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AGISTIN
Advanced Grid Interfaces for
innovative STorage INtegration

D2.2: LCA methodology for storage integrated in AGI

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EXECUTIVE SUMMARY

This deliverable provides a framework for practitioners to conduct the Life Cycle Assessment (LCA) of energy storage technologies integrated with Advanced Grid Interfaces (AGIs).

The document first introduces the fundamentals of the LCA concept and methodology (Chapter 1) as the standardised methodology for evaluating environmental impacts across a product's life cycle. At the same time, it introduces key concepts such as functional unit, system boundaries, inventory analysis, and impact assessment are to set a clear methodological foundation. The introduction is followed by a review of the current status of LCA applications in the field of energy storage (Chapter 2). This section presents a summary of the state-of-the-art, assessing several LCA studies on various energy storage technologies, including batteries, hydrogen systems, and pumped hydro, addressing aspects such as the functional unit, contribution of the different life cycle steps and conclusions to support the AGISTIN work. Challenges such as data gaps, renewable energy integration and the environmental burden of manufacturing processes are also discussed.

Then, the actual AGISTIN LCA framework is presented (Chapter 3), adapting existing LCA standards and methodologies to the specific requirements of AGI-integrated storage technologies. It details the goal and scope definition, functional unit selection, system boundary setting, and impact category selection. The framework underlines considerations such as ancillary grid services, technology readiness levels and data availability. Practical recommendations and examples are provided to guide practitioners in applying the framework effectively.

Key Contributions

- A tailored LCA methodology for energy storage and advanced grid-specific functionalities.
- A focus on lifecycle stages most critical to environmental performance, including use, manufacturing, and end-of-life.
- Alignment with EU Product Environmental Footprint (PEF) guidelines to ensure methodological consistency and comparability.

This deliverable will be used in the upcoming tasks dealing with the environmental and technoeconomic assessment of the two pilots in WP5 and WP6 and will be put into practice and improved based on the results of the application.

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LIST OF ABBREVIATIONS

Acronym	Description
AGI	Advanced Grid Interface
EoL	End of Life
ESS	Energy Storage System
GHG	Greenhouse Gas
GWP	Global Warming Potential
ILCD	International Reference Life Cycle Data
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LIB	Lithium-Ion Battery
LIPB	Lithium Iron Phosphate Battery
NMC	Nickel Manganese Cobalt Oxide Battery
PEF	Product Environmental Footprint
PEM	Proton Exchange Membrane
SOEC	Solid Oxide Electrolyser Cell

GLOSSARY

Term	Definition
Background System	Processes not specific to the analysed system, usually modelled using generic data from databases.
Cradle-to-Gate	An assessment approach that includes only the stages from raw material extraction to the product leaving the factory gate.
Cradle-to-Grave	An assessment approach that includes all stages of a product's life cycle, from raw material extraction to end-of-life disposal.
Critical Raw Materials (CRMs)	Materials essential for industries with significant supply risks due to limited sources or geopolitical factors.
Cut-off Criteria	Rules defining the exclusion of inputs or outputs from an LCA based on materiality, energy use, or environmental significance.
End of Life (EoL)	The final stage in a product's life cycle, including recycling, reuse, or disposal.
Endpoint Indicator	An environmental impact metric representing damage at the endpoint level, such as effects on human health, ecosystems, or resource availability.
Foreground System	Processes directly linked to the analysed product system, often requiring primary data for accurate modelling.
Functional Unit	A quantified description of the performance of a product system, used as a reference for all calculations in an LCA.
Impact Assessment	The stage in LCA where inventory data is translated into potential environmental impacts across selected categories.
Life Cycle Assessment (LCA)	A method to evaluate environmental impacts associated with all stages of a product's life cycle, from raw material extraction to disposal.
Life Cycle Inventory (LCI)	The collection and quantification of inputs (e.g., raw materials, energy) and outputs (e.g., emissions, waste) for the studied system.
Midpoint Indicator	An environmental impact metric focused on specific mechanisms (e.g., climate change) before damage occurs at the endpoint.
Product Environmental Footprint (PEF)	A method to evaluate the environmental performance of a product throughout its life cycle, based on EU recommendations.

Executive Summary

AGISTIN will enable industrial grid users to rapidly deploy renewables through advanced integration of innovative energy storage technologies interfacing the grid. Rapid industrial decarbonisation through electrification, renewable growth, and increasingly strict stability requirements present a unique opportunity for new forms of storage and integration schemes. The main objectives in the project are to develop new forms of energy storage that meet grid needs for short-duration flexibility and stability, reduce the impact of intensive demand on the grid, and reduce costs for large grid users through innovative storage integration. This project advances the state of the art for aqueous batteries, use of irrigation systems as energy storage, grid interface designs and provision of advanced grid services from large load users.

Two demonstrations and three test activities centred around renewable hydrogen electrolysis, irrigation pumping, and fast EV charging are used to demonstrate advanced concepts for energy storage, grid integration and grid users. The AGISTIN project is intended to reduce the grid connection cost for industrial grid users, reducing H_2 production cost by 10% and improved grid stability through advanced grid services enabling power grids to run with a higher share of renewables. The innovative storage technologies directly addressed in the project include: aqueous electrochemical recuperators (with properties between super capacitors and batteries), irrigation systems (used as energy storage), and flow batteries. These technologies will be tested and demonstrated in the targeted use cases (in Advanced Grid Infrastructures applications), resulting in TRL level increases. The consortium includes members across the value chain and from 9 different countries to better exploit the results. Partners include: storage and power electronics providers, industrial grid users, a grid operator, an engineering consultancy, research institutes, universities and an energy storage association.

This document delivers the framework that steering the environmental LCA assessment of the two demonstration cases in AGISTIN, building upon existing standards and going the extra mile to adapt these methods to the specific features of the project.

This document is structured as follows:

- Chapter 1 introduces the fundamentals of the LCA approach in a concise way to understand the life cycle thinking perspective.
- Chapter 2 presents the results of the literature review on LCA studies for energy storage focusing on extracting learnings supporting the upcoming work in the AGISTIN context.
- Chapter 3 describes the LCA framework itself. Determines main assumptions and guidelines to be followed in Tasks 5.5 and 6.5.

1 Introduction to the LCA concept and methodology

The earliest references to the very first LCA studies can be traced back to the late 60s and early 70s. At that time, economic aspects were the key factor in decision making processes, while the environmental dimension was largely left out of the equation. In this context, the studies by the Coca-Cola company evaluating different types of packaging (the can vs bottle dilemma) are frequently cited as the seed for the future life cycle analyses, although back then these studies were known as Resource and Environmental Profile Analysis (REPA) (Aviso, 2024). In the next 20 years there was a growing interest in the methodology, especially by companies that wanted to support market claims (Guinée et al., 2011). However, lack of harmonisation and scientific support flagged the need for a uniform and standard approach.

After five decades of constant progress, LCA evolved into a standardised methodology widely used to study environmental impacts, currently including social and economic aspects across the life cycle. In fact, some of the latest EU regulations highlight the importance of the LCA as the appropriate tool to evaluate environmental indicators. For example, Ecodesign for Sustainable Products Regulation (ESPR), the Energy Labelling Directive or the EU Taxonomy Directive. Formally, LCA is defined by ISO14040 as:

> …the collection and evaluation of all the inputs, outputs and potential environmental impacts of a product system across its life cycle, from raw material acquisition and processing up to final disposal.

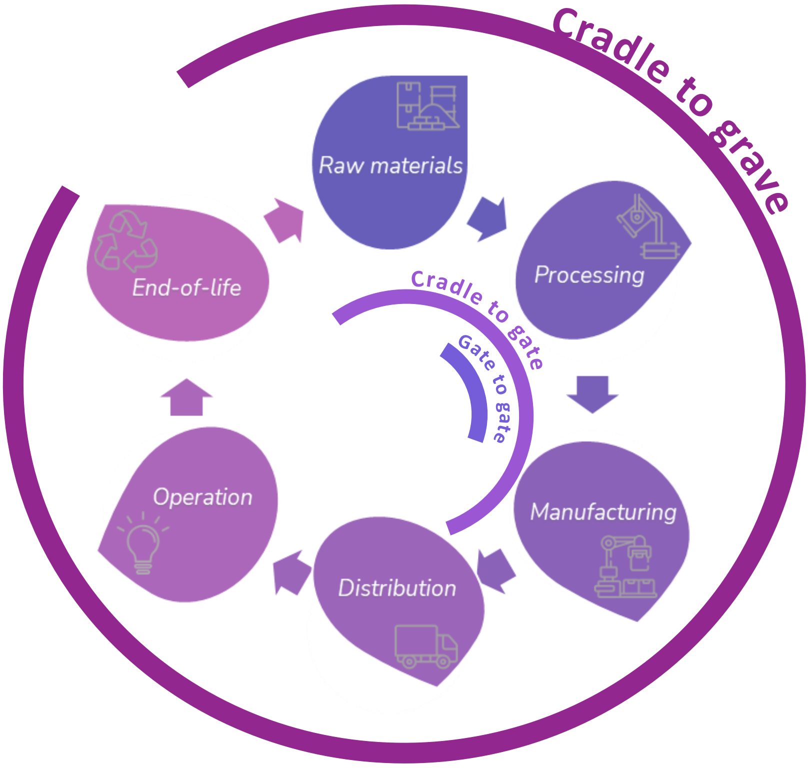

Figure 1. Main product life cycle stages and system boundaries.

There are two ISO standards that define the steps to be followed in every LCA study (Figure 2):

ISO 14040 (*Environmental management — Life cycle assessment — Principles and framework*) and ISO 14044 (*Environmental management — Life cycle assessment — Requirements and guidelines*). These steps include:

- Goal and scope definition.
- Inventory analysis.
- Impact assessment.
- Interpretation.

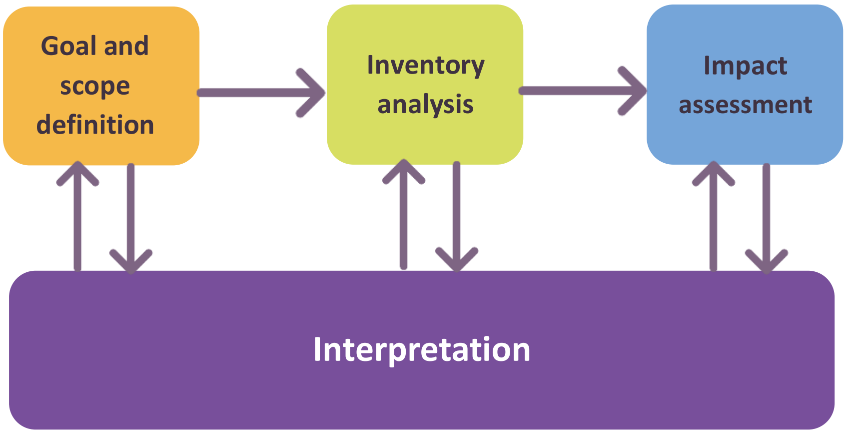

Figure 2. Main steps in an LCA as defined by ISO 14040.

