Life Cycle Assessment (LCA) Final Report – StoreMore Project

Flywheel Energy Storage (FES) and Gravity Energy Storage (GES)

Version 1

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1. 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 analyze 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) optimization 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:

- Gravity-Based Storage
- Flywheel Energy Storage
- Hydrogen Energy Storage
- Vanadium Redox Flow Batteries
- 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** established 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** – this work - 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 analyzed 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.

2. Goal and scope definition

The goal and scope definition is the first and foundational phase of a Life Cycle Assessment (LCA), where the purpose of the study is clearly established, along with its intended application and target audience. This phase outlines the system under study, defines the functional unit (a quantified measure of the function that the system provides), and sets the system boundaries, specifying which life cycle stages and processes will be included. It also identifies assumptions, limitations, and the level of detail needed to ensure the results are meaningful and aligned with the study's objectives. This phase ensures transparency and consistency, guiding data collection and interpretation throughout the LCA process [1].

2.1 Goal of the study

The primary goal of this study is to conduct an environmental comparison of two energy storage technologies: flywheel and gravity-based systems. Within the flywheel category, both composite high-speed rotors and steel low-speed rotors are examined. For gravity-based storage, the analysis includes systems using abandoned (legacy) mineshafts and tower structures. The study aims to identify key environmental hotspots within each technology, highlighting the components and processes that contribute most significantly to their environmental impact. This assessment is intended to support eco-design efforts and guide future optimization strategies for more sustainable energy storage solutions. The target audience is decision-makers and the general public in the Danube Region.

2.2 Functional unit

The functional unit is 1 kWh of electricity throughput - i.e. electricity stored and delivered - over the lifetime of the system.

2.3 System boundaries

System boundaries follow the structure set out in the EN15804+A2 standard [2]. All major stages are included, therefore the system boundaries are cradle-to-grave.

According to the Inception Report, 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. Therefore the cut-off value is set to be 1%.

Geographic scope: the production of complex electric components is assumed to be global. Simpler components such as cables, gravel and concrete is assumed to be of European origin. Similarly, the use and end-of-life stages are set in a European context, in alignment with the goals of the StoreMore project.

Temporal scope: the lifetime of the systems are 20-50 years depending on the technology.

The openLCA v2.4.1. is used as the modeling tool, while ecoinvent v3.11 served as the secondary database. In the absence of first-hand data, the foreground system is modeled using literature sources.

2.4 Flywheel Energy Storage

Flywheels store kinetic energy in the form of rotational energy and can provide fast response times in applications such as grid stability and the integration of renewable energy sources. Flywheel energy storage systems (FESS) primarily consist of a rotor (the flywheel), a motor-generator, bearings, and a containment system. The rotor is a heavy, rotating mass—often made from steel or composite materials—that stores energy in the form of kinetic energy when spun at high speeds. The motor-generator converts electrical energy to mechanical energy during charging (spinning the flywheel) and vice versa during discharging. Magnetic or mechanical bearings support the rotor while minimizing friction and wear. The entire assembly is housed in a vacuum-sealed containment system to reduce air resistance and ensure safe operation. The entire system is typically installed in an underground concrete structure and grouped in batches to allow for scalable operation.

According to Rahman et al. [3] Flywheel Energy Storage Systems (FESSs) are classified by their rotational speed: low-speed (LFES) and high-speed (HFES).

- Low-speed FESs generally operate at speeds up to 6,000 RPM and are typically constructed from steel. They can be supported by either magnetic or mechanical bearings.
- In contrast, high-speed FESs reach much higher speeds, up to 100,000 RPM. These systems commonly use carbon fiber and fiberglass for their construction, and they exclusively require magnetic bearings for support.

Regardless of speed, FESSs share several core components:

- Motor/Generator: This electrical machine is responsible for converting electricity into kinetic energy during charging and converting mechanical energy back into electricity during discharge.
- Housing: The housing encases the FESS in a vacuum, maintained by a vacuum pump, to minimize drag. It also serves as a critical safety feature, containing the rotor in the event of a system failure.
- Power Conversion System (PCS): A PCS is essential for converting alternating current (AC) to direct current (DC), DC to AC, or a combination of both, depending on the system's requirements.

Despite the long history of flywheels in various applications, there are only a few examples of their deployment at grid scale as energy storage. As Don Bender, a recognized expert in the field of FES, puts it:

> *"The single overarching challenge facing flywheel technology is the higher cost of a flywheel solution relative to the cost of many competing solutions. Flywheels are a*

> *mature technology with a long history. The constituent materials and components such as high strength steel and composite, motors, power electronics, vacuum systems etc. are also highly mature. As a result, the underlying cost of a flywheel system is reasonably straightforward to forecast once a detailed design is established. Cost trends do not favor flywheels. There is no "Moore's Law" for large mechanical systems. There is no path to drive cost out of a flywheel system that can follow the accelerating downward price trends for batteries. [...] Until effective business models for the deployment of flywheels are developed, they will remain a niche technology solution."* [4]

In their study, Rahman et al compared high-speed and low-speed FES systems from an environmental point of you using a case study for each technology. Rahman et al. previously conducted an environmental comparison of high-speed and low-speed FES systems, using a specific case study for each technology. As there haven't been many new grid-connected FES systems installed since their study, we will utilize the same case studies in this research.

The most well-documented high-speed FES installation is Beacon Power's successful 20 MW demonstration project in the United States, which serves as the first case study for this report.

Figure 1. Beacon Power's Flywheel Energy Storage System

As a representative low-speed FES system, in which the rotor is made of steel, the Minto project from Canada has been selected. This is much smaller installation of only 2MW in size and uses 10 spinning steel flywheels on magnetic bearings. It is constructed by Temporal Power in 2014.

Figure 2. Minto Flywheel Energy Storage System

Table 1. Flywheel energy storage performance indicators

Performance indicator	***Quantity***	***Unit***	***Source***
Reference service life	*20*	*Years*	*[5]*
Number of cycles over the lifetime	*100 000*	-	*[5]*
*Average energy capacity**	*25*	*kWh*	*[5]*
Power rating	*100*	*kW*	*[5]*
Roundtrip efficiency	*85*	*%*	*[5]*
Usable depth of discharge	*50*	*%*	*[6]*
Suitable storage duration	*seconds to hours*		*[5], [6]*
Standby loss	*0.03*	*kWh / kW / h*	*[5]*
Loss of performance over the lifetime	*0.14*	*% / year*	*[6]*

** Average energy capacity refers to the average of the initial capacity and the capacity at the end of-life.*

Primary applications: Frequency regulation, peak shaving, power quality and voltage support

2.5 Lifted-weight Gravity Energy Storage (LWGES)

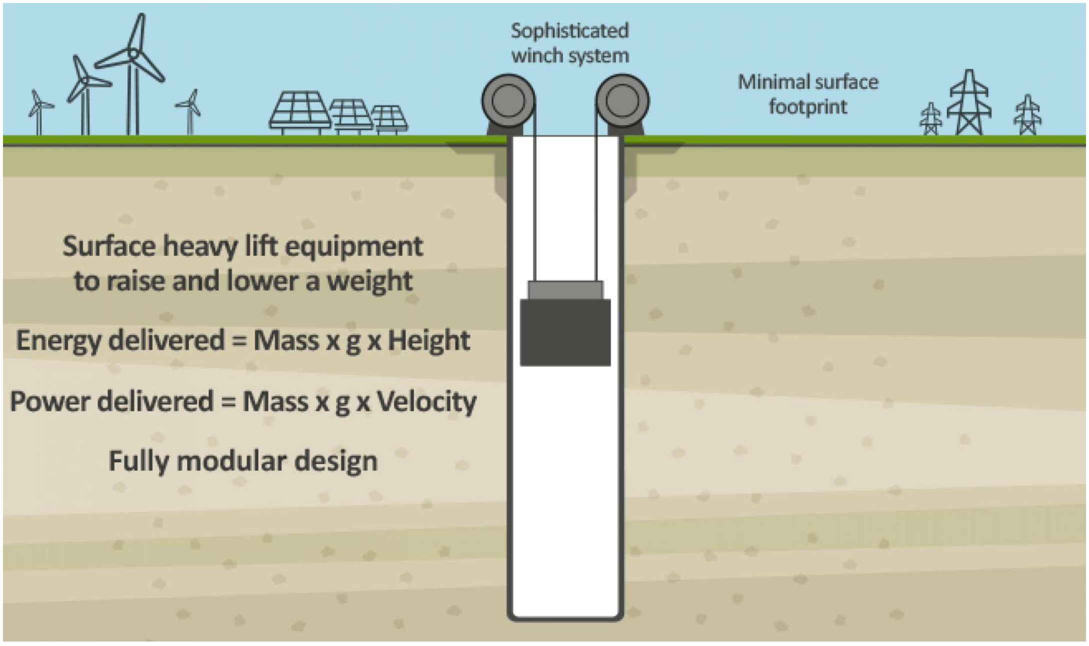
Gravity energy storage (GES) offers a promising solution for large-scale energy storage by harnessing the potential energy of elevated masses. Among the various GES technologies, such as pumped-storage hydroelectricity is the most widely used, but lifted-weight solid gravity energy storage systems are gaining significant attention due to their simplicity and scalability. These systems primarily involve lifting heavy solid masses to a height and then releasing them to generate electricity and can be broadly categorized into three main types:

- Shaft-based systems typically utilize abandoned mine shafts or purpose-built vertical shafts to lift and lower solid blocks.
- Piston-based systems involve hydraulic pistons that lift a heavy mass, often contained within a cylinder, and generate power as it descends.
- Tower-based systems, on the other hand, employ cranes or similar mechanisms to lift and stack solid blocks within or around a tall structure.

In this study, we will elaborate further on the abandoned mineshaft and tower-type solid gravity energy storage systems as these are the closest to real life application.

Abandoned mineshaft gravity energy storage

As of the writing of this report, there are no operational grid-scale mine shaft gravitational energy storage systems. The most advanced initiative to date is GraviStore, developed by the UK-based company Gravitricity. The company has announced several projects slated for completion in 2024, including one at an abandoned copper and zinc mine in Finland with a 530-meter-deep shaft[1], and another in the Czech Republic[7]. However, neither project appears to have been completed yet. Consequently, this report relies heavily on assumptions rather than real-world data to assess the environmental impacts of this technology.



[1] https://www.powerengineeringint.com/energy-storage/gravity-energy-storage-to-bring-new-life-to-finnish-mine/

Figure 3. Draft of Gravitricity's planned GraviStore Gravity Energy Storage

Table 2. Abandoned Mineshaft GES Performance indicators

Performance indicator	*Quantity*	*Unit*	*Source*
Reference service life	*30-50*	*Years*	*[8]*
Maximum number of cycles over the lifetime	*80 000*	-	*own calculation**
*Average energy capacity***	*1*	*MWh*	*[7]*
Power rating	*2*	*MW*	*[7]*
Roundtrip efficiency	*80*	*%*	
Depth of discharge	*100*	*%*	
Suitable storage duration	*seconds to years*		
Standby loss	*0*	*kWh / kW / h*	*[7]*
Capacity degradation	*0*	*% / year*	

** Using 4-hour charge-discharge cycles over 40 years*

*** Average energy capacity refers to the average of the initial capacity and the capacity at the end of-life.*

Tower Gravitational Energy Storage – Energy Vault

As of this report, there is only one prototype-scale Tower Gravitational Energy Storage system exists: a 60-meter-tall unit in Switzerland, completed in 2021 by Energy Vault. On the other hand, they are also nearing completion of their new EVx system in Rudong, China. This commercial, utility-scale system uses a grid-like structure, rather than a crane, to lift approximately 13 000 composite blocks, each weighing around 30 tons. Energy Vault claims these weights will be made from waste materials like fly ash, waste glass fiber from wind turbine blades, and dirt, using their patented pressing technology. The EVx system is designed to be scalable and modular, starting at 10 MW and increasing in 1 MW increments. For this study, we've considered a 20 MW / 80 MWh EVx system [9], [10], [11], [12].

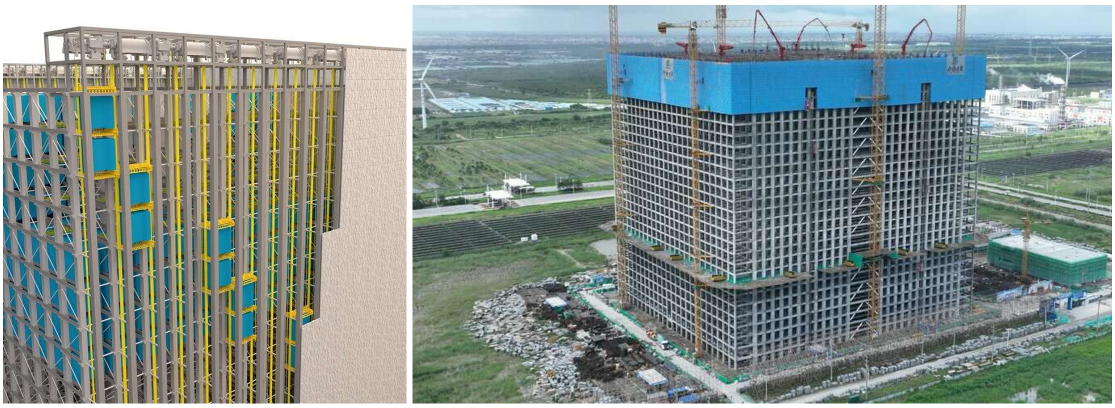


Figure 4. Energy Vault's planned G-Vault Gravity Energy Storage cross-section (left) and their 25 MW 100 MWh GES in Rudong, China under construction (right)

Table 3. Tower Gravity Energy Storage performance indicators

Performance indicator	***Quantity***	***Unit***	***Source***
Reference service life	*35*	*Years*	*[10]*
Maximum number of cycles over lifetime	*35 000*	-	*own calculation**
*Average energy capacity***	*80*	*MWh*	*[11]*
Power rating	*20*	*MW*	*[10]*
Roundtrip efficiency	*80*	*%*	*[10]*
Depth of discharge	*100*	*%*	*[10]*
Suitable storage duration	*seconds to years*		*[10]*
Standby loss	*0*	*kWh / kW / h*	*[10]*
Storage degradation	*0*	*% / year*	*[10]*

** Using 8-hour charge-discharge cycles over 35 years*
*** Average energy capacity refers to the average of the initial capacity and the capacity at the end of-life.*

Primary applications: Renewable energy integration and smoothing, peak shaving

3. Life Cycle Inventory (LCI)

3.1 Flywheel Energy Storage

In the inventory analysis, all the energy and material input requirements and the corresponding outputs at each stage of the FESs lifecycle are calculated for the 100 kW/ 25 kWh FES systems.

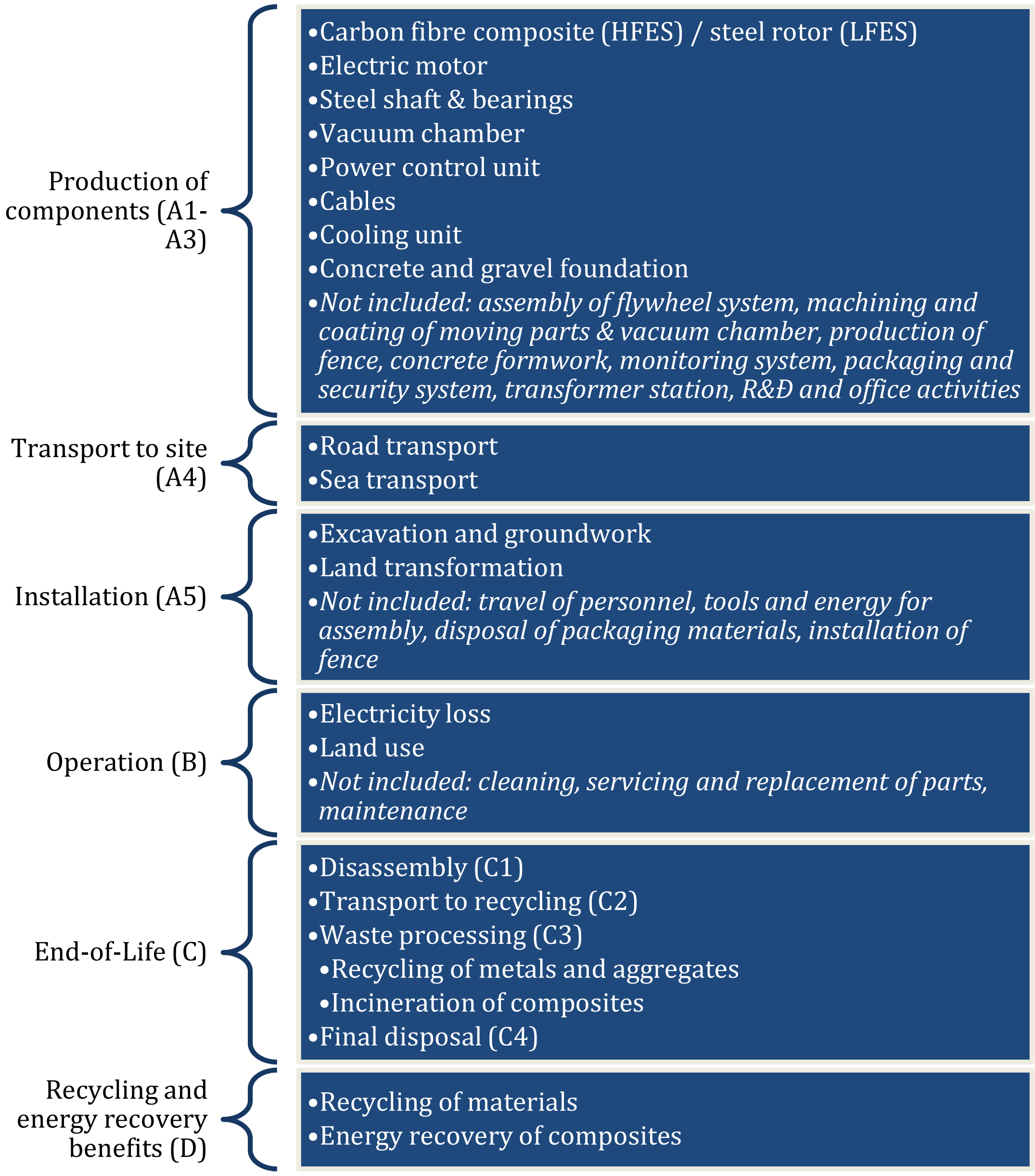


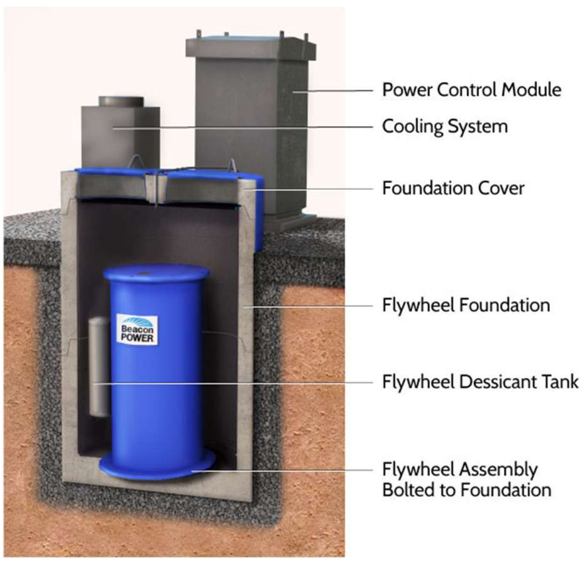
Figure 5. System boundaries of the flywheel energy storage system

Production of components (A1-A3)

Many assumptions had to be made during the data collection as there are no life cycle inventory or bill of materials publicly available for either FES system. We mostly used the information from Rahman et al [6] study where it was possible and completed the missing information by making estimates based on the available images.

