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Research paper

Life cycle assessment of electrochemical and mechanical energy storage systems

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ABSTRACT

The effect of the co-location of electrochemical and kinetic energy storage on the cradle-to-gate impacts of the storage system was studied using LCA methodology. The storage system was intended for use in the frequency containment reserve (FCR) application, considering a number of daily charge–discharge cycles in the range of 50–1000. The results show that a significant environmental benefit (up to a 96% decrease in cradle-to-gate global warming potential, from 1.65 ± 0.12 to 0.059 ± 0.004 kg CO_2-eq./kWh) can be obtained by the co-location of battery and flywheel storage systems, owing to the ability of the flywheel component to preserve battery lifetime by delivering the frequent charge events required in the FCR application. A moderate saving of 24% in global warming potential (from 1.65 ± 0.12 to 1.26 ± 0.11 kg CO_2-eq./kWh) could already be achieved by switching from a battery to flywheel storage system with repeated charge–discharge cycling (200 or more charge events per day). This study highlights the need to consider the intensity of charge–discharge cycling when choosing an environmentally preferable storage technology as well as introducing a methodology for incorporating the number of daily cycles in the analysis.

1. Introduction

As the world transitions from fossil fuels to renewable energy, the importance of electric grid flexibility is increasing rapidly. Unlike conventional energy production that has relied on oil, coal, gas, nuclear and hydropower, many of the green electricity production systems, such as wind and solar power, have a varying power output that depends on external conditions, causing unstable supply to the energy grids (Gallo et al., 2016). The increased use of such variable renewable energy sources presents obvious challenges for a reliable supply of electricity with consistent voltage and frequency. Frequency containment reserves (FCR) can be used to stabilise the grid power. Different methods being suggested for FCR include e.g. wind power deloading, which sacrifices some of the generator efficiency for a power margin (Bao and Li, 2015), and energy storage systems (ESS), which store excess energy during high supply/low demand and release it during low supply/high demand (IRENA, 2017). Both systems can be argued to have their place among FCR technologies. For example, deloading works directly through the wind generators and do not require additional infrastructure or devices, but they lose some of the available energy due to lower efficiency. ESS can utilise all of the available energy, but require more metals and other materials for the manufacturing of the storage devices.

ESS can be divided into mechanical, electro-chemical, chemical, thermal and electrical storage systems. The most common ESS include pumped hydro storage (i.e. the largest form of ESS in terms of capacity, covering approximately 96% of the global energy storage capacity in 2017 (Bao and Li, 2015; IRENA, 2017), rechargeable and flow batteries, thermal storage, as well as hydrogen (Majeau-Bettez et al., 2011). Pumped hydro is proposed for use as a large-scale application that would store excess wind and solar energy and release it later to compensate for a supply shortage (Demirbaş, 2006). However, the response time of pumped hydro storage remains on the scale of dozens of seconds to minutes (Blakers et al., 2021), while storage with even faster charge–discharge capability is needed to maintain a stable voltage and frequency in a renewables-powered grid. Furthermore, increasing the conventional pumped hydro capacity to meet the growing energy storage needs is restricted by the lack of suitable locations and environmental concerns related to the requirement of large land areas by new pumped hydro applications (IRENA, 2017). Thus, it is necessary to diversify the ESS catalogue to fully cater to the storage needs arising from the renewable energy transition. Globally, the need for ESS capacity is estimated to

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Abbreviations

DoD	Depth of discharge
ESS	Energy storage system
FCR	Frequency containment reserve
GWP	Global warming potential
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LFP	Lithium iron phosphate ($LiFePO_4$)
LIB	Lithium-ion battery
REE	Rare earth elements

increase up to 5000 TWh by 2030 and further to over 30,000 TWh by 2050 (Ram et al., 2019).

To provide versatile storage with capacity for fast response, batteries are increasingly being employed together with the use of renewable energy. However, many battery chemistries rely on critical raw materials, which may lead to difficulties in meeting the increasing production demands (Arrobas et al., 2017). Moreover, batteries have disadvantages in applications involving frequent charge and discharge events, which raise the battery cell temperature and thus accelerate battery ageing (Ram et al., 2019; Arrobas et al., 2017). To complement battery-based ESS, flywheel energy storage systems have been proposed to offer enhanced capacity. While they can generally store less energy for shorter times, flywheels have higher power output and longer cycle life, as well as lower life cycle costs and smaller size compared to battery ESS (Mousavi et al., 2017). Modern high-speed flywheels have been developed to transform energy efficiently between electrical and kinetic forms as well as to be coupled with renewable energy production and distribution systems (Mousavi et al., 2017).

Flywheels can also be used together with batteries in a hybrid flywheel–battery ESS, where the battery component provides the bulk, long-term storage capacity, while the flywheel component responds to the charge fluctuations. This limits the rise in battery cell temperature and enables the battery to last longer. These hybrid systems are predicted to have high efficiency, long lifetime and lower environmental impacts than either of the two systems alone in FCR applications (Dambone Sessa et al., 2018).

Since the transition to renewable electricity will require an increasing supply of FCR services, it is essential to minimise the environmental impacts of the storage technologies selected to deliver FCR. In particular, comparison of the environmental impacts of the different technologies, such as batteries, flywheels and their hybrids, is necessary in order to determine how the impacts can be minimised by the choice of technology. This is why increasing attention is being paid to environmental impact studies and life cycle assessments (LCA) of batteries and other ESS.

There are certain considerations that need to be accounted for in battery LCA. For example, thus far there is no convention about selecting the functional unit or system boundaries in a way that represents the energy throughput of the battery life cycle (Porzio and Scown, 2021). In addition, battery raw material resources and their extraction are often considered with only limited reflection on their dynamically changing nature and future trends (Porzio and Scown, 2021). Some LCA studies on lithium-ion batteries (LIB) have shown that the biggest sources of their environmental impacts are cell manufacturing, the positive electrode paste and negative electrode current collector (Ellingsen et al., 2014). Although there is some variation in literature, lithium iron phosphate (LFP) batteries have been shown to have higher overall environmental impacts during their life cycle compared to lithium nickel manganese cobalt oxide batteries, for instance (Quan et al., 2022). Nevertheless, LFP chemistry is suggested for stationary ESS applications due to its good cycle life and safety (Ellingsen et al., 2014; Quan et al., 2022) as well as its more abundantly available raw materials. For this battery chemistry, Majeau-Bettez et al. have previously reported a cradle-to-gate global warming potential (GWP) of 22 kg CO_2-eq./kg (Majeau-Bettez et al., 2011).

