOGIAN TUTKIMUSKESKUS VTT OY	VTT	Finland

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Executive Summary

The deliverable D4.1 "*Teaching roadmap and materials required for further activities*" is the first deliverable of the WP4 – Boosting research capacity in sustainability assessments. The aim of the deliverable is to present a feasible teaching roadmap for TBU including strategies and materials to support the way of thinking of a product's environmental, economic and social effects starting in the early battery cell development stage. First, the D4.1 provides an overview of the overall teaching strategy and materials and how these will be developed in cooperation with TBU until the end of the project. All teaching materials are explained in detail regarding their goals, realized activities and next steps. Relevant teaching materials are outlined and summarized where necessary. In addition, a first draft of the Sustainability guideline is provided as a base for upcoming teaching activities. The drafted section will be continuously updated and downfall in D4.2 Guidelines for Sustainability Assessment in month 30. The included methods are Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and social Life Cycle Assessment (s-LCA), Life Cycle Sustainability Assessment.

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1 Introduction

The working package (WP) 4 is designed to support the Tomas Bata University (TBU) for improved excellence, strategic networking, and raised research profile in life cycle thinking within a Responsible Research and Innovation (RRI) framework. It aims to improve the approach to determine the environmental, economic and social impacts of a product over its life cycle by using the methods of environmental life cycle assessment (LCA), life cycle costing (LCC) and social-LCA (s-LCA) and to apply them in the early development stage of innovative battery cells. The aim is to show what contribution the integration of these methods provides to a life cycle-based sustainability assessment (LCSA). Finally, an open question is how Social Sciences and Humanities (SSH) can be integrated into clean energy transition/energy storage research in the frame of RRI.

1.1 The Project TwinVECTOR – an Abstract

The TwinVECTOR project aims to create a center of excellence at the Tomas Bata University in Zlín (TBU), focusing on next generation battery sustainable design, energy business models, and sustainability assessments, with the support of an upgraded research and administration unit (RAU). The RAU coordinates the capacity building measures of the partners' activities to emphasise the synergy and the creation of the centre of excellence at TBU. Hence, TBU will team up with excellent foreign institutions: VTT, AIT, KIT, and BAYFOR. The whole spectrum of activities is planned to activate knowledge at TBU, set-up knowledge pool and capacity building activities enabling flexible, multidisciplinary project teams to address the topic of the next generation of batteries with the help of life cycle thinking via sustainability assessments.

Additionally, advanced battery technologies also need to be assessed via a combination of techno-economic simulation tools, cost-benefit analysis, and business model innovation. The widening country of Czechia, specifically the Zlín region, aims to increase scientific expertise and capacity in these areas and methods. The consortium members will share the expertise so that TBU can boost the research capacity to undertake world-class R&D activities in the energy storage field and bring them to the market. The ability to produce original ideas will be reflected in multiple outcomes expected in the short-term horizon: EU projects submitted in cooperation with excellent partners, scientific papers, conferences, and business agreements. High-impact research is expected long-term, with technology transfer into practice. The existing research capacity of all members will be strengthened via additional capacity-building activities in partnership with BAYFOR.

1.2 Purpose and Scope of the Deliverable

The deliverable 4.1 aims to provide a roadmap for the teaching strategies and materials of the TwinVECTOR project to support the way of thinking of a product's environmental, economic and social effects starting in the early battery cell development stage throughout its entire life. Furthermore, the document shall serve as a documentation of running activities and help TBU to

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use the developed materials. In line with this, a first draft of the sustainability guideline is presented in section 4.

The included methods are Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and social Life Cycle Assessment (s-LCA). The aim is to provide a robust base for further activities during the project and to support TBU with the expertise in the named methods. To do so, the deliverable is separated into three sections.

- Section one; includes the first input from TBU to define the scope of activities.
- Section two; provides a roadmap and frame for the planned and ongoing **activities**, how these will contribute to the overall project progress and how these will be interconnected.
- Section three: provides a detailed overview of the teaching activities, related materials and further planning
- Section four, the first draft of the **sustainability guideline** and related data is drafted, which will form the base for deliverable 4.2 in month 30.

The document drafted in section 4 will be updated continuously in parallel to the ongoing activities and will serve as a base for further deliverables and activities.

1.3 Process of Development

The document on hand has been created based on several iterations with TBU and other partners (AIT and VTT) starting from month one. Several meetings have been held to discuss the progress of the teaching strategy and to adapt to the outcomes of WPs 3 and 5 and TBU demands. A first version of the teaching roadmap has been provided to TBU in month five on the project SharePoint for commenting based on an initial meeting on November 14th 2022. Since then, the teaching strategy and activities have been developed to meet TBU needs over the course of the project. The general regulative issues of the TwinVECTOR project, written in both the Grant Agreement and the Consortium Agreement, have been followed and addressed.

1.3.1 Status Quo and Expected WP4 Contribution

An initial TBU-KIT online pre-meeting for expectations elicitation under WP 4 was held on 14th of November 2022. A total of 10 participants from TBU and two members from KIT participated. After a brief introduction of the WP goals, participants were asked to provide insights into which sustainability assessment methods they are already familiar with (see Figure 1). There was already knowledge of main methods at TBU, in particular in the field of life cycle-based methods. Here LCA was named the most, followed by LCC and s-LCA as core methods. Accordingly, participants were asked to provide preferences indicating what they would like to learn or which materials they considered the most important to increase their abilities in sustainability assessment (see Figure 2). Life Cycle Inventory (LCI) modelling was considered as most important, followed by a general way

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of approaching sustainability assessments, in particular for LCA. Third ranked was the provision of existing LCIs/models. Finally, expectations for a perfect project were expressed (Figure 3), which are mostly in line with the ranking displayed in Figure 2. The results were integrated as a starting point to draw a first roadmap of activities which was presented and discussion with TBU in month 5 in line with the MS 4.1: Definition of support actions - Adopted roadmap for the teaching strategies and materials.

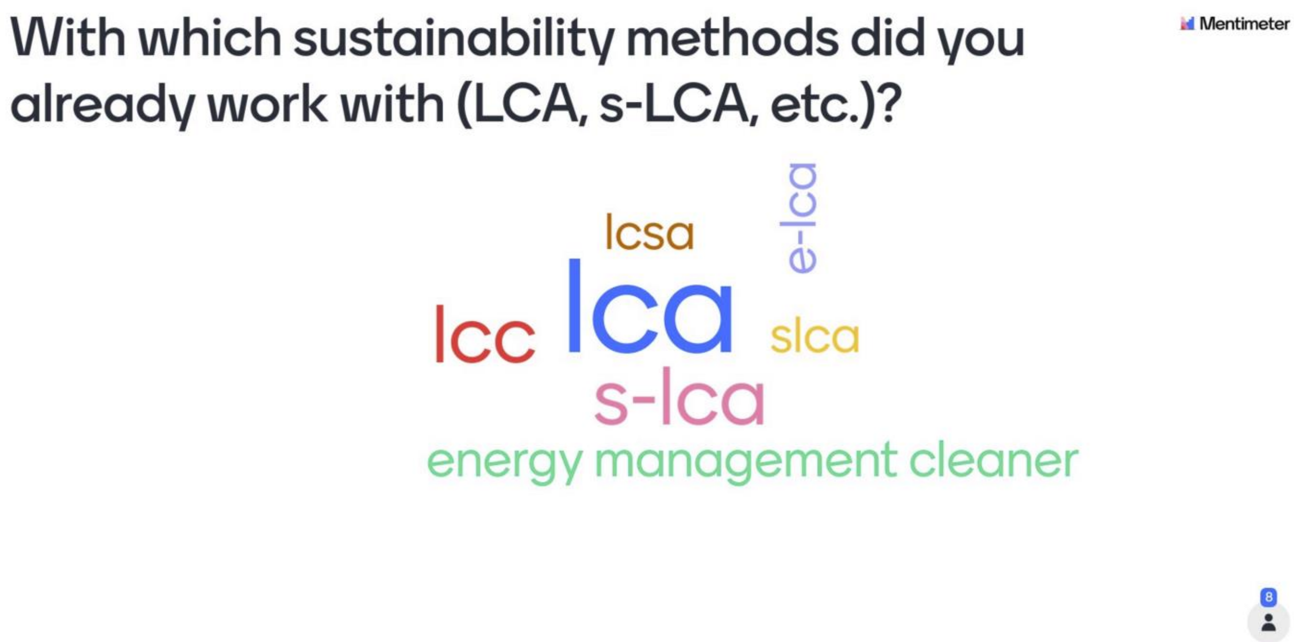

Figure 1 Experience in the field of sustainability assessment methods at TBU via mentimeter©

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Figure 2 Ranking of different aspects for working package 4 in line of teaching activities via mentimeter©

Figure 3 Expectations of TBU-participants in line of a “perfect” project via mentimeter©

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2 Teaching Roadmap and Strategy

The teaching roadmap goal is to draw a clear strategy for the provision of support activities for TBU regarding sustainability assessment of emerging battery technologies. Here, mainly life cycle-oriented methods are at the centre of most activities. A wide set of predefined activities and materials is used to provide support and knowledge to TBU. These activities have been adopted based on continuous discussions with TBU as explained in section 1.3.1. The teaching activities and materials include the following measures that will be explained in detail in the corresponding sections:

- Workshops: four events with broader thematic scope
- Webinars: six online events with specific topics
- Individual appointments for troubleshooting – Jour-Fixe: One fixed monthly online meeting to discuss predefined problems
- Exchange activities: Staff exchange from TBU to KIT and vice versa
- Support in master thesis supervision: two master theses from TBU co-supervised by KIT
- Sustainability theatre: Last activity of the WP4

Extended activities

- Common publications: Support in writing of journal and book contributions
- Workshop and conferences: Support in selection and contribution to relevant events in the field
- Common project proposals: Joint project proposal development

The teaching strategy with the interconnection of all activities and related materials is provided in Figure 4. All activities have a scope on life cycle-oriented methods as LCA, s-LCA, LCC and their combination. All teaching activities and materials are connected and partially built upon each other and have been discussed with TBU. In addition, the named activities and materials are used to provide a first draft of the Deliverable 4.2 “Guidelines for sustainability assessment” in section 4 of this deliverable. By doing so, a demand-oriented sustainability guideline document for TBU can be developed in month 30 focusing on the assessment of batteries. The latter will serve as the basis for the Sustainability Theatre in month 32 and will provide detailed guidance on relevant topics and methods. The entire guideline development process is carried out in an iterative procedure between KIT and TBU. An overview of the teaching roadmap including all named aspects including deliverables and milestones is provided in Figure 5. A detailed overview of the workshop, webinars and all other activities is provided in the GANTT chart in the annex.

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All activities and materials are backed up by corresponding data, as depicted in Figure 4. These are made available for the TBU team via the project MS TEAMS folder within an own folder for WP 4. Here all materials from, e.g., the Workshops and Webinars in form of presentations and protocols are made available within the consortium. Corresponding references to each folder where materials are available in the specific sections under the column ""materials". The specific teaching materials for the different methods as LCA and LCC will be made available in the subfolder ""teaching Materials". These materials have the aim to support TBU in the development of named methods. Here different guidelines, open access articles and relevant reports will be made available. In addition, models and data from open access publications from KIT will be provided. Data formats will be provided in MS Excel for life cycle costing or XML-based International Life Cycle Data system format (ILCD), for the exchange of LCA relevant data. Here, not all processes can be made available due to licences issues related to the used database Ecoinvent. All relevant materials are provided via direct links in tables for each activity for easier orientation for TBU.

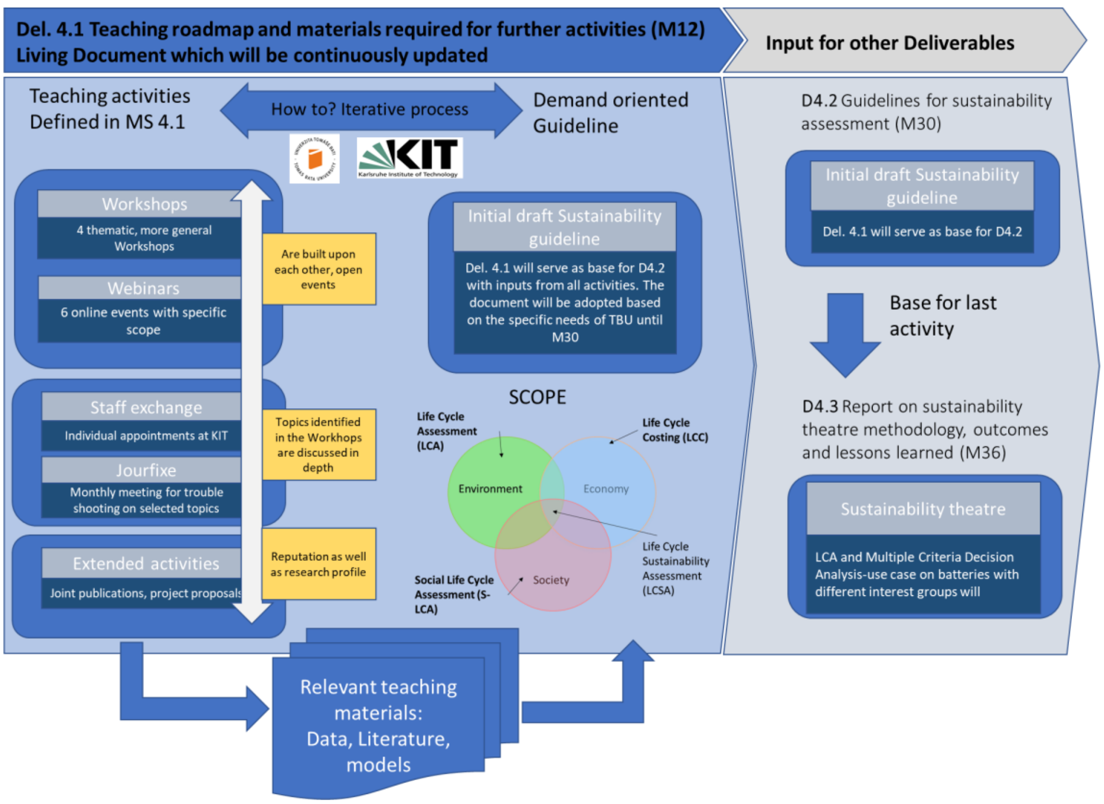

Figure 4 Overview of teaching materials and their interconnection in Del. 4.1 and how these downfalls in the upcoming activities and deliverables

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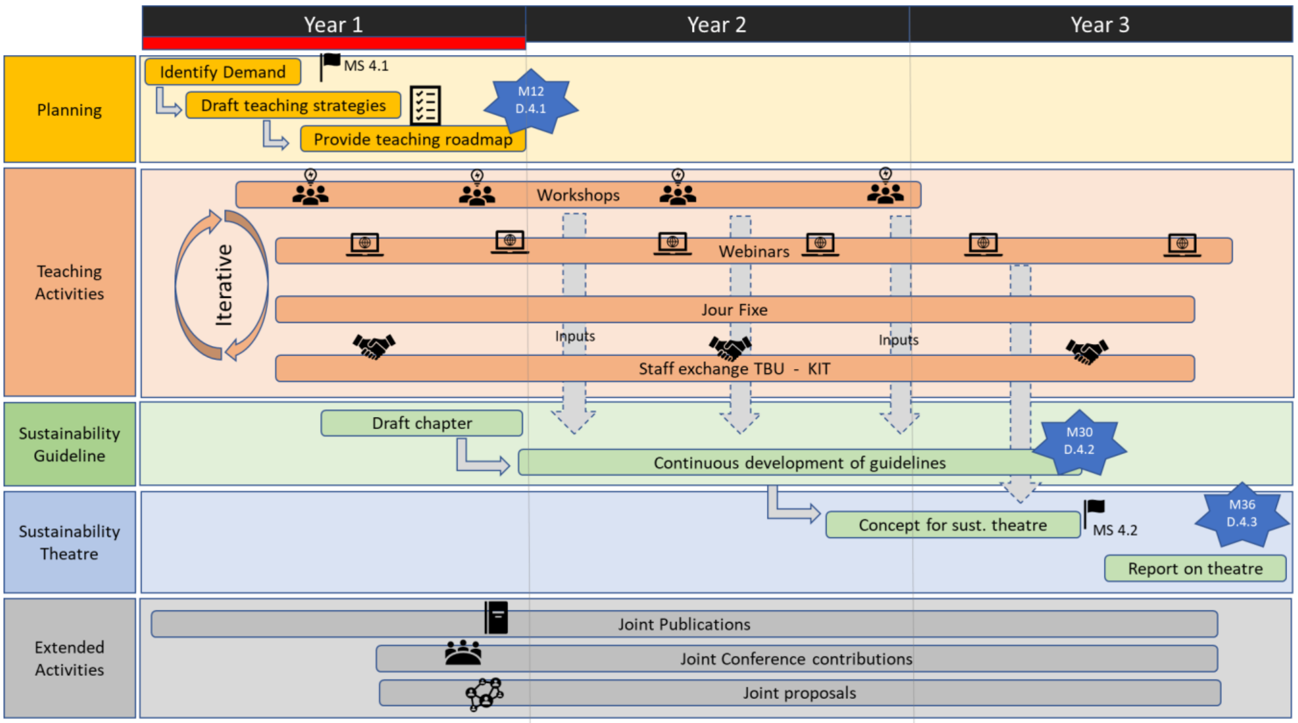

Figure 5: Roadmap for teaching activities and materials MS=Milestones, D=Deliverables, red bar represents the status quo of activities

3 Teaching Activities

This section provides an overview of all activities named in section 2. All activities are briefly introduced, then the goals are outlined and how these will be realized throughout the entire project. Corresponding materials are provided for each activity.

