Environmental Feasibility Analysis for Energy Storage Solutions

Inception report

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Introduction

The StoreMore project, implemented under the leadership of the city of Békéscsaba and in cooperation with partners from 10 Danube Region countries, aims to promote sustainable energy storage solutions throughout the Danube Region. The objective of the consortium is to improve energy storage efficiency, reduce environmental impact, and support the energy transition in the region.

Within the framework of the project, a range of key activities is being carried out, focusing on expanding knowledge related to energy storage solutions and developing innovative technologies. Through the mapping of stakeholders and the engagement of target groups, a comprehensive understanding of the region's energy storage needs and challenges is obtained. Based on these insights, the development of an online modeling tool and an AI-driven renewable energy (RES) optimization tool applies the latest technological innovations to address these needs effectively.

Project outputs include an online modeling tool that offers interactive guidance on energy storage options and an AI-powered RES optimization tool that forecasts energy production and optimizes storage. These tools will be accessible not only to project participants but also to the broader public, thus facilitating the widespread adoption of sustainable energy solutions.

Knowledge transfer and dissemination activities - such as workshops, conferences, and visual materials - are designed to enhance the project's visibility and impact. These activities enable the broad sharing of results, contributing to greater awareness of energy storage solutions across the Danube Region.

The expected outcomes of the StoreMore project represent significant progress in advancing the region's energy storage capacity. The project contributes to enhancing energy efficiency, reducing greenhouse gas emissions, and improving energy security. Through the application of the developed tools and knowledge-sharing activities, the wider use of sustainable energy sources is encouraged, supporting the green transition of the Danube Region.

One of the objectives of the StoreMore project is to analyse and catalogue sustainable energy storage solutions based on their technical, financial, and environmental characteristics. As part of this effort, a dedicated project activity evaluates the environmental impacts of preselected storage technologies to support the development of both an energy storage modeling tool and a renewable energy source (RES) optimisation tool.

This activity includes the preparation of a report conducting an environmental feasibility analysis of the shortlisted energy storage options. The analysis evaluates environmental impacts across a variety of contexts, ensuring the generation of high-quality data to inform the Catalogue of Sustainable Energy Storage Solutions (CSESS). The shortlisted energy storage solutions:

1. Gravity-Based Storage
2. Flywheel Energy Storage

3. Hydrogen Energy Storage
4. Vanadium Redox Flow Batteries
5. Ultracapacitors

The task is coordinated by Békéscsaba, City of County Rank, with implementation managed by its municipal energy entity, Békéscsaba Smart Management Kft. The work is divided into two main parts:

- The **Inception Report** - this work - establishes the methodological foundation for the environmental impact assessments. It introduces the Comparative Environmental Rating Methodology, which forms the core of the assessment process. Additionally, the report includes a detailed work plan, a refined methodology, and review of available data sources for Gravity-Based Storage and Flywheel Energy Storage - which serve as examples of the applied approach. Thus, the Inception Report defines the scope and methodological framework of the final analysis and acts as a checkpoint to validate the assessment approach before further resources are allocated.
- The **Final Report** applies the methodology defined in the Inception Report and follows the outlined work plan for the two assigned technologies. Meanwhile, the remaining technologies are being analysed in parallel by other consortium partners, using the same methodological basis. The environmental assessment of the remaining three technologies is carried out by other project partners within the consortium.

Goal and Scope

The goal of this Inception Report is to develop a comparative environmental rating methodology initially applied to Gravity-Based Storage and Flywheel Energy Storage, with built-in flexibility to be extended to the other shortlisted technologies: Hydrogen Energy Storage, Vanadium Redox Flow Batteries, and Ultracapacitors.

This methodology should be adaptable across a range of deployment settings, including urban environments, industrial sites, and abandoned mines. It aims to provide a comprehensive environmental evaluation, incorporating the following key criteria:

- Lifecycle greenhouse gas emissions
- Resource and material consumption
- Recyclability and end-of-life management
- Site-specific environmental impacts, particularly relevant to distributed and decentralized energy applications

The framework combines quantitative and qualitative metrics, enabling context-sensitive environmental ratings. It supports comparative analysis between technologies and is designed for scalability, allowing assessments across different geographic and operational contexts.

Compatibility with StoreMore's modeling and optimisation tools is a core requirement. The methodology should assist stakeholders in making informed decisions through transparent, consistent, and actionable environmental ratings. Emphasis is placed on ensuring data accuracy, methodological consistency, and alignment with established environmental standards.

This report outlines the approach for developing the environmental rating methodology. It also presents a detailed work plan for assessing the environmental impacts of the five shortlisted technologies, with a focus on Life Cycle Assessment (LCA). As a starting point, it includes a literature review and preliminary environmental analysis of two selected technologies:

- Gravity-Based Storage
- Flywheel Energy Storage

The remaining technologies will be evaluated by other partners within the consortium using the same methodological framework.

Thus this report has two key objectives:

- **Develop a comparative environmental rating methodology** for Gravity-Based and Flywheel Energy Storage, with adaptability for other shortlisted technologies. The methodology supports context-sensitive, lifecycle-based assessments and integrates with StoreMore tools.
- **Outline a work plan** and conduct preliminary analysis for assessing environmental impacts, including life-cycle analysis, starting with Gravity-Based Storage and Flywheels.