The overall environmental impacts of flywheel technologies have been studied less than those of batteries, but it is hypothesised that the impacts are significantly lower in comparison, especially in the case of hybrid flywheel–battery systems (Müller et al., 2017; Lazard, 2020). Recently, Rahman et al. have reported that a flywheel system produces less than half of the greenhouse gas emissions of a LIB system per MWh of delivered electricity in a frequency regulation application, with the majority of the flywheel production impacts arising from the carbon fibre composite used in the rotor (Rahman et al., 2021). However, these authors only disclosed results obtained with the assumption of 4000 yearly charge–discharge cycles, even though they identified the number of cycles as one of the most influential parameters, and considerably more frequent cycling can be expected in FCR.

Arising from the intense cycling needs in the FCR application, previous research on storage technologies for this purpose shows clear technical and economic benefits achievable by the co-location of battery and flywheel storage assets (Beltramin, 2018). However, the existing literature regarding the LCA of electrochemical and mechanical energy storage systems has been limited to the comparison between distinct battery (Rehman et al., 2015; Bolund et al., 2007) and flywheel (Rahman et al., 2021) systems. The present work fills this gap by comparing both of these technologies and their combination, taking into account the significant downscaling achievable for each component in the combined hybrid system. In order to account for the significant influence of the cycling intensity, this study focuses on the cradle-to-gate impacts of storage systems when used specifically in the FCR application, as a function of the number of daily cycles. Consequently, this work enables the comparison of alternative FCR technologies, depending on the intensity of the charge–discharge cycling, while accounting for the savings that can be obtained by co-location, which has not been possible based on earlier literature alone.

2. Methodology

This study follows the guidelines set by ISO 14040:2006 (ISO 14040, 2006) and ISO 14044:2006 (ISO 14044, 2006). The standardised methodology consists of four stages: 1. Goal and scope definition, 2. Life cycle inventory (LCI) analysis, 3. Life cycle impact assessment (LCIA), and 4. Interpretation. The LCA process is an iterative process, where previous phases are revisited and reviewed throughout the study.

2.1. Goal and scope

The goal of this study was to determine the most environmentally sound technology for delivering an FCR service depending on the required amount of daily charge–discharge cycles. For this purpose, flywheel, battery and their hybrid systems were considered, and the selected scope included the materials used in the energy storage devices from cradle to factory gate. The use phase was excluded, as that was not seen as essential for the comparison between flywheel, battery, and hybrid systems,

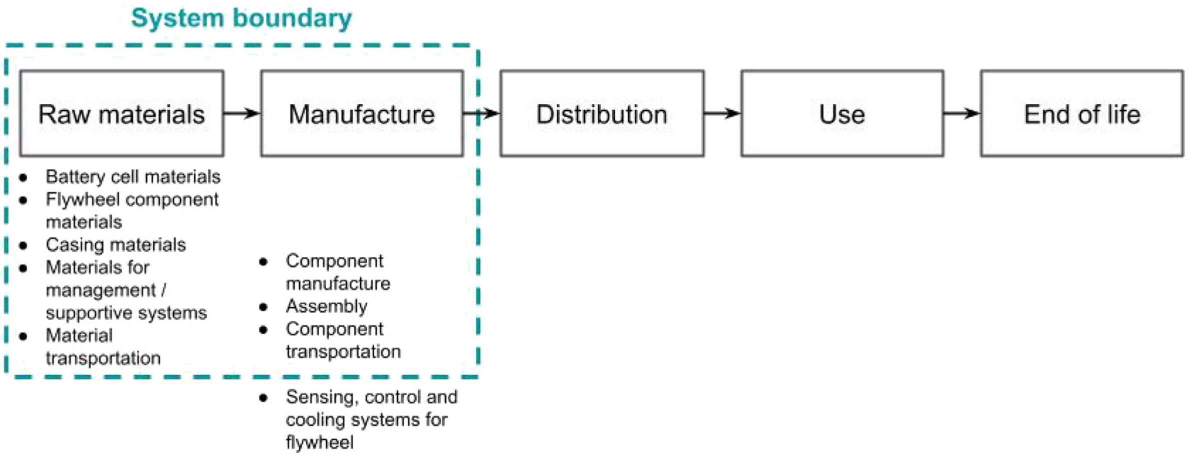

Fig. 1. Life cycle of the studied energy storage systems and the system boundary applied in the present study.

considering that all the alternatives were intended to be employed in the same use case with an identical energy source and with the same round-trip efficiency of 90%. Thus, the use phase impacts per kWh are expected to be approximately identical for the compared systems.

Likewise, the end-of-life phase was excluded, as it is still unclear what end-of-life strategies are going to be applied commercially. Especially in the case of LFP batteries, there are currently no efficient recycling methods in commercial application, and therefore their recycling impacts remain unknown as well. In addition, the sensing, control and cooling systems of the flywheel were excluded due to difficulties in obtaining data from suppliers. The applied system boundary is illustrated in Fig. 1.

2.2. Functional unit

In order to ensure the comparability of the environmental performance of the alternative systems, the functional unit selected was kWh of energy throughput during the system lifetime. To enable comparison with previous studies, we also report our results in terms of device mass in kg.

2.3. System description

2.3.1. System design

The battery chemistry considered in the current study was LFP, which is becoming the dominant type of battery used in stationary applications, owing to its favourable price and safety (Ellingsen et al., 2014; Quan et al., 2022). The gravimetric energy density of the battery was assumed to be 88 Wh/kg (Majeau-Bettez et al., 2011). Battery lifetime was estimated as 100 000 cycles at 0.2% depth of discharge (DoD) (Fox, 2013) or 7200 cycles at 80% DoD. The 0.2% DoD applies when the battery is operated alone (i.e. the battery directly delivers the microcycling demanded by the FCR application), whereas the 80% DoD applies when the battery is co-located with a flywheel (i.e. the battery is charged less frequently and discharged more fully, delivering energy to the flywheel component which performs the microcycling). The 7200-cycle lifetime estimation is based on earlier reports (Kalhammer, 2007; Shukla and Prem Kumar, 2008; Takahashi et al., 2005) of a battery lifetime of 6000 cycles at a DoD of 80% (Majeau-Bettez et al., 2011), with an added 20% extension because of the co-location (Dambone Sessa et al., 2018). In cases where the full cycle life was not reached in 25 years (300 or fewer daily cycles for the hybrid system), a calendric lifetime of 25 years was assumed.

The flywheel design under consideration was a hubless flywheel with a carbon fibre composite rotor levitated with permanent magnets and stabilised with active magnetic bearings. The flywheel power rating was 250 kW, energy rating 6 kWh and mass 2600 kg (including one replacement of the vacuum system and power electronics), corresponding to a gravimetric energy density of 2.3 Wh/kg. A lifetime of 1 825 000 cycles was conservatively estimated for the flywheel, although the mechanical storage mechanism and the shallow DoD in this application are likely to allow for a longer lifetime.