3.1 Workshops

The primary objective of the planned workshops is to share expertise and build up capabilities to equip TBU with the knowledge and skills necessary to conduct sustainability-oriented assessments out of a life cycle perspective, in particular LCA. The workshops will be carried out in an interactive way, to encourage an active exchange and dialogue, with experts providing guidance in the field on different life cycle methods and sustainability assessment topics. The workshops will be

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accomplished alongside the named materials for teaching in the sustainability guideline. The activity goals are:

- Active exchange - provide enough space for in-depth discussion
- Explore different topics in a broader sense
- Identify the needs of TBU for teaching activities and materials

Tentative dates for the events have been documented in the TwinVECTOR GANTT chart on SharePoint and the annex. Each workshop will include 3-4 overview presentations designed to serve as a basis for in-depth discussions. The intended skill level for participants is intermediate, not beginner. The scope of the workshops has been discussed and reformulated with TBU to better match their needs. The first workshop has already been conducted. The tentative titles for the planned workshops are as follows:

- Workshop 1 (already carried out): Introduction to RRI, sustainability and life cycle perspective (lab scale to market to society); (04.04.2023, 2:30 – 6:00 pm)
    - See detailed description in section 3.1.1 Overview of the first workshop
- Workshop 2: Life Cycle Costing – Practical Approaches in the context of LCSA modelling for batteries:
    - Understand how to employ Life Cycle Costing as a valuable instrument for making informed decisions, whether you're a product or service developer or a consumer looking to make a purchase, considering various viewpoints.
    - Insights about different LCC variant (E-LCC and s-LCC)
    - Monetarization of intangible elements
    - Differences of some process elements in comparison to LCA (e.g., finance services)
- Workshop 3: Multi-dimensional assessments: stakeholder integration and combination of sustainability metrics.
- Workshop 4: Future sustainability assessment:
    - Exploration of how SSH can be integrated into energy storage research concerning RRI,
    - Specific examples of the battery storage use cases.

The workshops will be held in a hybrid format, if necessary. A brief report will be produced for each workshop, contributing to the development of the sustainability assessment guideline, scheduled for completion in month 30.

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3.1.1 Overview of the first workshop

The first workshop was held on April 4th in Vienna at the Austrian Institute of Technology (AIT). The aim was to spur an active exchange and guidance about the different life cycle methods and sustainability assessment topics. The agenda is provided in Table 1 and all relevant workshop materials can be found in Table 2. The workshop was structured so that KIT provided initial presentations on selected topics (see in Figure 6), followed by a presentation by TBU on the same subject. For each topic, leading questions have been discussed covering the following aspects:

- What do you see as major challenges in early TRLs sustainability assessments?
- Do you think that a meta-heuristic like CT assessment makes sense?
- Which LCIA method do you prefer?
- Do you think that the impact categories Climate Change and Resources Depletion are sufficient for the assessment of battery technologies?
- How to choose a suitable sustainability approach for a specific product or technology (criteria for selection of sustainable assessment method)
- Goal and scope phases of assessment methods
- Process of developing an LCA study in general, initial thought process considering all dimensions
- How to combine those different assessment methods (social, economic, environmental)
- Completion of Goal and Scope analysis?
- Life cycle inventory analysis?
- Data procurement, Energy analysis, Transport data, Allocation
- Life Cycle Costing & Social-Life Cycle Assessment?
- Challenges in measuring lab-scale energy and material flow data?
- Specification of requirements for the subsequent scaling of the LCI data?

This approach provided a robust foundation for in-depth discussions on methodological issues related to LCA. Additionally, discussions extended to other pertinent methods, such LCC and s-LCA. The first workshop also served as a base for the first webinar, focusing LCIs for battery LCAs. All presentations and meeting minutes have been made available on the project sharepoint. TBU has agreed to maintain this format for the subsequent three workshops.

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Table 1 Agenda of the first Workshop on sustainability methods held in Vienna.

Time	TOP	Content – 4th April 2023
14:30	TOP 1	Welcome and Agenda (Manuel)
14:35	TOP 2	Overview on Constructive Technology Assessment as perspective for sustainability Assessment (Manuel)
14:45	TOP3	Life Cycle Perspective with a focus on Life Cycle Assessment (Jens)
15:00	TOP4	TBU-Perspective (Viera)
15:15	TOP5	Guiding questions, group discussion exchange on the topic, goal identify 1-2 presentations for the webinars (all)
16:00		Coffee break
16:15	TOP6	Measurement and scale-up of lab-scale LCI data (Merve)
16:35	TOP7	LCA Journey (Debashri & Thaiskang)
16:50	TOP8	Guiding questions, group discussion exchange on the topic, goal identify 1-2 presentations for the webinars (all)
17:45	TOP9	Wrap-up and next steps (notes from Discussion)
18:00		End

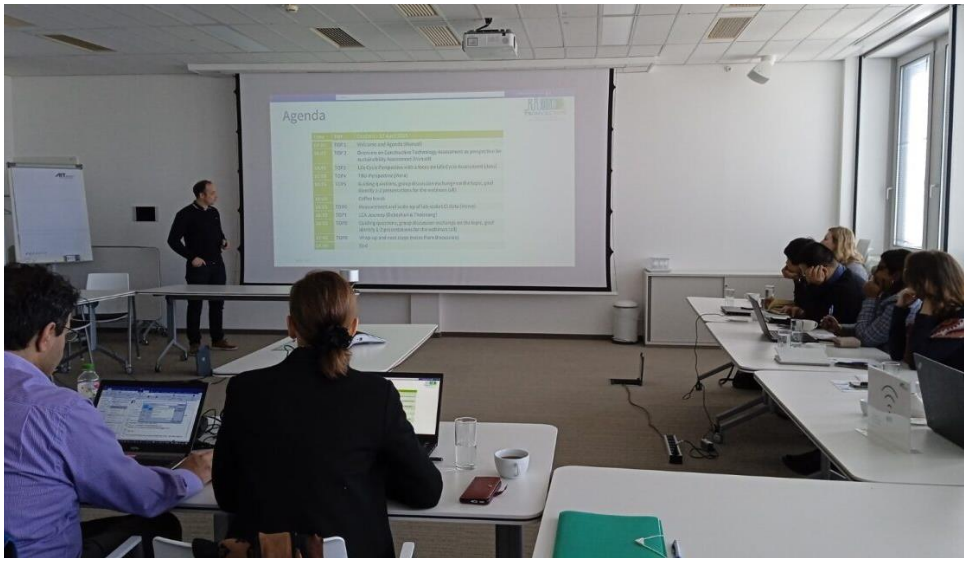

Figure 6 Impression of the first workshop in frame of WP 4 in Vienna at AIT

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Table 2 Relevant materials of the first workshop

Title and responsible person	Type	Description	Link/File name
KIT WS No1 Viera Pechancová	PowerPoint	Overview of TBU activities in battery research	WS TBU 1
Overview on RRI and CTA as perspective for sustainability Assessment Manuel Baumann	PowerPoint	General Introduction to RRI and CTA and challenges in prospective system analyses	Overview
Life Cycle Perspective Jens Buchgeister	PowerPoint	General introduction to LCA, goal and scope, Life Cycle impact assessment and interpretation	LCA_Overview
Measurement and scale-up of lab-scale LCI data Merve Erakca	PowerPoint	Overview of challenges and relevant methods and approaches for scale-up of battery technologies	LCA_Lab_Scale
Debashri Paul, Thaiskang Jamatia	PowerPoint	Overview of LCA experience at TBU and LFP use case	AIT_TBU

3.2 Webinars

In total, six online webinars, each with two presentations on the topic sustainability assessment and batteries, will be offered and carried out. Here, potential contributors from other networks and projects, the EU-project Storage Research Infrastructure Eco-System (StoRIES), EERA or POLiS – Cluster of Excellence Post Lithium Storage will be included as presenters outside of TwinVECTOR with different relevant use cases. Specifically, the webinar goals with a focus on TBU are:

- Allow In-depth view into specific topics via external experts
- Open up the discussion beyond TwinVECTOR
- Provide a comprehensive view on most recent developments on selected topics

The online webinars will be open to anybody and shall provide sufficient space for discussion. The length of each webinar is 2 hours, with presentations with a length of 20-30 minutes and sufficient time for discussion. The tentative dates are already provided in the corresponding GANTT charts in

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the annex. The topics of the Webinars are not predefined, rather they are based on ongoing discussions of the Jour fix and the workshops. This allows to match the needs of TBU in a better and more flexible way. The next Webinar is scheduled for December 2023 and will aim at the LCC of battery systems. An overview of the first online workshop which serves as a blueprint to follow webinars is provided in the following section.

3.2.1 Overview of the first webinar

The first Webinar “Life Cycle Inventory (LCI) Building and Modelling for Life Cycle Assessment (LCA) of Batteries" took place online on June 26, 2023, from 10:00 AM to 12:00 PM CEST. The event was announced via the European Energy Research Alliance (EERA) and the Joint Programme Energy Storage, the StoRIES project and LinkedIn. The event was held in an open format with preregistration. In total, about 40 participants took part in the webinar. The agenda for the first webinar can be found in Table 3.

Table 3 Agenda for the first Online Webinar, which serves as a blueprint for follow-up events

Time	Content
10:00	Welcome and Introduction
10:10	Mudit Chordia (Chalmers University of Technology) - “Navigating data gaps in Life Cycle Assessment of Lithium-ion battery production”
10:35	Discussion
11:00	Dr. Roland Hischier (EMPA) - “Towards more flexibility and transparency in life cycle inventories for Lithium-ion batteries”
11:25	Discussion
11:50	Wrap-up
12:00	End of webinar

In general, the event received a very positive feedback from both, speakers and listeners as it allowed and extended in-depth discussion on the presented topics. In the following, the content of both presentations will be elaborated.

Presentation 1: “Navigating data gaps in Life Cycle Assessment of Lithium-ion battery production” by Mudit Chordia:

Life cycle assessment (LCA) practitioners assessing environmental impacts of Lithium-ion battery (LIB) production are plagued with lack of data concerning the energy and material inputs to the production facility and the supply chain of raw materials. Although, LCA studies on LIB production

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have been conducted for several years, a number of recently published studies still rely on older ones for data – which were based on small-scale facilities, proxies, or stoichiometric calculations. Development of the GREET database has helped alleviate some issues regarding the availability of data. However, relying on a single source of data implies that there is lack of representativity, and the LCA practitioners are tied to the technical and methodological choices in GREET. LCA practitioners in recent years have presented studies based on technical permit applications, physics-based models, and vendor data. Although these approaches complement GREET, they lack the versatility to address the growing number of LIB chemistries and cell formats being implemented by battery manufactures. Further, with a growing interest in the industry to develop technologies reliant on less scare metals such as the sodium-ion batteries, there is a need to develop tools that guide technology development by estimating environmental impacts of future industrial-scale production.

Presentation 2: "Towards more flexibility and transparency in life cycle inventories for Lithium-ion batteries" by Roland Hischier

A successful evolution of the transportation sector towards electromobility depends, among others, on the battery chemistry and technology, and its related environmental impacts. Poor availability of data at the commercial production scale and the diversity in modelling choices made evaluating the environmental impacts of Lithium-ion batteries (LIB) over the past decade difficult and uncertain. At Empa, we aimed at contributing to the creation of flexible and transparent life cycle inventories of LIB for background databases by means of a consequently modular approach, applicable as a common framework to model various generations and chemistries of LIB. So far, we compiled such modular LCI datasets of current and near-future market LIB chemistries, namely NMC111, NMC811, NCA, and LFP by using the most recent data from existing sources, as well as the internal, technical know how. In a first analysis of our data, we included a wide range of sensitivity analysis in order to evaluate the relevance of choices in areas of scarce data availability. Besides a more detailed view on the established framework, we will focus in our presentation on a comparison of the results with other data sources, and dare a view into future developments and their influence on such an analysis.

3.3 Individual appointments for troubleshooting (Jour-Fixe)

The aim of the measure is to provide a Jour-Fixe (JF) for TBU with open questions and answers (Q&A) regarding LCA, LCC and s-LCA modelling. Specifically, the aim of this activity is to:

- Provide a base for continuous exchange with TBU on selected methods
- Support TBU in a demand driven way via different experts from KIT on corresponding methods
- Document the discussions for overall learning processes

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The JF takes place once a month and for 1 ½ h out via a fixed Teams meeting. TBU can send an overview of questions for selected topics e.g., LCC, s-LCA or LCA in advance to KIT, which allows KIT to prepare and structure the JF Q&A sessions. The questions, comments, and answers are carried out within an online document available on the SharePoint. A corresponding overview of the realized JF with a short overview on the main topic is provided in Table 4. Note that the JF dates have just been defined for 2023 and will be defined for the next years within the last meetings of the 2023. A detailed overview of the related materials is provided in Table 5.

Table 4 Overview of conducted and planned JFs.

Date	Content
19.04.2023	**Main topic: E-LCA** Discussion: goal and scope, functional unit, system boundaries, data collection, scaling up, LCI
17.05.2023	**Main Topic: E-LCA** Discussion: mainly on LCI topics for e.g., current collectors, tab for cell container etc., transportation of raw materials etc.
14.06.2023	**Main topic: E-LCA** Discussion: Chordia et al. paper on LCA, Greet/Batpac, collecting inventory data, JRC rules and general LCC topic **Additional topics: Master thesis topic definition**
12.07.2023	**Main Topic: E-LCA** Discussion: Initial system definition, other case studies, scale-up of lab scale battery
09.08.2023	Rescheduled due to summer break
18.09.2023	**Main topic: LCC** Discussion: Integration of LCC & LCA (system boundaries, functional unit), different forms of LCC, scope of different LCC approaches
04.10.2023	**Main topic: E-LCA of Li-Ion battery** Discussion: LCI modelling, redistribution of energy demand for spatial environment, modelling of electricity generation flows in Ecoinvent **Additional topics: Master thesis topic definition**
15.11.2023	TbD
29.11.2023	TbD

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Table 5 Relevant materials related to JF

Title / responsible	Type	Description	Link/File name
TwinVECTOR JF Topics KIT / TBU	Word document / Living Document	Collection of JF questions from TBU and responses from KIT	KIT JF
TwinVECTOR_WP4 JF KIT /TBU	PowerPoint	Collection of JF questions for Meeting kick-off	TBU JF

3.4 Exchange activities

Within the exchange activities, researchers and students from TBU can visit KIT over 2-30 working days to gather practical insights and support related to sustainability assessment activities. Also, researchers from KIT will visit TBU (2-3 days) for case study development, LCA and wider sustainability modelling support. The specific goals are:

- Provide in person support for TBU on specific methodological questions
- Deepen networking activities
- Provide insights to the overall KIT research landscape (lab visits, meetings)

The exchange activities from TBU to KIT-ITAS will be organized in person. The stays will be planned by TBU and coordinated with KIT-ITAS. To that end, coordinating partners from TBU will provide a staff exchange where the details of the exchanges are fixed and documented. The stays will be planned on an individual basis and can include e.g., the discussion on methods, data collection, life cycle modelling, joint work on publications, attendance at presentations and open meetings. It is important to initialize the exchanges as early as possible, e.g., 3 months in advance, since issuing a contract requires a long time. The contractual aspects of the research stay at KIT-ITAS will be regulated via the infrastructure usage contract.

3.4.1 Overview of first exchange activity

The first staff exchange with each of three project members from TBU and KIT was carried out on May 11, 2023, at KIT. Here a first in-person discussion on battery LCI was realized. After that, a visit to relevant KIT infrastructures was carried out, including the battery laboratories at the Institute for Applied Materials (IAM) and the Battery Technology Centre (BTC) of KIT. An overview of the first

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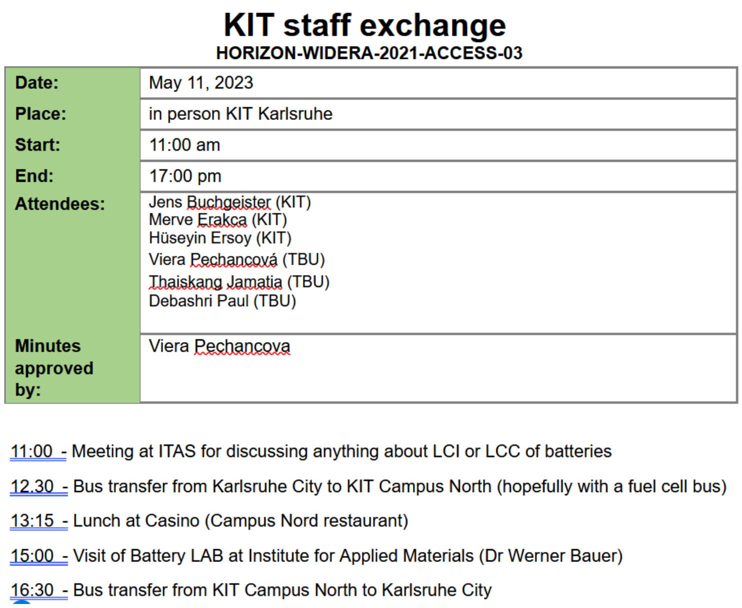
staff exchange is provided in Figure 7. Further exchange activities will be defined by the end of 2023. Relevant materials are provided in Table 6.



KIT staff exchange

HORIZON-WIDERA-2021-ACCESS-03

Date:	May 11, 2023
Place:	in person KIT Karlsruhe
Start:	11:00 am
End:	17:00 pm
Attendees:	Jens Buchgeister (KIT) Merve Erakca (KIT) Hüseyin Ersoy (KIT) Viera Pechancová (TBU) Thaiskang Jamatia (TBU) Debashri Paul (TBU)
Minutes approved by:	Viera Pechancova

11:00 - Meeting at ITAS for discussing anything about LCI or LCC of batteries

12.30 - Bus transfer from Karlsruhe City to KIT Campus North (hopefully with a fuel cell bus)

13:15 - Lunch at Casino (Campus Nord restaurant)

15:00 - Visit of Battery LAB at Institute for Applied Materials (Dr Werner Bauer)

16:30 - Bus transfer from KIT Campus North to Karlsruhe City

Figure 7 Overview of first staff exchange (TBU-KIT)

Table 6 Relevant materials related to staff exchange

Title / responsible	Type	Description	Link/File name
Staff exchange minutes Jens Buchgeister	Word document	Overview of the Agenda and minutes of the meeting as well as group picture	Staff_Exchange

3.5 Extended activities

The extended activities cover common journal or book publications and conferences as part of dissemination measures and to raise TBUs reputation as well as research profile in the field of sustainability assessments of battery storage technologies. In addition, explorative measures

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towards the stronger integration of social Sciences and Humanities (SSH) into battery research are carried out. Specifically, the goals are:

- Extend partnership between TBU, other partners and KIT
- Increase the visibility of TBU and recommend relevant conferences and networks
- Explore common interests

Here, KIT actively supports TBU in the process of journal and conference selection, abstract writing and manuscript development. So far, the following activities have been carried out:

Joint journal publications:

- Viera Pechancová, Patrick Stuhm, Manuel Baumann, Nibedita Saha, Petr Sáha, Social Sciences and Humanities agenda for sustainability in emerging battery technology research, Environmental Impact Assessment Review under review

Joint conference contributions:

- Viera Pechancová, Manuel Baumann, Nibedita Saha, Patrick Stuhm, Petr Sáha, Exploring social sustainability in emerging battery technologies, at the 17th Society and Materials conference, SAM17, on May 9-10, 2023, in Karlsruhe, Germany.

