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Review article

Enhancing vehicular performance with flywheel energy storage systems: Emerging technologies and applications

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ABSTRACT

Flywheel Energy Storage Systems (FESS) are a pivotal innovation in vehicular technology, offering significant advancements in enhancing performance in vehicular applications. This review comprehensively examines recent literature on FESS, focusing on energy recovery technologies, integration with drivetrain systems, and environmental impacts. A detailed comparison with lithium-ion batteries highlights the efficiency and sustainability of FESS. The study delves into various FESS technologies, components such as bearings and rotor design, and evaluates their advantages and limitations. It also addresses current challenges in FESS implementation, proposing potential solutions. Diverse applications of FESS in vehicular contexts are discussed, underscoring their role in advancing sustainable transportation. This review provides comprehensive insights and identifies emerging trends, paving the way for future research and development in energy storage technologies.

1. Introduction

The urgency to decrease emissions has never been more critical. The current path of greenhouse gas emissions is causing unprecedented shifts in the climate, which could have severe and irreversible consequences for ecosystems, economies, and communities [1]. The levels of carbon dioxide, a major greenhouse gas released by human activities, have reached unprecedented levels, leading to global warming and a wide range of climate disruptions [2]. Urgent and ongoing efforts to reduce emissions are crucial to address the severe consequences of climate change, safeguarding a stable and thriving planet for future generations. At this critical moment, the shift towards low-emission technologies and sustainable practices is crucial for both the environment and the well-being of humankind [3]. The road transport sector is a major contributor to global carbon dioxide emissions, accounting for approximately 25 % of the total emissions [4].

The domestic Greenhouse Gas (GHG) emissions from the transportation sector have remained relatively stable over the past three decades, while emissions from other sectors have decreased. The improvement in engine efficiency has been offset by the increase in the number of journeys made. Similarly, the rise in electric and hybrid vehicles has been counterbalanced by the increase in the number of diesel and petrol SUVs on the road. Cars and taxis account for 55.4 % of the United Kingdom's emissions from domestic transport, amounting to 67.7 $MtCO_2$ [5]. The primary objective of the UK government is to achieve transport decarbonization through zero tailpipe emissions [6]. However, it can be argued that this objective may provide a limited viewpoint on the wider environmental issues linked to transportation. Although zero tailpipe emissions do decrease local pollutant levels, it is important to recognise that this does not necessarily imply that electric vehicles are completely environmentally neutral. This is because the carbon footprint associated with generating the electricity required to power these vehicles must be considered. In areas where the energy grid is heavily dependent on fossil fuels, the transition to electric vehicles may not result in the desired overall decrease in GHG emissions [7]. Hence, the process of decarbonizing the transportation sector encompasses more than simply shifting to electric vehicles [8].

A comprehensive strategy is needed, encompassing the establishment of a low-carbon energy network, enhancements in the energy efficiency of all transportation methods, and funding for zero-carbon fuels that can be used to curtail the emissions from the existing fossil fuel-powered vehicles and for applications where electrification remains unattractive such as mining and off-road machinery [9]. In the near to intermediate future, a practical approach would entail decreasing emissions from current vehicles, a significant portion of which will continue to be utilised for the next two to three decades. In essence, the primary objective is to reduce overall emissions rather than simply shifting the origin of these emissions. Instead of completely replacing

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the existing vehicle fleet with new electric vehicles, which could unintentionally increase total emissions due to energy-intensive manufacturing processes and the potential GHG emissions associated with electricity production, it is recommended to adopt measures that reduce the emissions from the vehicles already in use. This approach not only conserves the stored energy and materials of the current vehicles but also avoids the significant emissions linked to the manufacturing of new vehicles, which may only reduce tailpipe emissions. Policy and innovation should prioritise improving the environmental performance of the transport sector in a comprehensive and sustainable manner [10].

The waste energy generated by vehicles can be utilised to improve the efficiency of the system. Energy Recovery Systems (ERSs) are used to retrieve the energy that would otherwise have been lost. These systems collect and store the unused energy, allowing it to be used later, which decreases the need for external energy sources or fuel. The deliberate utilisation of ERSs across various powertrain technologies greatly enhances the overall efficiency of the vehicle. ERSs play a crucial role in improving the energy efficiency of vehicles and are also instrumental in tackling concerns surrounding GHG emissions and the adverse effects of global warming. These solutions are crucial and can be implemented in the near to medium future. They help reduce the negative effects of the automotive industry on the environment by lowering carbon emissions and supporting the goals of sustainable transportation [11]. Research and innovation related to energy recovery (ER) have been ongoing since the 1970s [11]. Nevertheless, the automotive industry historically prioritised conventional areas of improvement, such as engine efficiency and aerodynamics, to enhance the fuel efficiency of vehicles. However, automotive manufacturers have recently recognised that ERSs offer a cost-effective solution. As a result, they are now fully exploring the potential benefits of these systems [11].

ERSs are currently present in certain vehicle models, regardless of the powertrain type. ERSs have already been incorporated into ICE vehicles by BMW and Renault [12,13]. However, Hybrid Electric Vehicles (HEVs) such as the Toyota Prius and BEVs such as the Nissan Leaf already incorporate kinetic energy recovery systems (KERSs) in their vehicles, which is also referred to as regenerative braking [14]. Amidst an automotive sector that prioritises efficiency improvements, the growing prevalence of new vehicles equipped with ERSs underscores the advantages derived from these systems in terms of fuel economy.

This review paper comprehensively explores the application of Flywheel Energy Storage Systems (FESS) in vehicular technologies, evaluating each system component and its compatibility with existing powertrain configurations. It provides an in-depth analysis of FESS technology in vehicles, comparing it with other storage systems and assessing its effectiveness in energy recovery. The paper begins by discussing various energy recovery systems. It then focuses on different energy storage devices, with a detailed examination of flywheel energy storage technology. Subsequently, the review highlights the current applications of FESS across multiple transportation modes, including vehicles, buses, trains, and trams. The analysis extends to key components and design considerations, such as bearing selection, rotor design, and control systems. Furthermore, it addresses the limitations of FESS, including safety challenges and gyroscopic effects, and concludes by discussing strategies for optimising standby losses, considering factors such as airgap size, rotor material, and slit wall design. The paper also looks ahead to future trends in FESS development, covering aspects such as hybrid systems and the expansion of FESS into commercial and public transport.

2. Energy Recovery Systems

An Energy Recovery System (ERS) is designed to make the most of an abandoned energy source and achieve a high ratio of energy recovery. The system should facilitate the ongoing extraction of energy and provide a significant improvement in efficiency under all driving conditions. An ideal ERS is anticipated to efficiently capture and store all retrievable energy with minimal losses during charge and discharge cycles [11]. Furthermore, an efficient ERS should integrate seamlessly into a vehicle's architecture without imposing significant additional weight or space demands. It should utilise existing vehicle components to the greatest extent feasible, ensuring that any necessary new parts are cost-effective, sustainable in terms of their life cycle (recyclable and non-toxic), and involve low embodied energy in their production. The system should be easy to retrofit, avoiding the need for extensive alterations to the existing vehicle framework [11]. ERSs are initially categorised based on the energy source that can be recovered, exhaust gas energy, energy from the vertical oscillations of the vehicle body, and kinetic energy from the vehicle inertia. After the initial classification, systems are further categorised based on the type of energy they recover, the storage mechanisms they use, and the specific technologies they employ. Fig. 1 displays the categorisation of the ERS for automotive applications.

Exhaust gases produced by Internal Combustion Engines (ICE) release significant thermal energy [15], which can be harnessed by employing systems such as Thermoelectric Generators [16] and Rankine Cycle Systems [17]. However, these systems face limitations in terms of retrofitting complexity and the inability to store energy for long durations [17]. Flywheel systems, in contrast, can store kinetic energy more efficiently, offering the flexibility to discharge it rapidly on demand [18]. While exhaust gas recovery systems excel at continuous energy recovery, FESS provides an advantage in its ability to manage power surges and supplement powertrain efficiency without the constraints of complex retrofitting [18]. Regenerative shock absorbers capture kinetic energy from vertical oscillations during vehicle motion, offering modest gains in fuel efficiency, particularly for heavy-duty vehicles and uneven terrains [19]. However, these systems face challenges in scalability for light-duty vehicles due to costs and frequent maintenance [19].

The primary source in inertial energy recovery is the vehicle's inertia resulting from its speed. When deceleration is required, a force must be applied to counteract the vehicle's inertia. This is typically achieved by the braking system, which reduces the speed by converting the kinetic energy into heat due to friction [11]. However, it is feasible to recover a fraction of this kinetic energy and store it, particularly during the process of acceleration, thus decreasing the engine's load and subsequently reducing fuel consumption. Systems that recover energy based on vehicle inertia are known as Kinetic Energy Recovery Systems (KERS) [20]. As these systems recover the energy mainly during braking events, the process of energy recovery is known as Regenerative Braking (RB) [21]. KERS technology varies in terms of energy capture and storage capabilities. Nonetheless, all KERSs share a common benefit stemming from the considerable mass and velocity of light-duty vehicles which present a high potential for energy recovery due to their high momentum [20]. The usage of KERS has seen a significant rise in the past decade, driven by the growing interest in enhancing the efficiency of ICE vehicles and the advancements in hybrid and electric vehicle technologies. RB is a well-established technology in the transport sector, particularly in electric locomotives. RB can be a crucial component of electric vehicles as it addresses the requirements of reducing battery size, range extension, and improving performance [22]. The primary limitation of KERS, however, lies in the intermittent nature of energy recovery, which is constrained to the duration of braking events.

While ERS systems such as thermoelectric generators, regenerative shock absorbers, and KERS each provide methods for recovering lost energy, their efficiency is often limited by storage capabilities and energy conversion losses. FESS offer a unique advantage by storing energy in mechanical form with high efficiency and rapid discharge capabilities. This makes FESS particularly suitable for applications that require short bursts of energy, such as acceleration in vehicles, offering more practical benefits over traditional ERS in vehicular contexts.

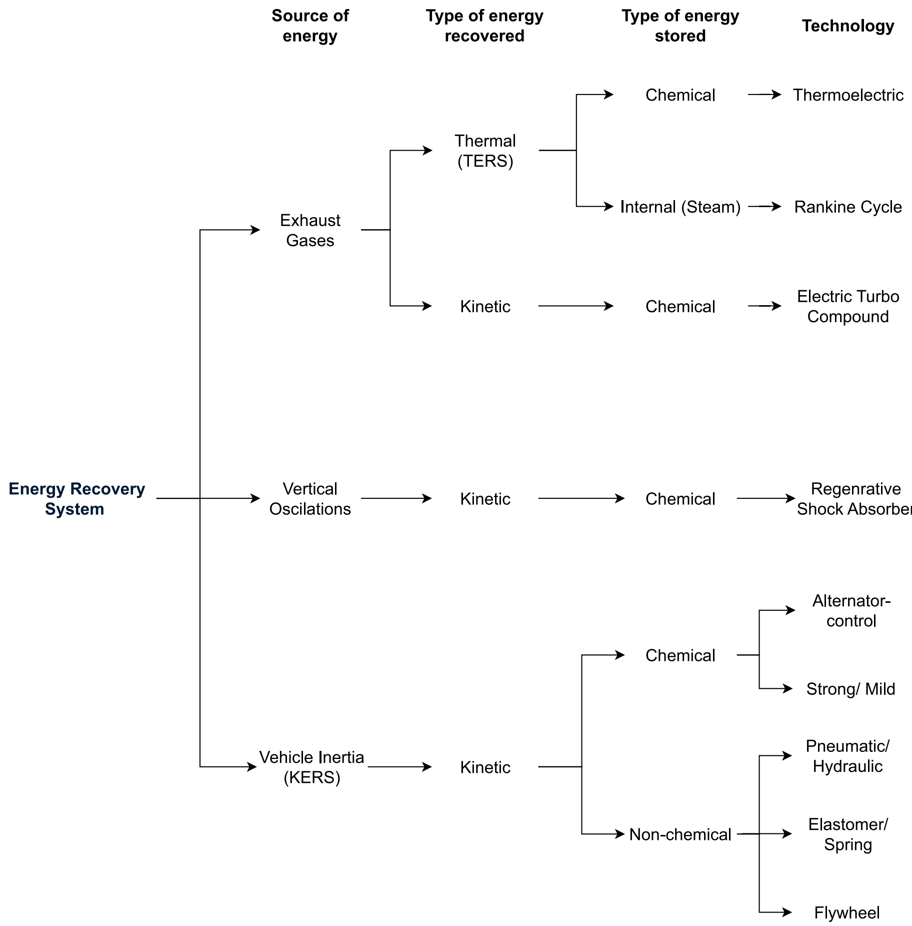

Fig. 1. The categorisation of energy recovery systems for automotive applications [11].