Assumptions:

- We assumed the vacuum chamber has a 50 mm thickness to withstand atmospheric pressure following Rahman et al. [6]. Using a geometry of around 250 cm height and 125 cm diameter, the weight of the chamber is around 3000 kg, which is in agreement with that of Rahman et al.'s.
- Concrete foundation is assumed to be 3.5 m tall concrete tube with a diameter of 2.5 m, wall thickness is 20 cm, top and bottom slab thickness is 40 cm, weighing around 20 t.
- Only the total weight of the main equipment were found, thus the weight and materials of the parts (rotor, hub, bearing, motor, shaft) had to be estimated (see Table 4).
- The assembly of the flywheel system, coating of moving parts & vacuum chamber, production of fence, concrete formwork, monitoring system, packaging and security system, transformer station, R&Đ and office activities and fencing is assumed to be negligible.



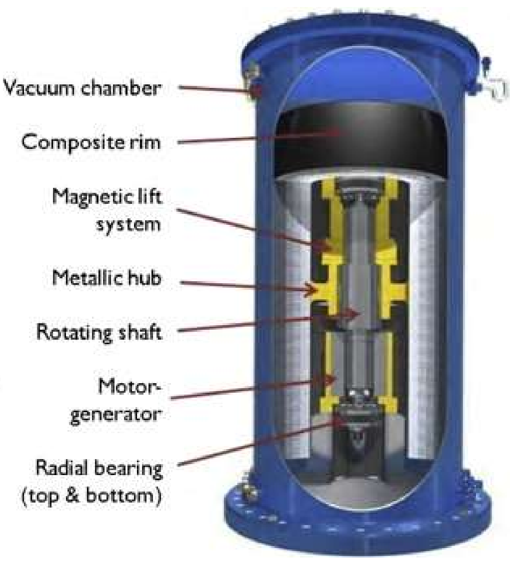


Figure 6. High-Speed Flywheel Energy Storage (HFES) cross section [5]

Table 4. LCI of the production of components

Input	HFES	LFES	Unit	ecoinvent dataset
Carbon and glass fiber composite flywheel rotor (208 cm height, 120 cm diameter)	1200	-	kg	-
of which glass fiber	*200*	-	*kg*	market for glass fibre reinforced plastic, polyester resin, hand lay-up, GLO
of which carbon fiber	*1000*	-	*kg*	market for carbon fibre reinforced plastic, injection moulded, GLO
Stainless steel flywheel rotor, shaft and bearing	300	6000	kg	market for steel, chromium steel 18/8, hot rolled, GLO
Production of chromium steel parts	300	6000	kg	market for metal working, average for chromium steel product manufacturing, GLO
Permanent magnet synchronous motor	300	300	kg	market for electric motor, electric passenger car, GLO
Concrete foundation	10	10	m3	market for concrete slab, RoW
Gravel for foundation (10 m3) and 15 cm x 50m2 area, around 15 m3 in total	25	25	t	market for gravel, crushed, RoW
Steel vacuum chamber, shaft and hub	3000	3200	kg	market for steel, unalloyed, GLO
Production of steel parts	3000	3200	kg	market for metal working, average for steel product manufacturing, GLO
Power control module	400	400	kg	market for electronics, for control units, GLO
Cooling system (100 kg)	0.25	0.25	unit	market for refrigeration machine, R134a as refrigerant, GLO
40-foot steel container	0.1	0.1	unit	market for intermodal shipping container, 40-foot, GLO
Electric cables	200	200	kg	market for cable, unspecified, GLO

Transport to site (A4)

The origin of the equipment is assumed to be from another continent (i.e. US or East-Asia) while gravel and concrete is assumed to be sourced locally.

Table 5. LCI of transport (A4)

Transport	Mode	Distance (km)	ecoinvent dataset
Electric and mechanical equipment (HFES: 6 t, LFES: 11 t)	Road	2000	market group for transport, freight, lorry, diesel, unspecified, GLO
Electric and mechanical equipment (HFES: 6 t, LFES: 11 t)	Sea	10000	transport, freight, sea, container ship, heavy fuel oil, GLO
Gravel & concrete (28 t)	Road	100	market for transport, freight, lorry, unspecified, RER

Installation (A5)

For the installation, the excavation of a 20 m3 hole and leveling & spreading gravel across a 50 m2 area per flywheel unit has been considered. Based on aerial photos, the 200 flywheels in the demonstration site occupies around 1 ha area, thus for a single unit, it equals to 10000 m2 / 200 units = 50 m2 of land transformation. As the original land use of the area can be various, we assumed forest cover.

Travel of personnel, tools and energy for assembly, disposal of packaging materials, installation of fence are all assumed to be negligible.

Table 6. LCI of installation (A5)

Input	Quantity	Unit	ecoinvent dataset
Excavation	25	m3	market for excavation, hydraulic digger, RER
Land transformation	50	m2	*Transformation, from forest, unspecified (elementary flow)* *Transformation, to industrial area (elementary flow)*

Operation (B)

In three months of operation, Beacon Power's 20 MW HFES installation delivered a cumulative of 11.655 GWh of energy [13], while for the Minto project for which no such data was available it is assumed be the same. With a roundtrip efficiency of 85% and scaling it to 20 years and one 100 kW flywheel unit, the estimated total energy loss is around **700 MWh** per flywheel unit over its 20 years lifetime which includes transformation losses and degradation of storage. To account for this loss, European electricity grid mix is used.

Cumulated land use for 20 years equals to 50 m2 x 20 years = 1000 m2*years.

It is mentioned that the vacuum pump is expected to be replaced at least once or every 10 years during the operational lifetime of the system.[6]

Table 7. LCI of operation and maintenance (A5)

Input	Quantity	Unit	ecoinvent dataset
Energy loss	700	MWh	market group for electricity, medium voltage - RER
Replacement vacuum pump	0.25	unit	market for refrigeration machine, R134a as refrigerant, GLO
Land use	1000	m2*year	*Occupation, industrial area (elementary flow)*
Energy storage provided	4 662	GWh	*NA*

Maintenance, servicing and replacement of parts are neglected. In normal conditions no emissions can be expected, only a slight noise of around 50 dBA.[5]

End of life (C)

Disassembly is assumed to be the same as the installation in terms of machinery and the distance from a recycling facility is 100 km. Concrete is reused as backfilling material after crushing similarly to gravel and a reinforcement steel content of 3% is assumed . A 90% recycling rate is applied to metal parts, and 90% incineration rate for plastics. All other residues and the glass fiber part is assumed to be landfilled.

Table 8. LCI of end-of-life (C)

Input	HFES	LFES	Unit	ecoinvent dataset
Disassembly (C1)	25	25	m3	market for excavation, hydraulic digger, RER
Transport to recycling facility (C2)	5400	6000	t*km	market for transport, freight, lorry, unspecified, RER
Recycling of steel (C3)	4	9.5	t	treatment of waste bulk iron, excluding reinforcement, sorting, Europe without Switzerland
Recycling of cables (C3)	200	200	kg	market for waste electric wiring, RoW
Treatment of plastics and carbon fibre (C3)	600	0	kg	market for waste plastic, industrial electronics, RoW
Recycling of concrete (C3)	24	24	t	treatment of waste reinforced concrete, recycling, RER
Landfill of glass fibre and recycling residues (C4)	600	1100	kg	treatment of inert waste, sanitary landfill, RER
Treatment of waste power control module	400	400	kg	market for used industrial electronic device, RoW

Benefits from steel recycling (D)	-4.2	-9.1	t	market for iron scrap, sorted, pressed
Benefits from copper recycling (D)	-160	-160	kg	market for copper scrap, sorted, pressed, GLO

3.2 Legacy Mineshaft Gravity Energy Storage (SGES)

In the inventory analysis, all the energy and material input requirements and the corresponding outputs at each stage of the SGES lifecycle are calculated.

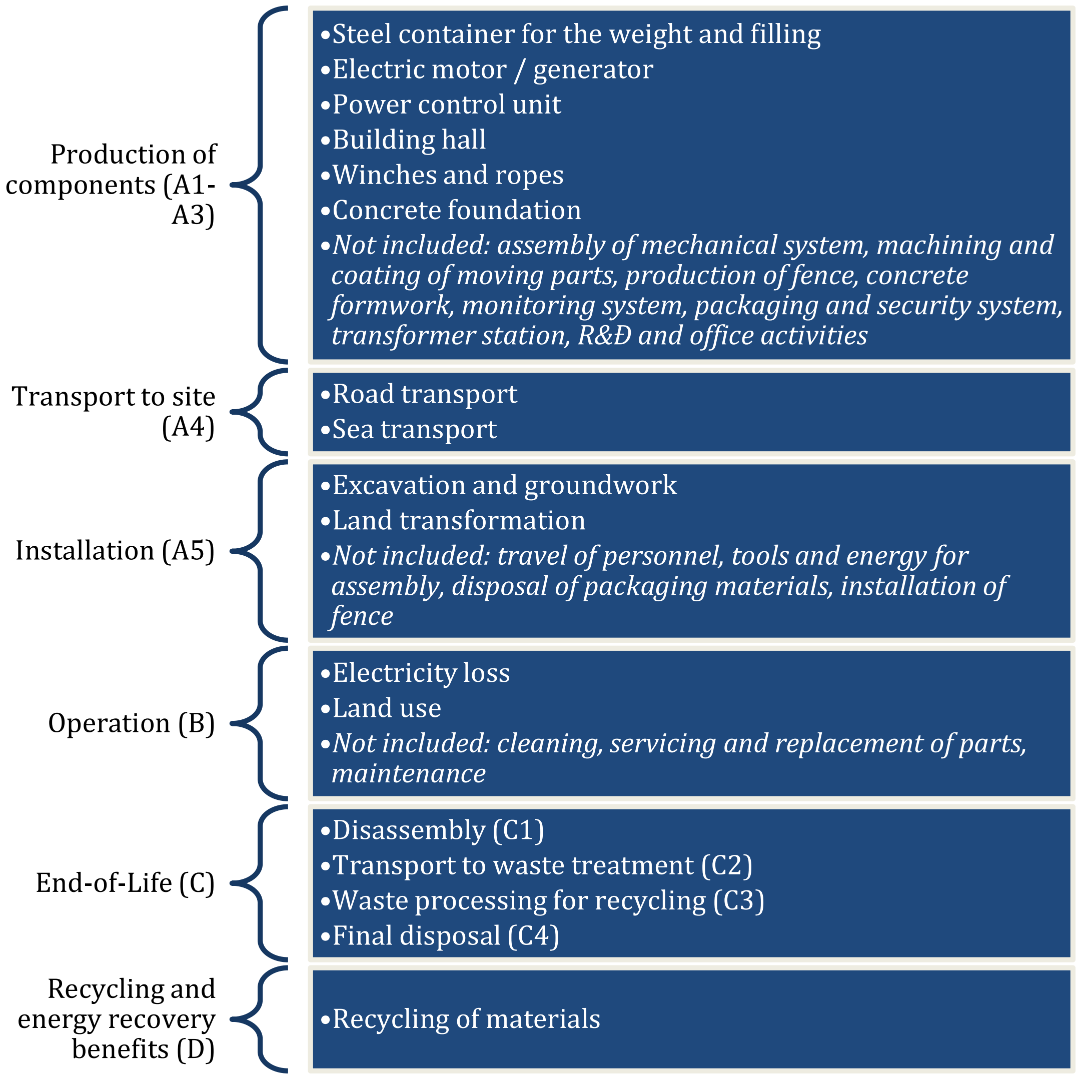


Figure 7. System boundaries of the SGES system

Production of components (A1-A3)

Many assumptions had to be made during the data collection as there are no life cycle inventory or bill of materials publicly available for the GraviStore GES. On the website of the company some of the main planned design parameters of the system can be found though [7].

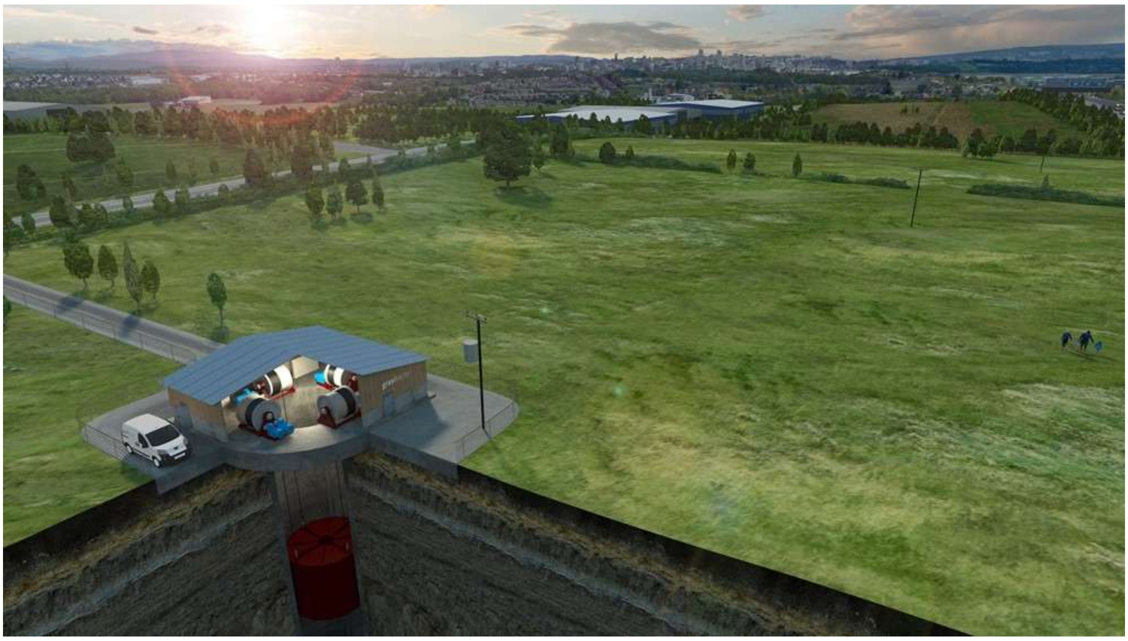


Figure 8. Beacon Power's Flywheel Energy Storage System cross section

- In order to deliver the 2 MWh energy storage with a 1000 metric ton suspended weight and the 80% efficiency, approximately a 917 m deep mineshaft is needed, which is realistic, as the Darkov mine in Czechia has two 1000 m deep mineshafts.
- A steel reinforced concrete foundation is assumed to be 1m thick with an area of around 500 m2 (see Figure 8.) amounting to be 500 m3.
- The suspended 1000 ton weight is also assumed to be of a cylindrical container made of 50 mm steel with a height of 6 m and a diameter of 8 m, **weighing around 100 ton** and containing 900 ton of inert material with a bulk density of 3000 kg / m3 such as iron ore.
- The weight of the steel cables required to lift 1000 tons from 1000 meters depth (with safety factor 5) is assumed to be around **250 metric tons.**
- We assume that there are four 0.5 MW generators each weighing around **2.5 tons.**
- Drum and frame is estimated to weigh around 15 tons each and there are four of them. Gearboxes and brakes add around 5 tons each, which equals to around **80 tons of steel in total.**

- Power electronics are assumed to be around 4 tons for the whole system.
- An industrial hall of around 200 m2 with a height of 5 m is assumed to provide shelter for the system on the surface.