The capacity of batteries and flywheels needed as well as their lifetime depends heavily on the intended use case. Here, FCR was selected as the application in question. FCR involves repetitive shallow charge–discharge cycles (can even reach the level of hundreds of microcycles per day), which are taxing for batteries (Beltramin, 2018). In order to select the environmentally optimal storage method for FCR use, it is essential to understand the different alternatives for this purpose and their potential for CO_2 savings. Here, battery, flywheel and battery–flywheel hybrid systems were compared with varying amounts of daily charge–discharge microcycles. Simplified system models are illustrated in Fig. 2, where the flywheel only, battery only and hybrid battery/flywheel systems take in power input with varying frequency and discharge a stable power output through microcycling.

The energy rating of the storage system was assumed to be 2500 kWh, including 1.32-fold oversizing as earlier reported for a battery system (Majeau-Bettez et al., 2011), resulting in a total system size of 3300 kWh. This capacity is an example selected for the purposes of this study. Capacities of actual systems vary based on local needs. A 25-year lifetime was considered for the full system. As such, one generation of storage (Tables 1–2) refers to one installation of 3300 kWh capacity. Cases with more than one generation involve the replacement of this capacity during the 25-year period (i.e. the expression '1.5 generations' refers to replacing the storage system once and using the new installation for half of its lifetime to achieve the full service life of 25 years).

Both batteries and flywheels were assumed to have a round-trip efficiency of 90%. The power rating of the battery system was assumed to be 2500 kW, and in the hybrid system, 10% of this power capacity (250 kW; i.e. one flywheel) was added as flywheel capacity. This rating of flywheel capacity was selected as an example, following a typical capacity allocated for flywheel in hybrid storage systems for FCR. However, the optimal sizing for a practical system should be determined case by case based on modelling of the precise use case.

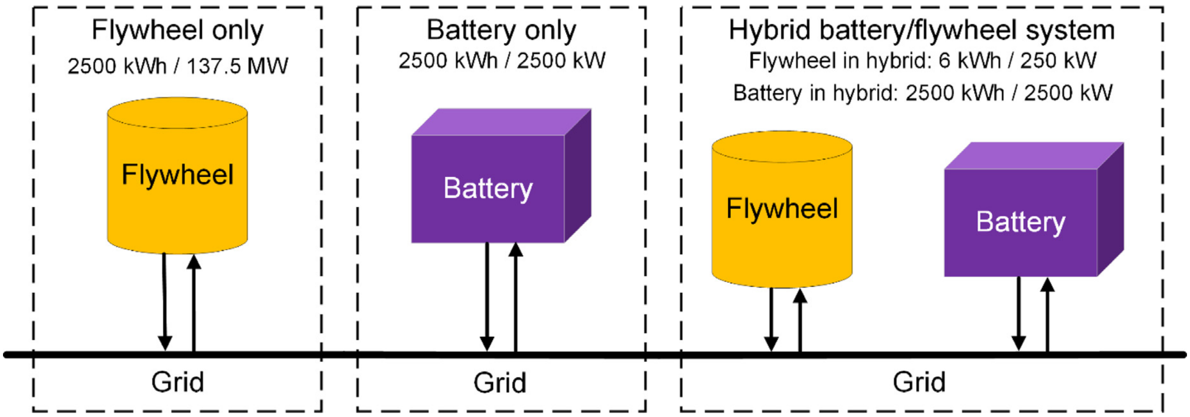

Fig. 2. Simplified system models illustrating the FCR function of the flywheel only, battery only and the hybrid battery/flywheel systems through microcycling. The systems are connected to the power grid, taking in and putting out power in varying frequency, producing the FCR service. The power capacities are presented for each system.

Table 1
LFP battery generations and mass required to implement the storage system with varying number of daily cycles.

Cycles per day	Daily throughput (kWh)[a]	Lifetime throughput (GWh)[b], Eq. (5)	Battery only		Battery in hybrid system	
			Battery generations, Eq. (4)	Battery mass per lifetime throughput (g/kWh), Eq. (1)	Battery generations, Eq. (4)	Battery mass per lifetime throughput (g/kWh), Eq. (1)
50	225	2.1	4.6	83	1	18.3
75	338	3.1	6.8	83	1	12.1
100	449	4.1	9.1	83	1	9.1
200	898	8.2	18.3	83	1	4.6
300	1350	12.3	27.4	83	1	3.0
400	1800	16.4	36.5	83	1.3	2.9
500	2250	20.5	45.6	83	1.6	2.9
1000	4500	41.1	91.3	83	3.2	2.9

[a] With 2500 kWh energy rating, 0.2% depth of discharge and 90% round-trip efficiency.
[b] Over 25 years.

The amount of storage needed to implement this system is indicated for different amounts of daily microcycles in Table 1 for batteries and Table 2 for flywheels, both alone and as part of the hybrid system. The storage mass per lifetime throughput $m_{lifetime}$ refers to the mass of the storage device required to deliver the 3300 kWh capacity $m_{storage}$, multiplied by the number of generations a and divided by the throughput over 25 years $E_{lifetime}$, calculated according to Eq. (1):

$$m_{lifetime} = \frac{m_{storage} \cdot n}{E_{lifetime}}, \tag{1}$$

Storage mass $m_{storage}$ needed per generation is calculated in the case of battery or flywheel following Eq. (2) or 3, respectively:

$$m_{storage\_battery} = \frac{E}{\rho_E}, \tag{2}$$

where E is 3300 kWh, and ρ_E is 88 Wh/kg (Majeau-Bettez et al., 2011).

$$m_{storage\_flywheel} = \frac{P}{\rho_P}, \tag{3}$$

where P is 250 kW in a hybrid system or 137.5 MW in a system with flywheel only, and ρ_P is 96 W/kg.

The required number of generations a depends on the number of daily cycles n according to Eq. (4):

$$a = \frac{n \cdot t}{n_{max}}, \tag{4}$$

where t is the system lifetime of 9125 days, and n_{max} is the cycle lifetime of the storage device, i.e.: 7200 cycles for battery alone, 100 000 cycles for battery as part of the hybrid system or 1 825 000 cycles for flywheel. In cases where the full cycle life was not reached in 25 years (≤200 daily cycles for flywheel or ≤300 daily cycles for the hybrid system), a calendric lifetime of 25 years was assumed for simplicity.

The energy throughput $E_{lifetime}$ during the full lifetime of the system was calculated following Eq. (5):

$$E_{lifetime} = n \cdot t \cdot RTE \cdot DoD \cdot E, \tag{5}$$

where n is the number of daily cycles, t is the system lifetime of 9125 days, RTE is the round-trip efficiency of 90%, DoD is the depth of discharge of 0.2%, except for the battery in the hybrid system with a DoD of 80%. E is the energy rating of the storage system, i.e.: 2500 kWh for battery (alone or in hybrid) or flywheel alone, or 6 kWh for flywheel in a hybrid.