3. Storage devices

Although RB maximises energy recovery in a vehicle, it requires a storage medium to store the captured energy. Some of the most cutting-edge technologies in the field include batteries, pneumatic/hydraulic storage, and flywheels. In addition, ongoing development in the field of supercapacitors has shown its potential as a future energy storage solution. Power density plays a crucial role in the effectiveness of KERS. Energy density is also considered when the same energy storage system serves as the main energy source for propulsion [23]. In most applications, the size of storage devices is crucial. Fig. 2(a) presents a comparison of the power density and energy density of different energy storage technologies. As power and energy densities increase, the volume needed for energy storage decreases. The compact technologies ideal for applications with limited volume can be found in the top right corner of Fig. 2(a), whereas the storage systems that require a larger volume are located in the bottom left corner [24].

Specific power and specific energy are valuable metrics that quantify the amount of power and energy in relation to weight. Fig. 2(b) provides a comparison of the specific power and specific energy of various energy storage technologies [24].

The weight of the energy storage system depends on the specific power and specific energy required to obtain a certain amount of energy. As evident in Fig. 2(a) the energy and power densities of most batteries,

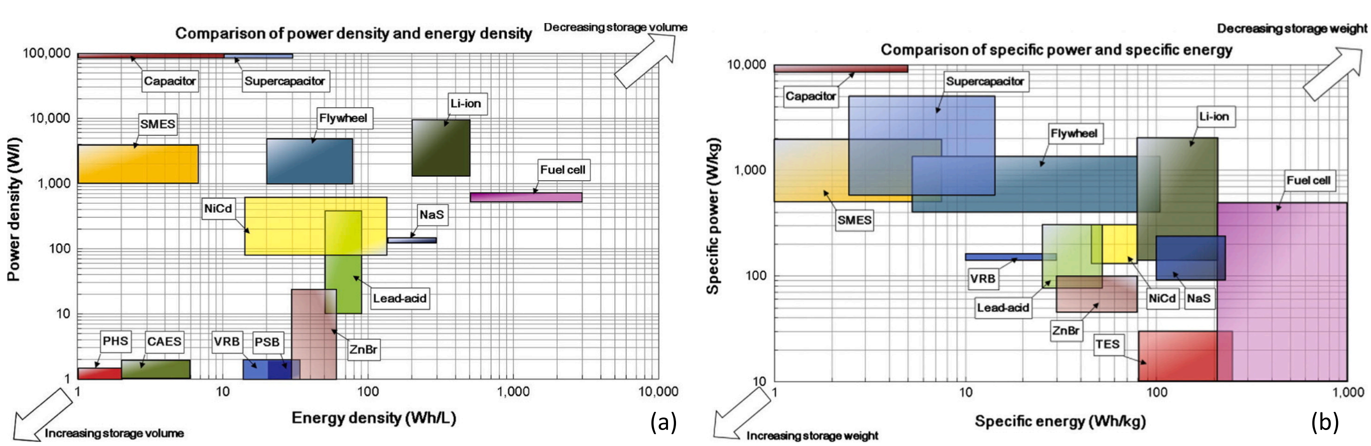

Fig. 2. Comparison of different energy storage systems based on: (a) power and energy densities and (b) specific power and specific energy [24].

flywheels, and fuel cells are relatively low [23]. Supercapacitors and capacitors boast impressive power densities, yet their energy densities leave much to be desired. Due to their rapid response time, capacitors and supercapacitors exhibit high specific power but relatively low specific energy [25]. It is worth noting that fuel cells possess a remarkable specific energy-to-power ratio, although their specific power-to-energy ratio is relatively low. Located at the middle levels of specific power and specific energy, flywheels have a wide range of applications. Finally, Li-ion batteries are known for their impressive high specific energy and specific power [26].

It is acknowledged that no individual energy storage technology can meet the needs of all energy storage system applications. An extensive analysis of different energy storage technologies relevant to the automotive sector has been conducted in this research work. Response times ranging from milliseconds to seconds and discharge durations spanning from seconds to hours are crucial for transportation applications. These requirements can be met by utilising a variety of energy storage technologies, including fuel cells, capacitors, supercapacitors, flywheels, and Li-ion batteries. Tables 1 and 2 present the characteristics of various energy storage technologies that can be utilised in vehicular applications. Although each technology possesses distinct characteristics, flywheel technology has been identified as a promising technology due to its outstanding power and specific power capabilities, rapid response time, and exceptional cycle life. The aforementioned attributes make flywheels highly suitable for automotive applications that require quick energy release and frequent cycling, providing a dependable and long-lasting energy storage solution. Although other technologies may have their advantages, flywheels provide a compelling equilibrium of performance, efficiency, and longevity.

Vehicles can use various energy storage systems, such as batteries, ultracapacitors, pneumatic systems, and elastomer-based solutions, to recover and store energy. Although each technology offers a set of benefits, FESS provide unique advantages in terms of rapid energy recovery and power delivery [55].

Electric KERS store energy in batteries, which are widely used for their availability and long-term storage capability [56]. However, batteries face challenges such as limited cycling durability, lower energy density, and reduced efficiency in cold conditions, making FESS a superior choice for applications requiring frequent energy cycling and high power output [57]. Alternator control systems enhance alternator output during braking but provide relatively low energy recovery compared to FESS [11]. While easy to retrofit, they offer incremental improvements compared to the substantial efficiency gains that FESS can deliver [58]. Ultracapacitors, though capable of rapid energy delivery, suffer from high self-discharge rates and cannot hold energy for extended periods, whereas FESS provides consistent power delivery without the same degradation [38]. Pneumatic and hydraulic systems, which store energy by compressing fluids, are typically better suited for heavy-duty vehicles due to their large size and mass, whereas FESS is more compact and efficient for light-duty applications [11,59]. Similarly, elastomer-based KERS, which store energy through elastic deformation, are mechanically efficient but require significant space, making them less practical compared to the more adaptable and space-efficient FESS [11].

3.1. Flywheel storage

In a FESS, the kinetic energy of the vehicle is stored as rotational energy by increasing the angular velocity of a flywheel. The amount of energy stored is proportional to the rotor's moment of inertia and the square of its rotational speed. Traditional flywheels, made from dense materials such as iron or steel, have been used for centuries in millstones and steam engines [55]. However, these conventional systems are limited to lower rotational speeds, typically up to 10,000 rpm, due to material constraints [38]. Modern FESS utilise advanced composite materials such as carbon fibre, enabling high-speed flywheels to reach

Table 1
Technical specifications of different energy storage technologies.

Technology	Mechanism	Power density (W/L)	Energy density (Wh/L)	Specific power (W/kg)	Specific energy (Wh/kg)	Rated energy capacity (MW h)	Power rating (MW)	Cycling time (cycles)	Discharge efficiency (%)	Response time	Cycle efficiency (%)	Daily self-discharge (%)	Lifetime (yr)
Flywheel	Mechanical	1000–2000 [27] 5000 [28]	20–80 [27]	400–1500 [27]	10–30 [27] 5-100 [29] 5-80 [30]	0.0052 [24] 0.75 [31] up to 5 [24]	<0.25 [27] 3.6 [24] 0.1–20 [24]	+20,000 [27] +21,000 [32]	90–93 [33]	<1 cycle [33] Seconds [24]	90–95 [27] 90 & 95 [31]	100 [27] >20 % per hour [29]	15 [27] +15 [32] 20 [33]
Li-ion	Chemical	1500–10,000 [28]	200–500 [27] 200–400 [28] 150 [31]	150–315 [27] 300 [31] 500–2000 [29]	75–200 [27] 90 [31] 120–200 [34]	0.024 [35] 0.004–10 [24]	0–0.1 [27] 1–100 [24] 0.005–50 [24]	1000–10,000 [27] Up to 20,000 [36]	85 [33]	Milliseconds, <1/4 cycle [37]	90–97 [27] 75–90 [24]	0.1–0.3 [27] 1 & 5 [38]	5–15 [27] 14–16 [39]
Capacitor	Electrical	+100,000 [27]	2–10 [27] 0.05 [40]	100,000 [27] >3000–10^7 [40]	0.05–5 [27] <0.05 [40]	–	0–0.05 [27]	+50,000 [27]	75–90 [24]	Milliseconds, <1/4 cycle [37]	60–70 [27] +70 [41]	40 [27] 50 in 15 min [42]	5 [27] 1–10 [37]
Ultracapacitor	Electrical	+100,000 [27]	10–30 [27]	500–5000 [27] 10,000 [40]	2.5–15 [27] 0.05–15 [40]	0.0005 [31]	0–0.3 [27] +0.30.001–0.1 [31]	+100,000 [27] +50,000 [32]	95 [33] Up to 98 [24]	Milliseconds, <1/4 cycle [33]	90–97 [27] 84–95 [43]	20–40 [27] 5 [44] 10–20 [45]	10–30 [27] 10–12 [43]
Hydrogen fuel cell	Chemical	+500 [27]	500–3000 [27]	+500 [27] 5–800 [40]	800–10,000 [27] 150–1500 [40]	0.312 [24]	<50 [27] <10 [28] 58.8 [24]	+1000 [27] +20,000 [46]	59 [27]	Seconds, <1/4 cycle [33]	20–50 [27] 32 [47] 45–66 [48]	Almost zero [27]	5–15 [27] 20 [49] +20 [46]

Table 2
Techno-economical characteristics of different energy storage technologies.

Technology	Discharge time at power rating	Suitable storage duration	Energy capital cost ($/kWh)	Power capital cost ($/kW)	Operating and maintenance cost
Flywheel	Up to 8 s [27] 15 s – 15 min [24]	Seconds to minutes [27] Short term (<1 h) [50]	1000–5000 [27] 1000–14,000 [51]	250–350 [27]	0.004 $/kWh [31]
Li-ion	Minutes-hours [27] 1–8 h [52]	Minutes-days Short to med term [27]	600–2500 [27] 2770–3800 [24]	1200–4000 [27] 900–1300 [29] 1590 [24]	–
Capacitor	Milliseconds –1 h [27]	Seconds-hours [27] 5 h [41]	500–1000 [27]	200–400 [27]	13 $/kW/year [24] <0.05 $/kWh [41]
Ultracapacitor	Milliseconds –1 h [27] 1 min [52] 10 s [53]	Seconds-hours [27] <1 h [50]	300–2000 [27]	100–300 [27] 250–450 [53]	0.005 $/kWh [31] 0.6 $/kW/yr [33]
Hydrogen Fuel cell	Seconds-24 h [27]	Hours-months [27]	15 [33]	500 [33] 1500–3000 [54]	0.0019–0.0153 $/kW [54]

rotational speeds between 10,000 and 100,000 rpm [29]. These composite materials are less dense but allow for greater energy storage at higher speeds [24]. To maximise energy capacity, the rotor is often cylindrical, with mass distributed far from the centre of rotation, increasing the moment of inertia [60]. High-speed operation also necessitates the use of magnetic bearings, which offer contact-free support and reduce friction, a significant source of energy loss in mechanical bearing systems. Although high-speed composite flywheels provide better performance, they come at a higher cost than traditional metal flywheels [24].

Their adoption in automotive applications is on the rise due to their higher power capacity and energy density compared to ultracapacitors [61]. Some FESS can deliver specific power outputs of 5–10 kW/kg, which is significantly higher than the typical electrochemical batteries. Advanced FESS can attain specific energies exceeding 100 Wh/kg, with some reaching up to 200 Wh/kg [62]. In comparison, the specific energy of lithium-ion batteries is above 100 Wh/kg, while commercial ultracapacitors have specific energies of around 6 Wh/kg [63]. While ultracapacitors could potentially demonstrate significantly greater specific power compared to lithium-ion batteries, thermal management is a major challenge for both ultracapacitors and lithium-ion batteries. This issue is considerably less problematic for flywheels [23].

The implementation of FESS can potentially reduce fuel consumption by 20–30 %. However, due to standby losses, the energy recuperated cannot be stored indefinitely [64]. To further improve the efficiency of the system, FESS may require additional components such as a transmission, a high-speed rotor, a vacuum chamber, and magnetic bearings. These high-technology components can significantly increase both the cost and complexity of the system. Nonetheless, flywheel technology is often considered to be more cost-effective compared to equivalent electric KERS solutions [20].

The durability of a flywheel is often characterised by its capacity to sustain extensive charge and discharge cycles, commonly exceeding one million cycles. The resilience of its composite resin construction contributes to its wear resistance. Material fatigue, which results from repeated loading cycles, is less of a concern for flywheels as long as the charge/discharge rates remain below predefined levels [65].

Unlike batteries, the cycle life of flywheels is independent of the depth of discharge. High temperatures and discharge rates significantly affect battery performance, issues that are less critical for FESS. For instance, Tesla, a leading EV manufacturer, reports that its lithium-ion battery packs last between 300,000 and 500,000 miles, equating to approximately 1500 cycles [66]. This indicates that a battery may require replacement once or twice during the lifespan of the vehicle. However, lithium-ion batteries present recycling challenges, raising environmental concerns [67]. Flywheels are considered to have a minimal environmental impact; they can be manufactured using non-toxic materials and are more readily recyclable compared to lithium-ion batteries, although recyclable, often face logistical hurdles in the recycling process due to the complexity of the materials involved [68]. Additionally, the Norwegian automobile federation has noted that cold weather can reduce an EV's range by up to 20 %, a drawback that FESS can mitigate [69]. Moreover, flywheels exhibit less temperature sensitivity than batteries, maintaining performance across a range of temperatures without the capacity and power losses experienced by lithium-ion batteries [18].