This report is based entirely on **desktop research**, reviewing relevant scientific and industry sources to identify the key environmental impacts of the shortlisted technologies.

Following a comparison of various assessment methods, the most commonly used and purpose-appropriate indicators will be selected for the analysis.

Part I: Environmental rating of energy storage solutions

Introduction

The environmental assessment of energy storage technologies is critical in the context of the transition towards sustainable energy systems to understand their sustainability and operational viability. Various energy storage technologies have unique environmental impacts and capacities for sustainable operation. In this section, a literature review is provided on the sustainability assessment frameworks of energy storage technologies. For this purpose, Elsevier's abstract and citation database, *Scopus*, was used as the primary research tool.

Various indicators are used to gauge the environmental performance of these systems, focusing on life cycle analysis (LCA) & carbon footprint, water use, land utilization being the most used indicators, and overall sustainability metrics.

The majority of studies evaluating the environmental impacts of energy storage systems rely on a single indicator (Baumann et al., 2019; Rahman et al., 2020; Sternberg & Bardow, 2015), often focusing on life-cycle greenhouse gas (GHG) emissions (i.e., carbon footprint) (Arbabzadeh et al., 2017) or specific resource uses such as land requirements (Asri et al., 2021; Beaudin et al., 2010; Ibrahim et al., 2008; Shan et al., 2022), non renewable resource use such as metals availability (Beaudin et al., 2010) or operational water consumption. This reductionist approach is understandable, considering the multitude of economic and technical challenges - as well as the complex optimization tasks - that engineers and decision-makers must navigate (Acar, 2018; Amir et al., 2023; Baumann et al., 2019). On the other hand, as highlighted by (Sharma et al., 2019), this simplified approach risks overlooking critical environmental aspects, potentially leading to suboptimal planning and decision-making.

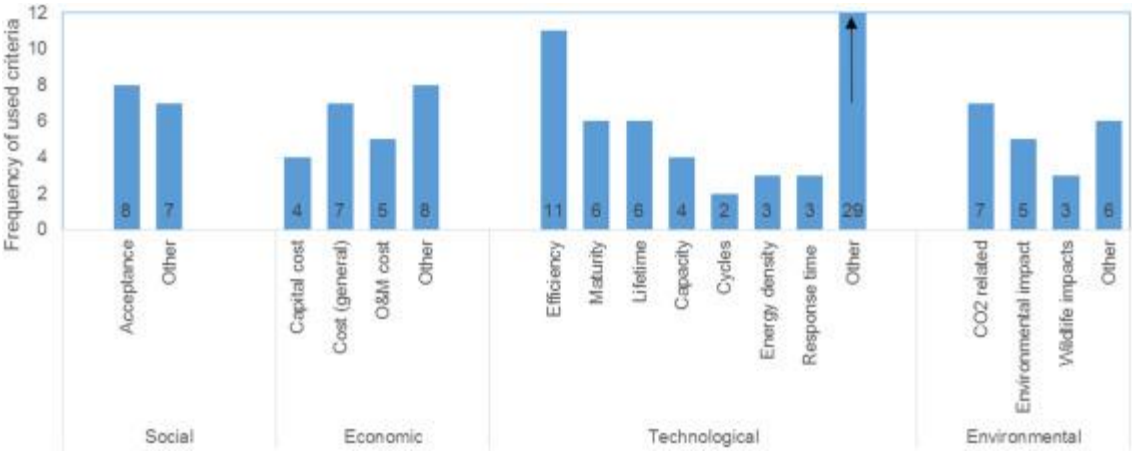

Figure 1. Overview of the frequency of criteria by number of studies. O&M: Operation and Maintenance (Baumann et al., 2019)

In response to this limitation, some studies adopt a more comprehensive assessment of environmental impacts. Newer strategies in energy storage are beginning to focus on minimizing material disposal issues and enhancing recyclability, which aligns with broader sustainability goals. For example Florin and Dominish (Florin & Dominish, 2017) provided a qualitative overview of many types of energy storage in an Australian context.