Since the use phase is excluded from the system under study, as specified above, it is essential to note that the reported impacts represent solely the impacts from producing the amount of battery and flywheel capacity indicated in Tables 1–2 from cradle to factory gate. As such, the impact varies as a function of daily cycles, not because of impacts related to the charging and discharging events themselves (occurring in the excluded use phase), but rather because delivering a larger number of daily cycles requires a larger amount of capacity (due to the replacements needed after reaching the full cycle lifetime). The impacts of producing this increased capacity are distributed over the larger amount of throughput delivered during the system lifetime, resulting in a decreasing or plateauing impact per kWh, as seen below.

Table 2
Flywheel generations and mass required to implement the storage system with varying number of daily cycles.

Cycles per day	Daily throughput (kWh)[a]	Lifetime throughput (GWh)[b], Eq. (5)	Flywheel only		Flywheel in hybrid system	
			Flywheel generations, Eq. (4)	Flywheel mass per lifetime throughput (g/kWh), Eq. (1)	Flywheel generations, Eq. (4)	Flywheel mass per lifetime throughput (g/kWh), Eq. (1)
50	225	2.1	1	697	1	1.27
75	338	3.1	1	464	1	0.84
100	449	4.1	1	348	1	0.63
200	898	8.2	1	174	1	0.32
300	1350	12.3	1.5	174	1.5	0.32
400	1800	16.4	2	174	2	0.32
500	2250	20.5	2.5	174	2.5	0.32
1000	4500	41.1	5	174	5	0.32

[a] With 2500 kWh energy rating, 0.2% depth of discharge and 90% round-trip efficiency.
[b] Over 25 years.

Table 3
Inventory for the production of one 250 kW/6 kWh flywheel. The life cycle data for the items without a sub-inventory were obtained directly from the Ecoinvent 3.8 database.

Process	Amount	Sub-inventory
Functional unit output		
Flywheel (unit, total weight 2600 kg)	1	
Material requirements		
Carbon fibre reinforced polymer (kg)	120	Table S1–S2
Stainless steel (kg)	1850	Table S3
Electrical steel (kg)	170	Table S4
Reinforcing steel (kg)	17	
Cast iron (kg)	27	
Copper (kg)	130	Table S5
Soft magnetic composite (kg)	18	Table S6
Permanent magnet (kg)	14	Table S7
Aluminium, cast alloy (kg)	170	
Polyethylene terephthalate (kg) - *proxy for the plastics used in power electronics*	90	
Ceramic tile (kg) - *proxy for silicon nitride*	2	
Synthetic rubber (kg) - *proxy for Viton fluoroelastomer*	0.2	
Ferrite (kg)	0.02	
Energy and processing requirements		
Assembly of generator and motor, heat and power co-generation unit (unit) - *proxy for flywheel assembly*	1	
Transport requirements		
Transport, freight, train (tkm)	0.17	
Transport, freight, 16–32 metric ton lorry (tkm)	44	

2.3.2. Inventory analysis

The inventory for the LFP battery system was defined based on the literature (Majeau-Bettez et al., 2011), with the changes specified in Table S7. For the flywheel system, the inventory (Table 3) was based on the bill of materials obtained from the manufacturer, combined with the inventory of the vacuum system and power electronics as estimated by Rahman et al. (2021). One replacement of the vacuum system and power electronics was assumed during the device lifetime. As such, the components of these systems are counted double compared to the Ref. (Rahman et al., 2021). As the detailed inventories for each subsystem (housing, stator, rotor, motor-generator, active magnetic bearing, back-up bearing and levitation) are confidential, Table 3 shows the total amount of each material used in the whole device.

The assessment was conducted using SimaPro software, applying the Ecoinvent 3.8 database with a cut-off allocation method and calculation set-up based on unit processes. The IPCC 2013 GWP 100a method was used to investigate the global warming potential using the IPCC climate change factors with a timeframe of 100 years. Also, the ReCiPe 2016 endpoint method (hierarchist version) was used (with normalisation/weighting set World ReCiPe H/A) in order to identify the impacts in different categories.

2.4. Uncertainty analysis

Uncertainty analysis was conducted in order to account for the uncertainty in the values obtained from the database as well as the estimations for the device lifetime. The rotor of the studied flywheel system was designed for a lifetime of up to ~2 million cycles. To keep the assessment conservative, however, it is necessary to consider that the actual lifetime may vary between 1.6 and 2 million cycles. As such, 1 825 000 cycles was selected as the baseline for the flywheel lifetime, as mentioned above. To account for the expected variation, an alternative scenario was considered with a lifetime range of $\pm 10\%$ compared to the base scenario, assuming a uniform distribution. A similar variation was assumed in the battery lifetime (100 000 $\pm$ 10% cycles for a battery only, 7200 $\pm$ 10% cycles for a battery when co-located with a flywheel), to take into account the differences in the values reported for battery lifetime in the literature. Likewise, a 10% variation was considered in the amount of steel used in the flywheel housing, as that figure is still uncertain and will depend on safety practices that are yet to be established in the field of kinetic energy storage.

3. Results

The results concerning the global warming potential of the studied systems, sensitivity analysis as well as environmental impacts in other categories are presented and discussed below. In general, the results imply that the number of daily cycles significantly influences whether battery or flywheel storage is favourable, while the hybrid system has benefits regardless of the cycling intensity.

Table 4
Contributions of the LFP battery components to total GWP of 1 kg of battery.

Subsystem	GWP per kg of battery (kg CO_2-eq.)	Contribution to total GWP
Cathode material	5.16	26.4%
Anode material	0.80	4.1%
Electrode substrates	0.69	3.5%
Electrolyte and separator	0.37	1.9%
Cell container and packing	2.03	10.4%
Battery management system	3.20	16.3
Manufacture	7.33	37.4%
Total	**19.58**	**100%**

Table 5
Contributions of the flywheel components to total GWP of 1 kg of flywheel, calculated based on a total GWP of 18 800 kg CO_2-eq. for a 2600-kg flywheel.

Subsystem	GWP per kg of flywheel (kg CO_2-eq.)	Contribution to total GWP
Housing and stator	2.33	32.3%
Rotor (load-bearing part)	1.56	21.6%
Motor-generator	0.24	3.3%
Active magnetic bearing	0.18	2.6%
Backup bearing	0.14	1.9%
Levitation	0.10	1.4%
Vacuum system[a]	0.07	0.9
Power electronics[a]	1.97	27.3
Manufacture	0.63	8.7%
Total	**7.22**	**100%**

[a] Assuming one replacement during device lifetime.