Common project proposals:

- One joint EU-Proposal with TBU and other relevant parameters in the field.

An overview of relevant materials is provided in Table 7.

Table 7 Relevant materials related to extended activities

Title	Type	Description	Link/File name
Conferences	Word documents and power points	Provision of conference Abstracts and presentations Documents: SAM2023	Conf
Journal articles	Word documents	Provision of joint journal publications	Articles
Other	TbD	Provision of other materials as, e.g., reports	

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3.5.1 Social Sciences and Humanities integration

The extended activities also include explorative measures towards the stronger integration of Social Sciences and Humanities (SSH) into clean energy transition/energy storage research regarding RRI. The goals are in line with the extended activities:

- Stronger explore SSH with TBU
- Develop a base for future activities beyond “classic" methods as LCC, LCA and s-LCA

This will be achieved through the fourth workshop, as described in section 3.1, and a preceding EERA-workshop, which serves as a base for further activities in the frame of TwinVECTOR. In the following, the contents will be described:

Leading scientists within the SSH-community recently emphasized the need for early integration of SSH concepts in research projects and highlighted the leadership role of SSH in smart consumption research in a well-received publication. Aiming for a more narrowly defined level, however, this as well applies to the assessment of sustainability in battery research. Although assessment is highly focused on a technological level, the importance of working conditions, raw material extraction and recycling constantly gains in importance. This makes it all the more important to include social components in the assessment.

This is the reason why within the framework of this project, a workshop will be held focusing on the integration of SSH in the development of next-gen batteries under the umbrella of the responsible research and innovation (RRI) principle. A first workshop “Exploring social dimensions of sustainability in emerging battery technology research” has been conducted before on 31st of May under the auspices of the EERA/M-era.net and EERA. The goal of the project was to look into the integration of social sciences and humanities (SSH) into the clean energy transition, with a particular emphasis on research on new battery technologies, as well as to understand SSH's role in battery development. To develop strategies for tackling the social elements of sustainability and promote interdisciplinary collaboration, the workshop brought scientists from several scientific disciplines together. Two sessions made up the workshop, at first, an open session, which featured three invited speeches about social sustainability, social dimension of sustainability assessment, and a special approach of social-life cycle evaluation with a larger perspective on the energy transition and later to battery research. For the second part, invited participants were split into three groups: STEM, SSH and interdisciplinary. The participants in the following course answered questions being recorded and evaluated in real-time using mentimeter.com. The question pattern is based on [1] concept of the seven-question technique.

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Table 8 Relevant materials related to Social Sciences and Humanities integration

Title	Type	Description	Link/File name
Workshop: Exploring social dimensions of sustainability in emerging battery technology research	Several presentations	Includes the keynotes on SSH, s-LCA and the interactive, MENTIMETER based session materials with different participants	Sessions

3.6 Sustainability theatre

The last activity is the sustainability theatre which is based on all the above-mentioned materials. It will address decision problems related to the development of battery cells in face of sustainability. The goals of this final activity are:

- Apply the learned methods and approaches
- Spur a critical discussion on sustainability assessment
- Provide an example for a co-creation space for sustainability-oriented technology development

Here, a transdisciplinary group of researchers will discuss in an active and moderated way on sustainability assessment of battery cells using an interactive decision-making tool developed at KIT. The latter allows to elicit the preferences actively from stakeholder groups and to contrast them. This will enable an in-depth discussion showing how preferences and selected indicators can impact decision making. As a base for this discussion, external experts will provide in-depth views on their works related to LSCA. Different groups will then be defined to provide a general multi-stakeholder perspective that illustrates how different preferences can affect the sustainability assessment decision-making process and how these can affect outcomes in terms of rankings and trade-offs. A report on the insights of theatre will be provided in month 36. Relevant materials will be developed until month 25 to 36 and downfall in the deliverable 4.3 in month 36.

4 Sustainability guideline document and data provision

The sustainability guideline will provide a fast-introductory basis to begin appropriate sustainability-oriented assessments of emerging batteries. It has to be stressed that the following chapter does

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not represent a final state, rather it shall serve as a base for discussion for the development of a demand driven sustainability guideline. In detail, the goals of the drafted sustainability guideline are:

- Provide a base for discussion and the development of a demand driven sustainability guideline for batteries
- To provide a fast overview on relevant life cycle-oriented methods for sustainability assessment and relevant frameworks
- Provide relevant initial literature and materials for TBU to carry out corresponding analyses
- Hands-on tips and outline potential pitfalls for different methods

All materials will be based on existing KIT-ITAS work and literature. In line with each chapter, data examples will be provided where possible (e.g., LCIs). Starting points are individual introductions to each topic (here, the subchapters). In addition, other items are addressed that could be expanded upon as the project progresses, based on feedback from TBU. As explained earlier, this section will be continually updated in line with ongoing and planned teaching activities to produce a sustainability assessment guideline for emerging batteries (deliverable 4.2 in month 30) as displayed in Figure 8.

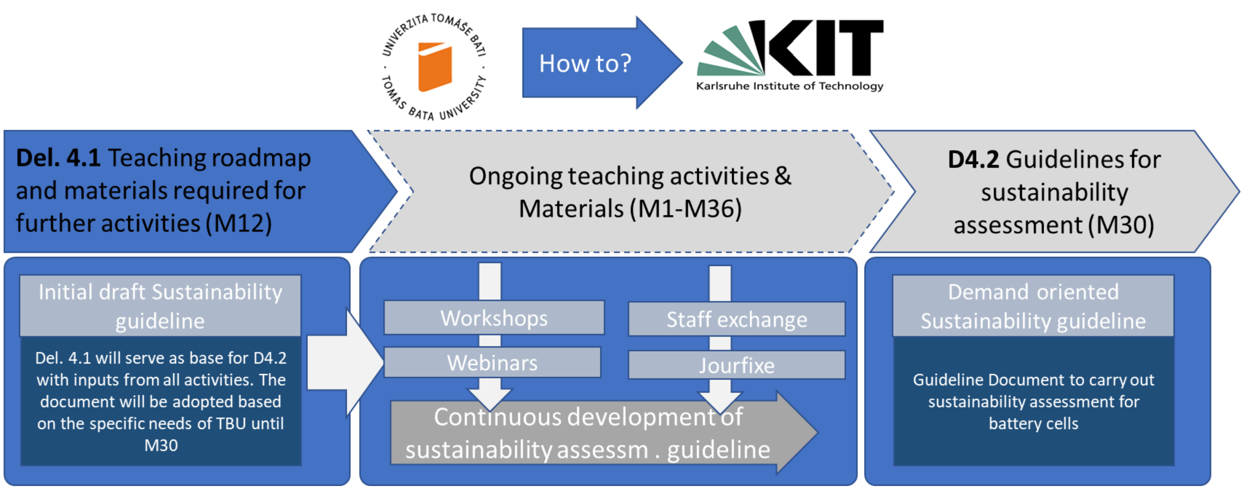

Figure 8: Development of a demand driven sustainability assessment guideline (deliverable 4.2) based on deliverable 4.1. and ongoing teaching activities.

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4.1 General Introduction

Designing and selecting emerging battery technologies in alignment with societal needs poses a complex decision-making challenge, particularly in an environment marked by significant uncertainty and the existence of multiple visions of the future (which material, which application etc.). In general, a diverse array of stakeholders, each with their own temporarily valid technological capabilities, interests, and beliefs, engage in technology development and aim to shape it toward market entry. These aspects have spurred visions on new approaches that are known as responsible research and innovation (RRI) and constructive technology assessment (CTA), which can serve as a guiding framework to develop more sustainable and societal benign (battery) technologies. The goal of creating a "better" or "more sustainable" technology, leads to a design and decision-making dilemma that involves determining the precise target criteria (e.g., environmental, economic, or social considerations) and establishing effective ways to define and measure these criteria. A further challenge is to find the right shape targets (e.g., environmental vs. economic vs. social aspects) and how to characterize these for emerging technologies where usually only scarce data is available (see Figure 9). This can be described by the so-called Collingridge dilemma which states that: in early technological development stages, opportunities to steer are plentiful (degree of freedom for design-Power), but hard to choose from (e.g., which material to select for a cathode), while at later stages this is reversed. In contrast, more data (knowledge) is available, making it easier to conduct corresponding assessments (e.g., energy demand, material flows etc.).

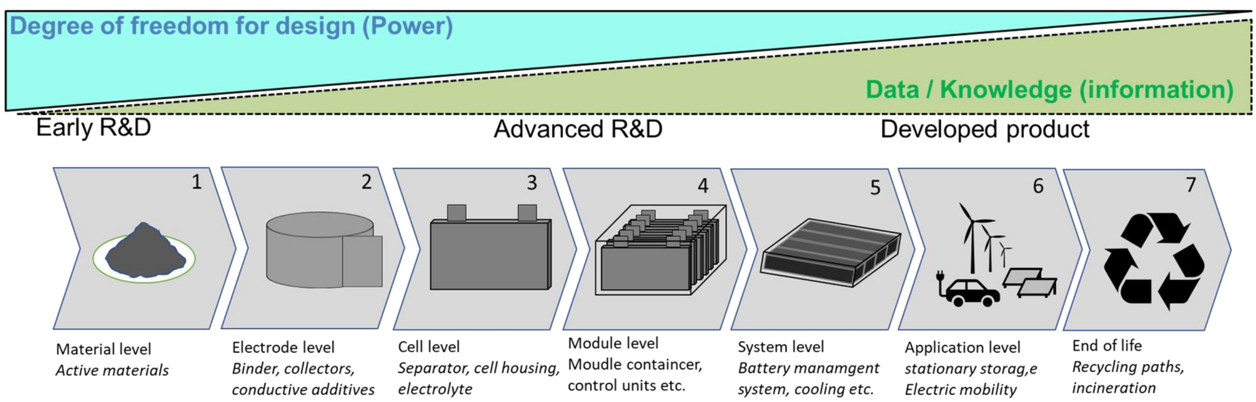

Figure 9: Power vs. Information dilemma (also named as collingridge Dilemma) for emerging batteries.

Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social-Life Cycle Assessment (s-LCA) are methodologies that facilitate the evaluation and quantification of potential advantages or

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drawbacks of emerging technologies in contrast to conventional alternatives. These methodologies cover the entire life cycle of a product, from the extraction of raw materials and production to its use phase, as well as its disposal or recycling. This evaluation involves accounting for the transfer of different burdens between different phases of the product's life cycle and monitoring their impacts across a wide range of impact categories. The combination of the named methods allows gathering a comprehensive picture of all relevant sustainability dimensions by combining these within a life cycle sustainability assessment (LCSA). Such assessments can be carried out using a framework as, e.g., CTA to tackle potential issues stemming from the above-mentioned Collingridge dilemma. However, here trade-off must be considered as well as the importance of a wide set of different criteria have to be included. Here, Multi-Criteria Decision Analysis models (MCDA) can help. As a sub-discipline of operations research, they explicitly consider complex decision problems and provide a possibility to tackle them and to unveil stakeholder preferences in a formalized and reproducible way. In addition, they allow it to combine different criteria and to make them comparable. An overview of RRI, CTA and the above-named methods is provided in Figure 10.

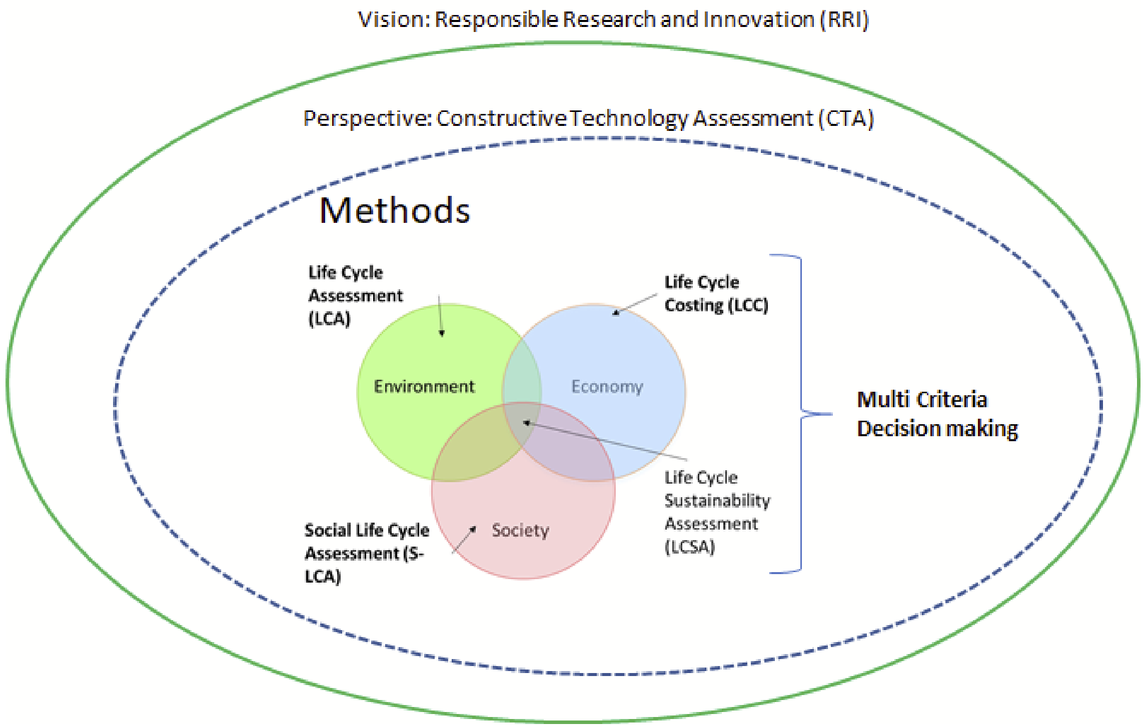

Figure 10 Overview of RRI, CTA and methods including their interconnection

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4.2 Responsible Research and Innovation

Responsible Research and Innovation (RRI) represents a vision formulation for a European policy perspective formulate by [2]. RRI can be considered as a broader framework for research and innovation schemes. In short, RRI aims to integrate society into the research and innovation processes and to shape and align the latter towards the expectation of the same. These expectations are centred on the question of how to embed new technology into the sociotechnical system in a sustainable way. In its core, RRI aims to build a bridge between R&I processes towards society and to identify potential risks and unintended consequences via a wide set of different methods. These methods should stipulate early engagement of stakeholder groups, users, and citizens, as well as generation of new knowledge to spur a more reflective and grounded R&I approach on a broader, more diverse, and thus more legitimate basis [3]. Within RRI, sustainability assessment methods play an integral role. As such, RRI can help to structure and reflect the use of methods as LCA, LCC and s-LCA in a broader context. Materials on the topic can be found in Table 9.

Table 9: Materials for RRI

Title / Responsible	Type	Description	Link/File name
Overview on RRI and CTA as perspective for sustainability Assessment Manuel Baumann	PowerPoint	General Introduction to RRI and CTA and challenges in prospective system analyses	RRI_CTA

4.3 Constructive Technology Assessment

The primary objective of CTA, which is comparable to RRI though with a stronger techno centric view, is to proactively enhance and steer the trajectory of technology development by identifying and mitigating potential innovation barriers or non-intended consequences at an early technology development stage, rather than evaluating the effects of nearly completed products afterward. Initiating CTA does not have an ideal timing; it should commence before entrenchment takes place, as implementing desired modifications may become prohibitively costly once the technology has already gained significant market penetration. As such, it can be considered as an ex-ante heuristic to guide sustainability assessment methods (regarding goal, stakeholder involvement, and reflection of approach). Participative measures are the kernel of CTA as a research framework and enable it

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to open the innovation process of technology and flanked, e.g., LCA by participative measures. The latter are e.g., active discussion with material or technology developers in any form; may it be a workshop, interview or survey.

To promote a sustainability-oriented technology development for batteries and in general, it is crucial to understand that the key actors involved have varying perspectives. Research by [4] identifies two types of actors in this context: insiders and outsiders. Insiders are closely linked to technology but often lack awareness of broader development issues across different professional fields (e.g., business, end-users, government) [5], [6] and other aspects as e.g., sustainability. They are highly focused on technology and are referred to as "Enactors" who aim to bring new technology to life and tend to emphasize its positive aspects (e.g., working in "enactment cycles") [6]. They may dismiss opposing viewpoints as irrational or driven by personal agendas. Enactors strongly identify with a technological alternative and believe that the world is eager for their product. Their approach focuses on perfecting the product first, then considering market and regulatory aspects, and finally addressing public acceptability concerns.

In contrast, outsiders, defined as "selectors," are non-technology-focused actors such as governments, regulatory bodies, NGOs, and end-users who encounter the final product, either directly or indirectly. They typically view technologies from an external perspective and assess them in comparison to other concurrent developments. For most of these stakeholders, the specific characteristics of a technology play a minor role (referred to as the "black box effect") when it comes to choosing the most suitable technology. Instead, they prioritize comparative factors like costs, suitability, environmental impacts, and safety for technology selection [SOURCE to be added]. Some materials on the CTA perspective are provided in Table 10.

Table 10: Materials for CTA

Title	Type	Description	Link/File name
Exploring emerging battery technology for grid-connected energy storage with Constructive Technology Assessment Versteeg, T.; Baumann, M.; Weil, M.; Moniz, A. B.	Journal article – subscription needed		Exploring emerging battery technology for grid-connected energy storage with Constructive Technology Assessment
Overview on RRI and CTA as perspective for	PowerPoint	General Introduction to RRI and CTA and	RRI_CTA

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sustainability Assessment Manuel Baumann	challenges in prospective system analyses

4.4 Life Cycle Assessment

Life cycle assessment is a systematic and comprehensive method for evaluating the environmental impact of a product, process, or service throughout its life cycle. This life cycle typically includes the extraction of raw materials, production, transportation, use, and ultimate disposal or recycling. LCA aims to provide a holistic understanding of the environmental footprint of the entity under study and helps to make informed decisions to reduce environmental impacts by identifying optimization areas such as material selection, production processes, transportation methods, and disposal practices. LCA is used in various sectors, including industry, government, and academia, to support sustainable and environmentally conscious decision-making. Life cycle assessment is standardized by ISO standards 14040 and 14044 [7]. According to these ISO standards, LCA includes four main steps, which are performed iteratively and are interdependent:

I. Goal and Scope definition
II. Life Cycle Inventory (LCI) analysis
III. Life Cycle Impact Assessment (LCIA)
IV. Interpretation

The goal of this section is to provide an overview of how to begin an LCA analysis for emerging batteries, based on the four steps of conducting an LCA.