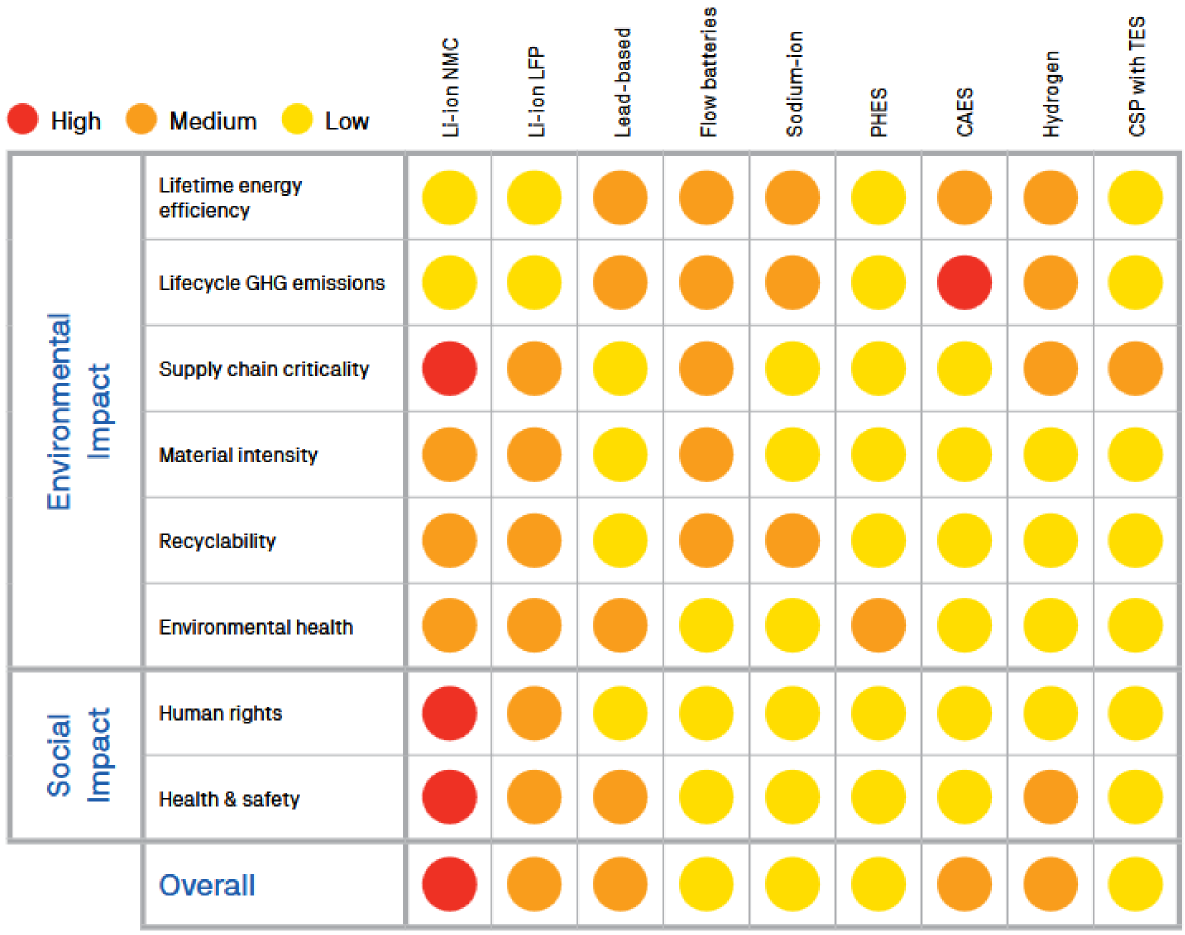

Figure 2. A qualitative overview of the environmental and social impacts of various energy storage technologies. NMC: Nickel Manganese Colbalt, LFP: Lithium Iron Phosphate, PHES: Pumped Hydro Energy Storage, CAES: Compressed Air Energy Storage, CSP: Concentrating Solar Power, TES: Thermal Energy Storage (Florin & Dominish, 2017)

For a more quantitative approach, the most widely used methods is life cycle assessment (LCA), which evaluates environmental impacts across all stages of an energy storage technology's life, from raw material extraction to end-of-life disposal. LCA is particularly helpful in comparing different technologies (Nemova et al., 2024).

In conclusion, environmental indicators such as life cycle assessment, resource use, recyclability, and land footprint can offer a meaningful and comprehensive evaluation of energy storage technologies—but only when considered together. No single indicator alone is sufficient; instead, a combination of approaches is necessary to fully capture the range of potential environmental impacts.
Broadly, methods for evaluating environmental impacts can be grouped into three main categories:

1. **Direct local impacts** that occur during the construction, operation, maintenance, and demolition phases.

2. **Indirect (life-cycle) impacts** that arise across the entire life cycle of the equipment, including material extraction, manufacturing, and disposal.
3. **Avoided impacts** resulting from the displacement of more polluting or less efficient technologies.

In the following chapters, each of these three assessment approaches is explored in detail. At the end of every subchapter we give a recommendation on how the specific aspect should be covered (in boxed format). This will be followed by a summary of the recommended evaluation framework, integrating all recommendations.

Impacts on local environment

The deployment of various energy storage technologies has implications for local environments and settlements, which manifest in several key areas including air or water pollution, chemical or fire hazards and resource requirements such as land or water use. Each technology presents distinct risks and impacts, necessitating careful consideration in planning and implementation (Chakraborty et al., 2022; Georgious et al., 2021; Kokkotis et al., 2017).

There are several already established frameworks to account for impacts on the local environment:

- **Environmental Impact Assessment** (EIA) in EU law is a process used to evaluate the potential environmental effects of certain public and private projects before they are approved. It is governed by Directive 2011/92/EU, as amended by Directive 2014/52/EU, and aims to ensure that environmental considerations are integrated into the decision-making process. It applies to projects likely to have significant environmental effects and includes an assessment of factors like air, water, biodiversity, and human health.
- **Risk assessment** in environmental management systems is the process of identifying, evaluating, and prioritizing environmental risks related to an organization's activities. It helps the organization understand potential environmental impacts, such as pollution or excessive resource use, and take steps to prevent or minimize them. This process also supports compliance with environmental laws and standards. In systems like ISO 14001, risk assessment involves examining environmental aspects, estimating the likelihood and severity of their impacts, and deciding on actions to manage the most significant risks.
- **Integrated Pollution Prevention and Control (IPPC) / Industrial Emissions Directive (IED):** In the EU, this framework ensures that factories use best available techniques (BAT) to prevent or minimize emissions to air, water, and land. Environmental assessments under IED include detailed evaluations of local impacts and compliance with emission limits.