In practice, this is an iterative process rather than a linear one, which means that the results of one step may require a re-evaluation of the previous one. For example, at some point of the assessment the practitioner might realize more data is needed. This means going back to earlier steps, refining the approach, and then moving forward again. This process helps ensure that the results are accurate and meaningful.

1.1 Goal and scope definition

Regardless of the application, the definition of the goal and scope is the very first step in any LCA study. This step sets the framework and the requirements that steering the rest of the analysis. During the goal definition, the field of application, the intended audience, and the communication context are defined along with the reasons behind conducting the study. Any possible limitations to the study, such as impact coverage, methodology, and assumption limitations, should also be included in this section. The scope definition involves the statement of the products/services to be analysed. Other aspects such as the methodology framework, quality of the data, functional unit, system boundaries, and impact categories should be clearly defined at this point.

Functional unit

The functional unit defines the key quantitative and qualitative aspects related to the function of the product(s) or service(s) under study. The definition of the functional unit is a critical step when comparing products or processes since a consistent comparison between two different products requires a proper functional unit.

For example, a comparison between two different materials would be meaningless without considering the final characteristics and functions of the products in which they are used.

System Boundaries

As the interactions between the different stages of a product's life cycle are usually complex, it is necessary to evaluate which ones are considered in the analysis and which ones are not. System boundaries help in the selection of the process stages that belong to the system under study. The boundaries separate the target system from the ecosphere (environmental system) and the technosphere (techno-economic system).

Cut-off

Although theoretically in a complete inventory all the material and energy flows could be included within the system boundaries, sometimes it is possible to disregard some of them if their contribution to the result is below a certain value (cut-off criteria). Additionally, data estimates of lower quality could be used to make the collecting stage easier, thus saving time and resources. However, it should be noted that a flow stream with a relatively low mass could potentially have a significant environmental impact, so each different stream should be carefully studied before applying the cut-off rule.

1.2 Inventory analysis

This is the most time and resource demanding task in the LCA process, since the development of a complete and representative system model requires a significant amount of information on the material and energy inputs and outputs of the process. This data set is the life cycle inventory (LCI) and normally comprises (non-exhaustive list):

- Energy consumption.
- Direct and indirect emissions.
- Material use and resource efficiency.
- Transport data.
- Waste generation.

The required information depends on the specificities of the product system under study, and in practice this means gathering a sizeable data set with the right quality for each of the steps in the life cycle.

At this point, it is important to mention the difference between the foreground system and the background system.

The foreground system includes all the processes that are directly related to the process under consideration, while the background system comprises all the processes that are not specific to the core of the analysed system and could be modelled using average data from the market. Based in these two categories, the standards define two main types of datasets:

- Primary data: The data specifically linked to the core of the processes (foreground system) that is required for the modelling, i.e. measurements and data retrieved directly from the factory where the assembly of a product takes place.
- Secondary data: The information coming from other external sources (databases, patents, literature…) used to model generic processes within the system boundaries. This type of information is useful for the analysis of the background system.

1.3 Impact assessment

The impact assessment stage involves the conversion of all the data collected in the inventory into environmental impacts related to different impact categories. The resulting impact categories depend on the impact assessment method selected in the goal and scope definition phase. The first step is the actual selection of the impact categories, which in essence are environmental areas where the system under study may have a particular impact. Once the categories have been chosen the ISO 14040/44 standards define two different kinds of elements:

- Mandatory steps: classification and characterisation.
- Optional steps: normalization, ranking, grouping and weighting.

This means that an LCA must always include classification and characterization. Classification involves assigning the LCI results from the previous step (such as emissions to air, water, and soil, or resource use) to the relevant impact categories. For example, CO_2 emissions would be classified under "climate change". Characterisation is the core calculation step where the LCI results are converted into midpoint (which focus on specific environmental mechanisms) and endpoint (broader indicators focusing on damage to areas of protection such as human health, or ecosystems) indicators. The characterisation factors are used to quantify how much each inventory flow (e.g., CO_2, methane, SO_2) contributes to the chosen impact categories.

The normalisation step is optional under ISO 14044:2006. It shows the relative value of an impact category indicator compared to a baseline. As the normalised results are dimensionless, it is possible to compare the values of the different indicators.

Finally, weighting involves assigning a relative weight to each category to express their importance so they can be added up across the different categories. This step is not allowed by the ISO standards when the results are intended to be made public because the relative subjectivity of the process, although it is usually performed in internal LCA studies.

1.4 Interpretation

The interpretation is the last stage of the LCA methodology, where the results of all the previous steps are considered. The aims of this stage are, first to evaluate and improve the quality and accuracy of the results in a continuous way and, second, to draw conclusions on the environmental performance of the product or service under study.

The results from the interpretation should be stated in a clear and transparent way according to the communication context. The quality of the data and the limitations of the study must also be included. Several approaches are used in the interpretation of the results, namely contribution analysis, sensitivity analysis and uncertainty evaluation. Additionally, the quality of the data must be evaluated in all these stages, and if necessary, the collection stage should be revisited to ensure the robustness of the analysis.

Contribution analysis

In this stage, key aspects such as material and energy flows, substances and impact categories are identified, which allows to focus on the most relevant stages of the system. At this point, the accuracy of the assumptions and the data can be assessed and refined, if necessary.

Sensitivity analysis

The sensitivity analysis evaluates the accuracy of the selected data by identifying the most influencing assumptions. The analysis is based on evaluating the change on the impact categories associated to a modification in any of the inputs. ISO 14044:2006 states that a sensitivity analysis is required when the LCA is to be used in comparative public assessments. This can be done by adjusting one variable at a time (one-at-a-time analysis) or by using more advanced methods, such as Monte Carlo simulations, to test multiple variables simultaneously. ISO 14044:2006 states that a sensitivity analysis is required when the LCA is to be used in comparative public assessments, ensuring that conclusions drawn from comparisons are robust and transparent

Uncertainty evaluation

The data used in an LCA analysis is subjected to uncertainty, coming from stochastic variations in data sources, uncertainties in assumptions, variability in measurement methods, and differences in system boundary definitions. Consequently, it is important to address the degree of uncertainty of the results, especially when making comparisons between systems or products since it determines whether the differences are statistically significant.

2 Current status of the LCA application in the field of energy storage

LCA has grown in popularity as the go-to tool to evaluate environmental impacts for products, processes and services in multiple sectors, and the energy storage applications have not been the exception. As a result, there is a growing body of works that have used LCA to assess the performance of different energy storage solutions for a wide range of applications to identify potential hotspots, identify trade-offs and improvement opportunities.

In consequence, as a first step in the preparation of the framework for AGISTIN, a review of the existing LCA studies of stationary energy storage systems was carried out to assess the state of the art in the field. For the initial search the following key words were used in alternative combinations: 'LCA', 'energy storage', 'electricity grids', 'advanced grids', 'renewable energy'. Thus, the results covered a wide spectrum of energy storage technologies and applications. Science Direct was the selected database for the search. This database was chosen as it offers access to peer-reviewed journals and high-impact articles, especially on the field of LCA. Studies older than 10 years were not considered to ensure that the selected works reflect the current state of knowledge.

After a preliminary screening process where the initial sample was scanned to address whether the different sources fit the purpose of the AGISTIN analysis, a total of 23 studies were selected (Table 1 shows the summary results. Annex I contains the full overview). For each study the following aspects were taken into consideration:

- Storage technology.
- Functional unit.
- Goal and scope of the analysis.
- Impact assessment method.
- Remarks and conclusions relevant for AGISTIN.

Table 1. Results of the literature review.

Reference	Storage technology	Functional Unit	Scope	Relevant conclusions for AGISTIN
Hiremath et al., 2015	*Lead-acid batteries, lithium-ion batteries, sodium–sulphur batteries and vanadium-redox-flow batteries*	1 megawatt-hour of electricity delivery (1 MWhd)	Cradle-to-gate	Misleading to compare the environmental performance of batteries only on a mass or capacity basis, priority for technologies with a higher round-trip efficiency.
Oliveira et al., 2015	*Compressed Air Energy Storage (CAES), Fuel Cells and Battery Systems (Li-ion, lead acid and NaNiCl; LiMn*	1 kilowatt hour of electricity stored and delivered from the storage	Cradle-to-grave	The environmental performance of each technology is a function of the origin of the electricity used (application) and overall dependent on its efficiency

Reference	Storage technology	Functional Unit	Scope	Relevant conclusions for AGISTIN
	Oxide and Sodium Sulphur)	system back to the grid.		
Koj et al., 2015	*Li-ion batteries*	Total primary control power demand of 551 MW which must be provided permanently for the period of 20 years	Cradle-to-gate	BESSs are a promising option to reduce environmental impacts of primary control provision because of reduced must-run fossil electricity generation.
Baumann et al., 2017	*Li-Ion batteries, lead acid batteries, sodium nickel chloride (NaNiCl) and Vanadium red-ox flow batteries*	1 kWh of energy storage capacity	Cradle-to-use	Long cycle lives need to be achieved, as otherwise the repeated need for cell replacements drives up costs and emissions.
Vandepaer et al., 2018	*Lithium metal polymer and lithium-ion stationary batteries*	Supply of 1 megawatt-hour (MWh) of electricity for the 2030 Swiss electricity system	Cradle-to-grave	The use of stationary batteries to integrate surplus from VRESs appears beneficial from an environmental point of view to in 12 out of 16 categories. Larger-scale changes in the grid have yet to be captured (increased penetration of VRESs, decrease in transport and distribution electricity losses)
Ryan et al., 2018	*Li-ion batteries*	Provision of 1 MW of symmetrical reserve capacity for one year	Cradle-to-grave	The magnitude of the upstream and EOL impacts of the battery system were small in comparison to the use stage. The electricity mix had the largest impact. Fuel price, congestion, and battery round trip efficiency had the next largest effects on net environmental impacts
Stougie et al., 2019	*Blue battery system, compressed air, lithium ion batteries, lead-acid batteries and pumped hydro*	A storage capacity of 10 kWh of each of the systems and a lifetime of 20 years	Cradle-to-grave	The multi-dimensional sustainability assessment did not lead to one preferred system; however, the generation of electricity and its supply chain is not considered.
Pellow et al., 2020	*Li-ion batteries*	Several FUs considered	Several boundaries	Provides 5 recommendations for LCA studies on energy storage: incorporate the use stage at grid-scale, accurate modelling of dispatch, ensure