4.4.1 Goal and Scope definition

Within the LCA framework, the goal and scope definition is the first step and can be considered as the base of the overall structure where all assessment specifications are defined clearly. It is important to define the goal and scope based on the purpose of the study to answer “what” to provide, “how” to provide and for “whom” the results will be relevant. The goal and scope are usually outlined in a preliminary manner, but they may need adjustments as the assessment progresses, ensuring it stays consistent. This adaptability aligns with the iterative nature of LCA.

The ILCD handbook is a significant resource that provides crucial information and guidance [8]. It outlines six key aspects to consider when defining goals in accordance with ISO standards. These aspects are explained with relevant examples, particularly in the context of assessing the environmental sustainability of battery technologies.

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In a first step, the goal of the study and the application of the results should be identified and discussed. The study goal influences the subsequent phases of the conducted assessment dominantly since it assists definition of system boundaries, inventory data, and interpretation of data. Potential applications could be the following:

- Comparing environmental impacts (i.e., comparison of environmental impacts for storing 1 kWh electricity in a battery system using LFP batteries and NMC batteries.)
- Hotspot identification in a product system (i.e., which component causes most of the impacts in an NMC based Li-ion battery)
- Analysing environmental performance improvements with changes in the product system (i.e., assessing environmental performance improvement potential of an Na-ion batteries using various anodes NaV(PO4)F and Na2MnPO4F)
- Documenting environmental impacts of a product (i.e., providing caused environmental impacts for an LFP battery pack)
- Criteria development for eco-labelling (i.e., environmental performance benchmarking of existing battery technologies of the same capacity)
- Policy development considering environmental impacts (i.e., identifying the caused impacts by lead-acid batteries and implementing policies for improved recycling rates)

The study's goal defines the specific purpose for which the study results are applicable and where they are not. For example, if a study assesses the climate change potential of LFP and NMC batteries, it can offer insights into their climate impact but not their overall environmental friendliness. Furthermore, the life cycle stages being considered must be defined to ensure a consistent comparison. For instance, comparing LCA results for battery packs of the same capacity using LFP and NMC batteries may not directly reveal their overall environmental performance in an electric vehicle (EV). Since to maintain the same energy capacity, a larger LFP battery pack is required, which can increase the EV's weight. On the other hand, the longer cycle lifetime of LFP batteries may compensate for this weight increase. However, such considerations can only be made if the study includes the use phase in its assessment. In alignment with its goal, it's crucial to grasp why a study is being conducted, as this will determine the level of detail required for the LCI. Understanding the drivers and motivations is essential, especially in the context of decision-making. Sometimes, it can be difficult to differentiate between "intended applications" and "reasons for conducting" a study. The following shall ease this differentiation:

- **Intended Application**: <u>What</u> does the study do?

  Example: The study evaluates the environmental impacts of two differently produced LFP cells and compares the results
- **Reasons**: <u>Why</u> is the study carried out?

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Example: The study is conducted to assess and comprehend the variations resulting from different processes for two identical lab-scale produced LFP cells. It further aims to determine which process has better environmental performance.

Based on the identified reasons, the assessment results can help distinguish between superior and inferior performance of the two processes, guiding decisions for process improvements, thus setting the decision context. The ILCD guidelines define three primary decision contexts: micro-level, meso/macro-level, and accounting decision support, depending on the scale of consequences, as elaborated in detail in the ILCD guideline [8].

The scope of the assessment plays a key role in specifying the product systems to be assessed and in describing the technical aspects of how the assessment will be conducted and reported. According to ILCD guideline [8], a well-defined scope should comprehensively address the following key elements

I. **Deliverables**: In accordance with the ISO 14044 standard, an LCA study must deliver an impact assessment, typically presenting LCI rand LCIA results in a transparent and reproducible manner. If normalization or weighting of results is applied, it requires documentation of numerical outcomes.

II. **Object of the assessment**:

- Function(s): An LCA study typically assesses one or more product systems, comprised of numerous unit processes that collectively contribute to the environmental impacts throughout the life cycle of these systems. Therefore, understanding the functions they provide is necessary to grasp these systems fully. Functions take precedence in assessing the environmental needs fulfillment, focusing on functions before products.

- Functional Unit: Following function determination, a suitable functional unit should be defined. To quantitatively evaluate function fulfillment (e.g., storing electricity), a functional unit is essential (e.g., 1 kWh of stored electricity). Furthermore, if two different product systems are being compared to provide the same function, a functional unit quantifying both qualitative aspects (stored electricity) and quantitative aspects (1 kWh) is required.

- Reference Flow: Once the functional unit is defined, it is followed by the specification of the reference flow. The reference flow represents the quantity of the required product necessary to achieve the defined functional unit. It is key to the LCI development, as the inventory is structured around acquiring the specified amount defined with the reference flow.

III. LCI modelling framework and handling of multifunctional processes:

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- Secondary functions and multifunctional processes: In scenarios where more than one function is associated with a product system, how this multifunctionality is managed must be explained. The choices made for LCI modelling and handling multifunctional processes should align with the defined goal and decision context, which will impact the later stages of the LCA study.
- Attributional or consequential modelling: The selection between attributional and consequential LCA for inventory modelling is a challenging task. It depends on the decision context situations. The ILCD guideline [8] recommend using attributional LCA for specific decision context situations (A, -C1, and -C2) and a mixed approach for situation B, combining attributional and consequential modelling for certain scenarios. Background processes are typically modelled differently in attributional and consequential LCA, with attributional models representing "average processes" and consequential models using "marginal processes."

IV. System boundaries and completeness requirements:

- Ideal system boundaries: Ideally, the system boundaries should encompass the unit processes necessary to deliver the reference flow, and secondary functions in cases of multifunctionality. This ensures that only elementary flows cross the system boundaries, with no materials, energy, products, or waste flowing out into the technosphere.
- Reasons to divert from ideal system boundaries: Practical constraints may necessitate deviations from ideal system boundaries, such as assessments that do not cover the overall life cycle or comparative assessments of systems providing the same function(s). Diversion can also occur when inventory modelling is not feasible, typically due to data limitations. In such cases, a cut-off criterion is applied.
- Completeness requirements: Completeness requirements are often defined quantitatively and vary depending on the study's goals, which can make setting quantitative completeness requirements based on a qualitatively defined study goal challenging. Practitioners may introduce a cut-off criterion (e.g., 0.1% on a mass basis) to address this, but it is crucial to ensure that excluded minor quantities do not significantly impact the environmental aspects of the system. The cut-off rule excludes irrelevant energy and material flows from system boundaries and usually applies to auxiliary flows or ones with quantities smaller than 1%. To make these decisions, sensitivity analysis within the iterative workflow is recommended.

4.4.2 Life Cycle Inventory analysis

The LCI phase comprises a systematic analysis of the resources and emissions at each stage of a product's life cycle. The LCI analysis is a critical and very time-intensive part of LCA and heavily

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influences its quality. Additionally, this step increases the knowledge and understanding of the system under study, as the individual processes within the system are carefully analyzed. Like the other LCA steps, the inventory analysis is iteratively conducted. Therefore, as data is collected and understanding about the system grows, there may be a change in the originally planned approach.

Before starting with the data collection and analysis, it is important to define the scope and boundaries of the foreground system, as described in the previous section. This does not only include the definition of the specific life cycle stages to be analyzed, e.g., raw material extraction, manufacturing, transportation, use, end-of-life, but also in which detail these steps need to be analyzed. It is crucial to identify relevant parameters for the study such as the Function(s), Functional Unit, or reference flow. This illustrates once again the importance of considering the study's goal, level of detail, application of results and its boundaries during the "Goal and Scope" phase, which forms the basis for the LCI. These stages are then iterated through to further define and adapt the relevant information for the LCI. When evaluating the environmental impact of a battery, not only data on the battery's energy and materials but also on aspects like its production environment (e.g., dry room), production volume, and its specific characteristics, such as cell geometry, energy density, and cycle lifetime, are required. In addition, information such as the geographic region or the temporal orientation of the analysis (e.g., which year the analysis should depict) must be defined and consistently adhered to when collecting the data. Moreover, information on the treatment of each waste flow (e.g., hazardous waste that needs to be incinerated) should be gathered to assess it reliably in the LCI.

When collecting inventory data for the manufacturing of a battery, it is important to clarify and document which and how certain processes and elements are accounted for, to what extent they are accounted for, and if they are not accounted for, a reasonable explanation for this fact. There are often specific processes, which are omitted or simplified when building battery LCIs, such as the use of auxiliary materials for washing of specific materials in battery production or the internal recycling of scrap material, which is directly fed back to the system. It is possible to omit irrelevant flows by applying the cut-off rule, as described in the previous section, as they would not impact the LCA results, which reduces unnecessary efforts.

To get an overview of the energy and material flows and to gain a better understanding of the system to be assessed, it is helpful to start with a process flow chart, as shown in Figure 11. The foreground system should be broken down into the smallest possible elements, called unit process, for which inputs and outputs are quantified. All flows entering or leaving these unit processes should be visualized in the process flow chart. This can be related to materials used (e.g., aluminum foil or NMC powder), solid wastes (e.g., scrap aluminum foil), emissions released to the air (e.g., evaporated water or NMP during electrode drying), or the energy used within a process (e.g., electricity for electrode drying). In addition, transportation flows and infrastructure items, such as the chemical factory or the dry room, can be pictured. It is advisable to make the flowchart as detailed and accurate as possible. Especially for complex systems, it might be helpful to conduct

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experts to ensure that all relevant steps and flows are covered. Such visualization will allow for a better understanding of the system and the identification of critical processes, which are often heating processes, cooling processes, processes with high waste and spatial environment, i.e., dry rooms.

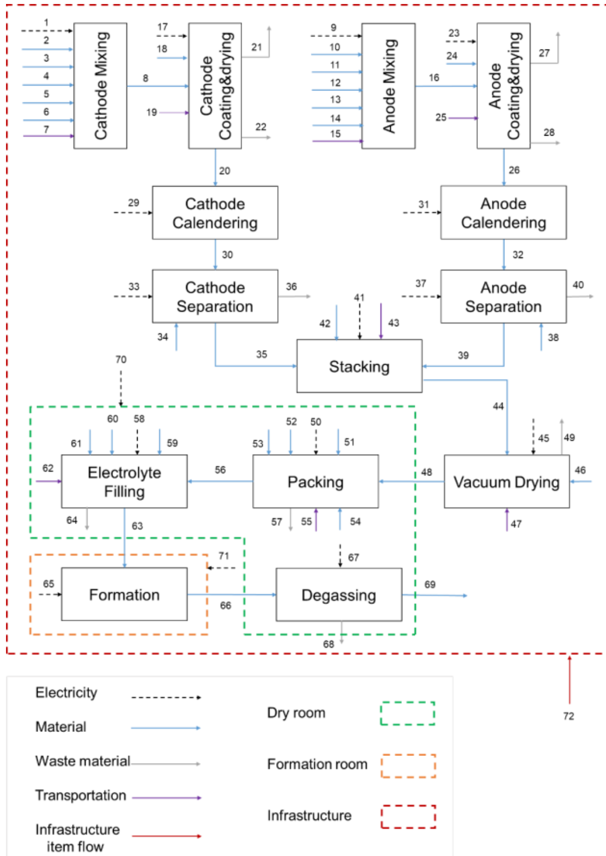

Figure 11 Exemplary process flowchart depicting all energy and material flows, and spatial aspects within a lab-scale battery cell production [9]

Once the system is defined and the processes to be analyzed are identified, the LCI data can be collected, processed and analyzed. Data collection is a meticulous process that requires attention to detail and a clear plan. Gathering accurate and representative data is crucial for the credibility and usefulness of the LCI. Working with experts in the field and being diligent in the data collection process will contribute to the LCI's quality. A starting point is to list all inputs (such as raw materials and energy) and outputs (including emissions, waste, and the final product) associated with the life cycle stages defined within the scope, which can be extracted from the process flow chart.

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For determining the energy data in an LCI during a product's manufacturing, two common methods are employed: the top-down (T-D) and bottom-up (B-U) approaches. In the T-D approach, energy consumption is calculated based on the total energy use of the entire manufacturing plant divided by its output. In the B-U approach, energy data is collected for individual production processes, and the plant's total energy demand is extrapolated from there. The T-D approach often results in a higher estimate of energy demand compared to the B-U approach for the same system. This discrepancy is due to the T-D approach accounting for additional activities or energy usage not directly related to the system being studied, which may be omitted in B-U modeling. However, the B-U modelling enables the identification of energy intensive steps which could potentially be environmental hotspots, whereas the T-U approach inherits a black-box character.

Potential data sources should be identified, which could be primary (collected firsthand) or secondary (existing data from databases, literature, etc.). Common secondary sources include government statistics, industry reports, academic publications, patents and databases like Ecoinvent or BatPaC. In some cases, Ecoinvent processes can be used as a starting point and modified based on own requirements. When using secondary data, such as academic publications, it must be ensured that the sources are relevant to the specific study. Thus, it is essential to compare the assumptions made in the sources and, if necessary, to customize the data to own needs. For instance, if LCI data for a NMC111 cell is provided, whereas data for a NMC811 battery is required, the mass share of the individual components and probably also the electricity consumption must be adjusted. The data sources need to be documented and verified for their quality and relevance. Sources should always be transparent in their assumptions. Before using them, it is advisable to check their reliability and consistency. Sometimes, it may be necessary to compare information from multiple sources to ensure accuracy. Table 11 provides an overview of potential data sources for the LCI of batteries.

Table 11 Potential LCI data sources for batteries

Type of source	**Source**
Databases	Ecoinvent GaBi SimaPro US LCI Database
Tools	BatPaC GREET Reaxys ChemSpider Aspen Technology
Academic publications	

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Lithium batteries	Erakca et al., 2023 [9] Birrozzi et al., 2022 [10] Jasper et al., 2022 [11] Degen and Schütte, 2022 [12] Accardo et al., 2021 [13] Chordia et al., 2021 [14] Crenna et al., 2021 [15] da Silva Lima et al., 2021 [16] Erakca et al., 2021 [17] Jinasena et al., 2021 [18] Kelly et al., 2021 [19] Shu et al., 2021 [20] von Drachenfels et al., 2021 [21] Wang and Yu, 2021 [22] Wessel et al., 2021 [23] Kallitsis et al., 2020 [24] Le Varlet et al., 2020 [25] Mohr et al., 2020 [26] Sun et al., 2020 [27] Tao and You, 2020 [28] Yang et al., 2020 [29] Ciez and Whitacre, 2019 [30] Cusenza et al., 2019 [31] Dai et al., 2019a [32] Dai et al., 2019b [33] Deng et al., 2019 [34] Ioakimidis et al., 2019 [35] Marques et al., 2019 [36] Philippot et al., 2019 [37] Thomitzek et al., 2019a [38] Thomitzek et al., 2019b [39] Wang et al., 2019 [40] Raugei and Winfield, 2019 [40] Cerdas et al., 2018 [41] Dai et al., 2018 [42] Peters and Weil, 2018 [43] Philippot et al., 2018 [36] Wu and Kong, 2018 [44] Ahmadi et al., 2017 [45] Dai et al., 2017 [46] Liang et al., 2017 [47] Pettinger and Dong, 2017 [48] Richa et al., 2017 [49] Vandepaer et al., 2017 [50] Wang et al., 2017 [51] Yuan et al., 2017 [52] Ambrose and Kendall, 2016 [53] Kim et al., 2016 [54] Troy et al., 2016 [55]

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	Zackrisson, 2016 [56] Dunn et al., 2015 [57] Hammond and Hazeldine, 2015 [58] Lastoskie and Dai, 2015 [59] Ellingsen et al., 2014 [60] Li et al., 2014 [61] Amarakoon et al., 2013 [62] Simon and Weil, 2013 [63] Dunn et al., 2012a [64] Dunn et al., 2012b [57] McManus, 2012 [65] Majeau-Bettez et al., 2011 [66] Notter et al., 2010 [67] Zackrisson et al., 2010 [68] Hischier et al., 2007 [69] Rydh and Sandén, 2005a [70], 2005b [71]
	Gaines and Cuenca, 2000 [72]
Sodium batteries	Peters et al., 2022 [73] Baumann et al., 2022 [74] Liu et al., 2022 [75]
	Peters et al., 2021 [76]
Solid-state batteries	Mandade et al., 2023 [77]
	Troy et al., 2016 [55]
Magnesium batteries	Bautista et al., 2021 [78]
	Montenegro et al., 2021 [79]
Organic batteries	Zhang et al., 2022 [80]

In the case of highly innovative and emerging technologies, such as new battery technologies, finding secondary data may be challenging. In such situations, primary data through surveys with experts, laboratory tests, or on-site measurements in a laboratory may be needed. A good starting point is to request relevant LCI data from technology developers in formats like Excel or Word, as displayed in Figure 12. However, it is crucial to communicate with developers to clarify the data requirements for an LCA since they might not always be aware of what is needed. Thus, it can be beneficial to structure the Excel or Word documents in a way that aligns with the LCA requirements. Specifically, an input-output oriented approach should be provided for data collection, clarifying the need for material and energy related data. Moreover, maintaining a steady communication with the technology developers providing the data is important to improve the data quality and to ensure its accuracy and reliability. The collection of data via Excel-based sheets should be an iterative process resulting in the data improvement over time.