All of these frameworks assess and categorize environmental hazards or impact sources into two main groups: resource use (inputs) and releases (outputs). Resource use refers to the consumption of elements such as land, water, and other resources, while releases include the following outputs:

- air pollutants,
- emissions or wastes to water and soil,

- noise and vibration, and
- radiation.

Importantly, these frameworks distinguish between aspects arising from normal operations and those resulting from incidents or accidental events. and the frequency or likelihood of harmful events occurring.

These environmental aspects can potentially lead to impacts or damages affecting one or more of the following **receptors:**

- human health (local population),
- local ecosystems,
- resource availability,
- and the built environment, infrastructure and landscape.

The level of risk associated with these impacts depends on vulnerability or susceptibility of the affected receptors, such as:

- the presence of cumulative impacts (such as existing background pollution levels),
- the effectiveness of mitigation measures in place, and a capacity for an adequate response.

The exposure route or pathway refers to the mechanism through which an environmental aspect, originating from a source, can reach and potentially affect the identified receptors. It describes how the impact is transmitted—whether through air, water, soil, or direct contact—thereby establishing the connection between the source of the pressure and the affected environment or population.

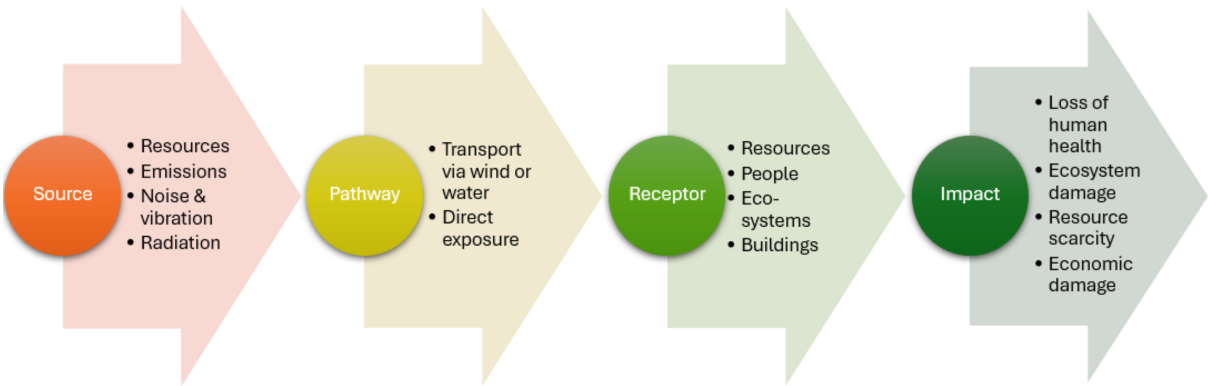

Figure 3. The source – pathway – receptor – impact model in Environmental Risk Assessment and Environmental Impact Assessment

It is clear that each type of energy storage technology previously mentioned requires careful spatial planning, taking into account local conditions such as proximity to urban areas, availability of natural resources, land use, and environmental sensitivity. In the following sections, a general overview is provided of the key potential sources of environmental impact associated with the pre-selected energy storage technologies. These should be further elaborated in the technology specific evaluation work in the StoreMore project.

Chemical hazards and safety

Energy storage systems may pose significant risks due to their chemical constituents and potential for hazardous incidents. For instance, hydrogen storage are associated with risks of fires and explosions under specific failure conditions as hydrogen is highly flammable and requires strict safety infrastructure. Vanadium redox flow batteries use liquid electrolytes that are corrosive and need careful containment to prevent leaks. These incidents can result not only in property damage but also in environmental contamination if not managed properly (Georgious et al., 2021). In rare cases, mechanical failure of flywheels can cause damage if containment is insufficient.

Land use and visual impacts

Several studies (Asri et al., 2021; Beaudin et al., 2010; Ibrahim et al., 2008; Shan et al., 2022) ranked different technologies based on their land use requirements which in turn mostly depend on volumetric energy density of the selected energy storage technologies and the need for specialized infrastructure. For example storage tanks and electrolyzers require significant space and zoning in the case of **hydrogen** production. **Flow batteries** require large tanks and pumps, especially for high-capacity storage. **Gravitational storage** requires tall structures or deep shafts that can alter landscapes or urban aesthetics.

Furthermore, the operational setups for storing these technologies—be they large warehouses for batteries or facilities for flywheel systems - can require significant land use, which may disrupt local populations and wildlife habitats (Seward et al., 2021).

Water use and pollution

Water use is also a crucial factor, particularly for technologies like **hydrogen-based storage**, as electrolysis consumes large amounts of water, potentially stressing local water supplies.which thereby presenting challenges in terms of regional sustainability. This factor is increasingly significant in areas experiencing water scarcity, making the comparative evaluation of energy storage technologies vital for informed decision-making (Nemova et al., 2024).