Reference	Storage technology	Functional Unit	Scope	Relevant conclusions for AGISTIN
				complete material inventories, include EoL processes and strive for primary data for the manufacturing stage
Delpierre et al., 2021	*Hydrogen (Alkaline and Proton Exchange Membrane - PEM electrolyser)*	1 kg of hydrogen at a pressure of 20 bars	Cradle-to-gate	Electricity consumption remains the largest contributor to environmental performances, even when renewable energy sources are considered. It is useful to combine LCA and scenario tool for large-scale analysis.
Mori et al., 2021	*Lead-acid battery, hydrogen (PEM electrolyser)*	The amount of energy provided in the form of heat and electricity during 1 year of operation.	Cradle-to-gate	Hydrogen and battery ES are promising solutions from environmental point of view, but for now at higher costs.
Porzio and Scown, 2021	*Li-Ion batteries*	Several FUs considered	-	For the use stage, knowledge about the performance of the storage system is critical. Disaggregating environmental impacts by location and type of operation can provide better transparency and accuracy.
Gandiglio et al., 2022	*Hydrogen (Alkaline electrolyser), Li-ion battery*	1 kWh of electricity provided by the energy system	Cradle-to-use	End-of-Life (EoL) excluded from the assessment. The renewable Powe to Power (P2P) system leads to an improvement over the current fossil-based generation system.
Jasper et al., 2022	*Lithium-Iron-Phosphate (LFP) battery*	1 kWh of energy delivered by the considered systems	Cradle-to-grave	Relevance of toxicity and resource use. Importance of manufacturing stage and component lifetime.
Bionaz et al., 2022	*Hydrogen (PEM electrolyser), Li-ion battery*	1 MWh of electricity generated onsite or supplied by the submarine cable	Cradle-to-use	Renewable energy scenario lower emissions than conventional. Results are highly dependent on the carbon intensity of the electricity mix.
Lamnatou et al., 2023	*Hydraulic*	1 kWh of generated electricity	Cradle-to-grave	PV/hydraulic storage offers low-carbon power with substantially lower environmental impacts than fossil fuel-fired power

Reference	Storage technology	Functional Unit	Scope	Relevant conclusions for AGISTIN
				generation. Selection of materials is important
Vilbergsson et al., 2023	*Hydrogen (alkaline, PEM, Solid Oxide Electrolyser Cell - SOEC)*	1 kg H2 produced by each electrolyser	Cradle-to-gate + distribution	H_2 production can only be recommended for electrical grids with a high ratio of renewable energy sources.
Huber et al., 2023	*LFP and Lithium nickel manganese cobalt oxides (NMC) batteries*	1 kW-hour (kWh) of consumed electricity in the residential and commercial sector	Cradle-to-grave	Decentralised systems reduce climate change impacts. Stationary batteries improve systems' performance without increasing environmental impacts significantly
Weidner et al., 2023	*Hydrogen*	Production of 500 Mt/yr of H2	Cradle-to-gate	Extraction and processing of metals for renewable energy infrastructure contributed the most to the environmental impacts of green hydrogen production
Jiao and Månsson, 2023	*Pumped hydro, hydrogen, LFP battery, lead-acid battery, Vanadium red-ox flow battery, supercapacitor, flywheel*	1 kWh generated electricity and 1 kWh delivered electricity	Cradle-to-grave	In large-scale utility applications, the cradle-to-gate GHG emissions from the HESS contribute to a major share of the life cycle GHG emissions due to an under-utilization of the cycle life. Number of operational cycles of the HESSs is a key parameter.
Han et al., 2023	*Lithium iron phosphate batteries, nickel cobalt manganese oxide batteries and vanadium redox flow batteries*	1 MWh of energy stored throughout the entire life cycle	Cradle-to-grave	Electricity mix in the use stage is the main contribution, integration of energy storage with renewable energy sources resulted in the most notable reduction in the GHG emissions. Relevance of round-trip efficiency.
Gu et al., 2024	*Hydrogen (Alkaline electrolyser), Li-ion batteries*	1 kg of hydrogen	Cradle-to-gate	Using a grid-connected hydrogen production mode can effectively balance system reliability and result in environmental impact as well as yielding economic benefits
Krishnan et al., 2024	*Hydrogen (Alkaline and PEM electrolyser)*	1 kg of produced hydrogen	Cradle-to-gate	The primary contributors to the assessed impact categories are the electricity source and the stacks. Focus on reducing the minimal load requirements and increase current density.

Reference	Storage technology	Functional Unit	Scope	Relevant conclusions for AGISTIN
Mączka et al., 2024	*Al-ion battery*	A single battery with normalized capacitance of 100 F/g.	Cradle-to-grave (excluding use stage)	The technology is still at an early stage of development, although results highlight the significance of battery performance and energy output, and the materials used for electrolyte and cathode construction.

The literature review reveals the wide range of assumptions, scopes and results. Different technologies are covered by the selected studies including batteries (with varying chemistries such as lithium-ion, lead-acid, and vanadium redox flow), pumped hydro storage (PHS), compressed air energy storage (CAES), and hydrogen storage. The environmental impact of each system greatly depends on the materials used at the manufacturing stage, component lifespan, efficiency, and system complexity. Consequently, selecting the appropriate functional unit and boundaries is key for fair comparisons between different LCA studies, as each technology comes with its own properties and boundary conditions that influence their environmental performance.

The use stage appears to be the dominant phase in terms of the contribution to the global life cycle impact and highlights factors like the round-trip efficiency, the electricity mix and the level of integration with renewable energy sources. The review also highlights the importance of overall system lifetime and component lifespan, as frequent replacements increase both costs and environmental impacts. Overall, minimising the environmental footprint of ESS during the use stage depends on enhancing the efficiency, extending component longevity, and prioritising the integration with a low-carbon energy mix.

The manufacturing phase is also highlighted as one of main sources of impact across the systems, especially for BES. This stems from the minerals required as raw materials (e.g., lithium, cobalt) and the energy-intensive nature of processing these materials. While recycling has the potential to reduce these impacts by recovering valuable secondary raw materials at the end of life, it comes with its own set of challenges, e.g. different recovery efficiency rates, technical barriers for material recovery and limitations in current recycling infrastructure.

In terms of environmental impact categories, the indicators that are more frequently assessed include the Global Warming Potential (GWP), Acidification, Eutrophication, Human toxicity, and Resource Depletion. Climate change impacts, in particular, are addressed in all the studies, as this category represents a common concern for all energy storage systems. Battery systems, such as lithium-ion batteries, show especially high GWP impacts owing to the energy-intensive processes involved in manufacturing and the reliance on critical raw materials like lithium and cobalt.

The studies use different functional units which affects the overall comparability of results. Common choices include kilowatt-hours of storage capacity or lifetime energy throughput. Many studies use lifetime energy delivered as a functional unit, which in general is well suited with the scope of energy storage systems but may need adaptation for assessing additional grid services. These adjustments could support AGISTIN's goal to assess the impact of energy storage integrated with AGIs.

Finally, the review highlights data limitations and the importance of conducting sensitivity analysis to evaluate different scenarios. Many studies indicate data challenges around the end-of-life and recycling stages, and detailed models of the use stage are required to obtain robust sets of data for this key step.

3 AGISTIN framework for the Life Cycle Assessment of AGI-integrated storage

As the share of variable renewable energy (VRE) sources in current power systems increases, the operations of the power systems themselves are getting increasingly complex as the addition of VRE introduces new layers of variability and uncertainty. For this reason, it is important to fully understand the impact of these new configurations and assess existing trade-offs.

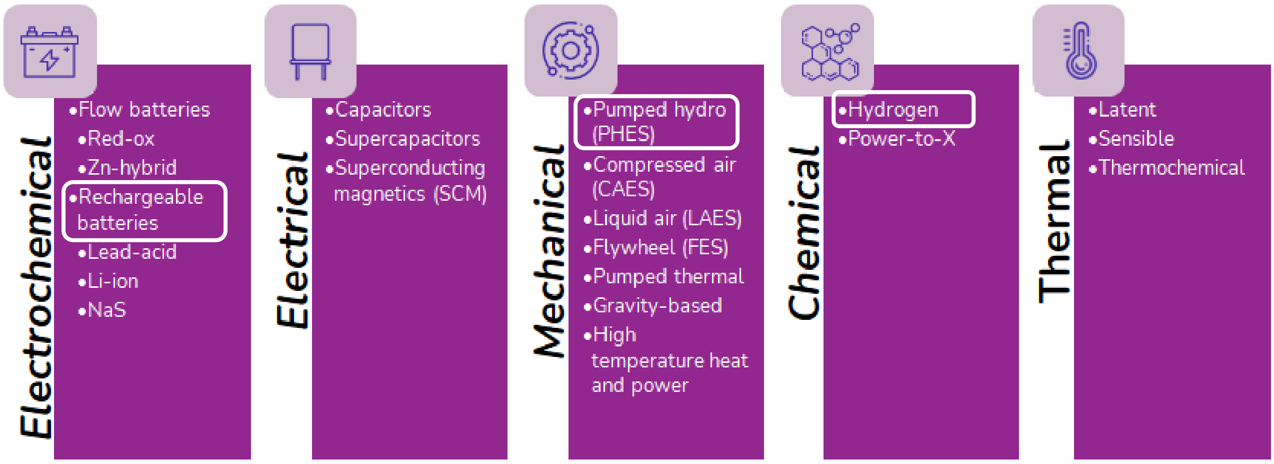

Figure 3.Energy storage technology classification – adapted from (Arabkoohsar, 2023)

Given the wide range of energy storage technologies (Figure 3) and applications, the study of the environmental impacts from a life cycle perspective may result in complex studies that are difficult to interpret and are subjected to the uncertainty that is often associated with the life cycle studies performed on a case-by-case basis. To this end, this document looks to set up a common framework for the LCA of AGI -integrated storage for practitioners working in the field.

This document is based on the ISO standards 14040 and 14044, the ILCD handbook, the Product Environmental Footprint (PEF) handbook, several frameworks for alternative applications (e.g. HyGuide project for fuel cells), the results of the literature review and the recommendations in the PEF methodology. The document is structured according to the standard LCA workflow and aims to support practitioners in the process of conducting an LCA study in conformity with the existing standards and the best-practices. It also uses the standard terminology for mandatory aspects (Shall) and recommendations (Should).