All other parts of system, the energy and materials needed for the assembly, machining and coating of winch parts, production of fence, concrete formwork, monitoring system, packaging and security system, transformer station, R&Đ and office activities are all assumed to be negligible.

Table 9. LCI of the production of components

Input	Quantity	Unit	ecoinvent dataset
Reinforced concrete foundation	500	m3	market for concrete slab, RoW
Motor / generator	10	t	market for electric motor, electric passenger car, GLO
Steel for ropes and mechanical parts and the suspended weight	430	t	market for steel, unalloyed, GLO
Industrial building	200	m2	market for building, hall, steel construction, GLO
Power control module	4000	kg	market for electronics, for control units, GLO
Steel parts manufacturing	430	t	market for metal working, average for steel product manufacturing, GLO

Transport to site (A4)

The origin of the mechanical and electric equipment is assumed to be from another continent (i.e. US or East-Asia) while concrete and construction materials for the building are assumed to be sourced locally.

Table 10. LCI of transport (A4)

Item	Mode	Distance (km)	ecoinvent dataset
Electric and mechanical equipment (500 t)	Road	2000	market group for transport, freight, lorry, diesel, unspecified, GLO
Electric and mechanical equipment (500 t)	Sea	10000	transport, freight, sea, container ship, heavy fuel oil, GLO
Concrete and building materials (2500 t)	Road	100	market for transport, freight, lorry, unspecified, RER

Installation (A5)

For the installation, the excavation of a 500 m3 hole has been considered. Based on images the facility occupies around 200 m2. As the original land use of the area can be various, we assumed forest cover.

Travel of personnel, tools and energy for assembly, disposal of packaging materials, installation of fence are all assumed to be negligible.

Table 11. LCI of installation (A5)

Input	Quantity	Unit	ecoinvent dataset
Excavation	500	m3	market for excavation, hydraulic digger
Land transformation	200	m2	*Transformation, from forest, unspecified* *Transformation, to industrial area*

Operation (B)

There are only one pilot-scale mineshaft gravity energy storage exist, and there is no mention of energy storage provided over time. If it completes the maximum 200 000 cycles claimed by the manufacturer over 40 years, it would equal to **400 000 MWh** per 1 MWh unit.

With an estimated roundtrip efficiency of 80% and scaling it to 40 years and one 1 MW GES unit, the estimated total energy loss will be around **80 000 MWh** per unit over its lifetime which includes transformation losses. To account for this loss, European electricity grid mix is used.

Cumulated land use for 40 years equals to 200 m2 x 40 years = 8000 m2*years.

Table 12. LCI of operation (A5)

Input	Quantity	Unit	ecoinvent dataset
Energy loss	80	GWh	market group for electricity, medium voltage - Europe without Switzerland
Land use	8000	m2*year	*Occupation, industrial area (elementary flow)*
Energy storage provided	400	GWh	*NA*

Maintenance, servicing and replacement of parts are neglected. In normal conditions no emissions can be expected.

End of life (C)

Disassembly is assumed to be the same as the installation in terms of machinery and the distance from a recycling facility is 50 km. Concrete is reused as backfilling material after crushing. A 90% recycling rate is applied to metal parts. All other parts are assumed to be landfilled.

Table 13. LCI of end-of-life (C)

Input	Quantity	Unit	ecoinvent dataset
Disassembly (C1)	500	m3	market for excavation, hydraulic digger
Transport to recycling facility (C2)	130 000	t*km	market group for transport, freight, lorry, diesel, unspecified
Recycling of steel (C3)	440	t	treatment of waste bulk iron, excluding reinforcement, sorting, Europe without Switzerland
Energy recovery of electronic parts (C3)	4000	kg	market for used industrial electronic device, RoW
Recycling of concrete (C3)	1200	t	treatment of waste reinforced concrete, recycling, RER
Benefits from steel recycling (D)	-400	t	market for iron scrap, sorted, pressed
Landfill of residues (C4)	50	t	treatment of inert waste, sanitary landfill, RER

3.3 Tower Gravity Energy Storage (TGES)

In the inventory analysis, all the energy and material input requirements and the corresponding outputs at each stage of the TGES lifecycle are calculated.

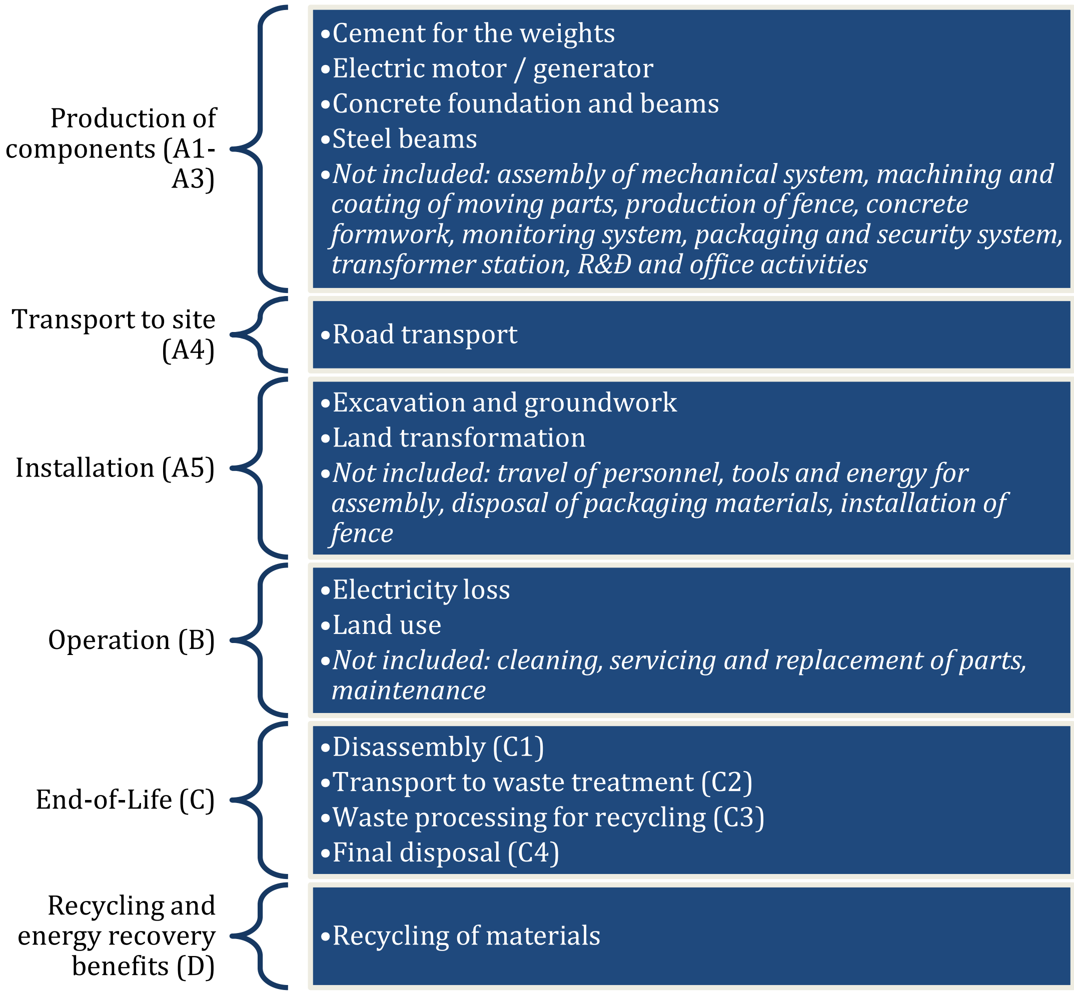


Figure 9. System boundaries of the TGES system

Production of components (A1-A3)

Many assumptions had to be made during the data collection as there are no life cycle inventory or bill of materials publicly available for the GraviStore GES. On the website of the company some of the main planned design parameters of the system can be found, though.

Figure 10. Energy Vault's Gravity Energy Storage System

- The tower has height of 120 m, and an area of 80 m x 86 m, while using 78 000 tons of weights [10], [11]. Based on the available images (see Figure 8), we can assume that around 10% the tower's total envelope volume is structural material, which would be around 40 000 m3. If 95% of the volume is concrete, while the rest is steel, we would need around 38 000 m3 concrete and 2000 m3 tons of steel. Assuming a 2400 kg / m3 density for concrete and 7850 kg / km3 density for steel, the whole structure needs around 90 000 tons of concrete and 16 000 tons of steel for the building. For such a building a substantial amount of reinforced concrete is needed for the foundation as well. As a rule of thumb we can assume that around ¼ of the weight of the structure (around 110 000 tons in total with weights) is needed for the foundation, thus around 28 000 tons of which around 3% is the amount of reinforcing steel. Therefore, the foundation adds an extra 1000 tons of steel and 27 000 tons of concrete to the material requirements, in total amounting to 117 000 tons of concrete and 17 000 tons of steel. Rounding it up and taking into account the steel needs for the machinery, **our assumption is that 120 000 tons of concrete and 20 000 tons of steel is used for the 20 MWh storage in total.**
- The **solid block weights** can be made from a variety of materials including local soil, bottom ash and waste glass fibers from decommissioned wind turbine blades [9] There is no public information is available on the typical composition of blocks or the binder material. It is estimated that **10% cement content** is needed the 8 MPa compressive strength claimed by the company [12], based on a study that investigated the production of stabilized earths blocks using fly ash and cement [14]. Production of weights is thus assumed to be the forming and compacting of such waste materials.

- We assume that there are twenty 1 MW motors / generators weighing around **5 tons each.**

All other parts of system, the energy and materials needed for the assembly, machining and coating of winch parts, production of fence, concrete formwork, monitoring system, packaging and security system, transformer station, R&Đ and office activities are assumed to be negligible.

Table 14. LCI of the production of components

Input	Quantity	Unit	ecoinvent dataset
Concrete	50 000	m3	market for concrete slab, RoW
Steel	20 000	t	market for steel, unalloyed, GLO
Manufacturing steel parts	20 000	t	market for metal working, average for steel product manufacturing, GLO
Cement for weight blocks	8 000	t	cement, all types to generic market for cement, unspecified - Europe without Switzerland
Motors / generators	100	t	market for electric motor, electric passenger car, GLO

Transport to site (A4)

Based on the steel production map of Europe[2] 500 km average distance is assumed for the steel parts as well as the for the cement that is needed for the solid weight blocks. Concrete and the bulk waste materials for the solid weight blocks are assumed to be sourced from much closer distance of 50 km. Transport of all other materials is considered to be negligible.

Table 15. LCI of transport (A4)

Item	Mode	Distance (km)	ecoinvent dataset
Steel, motors & cement (28 000 t)	Road	500	market for transport, freight, lorry, unspecified, RER
Concrete + waste materials for the weights (190 000 t)	Road	50	market for transport, freight, lorry, unspecified, RER

Construction (A5)

For the construction, the excavation of a 10 000 m3 hole has been considered. Based on the specification, the facility occupies around 1 ha area. As the original land use of the area can be various, we assumed forest cover.

[2] https://www.eurofer.eu/assets/Uploads/Map-20191113_Eurofer_SteelIndustry_Rev3-has-stainless.pdf

There were no information available on the machinery, energy use and emissions for erecting the structure and the use of hydraulic press to fabricate the solid weight blocks.

Travel of personnel, , disposal of packaging materials, installation of fence are all assumed to be negligible.

Table 16. LCI of installation (A5)

Input	Quantity	Unit	ecoinvent dataset
Excavation	10 000	m3	market for excavation, hydraulic digger
Land transformation	1	ha	*Transformation, from forest, unspecified* *Transformation, to industrial area*

Operation (B)

There are only one pilot-scale tower gravity energy storage exist, and there is no mention of energy storage provided over time. Assuming a maximum 50 000 charge-discharge cycles that is possible by dividing the 35 years lifetime with the 4-hour discharge time, the total amount of electricity provided by the system equals to **1000 GWh** per 20 MWh unit.

Similarly, with an estimated roundtrip efficiency of 80%, the estimated total energy loss will be around **200 GWh** per unit over its lifetime which includes transformation losses. To account for this loss, European electricity grid mix is used.

Cumulated land use for 35 years equals to 1 ha x 35 years = 35 ha*years.

Table 17. LCI of operation

Input	Quantity	Unit	ecoinvent dataset
Energy loss	200	GWh	market group for electricity, medium voltage - Europe without Switzerland
Land use	35	ha*year	*Occupation, industrial area (elementary flow)*

Maintenance, servicing and replacement of parts are neglected. In normal conditions no emissions can be expected, only a slight noise of around 50 dBA.[5]

End of life (C)

Disassembly is assumed to be the same as the installation in terms of machinery and the distance from a recycling facility is 50 km. Concrete is reused as backfilling material after crushing. A 90% recycling rate is applied to metal parts. All other parts are assumed to be landfilled.

Table 18. LCI of end-of-life (C)

Input	Quantity	Unit	ecoinvent dataset
Disassembly (C1)	500	m3	market for excavation, hydraulic digger
Transport to recycling facility (C2)	119 000	kt*km	market group for transport, freight, lorry, diesel, unspecified

Recycling of steel (C3)	20 000	t	treatment of waste bulk iron, excluding reinforcement, sorting, Europe without Switzerland
Recycling of concrete (C3)	120 000	t	treatment of waste reinforced concrete, recycling, RER
Benefits from steel recycling (D)	18 000	t	market for iron scrap, sorted, pressed
Landfill of residues (C4)	2000	t	treatment of inert waste, sanitary landfill, RER

4. Local environmental impacts and hazards

As outlined in the Inception Report, a more complete view on environmental impact is required besides lifecycle impacts.

Table 19. Local environmental impacts of the selected energy storage technologies

	Flywheel ES	Mineshaft GES	Tower GES
Water use	Not relevant	Not relevant	Not relevant
Land use	2 m^2 / kWh	0.2 m^2 / kWh	0.5 m^2 / kWh
Pollution	Insignificant	Insignificant	Insignificant
Other	Noise	Insignificant	Large structure, visual disturbance, noise
Recommended "Go-to" zones	Existing battery or renewable energy installations	Available mineshafts	Industrial area, brownfields

Water use is not a relevant concern for any of the systems, and pollution can be considered insignificant as well. In terms of land use, flywheel systems require the most space per unit of storage capacity (2 m^2/kWh), followed by tower GES (0.5 m^2/kWh) and mineshaft GES (0.2 m^2/kWh), reflecting the compactness of underground storage. While noise is noted as a minor issue for flywheels and towers, the tower system also raises concerns related to its large physical appearance and visual impact. Recommended deployment zones vary by system: flywheels are best suited for locations with existing battery or renewable energy infrastructure, mineshaft systems are ideal for areas with disused mining shafts, and tower systems are most appropriate in industrial zones or brownfield sites where visual and spatial disruptions are less problematic.

5. Life Cycle Impact Assessment (LCIA)

The LCIA is the third phase of a life cycle assessment (LCA), in which the potential environmental impacts of a product or system are evaluated based on the inventory data collected in the previous phase. In LCIA, the inputs and outputs from the secondary datasets, such as emissions, resource use, and waste, from the life cycle inventory are classified into impact categories (e.g., climate change, acidification, eutrophication, resource depletion). These flows are then characterized to quantify their contribution to each category, using scientifically established models. In this study, following the Inception Report, the EF3.1 indicators are adopted as described in the EN15804 standard [2]

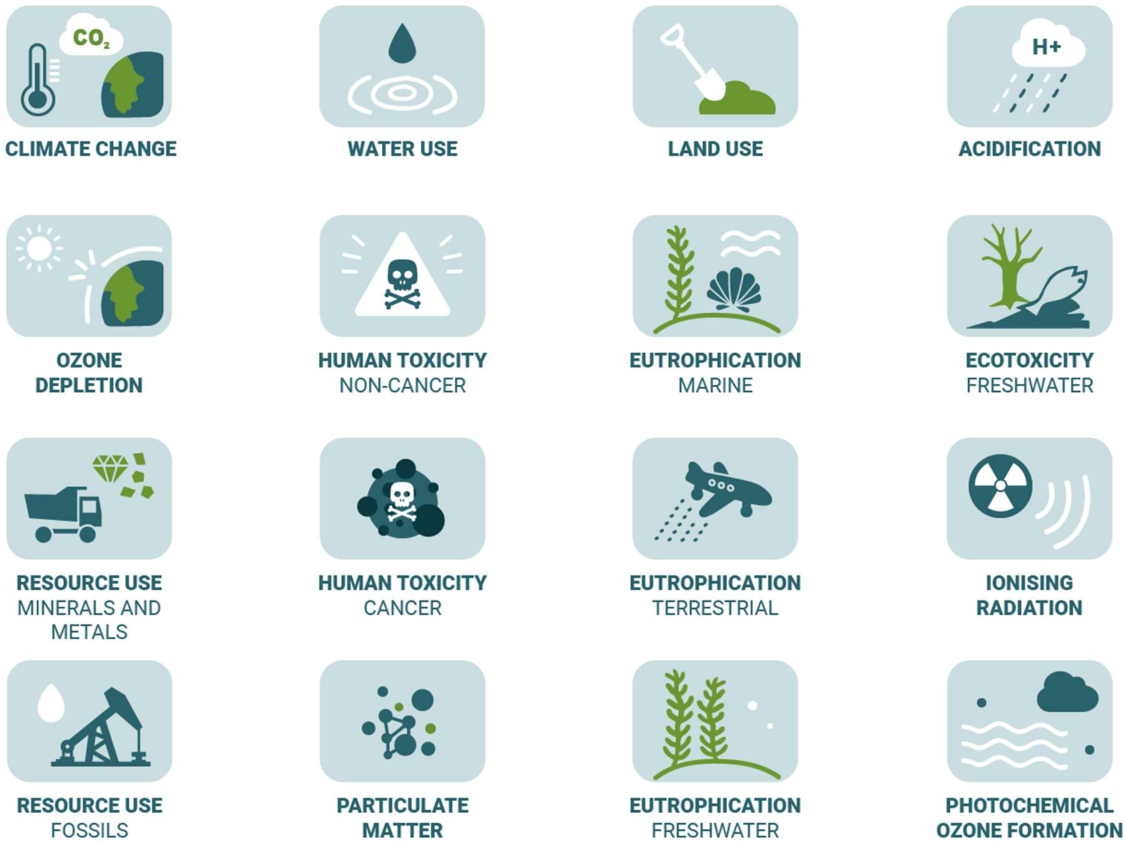


Figure 11. Visual representation of the 16 midpoint impact categories in the EF 3.1 method

Detailed LCIA results along with the optional resource use and output indicators described according to the EN15804 standard can be found in the Annex.