Gravity-based energy storage systems necessitate careful site selection to avoid disrupting local landscapes and ecologies. If improperly located, implementations of such systems could interfere with water flow or cause hydraulic changes in the immediate areas, affecting local agriculture or ecosystems (Nguyen et al., 2015).

Noise and vibration

In the case of **gravity based storage** mechanical lifting systems may produce noise during operation. Similarly, high-speed rotation of **flywheel energy storage** can produce sound and minor vibrations, depending on design and placement.

Summary

In summary, while energy storage technologies are crucial for the transition to renewable energy and the enhancement of local energy resilience, they entail a complex array of risks that must be critically evaluated. Safety concerns regarding chemical hazards, the resource-intensive nature of technology deployment, and the socioeconomic ramifications of implementation all highlight the necessity for comprehensive planning and community engagement in the integration of these systems into local settlements. Since the environmental impact of a given technology is highly dependent on its specific location and surrounding context, it is advisable to conduct impact assessments on a case-by-case basis for each proposed site.

Table 1. Overview of the local environmental aspects of the selected technologies

Technology	Land Use / Visual Impact	Noise / Vibration	Chemical / Fire Risk	Water Use
Gravity-Based Storage	High: requires tall structures or shafts	Moderate – mechanical systems	Low: minimal hazardous materials	None
Flywheel Storage	Low: compact footprint	Moderate – high-speed rotors	Low: risk if containment fails	None
Hydrogen Storage	High – tanks and equipment need space	Low – quiet operation	High: explosion and fire risk	High – electrolysis use
Vanadium Flow Batteries	Moderate – large tanks and infrastructure	Low – mostly quiet operation	Medium: corrosive electrolytes	Low
Ultracapacitors	Very Low – compact and modular	Very Low	Very Low: non-toxic materials	None

To streamline this process and support more efficient decision-making, it is recommended to utilize Geographic Information System (GIS) data in a manner similar to the renewable energy **'go-to zones'** established under EU Renewable Energy Directive (RED - EU 2023/2413) on the promotion of renewable energy. This legislation allows Member States to designate specific areas, so-called "go-to zones", where certain types of renewable energy projects, such as wind or solar, can benefit from a simplified and expedited permitting process. The goal is to reduce administrative burdens and accelerate the deployment of renewable technologies by pre-assessing environmental impacts at the zoning level, rather than requiring full-scale Environmental Impact Assessments (EIAs) for each individual project. Following this example, spatial planning for energy storage installations could similarly identify suitable zones where environmental risks are minimized, thereby enabling faster deployment while still safeguarding local ecosystems and communities.

Recommendation: land use, noise & vibration, chemical & fire hazards and water use should be evaluated as local environmental aspects of the selected energy storage

technologies at minimum. Furthermore, an initial zoning criteria or maps depicting "go-to" areas in the Danube Region should be provided for each technology.

Life cycle assessment

Life cycle assessment (LCA) is product-centric assessment method that is based on the ISO14040 standard. It takes into account the full lifecycle of a product or service from the extraction of raw materials through manufacturing, distribution, use and end-of-life. In the following chapters we explore specific LCA related methodological choices relevant to energy storage technologies.

Function and functional unit

To compare energy storage products that offer the same or similar functions within the research scope, it's important to clearly define their functional or declared units. For example a review identified 30 different functions of possible functions for electrical energy storage mitigating variable renewable energy sources only.(Beaudin et al., 2010). According to a review of energy storage technologies, the environmental performance of storage systems is application dependent (Oliveira et al., 2015).

Recommendation: The main function(s) and optional secondary functions of the evaluated technology shall be clearly reported. Since the main function of an energy storage is to store and release energy, the functional unit (FU) should be the average kilowatt-hour (kWh) of energy delivered by the energy storage system over its entire life cycle.

Technical information

The technical characteristics highly influence the environmental impact of a given energy storage technology. Arbabzadeh et al. (2017) gives an overview on the technical parameters driving environmental performance, e.g. service life, roundtrip efficiency, while others found other details such as operational energy loss (Oliveira et al., 2015) or the intensity of charge–discharge cycling (Lundahl et al., 2023) relevant.

Recommendation: at least the following information shall be reported for each evaluated technology:

- **Reference service life (years)**
- **Number of cycles over the lifetime**
- **Average energy capacity (MWh) which refers to the average of the initial capacity and the capacity at the end of-life.**
- **Power rating (MW)**
- **Roundtrip efficiency (%)**
- **Depth of discharge (%)**
- **Suitable storage duration (hours / days / weeks / seasonal)**

System boundaries

In general, the use stage of energy storage technologies dominates their life cycle impacts significantly, mainly due to the energy losses during operation. It is therefore misleading to compare the environmental performance of batteries only on a mass or capacity basis at the factory gate ("cradle-to-gate analyses") while neglecting their use stage impacts, especially when they have different technical parameters (Hiremath et al., 2015).