3.1 Goal Definition

For every LCA study, regardless of the scale and the storage technology under evaluation, the starting point is the definition of the goal. The objective of the study shall be stated in a clear, unambiguous way in accordance with the ISO 14044 standard and the recommendations in the ILCD handbook. This step shall include the definition of the following aspects:

- Reasons for the study: the motivation that led to the execution of the analysis and the rationale behind it.
- Intended application: the specific application of the study, paying attention to the context (e.g. internal or external use). Some of the most common applications cited by the ILCD handbook include: product improvement through eco-design, product comparison, decision making support.
- Target audience and type of audience: the recipient(s) of the results shall be clearly identified as this conditions the way the results are presented (granularity of the inventory and the results, technical aspects, etc). The audience shall be classified based on their level of awareness with the technologies and their position as stakeholder in the ecosystem (internal, public, technical, non-technical, etc).
- Whether the results will be used for public comparative evaluations.
- Commissioner of the study: state the responsible for the study, co-financing agents and any other relevant stakeholders that may have an influence or have been involved in the analysis.

Most of the studies found in the literature review state the relevance of the results for strategic decision support for future developments as many of the assessed technologies are still under development. However, the difference in the technology readiness and scale, especially in comparative studies (where the references usually are a well-established technology), may reduce the significance of the results as this may end up in over or underestimated impacts. These aspects should always be considered in comparative studies and the scale of each system is critical. However, a comparison between a low TRL energy storage technology and conventional baseline can still provide relevant insights to identify improvements opportunities and steer future developments. For this reason, as an additional recommendation for AGI-integrated storage product systems, the goal definition should include a detailed description of the storage technology(s) assessed, the scale and the topologies under evaluation.

Table 2. Recommendations for the goal definition.

Shall	Should
State the reasons behind the study	State the specific storage technology
State the intended application and context	
Define the target audience and type of audience	
State the limitations and the main assumptions	Specify the technology readiness of the technology under study and the reference (for comparative assertions)
Define whether the study will include a comparative public assessment	
Cite the commissioner of the study	

A summary of the main considerations and recommendations to be followed in the goal definition step are presented in Table 2. Finally, Table 3 presents an example of how the goal definition for an exemplary energy storage system that is related to the AGISTIN demo cases that is currently being piloted by Shell in the Energy Transition Campus in Amsterdam (ETCA)

Table 3. Example goal definition.

Goal item	Description
Technology Description	A **renewable energy storage system** combining a 72 kWp solar plant, a 25kW/2kWh battery and a 50 kW electrolyser to produce and store green hydrogen.
Scale	The system operates at a **medium-scale** to support a local distribution grid, equipping green H_2 with the required grid-supporting functionalities
Reasons for the Study	Assess environmental impacts of the hybrid hydrogen-battery system, aiming to quantify emissions reduction, hotspots and improvement opportunities.
Intended Application	Prospective LCA study for eco-design, policy support, and technical insights into sustainable energy storage deployment for grid applications.
Target Audience	**Technical**: Grid operators, LCA practitioners, energy researchers; **Non-technical**: Policymakers, sustainability advocates, and community stakeholders.
Public Comparative Use	This study will not include a comparative study for public disclosure as it just focuses on the technology under study.
Commissioner of the Study	Company XYZ, with support from EU funding and industry collaborators.

3.2 Scope Definition

The scope of the LCA details the specifications of the product system under evaluations in line with the goal of the study. All these specifications determine conditions and scenarios where the results are valid. Based on the PEF method guidelines, the scope definition shall include:

- Functional unit and reference flow.
- System boundaries.
- Impact categories.
- Assumptions/Limitations.

Product system and functional unit

The functional unit qualitatively and quantitatively describes the function(s) of the product system in scope. In addition, the functional unit is a key aspect in comparative assessment to ensure the robustness of the comparison. In accordance with the ISO standards and the PEF method, the selected functional unit should respond to the following questions:

- The function(s)/service(s) provided: what?
- The extent of the function or service: how much?
- The quality degree: how well?
- The lifespan time of the product: how long?

Broadly speaking, the function of an energy storage technology is to store the generated energy to be later delivered to the grid at will. Applications include: reducing the effects of generation variability, reduce renewable curtailment, improve efficiency and stability of the energy system. Thus, overall, counterbalancing the additional variability and uncertainty introduced by VREs such as wind and solar.

Based on these considerations and the results of the literature review, the functional unit should be able to reflect this function for the wide range of difference energy storage systems regardless of the underlying technology. Thus, enabling the possibility of comparing different alternatives. An example of a functional unit suitable for the AGISTIN demo cases and for other energy storage applications would be:

> "1 MWh of electricity delivered to the grid in the required conditions to ensure a stable and reliable operation for the service life of the system".

In addition, the functions provided by the system to support reliable grid performance go beyond the simple dispatch of electricity. That is the case for the ancillary services that come along with the electricity supply and support the operation of the grid. Some of these ancillary services and the implications have been mentioned in the Annex II.

Moreover, the analysis could explore additional functional units that are secondary to the core function of the system and allow to better understand the overall system. For example, in the case of a hydrogen-based energy storage system, the environmental footprint of the production of 1 kg of H_2 could be addressed. All additional functional units under study shall be clearly defined at this point, and the results shall be clearly referred to the functional units under study. For illustrative purposes, Table 4 presents an example definition of the functional unit:

Table 4. Example definition of the functional unit.

1. What?	Delivery of renewable electricity to the grid, including the provision of ancillary services (e.g., frequency regulation, voltage support, congestion relief) to stabilise the grid.
2. How Much?	Provision of 1 MWh of electricity to the grid, incorporating all necessary ancillary services within this output to ensure comparability with other energy delivery systems.
3. How Well?	Ensures reliable energy delivery by maintaining the AGI grid stability, including frequency at 50 Hz and voltage within specified limits. Reduces renewable curtailment by enabling storage.
4. How Long?	System lifespan of 20 years, covering hydrogen and battery storage components, AGIs, and associated balance of plant. This timeframe supports a complete life cycle analysis.

The goal definition can be further detailed in this section by providing additional aspects about the product system under consideration.

Given that a significant number of diverse technologies can be grouped under the category "Energy Storage", it is important to first understand the system(s) under study and provide a detailed characterisation of the fundamental technical parameters. This framework suggests a list of minimum relevant set of data that has to be provided for the system. The description should include:

- Energy storage capacity (kWh) to size the amount of energy that can be stored in the system.
- Charge and discharge rates (kW).
- Response time (in seconds, minutes).
- Lifetime of a storage system given as the number of cycles, years or stored/ provided energy (kWh), depending on the specific technology.
- Roundtrip efficiency to account for the energy lost in the storage cycle.
- Energy density (kWh/kg, kWh/m^3, Wh/l) and power density (kW/kg and kW/m^3).
- Expected service life (in years).
- Bill of materials of components.
- Information about the use of hazardous substances.
- Information about the presence of Critical Raw Materials (CRMs).
- Type of production site (laboratory, pre-commercial, commercial scale).
- Location of the site.
- Topology of the system.
- List of ancillary services that are provided by the system addressed in the study.

Additional parameters specific to the technology addressed in the analysis should be evaluated and included depending on the final application, as long as these are properly cited, and any relevant assumptions are mentioned. In addition, if the study evaluates only components or a part of the production chain, only these components/parts must be described but the product system which they are part of shall be mentioned.

System boundaries and completeness

The ISO 14040 defines the system boundary as a "*set of criteria specifying which unit processes are part of a product system*". This means that all the process steps to be included and excluded in the LCA study need to be clearly stated. As mentioned in the introductory chapter, the processes included in the system boundaries shall be divided into foreground processes (i.e. core processes in the product life cycle) and background processes. Figure 4 shows a simplified version of the system boundaries showing the main steps, inputs and outputs that shall be included.

The system diagram shall be included in the scope definition, highlighting the included and excluded activities and the steps where company-specific data is used.

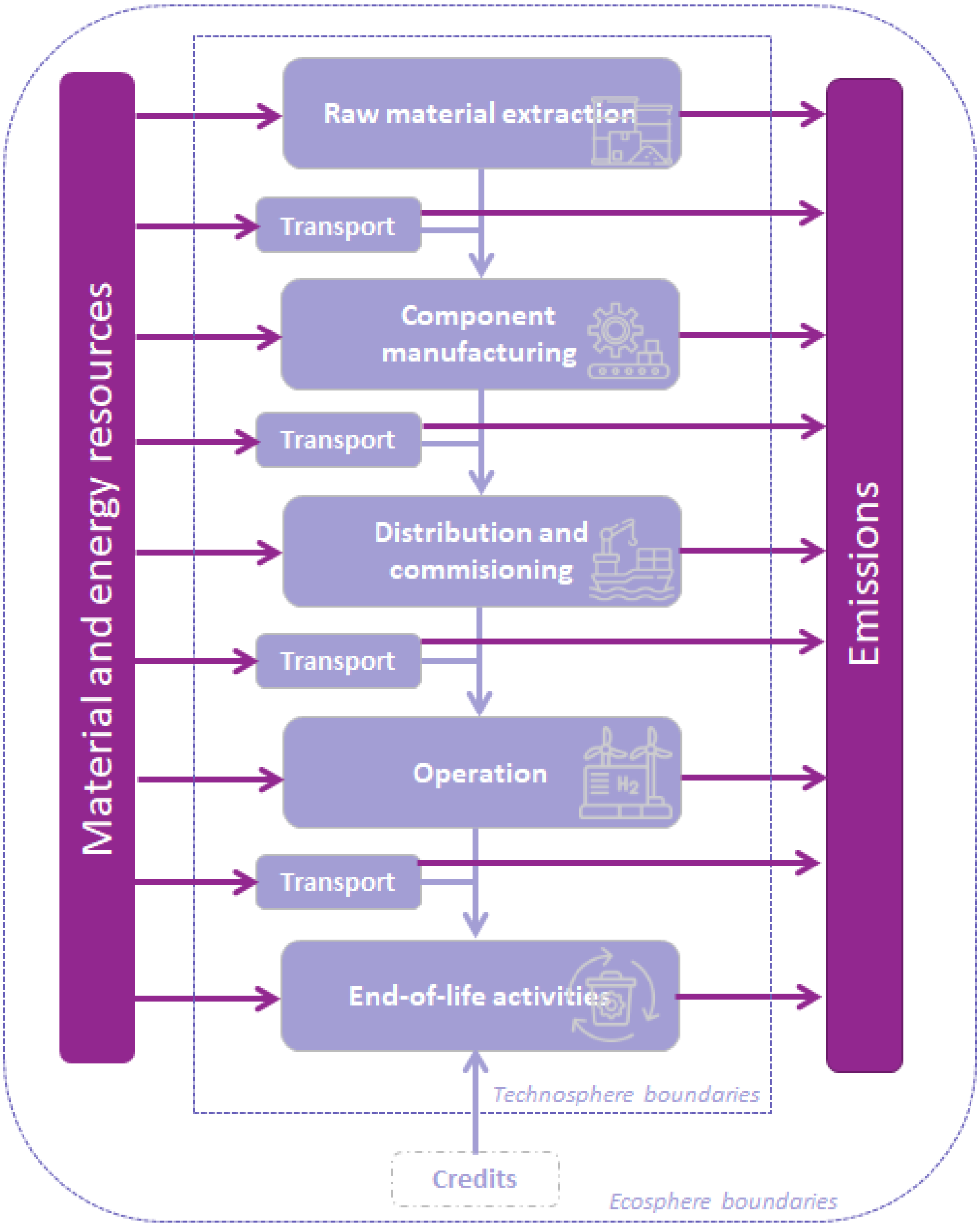

Figure 4. Simplified boundary limits

The description of the information that should be included is further detailed in Table 5.