The cost comparison between flywheels and batteries is complex due to the mass production of batteries, as opposed to the low volume production of flywheels. Nevertheless, it is understood that raw material costs represent a significant proportion (60–70 %) of the total cost in the large-scale manufacture of electrical machines. GKN Hybrid Power estimates the raw material cost for a standard ICE at approximately $685, while a low-power/low-energy flywheel (30 kW/111 Wh) is around $723 [70]. Flybrid has compared the cost-effectiveness of their FESS against hybrid vehicle systems, with findings indicating advantages for FESS in aspects such as weight, volume, cost, and efficiency, as detailed in Table 3 [71].

Key attributes of flywheels such as no performance degradation over time, extended cycle life, high power density, and simple state-of-charge assessment render them an attractive option for energy storage applications. Table 4 provides a comparative analysis of lithium-ion batteries and flywheel systems for power buffering in city buses. Subsequent sections will elaborate on the various advantages offered by FESS.

3.1.1. *The development of flywheel technology*

The most historical record on flywheel technology, including automotive applications, is written by Genta [73]. One of the early integrations of flywheel technology was the Oerlikon Gyrobus, which operated in various European and African cities during the 1950s. However, it was eventually discontinued due to technical challenges. Early flywheel road vehicle applications, like Clerk's Gyreacta and Hydreacta in England in the 1960s, combined flywheels with ICE using complex gear sets. Gyreacta had stepped shifts with speed loss; Hydreacta was smoother but less efficient. These complex and costly systems were pioneering for their time [74]. Rabenhorst's [75] introduction of the 'super-flywheel' concept in 1969 marked a significant milestone, featuring materials with high uniaxial tensile strength, capable of storing energy at 14 Wh/kg.

The 1970s witnessed heightened interest in flywheel technology spurred by U.S. government financing. Despite the initial enthusiasm, the focus on flywheel technology diminished with the stabilisation of oil prices by the late 1970s, leading to a reduction in research by the mid-

Table 3
Comparison between the hybrid electric and Flybrid systems [71].

Parameter	Hybrid electric system	Flybrid system
Cost per unit for production rate of 200,000 units	8000 USD	2000 USD
Volume	50 L	20 L
Weight	85 kg	35 kg
Round trip efficiency	34 %	74 %

Table 4
Comparison between Li-ion battery and flywheel systems for vehicular applications [72].

Type	Li-ion battery system	Flywheel system
Manufacturer	A123Systems	GKN
Energy capacity	26,400 Wh	456 Wh
Rated power	spe120 kW	120 kW
Specific power	500 W/kg	2200 W/kg
Specific energy	110 Wh/kg	8.3 Wh/kg
Cycle lifetime	$\sim 10^3$	$>10^6$
Weight	240 kg	55 kg

1980s. However, the 1990s saw a resurgence in interest due to stricter global emissions regulations [76]. Notable advancements during this period included the electromechanical battery developed by the American Lawrence Livermore Laboratory [77] and research at Eindhoven University in the Netherlands [78]. The advent of hybrid vehicles in the late 1990s further strengthened the interest in flywheels, propelled by developments in high-speed MGs, durable magnetic bearings, and high-frequency power electronics.

The declaration by the Federation Internationale de l'Automobile (FIA) in 2006, focusing on the recovery and reuse of kinetic energy in Formula One (F1) racing cars, was a pivotal moment for flywheel technology. The 2009 F1 season saw the introduction of KERS, including flywheel-based systems. However, regulations at the time favoured battery-based systems due to power, energy, and packaging constraints. In F1, where budgets are extensive, the use of costly batteries was deemed a feasible solution, unlike road vehicles [76]. Currently, several vehicle manufacturers are exploring the development of flywheels for commercial vehicles to achieve cost-efficiency and performance benefits. It is anticipated that the production of flywheel-based motor vehicles will soon become a reality, signifying a promising future for this technology [76].

4. Current applications of FESS

FESS applications can be distinguished based on their power capacity and discharge duration. Current advancements in flywheel technology have led to reduced costs and operational losses, with some systems capable of functioning efficiently for several hours. Furthermore, FESS are recognised for their extended lifecycle, rapid response times, and minimal thermal impact and sensitivity [79]. Primarily, FESS are deployed in vehicular and transportation sectors owing to their high power-to-mass ratio. Their adaptability and efficiency make them particularly suitable for applications where quick energy discharge and high power output are essential [65].

4.1. Vehicles

FESS primarily serve as energy storage in hybrid and electric automobiles, providing assistance during uphill climbs or when abrupt acceleration is needed. ICEs are utilised in hybrid vehicles to supply constant power, enabling the vehicle to operate at the desired speed [80]. This approach is considered to increase engine life and reduce fuel consumption, thereby decreasing both air and noise pollution [81]. Flywheels are believed to be capable of regulating the varying power demands in electric vehicles, which utilise chemical battery storage systems. Therefore, FESS can stabilise the battery's charge-discharge cycles, thus prolonging its lifespan [82]. A proposed full-electric powertrain with a flywheel-based four-wheel-drive system demonstrated significant enhancements in overall performance and battery longevity [157].

Read et al. [83] conducted a study to optimise the flywheel design in hybrid vehicles, for energy recovery during braking and auxiliary power delivery during acceleration. Results indicated that for a particular vehicle, an optimal flywheel size and depth of charge are needed to maintain a balance between high transmission efficiency and low system mass.

FESS have been utilised in F1 as a temporary energy storage device since the rules were revised in 2009. Flybrid Systems was among the primary suppliers of such innovative flywheel energy storage solutions for F1 race cars [84]. Flywheels in motorsport undergo several charge/discharge cycles per minute, thus standby losses are not a huge concern. Conventional driving schemes, on the other hand, necessitate a greater level of standby efficiency. On the New European Driving Cycle (NEDC), Flybrid Systems recorded an 18 % savings for a 1.7-ton saloon car and a 35 % savings for a 2.6-ton SUV [71]. The installed Flywheel Energy Storage Systems were designed to provide electricity by offloading a high-energy/low-power source. Flybrid Systems was purchased in 2014 by Torotrak PLC, which is a publicly traded company in London with a market capitalisation of $23 million [65]. Flybrid was acquired by the PUNCH Group in 2018, gaining access to the engineering and manufacturing capabilities of PUNCH Powerglide and PUNCH Torino within the PUNCH Group [85].

On the other hand, from 2011 Jaguar's hybrid automobile Jaguar XF featured a mechanical flywheel technology designed by Flybrid Automotive. A Torotrak/Xtrac CVT gearbox transmits power to the driving wheels via the flywheel, which is made of composite material. The system weighs 65 kg and stores 120 Wh at 60,000 rpm. The highest power delivered by this technology was 60 kW and the fuel savings were estimated to be around 20 % [86]. In addition, Volvo is currently working on integrating FESS into its powertrain. The Flybrid Systems' FESS, installed in a Volvo S60, was similar to the one utilised by Jaguar, resulting in a 60 kW power boost and a 20 % decrease in fuel consumption [87].

The Williams F1 team developed a technology similar to that of the Flybrid Systems, though it was not used in racing. However, it was used in the 2012 *Le* Mans 24 Hours when an Audi R18 *E*-Tron quattro became the first hybrid vehicle to win the event [87]. Their flywheel's magnetic section is composed of a magnetically loaded composite material, and the rotor operates in a partially depressurised environment to minimise peripheral drag losses while the bearings function at atmospheric pressure. This setup has a rated power of 150kW and a storage capacity of 140 Wh [88].

Hua et al. [89] have researched the implementation of flywheels as secondary energy storage devices in hybrid vehicles. Meanwhile, the use of flywheel-based KERS in ICE-powered vehicles has gained significant traction in the realm of motorsport. The 2009 F1 racing season introduced regenerative braking systems. Flybrid Systems LLP developed a mechanical KERS with an adaptable CVT for both F1 and mainstream vehicular applications [90]. Boretti [91] engineered a flywheel-based KERS with an integrated CVT for small vehicles. Beyond automotive applications, KERS has potential use cases in other sectors such as off-highway applications. An overview of applications for flywheel energy storage from different commercial manufacturers is presented in Table 5.

4.2. Buses

Buses operating in London have demonstrated potential energy consumption reductions of up to 45 % when employing FESS such as the Flybrid system [71]. A cutting-edge flywheel, constructed from composite materials, utilising magnetic bearings, was installed on a bus at the University of Texas at Austin in the 1990s. This FESS boasted a capacity of 2 kWh and a continuous power output of 150 kW [93]. In 1996, a subsequent application featured in an Eindhoven city bus comprised of a compact 40 kW generator powered by liquified petroleum gas, integrated with FESS to harvest energy during braking, and manage peak power demand. This combination achieved up to 30 % fuel savings and a remarkable 90 % reduction in emissions [94].

In 2015, Transport for London announced the forthcoming deployment of 500 buses, each equipped with a 0.4 kWh flywheel system

Table 5
Different commercial flywheel systems [92].

	Amber kinetics	Gyroticity	PowerThru	Stornetic	Kinetic traction systems	Vycon	Rosseta T2	Beacon Power Gen 4	Temporal power	Active power	Piller power bridge
Flywheel material	Steel	Laminated Steel	Fibre composite	Fibre composite	Fibre composite	Steel	Fibre composite	Fibre composite	Steel	Steel	Steel
Bearing system	NA	Mechanical & magnetic	Active magnetic	Active magnetic	Magnetic & hydrodynamic	Active magnetic	Rolling relieved magnetically	Rolling	NA	Rolling relieved magnetically	Rolling relieved magnetically
Max. RPM	10,000	20,000	52,000	45,000	37,800	36,000	25,000	16,000	11,500	7700	3300
Application	Micro-grid	Frequency stability, Railway	UPS	Railway, Grid	Railway, Micro-grid, UPS	Recuperation, UPS	Recuperation	Frequency stability	Voltage stability	UPS	UPS
Rated energy capacity (kWh)	32	0.069	0.63	4	1.5	0.83	4	25	50	0.9	4
Rated power (kW)	8	25	190	22	200	500	500	100	100–500	250	1600

capable of accelerating a bus from 0 to 50 km/h by using the energy recovered during braking. These systems were projected to conserve between 20 % and 25 % of the energy typically supplied by diesel engines, translating into an annual saving of around 5300 L of fuel per bus. An added advantage is the flywheel's retrofit compatibility with existing buses, which facilitates hybridisation without incurring significant capital expenditure [95]. In 2023, London's bus fleet comprises 3835 hybrid buses, 949 electric buses, and 20 hydrogen buses out of a total fleet of 8643 buses. The widespread implementation of flywheel-equipped buses in London, however, has been deferred to a longer-term strategy [96]. The Flybus consortium has achieved a noteworthy milestone with the successful integration of prototype hardware into an Optare Solo Midibus. This Flybus system, which is anticipated to be significantly more cost-effective than the existing electric hybrid propulsion system, incorporates a Ricardo Kinergy flywheel for energy storage and a Torotrak CVT for power delivery [97].

Additionally, the GKN Hybrid Power flywheel is a flywheel battery (FWB) that uses a high-speed carbon rotor. The APC 'Gyrodrive' project, which ended in September 2017, aimed to develop, and test this technology for use in the hybrid bus market. Along with an operational fleet of 35 buses equipped with Gyrodrive technology in the UK [98].

4.3. Trains

The energy consumption of light rail transit trains can be reduced by 31 % by energy recovery during braking, through the implementation of KERS such as FESS. The application of low-speed FESS is particularly beneficial for short-distance trains [79]. In the railway sector, FESS can be integrated by equipping diesel-electric locomotives with systems to store the kinetic energy that is usually lost. Additionally, enhancing the recuperation rate of DC systems, whether onboard or stationed at platforms, can also be an effective use of FESS [99].

The energy captured by one train during braking has the potential to power the acceleration of another. The Metro of Los Angeles exemplifies this application with the installation of a FESS at the Westlake/MacArthur Park Subway Station on the red line. Subsequent to the FESS installation, there has been an approximately 20 % reduction in energy consumption, leading to annual energy and cost savings of 540 MWh and $99,000, respectively [100]. The FESS was constructed from steel with magnetic bearings and an operational speed of 20,000 rpm.

Further advancements have been made by the University of Texas at Austin, which developed a flywheel capable of storing 130 kWh at 15,000 rpm. The rotor, constructed from carbon fibre composites, was supported both axially and radially by active magnetic bearings, achieving a specific rotor energy density of 56 Wh/kg [101].