6. Interpretation

In this chapter, the results of the impact assessment are analyzed to identify key environmental hotspots and the most significant impact categories. First, normalization and weighting are applied to determine overall impact scores, with a focus on different life cycle stages and processes. A significance analysis is then conducted to highlight the most influential processes in each technology. Finally, a sensitivity analysis is performed using alternative scenarios to assess how changes in specific assumptions or parameters affect the results.

6.1 Normalized and weighted results

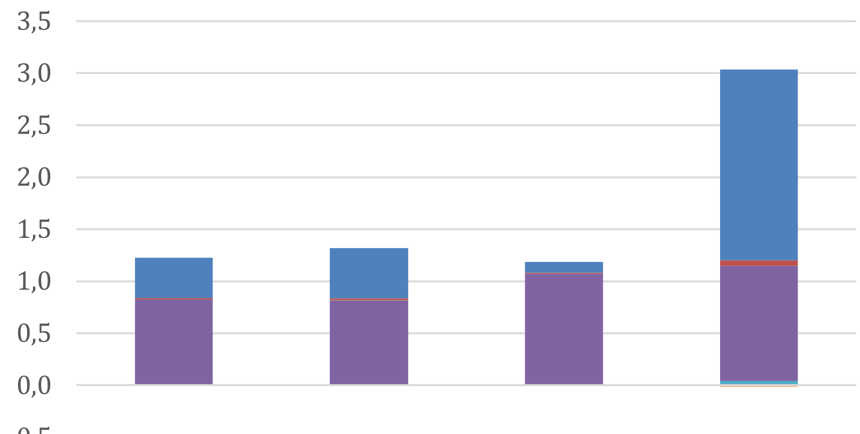
Using the default environmental footprint normalization and weighting factors [15], we can calculate the Product Environmental Footprint (PEF) score of each technology (see Figure 12).

Table 20. Normalisation and weighting factors [15]

Impact categories	Normalisation Factor Unit	Normalisation Factor	Weighting Factor [%]
Acidification	mol H+ eq./person	5.56E+01	6.20%
Climate change	kg CO_2 eq./person	7.55E+03	21.06%
Ecotoxicity, freshwater	CTUe/person	5.67E+04	1.92%
EF-particulate matter	disease incidences/person	5.95E-04	8.96%
Eutrophication, freshwater	kg P eq./person	1.61E+00	2.80%
Eutrophication, marine	kg N eq./person	1.95E+01	2.96%
Eutrophication, terrestrial	mol N eq./person	1.77E+02	3.71%
Human toxicity, cancer	CTUh/person	1.73E-05	2.13%
Human toxicity, non-cancer	CTUh/person	1.29E-04	1.84%
Ionising radiation	kBq U-235 eq./person	4.22E+03	5.01%
Land use*	pt/person	8.19E+05	7.94%
Ozone depletion	kg CFC-11 eq./person	5.23E-02	6.31%
Photochemical ozone formation	kg NMVOC eq./person	4.09E+01	4.78%
Resource depletion, fossils	MJ/person	6.50E+04	8.32%
Resource depletion, minerals and metals	kg Sb eq./person	6.36E-02	7.55%
Water use*	m^3 water eq of deprived water/person	1.15E+04	8.51%

First of all, it is evident that tower gravity energy storage appears to be the least environmentally friendly option compared to the other technologies. Both types of flywheel systems - whether high-speed with a composite rotor or low-speed with a steel rotor – as well as the legacy mineshaft GES have approximately half the Product Environmental

Footprint (PEF) score of the tower gravity system. From an environmental perspective, there is little difference between the two flywheel designs.



	High-Speed Flywheel	Low-Speed Flywheel	Mineshaft Gravity	Tower Gravity
Production (A1-A3)	3,89E-01	4,80E-01	1,05E-01	1,83E+00
Transport (A4)	9,71E-03	1,67E-02	9,52E-03	5,18E-02
Installation (A5)	6,49E-04	6,49E-04	4,09E-05	6,58E-04
Use (B)	8,18E-01	8,14E-01	1,07E+00	1,11E+00
End of life (C1-C4)	7,66E-03	3,48E-03	6,65E-04	3,92E-02
Recycling (D)	-7,56E-04	-1,61E-03	-8,17E-04	-1,47E-02

Figure 12. PEF score by technology and lifecycle stage per MWh

Second, the use stage energy loss dominates the lifecycle impacts of the selected technologies, except Tower Gravity Storage, where the majority of impacts are linked to the material production. This leads us to our first conclusion that the source of electricity that is used to charge the batteries matters a lot and require careful evaluation.

Leaving out the use stage, the production of components are the most significant contributor to the overall PEF score with more than 90% share across technologies (see Figure 13). Other stages, such as transport, installation, disassembly and end-of-life treatment contribute little to the overall impacts while recycling brings almost negligible benefit to the overall picture.

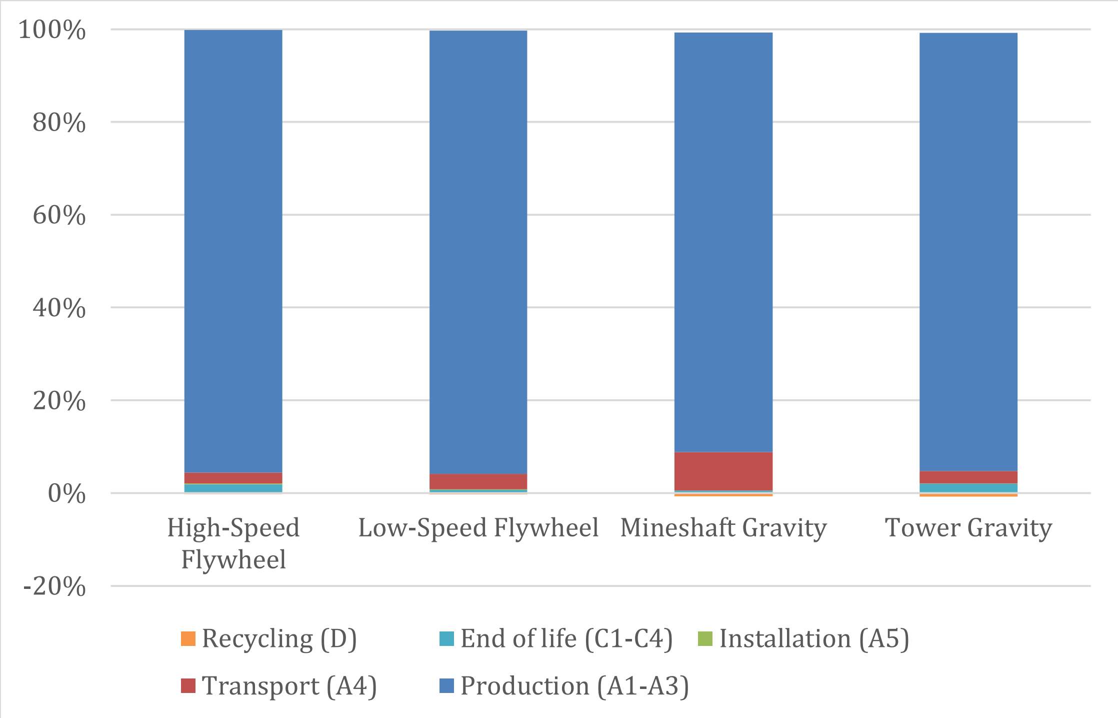


Figure 13. Share of lifecycle stages to the overall PEF score by technology without use stage

After applying the weighting factors, it becomes clear that the most relevant environmental impact categories are global warming (climate change) and the use of abiotic resources (see Figure 14). These two, along with freshwater eutrophication, together account for more than two-thirds of the total environmental impact across all four technologies. Particulate matter also contributes significantly, but its impact is notable only in the case of the tower gravity energy storage system.

Again, the similarity in environmental impact across the technologies is not surprising, as the majority of these impacts stem from the production of the energy that is ultimately lost during operation. This means that as long as the same type of energy is lost, the environmental impacts remain largely comparable—making roundtrip efficiency a strong indicator or proxy for evaluating environmental performance.

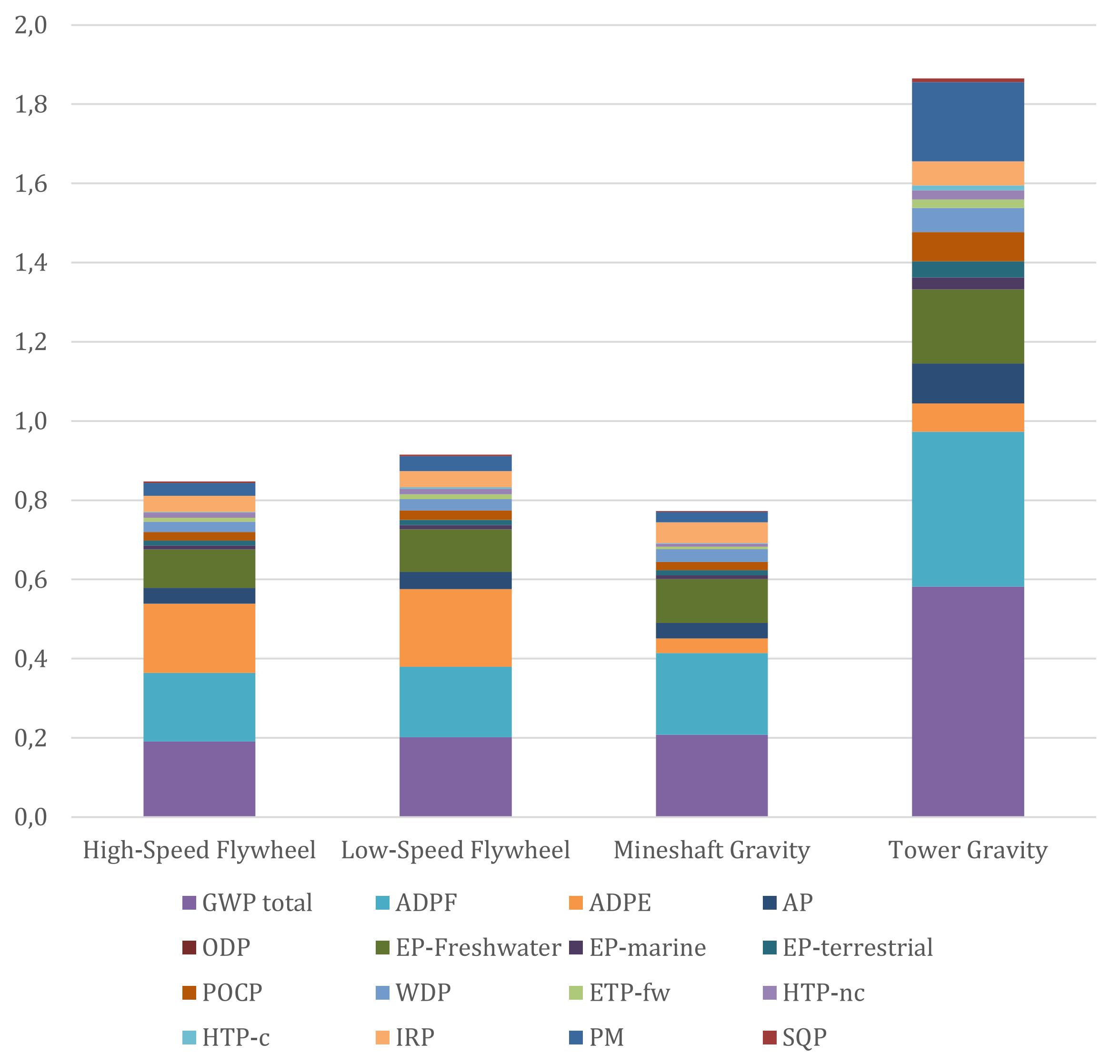


Figure 14. PEF score by technology and impact category per MWh

However, when we exclude the operational phase and focus solely on the product and end-of-life stages (see Figure 15 and 16), a more nuanced picture emerges. Mineshaft gravity storage stands out as the most environmentally friendly option, primarily due to its lower material requirements. It is followed by both flywheel technologies, which are relatively similar in impact, although high-speed composite rotor flywheel emerges a slightly better option. In contrast, tower-based gravity storage shows significantly higher impacts, largely because of the vast quantities of steel and concrete required for its construction—posing a serious environmental challenge. While the difference between the two flywheel technologies remains minimal, the dominant environmental concern at this stage becomes the use of non-fossil abiotic resources. This is especially linked to the use of rare and valuable materials such as gold in power electronics, tellurium in cables and electrical components, and chromium in stainless steel.

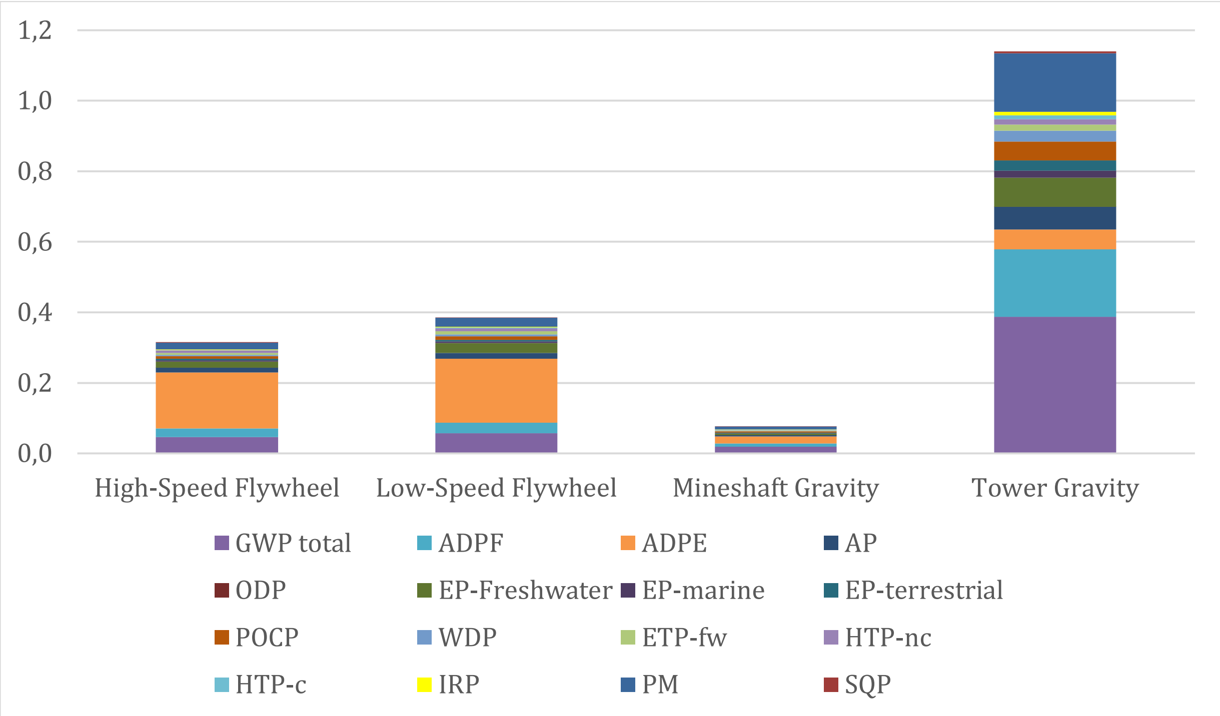


Figure 15. Normalized and weighted results by technology and impact category per MWh without the operation and maintenance (B1-B7) stage

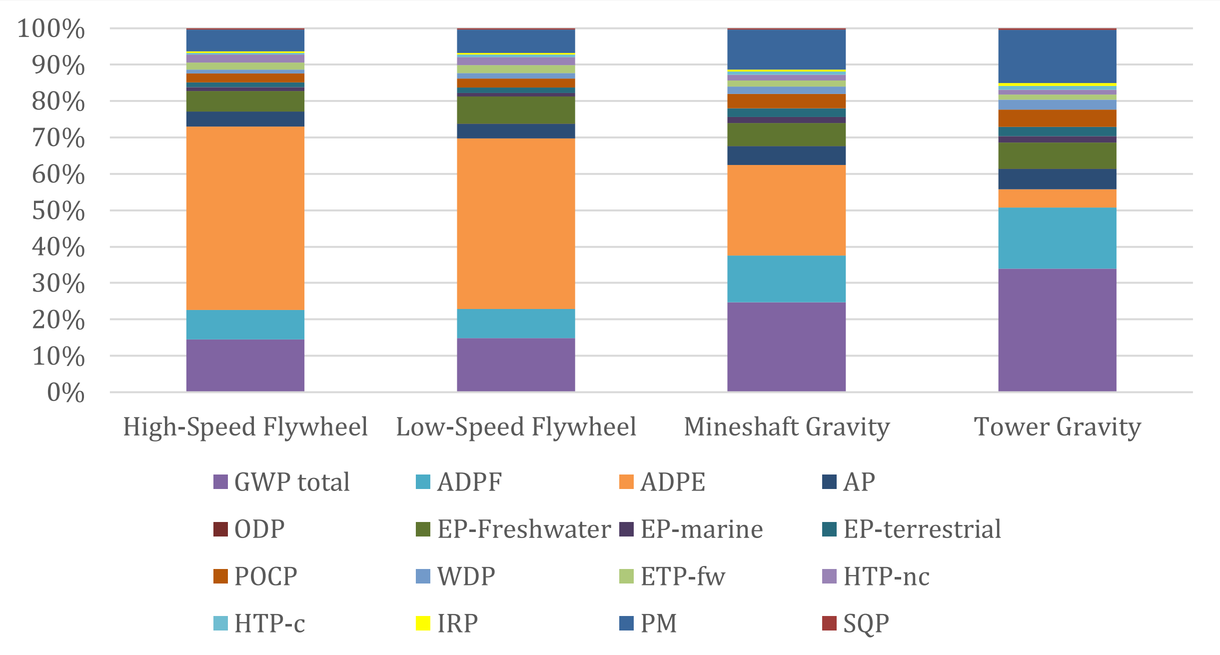


Figure 16. Share of impact categories to the PEF score by technology and impact category without the use (B) stage

6.2 Significance analysis

High-speed (composite rotor) flywheel energy storage

The production of the composite rotor and the power control unit accounts for the majority of environmental impacts across nearly all impact categories. The power control unit, in particular, stands out due to the use of precious metals in power electronics, which contribute to more than two-thirds of non-fossil mineral resource depletion and approximately half of the total PEF score. The only notable exception is ozone depletion, where the main contributor is the production of the vacuum pump, due to chlorofluorocarbon (CFC) emissions that are most likely used as coolants.