Table 5. Overview of formation to be included in each process step (non-exhaustive).

Life cycle stage	Short description of information included
Raw material acquisition and processing	Primary and secondary raw materials extraction and pre-processing, transport up to the manufacturing site.
Manufacturing	Manufacturing and assembly of the primary components, including electrolysers, batteries, AGI equipment, and electronic components like inverters, controllers, and power converters. Energy consumption, auxiliaries and emissions from manufacturing and assembly processes are considered.
Distribution and start-up	Processes related to transporting and installing the system on-site. This includes infrastructure setup (wiring, mounting, grid integration) and the energy and resources required for installation.
Operation	Day-to-day operations, including electricity consumption for charging and discharging the storage system, stand-by energy consumption, energy losses, and on-site emissions. Includes maintenance activities, replacement of components and consumables.
End of life	Collection, dismantling and disposal or recycling of system components. Includes processes for handling hazardous materials, recycling batteries and electronic components, and transportation to waste management facilities. The “credits” resulting from secondary raw materials displacing virgin raw materials should be also included and separately reported.

Impact categories

The selection of the impact categories has been done in accordance with the PEF requirements, which provide a comprehensive list of sixteen indicators that address multiple environmental effects (Table 6).

Table 6. List of impact categories.

Impact category	Indicator	Unit
Climate change, total	Radiative forcing as global warming potential	kg CO_2 eq.
Ozone depletion	Ozone Depletion Potential	kg CFC-11 eq.
Human toxicity, cancer	Comparative Toxic Unit for humans	CTUh
Human toxicity, non-cancer	Comparative Toxic Unit for humans	CTUh
Particulate matter	Impact on human health	disease incidence
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U235 eq.
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC eq.
Acidification	Accumulated Exceedance	mol H^+ eq.
Eutrophication, terrestrial	Accumulated Exceedance	mol N eq.
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment	kg P eq.
Eutrophication, marine	Fraction of nutrients reaching marine end compartment	kg N eq.
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems	CTUe

Impact category	Indicator	Unit
Land use	Soil quality index Biotic production Erosion resistance Mechanical filtration Groundwater replenishment	Dimensionless (pt) kg biotic production kg soil m^3 water m^3 groundwater
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq.
Resource use, minerals and metals	Abiotic resource depletion	kg Sb eq.
Resource use, fossils	Abiotic resource depletion – fossil fuels	MJ

Additional information

In accordance with the PEF general requirements, there might be relevant potential environmental impacts that go beyond the Environmental Footprint impact categories. In this case it is important to consider and report them, whenever feasible, as additional environmental information. Some of these additional environmental aspects, as defined by the PEF rules include:

- Information on local/site-specific impacts.
- Offsets.
- Environmental indicators or product responsibility indicators (as per the Global Reporting Initiative (GRI)).
- Description of significant impacts of activities, products, and services on biodiversity in protected areas and in areas of high biodiversity value outside protected areas.
- Electromagnetic Interference (EMI) and noise impacts.

Assumptions/Limitations

Every LCA study faces limitations and challenges, especially linked to low data availability, outdated datasets or time or resource-wise restrictions. To ensure the robustness and consistency of the study, all the limitations and assumptions shall be clearly documented to prevent the results from being interpreted in the wrong way. This includes assumptions about expected lifespan, projected grid efficiency improvements, and operational data estimates. For example: "*Inverters and transformers are considered to have a life of 30 years, but parts must be replaced every 10 years, amounting to 10% of their total mass according to well-established data from the power industry on transformers and electronic components*" (Huber et al., 2023).

Comparative evaluations

As aforementioned, when comparing different types of energy storage systems, there can be differences arising from the different technologies used, the application, the scale and the operating conditions. For these reasons, the following aspects shall be taken into consideration:

- The equivalence of the functional unit of compared alternatives.
- The selection of the compared alternatives and the reference scenarios.
- Durability.
- Lifespan of the alternatives shall be considered.
- Methodological assumptions and data consistency.

3.3 Life Cycle Inventory

As introduced in section 1, the inventory consists of all material, energy and waste inputs and outputs and emissions into air, water and soil for the product system under study and shall be compiled as the starting point for the impact assessment. The analysis should use an attributional modelling approach in line with the requirements of the ILCD Handbook and should follow the additional requirements of the PEF for inventory modelling.

It is recommended to begin the process with an initial screening of the inventory, as it can help to identify potential hotspots and data gaps requiring more attention in the future. At this point it is important to define the cut-off of the analysis. This value sets the threshold that limits the amount of information that is included in the inventory. This simplifies the process, since following the life cycle approach in iterations would result in the system boundaries virtually containing the whole technosphere, which would turn the LCA into an unrealistic effort.

The cut-off solves this problem by allowing the practitioner to set realistic limits to the study. According to the PEF principles, processes and elementary flows may be excluded up to 3.0%, based on material and energy flows intensity and the level of environmental significance (in addition to the cut-off already included in the background datasets). In practice this means that the processes that in total account for less than 3.0% of the material and energy flow and environmental impact for each impact category may be excluded. This shall be clearly stated in the LCA study.

The inventory data shall be collected for the different process steps that fall within the boundary limits, following the recommendations in section 3.2 of this document. The modelling recommendations in the PEF shall be used to construct the inventory in the absence of data. This section shows some of the aspects that are relevant to the AGISTIN product system, but the practitioner is advised to consult the complete PEF set of recommendations:

Electricity use

Electricity from the grid shall be modelled as precisely as possible giving preference to supplier-specific data. If (part of) the electricity is renewable, it is important that no double counting occurs. Therefore, the supplier shall guarantee that the electricity supplied to the organisation is effectively generated using renewable sources and is not available anymore for other consumers.

Two types of electricity mixes are defined:

- The consumption grid mix which reflects the total electricity mix transferred over a defined grid including green claimed or tracked electricity.
- The residual grid mix, consumption mix (also named residual consumption mix), which characterizes the unclaimed, untracked or publicly shared electricity only.

The following electricity mix shall be used, in hierarchical order:

- Supplier-specific electricity shall be used if for a country there is a 100% tracking system in place.
- The 'country-specific residual grid mix, consumption mix' shall be used. Country-specific means the country in which the life cycle stage or activity occurs.
- As a last option, the average EU residual grid mix, consumption mix (EU-27 +EFTA), or region representative residual grid mix.

Transport and logistics

Important parameters that shall be considered when modelling transport include:

- Transport type: The type of transport, e.g. by land (truck, rail, pipe), by water (boat, ferry, barge), or air (airplane).
- Vehicle type & fuel consumption: The type of vehicle by transport type, as well as the fuel consumption when fully loaded and empty. An adjustment shall be applied to the consumption of a fully-loaded vehicle according to loading rate.
- Loading rate (=utilisation ratio): Environmental impacts are directly linked to the actual loading rate, which shall therefore be considered.
- Number of empty returns: the number of empty returns (i.e. the ratio of the distance travelled to collect the next load after unloading the product to the distance travelled to transport the product), when applicable and relevant, shall be considered. The kilometres travelled by the empty vehicle shall be allocated to the product. In default transport datasets this is often already considered in the default utilisation ratio.
- Transport distance: Transport distances shall be documented, applying average transport distances specific to the context being considered.
- Fuel production: Fuel production shall be included.
- Infrastructure: the transport infrastructure, that of road, rail and water, unless they may be excluded based on the cut-off criteria.
- Resources and tools: the amount and type of additional resources and tools needed for logistic operations such as cranes and transporters, unless they may be excluded based on the cut-off criteria.

For example, Table 7 contains recommended values for distances that should be used when no primary information is available for supplier to factory transport.

Table 7. Recommended distances from the PEF guidelines for supplier to factory transport.

Within Europe	Outside Europe

Truck – 130 km	Truck – 1,000 km
Train – 240 km	Ship (Transoceanic container) – 18,000 km Or Plane (cargo) – 10,000 km
Ship (Barge) – 270 km	

Data quality requirements

Using reliable data is instrumental for the success of the LCA evaluation, as the inventory consists of an extensive set of data points coming from many different sources. For this reason, it is important to define the quality requirements to assess the reliability of the available information. The PEF guidelines define the following set of criteria:

- Two minimum requirements: (i) completeness, and (ii) methodological appropriateness and consistency, to ensure that the LCI covers all the emissions and resources of the processes and products that are required to calculate all impact categories.
- Four quality criteria: technological, geographical, time-related representativeness, and precision. These criteria shall be subject to a scoring procedure.
- Three quality aspects: documentation, nomenclature and review. These criteria are not included within the semi-quantitative assessment of the data quality.

Each data quality criterion is to be rated according to the following five levels (The full description of the scoring system can be consulted in detailed in the PEF guidelines):

- 1: Excellent.
- 2: Very good.
- 3: Good.
- 4: Fair.
- 5: Poor.

Based on this scoring system for the four criteria, the overall data quality is assessed as the sum of the scores for Technological representativeness, time-related representativeness, geographical representativeness and precision, divided by four. The data quality of each LCA study shall be calculated and reported based on these recommendations.

In summary, the inventory shall comply with the completeness requirements based on the boundaries defined in the scope definition and in accordance with the cut-off rule. The inventories shall be documented and reported at least to the stakeholders involved in the study.

3.4 Impact assessment

Once the Life Cycle Inventory (LCI) has been compiled, the impact assessment comes into play to calculate the environmental performance of the product, using all the selected impact categories and models. As already presented in section 1, this step consists of four different calculation stages (Classification, Characterisation, Normalisation and Weighting).