4.4. Trams

Several European cities have expressed interest in operating urban tram systems without the overhead cables traditionally used for electrical power supply. For short distances ranging from 0.8 km to 2 km within city centres, a short-term Energy Storage System (ESS) such as flywheels or ultracapacitors could be an optimal solution. In Zaragoza, Construcciones y Auxiliar de Ferrocarriles (CAF) has successfully implemented such a system [102]. Additionally, there has been an integration of a flywheel into the drivetrain of a tram in Karlsruhe. This tram, an eight-axle articulated model, originally constructed in 1959, has since been decommissioned. It featured three compartments with a total length of 27 m. Alstom, as part of a European consortium, conducted trials of the Capacitor Charging Method (CCM) system. This system was integrated into a Citadis tram operating in Rotterdam, a city which sought a viable solution to traverse the Erasmus Bridge without reliance on a catenary system. These tests, conducted in 2005, confirmed the viability of the concept [103]. Subsequently, there has been an established collaboration with GKN to implement their advanced flywheel system [104].

4.5. Non-vehicular applications

Flywheel technology has found significant use in several non-vehicular sectors. In mobile applications, FESS is used in goods handling equipment such as Rubber-Tyred Gantry (RTG) cranes, which benefit from the flywheel's ability to handle short, frequent power surges [105]. By storing energy during the lowering of loads and using it for lifting, flywheels can reduce fuel consumption by up to 38 % and emissions by 26 %, enhancing the efficiency of container handling operations [106].

In grid-connected power management, flywheels play a vital role in frequency regulation and ramp management, helping to stabilise electric grids impacted by the variability of renewable energy sources [107]. Beacon Power's flywheel systems, for instance, contribute to grid stability in the US, reducing the load fluctuations caused by renewable energy integration [108].

Flywheels are also used in industrial power management, particularly in transit systems where they store energy from regenerative braking [79]. This application can lead to significant energy savings, reducing electrical consumption in transit networks by up to 10 % [109]. In mining, flywheels help mitigate load fluctuations in draglines, reducing voltage flicker and improving operational stability [110].

In pulsed power applications, flywheels provide high-energy bursts for systems such as the Electromagnetic Aircraft Launch System (EMALS) on aircraft carriers [111]. From the research point of view, flywheels power large projects such as the Joint European Torus (JET), providing rapid energy discharges for nuclear fusion experiments [44]. Finally, uninterruptible power supplies (UPS) utilise flywheels to provide backup power during outages [112]. Flywheels offer a more durable and environmentally friendly alternative to traditional batteries, ensuring critical systems remain operational until other backup generators come online [33].

5. FESS-based powertrain for vehicles

Depending on the drivetrain system, type, structure, performance, and vehicle requirements, the FESS can be used in a vehicle in different ways. The design of the powertrain is essential to improving both the overall system performance and the energy management characteristics [18].

5.1. FESS ICE-based powertrain

Britain was the first to develop FEES with an integrated and differentiating planetary gear unit, using a complex mechanical transmission [74]. A similar powertrain was developed by the University of Wisconsin [113], and several others were developed by the Imperial College London [114] and the University of Eindhoven [115].

Such powertrains typically employ non-electric transmissions. Various configurations and operational modes are feasible, where the flywheel may be connected in either series or parallel. There has been at least one study investigating the use of a flywheel in a series configuration with two CVTs. Nonetheless, the parallel configuration, shown in Fig. 3, remains a more conventional approach, adopted by the University of Eindhoven [115]. In this setup, the flywheel operates in tandem with the ICE at speeds of up to 100 km/h, beyond which the ICE functions independently. The most efficient operating range for an ICE, particularly for charging the flywheel to its operational capacity, lies between 10 km/h and 55 km/h in a low-speed hybrid mode [116]. The flywheel is then used for driving the vehicle when the preferred flywheel speed is achieved so that the ICE is in the enabling mode. The ICE is always in operation between 55 and 100 km/h, with the flywheel acting as an auxiliary power source. The flywheel is furthermore switched off, and ICE drives the vehicle. The fuel economy is mainly enhanced by engine operation enhancement with a small contribution from regenerative braking [115].

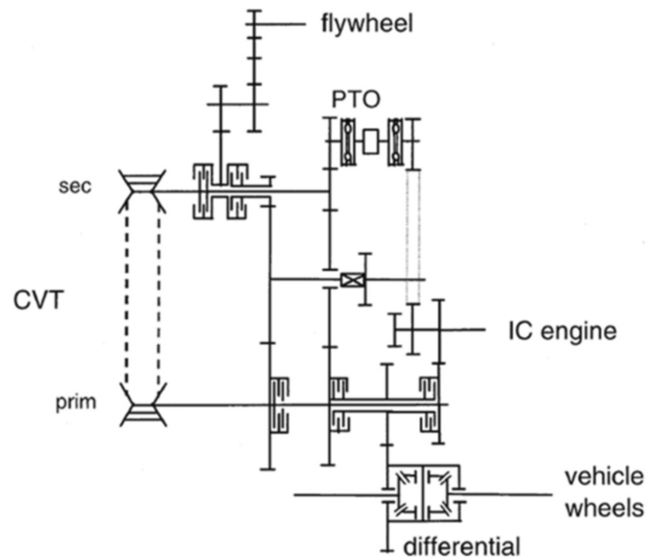

Fig. 3. The system configuration used by Eindhoven University [115].

The improvement of fuel economy can be achieved by the reduction of losses from the flywheel system. The hybrid flywheel drive system's enhanced prototype demonstrates the fuel economy in urban traffic by up to 35 % [60]. A novel configuration from Imperial College London, shown in Fig. 4, adds a flywheel to the standard ICE powertrain with a mechanical drive. The primary role of the flywheel is to capture energy during regenerative braking, which would otherwise be dissipated as heat. During the braking process, the flywheel stores the kinetic energy, which is then released when the vehicle accelerates. In this configuration, the engine is deactivated when the flywheel is working. It has been reported that the fuel economy of buses and cars can improve by up to 33 % and 22 %, respectively, compared to conventional powertrains

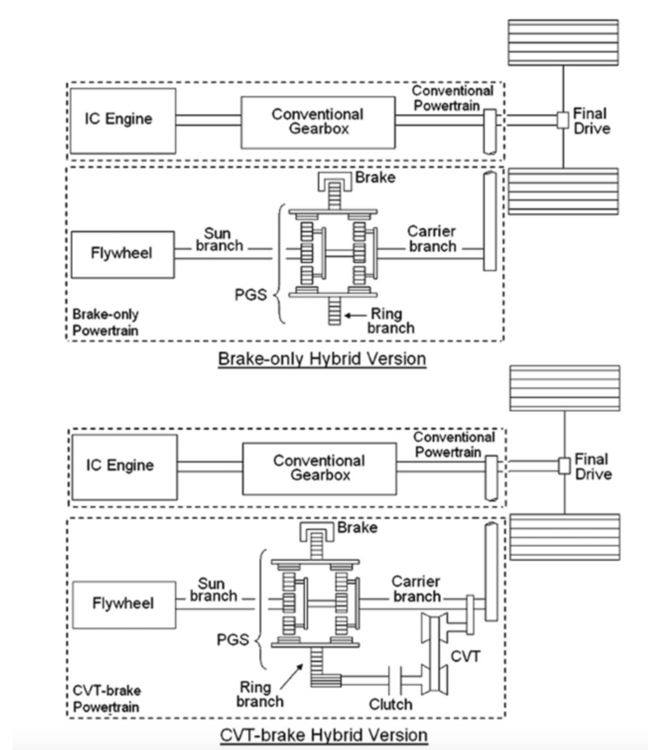

Fig. 4. Imperial College concepts for brake-only and CVT-brake hybrid systems [114].

[114].

5.2. FESS HEV powertrain

The series configuration of hybrid electric vehicles is another common setup, as illustrated in Fig. 5. In this arrangement, the ICE generates electrical energy that powers electric motors, with the flywheel acting as an energy storage medium. The University of Alberta, UT-Austin, and the University of Eindhoven have all developed FESS using a similar configuration [117]. This setup has been predominantly used in public transport systems, operating similarly to the battery-based series HEV powertrains. ETH Zurich developed a parallel hybrid powertrain known as the ETH-Hybrid III, the schematic of which is depicted in Fig. 6 [118]. This powertrain integrates a flywheel coupled with a CVT, batteries, an asynchronous electric machine, and an ICE. The presence of various components enables multiple operational modes, effectively combining the functions of battery charging and the strategy similar to that outlined by the University of Eindhoven. Despite its potential, the system was considered complex in both construction and control [78].

5.3. FESS electric powertrains

One of the primary challenges of EVs is the limitations imposed by their battery storage systems. The cost of the vehicle and the limited range are factors that detract from their appeal. Employing a high-power storage device such as a flywheel to complement the 'state of charge' of batteries may mitigate some of these constraints. The battery would supply steady average power, while the flywheel would regulate power during deceleration and acceleration. This approach could extend the driving range and enhance battery longevity by alleviating the strain from power spikes, and concurrently reduce the cooling requirements of the battery system. Typically, flywheels are incorporated within a Flywheel Battery (FWB) system, a combination of a flywheel and a MG unit, often employing magnetic bearings, as depicted in Fig. 7 [93].

Recent studies by Lundin [119] involved using an FWB system with dual-voltage stages between the battery and the traction motor. The high-voltage section interfaces with the traction motor, while the battery connects to the low-voltage side. The FWB is capable of both charging and discharging the traction motor and battery at differentiated voltage and power levels, showing that partial charge/discharge cycles are significantly reduced, thereby diminishing the associated current and battery-resistive losses compared to systems without a flywheel.

Mechanical coupling of the flywheel and the EV drivetrain provides advantages in cost, and simplicity, and eliminates the need for energy conversion. Preliminary research funded by the US government in the 1970s examined this approach. However, at the time, EV performance was markedly inferior to conventional vehicles, and even with a flywheel, they did not offer a competitive edge [120]. Currently, research into this application continues at the City, University of London, examining the feasibility of the system considering the recent advancements in flywheel and EV technologies [121].

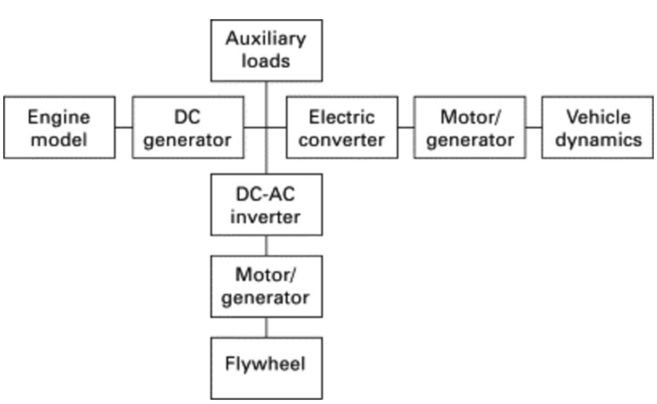

Fig. 5. Hybrid electric powertrain with flywheel acting as an energy storage [117].

6. Key components and design considerations

A flywheel is a mechanical device mounted on a shaft and supported by bearings. It can be paired with a MG for electrical energy transmission, which, in its simplest form, resembles a standard electrical machine. However, the required high operational speeds in FESS applications introduce unique engineering challenges that differentiate these systems from conventional flywheel applications [81]. Key aspects of FESS that require specialised consideration include the bearings, control systems, housing environment, transmission, and the flywheel. Each of these components and their associated engineering challenges will be thoroughly examined in the following sections.

6.1. Bearing selection

The design and selection of bearings are critical for the efficient operation of FESS, as they must support both static rotor loads and dynamic forces, including shock and gyroscopic effects. In addition to withstanding these forces, the bearings should have a long operational life, be cost-effective, require minimal maintenance, and contribute to low energy losses during operation [122]. Bearing selection for FESS must also account for the types of loads the system will encounter, such as sudden impacts from road irregularities such as potholes, vibrations from uneven surfaces, and stresses from vehicle manoeuvres, including cornering, acceleration, and deceleration. The most significant load factor is often the shock from abrupt road irregularities. Therefore, the choice of bearings must balance factors such as durability, cost, volume, and compatibility with low-pressure operation to ensure optimal performance and longevity of the FESS [123].

Air foil bearings are not a viable option for FESS due to their high costs. Additionally, sealing these bearings in a low-pressure system poses considerable challenges. The requirement of an external air supply for air foil bearings further compounds the issue, as it would increase both the weight and cost of the system [124]. Hydrodynamic bearings, while another potential choice, are also unsuitable for FESS. Their significant losses, high costs, and the necessity of an accompanying oil system (which adds weight and cost) render them impractical. The low pressure required by these bearings makes their integration into the oil system of a vehicle unfeasible. Moreover, sealing hydrodynamic bearings in a low-pressure environment presents considerable difficulties [124].

Passive magnetic bearings, despite gaining attention in recent years, are not capable of withstanding the loads encountered in a FESS, leading to the risk of premature failure. While the development of superconducting magnetic bearings holds promise for future applications in systems such as FESS, they are not yet a practical solution. Active magnetic bearings emerge as a suitable choice for such systems; however, they require support for high-speed operation and consume significant power, which necessitates additional space due to their larger volume [124].