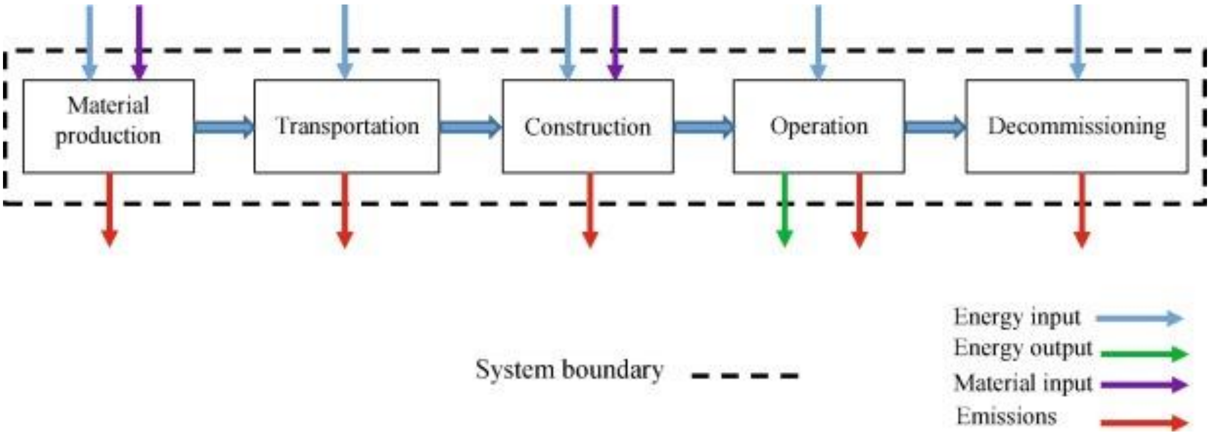

Figure 4. General life-cycle of an energy storage system (Rahman et al., 2020)

Recommendation: the system boundary should follow a cradle-to-gate approach according to EN15804+A2 standard as follows:

Production stage(A1-A3)	A1 Raw materials production
	A2 Raw material transportation
	A3 Product manufacturing
Distribution stage(A4)	A4 Product transportation
Construction/Installation stage(A5)	A5 Installation and construction
Use stage (B1-B7)	B1 Product use
	B2 Product Maintenance
	B3 Product repair
	B4 Product replacement
	B5 Product refurbishment
	B6 Operation energy use
	B7 Operation water use
End-of-life stage (C1-C4)	C1 De-construction
	C2 Waste transportation
	C3 Waste sorting or disposal
	C4 Waste incineration or landfill
Reuse, Refurbishment or Recycling Burdens and Potential Benefits	D Reuse, Refurbish or Recycle

Data collection and assumptions

In their product category rules (PCR) for battery energy storage, Han & Li (2022) recommended a default **cut-off value of 1%.** In other words, the inventory data provided should account for at least 99% of the results in each environmental impact category. Additionally, it should cover at least 99% of the product's total mass and 99% of the energy used throughout its life cycle. While achieving these thresholds, it is important to avoid excluding data unnecessarily - ideally, all available inventory data should be included.

Recommendation: a cut-off value of 1% shall be adopted in terms of mass and energy balances as well as considering the environmental impact.
The following processes should not be included in the LCA system boundaries:

- **Manufacture of production equipment, buildings and other capital goods,**
- **Personnel business travel and commute to and from work,**
- **Accidental or environmental incidents, and**
- **Research and development, sales and other office activities.**

Assumptions, data collection procedures and allocation should be described clearly.

Impact assessment method

Rahman et al. reviewed the life-cycle assessment impact categories employed in case studies (Rahman et al., 2020). The overwhelming majority of the studies focuses on carbon footprint from the wide range of life cycle impact categories. This is because carbon footprint is often perceived as more robust than other life cycle impact categories due to more available and precise data points. Also, since the energy sector is responsible for the highest share of among all types of impacts globally, this underpins the use of climate change impacts.

Most of the authors, who turned towards a more complex view on impacts applied the ReCiPe 2016 (Huijbregts et al., 2017) impact assessment method e.g. (Oliveira et al., 2015), which is favored for its aggregated and concise presentation of endpoint damage-oriented impacts to ecosystems, human health, and resource availability.

However, inconsistencies arise as many studies also report carbon footprint separately from the ReCiPe endpoint categories e.g. (Li et al., 2024), despite climate change already being included within these aggregated metrics. This practice can lead to redundancy and misinterpretation of results.

To address this issue, we recommend the use of the Environmental Footprint (EF) 3.1 impact assessment method. EF 3.1 includes a comprehensive set of relevant impact categories for energy storage systems, such as climate change, land use, water use, and human toxicity. Moreover, the method provides default normalization and weighting factors tailored for European contexts thus the results can be aggregated into a single PEF score. Its adoption is increasing, partly due to recent EU legislation—such as the Battery Regulation—which mandates the inclusion of environmental footprint indicators in the battery passport. Using EF 3.1 ensures compatibility with these legal requirements and supports comparability of StoreMore results with future studies.

Furthermore, manufacturers of energy storage technologies may already be familiar with EF impact categories, as the method aligns with the EN 15804 standard. This standard is increasingly adopted in environmental product declarations (EPDs), including the Chinese EPD program, which currently offers the only product category rules (PCR) relevant to energy storage systems (Han & Li, 2022), based on EN 15804+A2.

Recommendation: Environmental Footprint (EF) 3.1 should be used as the selected life cycle impact assessment (LCIA) method.