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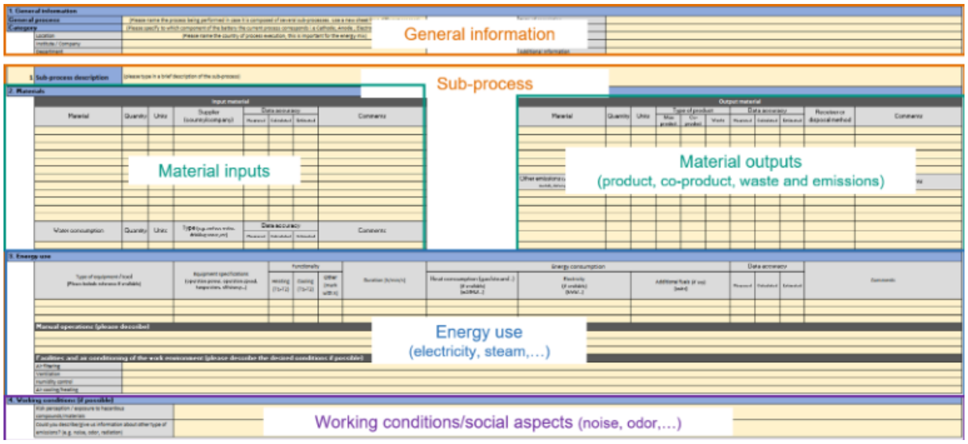

Figure 12 Exemplary data collection sheet considering input and output materials, emissions, energy use and working conditions.

Direct measurements offer another approach for gathering primary data on equipment and technology. These measurements can be tailored to suit specific goals and scopes, enabling a detailed analysis of critical processes and the potential for optimization. However, it's important to note that measurements can be time-consuming and challenging. To streamline the measurement process, the following steps can be considered:

I. **Technical challenges:**

- Lab-scale processes often come with high uncertainties, leading to frequent experiment failures. This necessitates advance planning for measurement replication. Additionally, energy consumption may be too low, or processes may be too short to measure accurately.
- Utilizing measurement devices might require assistance from an electrician, requiring proper planning.

II. **Process Flow Chart:** A process flow chart should be developed to gain insights into energy, material, and waste streams. This aids in identifying critical processes and machines that require direct measurements.

III. **Selecting appropriate measuring devices:**

- For precise *material* quantification, accurate weighing scales can be used. In some cases, measuring by volume may be necessary, especially for bulk materials like liquids or gases.
- To quantify *energy* sources, energy meters, such as kilowatt-hour (kWh) meters, can be installed in the production process to directly measure electricity consumption.

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These meters can be connected directly between the socket and the machine to record electricity usage. Another option is using energy loggers, which can measure three-phase current and provide not only energy consumption data but also operational power information for more detailed assessments. Various meters are available for measuring sources of energy other than electricity, such as compressed air meters.

IV. **Process Parameters:** Process parameters like speed or temperature must be precisely recorded to evaluate and comprehend the results and to transfer the findings to other technologies accurately.

V. **Data Analysis and Validation:**

- The accuracy and reliability of the measurements should be ensured by validating data through multiple measurements, cross-checks, or calibration as necessary.
- In cases of inefficiencies and low throughput, the allocation and utilization of the energy demand should be considered.

For some precursor materials, neither secondary data is available nor is it possible to conduct measurement. In these cases, stoichiometric calculations can be conducted, which however, entail some uncertainties. Another approach is the use of similar, commonly used proxy materials. An expert should be consulted to identify appropriate proxy materials with similar chemical characteristics and composition. For example, if an innovative binder must be replaced by a commercially available one due to data limitations, similar toxicity levels should be considered. Special attention should be paid to the quantities used, as they will change. Nevertheless, it is important to note that the use of proxies should be the last resort due to this approach's high level of uncertainties.

Once data has been collected from secondary, primary, or mixed sources, its quality should be assessed. A quantitative method for quality assessment involves using the Pedigree matrix, which rates data reliability, completeness, temporal correlation, geographical correlation, and technological correlation on a scale from 1 (good) to 5 (bad). Qualitative assessment can be done by answering the following questions:

- **Accuracy**: How precise and correct is the data?
- **Completeness**: Are there any gaps or missing information?
- **Reliability**: Is the data from a reputable source, and can it be verified?
- **Representativeness**: Does the data accurately reflect the study's conditions?
- **Consistency**: Are the same conditions in all steps assumed (e.g., full utilization)?

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When utilizing various data sources, it is imperative to guarantee the consistency and comparability of the data. If data from different sources lack direct comparability, it may be necessary to standardize them to a uniform unit or reconcile variations. If the system under examination encompasses co-products (multiple products arising from a single process), it is crucial to distribute the environmental impacts among these products through a suitable method, such as economic or mass allocation. To maintain transparency and dependability, a comprehensive record of the data collection and the underlying assumptions must be furnished. This enables others to grasp the analysis. The methods employed for data collection, encompassing any conversions or adjustments, should be transparently documented. As previously mentioned, developing an LCI is not a singular endeavor but an iterative undertaking. As new data emerges or comprehension of the system advances, the LCI has to be adjusted and updated.

In addition to the primary system under study, data collection for the background system has to be considered. Background data refers to information linked with processes or activities that lie beyond the specific system boundaries of the product. This encompasses data concerning energy production, transportation, infrastructure, and other general activities. In most instances, databases like Ecoinvent provide this background data. The choice of the source for background data must align with the objectives and scope of your LCA and correspond to the geographical region and time frame of the study. Local conditions, such as the energy mix and infrastructure, can significantly impact the environmental performance of the product. For example, this might necessitate the adaptation of energy generation processes to align with the timing of the foreground data. In such scenarios, existing Ecoinvent processes can be employed as a base, with adjustments made to their content.

Transportation data encompasses details regarding how materials are moved from one place to another, typically quantified as kg*km, which signifies the distance a specific amount of material travels during this process. To evaluate transportation, it is crucial to collect data on the distances covered, the modes of transport employed (such as trucks, trains, ships, and planes), and the quantity of material involved.

To evaluate infrastructure facilities such as chemical factories or electronic component factories, the datasets provided by Ecoinvent can be employed. The capacity or output of these factories, such as tons of chemical products per year and the lifetime of the facility, is provided by Ecoinvent so that the maximum lifetime capacity can be calculated. When using this infrastructure element, the theoretical amount needed of this single item according to the system's capacity has to be adjusted to the item's total output capacity.

4.4.3 Life Cycle Impact Assessment

The basis for the quantitative determination of environmental impacts is provided by the ISO 14040 and 14044 standards, which specify corresponding requirements. The aim of the standards is to provide a complete quantitative assessment of all aspects of environmental impact. The task of

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completely considering the large number of different environmental aspects alone is extremely difficult. The following Figure 13 is a selection of environmental aspects and their impact relationships, which have a significant influence on the overall environmental impact.

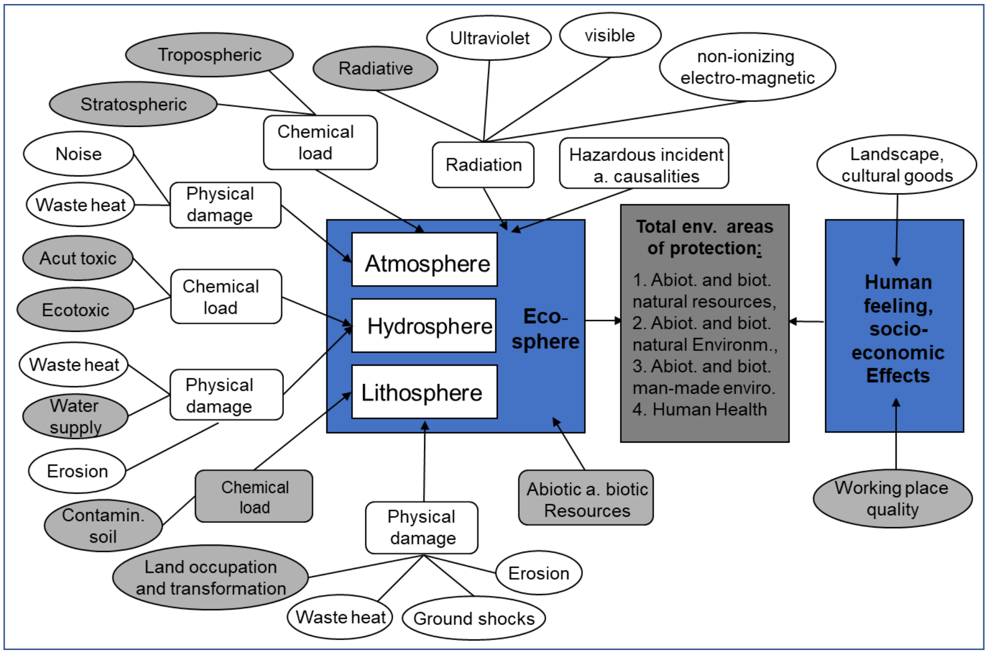

Figure 13 Selection of environmental aspects and their impact relationships, which have a significant influence on the overall environmental impact [81]

The figure is intended to illustrate how difficult and complex the task of fully incorporating all impacts on the environment is. For clarification, the impact relationships that exist between different environmental aspects, for example at the points where chemical load and physical damage occur simultaneously, have not been shown for simplification and clearness.

The LCIA phase is carried out based on the LCI, which contains the required information on land use and transformation, as well as the energy and material flows of the object under investigation. This means that the impact assessment represents both, the relationship of the determined raw material extractions from the natural environment (input side elementary flows) as well as the emitting of emissions into the atmosphere (output side elementary flows) of an investigated object to influence the state of the environment. In this context, under the term environment the following environmental protection goods are understood in the framework of LCA:

- Abiotic and biotic natural resources (raw materials, water, soil area, flora and fauna)

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- abiotic and biotic natural environment (e.g., high mountains, environmental media water, soil, air)
- Abiotic and biotic man-made environment (cultural landscape and cultural goods)
- Human health

The quantitative determination of environmental impacts involves the establishment of a functional relationship that can be used to a mathematical operationalization of environmental impacts, the so-called environmental aspects [7].

To this end, a general structure has been developed as a framework for the environmental impact assessment. This general framework provides for assigning the environmental aspects from the previous figure, e.g., chemical loading of the troposphere and stratosphere by released greenhouse gases, to an impact category, e.g., climate change, and then defining an impact pathway (environmental mechanism) to the defined environmental protection areas. This pathway contains a scientifically validated functional relationship to describe the state of change caused by greenhouse gas emissions to the environmental protection areas. Figure 14 below depicts this general framework [82].

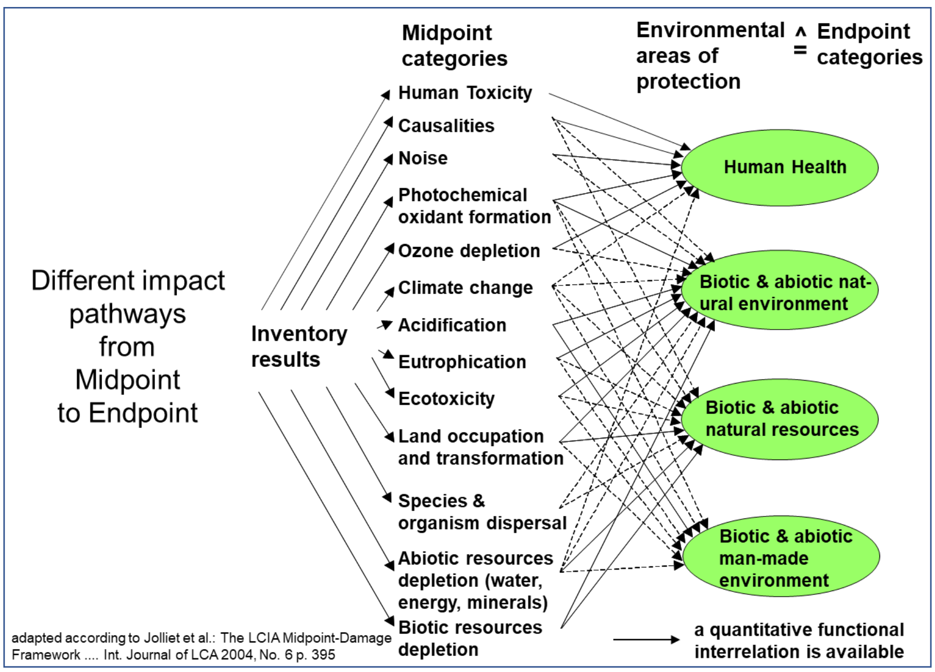

Figure 14 General structure of environmental impact assessment framework [82]

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The strength of this adaptable approach lies in its capacity to seamlessly incorporate newly identified or previously unquantifiable environmental impacts and aspects as fresh impact categories within its framework. Moreover, it takes into consideration the growing body of knowledge regarding environmental effects and the causal links between impacts, such as the increase in human skin cancer caused by higher UV-B radiation due to lower ozone concentrations caused by the release of ozone-depleting CFC-containing substances. This necessitates an in-depth understanding of the specific pathways by which each emitted substance enters the environment, both in terms of spatial distribution and temporal progression, to accurately estimate the substance's dispersion behavior and the resultant environmental repercussions in the atmosphere, hydrosphere, and lithosphere. In Figure 11, the differentiation between dashed, and solid arrows show the varying levels of knowledge regarding the operationalization of the functional relationship associated with an impact category. Only in the case of solid arrows, it is possible to quantitatively describe the environmental harm related to the impact category at the impact endpoint through a functional impact relationship. This implies that the impact category indicator enables a quantitative expression of the environmental consequences of an emission, encompassing the damage to one or more environmental protection areas, the so-called impact endpoints, as a metric measurement. In the case of the dashed arrows, the impact relationship is only known qualitatively.

According to the ISO standard, the impact category indicator can be freely defined along the entire environmental impact path between the LCA result and the impact endpoints in the environment [7]. There are two different approaches for determining at which point along the impact pathway the functional relationship for the mathematical description of the impact indicator begins, which are referred to in the literature as the midpoint and endpoint approaches [83]. While the midpoint approach uses the impact indicator to quantitatively describe only the potential change in the state of the environment, the endpoint approaches use the indicator to try to establish causal links to real changes and impacts on one or more endpoint categories.

To illustrate the aforementioned differences between the midpoint and endpoint approaches, the following Figure 15 displays an example of the full impact pathway for ozone-depleting emissions to changes in environmental assets for the impact category stratospheric ozone depletion.

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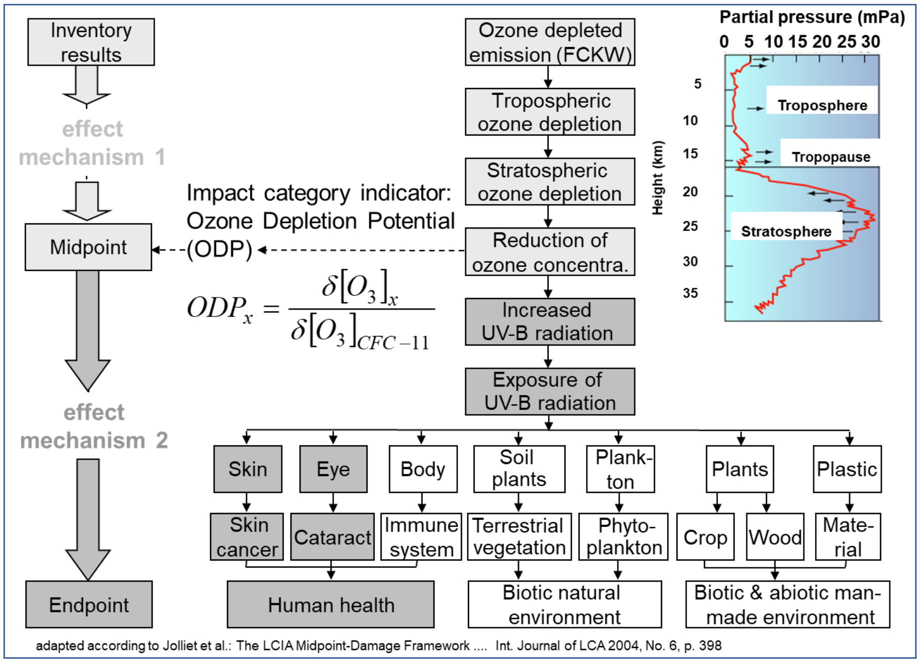

Figure 15 Midpoint – Endpoint approach of environmental impacts in case of stratospheric ozone-layer depletion

The distribution of ozone-depleting emissions occurs first in the troposphere, before reaching the higher stratosphere after an average of about four years, where they accumulate completely [84]. As the ozone-depleting substances rise into the higher air layers, they are broken down by solar radiation. As a result of the splitting, the substances are transformed into highly reactive radicals (mostly chlorine or bromine atoms), which react with the ozone molecules (O_3) present in the stratosphere and measurably reduce the ozone concentration. This mechanism of ozone depletion, the indicator of effect, follows a very similar pattern after release for all ozone-depleting substances, whether halons, CFCs or HCFCs. This allows a relative relationship to be established between the individual substances in terms of the quantitative magnitude of the ozone concentration reduction. By definition, the midpoint approach expresses the stratospheric ozone depletion potential of the ozone-depleting substances relative to the reduction in ozone concentration by the reference substance, trichlorofluoromethane ($CFCl_3$ or CFC-11), as shown in Figure 15.

As a result of the mechanism of action described above, the reduction in stratospheric ozone concentration results in increased solar radiation on Earth, which has been shown to cause a permanent increase in ultraviolet (UV) radiation at the Earth's surface [85]. As a rule of thumb, for every one percent reduction in stratospheric ozone concentration, UV radiation increases by about two percent. The depletion of the ozone layer leads to a significant increase in UV-B radiation, which is responsible for sunburn in humans and, in the case of long-term exposure, for the development

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of skin cancer. This direct relationship between UV-B radiation and skin cancer has been observed for the common forms of basal cell and prickle cell skin cancer [86].

It is also known from health studies that prolonged exposure of the human eye to elevated UV-B radiation leads to cataracts. It is also believed that increased UV-B radiation influences marine vegetation, plankton, and the earth's surface, since plants, like humans, do not have protective mechanisms or have too little time to adapt to the conditions in an evolutionary development. Of course, increased UV radiation also affects the aging process of materials whose molecular structure is sensitive to UV radiation, such as plastics. In the case of plastics, it is known that increased UV-B radiation accelerates the degradation of long-chain carbon compounds.

However, there is no knowledge or accurate calculation of how this effect translates into higher maintenance and replacement costs for buildings, equipment and other products that are partially or fully made of plastic and exposed to direct sunlight during use. This means that at this point in time, for the endpoint approach with the increase in UV-B radiation, only the effect relationships on the development of human skin cancer and cataracts can be operationalized quantitatively. For this purpose, the concept of DALY (Disability-Adjusted Life Years) is used as an impact category indicator, which indicates the loss of life years or an equivalent in the case of disease effects. A comprehensive description of the DALY concept can be found in the following literature [87].