Rolling element bearings emerge as a suitable choice for applications such as FESS, especially when equipped with grease lubrication to function effectively in low-pressure systems without the need for an accompanying oil supply. These bearings are simpler and more cost-effective compared to other types discussed. Considering the requirements for low loss, low cost, and high capacity, the selection of bearings for FESS is largely limited to rolling element types. Despite the relatively small rotor weight and imbalance loads, rolling bearings must also accommodate gyroscopic effects and acceleration shocks. While magnetic bearings could be ideal for stationary applications, they would need to be substantially larger to handle these additional loads. An

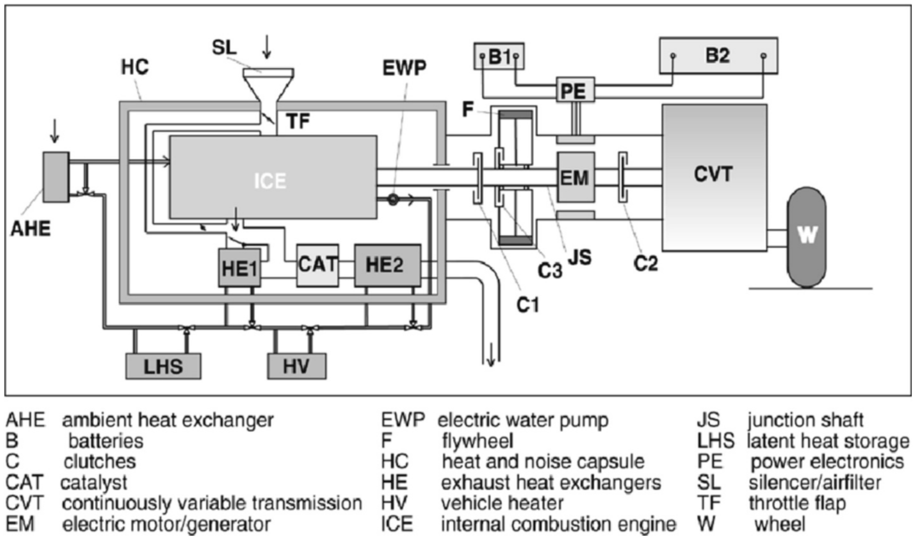

Fig. 6. ETH-III powertrain schematic for hybrid powertrain with flywheel [118].

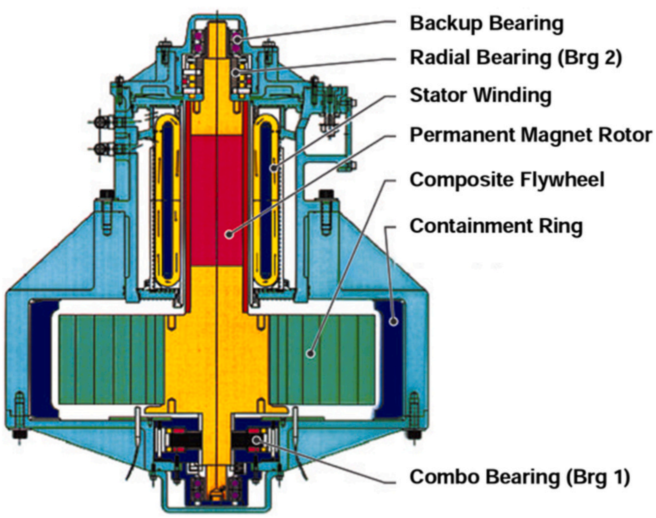

Fig. 7. Schematic of the flywheel battery components [93].

alternative approach involves positioning the FESS such that gyroscopic moments are not imparted to the rotor and casing [125].

A comparison of the two most suitable bearings for FESS is presented in Table 6. Rolling bearings are advantageous due to their low loss moments, enabling them to withstand short-term loads or shocks that significantly exceed the constant design load, provided they offer sufficient fatigue life for regular operation. Angular contact bearings are typically the preferred choice, with options ranging from all-ceramic to steel balls at various accuracy levels, depending on cost considerations. Most manufacturers provide a loss correlation that includes a fixed loss moment and a speed-dependent loss moment component. It is important to note that over recent decades, technology in rolling element bearings has advanced significantly towards reduced loss moments and enhanced durability.

Table 6
Comparison of suitable bearings for FESS.

	Rolling element bearings	Magnetic bearings
External support	Grease: None Oil: Oil supply	Power supply & control system
Bearing size	Small to medium	Large
Complexity	Simple	Complex
Resistance to contamination	Low to medium	High
Cleanliness	Low	High
Reliability	Medium to high	High
Damping	Low to medium	Control system to limit vibration
Speed	Low to high	Very high
Pressure	Lubricant limited	Virtually independent
Temperature	-20 to 150 $^{\circ}C$	-250 to 200$^{\circ}C$

Bischof et al. [125] conducted numerical analyses on different orientations of a flywheel and discovered that the lowest total bearing loads were associated with a vertically oriented rotor spin axis. Isono et al. [123] reported the benefits of using high-temperature superconductors in applications such as FESS. However, relying exclusively on these may not be optimal, as they may not necessarily stabilise the rotor to the required level. Integrating active magnetic bearings with superconducting magnetic bearings could mitigate vibrations experienced by the rotor. Additionally, Murakami et al. [126] introduced a novel design where the flywheel rotor is supported by a passive magnetic bearing at the top for positional control, while a superconducting magnetic bearing at the bottom dampens vibrations. To facilitate the cooling requirements of a superconducting magnetic bearing, a cryocooler needs to be strategically installed. Flybrid opted for off-the-shelf rolling element bearings, having determined that the mechanical losses from these bearings do not significantly impact the performance of their FESS. This design choice simplified the system and reduced the overall cost [76].

6.2. Control

Despite the pursuit of ideal control solutions in engineering, many methods diverge from conventional optimal control strategies due to a lack of publicly available information on FESS control systems since industrial entities often protect their intellectual property. Cross et al. [127] and Boretti [91] have not specified any control strategies but have provided descriptions that align with classic control approaches, including trial and error. Ghedamsi et al. [128] discussed the application of a PID control strategy used in wind generators, characterising it as a Multiple Inputs, Multiple Outputs (MIMO) control system. Furthermore, Ye et al. [129] referenced various energy recovery system strategies employed in the past, including neural network control, intelligent control, fuzzy control, and variable structural control. Cheng and Ye [130] also explored the use of genetic algorithm-based neural networks as a control technique alongside robust sliding mode control, H-infinity control, and fuzzy PID. Meanwhile, Hua et al. [89] introduced methods for constant power and constant torque control. Kirk [131] defined optimal control as the process of determining the control signals that cause a process to satisfy physical constraints and optimise a performance criterion, often related to energy or time, making it an appropriate choice for KERS applications seeking to maximise stored energy efficiency. Optimal control theory is commonly implemented through two independent methodologies: Pontryagin's Maximum Principle and Dynamic Programming, the latter being more frequently utilised due to the mathematical complexity of the former.

Cikanek et al. [132] have researched regenerative braking in hybrid electric vehicles, developing algorithms using MATRIXx software, with vehicle-based testing of the code. Inoue et al. [133] applied a variational method to devise an optimal torque controller, testing the strategy with the SimPowerSystems toolkit in MATLAB/Simulink. Ye et al. [129] developed a strategy that integrates auxiliary and primary power sources of an EV to enhance performance by controlling regenerative current with an H2/H-infinity control strategy, improving performance by 6 % and 3 % for emergency and soft braking, respectively. Cao et al. [134] focused on improving the regenerative process without compromising the energy storage system, proposing a robust control solution for EVs. They highlighted the inherent robustness of the standard PID but acknowledged the need for enhanced operational effectiveness. The results indicated improved charging currents with the PI control.

Xiao et al. [135] analysed control systems for FESS, typically requiring two steps: accurate regulation of the rotor's rotational speed and axial movement, and a synchronisation controller to mitigate gyroscopic rotations due to external disturbances and model uncertainty. The case studies demonstrated that well-tuned control systems could stabilise an unsteady rotor and counteract gyroscopic effects, even at high speeds. Active magnetic bearings in particular benefit from closed-loop control systems to dampen system vibrations and adequately respond to sudden load changes. The rotor can exhibit two types of whirls, conical and translational. The conical whirl, influenced by gyroscopic forces, can significantly impact stability, while the translational whirl restricts radial motion to prevent rotation, a common industry practice. Synchronisation control has shown to be highly effective in managing nonlinear systems and rejecting disturbances within synchronous motion systems. Previously, the application of synchronisation control was confined to stable mechanical systems and was not easily adaptable to highly nonlinear and unstable systems, a constraint overcome by the advent of modern synchronisation control methods [135]. A detailed comparison of various control methods used in FESS, along with their respective advantages and disadvantages, is presented in Table 7.

6.3. Transmission

The transmission is an integral component that connects the wheels and the energy storage system. It enables the transformation of kinetic energy from the wheels to the flywheel during braking, and conversely from the flywheel to the wheels during acceleration. The defining attributes of transmission for this application include high power density to ensure rapid operation during acceleration or deceleration, a high energy density for maximum energy storage, and high efficiency to minimise energy losses [145].

Lechner and Naunheimer [146] reviewed various transmission types within the automotive sector, concluding that they generally fall into two categories: Continuously Variable Transmissions (CVT) and geared transmissions. To incorporate a FESS in a conventional vehicle, the flywheel must seamlessly integrate with the vehicle's powertrain, accommodating continuous variations in speed as the vehicle accelerates or decelerates. The flywheel is required to absorb kinetic energy at different rotational speeds and release this energy back to the powertrain at the required speed. The optimal method of connecting a FESS to the vehicle's powertrain is through a CVT, which allows for bidirectional

Table 7
Comparison of different FESS control systems.

Control strategy	Advantages	Disadvantages	References
Proportional-integral (PI)	• Simplicity of implementation • Absence of steady-state error • Linearity	• Inadequate transient response • Inability to respond to non-linearity • Limited stability range	[136]
Proportional integral derivative (PID)	• Simplicity of implementation • Requires fewer resources • Has a good response to unmeasured interference	• Inability to perform operations with a longer deadtime • Inability to respond to non-linearity • Inability to respond to multiple variables	[137]
Feedback linearization (FL)	• Able to respond to a system's non-linearity • Able to transform original system models into simpler equivalent models • Able to transform non-linear systems into linear	• Inability to respond to all operating points due to a lack of robustness	[138]
Fuzzy logic control (FLC)	• Simplicity in computation. • Able to deal with non-linearity and uncertainty in the system. • Exceptional convergence speed. • Able to control one or more input/output systems.	• •Difficult to design • Success is contingent upon the expert's knowledge and experience.	[139]
Field-oriented control (FOC)	• Accurate dynamic speed control. • Torque can be controlled at low speeds and frequencies. • Able to operate in all four quadrants.	• Has a short-term overload capability. • Accurate rotor positioning requires the use of a sensor	[140]
Artificial neural network (ANN)	• Able to tolerate failures • Able to store large amounts of data over the network • Able to function even when presented with incomplete information	• Success is contingent upon the expert's knowledge and experience. • Expensive • Limited to numerical data	[141]
Model predictive control (MPC)	• Responds with greater precision and accuracy • Optimal Controller • Possibility of controlling back-to-back multilevel converters	• Extensive computational time and expense • Requires the development of an accurate dynamic model	[142]
Direct torque control (DTC)	• Able to control flux and torque more rapidly • Less sensitive to parameter changes	• More noise in voltage and current signals • Higher Torque ripple and current distortion	[140]
Optimization	• Irrespective of the ability of the user • The system's total cost can be minimised. • Able to determine the true optimal value of	• Must adhere to a set of rules for selecting the procedure's indices	[143]

(continued on next page)

Table 7 (*continued*)

Control strategy	Advantages	Disadvantages	References
V/f	a response with fewer trials • Requires a lower starting current • Allows the motor to operate in a relatively stable region • Assures that the output voltage is proportional to the frequency • Prevents magnetic saturation from deteriorating	• High installation cost • Unable to handle regenerating load	[144]

energy transfer with high efficiency. The CVT in a flywheel hybrid vehicle necessitates a broader ratio range, particularly when employing a high-speed flywheel with a low depth of discharge. Additional considerations for the CVT include cost-effectiveness, low weight, and ease of control [91]. Flywheel-based KERS transmissions can also be segmented into two subcategories: mechanical and electrical [128].

6.3.1. Mechanical power transfer

CVT is an ideal solution if the vehicle needs a transmission system to transform the recovered energy into kinetic energy with minimal losses. CVTs are recognised for their high efficiency; however, they are often limited by their torque capacity. Despite this limitation, CVTs hold significant potential as a future transmission system for KERS applications due to ongoing developments to enhance their torque-handling capabilities. The most prevalent CVT designs include the Toroidal, Pulley, and Hydrostatic models [145].

6.3.1.1. Hydrostatic transmission. Hydrostatic transmissions transfer power through fluid dynamics, regulated by a variable displacement pump that modulates the flow to the hydrostatic motor. This type of transmission comprises two hydraulic components: a variable displacement pump and a connected motor. Mechanical energy is converted into hydraulic pressure, which the motor can then reverse. Infinitely Variable Transmission (IVT) is achieved by adjusting the displacement of the pump, which eliminates the need for a starter clutch. While hydrostatic transmissions are relatively simple and adaptable, their large size and noise level generally make them more appropriate for heavy-duty applications rather than passenger vehicles [147].