Use stage and end-of-life

Since the majority of the environmental impacts of energy storage systems are associated with the production of energy that is lost during operation, special attention should be directed at selecting the most appropriate source of this energy. On the other hand this might be location-specific which might not be available at the time of the evaluation. For this reason, to enhance comparability, it would preferable to use a common energy mix if possible. Since the all Danube Region countries are part of the European synchronous grid (ENTSO-E), the best option is to use European average data.

When allocating the impacts and benefits of reuse, recovery, and/or recycling, the most widespread approach is Polluter Pays Principle (PPP). According to this principle, the entity that benefits from recycling or reuse assumes responsibility for the associated environmental impacts and benefits. This means the original product manufacturer is not accountable for these impacts and does not share in the environmental benefits—such as those arising from avoiding the production of equivalent new products. As a result, the environmental effects related to recycling and reuse are not included in the waste phase of the original product and must be calculated and reported separately.

Recommendation: The impacts arising from the loss of assumed production of energy that is stored during operation should be reported separately. If not known, European average energy mix should be used as a default. Reuse, recovery, and/or recycling should be modelled according to realistic waste management scenarios today in the Danube Region while impact and benefits should be allocated according to the Polluter Pays Principle (PPP).

Avoided impacts

The integration of energy storage systems (ESS) with intermittent renewable sources, significantly mitigates several environmental and energy-related impacts. First, energy storage facilitates better load management and energy supply consistency, thus **reducing the reliance on fossil fuel backup generation**, which is often utilized to compensate for the intermittency of renewables. By storing excess energy generated during peak production times, battery systems enable a more reliable provision of electricity, which can lead to fewer emissions from power generation and a lower carbon footprint (Raugei et al., 2020; Sternberg & Bardow, 2015). This can also lead to **decreased wear on grid infrastructure and reduced** impacts associated with **rapid adjustments in conventional energy generation**. Thus, incorporating energy storage not only amplifies the efficiency of renewable energy systems but also contributes to environmental sustainability by diminishing reliance on carbon-intensive energy sources and enhancing grid resilience.

Furthermore, according to Lundahl et al., co-locating different energy storage technologies can help reduce environmental impacts, as each technology may serve a distinct role within the energy supply system, complementing one another (Lundahl et al., 2023).

Recommendation: if the energy storage under evaluation is likely to replace or reduce the use of other types of systems - such as backup diesel generators, gas turbines, the grid or other types of storages - these should be included in the system boundary, but the environmental benefits should be reported separately to avoid double counting.

Data quality and sensitivity assessment

Comparing the shortlisted technologies presents several challenges, including difficulties in data collection, differences in technological maturity, varying degrees of modularity and scalability, differences in technical performance depending on specific use cases, and varying levels of uncertainty across different life cycle stages.

Ideally, environmental impact results should be presented as a range of values based on a 95% probability distribution or through the use of multiple scenarios. However, since it's not always feasible to determine such ranges, a thorough sensitivity analysis is recommended. This analysis should focus on the parameters and assumptions that are both highly uncertain and have a significant impact on the results.

To ensure robust data quality assessment in life cycle analysis (LCA), it is recommended to adopt the data quality pedigree matrix method, a well-established approach for evaluating the reliability and completeness of data (Lewandowska et al., 2004).

Recommendation: to assess data quality the data quality pedigree matrix method should be used along with a sensitivity analysis. Ecoinvent is recommended as the background database.

Identification of key design parameters

The life cycle assessment (LCA) is usually a laborous and resource intensive exercise. However, some case studies demonstrate that design parameter estimation have facilitated quicker calculation of LCA results. For example, Szilágyi and Gróf demonstrated that the environmental footprint of a grid-connected photovoltaic system can be approximated rapidly by utilizing certain design parameters, streamlining what is traditionally a time-intensive process (Sharma et al., 2019; Szilágyi & Gróf, 2020).

One key aspect of accelerating LCA estimates lies in the identification and use of critical design parameters that are indicative of the overall environmental impact. These parameters may include the total area of the system, roundtrip efficiency and the expected operational lifespan of the system. By focusing on these specific metrics, researchers can apply predictive models that correlate these design variables with environmental outcomes.

Moreover, researchers suggest the integration of software tools that leverage existing databases and algorithms to process the selected design parameters into meaningful LCA results. These tools can quickly provide estimates - though less accurate - by utilizing pre-existing environmental impact factors associated with similar systems or technologies, which have been compiled in LCA databases. This reduces the labor involved in manually calculating and compiling LCA data through every phase of the product lifecycle (Sharma et al., 2019; Szilágyi & Gróf, 2020).

Such advancements are instrumental for policymakers and engineers who require timely data to make informed decisions regarding the deployment and regulation of renewable energy technologies.

Recommendation: the most environmentally influential technical design parameters should be identified, along with the relationship with each other - depending on relevant scenarios and impacts.

Communication of the results

Full LCA results can be complex and overwhelming for non-experts, due to the wide range and scale of environmental impacts involved. To improve understanding and accessibility, efforts have been made to translate these results into more user-friendly formats, such as eco-labels. One example is the "Planet Score," originally developed for the garment industry, but potentially adaptable for quickly communicating the environmental performance of energy storage technologies as well.