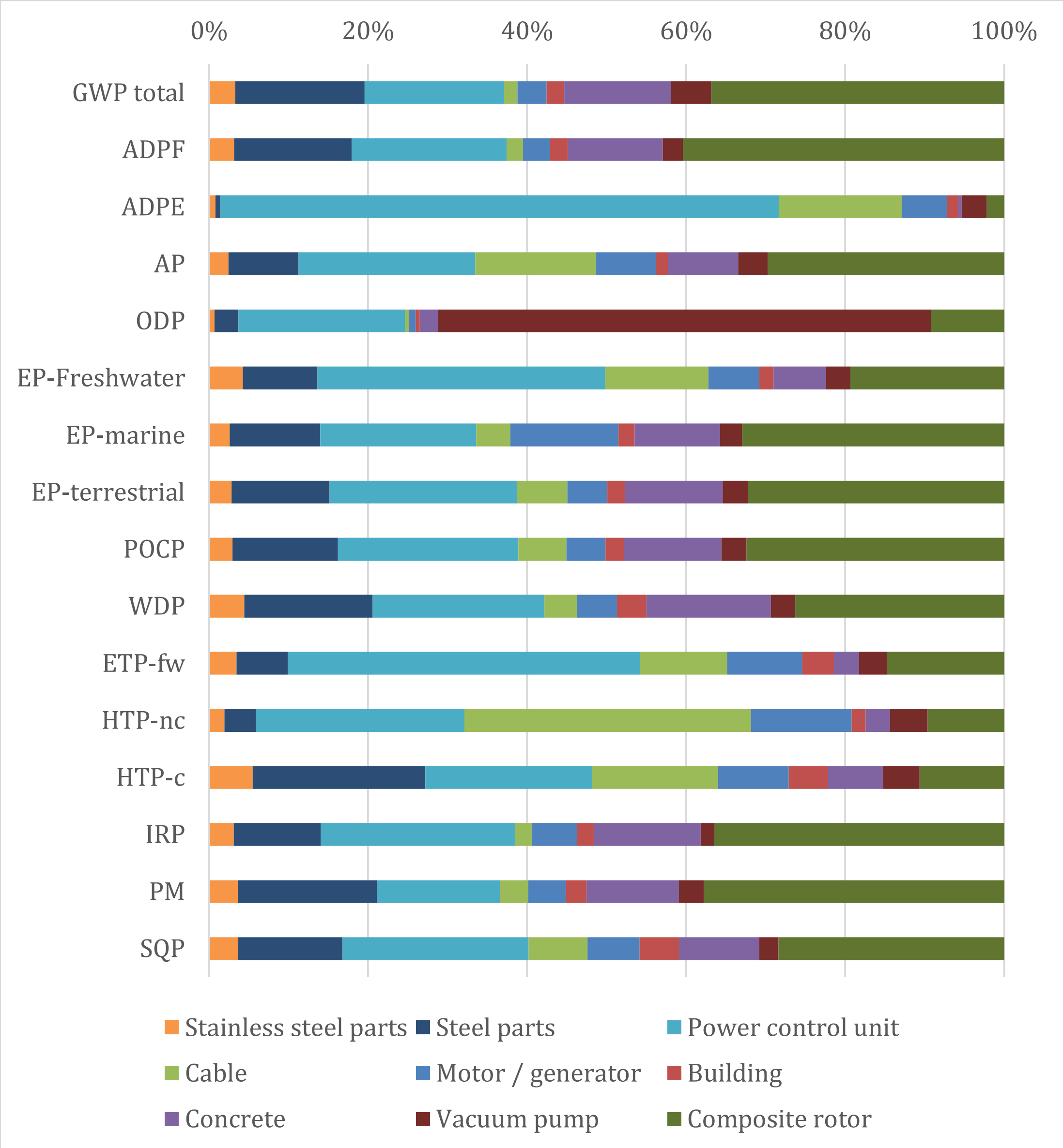


Figure 17. Share of HFES components by impact category in the product (A1-A3) stage

Low-speed (steel) flywheel energy storage

The overall environmental impact profile of this system closely resembles that of the high-speed flywheel energy storage (HFES) system. The only significant difference lies in the production of stainless steel components - particularly the rotor - which replaces the composite rotor used in the HFES. Not only does this substitution shift the source of impacts, but it also results in higher overall impacts compared to the composite rotor in the

HFES, due to the greater environmental burden associated with the heavier stainless steel rotor production.

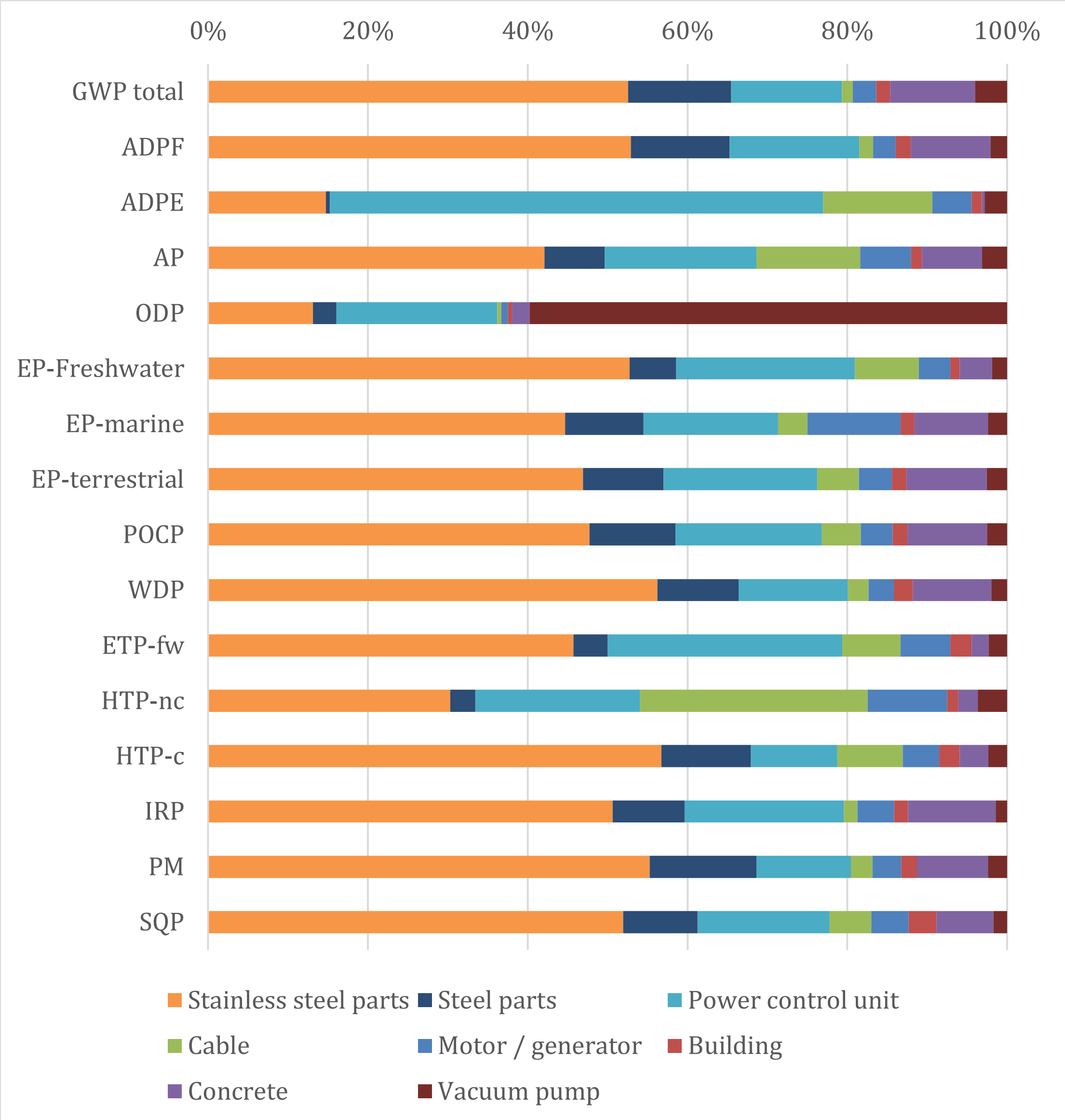


Figure 18. Share of LFES components by impact category in the product (A1-A3) stage

Legacy (abandoned) mineshaft gravity energy storage (SGES)

Across most impact categories, steel parts are the dominant contributor almost uniformly, especially in categories such as Global Warming Potential (GWP), Acidification Potential (AP), and several forms of Eutrophication and Ecotoxicity. The power control unit also contributes significantly, particularly to Abiotic Depletion Potential for elements (ADPE), largely due to the use of precious metals. Building and motor/generator components contribute modestly across most categories. Overall, the results highlights that steel and power control unit production are the key environmental hotspots in the SGES system.

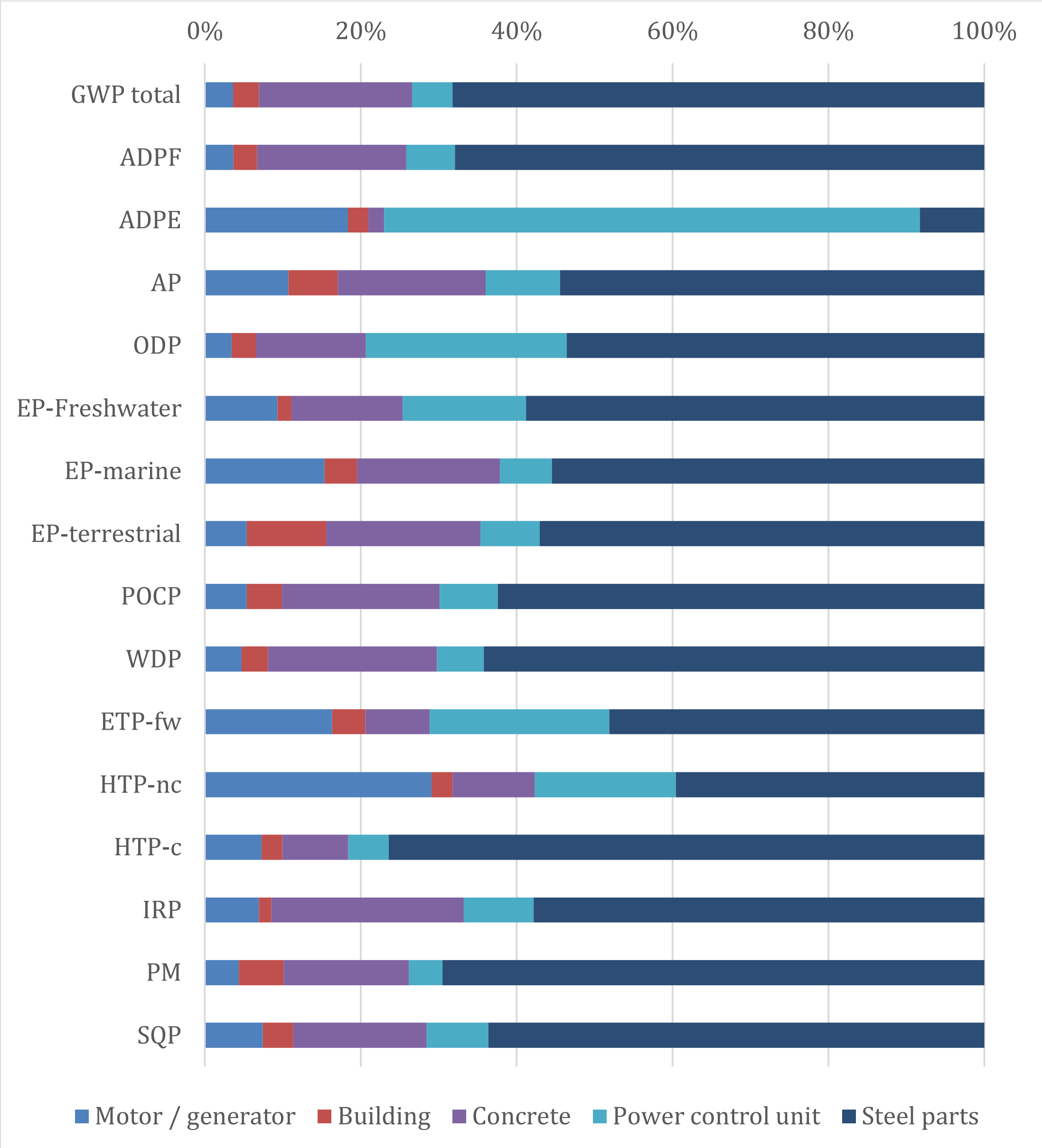


Figure 19. Share of SGES components by impact category in the product (A1-A3) stage

Tower gravity energy storage (TGES)

The vast majority of environmental impacts in the TGES system are associated with the construction materials required for the large tower structure. In most impact categories, steel beams contribute slightly more than the concrete foundation and structural elements. The only significant exception is abiotic depletion of non-fossil minerals (ADPE), where the motor/generator accounts for around 25% of the impact, primarily due to the use of tellurium and copper in its production.