However, the selection of impact categories and methods is not usually straightforward. There are several different categories and sometimes even multiple methods for one impact category which in practice may lead to significantly different results depending on the assumptions made at this stage. To reduce the degree of uncertainty associated to the selection of the impact categories, the study shall select the impact categories set by the EF method (See Table 6 for the detailed description).

Note that life cycle impact assessment shall be limited only to midpoint indicators, because the level of uncertainty increases with single- or end-point indicators. Also note that a detailed knowledge of impact assessment method is necessary to interpret and report results properly.

Table 8. Recommendations for the impact assessment.

Shall	Should
Use all the PEF impact categories	Other categories or methods may be applied, but shall be justified, documented and reported.
Focus on midpoint impact categories	A materiality assessment could be used to prioritise the categories.
Weighting is not recommended	

3.5 Interpretation

According to the ISO standards, the Life Cycle Interpretation phase is defined as the "*stage in the Life Cycle Assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and Recommendations*".

For this reason, this step is used to assess the robustness and completeness of the results and to check whether the results match the assumptions and the targets set in the Goal and Scope definition. There are a number of checks that should be used to ensure that the models and assumptions are consistent and the quality of the data is right and to overall draw robust conclusions:

- Contribution analysis and hotspot identification.
- Uncertainty and sensitivity analysis.
- Conclusions and recommendations.

Contribution analysis and hotspot identification

The first step in a contribution analysis should express the results in a suitable graphic way for interpretation, such as stacked column charts or pie charts, to show the relative contribution of the different processes or flows to the impact categories under study. These graphs support the contribution analysis by revealing how the different processes within the system boundaries relate to the selected impact categories. The results should be expressed using the right graphics depending on the target audience and on the complexity of the system, and should be easy to interpret in a transparent way based on standard environmental communication practice. From these results, the main contributors are identified and named. This step is aligned with one of the core objectives of conducting an LCA: identifying environmentally significant issues (hotspots). According to the PEF guidelines, the LCA study should identify and report at this point (Table 9):

- Most relevant impact category.
- Most relevant life cycle stage.
- Most relevant processes and elementary flows.

Table 9. PEF criteria for the hotspot analysis.

	Impact category	Life-cycle stage	Process and elementary flow
Criteria	*Categories that cumulatively contribute to at least 80% to the total environmental impact.* *Three relevant impact categories shall be identified as the most relevant ones.*	*The ones that together contribute to at least 80% to any of the most relevant impact categories identified.* *If the use stage accounts for > 50% of the total, the procedure shall be re-run without the use stage.*	*Those that collectively contribute to at least 80% to any of the most relevant impact categories identified.*

Depending on the methodological assumptions, the results may lead to negative values, or credits that may be difficult to interpret. In this case, negative values, credits and avoided impacts shall be reported separately to facilitate the interpretation of the results. Negative values in an LCA typically indicate an environmental benefit or credit, meaning that a particular process, product, or system is avoiding, offsetting, or reducing environmental burdens rather than contributing to them.

In addition, the recommendations in the PEF guidelines should be used to further deal with negative values in a clear way in the contribution analysis, that is, when identifying the percentage impact contribution for any process or elementary flow, absolute values shall be used. This allows to identify the relevance of any credits (e.g., from recycling). In case of processes or flows with a negative impact score, the following procedure shall be applied:

- Consider the absolute values (i.e. impacts of processes or flows to have a plus sign, namely a positive score),
- The total impact score needs to be recalculated including the converted negative scores,
- The total impact score is set to 100%,
- The percentage impact contribution for any process or elementary flow is assessed to this new total.

This procedure does not apply to identify the most relevant life cycle stages.

Uncertainty and sensitivity analysis

Uncertainty in an LCA study comes from various sources, including the different data quality levels, methodological choices and assumptions, and the impact assessment method.

Parameter uncertainty stems from incomplete knowledge about the actual value of a data point, often caused by measurement errors or variability in the inventory. To evaluate this type of uncertainty, several established techniques should be employed. These include Monte Carlo simulations, Bayesian statistics, analytical uncertainty propagation methods, and semi-quantitative expert judgment. Each method provides a different perspective for exploring how variations in input data can influence the overall results and thus the relevance of the different assumptions. The selected method for the uncertainty analysis shall be reported as part of the interpretation (Zimmerman et al., 2018).

It is important to note that while data precision is a key aspect of uncertainty analysis, structural and modelling uncertainties in both the life cycle inventory (LCI) and life cycle impact assessment (LCIA) stages often have a more impact. These structural uncertainties, which include decisions on system boundaries, allocation rules, or the choice of characterisation models, cannot always be directly or quantitatively addressed in uncertainty calculations.

In comparative studies, the comparative analysis shall not be carried out independently for each alternative, since the comparison of probability distribution can lead to wrong interpretations. Consequently, the comparison of different scenarios shall be carried out jointly.

Conclusions and recommendations

Finally, the interpretation step concludes with the analysis of the outcomes and the preparation of recommendations depending on the intended audience and context. The PEF guidelines stresses the complementarity between the LCA results and other assessments and instruments such as site-specific environmental impact assessments or chemical risk assessments.

Recommendations should be logical and supported by the study's conclusions. It is essential to avoid excessive interpretation of the results, such as highlighting minor or insignificant differences or drawing generic conclusions from specific case studies. Additionally, the practitioner should avoid subjective or biased statements, as well as inaccurate suggestions of equivalence between alternatives when meaningful differences may exist. Also, when making recommendations, the practitioner should mention additional environmental information not directly resulting from the LCA as mentioned in section 3.2 of this document.

Potential improvement opportunities should be identified, for example switching to different manufacturing production techniques, changes in product design, improvement on the operational set-up or other systematic approaches. Conclusions, recommendations and limitations shall be described in accordance with the defined goals and scope of the LCA study. First, this section should include a summary of identified value chain “hotspots” and the potential improvements associated with management interventions as identified in the “hotspot analysis” section of this document.

The recommendations should be actionable and connected to the study's findings, addressing opportunities for reducing environmental impacts or improving system performance. Finally, the limitations shall acknowledge in a transparent way all the assumptions made during the study, the potential lack of representativeness in data, and the boundaries of the analysis. Altogether, these three elements ensure the robustness and the relevance of the results of the evaluation.

Table 10. Recommendations for the interpretation step.

Shall	Should
Identify the significant issues by quantifying which life cycle steps/categories/processes/flows are major contributors to the total impact.	Document any inconsistencies found in the goal and scope and the results.
Report the degree of completeness achieved by including a justification about the excluded flows and processes and the cut-off criteria.	Use material and energy balance to check completeness of the inventory and results.
At least use a basic uncertainty approach covering sensitivity analysis and scenario analysis for key parameters.	Use a quantitative method to assess the uncertainty, e.g. Montecarlo Analysis.
Report complete and accurate results and conclusions of the LCA study without bias.	
Emission reductions from substitution effects shall be interpreted as environmental benefits and not as negative emissions, and shall be reported separately.	

4 Conclusions and next steps

The development of the AGISTIN LCA framework represents the starting point towards the harmonised evaluation of the two AGISTIN pilots to understand the environmental impacts and trade-offs in the application of these technologies. The framework builds upon existing standards such us ISO 14040, ISO 14044 and is aligned with the EU PEF guidelines to ensure the robustness of the results.

The literature review conducted stresses the importance of understanding the environmental profiles of these systems, paying attention to aspects such as the level of integration with renewable energy sources, system efficiency, and durability to reduce environmental impacts. As a result, this methodology allows to evaluate all the lifecycle stages, from raw material extraction to end-of-life, addressing the challenges and opportunities of energy storage systems, such as resource use, operation inefficiencies, and grid integration. The framework also integrates specific aspects for grid-connected storage systems, such as the inclusion of ancillary services that will be further explored in the pilot tests.

The next steps involve applying this framework to the two project field demonstrators (AGI-integrated innovative storage for green H_2 production in Amsterdam and AGI-integrated innovative storage for large pumping loads in the Segrià Sud region in Spain). The validation includes collecting and refining actual inventory data and performing a detailed impact assessment and interpretation to identify improvement opportunities. Finally, the framework will be further refined based on the lessons learnt from the actual application and the feedback from the consortium members.

References

1- Aviso, 2024. Kathleen B Aviso. *Overview of LCA—History, Concept, and Methodology* in *Encyclopedia of Sustainable Technologies* (Second Edition), Elsevier, 2024, Pages 107-114, ISBN 9780443222870. https://doi.org/10.1016/B978-0-323-90386-8.00113-3.

2- Guinée et al., 2011. Guinee, J.B., Heijungs, R., Huppes, G., et al., 2011. Life cycle assessment: past, present, and future. Environmental Science & Technology / Vol. 45, no. 1, 201.

3- Arabkoohsar, 2023. *Classification of energy storage systems*, in *Future Grid-Scale Energy Storage Solutions*.

4- Gandiglio et al., 2022. M. Gandiglio, P. Marocco, I. Bianco, D. Lovera, G.A. Blengini, M. Santarelli. *Life cycle assessment of a renewable energy system with hydrogen-battery storage for a remote off-grid community*. International journal of hydrogen energy 47 (2022) 32822-32834. https://doi.org/10.1016/j.ijhydene.2022.07.199.

5- Jasper et al., 2022. Friedrich B. Jasper, Jana Späthe, Manuel Baumann, Jens F. Peters, Janna Ruhland, Marcel Weil. *Life cycle assessment (LCA) of a battery home storage system based on primary data*. Journal of Cleaner Production 366 (2022) 132899. https://doi.org/10.1016/j.jclepro.2022.132899.

6- Bionaz et al., 2022. David Bionaz, Paolo Marocco, Domenico Ferrero, Kyrre Sundseth, Massimo Santarelli. *Life cycle environmental analysis of a hydrogen-based energy storage system for remote applications*. Energy Reports 8 (2022) 5080–5092. https://doi.org/10.1016/j.egyr.2022.03.181.

7- Delpierre et al., 2021. Mathieu Delpierre, Jaco Quist, Jan Mertens, Anne Prieur-Vernat, Stefano Cucurachi. *Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis*. Journal of Cleaner Production 299 (2021) 126866. https://doi.org/10.1016/j.jclepro.2021.126866.

8- Mori et al., 2021. Mitja Mori, Manuel Gutiérrez, Pedro Casero. *Micro-grid design and life-cycle assessment of a mountain hut's stand-alone energy system with hydrogen used for seasonal storage*. International Journal of Hydrogen Energy 46 (2021) 29706 -29723. https://doi.org/10.1016/j.ijhydene.2020.11.155.