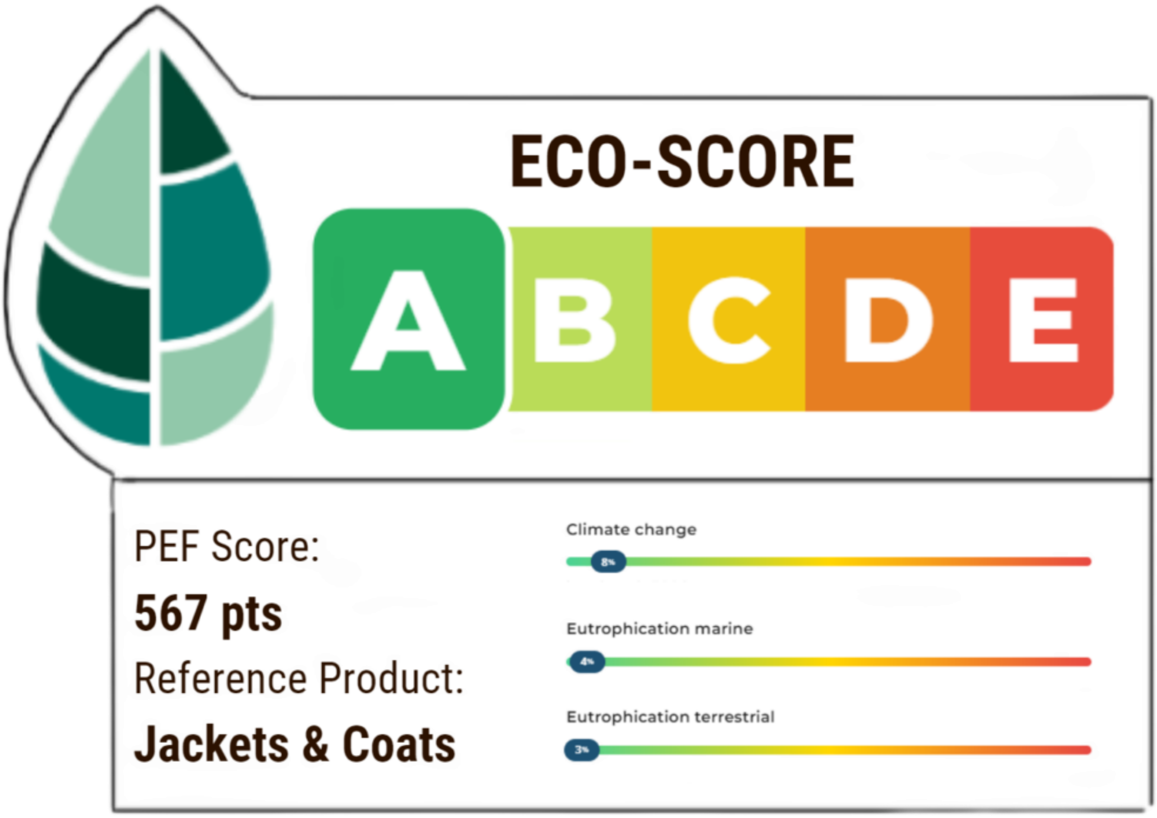

Figure 5. The planet score. Source: https://www.planet-score.org/en/

To determine a final rating (e.g., A - F), the normalization and weighting approach from the Environmental Footprint (EF) method can be used, as it produces a single aggregated score. Additional impact categories can be visually represented as sliders on the label, but their selection should be made after all five shortlisted energy storage technologies have been evaluated in the StoreMore project. This will allow for the identification of the most relevant impact areas - such as climate change, resource use and critical materials, or land footprint - to be featured prominently on the label.

Furthermore, there might be correlations among various impact categories, suggesting that a limited subset may be sufficient to convey an overarching picture of environmental impact. A promising methodological advancement involves objective reduction followed by multi-criteria optimization, enabling the selection of a reduced number of impact categories that capture the majority of variance in environmental effects (Sharma et al., 2019).

Summary of the evaluation framework

Evaluation of Local Environmental Aspects

- Shortlisted technologies must be assessed for land use, noise, vibration, water usage, and chemical/fire hazards.
- The use of “go-to” zones (as in the EU’s Renewable Energy Directive) is recommended to simplify permitting by identifying environmentally low-impact zones.

Life Cycle Assessment (LCA):

- Function should be clear but functional unit is the same across all technologies (energy delivered per kWh over a system's life),
- System boundary is cradle-to-gate and follows EN15804 standard with a 1% cut-off threshold for data coverage.
- The Environmental Footprint (EF) 3.1 method is advised for impact assessment, aligning with EU standards.
- Avoided impacts (benefits) like reducing reliance on fossil fuels or stabilizing the grid - should be reported separately to avoid double-counting in LCA models.
- Default European energy mix should be used unless local data is available, and end-of-life impacts should follow the Polluter Pays Principle (PPP). Ecoinvent database is recommended as a background database.
- Clear documentation of assumptions, data quality using pedigree matrices, and sensitivity analysis are essential.

Dissemination:

- To simplify environmental assessments, key design metrics (e.g., roundtrip efficiency, service life) should be identified early. These can help produce quicker estimates using LCA tools.
- Environmental performance results should be made accessible using intuitive formats like "Planet Score"-style eco-labels. These labels would summarize environmental ratings and key impact indicators for each technology.

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