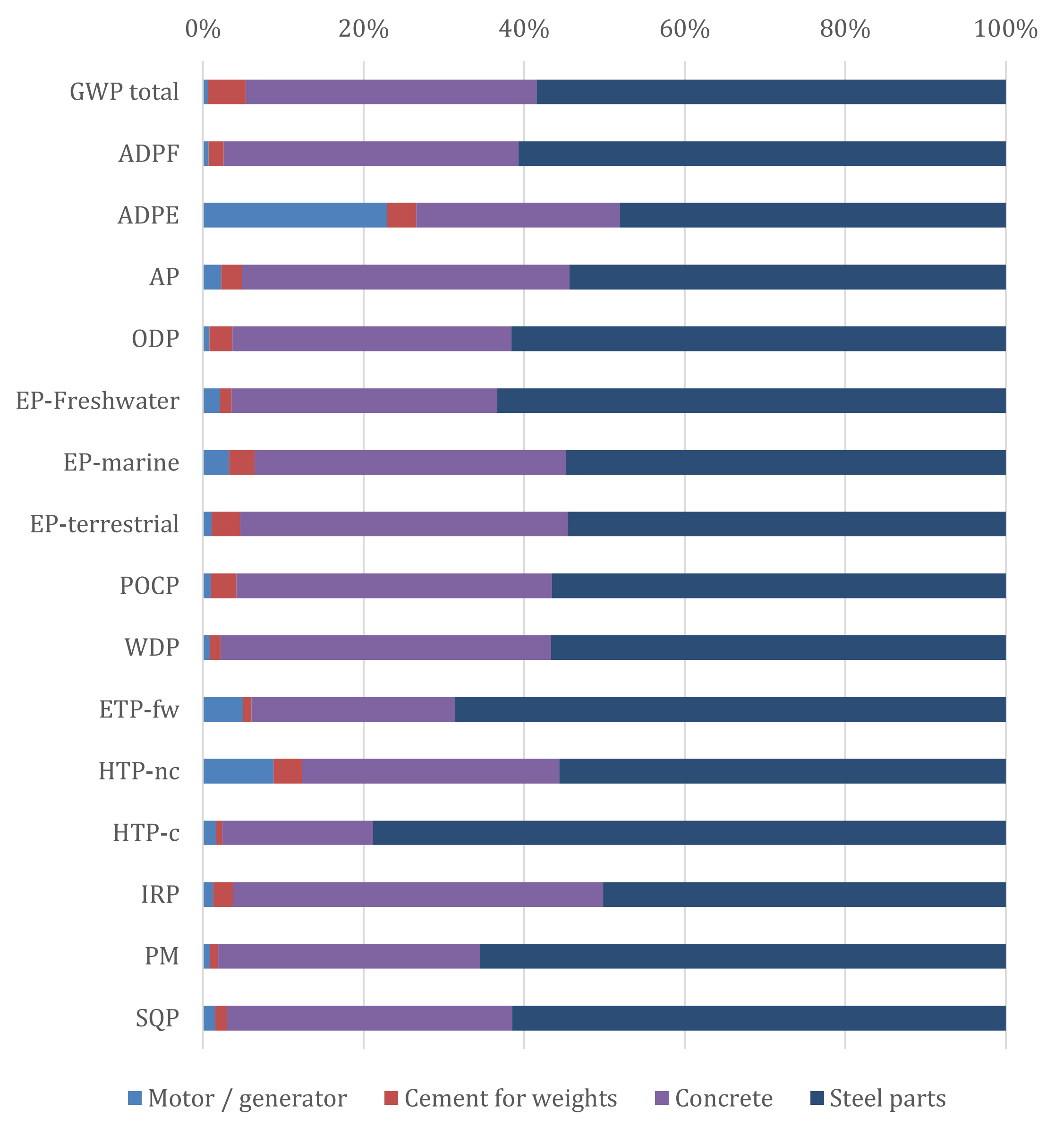
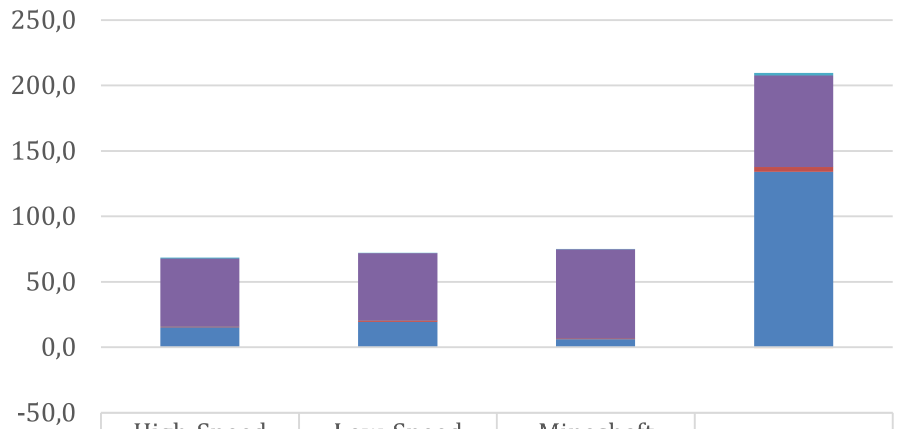


Figure 20. Share of TGES components by impact category in the product (A1-A3) stage

6.2 Carbon footprint

Our results clearly shows that tower gravity storage has the highest total carbon footprint by a wide margin, exceeding 200 kg CO_2-eq/MWh, largely driven by emissions from the production stage (134 kg CO_2-eq). In contrast, the other three technologies have similar and significantly lower total impacts, each around 70–80 kg CO_2-eq/MWh in total, or around 10-20 kg CO_2-eq/MWh without considering the energy loss.



	High-Speed Flywheel	Low-Speed Flywheel	Mineshaft Gravity	Tower Gravity
Recycling (D)	0,0	-0,1	0,0	-0,7
End of life (C1-C4)	0,7	0,3	0,0	1,9
Use (B)	52,1	51,7	68,0	69,9
Installation (A5)	0,0	0,0	0,0	0,0
Transport (A4)	0,6	1,1	0,6	3,5
Production (A1-A3)	15,2	19,3	6,2	134,1

Figure 21. Carbon footprint of energy storage technologies by lifecycle stage per MWh storage delivered in kg CO2 equivalents

6.3 Circularity and recyclability

In general, most components of these systems are made from highly recyclable materials such as steel, aluminum, and copper, all of which have high recycling rates and well-established recycling processes and markets. However, the recovery of rare earth elements used in specialized components—like permanent magnets in motors—or precious metals in power electronics is more challenging due to their low concentrations in these parts. Concrete recycling is also possible but typically results in downcycling, where the recycled material cannot be reused for high-quality applications and is instead used as backfill or as a partial substitute for aggregates in new concrete. Gravity energy storage systems may offer a sustainability advantage by being able to reuse such downcycled materials as ballast or weights. This is well reflected in the resource use of secondary materials (SM) value (see Annex), that is 1.39 kg/MWh for HFES, 1.17 kg/MWh for the SFES, is 20.9 kg/MWh for SGES, and whopping 51.3 kg/MWh for the TGES system indicating high level of circularity.

7. Sensitivity and uncertainty analysis

7.1 Variable sensitivity

Operational energy loss and roundtrip efficiency

Among the variables that influence energy losses during operation, roundtrip efficiency stands out as the most sensitive parameter, as it directly affects the overall performance and environmental impact of an energy storage system. For flywheel energy storage, manufacturers typically report roundtrip efficiencies of around 85% [5], while other sources cite values as high as 90% [6], [16]. Similarly, gravity-based energy storage systems report a roundtrip efficiency range of 75% to 85%, depending on the design and operational conditions.

Throughput and number of cycles

Another critical factor is the number of charge-discharge cycles a system can perform over its lifetime. This parameter is influenced by ramp-up speed, power rating, and the expected lifespan of the system. Generally, a higher number of cycles leads to lower environmental impacts per functional unit, as more energy is delivered over the same amount of equipment and materials.

However, both flywheel and gravity-based storage technologies are still maturing. As such, it is difficult to precisely determine their maximum cycle life or to estimate their long-term operational lifespan with confidence. Moreover, the number of completed cycles is heavily influenced by external factors such as the intermittency of renewable energy sources, the availability of excess energy, and the interaction with other types of storage systems.

A notable example is the 20 MW HFES in this study, which delivered approximately 11.655 GWh of energy in just three months of operation[13] . If this rate of throughput is sustained, it would result in roughly 190,000 cycles over 20 years—nearly double the 100,000-cycle estimate provided by the manufacturer [5]. Interestingly, one study even considered 1,825,000 cycles a conservative estimate for a similar system [16].

Power rating

Larger power ratings enable energy storage systems to complete more cycles for a given storage capacity, effectively increasing the total energy throughput. This has two effects:

1. The relative environmental impact from equipment production decreases, since more energy is delivered per unit of environmental burden.
2. The use-phase impacts (e.g., from energy losses during operation) become more significant in the overall life cycle assessment.

Quantity of materials

There is significant uncertainty in the life cycle inventory due to the lack of detailed bills of materials and the absence of manufacturer-provided data. As a result, many values are based on estimates, which greatly affects the reliability of the results. This is particularly important because the production phase is the main contributor to the overall environmental impacts for all the technologies studied.

The uncertainty is further amplified by the fact that these technologies are either not yet deployed at grid scale or, in the case of flywheel systems, only exist in a few real-world applications. Even when data is available for one system, it may not accurately represent others, given the limited number of implementations.

For instance, in the case of flywheel systems, the environmental impact is largely driven by the use of precious metals in the power control units and stainless steel in structural components. However, the actual quantities of these materials are uncertain and were estimated based on photographs and rough approximations. It is possible that the real material needs are much lower—potentially by a factor of ten. In this study, conservative estimates were used, meaning the actual environmental impacts might be lower than reported.

A similar situation applies to tower-based gravity energy storage, where the estimated quantities of steel and concrete might significantly exceed what would be required in practice.

7.2 Scenario assumptions

Electricity source

The most critical assumption affecting the results is the source of electricity used during the operation of the energy storage systems, due to the considerable energy losses involved. Integrating these systems with renewable energy sources—such as wind power—can lead to significant environmental benefits. For instance, using wind electricity reduces the total impacts by over 50% for flywheel systems and by nearly 80% for mineshaft gravity storage. Even in the case of the production-intensive tower gravity storage, environmental impacts can be reduced by about one-third when powered by wind energy (see Figure 22).

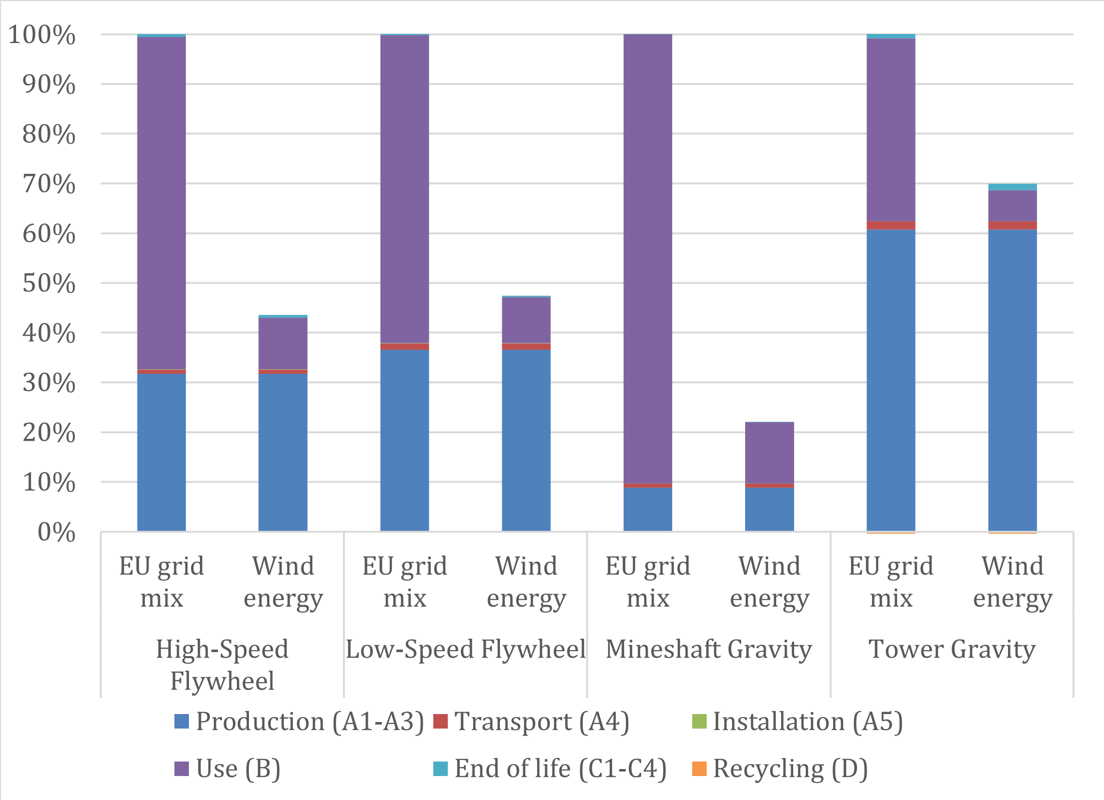


Figure 22. Relative PEF score reduction by technology and lifecycle stage in case of switching from grid electricity to wind turbines to charge the batteries

Rotor material in FES systems

In the case of flyhweels, there was only a slight difference between the material selection, both steel and composite rotors performed similarly.

Figure 23 illustrates the percentage increase in environmental impacts when switching from a composite rotor to a steel rotor in flywheel energy storage (FES) systems. The data shows a consistent rise across all impact categories, highlighting the greater environmental burden of stainless steel compared to composite materials.

The most substantial increase is observed in Human Toxicity, cancer effects (HTP-c), which jumps by 94%, indicating a significant rise in toxic emissions owing mostly to chromium and benzo(a)pyrene emissions during to stainless steel production. Other categories with notable increases include EP-Freshwater (+62%), Water Deprivation Potential (WDP) (+57%), and Freshwater Ecotoxicity (ETP-fw) (+47%), reflecting steel's higher water and pollution footprint. Categories like Particulate Matter (PM), Photochemical Ozone Creation Potential (POCP), and EP-terrestrial also show increases of around 25–31%. Even in the category with the smallest rise, Ozone Depletion Potential (ODP), there is still a 7% increase.

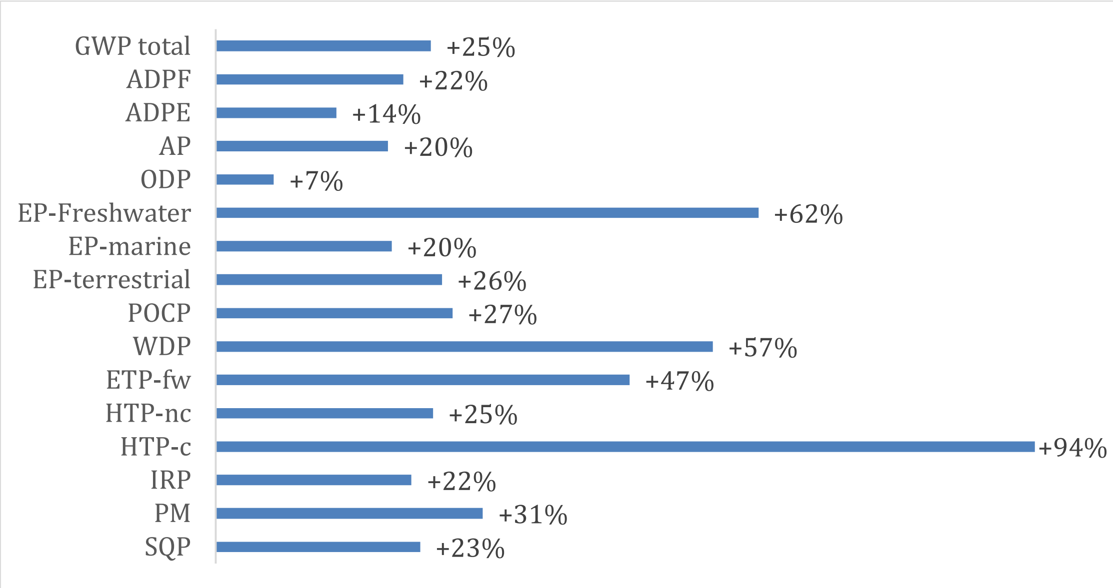


Figure 23. Increase of environmental impacts switching from composite to steel rotor in FES

Hybrid flywheel systems

Co-locating flywheel energy storage systems with lithium-ion batteries can reduce environmental impacts by combining their complementary strengths. Flywheels offer fast response and high power density, ideal for short-term fluctuations, while lithium-ion batteries provide high energy density for longer-term storage. This integration improves overall efficiency, reduces reliance on fossil fuels during peak demand, and lowers greenhouse gas emissions. Since flywheels use fewer critical raw materials than batteries, their use can also reduce the environmental burden linked to lithium, cobalt, and nickel mining—making the combined system more sustainable and resource-efficient[16].

Lundahl et al. [16] conducted a detailed life-cycle assessment comparing standalone flywheel, lithium-ion battery, and hybrid energy storage systems, based on varying daily cycle demands. They found that adding a 6 kWh flywheel to a 3300 kWh lithium-ion battery could extend the battery's lifetime by a factor of 18.3 under a scenario with 200 daily cycles. This is because the flywheel handles frequent, short-duration "microcycles" (charge-discharge cycles below 0.2% depth of discharge), which are particularly damaging to battery lifespan.

Using their assumptions and the *"market for battery, Li-ion, LFP, rechargeable, GLO"* process from ecoinvent—assuming a gravimetric energy density of 88 Wh/kg—we replicated the assessment with a scaled-up version of the HFES (high-speed flywheel energy storage) system. Only production-stage impacts were considered, as operational impacts are minimal or dependent on electricity source.

As shown in Figure 24, the hybrid system results in a 94% reduction in carbon footprint compared to a lithium-only system and 91% compared to a flywheel-only system. A similar trend is seen for abiotic depletion of non-fossil resources, with a 91% reduction compared to lithium-only and a 37% reduction compared to flywheel-only.

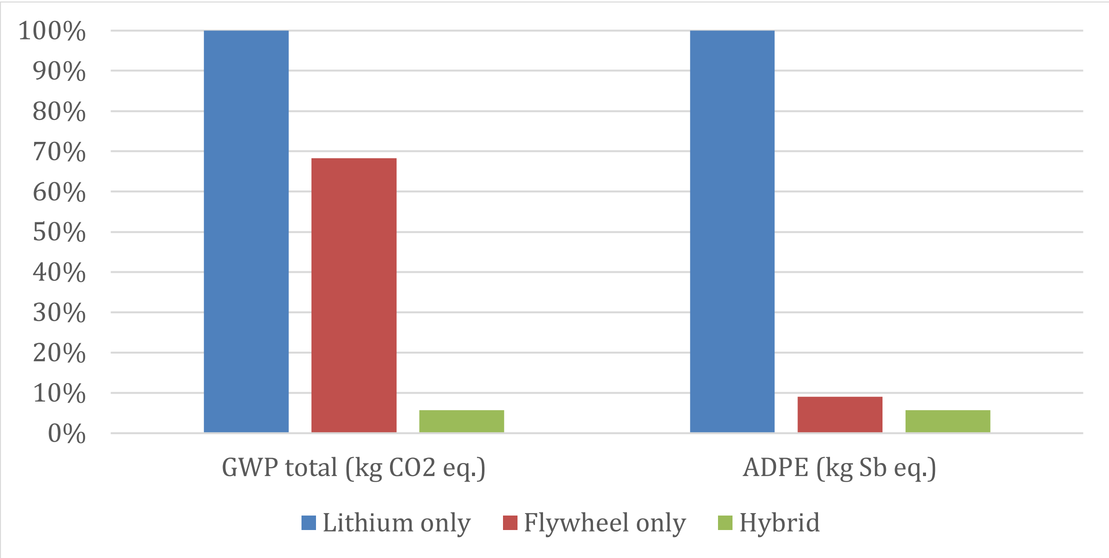


Figure 24. Environmental impacts of hybrid vs. standalone battery systems

Choice of secondary datasets

Linking the life cycle inventory to datasets from the ecoinvent database can significantly influence the results, as most environmental impacts come from background (secondary) data rather than direct emissions from the technologies themselves. This is particularly important for specialized components such as rotors, generators, and control units, where suitable matches in the database are lacking, and realistic substitutions must be made.