6.3.1.2. Traction continuously variable transmission. Traction CVTs transmit torque through the frictional force between two surfaces, with the transmission ratio altered by varying the radius at the point of contact. These drives typically have a restricted ratio range and come in two main types: rolling traction drives and belt drives [147]. Rolling traction drives, such as toroidal transmissions, consist of two discs and two interposed rollers. By rotating the rollers, the contact point and thus the gear ratio can be continuously varied. Torotrak is a leading manufacturer of such transmissions [148]. The Milner CVT, another rolling traction drive, employs spherical planetary rollers to transfer power between the discs and the carrier, with the ratio adjusted by axial displacement [149]. Belt drive CVTs utilise two pulleys with varying diameters linked by a belt, where the variable diameter pulleys result in different input/output ratios. Belts are typically made from rubber or steel, with rubber V-belt CVTs being the most common [150]. An improved version using steel blocks connected by steel ribbons was developed by Van Doorne [151], enhancing the capabilities of rubber belt drives. Another variation is the flat rubber strap design by Kumm Industries, which adjusts the transmission ratio by radially positioning the belt along guideways [152].

6.3.1.3. Mechanical transmission. The simplest form of mechanical CVT involves a clutch in series with a stepped gearbox. The gearbox operates with discrete ratios, and the clutch engages to achieve the desired ratio at each stage. Although power loss from clutch slip can be reduced using a gearbox with multiple ratios, the cost may be prohibitive. Read [153] proposed a method that combines a small gearbox with a multi-step gearbox to simulate a larger number of gears. Additionally, Beachley and Frank [147] suggested a design that allows a flywheel to connect to a hybrid drivetrain using a Planetary Gear Set (PGS). Typically, one element of the PGS is fixed while the others serve as inputs or outputs. If the PGS is utilised as a CVT, all three elements would be free to rotate, offering two degrees of freedom. The CVT function is accomplished by controlling the speed of any two elements, as PGS operates as a speed synchroniser [114].

6.3.1.4. Mechanical transmission topology. Mechanical hybrid powertrains that incorporate flywheels utilise purely mechanical means for power transmission. The CVT's ability to shift smoothly facilitates efficient charging and discharging of the flywheel without requiring energy conversion [154]. Mechanical components typically offer a cost advantage over their high-power electronic counterparts and, despite having a lower energy storage capacity, are generally sufficient for recuperating the majority of energy during braking [155]. The design of an effective mechanical hybrid powertrain involves meticulous consideration of the topology and the dimensions of the flywheel. The challenge in optimisation arises from the need to simultaneously address diverse objectives related to marketing and production, which can often conflict. Given the multitude of design parameters encompassing topology, component selection, flywheel size and mass, as well as powertrain benchmarks and operating conditions, it becomes a complex task to execute a comparative analysis. Moreover, as the control strategy is also tailored for each design iteration, the process of identifying the most effective powertrain configuration is inherently iterative.

6.3.2. Electric power transfer

In electric and hybrid vehicles, transmissions based on MG units are often employed to convert recovered kinetic energy into electrical energy, which can then be used to charge the battery pack. The MG is connected to the flywheel, enabling energy conversion. When the vehicle decelerates, ICE functions as a generator, extracting electrical energy to accelerate the flywheel and storing energy. Conversely, during discharge, the MG retrieves the energy stored in the flywheel [30]. Several types of electric machines can be paired to a FESS, including [156]:

6.3.2.1. Induction Machines. Induction Machines (IMs) also referred to as asynchronous machines, typically have lower power and efficiency compared to permanent magnet motors. The absence of permanent magnetisation significantly mitigates idling losses. Although robust and mechanically simple, IMs do experience considerable losses within the rotor, which should be kept minimal to prevent overheating, especially when the flywheel is suspended in a vacuum on magnetic bearings. IMs are often chosen for their robustness, high torque capabilities, and cost-effectiveness. However, they are also subject to speed limitations, necessitate complex control systems, and have greater maintenance needs [157].

6.3.2.2. Permanent Magnet Synchronous Machines. Permanent Magnet Synchronous Machines (PMSMs) are popular choices for FESS due to their high efficiency and low rotor losses, due to a permanent magnet-generated rotor flux. These machines are well-suited to high-speed applications and have high energy density and overall efficiency. Eddy current losses and camper hysteresis can be reduced using PMSMs. However, unlike an IM, PMSMs are more expensive, less robust, and temperature sensitive. PMSM issues include eddy current-based idle losses, low robustness, and high cost [158].

6.3.2.3. Brushless Direct Current Machine. Brushless Direct Current Machines (BLDCMs) are a type of asynchronously controlled machine that uses permanent magnets and an inverter to regulate the current through the stator windings. They offer advantages such as compact build, mechanical robustness, broad operational speed range, high efficiency, and high power density [159].

6.3.2.4. Variable Reluctance Machine. Variable Reluctance Machines (VRMs) are beneficial for applications such as FESS due to their simplicity and low idle losses. They are resilient and capable of operating across a broad speed range, even in harsh conditions with temperatures surpassing 400 °C. VRMs can produce high torque but may present challenges in low-speed torque control, though at high speeds, control is easier compared to IMs [160].

6.3.2.5. Homopolar Machine. Homopolar Machines (HMs), or AC homopolar synchronous machines, provide a robust rotor structure and low idling losses. They are known for their reliability, making them suitable for sustained high-speed operation [161].

6.3.2.6. Bearingless Machine. Bearingless Machines (BMs) combine torque production and magnetic suspension in a single device. Compared to conventional magnetic bearings, BMs offer a more accessible structure, are compact, and can lead to cost reductions. They are appropriate for high-speed FESS applications, and there has been a range of BMs developed, including bearingless PMSMs, BLDCMs, IMs, reluctance machines, and Switched Reluctance Machines (SRMs) [162]. Table 8 provides a summary of the essential characteristics of various electric machines suitable for FESS.

6.3.2.7. Electrical transmission topology. The integration of a MG unit into a FESS can be realised through three distinct approaches: fully integrated, partially integrated, and non-integrated, as depicted in Fig. 8.

Fully Integrated Design: In this configuration, the flywheel and MG are combined, with the flywheel being part of the MG mass. This design maximises the power and energy densities of the system while maintaining compactness. However, due to the vacuum containment needed for high-speed operation, cooling becomes a challenge as heat can only be dissipated via radiation, necessitating an effective cooling system. High sealing is achieved in this configuration, with the unit requiring only electrical connections [93]. An example of a fully integrated design is the "hub less" configuration, where the MG and bearings are incorporated directly into the flywheel rim, eliminating the need for a central shaft.

Partially Integrated Design: In this configuration, the flywheel and MG share the same shaft and are housed together, which enhances the power density and energy storage capabilities of the system. Nevertheless, a vacuum environment is necessary to minimise windage losses, particularly for high-speed FESS applications, which bring additional thermal management requirements. An application of this design with active magnetic bearings has been utilised in the UT-CEM project in a hybrid bus [165].

Non-Integrated Configuration: In this setup, the flywheel is connected to the MG through a detachable link, offering considerable flexibility in terms of energy and power storage capabilities. It is the simplest and largest of the three configurations and eliminates the need for a complex cooling system due to the absence of the need for a vacuum environment [93].

Table 8
Comparison of electric machines used with a FESS [163,164].

	Permanent Magnet Synchronous	Variable Reluctance	Asynchronous
Cost	High	Low	Low
Demagnetization	Yes	No	No
Maximum speed	Low	High	Medium
Torque ripple	Medium	High	Medium
Tensile strength	Low	Medium	Medium
Size	2.3 L/kW	2.6 L/kW	1.8 L/kW
Control	Trapezoidal: DSP. Sinusoidal: vector control.	Switched: DSP. Synchronous: vector control.	Vector control
Efficiency	95.2 %	93 %	93.4 %
Spinning losses	Static flux, non-removable	Removable by annulling flux	Removable by annulling flux
Rotor losses	None	Iron	Iron and copper
Specific power	High	Medium	Medium
Power	Medium & low	Medium & low	High

6.4. Rotor design

The efficiency of a FESS is significantly influenced by the careful selection of materials used and the optimisation of the flywheel geometry. The primary goal in flywheel design is to maximise specific energy storage, guided by the stress limits that the materials can withstand. Employing high-strength materials or composites allows for a reduction in mass while permitting higher rotational speeds, which in turn, enhances the specific energy storage capacity [73]. Advanced composite materials, renowned for their directional strength and low density, facilitate the construction of rotors tailored for high-speed FESS applications. This advantage is particularly pronounced when using multi-rim composite rotors, where the number of rims, the material sequence, and the interference levels between rims, including their thicknesses, are strategically designed to boost energy capacity [166].

In contrast, metal flywheels, while simpler and less expensive to manufacture, generally operate at lower speeds. Although this limits their specific energy capacity, it reduces standby losses associated with components such as bearings and the electrical machine. These losses are proportional to speed, making metal flywheels more favourable in applications where low standby losses are required [160]. Considering the lifecycle, the cost-efficiency of energy storage technologies is crucial, with flywheels offering exceptional longevity. Although advanced composite flywheels may initially be less cost-competitive compared to battery storage solutions, they prove economical in medium to longer terms, with potential operational lifetimes extending over decades and cycle durability reaching 106 cycles, far exceeding that of conventional batteries [24].

Hybrid flywheels, which combine steel hubs with composite rims, offer an optimised balance by leveraging the strength of composites to handle high stresses along the fibre direction, while retaining the structural benefits of steel. Nonetheless, the complexity and cost of manufacturing such hybrid systems remain significant challenges [167]. The shape factor (K) plays a crucial role in flywheel design, with isotropic materials such as steel demonstrating equal radial and tangential strengths, making them suitable for designs with $K = 1$, such as the Laval disc [81]. Conversely, anisotropic composite materials are better suited to shapes that exploit their unidirectional tensile strength, such as thin hollow flywheels, which have been identified as optimal for high-speed applications [107,168,169].

The geometry of composite flywheels, particularly those using hollow cylindrical designs, has been shown to significantly enhance performance. Studies by Singh and Chaudhary [170] employing nature-inspired optimisation algorithms, such as the Jaya algorithm, demonstrated that optimised flywheel shapes could store 36.55 % more energy than conventional designs without exceeding material stress limits. While these optimised designs show promise, they often present practical challenges due to complex manufacturing requirements.

Kale and Secanell [160] conducted an optimisation study on

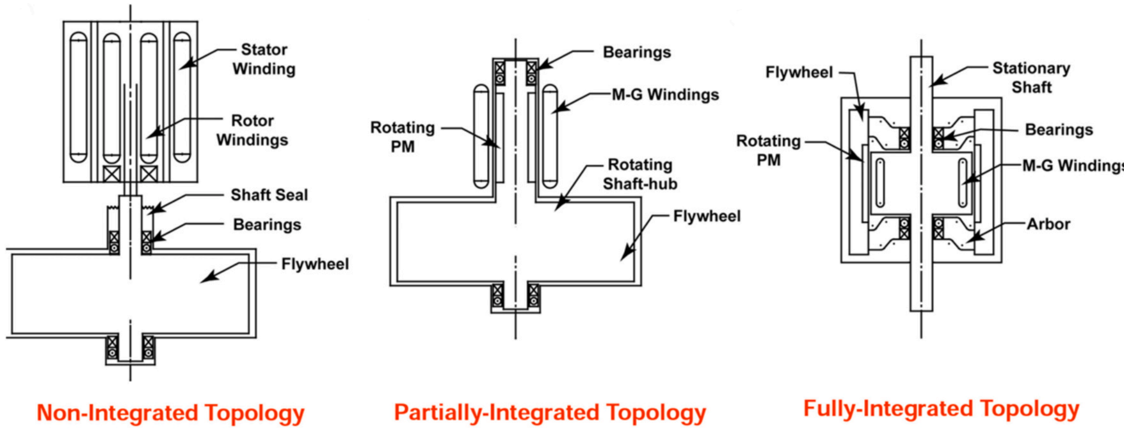

Fig. 8. Three different MG and FESS configurations [165].

flywheel rotors manufactured from diverse metals and composites to ascertain the most suitable material based on system performance criteria. Their findings suggested that while composite rotors exhibited higher specific energy, metal rotors were more cost-effective in terms of energy storage. In situations where only tensile material failure was considered, composite rotors exhibited significantly lower specific energy than metallic counterparts, highlighting the critical role of material failure modes and other physical constraints. Further investigation into flywheel performance indicated that press-fitted, multi-rim composite rotors with strategically selected material combinations surpassed both single-rim composite and metal flywheels with respect to total and specific energy metrics. Additionally, the influence of fatigue on varied flywheel rotor types throughout their service life can be pivotal in deciding the material used, as long-term durability impacts overall performance.