When comparing the two approaches, midpoint and endpoint, for quantifying the cause-effect relationship, it should be noted that the endpoint approach requires a longer causal chain in the mathematical mapping. Two environmental effect mechanisms must always be functionally linked. This results in a pronounced differentiation of the damage to the individual environmental protection areas, the impact endpoints. However, a longer causal chain is required for the mathematical description, which leads to a higher error uncertainty between the causal emissions and the environmental effects to be measured with each additional link in the chain. Furthermore, this differentiation to determine the totality of specific changes in the bio-, litho-, hydro- and atmosphere cannot be carried out at present due to a lack of knowledge or too high a cost of data collection in the exact spatial differentiation of the impact process.

This insight was also taken up by the Joint Research Center in its recommendation of characterization models to be used for different impact categories, which were developed in a multi-stage process based on scientific criteria with the leading scientists in this field and finally published in the International Reference Life Cycle Data (ILCD) handbook [8]. For some impact categories, the characterization model to be recommended was updated [88]. As a result, the updated ILCD environmental impact assessment method was given the name ILCD Midpoint 2.0.

The ILCD method considers 16 midpoint impact categories, which copes single environmental aspects. Table 12 lists the impact categories considered, their recommended characterization models with the associated literature sources, and the physical unit of the impact indicators.

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Table 12 Updated list of impact categories, characterization models and impact category indicators according to the ILCD Midpoint Method 2.0.

Impact category	**Recommended characterisation model**	**Impact indicator and unit**
Climate change	Base climate model at 100 years residence time from Intergovernmental Panel of Climate Change (IPCC); Status: 5th IPCC report 2013 [89]	Radiative forcing in W/m² as global warming potential (GWP 100) in CO2 equivalents
Stratospheric ozone depletion	Equilibrium state model of the ozone depletion potential of world meteorological organisation (WMO); Status: WMO 1999 [90]	Reduction of stratospheric ozone concentration as ozone depletion potential (ODP steady state) in CFC-11 equivalents
Human toxicity, cancerogenic effects	USEtox model; Status: Rosenbaum et al. 2008 [91]	Comparative toxic units for humans (CTUh)
Human toxicity, non-cancerogenic effects	USEtox model; Status: Rosenbaum et al. 2008 [91]	Comparative toxic units for humans (CTUh)
Ecotoxicity (freshwater)	USEtox model; Status: Rosenbaum et al. 2008 [91]	Comparative toxic units for ecosystems (CTUe)
Respiratory effects, inorganics/ particulate matters	RiskPoll model; Status: Rabl, A. a. Spadaro, J. 2004 [92], Greco et al. 2007 [93] and Humpert 2009 [94]	Human intake of particulate matter in kg PM2.5 equivalents per kg particulate matter emission
Photochemical ozone formation	LOTOS-EUROS model; Status: van Zelm et al., 2008 as implemented in ReCiPe Midpoint [95]	Increase in tropospheric ozone concentration in kg ethene equivalents
Acidification	Accumulated exceedance of the critical acidification load value; Status: Seppälä et al. 2006 [96], Posch et al. 2008 [97]	Acidification equivalents (mol H+ equivalents) per year
Eutrophication, terrestrial	Accumulated exceedance of the critical load for terrestrial	Eutrophication equivalents (mol N equivalents) per year

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	eutrophication; Status: Seppälä et al. 2006 [96], Posch et al. 2008 [97]	
Eutrophication, freshwater	EUTREND model; Status: Struijs et al. 2009 as implemented in ReCiPe Midpoint [98]	Fraction of nutrients in freshwater (in kg P equivalents)
Eutrophication, marine water	EUTREND model; Status: Struijs et al. 2009 as implemented in ReCiPe Midpoint [98]	Proportion of nutrients in marine water (in kg N equivalents)
Ionising radiation, human health	Human health effect model; Status: Frischknecht et al. 2000 [99]	Human exposure efficiency relative to kBq U235
Land use	Soil quality index based on LANCA; Status Bos et al. 2016 [100]	Soil quality index in points (Biotic production, erosion resistance, mechanical filtration a. groundwater replenishment)
Resource use, minerals and metals	Abiotic resource scarcity model based on ultimate reserves; Status: van Oers et al. 2020 [101]	Abiotic resource depletion of minerals and metals in kg Sb equivalents
Resource use, fossil fuels	Abiotic resource scarcity model based on fossil fuels; Status: van Oers et al. 2002 [101]	Abiotic resource depletion of fossil fuels in MJ
Freshwater Scarcity	Available WAter REmaining (AWARE) model, Boulay et al. 2018 [102]	User deprivation weighted water consumption in kg world equivalents deprived

In the publication by [97] the environmental impacts of lithium-ion batteries, an analysis of 16 studies is conducted on the methods used to estimate environmental impacts [103]. The analysis shows that the most used impact assessment methods are ReCiPe, CML, Eco-Indicator 99 and ILCD. The most assessed impact category is global warming potential (GWP), followed by cumulative energy demand (CED). Other environmental impact categories analyzed include Abiotic Depletion Potential (ADP), Acidification Potential (AP), Eutrophication Potential (EP), Human Toxicity Potential (HTP), and Stratospheric Ozone Depletion Potential (ODP) [103].

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4.4.4 Interpretation

The interpretation of the LCA results comprises all the other LCA steps mentioned earlier, involving the identification of critical results and subsequent sensitivity, scenario, and uncertainty analysis. Typically, the interpretation does not serve as a final step; rather, it commences with the analysis and identification of critical issues linked to scope and goal definition, LCI analysis and LCIA. Therefore, the interpretation phase should be considered a continuous process that leads to an iterative adjustment of an LCA and aids to reach conclusions and according recommendations [6]. Table 13 offers insights into potential pitfalls in conducting an LCA, to which attention should be paid for proper interpretation. For a comprehensive and practical reference, one can gain valuable insights from [7], which provides a well-illustrated guide with concrete examples.

Table 13 Life cycle interpretation examples of significant issues for batteries based on [104] and ILCD [8]

What to look for	How to identify relevant issues
Goal and Scope	
Functional Unit	Choice of functional unit, does it represent the properties? Often for batteries per delivered kWh, if the FU does not fit, it can lead to misleading results.
Handling of multifunctional processes System expansion Allocation criteria Cut off decisions and boundaries	System expansion (assumption of alternative/ replaced technologies), allocation model and setting of system boundaries are discrete choices that can be checked by running the different possibilities as scenarios and comparing the results to determine their influence on the final outcome and conclusions. One example can be the recycling of batteries
Inventory analysis—data for product system processes	
Data for activities occurring in the product system, here cell production, raw materials Data for key processes: processes that contribute substantially to the environmental impact Data for key elementary flows: processes that contribute substantially to the overall results for an impact category Impact categories that dominate the total impacts from the product system	Sensitivity analysis is performed by varying the single issue, or in case of interdependency by joint variation of the issues concerned and analyzing their influence on the outcome of the study. The range of variation applied for a given issue should reflect the uncertainty by which it is accompanied. Typically, for batteries these can be energy densities, cycle lifetime, raw materials origin, selected electricity mixes etc.
Impact assessment factors	

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Characterization or normalization factors used in the impact assessment	Sensitivity analysis is performed by varying a single issue (e.g., parameter), or in case of interdependency by joint variation of the concerned issues and analyzing their influence on the outcome of the study. The range of variation applied for a given issue should reflect the uncertainty by which it is accompanied
Choice of impact assessment method and selection of impact categories	Other impact assessment methods and potentially omitted impact categories may be tested to see if they give different outcomes of the study to avoid burden shifting, e.g., resource depletion vs. Global warming potential

The interpretation phase includes the assessment of all phases and their results in the light of the achieved accuracy, completeness, and precision of the applied data, and the assumptions, which have been made throughout an LCA [7]. Following [104] and the ILCD Handbook [8], the interpretation includes the following aspects/steps, contribution analyses, completeness, sensitivity, and consistency checks which will be explained briefly in the following:

- **Contribution analysis:** Aims to identify the main contributors to the LCIA results, i.e., the most relevant life cycle stages, processes and elementary flows, and the most relevant impact categories. Typically, this is realized by quantifying which contributor contributes how much to the total result. Alternatively, a dominance analysis can be carried out, where the processes or stages are ranked according to their relative share in the total impact.
- **Completeness check:** These are performed for the LCI and LCIA to determine if available data is complete for the processes and impacts, which were identified as significant issues. If relevant information is found to be missing or incomplete for some of the key processes or the most important elementary flows or impact categories, the necessity of such information for satisfying the goal and scope of the LCA must be investigated. A major challenge is to judge the completeness of an inventory without knowing the absolute numbers of the inventors. In general, as much data as possible should be included to provide the best possible picture. Doing so also allows addressing potential questions on missing flows that may come from reviewers or third parties [7].
- **Sensitivity check:** Aims to identify key processes and most important factors that contribute most to the overall impacts from the product system, the reliability of resulting results and the conclusions and recommendations of an LCA study. Sensitivity analysis can be performed, together with information about the uncertainties stemming from inventory data, impact assessment data and methodological assumptions and choices. Quantitative

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methods to do so are, Scenario analysis, uncertainty calculations and parametric studies. Some examples of typical factors that can be varied for batteries are provided in Table 14.

Table 14 Life cycle interpretation examples of significant issues for batteries

Production	Use	Recycling
• Energy density • example variation of energy density • Electricity mix for production • Heat sources • Transport routes • Sourcing countries	• Cycles per day • Electricity mix / source • Cycle and calendric lifetime • System periphery	• Recycling rate of materials • Analyzed processes • Energy mix / source • Transport routes

- **Consistency check:** is performed to investigate if the assumptions, methods, and data have been applied consistently throughout the LCI/LCA study. The consistency check applies both to the life cycle of an analyzed system and between compared systems [7]. An example is in the case of a comparative LCA if allocation rules and system boundary and impact assessment has been consistently applied to all compared product systems.

As a last step conclusions, limitations, and recommendations are derived. This is done by integrating the named elements of the interpretation phase including the main findings from the earlier phases of the LCA. Then, as a last step, conclusions are drawn and limitations of the LCA are identified. Based on these, corresponding recommendations can be provided based on the most significant findings which should relate to the intended application of the study as defined in the goal definition. Recommendations can entail for example to focus on the improvement of a specific process; to change a supplier with a lower impact [8].

Example for the interpretation phase for Sodium-ion and Lithium-ion batteries

In the following a short example for an interpretation of an LCA study on Sodium Ion batteries (SIB) in relation to lithium-Ion batteries (LIB) is presented. The use case is based on the work of [76], where a set of different sodium ion batteries (SIB) is compared with state-of-the-art lithium-ion batteries (lithium-Ion Phosphate and Lithium-ion manganese LFP, nickel cobalt - NMC). Here two different impact categories are selected for demonstration purposes, the global warming potential

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(GWP) vs. the abiotic resource depletion (ADP). As shown in Figure 16, out of a cradle-to-gate perspective the GWP of the SIB as a new technology are higher in relation to those of the state-of-the-art LIB benchmark (LFP and NMC 622). In contrast, looking at the ADP shows a different picture. Here SIB perform, depending on the chemistry, significantly better than their LiB counterparts. So, consequently, avoiding a certain impact category can lead to potentially wrong of short-sighted conclusions. It is thus highly important to check several impact categories before deriving any final conclusions, or to address potential issues in the limitations of the study.

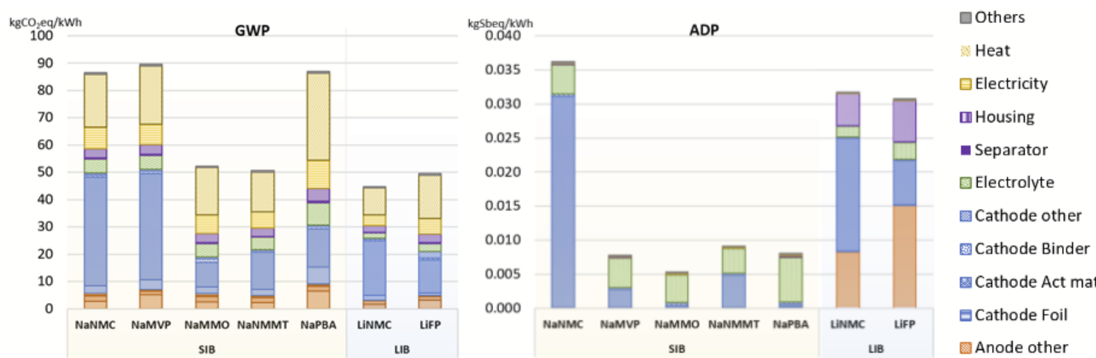

Figure 16 Comparison of cradle to gate results for different SiBs in comparison to LiB, for two different impact categories, namely Global Warming Potential (GWP) and abiotic resource depletion (ADP), based on [76]

As mentioned before, system boundaries are discrete choices that should always be checked. A typical example is to omit the end-of-life phase of a newly developed battery cell (here SiB) due to the lack of data. This decision can lead to significant differences in the interpretation. The potential differences are again demonstrated via the example of SIB vs. LIB (see Figure 17). Here, different recycling options (simple mechanical and advanced hydrometallurgical recycling) are analyzed for the impact categories GWP and ADP. Deep recycling can lead to significant reductions of GWP for LIB and have a negative effect for SIB (higher energy efforts to recover used materials) supporting the conclusions from Figure 16. However, looking at the impact of different recycling routes on the ADP shows that the advantages of SIB can be mitigated by LIB, leading to a new conclusion and potential recommendations.

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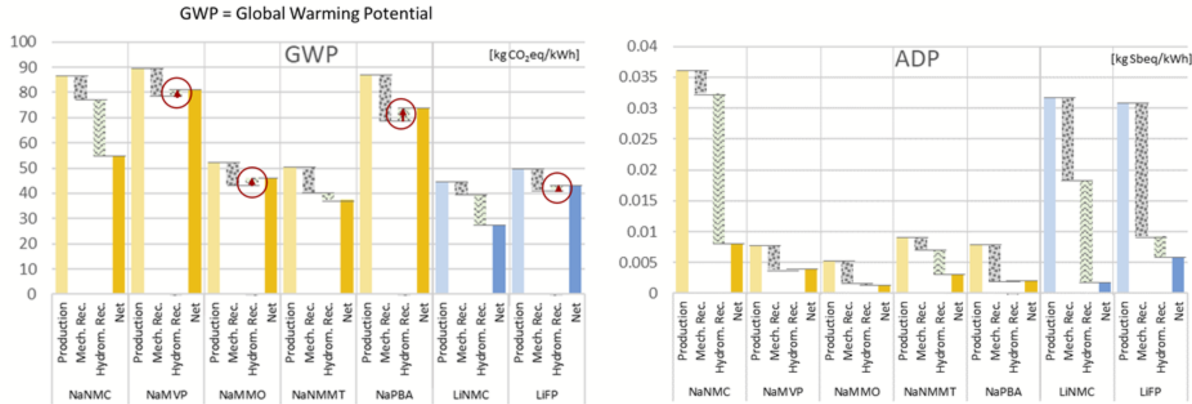

Figure 17: Overview of different recycling paths for SIB and LIB for two different impact categories, namely Global Warming Potential (GWP) and Abiotic Resource Depletion (ADP), based on [76]

In Figure 18, the result of the entire life cycle of SIB and LIB are compared considering all relevant phases (production, use, and end of life treatment/recycling). Here, the results are displayed with recycling (with bars) and no recycling (yellow dots). In addition, the electricity source for the operation of the battery cells has been varied from photovoltaics (PV) to a European grid mix (including the recent power plant generation from 2020). Here it can be seen that depending on the used electricity mix, either the production or use phase are the main drivers for both GWP and ADP. Here, the efficiency losses are attributed directly to the battery (the discharged amount of energy is not credited). Furthermore, the replacement can be allocated to the use phase as it marks the number of cells that must be exchanged over the entire project duration (here 20 years). For example, some cells have a lower cycle lifetime than others, leading to higher potential impacts as more cells have to be produced. Depending on the use case, such aspects must be considered to provide a robust picture. Usually, there is a scarce of data when it comes to performance values for new battery types as SIB. Typically, this related to e.g., cycle lifetime or energy density and can cause, depending on the assumptions, very high uncertainties as displayed via the error whiskers in Figure 18.

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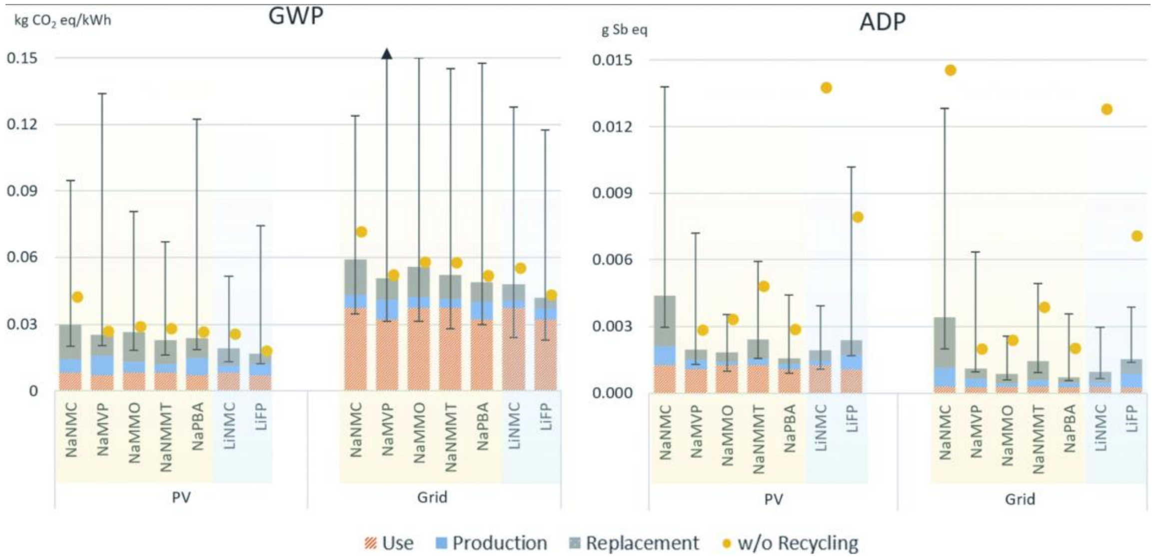

Figure 18: Comparison of all relevant life cycle phases for SiB and LiB for two different impact categories, namely Global Warming Potential (GWP) and Abiotic Resource Depletion (ADP), based on [76]

It is thus important to understand from where these uncertainties come from. Typically, parametrizing is one way to understand the impact of different variables on results. An example for a sensitivity analysis of energy densities of different SIB and LIB is provided in Figure 19. Here it can be clearly seen how increasing the energy densities can lead to significant reductions of impacts on a cradle to gate perspective. This is due to the number of materials required on a kg/kWh basis. The higher the energy density, the lower the material demand. However, energy density is a factor that can vary, but usually on the cost of other performance indicators such as e.g., power density or cell cycle lifetime. Relevant materials used for the presented use case can be found in Table 19.