9- Lamnatou et al., 2023. Chr. Lamnatou, N. Guignard, D. Chemisana, C. Cristofari, V. Debusschere. *Photovoltaic power plants with hydraulic storage: Life-cycle assessment focusing on energy payback time and greenhouse-gas emissions - a case study in Spain*. Sustainable Energy Technologies and Assessments 60 (2023) 103468. https://doi.org/10.1016/j.seta.2023.103468

10-Vilbergsson et al., 2023. Kristjan V. Vilbergsson, Kevin Dillman, Nargessadat Emami, Einar J. Ásbjörnsson, Jukka Heinonen, David C. Finger. *Can remote green hydrogen production play a key role in decarbonizing Europe in the future? A cradle-to-gate LCA of hydrogen production in Austria, Belgium, and Iceland*. International Journal of Hydrogen Energy 48 (2023) 17711 -17728. https://doi.org/10.1016/j.ijhydene.2023.01.081.

11-Huber et al., 2023. Dominik Huber, Daniele Costa, Alex Felice, Pieter Valkering, Thierry Coosemans, Maarten Messagie. *Decentralized energy in flexible energy system: Life cycle environmental impacts in Belgium*. Science of the Total Environment 886 (2023) 163882. http://dx.doi.org/10.1016/j.scitotenv.2023.163882.

12-Weidner et al., 2023. Till Weidner, Victor Tulus, Gonzalo Guillén-Gosálbez. *Environmental sustainability assessment of large-scale hydrogen production using prospective life cycle analysis*. International Journal of Hydrogen Energy 48 (2023) 8310 -8327. https://doi.org/10.1016/j.ijhydene.2022.11.044.

13-Jiao and Månsson, 2023. Yang Jiao, Daniel Månsson. *Greenhouse gas emissions from hybrid energy storage systems in future100% renewable power systems – A Swedish case based on consequential life cycle assessment*. Journal of Energy Storage 57 (2023) 106167. https://doi.org/10.1016/j.est.2022.106167.

14-Porzio and Scown, 2021. Jason Porzio and Corinne D. Scown. *Life-Cycle Assessment Considerations for Batteries and Battery Materials*. Adv. Energy Mater. 2021, 2100771. https://doi.org/10.1002/aenm.202100771.

15-Baumann et al., 2017. M. Baumann, J. F. Peters, M. Weil, and A. Grunwald. *CO_2 Footprint and Life-Cycle Costs of Electrochemical Energy Storage for Stationary Grid Applications*. Energy Technol. 2017, 5, 1071 – 1083. http://dx.doi.org/10.1002/ente.201600622.

16-Han et al., 2023. Xiaoqu Han, Yanxin Li, Lu Nie, Xiaofan Huang, Yelin Deng, Junjie Yan, Dimitrios-Sotirios Kourkoumpas, Sotirios Karellas. Comparative life cycle greenhouse gas emissions assessment of battery energy storage technologies for grid applications. Journal of Cleaner Production 392 (2023) 136251. https://doi.org/10.1016/j.jclepro.2023.136251.

17-Hiremath et al., 2015. Mitavachan Hiremath, Karen Derendorf, and Thomas Vogt. *Comparative Life Cycle Assessment of Battery Storage Systems for Stationary Applications*. Environ. Sci. Technol. 2015, 49, 4825–4833. DOI: 10.1021/es504572q.

18-Stougie et al., 2019. Lydia Stougie, Giulia Del Santo, Giulia Innocenti, Emil Goosen, David Vermaas, Hedzer van der Kooi, Lidia Lombardi. *Multi-dimensional life cycle assessment of decentralised energy storage systems*. Energy 182 (2019) 535-543. https://doi.org/10.1016/j.energy.2019.05.110.

19- Oliveira et al., 2015. L. Oliveira, M. Messagie, J. Mertens, H. Laget, T. Coosemans, J. Van Mierlo. *Environmental performance of electricity storage systems for grid applications, a life cycle approach*. Energy Conversion and Management 101 (2015) 326–335. http://dx.doi.org/10.1016/j.enconman.2015.05.063.

20-Vandepaer et al., 2018. Laurent Vandepaer, Julie Cloutier, Christian Bauer, and Ben Amor. Integrating *Batteries in the Future Swiss Electricity Supply System*. Journal of Industrial Ecology (2018). DOI: 10.1111/jiec.12774.

21- Koj et al., 2015. Jan Christian Koj, Peter Stenzel, Andrea Schreiber, Wilfried Hennings, Petra Zapp, Gunnar Wrede, Ina Hahndorf. *Life Cycle Assessment of primary control provision by battery storage systems and fossil power plants*. Energy Procedia 73 (2015) 69 – 78.

22-Gu et al., 2024. Yu Gu, Qianqian Chen, Danfeng Wang, Zhiyong Tang. *Strategy-based optimization and life cycle environmental impact assessment of a stable photovoltaic power-to-hydrogen system*. Energy Conversion and Management 315 (2024) 118747. https://doi.org/10.1016/j.enconman.2024.118747.

23-Ryan et al., 2018. Nicole A. Ryan, Yashen Lin, Noah Mitchell-Ward, Johanna L. Mathieu, and Jeremiah X. Johnson. *Use-Phase Drives Lithium-Ion Battery Life Cycle Environmental Impacts When Used for Frequency Regulation*. Environ. Sci. Technol. 2018, 52, 10163–10174. DOI: 10.1021/acs.est.8b02171.

24-Krishnan et al., 2024. Subramani Krishnan, Blanca Corona, Gert Jan Kramer, Martin Junginger, Vinzenz Koning. *Prospective LCA of alkaline and PEM electrolyser systems*. International Journal of Hydrogen Energy 55 (2024) 26–41. https://doi.org/10.1016/j.ijhydene.2023.10.192.

25-Mączka et al., 2024. Magda Mączka, Maciej Guzik, Michał Mosiałek, Magdalena Wojnarowska, Paweł Pasierb, Tomasz Nitkiewicz. *Life cycle assessment of experimental Al-ion batteries for energy storage applications*. Science of the Total Environment 912 (2024) 169258. https://doi.org/10.1016/j.scitotenv.2023.169258.

26-Pellow et al., 2020. Matthew A. Pellow, Hanjiro Ambrose, Dustin Mulvaney, Rick Betita, Stephanie S. *Research gaps in environmental life cycle assessments of lithium ion batteries for grid-scale stationary energy storage systems: End-of-life options and other issues*. Sustainable Materials and Technologies 23 (2020) e00120. https://doi.org/10.1016/j.susmat.2019.e00120.

27-Zimmerman et al., 2018. Zimmermann, Arno; Müller, Leonard Jan; Marxen, Annika; Armstrong, Katy; Buchner, Georg; Wunderlich, Johannes; Kätelhön, Arne; Bachmann, Marvin; Sternberg, André; Michailos, Stavros; Naims, Henriette; Styring, Peter; Schomäcker, Reinhard; Bardow, André. *Techno-Economic Assessment & Life-Cycle Assessment Guidelines for* CO_2 *Utilization*. 2018. DOI: 10.3998/2027.42/145436.

Annex I – Detailed results of the literature review

Chapter 2 of this document presented the condensed overview of the results of the literature review of relevant works in the field of LCA in energy storage systems. This annex includes the expanded version of the results. For each study the following aspects were taken into consideration:

- Storage technology.
- Functional unit.
- Goal and scope of the analysis.
- Impact assessment method.
- Remarks and conclusions relevant for AGISTIN.

Reference	Storage technology	Functional Unit	Goal of the study	Impact assessment method	Scope	Relevant conclusions for AGISTIN
Hiremath et al., 2015	*Lead-acid batteries, lithium-ion batteries, sodium–sulfur batteries and vanadium-redox-flow batteries*	1 megawatt-hour of electricity delivery (1 MWhd)	Comparative life cycle assessment of of four stationary battery technologies: lithium-ion, lead-acid, sodium– sulfur, and vanadium-redox-flow.	Cumulative energy demand (CED) and global warming potential (GWP)	Cradle-to-gate	Misleading to compare the environmental performance of batteries only on a mass or capacity basis, priority for technologies with a higher round-trip efficiency.
Oliveira et al., 2015	*CAES, Fuel Cells (PEMFC) and Battery Systems (Li-ion, lead acid and NaNiCl; LiMn Oxide and Sodium Sulphur)*	1 kilowatt hour of electricity stored and delivered from the storage system back to the grid.	Life cycle analysis of the energy storage systems that are considered as a suitable backup and balancing tool in a large scale energy grid	ReCiPe 2008 + single score evaluation	Cradle-to-grave	The environmental performance of each technology is a function of the origin of the electricity used (application) and overall dependent on its efficiency
Koj et al., 2015	*Li-ion batteries*	The total primary control power demand of 551 MW to be provided for 20 years	Compares the environmental performances of PCP provision by BESSs and by CPPs according to German primary control power market conditions.	International Reference Life Cycle Data System (ILCD)	Cradle-to-gate	BESSs are a promising option to reduce environmental impacts of primary control provision as a result of must-run fossil electricity generation.

Reference	Storage technology	Functional Unit	Goal of the study	Impact assessment method	Scope	Relevant conclusions for AGISTIN
Baumann et al., 2017	*Li-Ion batteries, lead acid batteries, sodium nickel chloride (NaNiCl) and Vanadium red-ox flow batteries*	1 kWh of energy storage capacity	Combines lifecycle assessment, Monte-Carlo simulation, and size optimization to determine life-cycle costs and carbon emissions of different battery technologies in stationary applications	IPCC 2013	Cradle-to-use	Long cycle lives need to be achieved, as otherwise the repeated need for cell replacements drives up costs and emissions.
Vandepaer et al., 2018	*Lithium metal polymer and lithium-ion stationary batteries*	Supply of 1 megawatt-hour (MWh) of electricity for the 2030 Swiss electricity system	Determines the direct and indirect environmental implications of the decision to integrate LMP or Li-ion stationary batteries in the Swiss electricity system in the event of intermittent renewable electricity sources producing surplus power.	International Reference Life Cycle Data System (ILCD)	Cradle-to-grave	The use of stationary batteries to integrate surplus from VRESs appears beneficial from an environmental point of view to in 12 out of 16 categories. Larger-scale changes in the grid have yet to be captured (increased penetration of VRESs, decrease in transport and distribution electricity losses)
Ryan et al., 2018	*Li-ion batteries*	Provision of 1 MW of symmetrical reserve capacity for one year	Life cycle environmental impact of using energy storage, namely Li-ion battery systems, for frequency regulation	Global Warming Potential (GWP), Cumulative Energy Demand (CED), and Acidification.	Cradle-to-grave	The magnitude of the upstream and EOL impacts of the battery system were small in comparison to the use stage. The electricity mix had the largest impact. Fuel price, congestion, and battery round trip efficiency had the next largest effects on net environmental impacts
Stougie et al., 2019	*Blue battery system, compressed air, Li ion batteries, lead-acid batteries and pumped hydro*	A storage capacity of 10 kWh of each of the systems and a lifetime of 20 years	Evaluates the sustainability of lead acid, lithium-ion and concentration gradient flow batteries, compressed air and pumped hydro energy storage (PHES) systems by conducting a multi-dimensional life cycle assessment	ReCiPe 2016 method V1.00	Cradle-to-grave	The multi-dimensional sustainability assessment did not lead to one preferred system, however, the generation of electricity and its supply chain is not taken into account.