3.1. Global warming potential (GWP)

The present work found that, in both studied systems, the active component in energy storage (cathode material for battery, rotor for flywheel) was among the most significant contributors to the global warming potential (>20% of total GWP, Tables 4–5). In the case of the LFP battery, 42% of the cathode material emissions originate from the production of $LiFePO_4$ (GWP 10 kg CO_2-eq./kg) and, surprisingly, 56% originate from the production of tetrafluoroethylene (GWP 121 kg CO_2-eq./kg, proxy for polytetrafluoroethylene). The total GWP per kg of battery (19.58 kg CO_2-eq./kg) was at a similar level as published before when using the referenced inventory (22 kg CO_2-eq./kg Majeau-Bettez et al., 2011); the small difference probably arises from the few proxies used and/or recent updates to the database. In the flywheel case, the rotor emissions are mainly due to the energy intensity of the production of the carbon fibre (GWP 49 kg CO_2-eq./kg) used for mechanical reinforcement.

In both systems, the casing also makes a significant contribution, represented by the cell container and packing in the battery (10.4% of total GWP, Table 4) and by the housing and stator in the flywheel (32.3% of total GWP, Table 5). The effect of the casing is particularly large for the flywheel because of the need for the housing to contain a vacuum and provide a safety barrier in the rare case of rotor failure. Another significant contributor is the manufacture, which accounts for the largest portion (37.4%, Table 4) of battery GWP or 8.7% of flywheel GWP (Table 5).

The cradle-to-gate GWP of the different storage systems was normalised against the energy delivered during the system lifetime, assuming different numbers of daily cycles, which influences how fully the initial installation is used before its end of life and how many replacements are necessary (Tables 1–2). The results show that the production of the battery-only system generates 1.62 kg CO_2-eq./kWh, regardless of the number of daily cycles (Fig. 3). This is because, according to the assumptions, the upscaling of the system to more intense cycling is attained by adding more battery generations (i.e., replacing the battery capacity) in corresponding proportion. As such, both the battery capacity and total kWh throughput increase in the same ratio, keeping the GWP per kWh constant.

For a system with flywheel storage only, the cradle-to-gate GWP per kWh drops until it reaches a number of daily cycles (200) that cannot be accomplished with only one flywheel generation, assuming a lifetime of 1 825 000 cycles. From this point onwards, the throughput and required flywheel capacity grow proportionally, which keeps the GWP per kWh steady. The flywheel GWP decreases below that of the battery system between 100 and 200 cycles per day. This shows that, with a low number of daily cycles, switching from battery to flywheel fails to pay off, because the required amount of battery generations remains low (<9, Table 1). Thus, switching to a flywheel system with a longer cycle lifetime is not justified due to the flywheel's lower energy density, which causes the need for a large capacity to implement the desired system. In this case, the installed flywheel capacity even remains underutilised, as the flywheel does not reach its full lifetime at this low amount of daily cycling. A similar trend has been previously reported for battery systems by Hiremath et al. with cradle-to-gate impacts decreasing as the storage approaches its full utilisation and reaching a plateau when used up to its full cycle lifetime (Hiremath et al., 2015).

When co-locating the battery with a flywheel, the GWP per kWh (i.e. the GWP of the production of both components divided by the total amount of energy delivered during the system lifetime) drops until it reaches a number of daily cycles (400) that cannot be delivered by only one generation of both batteries and flywheels. Until that point, the GWP per kWh drops because the employed system it used increasingly more effectively up to the full capacity of both components: the flywheel reaching its full cycle lifetime at 200 daily cycles and the battery component at 400 daily cycles. Importantly, these values refer to the cycles delivered by the whole system. While the whole system experiences 400 microcycles of 0.2% depth of discharge (DoD), the battery component only goes through one cycle per day at a DoD of 80%, as the microcycles are delivered by the flywheel component. For this reason, one battery generation lasts significantly longer in a co-located system compared to one with battery storage alone.

At >400 cycles per day, additional throughput of the hybrid system is gained by increasing capacity in proportion, thus maintaining the GWP per kWh level, similarly to the system with battery storage only and flywheel only at >200 cycles per day.

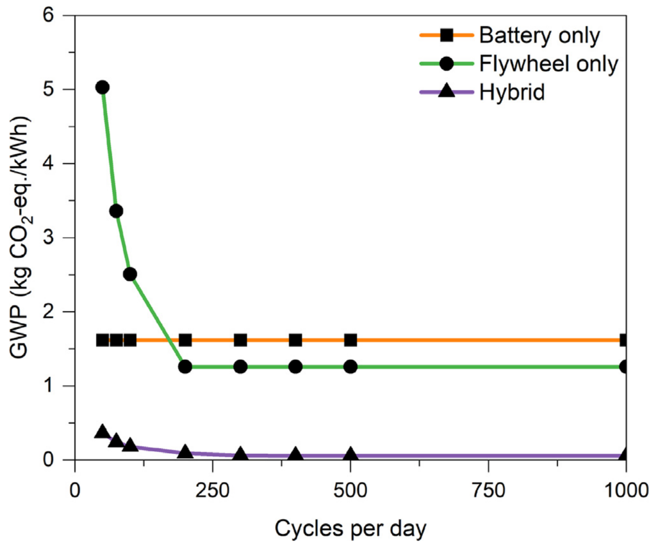

Fig. 3. Cradle-to-gate GWP per lifetime capacity, measured as kg CO_2-eq./kWh, for battery, flywheel and battery–flywheel hybrid systems.

Significantly, at any number of daily cycles, the hybrid system has the lowest GWP per kWh. This is because the co-location mitigates the downsides of each component. On the one hand, it decreases the need for new battery generations, as it eliminates the need for the battery to do frequent microcycling, which is handled by the flywheel component. On the other hand, co-location decreases the required amount of flywheel capacity, since the need for bulk energy storage is taken over by the battery component with a higher energy density. As such, a hybrid system can be regarded as generally recommendable for FCR applications, although at high numbers of daily cycles, switching from battery to a flywheel system already brings about a benefit.

The reason behind the environmental benefits of the flywheel and hybrid systems are highlighted by the masses of storage capacity needed to deliver the targeted function, as shown in Tables 1–2. Delivering 400 cycles per day for 25 years (lifetime throughput 16.4 GWh) by battery only requires 36.5 generations of batteries, each generation including 83 g of battery per kWh of lifetime throughput (i.e. nearly 50 000 metric tons of batteries). In contrast, when the battery is part of a hybrid system and benefits from the flywheel component handling the repetitive cycling, only 1.3 generations are sufficient, each of them with 2.9 g of battery per kWh of lifetime throughput (i.e. 62 metric tons of batteries in total). The decrease in battery need from 50 000 metric tons to 62 metric tons over the system lifetime explains most of the drastic drop in GWP.