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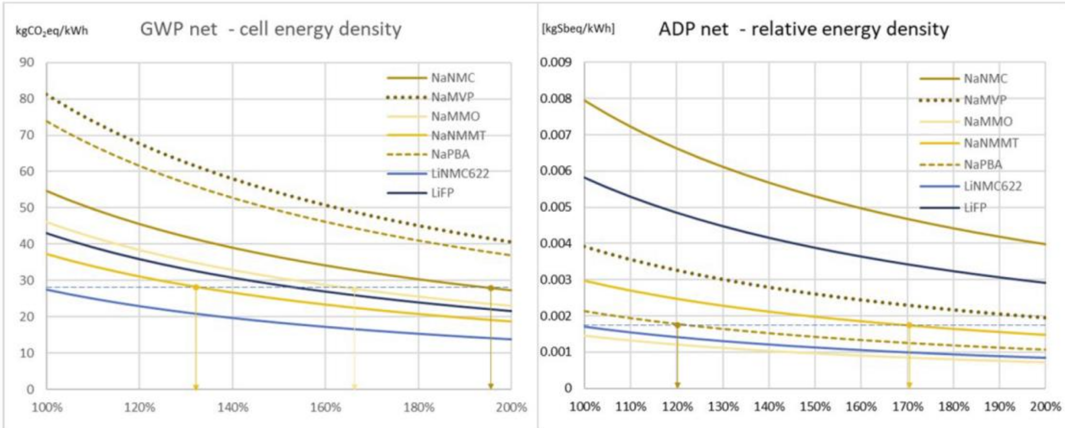

Figure 19 Example of a sensitivity analysis of energy densities for SIB a. LIB for two different impact categories from a cradle-to-gate perspective, namely global warming potential (GWP) a. abiotic resource depletion (ADP), based on [76]

Table 15 Relevant materials related to the LCA interpretation phase

Title	Type	Description	Link/File name
Peters et al. On the environmental competitiveness of sodium ion batteries und a full life cycle perspective	Journal article	Full LCA and supplementary materials for LCI and interpretation of SIB And LIB	SEF
Cell Model	Excel model	Model from [76]	LCI interpretation
Baumann et al., Parametric study on LiB and SiB batteries	PowerPoint	Presentation on use phase of SIB and LIB for the EnInnvo2022	EnInnov

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4.5 Life Cycle Costing

The aim of the section is to provide an overview of how LCC for batteries can be carried out. This includes an overview of used LCC methods and how to start with the cost modelling. Here, a strong overlap with Austrian Institute of Technology (AIT) is given (techno-economics assessment). Here the perspective entails the entire life cycle, and more insights to bottom-up modelling of cell cost will be provided.

Among life cycle methods, life cycle costing is the oldest. The origins of life cycle costing go back to the year 1933, when the General Accounting Office (GAO) from the US requested an assessment of the costs of tractors that considered a life cycle perspective in a request for tender [105]. Additional in the 1960s, the US military in particular began to realize that a purchase decision based solely on acquisition costs is not ideal, but that the cost contributions resulting from the operation, maintenance, and logistics of the goods to be purchased must also be considered. For this reason, the U.S. Department of Defense has already been very insistent that the use of life cycle costs be included in the contract definition phase of military equipment purchases [106]. In the further course of the methodological development of LCC, three variants have emerged. One is the conventional LCC, also referred to as financial LCC, is the original method, which is in many ways synonymous with TCO (Total Cost of Ownership). The second is the environmental LCC, which, in relation to the LCA, includes the same phases for the procedure (Goal and Scope, Inventory, Interpretation, and sensitivity analysis) as well as the same product system, functional unit and system boundaries to be defined. Thirdly, the societal LCC, which additionally includes the effects of social costs on society (e.g., health costs due to air pollutants), in the calculation. Here, a monetarization of other externalities takes place, which are caused by environmental impacts as well as social impacts.

There is no common standard for the three methods, as the calculation methodology has different objectives depending on the perspective (manufacturer, user, society, industrial sector, service provider, etc.). However, standards for conventional LCC have been developed by various government agencies and industry sectors. Among them are the following guidelines: IEC 60300-3-3, ISO 15686, VDI 2067 [107]. For environmental LCC, the work of the scientific working group on LCC within SETAC led to the LCC methodology described in [108]. This has also found its way into the joint work within the UNEP-SETAC LCI initiative on the overarching methodology for Life Cycle Sustainability Assessment [105]. The methodological development of societal LCC is still ongoing and represents a great challenge, since the integration of all relevant external effects (environmental and social effects) of an investigated system with high model accuracy and low uncertainty proves to be extremely difficult. A good insight into the methodological approach for the calculation of externalities due to air pollution can be found in the publication on the ExternE project [109].

The following Figure 20 shows the differences between the three variants of LCC methods.

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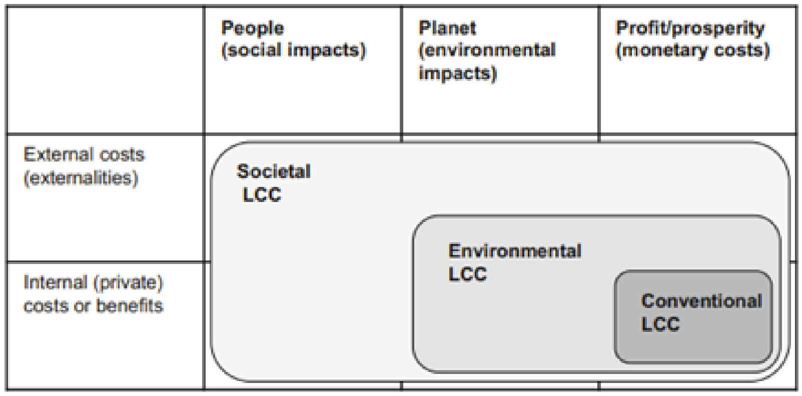

Figure 20: Comparison of the different types of LCC [103]

The figure shows that the conventional LCC is limited only to internal costs or benefits. The differences to the environmental LCC are the point that there are not considered costs due to environmental impacts, for example for CO2 emissions which cause cost appropriate the European CO2 emission trading system. Other environmental-related costs are air pollutant substances like sulfur dioxide (SO2) which is included in the US allowance-trading program since 1990 [110].

Different types of costs and terminology

In the following Table 16 relevant terms of different types of costs and terms in relation to the method of life cycle costing are defined.

Table 16: Definition of different types of costs and terms of LCC [103]

Terms	**Definition**
Life Cycle Costs	The sum of value added over the life cycle of a product or a system [111]
Price	The amount of money that will purchase a finite quantity, weight, or other measure of a good or service [112]
Revenue	The income generated from sale of goods or services, or any other use of capital or assets, associated with the main operations of an organization before any costs or expenses are deducted
Internal cost	Costs borne by actors directly involved in the life cycle of the system under study
External cost	External costs (also termed externalities) are value changes caused by a business transaction, which are not included in its price, or which occur as side effects of economic activity [113]

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Value add	Value added is the difference between the sales of products and the purchases of products or materials by a firm, covering its labour costs and capital costs as well as its profits [108]
Net Present Value (NPV)	NPV is the sum of all the discounted future cash flows that considers the time value of money over the entire lifetime [112]
Discounting rate	A method used to convert future costs or benefits to present values using a discount rate [114]
Inflation rate	A measure of the overall change in prices for goods and services over time
Exchange rate	Currency conversion between different currencies
Investment cost	Represent the economic magnitude of the introduction of a technology. It includes all costs for all the project implementation phases relating to purchase of equipment, installation, construction of roads, buildings, engineering services, etc.

General cost calculation method used in LCC

The classic used method for LCC calculation is a dynamic investment calculation method, the annuity method which is based on the Net Present Value (NPV). The general formula is shown in the following Figure 21 [115]. The annuity method calculates the average constant yearly pay-out of an investment project (for example a battery) over the investment period (T), considering the time value of money. The annuity is the capital recovery factor multiplied with the NPV.

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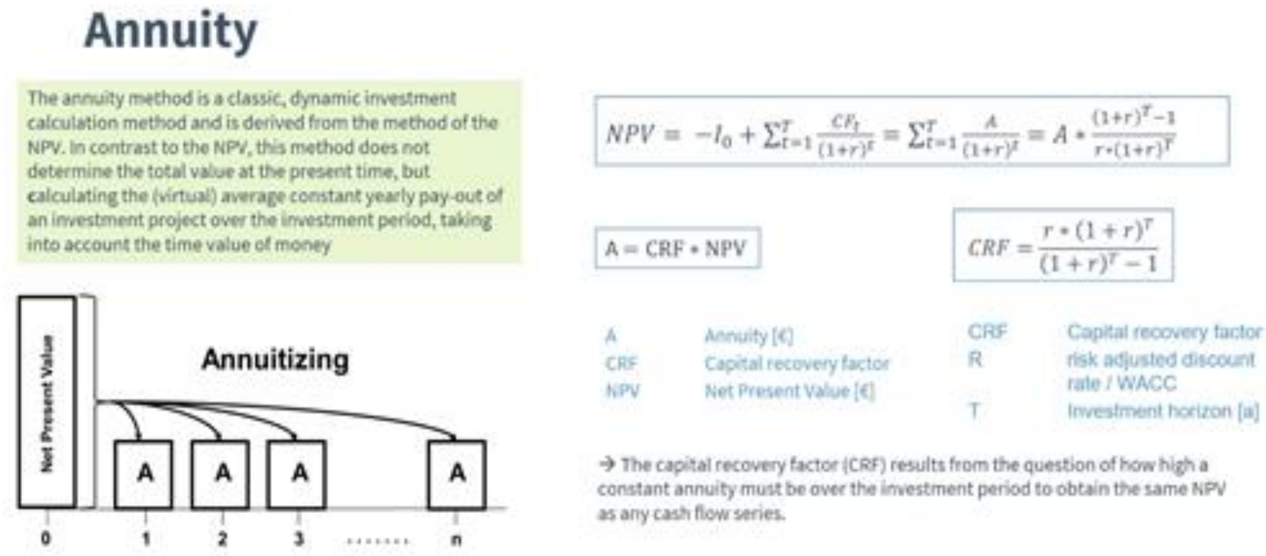

Figure 21: Overview of the Annuity method [Resch 2023]

These calculation methods will be applied in principle to each life cycle phase from raw material extraction over manufacturing of materials and components to usage and maintenance and is closed with End of life. In the following are shown some examples of components of a battery. In general, for any cost calculation of a battery, the BatPaC cost calculation model presented by Argonne National Laboratories is a good support [116].

Cost calculation of cathode active material based on [75]

The price of a cathode active material had to be estimated based on the cost of the raw materials plus the manufacturing costs [116]. The calculation formula and parameter are shown in Equation (1).

Eq. (1) $C\left(\frac{€}{kg}\right) = C_0 + \frac{1}{MW}\sum_i x_i \, C_i MW_i$

where: C = Final cost (€/kg), Co = Baseline cost (€), Ci = Price of the raw materials (€/kg), xi = Molar stoichiometry (-), MWi = Molecular weight of the raw material (g/mol), and MW = Molecular weight of the final product (g/mol).

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Cost data collection

The availability of reliable cost data is crucial in order to perform a realistic life cycle cost analysis. Gathering financial data can be time-consuming and will depend on the collaboration with the companies and institutions involved.

Financial data can be very sensitive, especially if the results are intended to be published. In these cases, most of the data needs to be gathered from other independent data sources and references. Public databases are shown in the following Table 17. The aforementioned databases provide an overview of the various cost categories. These data are published at least once a year. However, the scope of each database varies, and it is important to check each data source for completeness, validity for different regions, currencies, and time to ensure that the data are comparable.

Table 17 Public database for life cycle cost adapted according to [102]

Type	Scope	Name	Link
Crude oil	Sectors, monthly, country	International Energy Agency	https://www.iea.org/statistics/topics/
Plastics	Global, weekly	The Plastic Exchange	www.theplasticsexchange.com/
Marine fuel oils	Sector, daily, global	Ship and Bunker´s	www.shipandbunker.com/
Chemicals	Sector, daily, global	ICIS, Part of RELX Group	www.icis.com/explore/commodities/chemicals/
Metals	Sector, daily, global	London Metal Exchanges	www.lme.com/
Commodities	Sector, yearly, global	United Nations	https://comtrade.un.org/db/
Inflation	Sector, country, monthly	World Bank	https://data.worldbank.org/
Wages	Sector, country, yearly	International Labour Organization	www.ilo.org/global/lang--en/index.htm
Currency exchange rates	Yearly, monthly	World Bank	https://data.worldbank.org/
Power, gas, coal, oil	Daily	European Stock Exchange	www.eex.com/en

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Principal differences between environmental LCC and LCA

An important difference between environmental LCC and LCA is the use of cut-off criteria. Especially in complex systems with more than a thousand processes, process-based LCA omits processes that are assumed to make a negligible contribution, thus introducing truncation criteria. Environmental LCA, on the other hand, does not suffer from these truncation errors because it assumes that costs upstream in the supply chain are included in the price of a product or service. For example, the cost of purchasing a lithium-ion battery includes all costs associated with producing the battery, including raw materials, overhead, financial services, R&D, marketing, supply chain profits, and so on. In an LCA, the financial services, R&D and marketing of a product are typically not included in the system boundary.

4.6 Social-Life Cycle Assessment

As far as s-LCA is concerned, there are many questions, including: what is it, what are the challenges associated with it, and how does it fit in battery context? The aim is to give a method overview based on literature. In line with this, some relevant s-LCA materials would be given for reference.

It is important to recognize that batteries play a critical role in the energy transition, whether it be storing renewable energy, being used in the automotive sector or powering grids; they have both positive and negative consequences on society, depending on their lifecycle stage. The intertwined nature of global markets for batteries and raw materials makes the supply chain full of complexities, alongside social and socio-environmental impacts. To understand and improve a sustainable supply chain for batteries, an analytical methodological approach such as the Social Life Cycle Assessment can be useful.

s-LCA is an integral component of sustainability assessment, which complements the costing and environmental components. With the application of life cycle thinking approach, it pays attention to people and society and assesses potential social risks associated with products throughout their life cycle, from raw material extraction to end-of-life recycling. The main goal of the s-LCA is to promote good social conditions for the general wellbeing of humanity. By integrating ELCA, LCC, and s-LCA, burden shifting can be avoided and sustainability impacts, benefits, and associated tradeoffs can be assessed holistically and effectively.

As the latest method developed by UNEP in collaboration with SETAC, s-LCA draws from the same methodological framework as the environmental LCA according to ISO 14040 standards with the four iterative stages shown in the figure 22 below [116]. Instead of focusing on the ecological aspects such global warming potential, s-LCA focuses on the social and socio-economic impacts. It investigates on two types of social impacts caused by either negative or positive pressures. These pressures stem from various aspects of society, including behaviour, capitalism, and cultural

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heritage. As a result, there are negative impacts such as child labour, discrimination, low wages, conflict fuelling possibilities, corruption, and so on, or positive impacts such as opportunities for economic growth.

From the UNEP Methodological sheet, it outlines six stakeholder groups that are impacted by the social structures including children, workers, local community, consumers, society, and value chain actor [118]. Within each group are associated social indicators that allow for the assessment and quantification of the social impacts using an activity variable such as worker hours. Although the Guidelines sheet does give a standardised social impact assessment method, the reference scale assessment and the impact pathway assessment approach have been adopted so far. These approaches are explained later in the chapter.

An overall benefit of s-LCA is that it can provide information regarding the possible socio-economic performance of niche innovation technologies, especially energy battery technologies. It can also assist in decision-making when it comes to assessing how a product's life cycle, such as batteries, will impact society and the economy. Nonetheless, social impact assessment is still undergoing scrutiny and refinement due to shortcoming in terms of methodological development and harmonization of sectors. Unlike environmental impacts, which can be more easily standardized and quantified, social impacts are not governed by natural laws and are difficult to assess and quantify because of subjectivity, complexity and a wide array of global social problems.

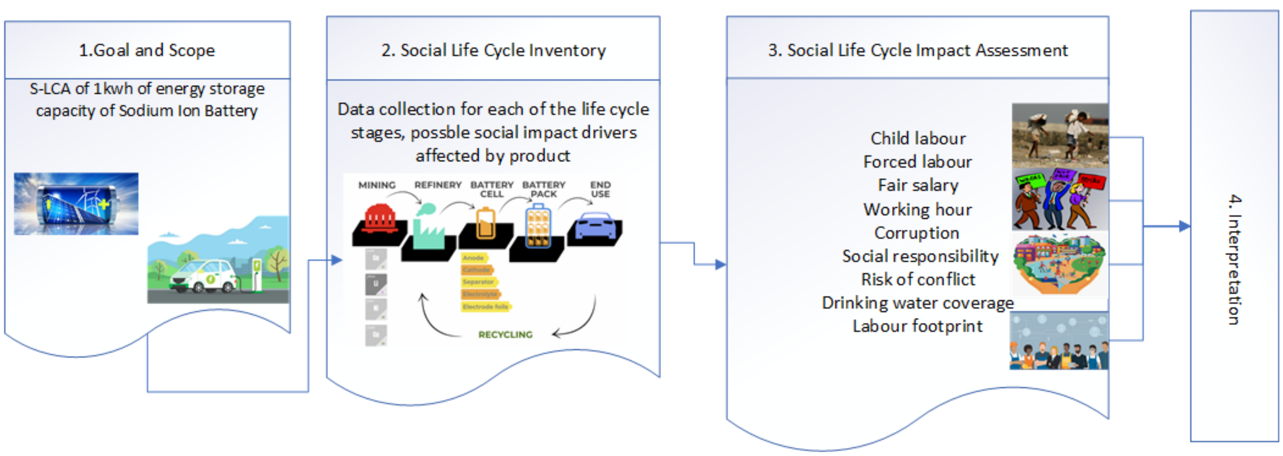

Figure 22 illustrates the four steps used for social LCA

4.6.1 Goal & Scope Definition

Just like the LCA, it is important to first define the reason for the social studies. What do you want to assess? What is the intended use of the study? What stakeholder group do you want to focus

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on? The scope allows for more visibility of the investigation and outlines the breadth and depth of the studies. It helps with limitations and setting boundaries for the product system. Setting the goal and scope for s-LCA involves specifying the functional unit, stakeholder groups, subcategory impact indicators etc. For instance, you may want to perform a social LCA of a 1kWh of battery storage, focusing on only the worker stakeholder group. By doing this, social indicators related to the worker can be examined, such as the right to form a union, forced labour, and hours of work.