Reference	Storage technology	Functional Unit	Goal of the study	Impact assessment method	Scope	Relevant conclusions for AGISTIN
Pellow et al., 2020	*Li-ion batteries*	Several FUs considered	Surveys the existing studies on grid-scale stationary LIB ESS, and highlights research gaps concerning comprehensive environmental impacts	Several methods and impact categories	Several boundaries	Provides 5 recommendations for LCA studies on energy storage: incorporate the use stage at grid-scale, accurate modelling of dispatch, ensure complete material inventories, include EoL processes and strive for primary data for the manufacturing stage
Delpierre et al., 2021	*Hydrogen (Alkaline and PEM electrolyser)*	1 kg of hydrogen at a pressure of 20 bars	LCA of potential future states of hydrogen production and use in vehicles in the Netherlands in 2050 using PEM and AE electrolysers and wind energy	ILCD 2021	Cradle-to-gate	Electricity consumption remains the largest contributor to environmental performances, even when renewable energy sources are considered. It is useful to combine LCA and scenario tool for large-scale analysis.
Mori et al., 2021	*Lead-acid battery, hydrogen (PEM electrolyser)*	The amount of energy provided in the form of heat and electricity during 1 year of operation.	Determine and compare the environmental impacts of different energy-system configurations for a mountain hut for electricity and heat distribution	Environmental Footprint 2.0	Cradle-to-gate	Hydrogen and battery ES are promising solutions from environmental point of view, but at higher costs.
Porzio and Scown, 2021	*Li-Ion batteries*	Several FUs considered	Explores common practices in lithium-ion battery LCAs and makes recommendations for how future studies can be more interpretable, representative, and impactful	-	-	For the use stage, knowledge about the performance of the storage system is critical. Disaggregating environmental impacts by location and type of operation can provide better transparency and accuracy.

Reference	Storage technology	Functional Unit	Goal of the study	Impact assessment method	Scope	Relevant conclusions for AGISTIN
Gandiglio et al., 2022	*Hydrogen (Alkaline electrolyser), Li-ion battery*	1 kWh of electricity provided by the energy system	Comparison of the main environmental impacts associated with (i) the current diesel-based energy system (Reference scenario) and (ii) the proposed RES-based energy system (battery/hydrogen) in a remote community	Product Environmental Footprint midpoint method	Cradle-to-use	EoL excluded from the assessment. The renewable P2P system leads to an improvement over the current fossil-based generation system.
Jasper et al., 2022	*LFP battery*	1 kWh of energy delivered by the considered systems	Quantification of the potential environmental impacts of the peripheral components on the of a typical HSS under a full life-cycle perspective, based primary data for the system composition	ILCD (Global warming potential, resource use, ecotoxicity)	Cradle-to-grave	Relevance of toxicity and resource use Importance of manufacturing stage and component lifetime
Bionaz et al., 2022	*Hydrogen (PEM electrolyser), Li-ion battery*	1 MWh of electricity generated onsite or supplied by the submarine cable	The REMOTE solution (hydrogen + battery storage) was compared with two different scenarios: replacement of the submarine cable and installation of diesel generators to cover the entire load	GHG emissions	Cradle-to-use	RES scenario lower emissions than conventional. Results are highly dependent on the carbon intensity of the electricity mix.
Lamnatou et al., 2023	*Hydraulic*	1 kWh of generated electricity	Evaluates the environmental profile of a Photovoltaic (PV) plant with hydraulic storage in Catalonia (Spain) under 8 different configurations	IPCC 2021 GWP100	Cradle-to-grave	PV/hydraulic storage offers low-carbon power with substantially lower environmental impacts than fossil fuel-fired power generation. Selection of materials is important
Vilbergsson et al., 2023	*Hydrogen (alkaline, PEM, SOEC)*	1 kg H2 produced by each electrolyser	Compare the environmental impacts of remote-produced hydrogen with local production at three locations in mainland Europe	ReCiPe 2016 (H)	Cradle-to-gate + distribution	H2 production can only be recommended for electrical grids with a high ratio of renewable energy sources.

Reference	Storage technology	Functional Unit	Goal of the study	Impact assessment method	Scope	Relevant conclusions for AGISTIN
Huber et al., 2023	*LFP and NMC batteries*	1 kW-hour (kWh) of consumed electricity in the residential and commercial sector	Assess the environmental impacts of each technology installed in the decentralized energy systems in Belgium for different scenarios	ReCiPe 2016	Cradle-to-grave	Decentralised systems reduce climate change impacts. Stationary batteries improve systems' performance without increasing environmental impacts significantly
Weidner et al., 2023	*Hydrogen*	Production of 500 Mt/yr of H2	Assess and contextualize the environmental impacts of large-scale hydrogen production at different stages of technological development	Planetary Boundaries framework LCIA, in short PB-LCIA, ReCiPe2016 (Midpoint) Hierarchist, Environmental Footprint 3.0 (Midpoint), CML-IA baseline 4.8 from 2016 (Midpoint)	Cradle-to-gate	Extraction and processing of metals for renewable energy infrastructure contributed the most to the environmental impacts of green hydrogen production
Jiao and Månsson, 2023	*Pumped hydro, hydrogen, LFP battery, lead-acid battery, Vanadium red-ox flow battery, supercapacitor, flywheel*	1 kWh generated electricity and 1 kWh delivered electricity	Evaluates the GHG emissions from different combinations of HESSs, pumped hydro, hydrogen, batteries, supercapacitors and flywheels	IPCC 2021 GWP100	Cradle-to-grave	In large-scale utility applications, the cradle-to-gate GHG emissions from the HESS contribute to a major share of the life cycle GHG emissions due to an under-utilization of the cycle life. Number of operational cycles of the HESSs is a key parameter.
Han et al., 2023	*Lithium iron phosphate batteries, nickel cobalt manganese oxide batteries and vanadium redox flow batteries*	1 MWh of energy stored throughout the entire life cycle	Investigate the GHG emissions throughout the entire life cycles of LIPBs, NCMBs, and VRFBs for grid applications, including electrical grid peak-shaving and renewable energy support scenarios	Recipe 2016 Midpoint H - GHG emissions	Cradle-to-grave	Electricity mix in the use stage is the main contribution, integration of energy storage with renewable energy sources resulted in the most notable reduction in the GHG emissions. Relevance of round-trip efficiency.

Reference	Storage technology	Functional Unit	Goal of the study	Impact assessment method	Scope	Relevant conclusions for AGISTIN
Gu et al., 2024	*Hydrogen (Alkaline electrolyser), Li-ion batteries*	1 kg of hydrogen	To assess the environmental impact of a solar energy-based hydrogen production system.	CML2001	Cradle-to-gate	Using a grid-connected hydrogen production mode can effectively balance system reliability and result in environmental impact as well as yielding economic benefits
Krishnan et al., 2024	*Hydrogen (Alkaline and PEM electrolyser)*	1 kg of produced hydrogen	To assess the environmental impact of AE and PEM systems with a focus on the current state-of-the-art stacks, termed baseline design, and the expected future stacks design commercially available within a decade	Product Environmental Footprint 3.0 midpoint method	Cradle-to-gate	The primary contributors to the assessed impact categories are the electricity source and the stacks. Focus on reducing the minimal load requirements and increase current density.
Mączka et al., 2024	*Al-ion battery*	A single battery with normalized capacitance of 100 F/g.	To compare experimental variants of Al-Ion battery construction with regard to environmental performance and its coherence with circular economy priorities	ReCiPe Endpoint (H) V1.07	Cradle-to-grave (excluding use stage)	The technology is still at an early stage of development, although results highlight the significance of battery performance and energy output and the materials used for electrolyte and cathode construction.

Annex II – Shortlist of ancillary services

As mentioned in section 3.2 (Scope definition), the LCA of energy storage systems integrated with AGIS should mention the ancillary service included in the study. The following table presents a list of the most common ancillary services required and the potential modelling provisions for LCA studies. The implications of addressing the different services will be further discussed in the upcoming activities in WP5 and WP6, prioritising those services that could be modelled with available data from the operation and the simulations.

Ancillary service	Short description	LCA modelling implications
Frequency Regulation	Maintains grid frequency by balancing supply and demand.	Model storage systems as fast-responding assets; quantify emissions avoided by reducing reliance on slower, fossil fuel-based generators. Include temporal modelling for response times.
Voltage Support	Supports stable grid voltage levels through reactive power management.	Incorporate reactive power provisioning from storage inverters; compare avoided emissions and resource use against traditional synchronous generators.
Congestion Relief	Reduces grid strain by managing localised power flows to avoid overloading of the transmission lines.	Quantify energy shifted locally by storage to relieve grid congestion. Assess impacts on emissions, avoided grid expansions, and the life cycle cost of transmission upgrades.
Spinning Reserve	Maintains standby generation capacity to respond to sudden changes in demand or supply.	Model emissions reductions from storage replacing fossil-fuel-based spinning reserves. Consider the energy losses during idle or standby modes of both conventional and storage systems.
Black Start Capability	Restarts the grid after outages without relying on external power.	Include avoided emissions from replacing diesel generators with storage systems. Model storage performance under black start scenarios, accounting for cycle durability and readiness.
Load Shifting	Stores excess energy during low demand and releases it during peak demand to balance the grid.	Assess changes in grid emissions by modelling energy stored and discharged during periods of differing grid carbon intensity. Incorporate round-trip efficiency losses.
Curtailment Reduction	Prevents renewable energy curtailment by storing surplus energy for later use.	Model emissions avoided through reduced curtailment of renewables; assess efficiency gains and reduced reliance on peaking fossil fuel plants.

Ancillary service	Short description	LCA modelling implications
Grid-Forming Capability	Provides synthetic inertia to maintain grid stability, supporting frequency and voltage autonomously.	Model synthetic inertia and compare its environmental impacts to conventional grid-forming assets. Assess emissions reductions and avoided resource use for rotating machinery.