Likewise, the need for flywheel capacity drops significantly, from 174 g/kWh to 0.32 g/kWh per generation when the flywheel is used as part of a hybrid system. This is because the battery covers most of the bulk energy storage capacity and a much smaller flywheel installation is needed to respond to quick changes in charge. This difference is so stark because of the much smaller energy density of the flywheel (2.3 Wh/kg) compared to the battery (88 Wh/kg Majeau-Bettez et al., 2011). Even a small amount of battery can deliver the bulk storage capacity that would otherwise take a large flywheel installation. Nevertheless, when comparing the flywheel and battery alone with high cycling, the impacts of the flywheel production are smaller because of the limited cycle life of the battery resulting in the need for 50 000 metric tons of battery to deliver 400 daily cycles, as explained above.

3.2. Uncertainty analysis

The uncertainty of the results was analysed in order to confirm the trend of GWP decrease from battery to flywheel to hybrid storage at intense cycling (≥400 cycles per day, i.e. the plateau level in Fig. 3), considering the uncertainty of the database values as well as a variation of ±10% in the cycle lifetime and the mass of flywheel housing. Applying these ranges in the assumptions caused a ±10% variation in the required storage mass (Fig. 4a), which resulted in a variation of ±7% in the GWP of battery and hybrid systems or ±8% in the GWP of the flywheel system (Fig. 4b). Even with this extent of uncertainty, the same conclusion applies: switching from battery to flywheel can decrease the GWP by 24% (from 1.65 ± 0.12 to 1.26 ± 0.11 kg CO_2-eq./kWh), while using a hybrid system instead decreases the GWP further, even by as much as 96% (from 1.65 ± 0.12 to 0.059 ± 0.004 kg CO_2-eq./kWh).

3.3. Other impact categories

In all of the ReCiPe midpoint impact categories, the hybrid storage system appeared preferable with the lowest impacts (Fig. 5). This is because this system needs the smallest amount of storage device installations (Tables 1–2), as the storage capacity of the battery and the cycling capacity of the flywheel complement each other. Among the single-component systems, the battery causes the highest impact in most of the categories due to the heavy need for many battery generations at frequent cycling (≥400 cycles per day, Fig. 5, Table 1). However, the flywheel causes higher impacts on human carcinogenic toxicity and has comparable impact levels to the battery regarding mineral resource scarcity, terrestrial ecotoxicity and marine eutrophication.

In the flywheel case, human carcinogenic toxicity and mineral resource scarcity are mainly caused by the production of steel for the structure, while terrestrial ecotoxicity arises mainly from the production of copper for the power electronics and coils used in the active magnetic bearings and motor/generator. Marine eutrophication is mainly caused by the production of the permanent magnets used in the motor/generator, active magnetic bearings, and levitation systems. These impacts highlight the importance of optimising the housing and stator structures. Also, finding alternatives for permanent magnets, such as using a permanent magnet free rotor design or acquiring the permanent magnets in recycled form could mitigate the impacts on marine eutrophication.

4. Discussion

4.1. Effect of co-location

The results show that, among the compared storage systems, the hybrid system can be considered the most recommendable in terms of GWP and all the ReCiPe impact midpoint categories. This is because the co-location significantly downscales the need for each component (Tables 1–2) by capitalising on the key advantages of the different storage technologies: the battery acts as the bulk energy storage with its larger storage capacity, while the flywheel handles the repetitive charge events as the more resilient technology against frequent cycling. This is in alignment with the technical and economic benefits shown for hybrid systems previously (Beltramin, 2018).

Despite the benefits expected from co-location, previous research regarding the LCA of electrochemical and mechanical energy storage technologies has been limited to the comparison between different battery (Rehman et al., 2015; Bolund et al.,

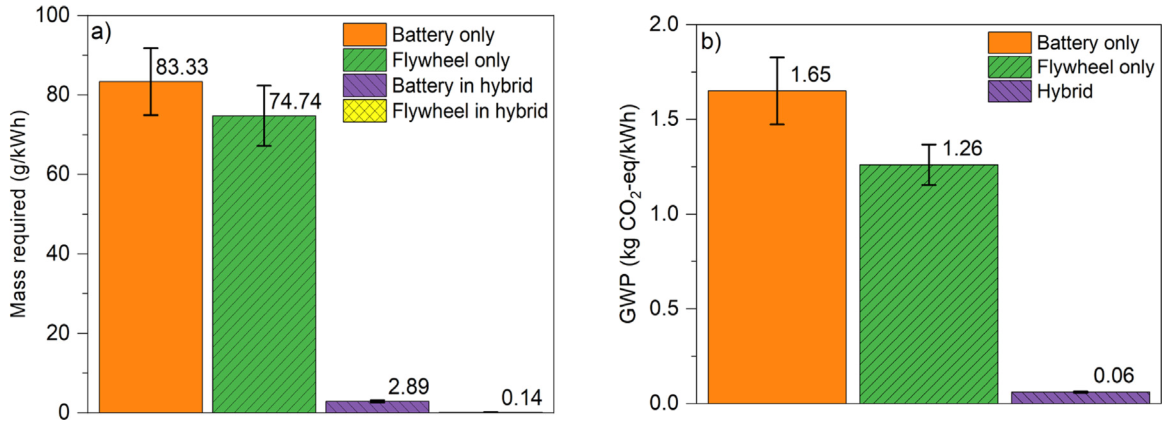

Fig. 4. (a) Need for storage at plateau level (≥400 cycles per day) as required mass and (b) cradle-to-gate GWP at plateau level as kg CO_2-eq./kWh (b). Error bars are based on sensitivity analysis considering ±10% variation in battery and flywheel lifetimes.