Reviewing utility-scale flywheel storage solutions reveals a current production trend that balances the use of both composite and metal flywheels [160]. Composite materials enable high performance, but metal rotors remain appealing for their cost benefits and ease of manufacture. The impact of fatigue on various rotor types throughout their service life is a crucial consideration, as durability directly affects performance, making the choice of material a key determinant in the overall efficiency and utility of the FESS [160].

6.4.1. Rotor material

Material selection is a critical factor in FESS rotor design, where the specific strength (the ratio of strength to density) determines the energy density of the FESS. High-strength composite materials are ideal for this purpose, although their anisotropy can limit performance in designs that require strength in multiple directions. Advances in multidirectional composites, as well as the use of reinforced plastic materials such as fibreglass, glass-fibre, or Kevlar, offer potential alternatives to uniaxial composites. Fibreglass, while more economical, is limited by its lower Young's modulus, reducing its suitability for high-performance applications [70]. Additionally, materials with high stiffness experience reduced dynamic displacements, simplifying the mechanical design of the rotor shaft connection [171].

The trade-off between material density and operational speed is another key consideration. High-density materials, such as steel, can store more energy at lower speeds but are limited by higher internal stresses. Conversely, low-density materials experience less stress, enabling higher operational speeds and greater energy storage efficiency, despite lower system weights. Composite rotors, in particular, are favoured for their benign failure modes, as they gradually degrade rather than shattering into dangerous projectiles, which is a common risk with metallic flywheels [172]. Table 9 presents a comparison of current rotor materials with some emerging options, highlighting the future potential of FESS.

Table 9
The characteristics of various flywheel rotor materials [60,65,173].

Material	Ultimate tensile stress (MPa)	Density (kg/m^3)	Specific energy (W/kg)	Cost (£/kg)
Steel 4340	1520	7700	50	2.5
Aluminium 7075	572	2810	28	4
17-7 PH Stainless steel	1650	7800	29	4.7
Alloy steel 30CrNiMo8	1000	7760	36	6
Maraging steel 18Ni250	1860	8000	65	35.5
Titanium Ti-15V-3Cr-3Al-3Sn ST 790 °C	1380	4760	202	20
Advantix E-glass (glass fibre)	1400	2146	90	–
S-Glass	1470	1920	210	19.5
Kevlar	3800	1450	370	31
Vapour grown carbon nanofibers	2920	2000	202	–
Toray T1000G composite	3040	1800	234	80
Toray T1000G fibre	6370	1800	491	–
Carbon fibre reinforced composite material T700 +epoxy resin	2450	1550	439	51.5
T-700 graphite	7000	1780	545	–
Multi-walled carbon nanotubes (low end)	10,000	1750	793	–
Single wall carbon nanotube (low end)	50,000	1300	5341	–
Multi-walled carbon Nanotubes (high end)	60,000	1750	4761	–
Single wall carbon nanotube (high end)	500,000	1300	53,418	–

6.4.2. Composite rotors

Composite materials present several distinct advantages in the design of FESS. One of the primary benefits is their high energy density, which has been previously discussed in detail. Additionally, composite rotors exhibit favourable failure behaviour. In the event of rotor failure, composites tend to pulverise rather than fragment into large, hazardous pieces, thereby reducing the risk. This characteristic also facilitates a more controlled shutdown, contributing to the overall safety of FESS in vehicular applications [174].

Another critical advantage of composites, particularly in automotive settings, is their superior resistance to high cycle fatigue (HCF) in low-load conditions. Materials such as S-glass/epoxy and E-glass/epoxy have demonstrated the ability to withstand a large number of cycles without significant degradation in performance, unlike steel, which tends to show pronounced fatigue under similar conditions [175]. This fatigue resistance is particularly valuable in vehicular applications where frequent charging and discharging cycles occur. However, it is important to note that composite materials are susceptible to ageing, particularly due to environmental factors such as temperature fluctuations, humidity, and ultraviolet (UV) radiation. These factors can degrade the polymer matrix over time, thus, the long-term durability of composites in diverse environmental conditions remains an area requiring further investigation [174].

Despite their numerous advantages, composite rotors also come with notable drawbacks. One of the most significant challenges lies in their production complexity and associated costs. The manufacturing process requires a high degree of precision, particularly in the winding and curing of resins. This limits the number of manufacturers capable of producing composite rotors with the necessary accuracy, which can drive up production costs [176]. Thermal sensitivity is another limitation of composite rotors. Their poor thermal conductivity makes them vulnerable to high operating temperatures, which are common in vehicular applications. Composite materials such as graphite/epoxy experience a sharp decline in mechanical properties when exposed to temperatures above 200 °C. This poses a significant challenge, especially in electric vehicles where heat management is crucial for maintaining performance and safety [174].

6.4.3. *Impact on vehicle performance*

The use of composite rotors in FESS offers the potential for substantial improvements in vehicle performance due to their reduced weight and increased energy density. These characteristics make composite rotors an attractive option for automotive applications, particularly in electric vehicles where energy efficiency is paramount. However, the limitations related to thermal management and long-term durability necessitate further research and innovation [174]. Advances in multi-layer carbon composite structures and the development of improved resin matrices will be key to addressing these challenges, enabling composite rotors to fully replace steel rotors in mass-market vehicles [177].

6.4.4. *Development goals for steel rotors*

While composites continue to gain traction, steel rotors remain an important component of FESS due to their specific mechanical properties and cost advantages. A critical trade-off between steel and composite rotors is the difference in their failure modes. Steel rotors, with their tendency to fracture into large fragments, require robust burst containment systems to mitigate risk. In contrast, composite rotors, which delaminate and pulverise upon failure, produce smaller and more manageable debris [174].

Steel rotors also maintain a distinct advantage in terms of balance quality. Due to their dimensional stability, steel rotors allow for easier mounting of balancing weights, which contributes to smoother operation. Composite rotors, on the other hand, can suffer from the release of residual stresses within the matrix material, complicating balance and potentially reducing operational stability [178].

In terms of thermal performance, steel outperforms composites by retaining strength and efficiently dissipating heat at higher temperatures. This characteristic is particularly important for vehicular applications, where rotors are subjected to significant heat during high-speed operation. The superior temperature resistance and thermal conductivity of steel make it a reliable material for applications where heat management is critical, despite its lower energy density compared to composite alternatives [174].

In the advancement of rotor materials for FESS, the choice between gear steel and aluminium alloys plays a significant role in terms of system performance. Gear steel, with its high density, offers superior energy storage capacity at lower rotational speeds, making it ideal for applications where durability and robustness are crucial. Its ability to withstand mechanical stresses and cost-effectiveness make it a practical choice for long-term use [174]. On the other hand, aluminium alloys, while lightweight and capable of achieving higher rotational speeds, require much faster operation to store the same energy as steel due to their lower density [179]. Furthermore, aluminium alloys typically exhibit lower tensile strength and are more susceptible to thermal deformation at high speeds, limiting their suitability for high-stress applications. While gear steel proves more promising for FESS, offering a balance of energy storage efficiency, durability, and cost, aluminium alloys may present added challenges due to their thermal and mechanical limitations at higher speeds [179].

The Clean Motion Offensive (CMO) Rotor project demonstrates the potential of using soft magnetic cobalt-iron alloys in FESS for electric vehicles [180]. These alloys were selected for their high flux density and mechanical strength, qualities that are essential for maintaining performance under high centrifugal forces. A notable feature of this project was the annealing of the cobalt-iron alloys at elevated temperatures, which allowed for the optimisation of both mechanical and magnetic properties of the material. This process makes cobalt-iron alloys a viable option for flywheels in applications where high rotational speeds are required [181]. In terms of structural integrity, the CMO rotor employs full-face bonding between its layers, ensuring long-term balance stability. This characteristic is critical for high-speed vehicular applications, where imbalance can lead to vibrations that negatively affect performance and safety. While no burst tests were conducted on the CMO rotor due to budget constraints, it is assumed (based on similarities to other tested systems) that the rotor would exhibit controlled pulverisation in the event of failure. This failure mode would enhance containment safety, an essential consideration for FESS in vehicles [182].

6.4.5. *Rotor length*

The optimal flywheel rotor length is fundamentally linked to its dynamic characteristics. A rotating body in a flywheel system can give rise to bending resonance modes, referred to as “criticals”, which affect the rigidity of the system. A highly rigid system can lead to substantial energy losses. Therefore, a sufficiently soft bearing system is often chosen to ensure that these criticals occur at lower speeds. This approach allows the critical effects to be transmitted during the run-up, after which the rotor rotates around its centre of mass, resulting in lower bearing forces and damping losses. Achieving this efficiency requires a well-balanced rotor with minimal centre shift. The rotor length has a significant influence on the system dynamics, particularly in terms of its effect on the rigidity of the conical body, which is contingent on the rigidity of the chosen bearing. To prevent excitation of this mode within the operational speed range of the machine, the rotor length-to-diameter ratio should be significantly $>$1:1. This consideration leads to a choice between a cylindrical or a disc rotor shape. Typically, the length is minimised to allow operation at maximum stress velocity, aiming to lower the rotor speed [81].

In the context of hybrid powertrains, the size of the flywheel system has a direct impact on fuel consumption. Larger flywheels facilitate more efficient braking energy recovery, leading to lower fuel consumption. However, beyond a certain size, the drawbacks, including increased drag and a reduced dynamic speed range, begin to outweigh the benefits, resulting in increased fuel consumption. The relative payback period in hybrid powertrains is an essential metric, quantifying the fuel saving advantages relative to the capital investment in hybridisation and the service life of passenger vehicles [183].

6.4.6. *Hub design*

Increasing the energy capacity of a flywheel at a fixed speed can be more efficiently achieved by enlarging the radius rather than the length of a conventional flywheel rotor. However, in vehicular applications, augmenting the rotor length offers the advantage of a greater bearing span. This extended span effectively reduces bearing loads, particularly under gyroscopic couples, which are significant in dynamic vehicular environments. Traditional flywheel designs typically feature an energy storage ring attached to a symmetrical hub. Various hub designs, such as simple disc and spoke configurations, are depicted in Fig. 9. Precision in hub design becomes increasingly critical when operating at higher speeds to prevent issues with the rim. For instance, if a metal rim expands more than the hub during operation, a loss of contact can occur, leading to operational inefficiencies or mechanical failures. Conversely, if the rim expands less than the hub, it can result in elevated stress levels within the flywheel [184].

7. Challenges and limitations of FESS

7.1. Safety

Safety considerations are vital in the design and operation of flywheels, especially due to the potential hazards arising from premature system failure. Flywheels utilised for energy storage applications endure considerable centrifugal forces, particularly at rotational speeds approaching 10,000 rpm which is deemed relatively low. These forces increase exponentially at speeds ranging between 10,000 and 100,000 rpm. In the event of premature rotor failure, fragments could be ejected at high velocity. To mitigate such risks, flywheel housing is typically constructed of steel, with recommended thicknesses being doubled those used when operating within a low-pressure environment. Despite the infrequency of catastrophic failures, failure of high-speed flywheels made of composite materials is more common, while steel flywheels, which operate at lower speeds, tend to exhibit gradual failure, allowing for early detection before complete fracture [178].

7.1.1. Safety research and operational limits

In the United States, various safety-related research initiatives have been sponsored by organisations such as the Defence Advanced Research Projects Agency, the Metro Transit Authority of Houston (Texas), and NASA, which propose different strategies to enhance safety measures. A common approach to ensure safe operation involves setting the maximum operational speed well below the speed at which failure is anticipated [185]. Dynamic stress analysis and destructive spin tests are employed to ascertain the maximum permissible operational speed, with spin tests identifying the rate at which failure occurs. Stress variation analyses in relation to speed help establish the safety margin and operational speeds are determined such that they remain well below the identified failure rate.

Another aspect of safety strategy involves safeguarding against material defects and cracks. Health monitoring sensors can be integrated within the flywheel system to monitor critical parameters, encompassing electronics, transmission, magnetic bearings, and the structural integrity of the flywheel system. These sensors, in conjunction with onboard computers, enable the system to execute an immediate shutdown in the event of a failure or when abnormal conditions are detected [186].

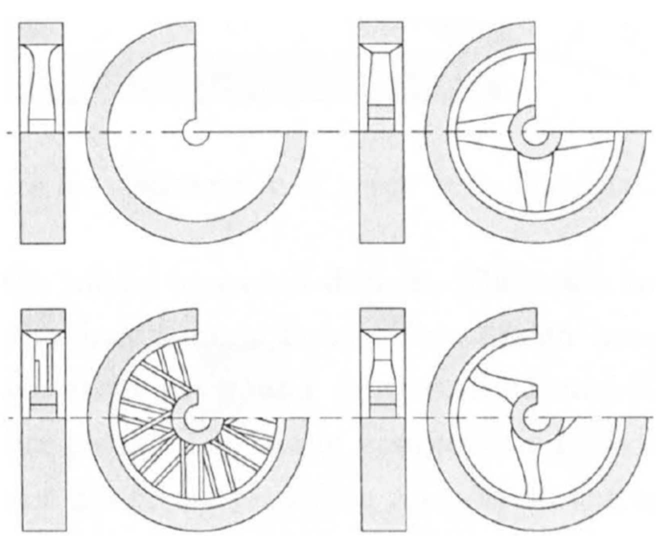

Fig. 9. Schematic diagram of different flywheel hub designs [184].