4.6.2 Social Life Cycle Inventory

For the different life cycle stages, input, and output data is collected based on the functional unit. Data such as cost, added value or worker hours are imputed into the model as well as the social indicators that act as output flows. Unlike environmental LCA, the output flows for s-LCA also include social inventory indicators, which are interlinked with an activity variable. The activity variable here shows the relevance a social impact has on a process output. Until now, worker hours and value added are the two activity variables used for s-LCA. However, the most common activity variable used is the work hours, defined as the time in hours spent to produce an output. s-LCA relies a lot on data collection for a foreground and background modelling, finding primary onsite data could be very tedious and time consuming. As a result, the modelling of s-LCA usually depends on generic databases. The two main existing databases are the Product Social Impact Life Cycle Assessment (PSILCA) and the Social Hotspot Database (SHDH).

4.6.3 Social Life Cycle Impact Assessment

The aim of the s-LCIA stage is to comprehend and quantify the possible social and socio-economic impacts of the investigated product system. Currently, there is still no clear consensus on the impact assessment method to be used for s-LCA. Presently, two approaches have been developed so far.

Type 1 also known as the reference scale approach: This approach focuses on the social risks related to the behaviour of an organisation that is involved in the product system along its life cycle stages. The PSILCA and SHDH databases apply this approach for social impact assessment.

Type 2, Impact pathway Assessment: involves a cause-effect relationship that impacts of the product system: it assesses the consequences resulting from the product system most comparable to environmental impact assessment.

4.6.4 Interpretation

This final stage also draws knowledge from how the E LCA is done. It involves analysing the results of considered phases. It covers a completeness check sensitivity analysis, data quality, limitations, conclusions and some final outlook.

Table 18: Literature sources on s-LCA for reference

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Title	Type	Description	Link
Guidelines for Social Life Cycle Assessment of products and organizations 2020 [117].	PDF	Presents guidelines on social and socio-economic life cycle assessment.	https://wedocs.unep.org/20.500.11822/34554
Guidelines for Social Life Cycle assessment of products [119].	PDF	It provides context and key elements pertaining to stakeholder engagements in the social and socio-economic impact assessment.	https://wedocs.unep.org/bitstream/handle/20.500.11822/7912/-Guidelines%20for%20Social%20Life%20Cycle%20Assessment%20of%20Products-20094102.pdf?sequence=3&amp%3BisAllowed=
Methodological sheet for subcategories in s-LCA [118]	PDF	This sheet complements the UNEP s-LCA Guidelines ad it documents tools that can be used to conduct S LCAs	Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA) 2021 (rwth-aachen.de)
Responsible and sustainable sourcing of battery raw materials [120]	PDF	Provides an understanding and quantification of risks on the mining stage of battery raw materials. It also applies technical frameworks such as s-LCA used for social sustainability assessment	https://dx.doi.org/10.2760/562951
Contribution of Social Life Cycle to reach the sustainable development goal [121]	PowerPoint	Using case studies, it illustrates how the s-LCA methodology can be used to support and achieve the sustainable development goals.	https://www.greendelta.com/wp-content/uploads/2015/10/S-LCA_Eisfeldt.pdf

4.7 Life Cycle Sustainability Assessment for Decision-making

The conceptualization of sustainability is often used in a way to address only the environmental impacts stemming from a product's life cycle. Nevertheless, there are certain connections between environmental, economic, and social dimensions often referred to as conditions for absolute sustainability. Hence, life cycle sustainability assessment (LCSA) is emerged in quest of absolute

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sustainability or identifying the most sustainable alternative matching all the requirements to ensure benefits of each stakeholder group. LCA as a state-of-the-art analytical environmental sustainability assessment tool provides the means for extension to cover the economic and social aspects. As a result, initially aiming for a broader coverage and accounting of impacts on various dimensions (e.g., environmental, social, and economic) to support informed decision making. Since it is hard to prioritise over dimensions, the LCSA suggests the consideration of so-called “Triple bottom line (TBL)” defining sustainability as a composition of environmental, social and economic pillars, attributing equal importance to each dimension. The concept of TBL proposes that the business sector should approach and manage environmental, social, and economic risks in a quantitative way as the financial aspects are managed in the accounting (see in Figure 23). Hence, the LCSA framework employs a common goal & scope definition and uses LCA, LCC, and s-LCA as analytical methods for assessing the impacts.

Figure 23 Triple Bottom Line: measuring social, environmental, and economic KPIs [122]

Initial claim about sustainability bases upon trade-offs, since it is mostly not possible to achieve improved performance in all dimensions. But understanding interdependencies and communication with stakeholders should assist definition of weightings to identify the most promising alternatives.

Since the LCSA aims to provide better decision-making support in terms of providing adequate knowledge about impacts, following the typical LCA framework steps (goal & scope definition,

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inventory, impact assessment, interpretation) iteratively the final interpretation is carried out by the use decision-making tools (i.e., MCDA).

4.7.1 Multi-criteria Decision Making for Sustainability Assessment.

MCDA represents a set of methods which allows combining different methods, better said their results and to include the preferences of stakeholders (See Figure 24). Doing so allows to provide support to decision makers to organize available information, to rethink the consequences of different alternatives (e.g., different battery chemistries) and to explore their perceptions and needs. The decision processes are formulated as equations, inputs, and coefficients which can be observed and reproduced via a set of different methods. All of them concentrate on discrete decision spaces where potential alternatives have already been predetermined. A major advantage is that MADM is that criteria with different scales or units, e.g., stemming from LCA, LCC or s-LCA can be simultaneously compared considering stakeholder preferences.

Usually, an MCDA starts with defining the goal and scope of the decision problem that is beeing solved (e.g., identifying the most sustainable electrolyte for new battery type among various alternatives). In line with that the most practical MCDA method, relevant alternatives and evaluation criteria should be defined. Then a kind of interface to express preferences regarding the selected criteria should be provided to involved stakeholders. Again, these steps should be seen as iterative steps, where the continuous discussion with stakeholders leads to an adjustment of the overall MCDA approach for LCSA. All in all, this phase is sometimes referred to as the construction phase.

Weights are ideally provided by the decision makers during a so-called exploitation phase. Besides weight attribution, the performance of different alternatives regarding the defined criteria has to be measured and to be made comparable with other alternatives (named as criteria aggregation). For LCSA, this is done via LCA, LCC and s-LCA. A wide set of different methods is available for this purpose, which again must be selected carefully in respect to the goal and scope definition. Attention should be paid if selected methods have sufficient flexibility to integrate a high variety of data typologies with various degrees of freedom into an assessment.

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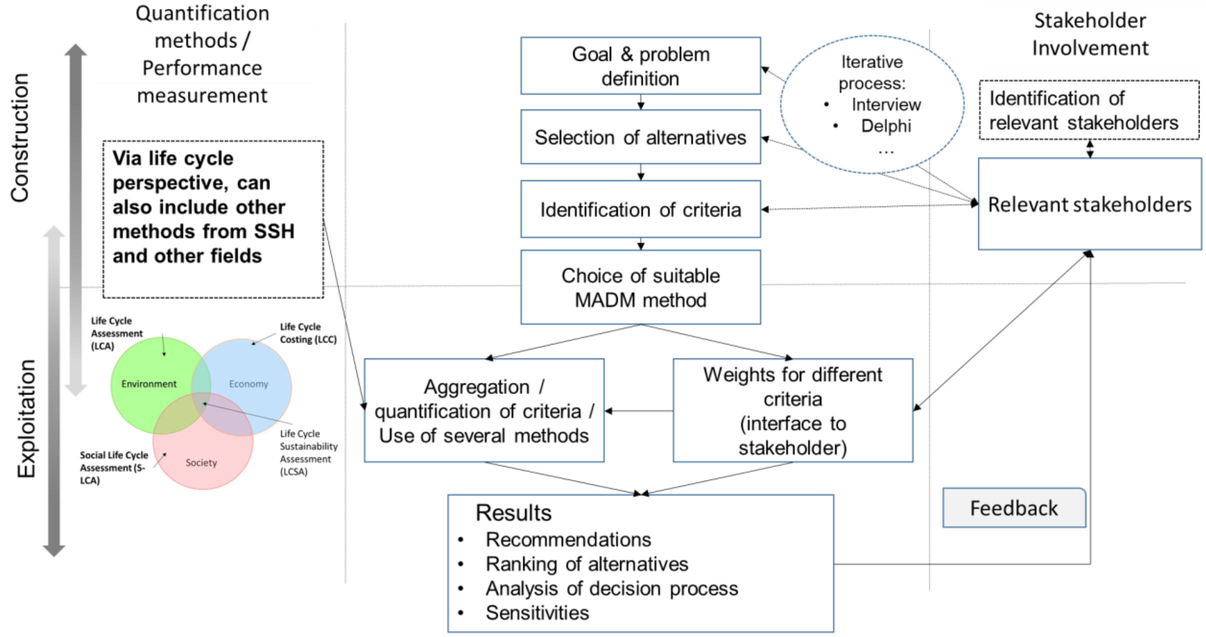

Figure 24 Simplified MCDA approach for LCSA approaches based on [123]

It is highly important to point out that MCDA cannot identify the ultimate right solution, as there is never a perfect solution available in real life. Rather, it is a way to provide a wider picture of potential implications of battery storage in terms of sustainability. Here two main groups can be distinguished as presented in Figure 25, value and utility theory and outranking approaches.

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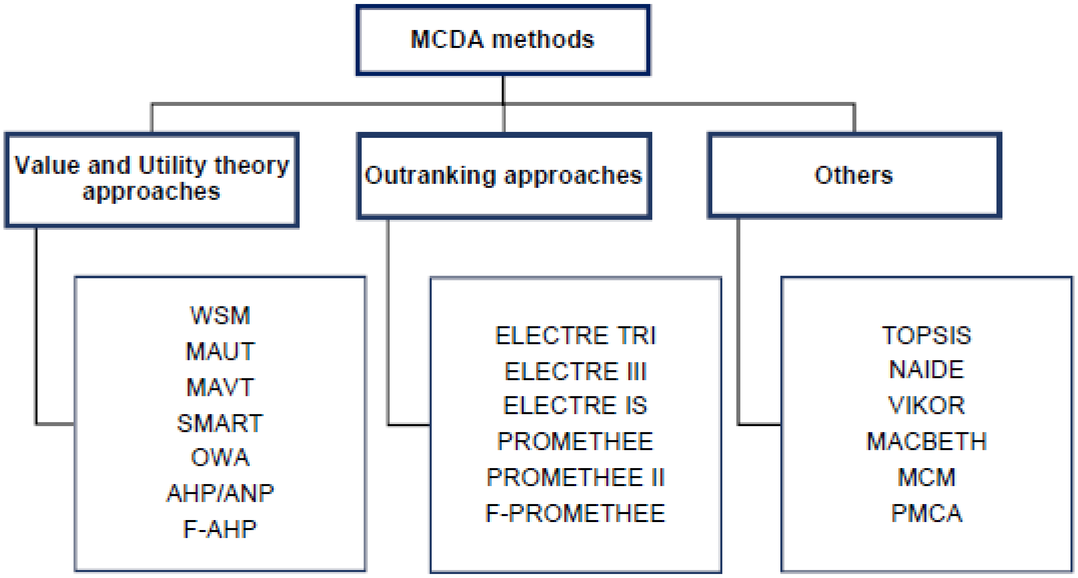

Figure 25: MCDA methods classification based on [124]

Some general recommendations based on [123] are:

Stakeholder involvement: should happen as early as possible, starting with the problem definition with a broad set of relevant stakeholders (in line with the goal and scope here). One-iteration processes should be avoided (e.g., just gathering weights).

Criteria selection and definition: To a certain degree a set of criteria is already available within LCSA, however the final selection of these should be discussed with stakeholders and reflect the essential properties of the battery storage technology.

Choice of MADM: this should be based on the type of problem, desired results, and stakeholder preferences. Most importantly, the method should be suitable for the available input information (quantitative and / or qualitative). The reason of why selecting a certain method among others should be highlighted in any case.

Definition of application cases and related battery cell design: The performance of a battery cell is highly dependent on the materials used and its design, which at the end makes it suitable for a certain application. In any case, applications must be comparable when different systems are compared. Usually, critical points are the same as for the other methods used as e.g., cost, maturity, and efficiency grades.

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Presentation of results: These should be described in the specific context in which they are applicable and be considered only indicative. Ranking can also be interpreted in different ways, e.g., the selection of a material selection case for a battery is entirely justified, that it can be recommended after certain modifications or in the worst case, may not be recommendable.

Consideration of uncertainties: As for all other methods, a sensitivity analysis should be provided along with the results. Typically, this is done by variation of weight or performance data. Doing so, allows to better the robustness of the results (e.g., how attributing a different weight can lead to a different rank) and potential implications related to his decision

Table 19 Relevant materials related to Life Cycle Sustainability Assessment

Title	Type	Description	Link/File name
MCDA for sustainability assessment – insights to Helmholtz Association activities Working Paper	PDF with supplementary materials	Overview of MCDA methods for sustainability assessment of energy technologies with multiple use cases to illustrate the use of MCDA	Zenodo
MCDA Review	PowerPoint	Overview of MCDA methods applied to energy storage	DLR_VE
MCDA-KIT	Software	Freely available MCDA Software with different methods	Tool

4.8 Next steps

The chapter provides a first overview of the different topics that that will be further developed based on the different teaching activities and feedback from TBU, e.g., during the JF or the workshops. Here, more details and specific examples will be added to the different methods as LCC and sLCA until month 30 for deliverable 4.2.

5 Conclusion

The document on hand provides a detailed overview of the teaching strategy, related materials and the corresponding roadmap. Here fore, all activities are highlighted in terms of the goals, procedure and already realized teaching activities. In addition, relevant data has been added on the common

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teams share point. A first draft of the sustainability guideline with general overview chapters is provided as a starting point for further exchange. Life Cycle Assessment has been described in more detail in relation to the other methods as LCC, s-LCA, LCSA and MCDA as most of the carried-out activities have been centered around this method. This draft will be continuously updated based on the activities, exchange, and input from TBU and will be extended in the Deliverable 4.2 to assure the provision of demand driven sustainability guideline. Finally, the latter will serve as theoretical foundation for the planned sustainability theatre.

6 Gantt chart

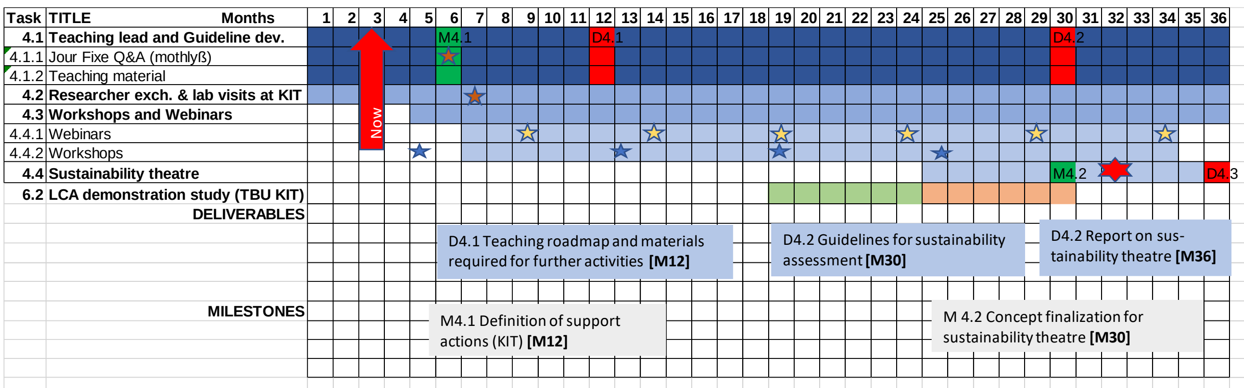

Figure 26 Gantt chart for WP4

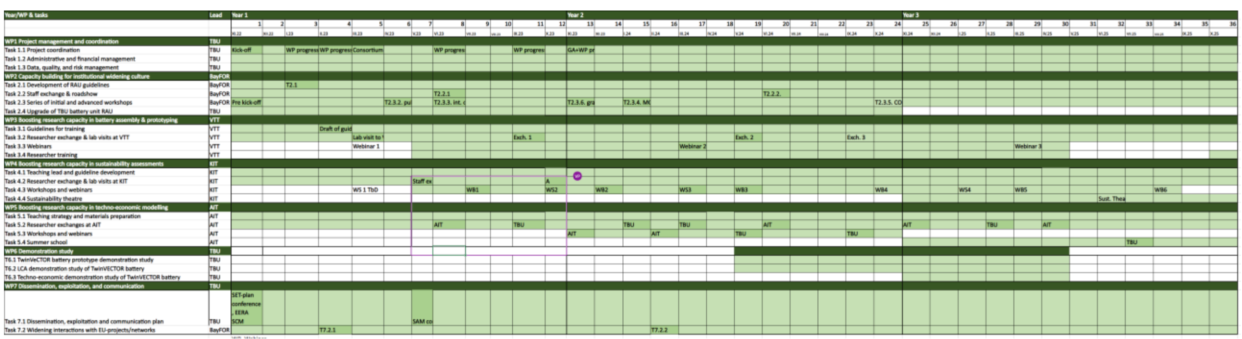

Figure 27 Gantt chart for the entire project

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