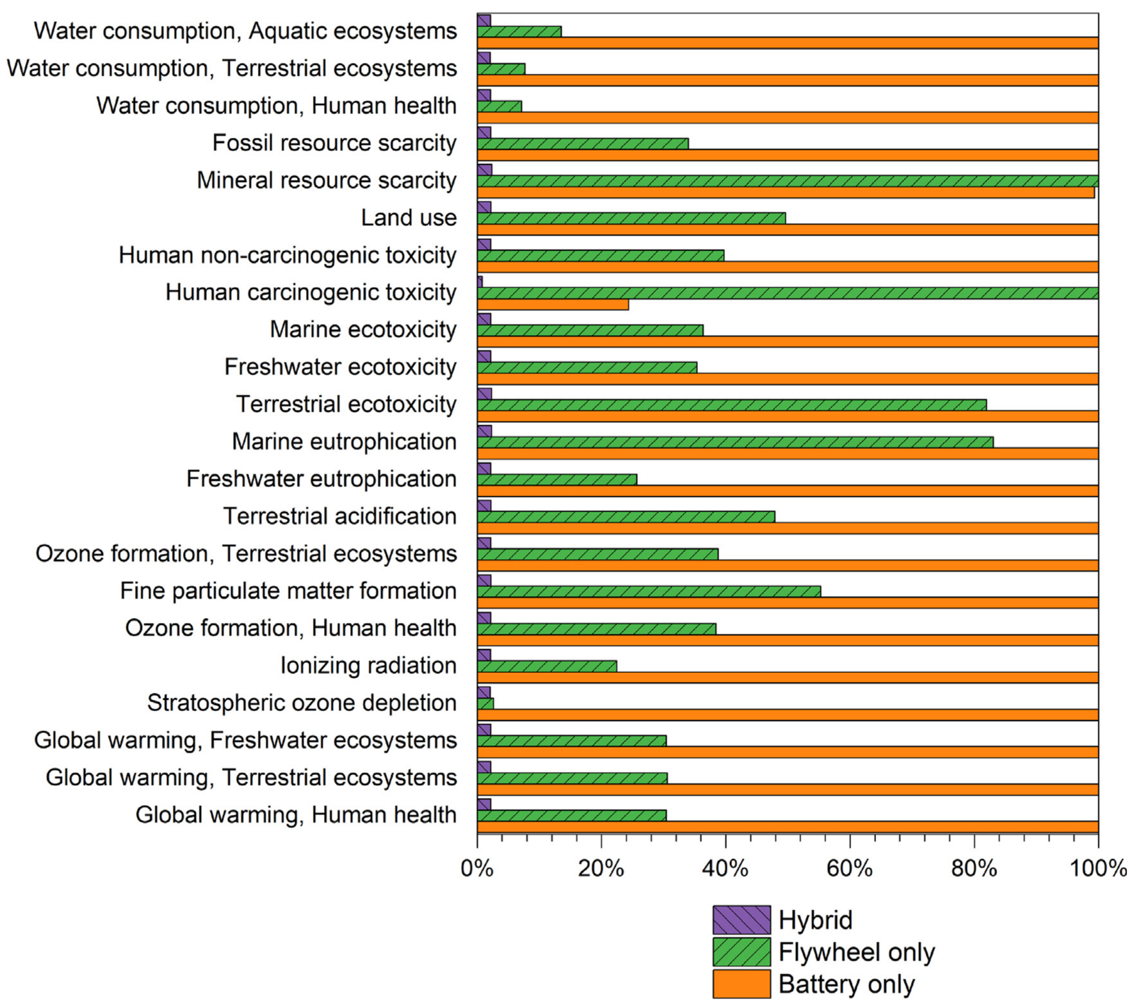

Fig. 5. Relative impacts in ReCiPe midpoint categories at the plateau level (≥400 cycles per day).

2007) and flywheel (Rahman et al., 2021) systems. The present methodology compared alternative storage technologies and their combination, while taking into account the significant downscaling achievable for each component of the hybrid system. The results show that co-location can bring about not only techno-economic but also clear environmental benefits (i.e. a decrease of up to 96% in cradle-to-gate GWP, Figs. 2–4, and a significant reduction in all the ReCiPe midpoint impact categories, Fig. 5).

4.2. Effect of the number of daily cycles

In the case of a single-component storage system, the choice of the best environmental performance depends on the expected number of daily charge events. A battery is preferable for fewer (<150) charge events and a flywheel for more frequent (>150) charge events, in terms of GWP and most of the ReCiPe midpoint impact categories. This trend in the cradle-to-gate impacts arises from the characteristics of the energy storage systems studied.

As an electrochemical storage, batteries are subject to increasing cell temperature upon frequent charging and discharging, which accelerates their ageing (Ram et al., 2019; Arrobas et al., 2017). For example, for a stationary LFP battery ESS operated with one full cycle per day, the degradation has been estimated to be approximately 1% in capacity loss per year (Müller et al., 2017). With an increased number of shallow cycles, as would be the case in FCR applications, the degradation rate can be expected to be notably higher. This leads to the need for frequent battery replacements, as reported earlier by Hiremath et al. who estimated 4.6 generations of Li-ion batteries in an FCR application during 20 years with 34 daily cycles of 5% DoD, while other applications with $\leq$2 daily cycles of 80% DoD only required 1.7 generations (Hiremath et al., 2015). As a mechanical storage system, flywheel lifetime is longer and essentially unaffected by the intensity of charging and discharging. However, a flywheel has an intrinsically lower energy density than a Li-ion battery (Bao and Li, 2015; Shukla and Prem Kumar, 2008), which leads to the need for a large installation to achieve the desired energy storage capacity when flywheels are used alone.

The difference between battery and flywheel systems (24% lower GWP for the flywheel at the plateau level) is somewhat less than was concluded in the earlier study by Rahman et al. i.e. ~50% lower cradle-to-gate greenhouse gas emissions for a composite flywheel in comparison to a Li-ion battery (Rahman et al., 2021). However, it is not fully feasible to make a direct comparison across studies, as the systems under consideration were different in terms of size and configuration. In particular, the other authors assumed flywheel energy and power capacities of 25 kWh and 100 kW, respectively (Rahman et al., 2021). This represents a flywheel optimised for energy storage rather than for power generation, in contrast to the present assumption of 6 kWh of energy and 250 kW of power capacity. With the larger energy storage capacity, the emission reduction was already achieved at 4000 cycles per year (Rahman et al., 2021), while the present results indicate that at least 200 daily cycles would be required to attain the same benefit with a power-optimised flywheel. This kind of flywheel is preferable in practice, however, in applications like FCR where a fast response is more critical than high energy content.

Previous studies concerning FCR applications have been limited to a single assumption for the daily charge events (between 10 and 34) (Chen et al., 2009; Bolund et al., 2007), even though the real intensity of cycling can vary unpredictably and reach hundreds of microcycles per day. The methodology presented here provides a simple way to assess the cradle-to-gate environmental performance of different storage systems as a function of daily cycles. The future work is relevant concerning the employment of this approach on other storage configurations and technologies, especially in applications characterised by intense cycling.

4.3. Leverage for impact reduction

The environmental impacts of battery systems depend largely on the battery chemistry and materials. Generally, the impacts can be reduced by choosing better performing materials and production processes that offer the same function with smaller GWP contributions. Recycled raw materials in battery production can significantly decrease impacts (Rinne et al., 2021), especially in the case of nickel- and cobalt-containing battery cells. However, this is not necessarily true for battery cells with low-cost and more abundantly available materials, such as LFPs, which can even show increased impact values due to recycling (Goris and Severson, 2018; Rinne et al., 2021).