For example, the motor or generator was matched with a dataset for an electric motor used in a passenger vehicle due to the absence of a more appropriate option. However, these two products may differ significantly in terms of materials, design, and manufacturing processes, which can affect the accuracy of the results. In the case of composite rotors, no sufficiently similar dataset was available, so only the raw material inputs were considered.

Fortunately, a large portion of the inventories consists of relatively simple and widely used materials like steel and concrete, for which high-quality, well-established datasets are available in the database.

7.3 Data quality assessment

In terms of data quality the following table summarizes the geographic, technical and time-related representativeness of the secondary datasets used in the study. See more details about data quality level and criteria of the UN Environment Global Guidance on LCA database development, Table E.1 in EN 15804 standard [2]. In general, data quality can be considered as good in terms of the secondary datasets. Technological representativeness of composite rotor and the vacuum pump in the case of FES and the material of the weights in the case of tower GES leaves some room for improvement, but acceptable, given the absence of more realistic information.

Table 21. Data Quality Assessment of the secondary datasets used in the study

Process	Geo-graphical	Techno-logical	Temporal	Overall score
cement, all types to generic market for cement, unspecified, Europe without Switzerland	Very good	Fair	Very good	**Good**
excavation, hydraulic digger, RER	Very good	Good	Very good	**Very good**
intermodal shipping container production, 40-foot, GLO	Very good	Good	Very good	**Very good**
market for building, hall, steel construction, GLO	Good	Good	Very good	**Good**
market for cable, unspecified, GLO	Very good	Good	Very good	**Very good**
market for carbon fibre reinforced plastic, injection moulded, GLO	Very good	Fair	Good	**Good**
market for concrete slab, RoW	Good	Very good	Very good	**Very good**
market for copper scrap, sorted, pressed, GLO	Fair	Good	Very good	**Good**
market for electric motor, electric passenger car, GLO	Very good	Fair	Good	**Good**
market for electronics, for control units, GLO	Very good	Good	Good	**Good**
market for glass fibre reinforced plastic, polyester resin, hand lay-up, GLO	Very good	Fair	Very good	**Good**
market for gravel, crushed, RoW	Very good	Very good	Very good	**Very good**
market for iron scrap, sorted, pressed, RER	Very good	Very good	Very good	**Very good**
market for metal working, average for chromium steel product manufacturing, GLO	Very good	Very good	Very good	**Very good**
market for metal working, average for steel product manufacturing, GLO	Very good	Very good	Very good	**Very good**
market for refrigeration machine, R134a as refrigerant, GLO	Very good	Fair	Very good	**Good**
market for steel, chromium steel 18/8, hot rolled, GLO	Very good	Very good	Very good	**Very good**
market for steel, unalloyed, GLO	Very good	Very good	Very good	**Very good**
market for transport, freight, lorry, unspecified, RER	Very good	Very good	Very good	**Very good**
market for transport, freight, sea, container ship, heavy fuel oil, GLO	Very good	Very good	Very good	**Very good**
market for used industrial electronic device, RoW	Good	Good	Very good	**Good**
market for waste electric wiring, RoW	Good	Good	Very good	**Good**

market for waste plastic, industrial electronics, RoW	Good	Good	Very good	**Good**
market group for electricity, RER	Very good	Very good	Very good	**Very good**
market group for transport, freight, lorry, diesel, unspecified, GLO	Very good	Good	Very good	**Very good**
treatment of inert waste, sanitary landfill, RER	Very good	Very good	Very good	**Very good**
treatment of waste bulk iron, excluding reinforcement, sorting plant, Europe without Switzerland	Very good	Very good	Very good	**Very good**
treatment of waste reinforced concrete, recycling, Europe without Switzerland	Very good	Very good	Very good	**Very good**

8. Summary

8.1 Conclusions

Tower gravity energy storage is the least environmentally friendly option, with a Product Environmental Footprint (PEF) score roughly twice that of flywheel systems and mineshaft gravity storage. The two flywheel types have nearly identical environmental impacts, while mineshaft gravity storage emerges as the most favorable due to lower material needs. Across all technologies, lifecycle impacts are primarily driven by energy losses during use, except for tower systems, where material production dominates. When use-phase impacts are excluded, component production accounts for over 90% of the total footprint, with transport, installation, and recycling contributing minimally. The most critical impact categories are climate change and abiotic resource use, followed by freshwater eutrophication.

Across all systems, the main environmental impacts stem from the materials used in key structural and functional components:

- In the high-speed flywheel system (HFES), the composite rotor and power control unit dominate most impact categories, with the latter notably contributing to mineral resource depletion due to precious metals.
- The low-speed flywheel system (LFES) shows a similar impact profile, but with higher overall impacts due to the use of a heavier stainless steel rotor.
- In the legacy mineshaft gravity energy storage (SGES) system, steel components are the primary contributors across almost all categories, followed by the power control unit, again due to precious metals.
- Lastly, in the tower-based gravity system (TGES), construction materials—especially steel beams and concrete—are the main impact drivers, with motor/generator impacts emerging only in the category of mineral depletion due to tellurium and copper.

8.2 Recommendations

Co-locating flywheel and lithium-ion battery storage systems significantly reduces environmental impacts—cutting carbon footprint by up to 94%—by leveraging the flywheel's ability to handle short, frequent cycles and extending battery life, thus minimizing resource use and emissions associated with battery production.

Since the most influential factor in the environmental impact of energy storage systems is the electricity source used during operation, switching to renewable energy, like wind power, can cut impacts by over 50% for flywheels, nearly 80% for mineshaft gravity storage, and around one-third for tower gravity systems.

Material choice also matters: while both steel and composite flywheel rotors perform similarly overall, switching from composite to steel leads to consistently higher environmental impacts across all categories. The most notable increase is in human toxicity (cancer effects), which rises by 94%, largely due to emissions from stainless steel production. Other significant increases are seen in freshwater eutrophication, water use, and ecotoxicity, underscoring the environmental burden of steel compared to composites.

Designing flywheel energy storage systems involves several trade-offs that affect their lifetime, power rating, and efficiency:

- One key consideration is the choice between magnetic levitation and conventional mechanical bearings. Magnetic levitation eliminates friction and reduces wear, significantly increasing the system's lifetime and improving roundtrip efficiency. However, it adds complexity, cost, and requires continuous control systems and energy to maintain levitation. Mechanical bearings are simpler and cheaper but are subject to greater wear and energy loss due to friction, leading to more frequent maintenance and shorter operational life.
- Another important trade-off involves the use of a vacuum enclosure to minimize air resistance and improve energy retention. While vacuum operation reduces aerodynamic drag and boosts efficiency, it requires a vacuum pump, which consumes energy and introduces a maintenance burden. If the vacuum pump leaks or fails, performance can degrade significantly.
- Additionally, material choices, like using composite rotors for higher speed and energy density versus steel rotors for durability, also affect these system parameters.
- Similarly, optimizing for higher power ratings may require larger or more complex motor-generator units, which can introduce greater losses and increase material use.

Gravity energy storage also has a multitude of design considerations:

- Heavier weights store and deliver more energy, but necessitate stronger and more expensive support systems.
- Similarly, using denser materials like steel or concrete improves energy density, but raises structural demands and environmental impact due to material production.
- Larger motors and generators allow for higher power output and faster cycling, though they increase material requirements and may operate inefficiently under partial load.
- In case of abandoned mineshaft GES systems, deeper shafts enable greater energy storage by increasing gravitational potential, but require more stronger structure higher refurbishment and maintenance efforts.
- A larger capacity tower GES needs more land since, lifting more weights at the same time means larger area, but in exchange, it provides better grid balancing.

Optimizing a these energy storage systems, therefore, requires balancing these factors according to the specific needs of the application, such as frequency of cycling, required response time, and other physical, environmental, social and economic constraints.

9. References

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Annex: Life cycle impact assessment (LCIA) result tables

Environmental impacts (EF3.1) of High-Speed FES

Indicator	Unit	A1-A3	A4	A5	B1-B7	C1-C4	D
Global Warming Potential - biogenic (GWP-biogenic)	kg CO2 eq.	1.68E-01	7.29E-04	1.07E-06	1.70E+00	5.08E-04	1.32E-04
Global Warming Potential - fossil fuels (GWP-fossil)	kg CO2 eq.	1.50E+01	6.21E-01	3.14E-03	5.02E+01	6.61E-01	-3.40E-02
Global Warming Potential - land use and land use change (GWP-luluc)	kg CO2 eq.	2.34E-02	1.44E-03	3.54E-07	1.47E-01	5.47E-05	-4.16E-05
Global Warming Potential - total (GWP-total)	kg CO2 eq.	1.52E+01	6.23E-01	3.14E-03	5.21E+01	6.62E-01	-3.39E-02
Abiotic depletion potential - fossil resources (ADPF)	MJ	1.87E+02	8.56E+00	4.07E-02	1.16E+03	2.81E+00	-4.68E-01
Abiotic depletion potential - non-fossil resources (ADPE)	kg Sb eq.	1.34E-03	1.76E-06	1.48E-09	1.30E-04	-7.49E-07	-1.47E-06
Acidification potential, Accumulated Exceedance (AP)	mol H+ eq.	1.08E-01	6.12E-03	2.75E-05	2.47E-01	1.01E-03	-3.11E-04
Depletion potential of the stratospheric ozone layer (ODP)	kg CFC-11 eq.	4.27E-07	1.02E-08	6.63E-11	1.02E-06	4.27E-09	-5.36E-10
Eutrophication potential - freshwater (EP-freshwater)	kg P eq.	1.01E-02	5.38E-05	1.46E-07	4.55E-02	9.40E-06	-1.47E-05
Eutrophication potential - marine (EP-marine)	kg N eq.	1.98E-02	1.82E-03	1.27E-05	4.40E-02	4.76E-04	-8.09E-05
Eutrophication potential - terrestrial (EP-terrestrial)	mol N eq.	1.83E-01	1.99E-02	1.39E-04	3.78E-01	4.95E-03	-8.98E-04
Photochemical Ozone Creation Potential (POCP)	kg NMVOC eq.	5.73E-02	6.10E-03	4.19E-05	1.21E-01	1.63E-03	-2.78E-04
Water (user) deprivation potential (WDP)	m3 World eq.	4.68E+00	4.46E-02	1.48E-04	3.06E+01	6.98E-02	-6.54E-03
Global warming potential except emissions and uptake of biogenic carbon (GWP-IOBC/GHG)	kg CO2 eq.	1.51E+01	6.23E-01	3.14E-03	5.05E+01	6.61E-01	-3.42E-02
Potential Comparative Toxic Unit for ecosystems (ETP-fw)	CTUe	1.66E+02	1.38E+00	2.36E-03	1.18E+02	6.23E+00	-1.87E-01
Potential Comparative Toxic Unit for humans - non-cancer effects (HTP-nc)	CTUh	4.68E-07	5.22E-09	6.04E-12	3.93E-07	1.03E-08	-1.36E-09
Potential Comparative Toxic Unit for humans - cancer effects (HTP-c)	CTUh	1.06E-08	1.48E-10	4.21E-13	8.52E-09	9.10E-11	-2.13E-11
Potential Human exposure efficiency relative to U235 (IRP)	kBq U235 eq.	1.18E+00	7.36E-03	2.77E-05	3.26E+01	2.02E-03	-2.64E-03

Potential incidence of disease due to PM emissions (PM)	Disease Incidence	1.14E-06	5.13E-08	7.78E-10	9.22E-07	6.14E-08	-4.64E-09
Potential Soil quality index (SQP)	Dimensionless	7.41E+01	5.55E+00	6.11E+01	1.96E+02	1.44E+00	-6.72E-01

Resource use indicators (EN 15804) of High-Speed FES

Indicator	Unit	A1-A3	A4	A5	B1-B7	C1-C4	D
Output | Components for re-use (CRU)	kg	-1.19E-19	-7.22E-21	-1.17E-23	3.17E-19	1.14E-21	-2.22E-22
Output | Exported electrical energy (EEE)	MJ	1.29E-01	8.84E-04	3.83E-06	5.64E+00	5.19E-03	-4.14E-04
Output | Exported thermal energy (EET)	MJ	1.87E-01	1.40E-03	1.33E-06	7.03E-02	2.78E-03	-1.35E-04
Output | Materials for energy recovery (MER)	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Output | Materials for recycling (MFR)	kg	1.23E+00	7.17E-03	3.50E-05	1.55E+01	8.00E-02	-1.46E-03
Resource | Total use of non renewable primary energy resources (PENRT)	MJ	1.87E+02	8.57E+00	4.07E-02	1.16E+03	2.81E+00	-4.68E-01
Resource | Total use of renewable primary energy resources (PERT)	MJ	2.19E+01	1.20E-01	3.88E-04	2.61E+02	1.13E-02	-5.39E-02
Resource | Use of net fresh water (FW)	m3	1.05E-01	1.12E-03	2.77E-06	7.11E-01	1.15E-03	-1.50E-04
Resource | Use of non renewable primary energy resources used as energy carrier (PENRE)	MJ	1.87E+02	8.57E+00	4.07E-02	1.16E+03	2.81E+00	-4.68E-01
Resource | Use of non renewable primary energy resources used as raw materials (PENRM)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of non renewable secondary fuels (NRSF)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of renewable primary energy resources used as energy carrier (PERE)	MJ	2.19E+01	1.20E-01	3.88E-04	2.61E+02	1.13E-02	-5.39E-02
Resource | Use of renewable primary energy resources used as raw materials (PERM)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of renewable secondary fuels (RSF)	MJ	1.49E-01	9.88E-04	5.62E-06	9.40E+00	1.92E-04	-6.67E-04
Resource | Use of secondary materials (SM)	kg	8.73E-01	6.77E-03	4.21E-05	1.49E+01	-9.34E-01	-9.37E-01
Waste | Hazardous waste disposed (HWD)	kg	1.60E+00	1.23E-02	5.58E-05	1.14E+00	1.76E-02	-1.71E-03

Waste | Non hazardous waste disposed (NHWD)	kg	1.90E+01	8.10E-02	4.51E-04	8.25E+00	6.57E-01	-2.07E-02
Waste | Radioactive waste disposed (RWD)	kg	3.44E-04	1.80E-06	6.84E-09	8.37E-03	4.81E-07	-6.72E-07

Environmental impacts (EF3.1) of Low-Speed Flywheel Energy Storage

Impact category	Unit	A1-A3	A4	A5	B1-B7	C1-C4	D
Global Warming Potential - biogenic (GWP-biogenic)	kg CO2 eq.	3.48E-01	1.29E-03	1.07E-06	1.70E+00	6.89E-04	2.89E-04
Global Warming Potential - fossil fuels (GWP-fossil)	kg CO2 eq.	1.89E+01	1.06E+00	3.14E-03	4.98E+01	2.50E-01	-7.22E-02
Global Warming Potential - land use and land use change (GWP-luluc)	kg CO2 eq.	2.41E-02	2.61E-03	3.54E-07	1.47E-01	1.24E-05	-8.59E-05
Global Warming Potential - total (GWP-total)	kg CO2 eq.	1.93E+01	1.07E+00	3.14E-03	5.17E+01	2.51E-01	-7.20E-02
Abiotic depletion potential - fossil resources (ADPF)	MJ	2.24E+02	1.46E+01	4.07E-02	1.16E+03	2.51E+00	-9.93E-01
Abiotic depletion potential - non-fossil resources (ADPE)	kg Sb eq.	1.53E-03	2.98E-06	1.48E-09	1.28E-04	-2.41E-06	-3.18E-06
Acidification potential, Accumulated Exceedance (AP)	mol H+ eq.	1.27E-01	1.09E-02	2.75E-05	2.47E-01	6.53E-04	-6.63E-04
Depletion potential of the stratospheric ozone layer (ODP)	kg CFC-11 eq.	4.51E-07	1.71E-08	6.63E-11	1.02E-06	4.01E-09	-1.14E-09
Eutrophication potential - freshwater (EP-freshwater)	kg P eq.	1.64E-02	9.33E-05	1.46E-07	4.55E-02	-7.06E-06	-3.18E-05
Eutrophication potential - marine (EP-marine)	kg N eq.	2.31E-02	3.20E-03	1.27E-05	4.38E-02	3.55E-04	-1.72E-04
Eutrophication potential - terrestrial (EP-terrestrial)	mol N eq.	2.24E-01	3.50E-02	1.39E-04	3.77E-01	3.82E-03	-1.91E-03
Photochemical Ozone Creation Potential (POCP)	kg NMVOC eq.	7.09E-02	1.07E-02	4.19E-05	1.21E-01	1.33E-03	-5.90E-04
Water (user) deprivation potential (WDP)	m3 World eq.	7.40E+00	7.57E-02	1.48E-04	3.06E+01	5.37E-02	-1.40E-02
Global warming potential except emissions and uptake of biogenic carbon (GWP-IOBC/GHG)	kg CO2 eq.	1.91E+01	1.07E+00	3.14E-03	5.01E+01	2.50E-01	-7.25E-02
Potential Comparative Toxic Unit for ecosystems (ETP-fw)	CTUe	2.51E+02	2.39E+00	2.36E-03	1.14E+02	2.19E+00	-4.00E-01
Potential Comparative Toxic Unit for humans - non-cancer effects (HTP-nc)	CTUh	5.96E-07	8.81E-09	6.04E-12	3.83E-07	6.91E-11	-2.93E-09
Potential Comparative Toxic Unit for humans - cancer effects (HTP-c)	CTUh	2.08E-08	2.53E-10	4.21E-13	8.46E-09	2.57E-11	-4.59E-11
Potential Human exposure efficiency relative to U235 (IRP)	kBq U235 eq.	1.45E+00	1.22E-02	2.77E-05	3.26E+01	-2.04E-04	-5.69E-03