Significant savings in the GWP of a flywheel could be attained by substitution with low-impact carbon fibre, such as carbon fibre produced with renewable energy, using alternative precursors and/or switching (partly) to recycled carbon fibre. Presently, however, there are relatively few lower impact options for carbon fibre available. Likewise, the impacts of the housing could be mitigated by optimising the sizing of the steel housing and considering other housing materials with lower impact. This is challenging, however, as the housing needs to maintain a vacuum inside and provide a safety barrier in the rare case of rotor failure.

Rahman et al. concluded that composite rotor materials made a more significant GWP contribution than housing (Rahman et al., 2021). This is because these authors assumed the use of ~600 kg of housing per ~120 kg of composite rotor, while the present flywheel design involves ~1 metric ton of housing for a similar amount of rotor. This highlights how the flywheel design influences the criticality of each component in terms of cradle-to-gate GWP. As such, the most effective strategy to reduce flywheel impacts may be to substitute the most easily replaceable materials and minimise the use of the rest through the design.

4.4. End-of-life

The end-of-life stage was not considered in the quantitative analysis here, due to the remaining uncertainties regarding the recycling scenarios for batteries and flywheels on a large scale. LFP battery cells are currently not recycled on commercial scale due to the low economic value of the cathode materials and challenges in recycling technologies (Wang et al., 2022). According to the current research, there are different technical solutions to extract lithium from spent LFP batteries, but they all have their drawbacks. Using state-of-the-art technologies, none of the LFP cathode elements (Li, Fe, phosphate) are recovered by the existing pyrometallurgical plants, whereas hydrometallurgical methods have also recently been developed for Ni- and Co-rich battery chemistries, disregarding LFP elements other than lithium. Currently, the most viable end-of-life strategy for LFP batteries are various second life applications (Wang et al., 2022); however, this does not solve the challenge of true end-of-life for battery materials.

Recycling has been shown to reduce the GWP values of batteries in general, although the majority of the impacts arise from the energy consumption in cathode material manufacturing (Dunn et al., 2014), which may not be significantly lower in recycling processes. For LFP batteries, recycling is estimated to reduce the GWP over the cell life cycle by approximately 5%–10% (Forte et al., 2021). A review by Murdock et al. even concluded that no amount of LFP recovery could offset the greenhouse gas emissions from both the recycling process and the incineration of other waste components per se; climate benefits can be attained only if direct recycling of LFP cathodes becomes technically and industrially feasible (Murdock et al., 2021). This has been suggested as technically possible for LFP batteries via a regeneration method using a pre-lithiated graphite anode (Wang et al., 2020). However, many other factors, such as battery waste heterogeneity, the manual processing steps required or the need for additional virgin materials, must be considered when evaluating the industrial feasibility of direct recycling processes (Ji et al., 2021).

In contrast, flywheel recycling is more accessible via existing industrial processes. According to the inventory of flywheel production (Table 3), 91% (2360 kg) of the mass of the product consists of steel, copper and aluminium with existing circular economy practices (Euractiv, 2018). In addition, commercial processes are emerging for recycling carbon fibre (72 kg, 2.8% of the total mass, Table 3) based on pyrolysis and solvolysis (Karuppannan Gopalraj and Kärki, 2020). However, their widespread commercial implementation is largely being held back by the lack of markets, high cost of recycling and lower quality of the recyclates (Yang et al., 2012).

The remaining 168 kg of the flywheel includes 14 kg of permanent magnets (0.6% of total mass, Table 3). Presently in the EU, there is negligible industrial recycling of critical rare earth elements (REE) from end-of-life permanent magnets (<1% recovery rate of rare earth permanent magnet scrap), which has been identified as a critical topic regarding European independence of raw materials (Gauz et al., 2021). Magnet recycling is hindered mainly by challenges with the collection and separation of magnet scrap from waste streams (Binnemans et al., 2021) as well as the lack of incentives (Binnemans et al., 2013). As such, the permanent magnets in decommissioned devices represent a large, untapped resource that could make the permanent magnet industry significantly more sustainable and geographically distributed. In addition to separation, another challenge arises in the metallurgical recycling after demagnetisation and crushing, as the similarity of different REE makes the process of separating them from each other a complex one (Liu et al., 2020). Hydrogen decrepitation (Walton et al., 2015) has been proposed as a method for selective recovery of NdFeB and is in the process of commercialisation. Other selective processes exist as well, such as ammonium sulfate roasting, which is already being employed in China (Liu et al., 2021).

Consequently, extensive R&D efforts and investments are needed in order to establish large-scale recovery and recycling of both rare earth permanent magnets and carbon fibre. When set up industrially, the recycling of carbon fibre and permanent magnets could increase the recyclable content of the flywheel to above 94%. Furthermore, technical developments in the area of recyclable thermoset resins could also enable the recycling of epoxy resin (48 kg or 1.8% of the total mass) and soft magnetic composite (18 kg or 0.7% of the total mass), increasing the recyclable content above 99%. It should be noted, however, that the recycling rate will remain lower than that, due to inevitable losses in the separation and recycling processes.

It is also important to consider that the practical feasibility of recycling these materials depends on the possibility to separate them from the product. In particular, challenges are expected with separating the components of the rotor, which consists of carbon fibre reinforced epoxy resin attached to steel, soft magnetic composite and permanent magnets. A design-for-disassembly approach is necessary to design rotors that can be feasibly separated into their components for recycling.

5. Conclusions

This study showed that a significant environmental benefit (up to 96% decrease in cradle-to-gate GWP and significant reduction in all ReCiPe midpoint impact categories) could be achieved by the co-location of battery and flywheel storage systems for use in FCR applications. A moderate saving of 24% in GWP could already be achieved by switching from a battery to flywheel storage system with intense charge–discharge cycling (200 or more charge events per day). This trend arises from the accelerated battery ageing due to frequent cycling, the limited energy density of the flywheel and the capability of both components to compensate for each other's shortcomings in the hybrid system, leading to significant downscaling in the need for storage capacity. The trend was clear even considering the uncertainty analysis that showed a ±7%–8% variation in the GWP of the systems studied here.

The impacts could be reduced by selecting better performing materials and processes that provide competitive performance with lower impact, especially for the active storage components (i.e. cathode material for battery and rotor for flywheel), casing and manufacture, which cause the majority of the GWP. In the future, further improvements in recycling technologies, along with appropriate design for recycling, may also reduce the environmental impacts. Extensive R&D efforts are needed to establish a circular economy for the critical materials included in the systems studied, such as LFP cathode material, permanent magnets and carbon fibre composite. Also, further analysis including the end-of-life phase would clarify the influence of different recycling scenarios on the life cycle impacts.

CRediT authorship contribution statement

Meri Lundahl: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Funding acquisition, Project administration. **Heikki Lappalainen:** Investigation, Visualization, Writing – original draft. **Marja Rinne:** Validation, Writing – review & editing. **Mari Lundström:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data is available in the manuscript and the supporting information.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.egyr.2023.08.088.

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