Potential incidence of disease due to PM emissions (PM)	Disease Incidence	1.50E-06	8.67E-08	7.78E-10	9.19E-07	5.77E-08	-9.91E-09
Potential Soil quality index (SQP)	Dimensionless	1.05E+02	9.37E+00	6.11E+01	1.96E+02	9.28E-01	-1.44E+00

Resource use indicators (EN 15804) of Low-Speed Flywheel Energy Storage

Indicator	Unit	A1-A3	A4	A5	B1-B7	C1-C4	D
Output | Components for re-use (CRU)	kg	-1.52E-19	-1.27E-20	-1.17E-23	3.14E-19	-2.13E-21	-5.31E-22
Output | Exported electrical energy (EEE)	MJ	1.39E-01	1.41E-03	3.83E-06	5.64E+00	4.86E-03	-8.94E-04
Output | Exported thermal energy (EET)	MJ	2.21E-01	2.12E-03	1.33E-06	7.02E-02	2.73E-03	-2.87E-04
Output | Materials for energy recovery (MER)	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Output | Materials for recycling (MFR)	kg	1.62E+00	1.22E-02	3.50E-05	1.55E+01	7.88E-02	-3.15E-03
Resource | Total use of non renewable primary energy resources (PENRT)	MJ	2.24E+02	1.46E+01	4.07E-02	1.16E+03	2.51E+00	-9.93E-01
Resource | Total use of renewable primary energy resources (PERT)	MJ	3.90E+01	2.02E-01	3.88E-04	2.60E+02	-4.28E-02	-1.16E-01
Resource | Use of net fresh water (FW)	m3	1.64E-01	1.91E-03	2.77E-06	7.10E-01	5.27E-04	-3.23E-04
Resource | Use of non renewable primary energy resources used as energy carrier (PENRE)	MJ	2.24E+02	1.46E+01	4.07E-02	1.16E+03	2.51E+00	-9.93E-01
Resource | Use of non renewable primary energy resources used as raw materials (PENRM)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of non renewable secondary fuels (NRSF)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of renewable primary energy resources used as energy carrier (PERE)	MJ	3.90E+01	2.02E-01	3.88E-04	2.60E+02	-4.28E-02	-1.16E-01
Resource | Use of renewable primary energy resources used as raw materials (PERM)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of renewable secondary fuels (RSF)	MJ	1.86E-01	1.56E-03	5.62E-06	9.40E+00	-3.71E-04	-1.44E-03
Resource | Use of secondary materials (SM)	kg	1.81E+00	1.13E-02	4.21E-05	1.38E+01	-1.99E+00	-1.99E+00
Waste | Hazardous waste disposed (HWD)	kg	8.79E+00	2.15E-02	5.58E-05	1.13E+00	1.00E-02	-3.66E-03

Waste | Non hazardous waste disposed (NHWD)	kg	3.33E+01	1.37E-01	4.51E-04	8.44E+00	8.46E-01	-4.46E-02
Waste | Radioactive waste disposed (RWD)	kg	4.15E-04	2.98E-06	6.84E-09	8.37E-03	-8.67E-08	-1.45E-06

Environmental impacts (EF3.1) of Mineshaft Gravity Energy Storage

Indicator	Unit	A1-A3	A4	A5	B1-B7	C1-C4	D
Global Warming Potential - biogenic (GWP-biogenic)	kg CO2 eq.	1.50E-01	7.12E-04	2.50E-07	2.26E+00	2.16E-04	1.49E-04
Global Warming Potential - fossil fuels (GWP-fossil)	kg CO2 eq.	6.01E+00	6.09E-01	7.33E-04	6.55E+01	3.71E-02	-3.63E-02
Global Warming Potential - land use and land use change (GWP-luluc)	kg CO2 eq.	6.11E-03	1.40E-03	8.24E-08	1.95E-01	-1.92E-05	-4.21E-05
Global Warming Potential - total (GWP-total)	kg CO2 eq.	6.17E+00	6.12E-01	7.33E-04	6.80E+01	3.73E-02	-3.62E-02
Abiotic depletion potential - fossil resources (ADPF)	MJ	6.84E+01	8.40E+00	9.50E-03	1.53E+03	5.13E-01	-4.99E-01
Abiotic depletion potential - non-fossil resources (ADPE)	kg Sb eq.	1.62E-04	1.73E-06	3.45E-10	1.44E-04	-1.44E-06	-1.63E-06
Acidification potential, Accumulated Exceedance (AP)	mol H+ eq.	2.96E-02	5.98E-03	6.42E-06	3.25E-01	8.44E-05	-3.35E-04
Depletion potential of the stratospheric ozone layer (ODP)	kg CFC-11 eq.	5.84E-08	1.00E-08	1.55E-11	1.10E-06	8.53E-10	-5.73E-10
Eutrophication potential - freshwater (EP-freshwater)	kg P eq.	2.73E-03	5.27E-05	3.41E-08	6.03E-02	-8.94E-06	-1.62E-05
Eutrophication potential - marine (EP-marine)	kg N eq.	6.82E-03	1.78E-03	2.96E-06	5.76E-02	8.74E-05	-8.63E-05
Eutrophication potential - terrestrial (EP-terrestrial)	mol N eq.	6.64E-02	1.95E-02	3.24E-05	4.94E-01	9.35E-04	-9.59E-04
Photochemical Ozone Creation Potential (POCP)	kg NMVOC eq.	2.04E-02	5.97E-03	9.76E-06	1.58E-01	3.22E-04	-2.97E-04
Water (user) deprivation potential (WDP)	m3 World eq.	1.96E+00	4.38E-02	3.45E-05	4.06E+01	-4.80E-04	-7.12E-03
Global warming potential except emissions and uptake of biogenic carbon (GWP-IOBC/GHG)	kg CO2 eq.	6.11E+00	6.11E-01	7.33E-04	6.59E+01	3.70E-02	-3.64E-02
Potential Comparative Toxic Unit for ecosystems (ETP-fw)	CTUe	3.77E+01	1.35E+00	5.51E-04	1.45E+02	-4.67E-02	-2.03E-01
Potential Comparative Toxic Unit for humans - non-cancer effects (HTP-nc)	CTUh	8.08E-08	5.13E-09	1.41E-12	4.94E-07	-8.46E-10	-1.49E-09
Potential Comparative Toxic Unit for humans - cancer effects (HTP-c)	CTUh	5.13E-09	1.46E-10	9.81E-14	1.09E-08	-7.49E-12	-2.33E-11
Potential Human exposure efficiency relative to U235 (IRP)	kBq U235 eq.	3.77E-01	7.26E-03	6.45E-06	4.35E+01	-1.31E-03	-2.90E-03

Potential incidence of disease due to PM emissions (PM)	Disease Incidence	4.84E-07	5.05E-08	1.81E-10	1.15E-06	2.73E-08	-5.01E-09
Potential Soil quality index (SQP)	Dimensionless	2.55E+01	5.46E+00	2.85E+00	2.21E+02	-9.41E-02	-7.31E-01

Resource use indicators (EN 15804) of Mineshaft Gravity Energy Storage

Indicator	Unit	A1-A3	A4	A5	B1-B7	C1-C4	D
Output | Components for re-use (CRU)	kg	-3.45E-20	-7.06E-21	-2.72E-24	4.21E-19	-1.00E-21	-2.94E-22
Output | Exported electrical energy (EEE)	MJ	4.39E-02	8.77E-04	8.92E-07	7.50E+00	-2.00E-04	-4.57E-04
Output | Exported thermal energy (EET)	MJ	3.30E-02	1.40E-03	3.11E-07	8.52E-02	1.80E-04	-1.44E-04
Output | Materials for energy recovery (MER)	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Output | Materials for recycling (MFR)	kg	8.12E-01	7.04E-03	8.15E-06	2.05E+01	7.97E-03	-1.60E-03
Resource | Total use of non renewable primary energy resources (PENRT)	MJ	6.84E+01	8.41E+00	9.50E-03	1.53E+03	5.13E-01	-4.99E-01
Resource | Total use of renewable primary energy resources (PERT)	MJ	6.13E+00	1.18E-01	9.06E-05	3.47E+02	-3.97E-02	-5.94E-02
Resource | Use of net fresh water (FW)	m3	3.79E-02	1.10E-03	6.46E-07	9.43E-01	-3.85E-04	-1.64E-04
Resource | Use of non renewable primary energy resources used as energy carrier (PENRE)	MJ	6.84E+01	8.41E+00	9.50E-03	1.53E+03	5.13E-01	-4.99E-01
Resource | Use of non renewable primary energy resources used as raw materials (PENRM)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of non renewable secondary fuels (NRSF)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of renewable primary energy resources used as energy carrier (PERE)	MJ	6.13E+00	1.18E-01	9.06E-05	3.47E+02	-3.97E-02	-5.94E-02
Resource | Use of renewable primary energy resources used as raw materials (PERM)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of renewable secondary fuels (RSF)	MJ	5.51E-02	9.81E-04	1.31E-06	1.25E+01	-3.97E-04	-7.37E-04
Resource | Use of secondary materials (SM)	kg	6.17E-01	6.66E-03	2.25E-00	2.01E+01	-1.00E+00	-1.00E+00
Waste | Hazardous waste disposed (HWD)	kg	6.74E-01	1.21E-02	1.30E-05	1.44E+00	-7.72E-04	-1.86E-03

Waste | Non hazardous waste disposed (NHWD)	kg	1.42E+01	7.96E-02	1.05E-04	1.02E+01	3.94E-01	-2.27E-02
Waste | Radioactive waste disposed (RWD)	kg	1.14E-04	1.78E-06	1.59E-09	1.11E-02	-3.41E-07	-7.40E-07

Environmental impacts (EF3.1) of Tower Gravity Energy Storage

Impact category	Unit	A1-A3	A4	A5	B1-B7	C1-C4	D
Global Warming Potential - biogenic (GWP-biogenic)	kg CO2 eq.	3.03E+00	2.19E-03	2.00E-06	2.26E+00	4.51E-03	2.69E-03
Global Warming Potential - fossil fuels (GWP-fossil)	kg CO2 eq.	1.31E+02	3.53E+00	5.86E-03	6.74E+01	1.91E+00	-6.53E-01
Global Warming Potential - land use and land use change (GWP-luluc)	kg CO2 eq.	1.25E-01	1.23E-03	6.59E-07	1.95E-01	-1.20E-05	-7.58E-04
Global Warming Potential - total (GWP-total)	kg CO2 eq.	1.34E+02	3.54E+00	5.86E-03	6.99E+01	1.92E+00	-6.51E-01
Abiotic depletion potential - fossil resources (ADPF)	MJ	1.42E+03	5.10E+01	7.60E-02	1.56E+03	2.73E+01	-8.99E+00
Abiotic depletion potential - non-fossil resources (ADPE)	kg Sb eq.	5.18E-04	1.18E-05	2.76E-09	1.22E-04	-2.28E-05	-2.93E-05
Acidification potential, Accumulated Exceedance (AP)	mol H+ eq.	5.51E-01	1.63E-02	5.13E-05	3.35E-01	9.13E-03	-6.03E-03
Depletion potential of the stratospheric ozone layer (ODP)	kg CFC-11 eq.	9.46E-07	7.76E-08	1.24E-10	1.14E-06	4.09E-08	-1.03E-08
Eutrophication potential - freshwater (EP-freshwater)	kg P eq.	4.72E-02	2.50E-04	2.73E-07	6.03E-02	-9.30E-05	-2.91E-04
Eutrophication potential - marine (EP-marine)	kg N eq.	1.29E-01	6.37E-03	2.37E-05	6.24E-02	4.83E-03	-1.55E-03
Eutrophication potential - terrestrial (EP-terrestrial)	mol N eq.	1.29E+00	6.95E-02	2.59E-04	5.46E-01	5.24E-02	-1.73E-02
Photochemical Ozone Creation Potential (POCP)	kg NMVOC eq.	4.20E-01	2.44E-02	7.81E-05	1.75E-01	1.74E-02	-5.35E-03
Water (user) deprivation potential (WDP)	m3 World eq.	4.12E+01	2.82E-01	2.76E-04	4.07E+01	7.06E-02	-1.28E-01
Global warming potential except emissions and uptake of biogenic carbon (GWP-IOBC/GHG)	kg CO2 eq.	1.33E+02	3.54E+00	5.86E-03	6.77E+01	1.91E+00	-6.56E-01
Potential Comparative Toxic Unit for ecosystems (ETP-fw)	CTUe	4.91E+02	6.70E+00	4.40E-03	1.46E+02	5.90E-01	-3.66E+00
Potential Comparative Toxic Unit for humans - non-cancer effects (HTP-nc)	CTUh	1.07E-06	3.56E-08	1.13E-11	4.88E-07	-6.90E-09	-2.69E-08
Potential Comparative Toxic Unit for humans - cancer effects (HTP-c)	CTUh	9.26E-08	9.07E-10	7.85E-13	1.10E-08	1.28E-10	-4.20E-10
Potential Human exposure efficiency relative to U235 (IRP)	kBq U235 eq.	8.09E+00	6.31E-02	5.16E-05	4.35E+01	-6.26E-03	-5.23E-02

Potential incidence of disease due to PM emissions (PM)	Disease Incidence	9.56E-06	3.49E-07	1.45E-09	2.29E-06	1.17E-06	-9.02E-08
Potential Soil quality index (SQP)	Dimensionless	4.91E+02	3.81E+01	5.70E+01	2.75E+02	8.25E+00	-1.32E+01

Resource use indicators (EN 15804) of Tower Gravity Energy Storage

Indicator	Unit	A1-A3	A4	A5	B1-B7	C1-C4	D
Output | Components for re-use (CRU)	kg	-1.38E-19	-2.38E-20	-2.18E-23	3.97E-19	-2.54E-20	-5.30E-21
Output | Exported electrical energy (EEE)	MJ	9.77E-01	1.00E-02	7.14E-06	7.49E+00	-9.19E-04	-8.23E-03
Output | Exported thermal energy (EET)	MJ	8.05E-01	2.09E-02	2.48E-06	9.37E-02	8.67E-03	-2.59E-03
Output | Materials for energy recovery (MER)	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Output | Materials for recycling (MFR)	kg	1.51E+01	4.41E-02	6.52E-05	2.05E+01	2.77E-03	-2.89E-02
Resource | Total use of non renewable primary energy resources (PENRT)	MJ	1.42E+03	5.10E+01	7.60E-02	1.56E+03	2.73E+01	-8.99E+00
Resource | Total use of renewable primary energy resources (PERT)	MJ	1.28E+02	8.48E-01	7.24E-04	3.46E+02	-4.81E-01	-1.07E+00
Resource | Use of net fresh water (FW)	m3	8.15E-01	6.52E-03	5.17E-06	9.39E-01	-4.32E-03	-2.95E-03
Resource | Use of non renewable primary energy resources used as energy carrier (PENRE)	MJ	1.42E+03	5.10E+01	7.60E-02	1.56E+03	2.73E+01	-8.99E+00
Resource | Use of non renewable primary energy resources used as raw materials (PENRM)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of non renewable secondary fuels (NRSF)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of renewable primary energy resources used as energy carrier (PERE)	MJ	1.28E+02	8.48E-01	7.24E-04	3.46E+02	-4.81E-01	-1.07E+00
Resource | Use of renewable primary energy resources used as raw materials (PERM)	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Resource | Use of renewable secondary fuels (RSF)	MJ	1.21E+00	1.19E-02	1.05E-05	1.25E+01	-3.90E-03	-1.33E-02
Resource | Use of secondary materials (SM)	kg	1.41E+01	5.00E-02	7.02E+01	3.05E+00	-1.80E+01	-1.80E+01
Waste | Hazardous waste disposed (HWD)	kg	1.28E+01	5.22E-02	1.04E-04	1.45E+00	2.73E-03	-3.34E-02

Waste | Non hazardous waste disposed (NHWD)	kg	2.93E+02	5.44E-01	8.41E-04	1.62E+01	6.42E+00	-4.09E-01
Waste | Radioactive waste disposed (RWD)	kg	2.08E-03	1.56E-05	1.28E-08	1.11E-02	-1.88E-06	-1.33E-05

The content of this document does not necessarily represent the official position of the European Union.

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