7.1.2. Design strategies for enhancing safety

Effective containment solutions must balance the demands of low weight and cost while withstanding the forces of an impulsive flywheel rupture. An alternative strategy is to design the flywheel in such a way that mitigates the likelihood of catastrophic rotor failure modes. Currently, carbon fibre is the most widely used composite material in FESS due to its disintegration into fine particles upon failure, which, while creating high axial forces within the housing, behave more like a fluid and can reduce the impact of failure [187]. Table 10 lists potential failure triggers within a flywheel system along with their possible repercussions.

Hansen et al. [92] have explored the issue of FESS failure and proposed measures to mitigate it. Key design considerations for enhancing system safety include: implementing containment specifically tailored to the flywheel design, integrating instruments capable of early failure detection, designing for incremental failure that results in fewer, smaller

Table 10
Flywheel failure modes, reasons, and their consequences [174,175].

Trigger	Reason	Initial failure mode	Consequences
Rotor shafts or housing break	Torsional or other stresses	Rotor imbalance, can fly off in the radial direction	• Projectiles bursting through the housing. • Excessive noise. • Excessive axial impulses penetrating the housing. • Significant torsional loads on the housing. • Large number of radial bending impulses on the housing.
Rotor cracks	Circumferential stresses	Fragments break out, parts fly off in tangential and radial directions	• Projectiles bursting through the housing. • Excessive noise. • Excessive axial impulses penetrating the housing. • Significant torsional loads on the housing. • Large number of radial bending impulses on the housing.
Composite rotors form cracking or softening	Overheating	Fragments break out, parts fly off in tangential and radial directions	The rotor degrades into numerous small particles, resulting in an abrasive "pyro-plastic flow" and high hydrodynamic pressure, resulting in: 1. "Fluid" pressure cracks or deforms the housing. 2. "Fluid" flows along the housing, producing large impulses in the axial direction, lifting, or cracking the housing.

fragments rather than the disintegration of the entire rotor, and allowing a larger margin between the operational stress levels and the material's ultimate strength, which can extend the lifespan of the system but may also increase its mass. The authors assert that the only viable automotive flywheel solution is one that guarantees containment without depending on devices or other measures under all anticipated conditions. Considering the need for cost-effective materials, the system and its parts may not undergo frequent checks, inspections, or monitoring. Therefore, the flywheel must not only be effectively contained; it should also be designed such that the angular deceleration rate of any fragments is sufficiently low to prevent the generation of dangerously high torque levels that could compromise the housing. In the event of a crack reaching a critical size, metal-based flywheels typically fracture into three large pieces, requiring a robust housing capable of containing and absorbing the flywheel energy.

7.1.3. Housing design for safety

The housing of a FESS plays a critical role in ensuring the system's safety, functionality, and overall performance. Its primary functions include serving as the interface between the flywheel and the vehicle, maintaining vacuum tightness for optimal operational conditions, and providing a robust protective barrier that can contain any fragments in the event of a rotor failure. Constructed from high-strength materials such as thick steel, the housing must be able to withstand the high-speed impact of projectiles generated during a catastrophic rotor failure [178]. This protective function is essential in vehicular applications where safety is paramount.

In the case of flywheel failure, the kinetic energy released can be substantial. For example, a 1.5 kWh flywheel, if it fails, generates kinetic energy equivalent to that of a car travelling at over 300 km/h. The most significant risk in such an event is the fragmentation of the rotor and the high-energy impact of those fragments at rim speeds. Therefore, the housing must be designed to contain these fragments and ensure that no debris escape, which could otherwise cause severe damage or injury. In practical terms, housing serves as the last line of defence against catastrophic failure.

The safety requirements extend to include crash tests and impact testing. For example, vehicles equipped with flywheel energy storage must pass stringent safety tests, such as those mandated by the EuroNCAP regulations, to ensure that the housing can protect against damage even during crashes. The European Enhanced Vehicle-Safety Committee (EEVC) guidelines also apply, requiring that the housing be designed to maintain integrity at accelerations up to 40 g in crash scenarios, such as during bumper destruction [189]. Tests conducted by Flybrid subjected a flywheel module to accelerations exceeding 200 g during a Formula 1 crash scenario. These tests demonstrated the housing's ability to prevent any adverse effects on the flywheel's operational reliability, highlighting the essential role of robust housing in real-world crash situations [190].

Moreover, the housing must balance robustness with weight reduction to optimise the overall system efficiency. In high-performance vehicular applications, where space is limited, and weight is a significant factor, reducing housing mass is critical [191]. However, this must not compromise the housing's ability to withstand high rotational forces and protect against potential failure. For example, in crash tests such as the AZT/RCAR repair test, the impact speed is defined at 15 km/h for both front and rear tests. Such assessments ensure that the housing can absorb shocks without structural failure, providing a fail-safe for both low-speed impacts and more severe accidents [190].

In addition to crash safety, the housing must provide structural integrity for the integration of the flywheel with the vehicle. Particularly in commercial vehicles, where installation space is more readily available, housing integration becomes a more straightforward process. Yet, it remains a critical design consideration, ensuring the flywheel system can seamlessly interface with the overall structure of the vehicle [64]. The housing also plays a crucial role in containing rotor fragments during failure. Predicting the exact mechanisms of failure and how the debris will behave is complex, and as a result, experimental studies are required to improve containment strategies. Research has been conducted to better understand the failure modes of flywheels and to observe impact behaviour in containment systems [178,192]. These studies have led to practical design improvements and continue to inform the development of safety protocols for flywheel systems [73].

One innovative approach to housing design is the s-bracket containment structure, developed by Boeing Phantom Works. This design is specifically tailored for composite rotors and employs s-shaped steel fins to absorb deformation energy. The rotor, made from anisotropic fibre composite material, is allowed to expand within the housing, and the contact forces acting on the rotor increase progressively with its diameter [193]. Although this design has proven effective for stationary FESS, the challenges associated with mobile applications remain, necessitating further research into optimised housing structures that reduce the overall weight of the system while maintaining the necessary safety standards.

7.2. Gyroscopic moment effect

Gyroscopic effects can have detrimental impacts on vehicle handling and stability. A gyroscopic moment arises when the axis of a rotating flywheel is subject to rotation, and this axis is oriented perpendicularly to the rotor's axis of rotation. This situation leads to the generation of gyroscopic torque, influenced by the magnitude of torque, the angular velocity of the flywheel, and the rate at which the flywheel's axis is turning [194]. During vehicular manoeuvres such as cornering, or when traversing inclines or dips in the road, the vehicle can experience rotational forces around the cornering axis due to these gyroscopic interactions. McDonald [195] conducted comprehensive research into the issues posed by gyroscopic torque in vehicles equipped with flywheels, examining its influence on vehicle dynamics.

For vehicle dynamics and their effects on the flywheel, yaw angular speed is the most significant vertical axis. This is sometimes less suitable for mechanical transmission, particularly when a linear or cross-axis motion is preferred. The gyroscopic torque can prevent rolling momentum, thereby improving road tenure through cross-sector weight transfers when the axis is transverse. McDonald's primary finding indicates that the gyroscopic torques produced were typically insignificant compared to other vehicle dynamics [195]. It is a question that needs attention, but it is not essential. As previously mentioned, it is of particular concern that the bearings can accept the subsequent loads to support the gyroscopic torque. Otaki [196] and McDonald [195] stated the fundamental equations of the gyro-dynamic forces. The flywheel's angular momentum is dependent on the flywheel's inertia and rotational speed. The angular momentum of a flywheel can be calculated by the following equation:

$$H = I\omega \tag{1}$$

where I is the flywheel inertia and ω is the flywheel rotational speed.

The most significant torque produced from a flywheel will be at the highest rotational speed since the flywheel inertia does not change. The torque applied on a flywheel can be calculated by the following expression:

$$T_{ap} = \frac{dH}{dt} \tag{2}$$

The exerted reaction torque from the flywheel can be calculated by the following equation:

$$T_r = -T_{ap} = \frac{dH}{dt} \tag{3}$$

When the vehicle manoeuvres, the rate of rotation on the flywheel is referred to as the precession rate (Ω). The precession rate affects the angular momentum, and the rate of change can be calculated by the following relationship:

$$\frac{dH}{dt} = H \times \Omega \tag{4}$$

From Eq. 2 and 4 the reaction torque can be written as:

$$T_r = H\Omega\sin\theta \tag{5}$$

where θ is the angle between the vectors shown in Fig. 10, the reaction torque is perpendicular to both the momentum and precession rate vectors.

The manoeuvres of the vehicle can be in three directions, with each having a different effect on the vehicle. Fig. 11 and Table 11 show the corresponding reaction torque in each direction.

7.2.1. Gyroscopic effects and dynamic coupling in high-speed FESS

In conventional vehicles, the track width is typically narrower than the wheelbase, leading to a relatively small torque reaction to the vehicle pitch or yaw movements, with roll motions being insignificant under normal operating conditions. Research by Otaki [196] and McDonald [195] demonstrated that the gyroscopic reactions of flywheels within automobiles are relatively minor during regular driving. However, more extreme scenarios, such as accidents or sharp manoeuvres, need careful consideration, particularly in relation to high-speed FESS. At higher rotational speeds, the gyroscopic forces produced by the flywheel increase, exerting additional dynamic loads on the bearings and potentially affecting vehicle stability.

The dynamic coupling between the rotor and bearings becomes critical under these high-speed conditions. The gyroscopic forces not only increase the mechanical stress on the bearings but also challenge the system's ability to maintain stability [199]. Bearings must be carefully designed to handle these loads and minimise friction, with advanced solutions such as magnetic bearings often used to manage dynamic forces. Failure to account for these interactions can lead to system instability, especially during sudden manoeuvres or extreme conditions [199]. Although gyroscopic reactions may be minor under normal circumstances, they could significantly affect performance and safety in the event of accidents.

Composite flywheels are often touted for their safety, since, upon failure, the material tends to shatter into dust-like particles, exerting pressure on the containment vessel more akin to a fluid than solid fragments. Simulating realistic catastrophic failures is a significant challenge in ensuring the safety of composite flywheels, as they are designed with high safety factors, making actual explosive failures at excessively high speeds unlikely [174].

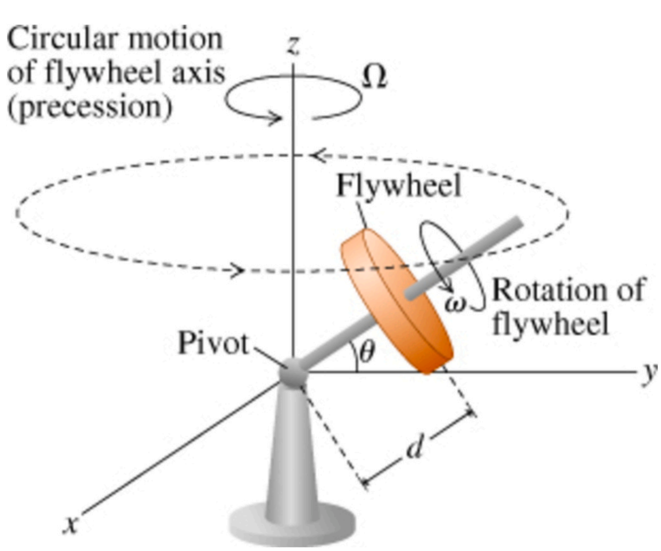

Fig. 10. The angle between the precession rate and angular momentum vectors [197].

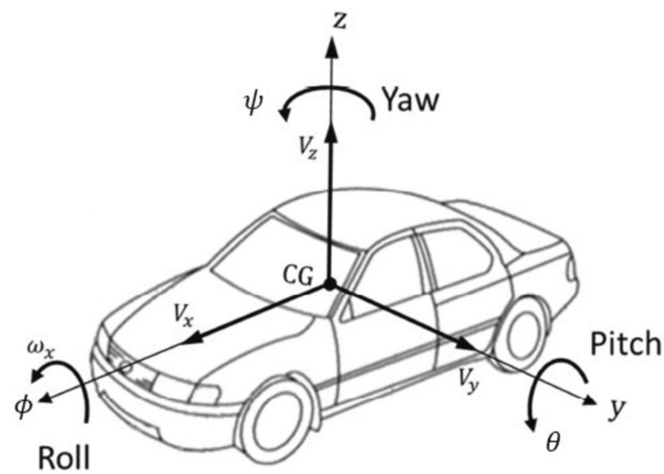

Fig. 11. Vehicle manoeuvres and the corresponding reaction torque [198].

Table 11
The flywheel orientation and their reaction torque sense [195].

The orientation of the flywheel	Precession direction		
	+ Pitch	+ Roll	+ Yaw
+Lateral	None	+Yaw	−Roll
+Longitudinal	−Yaw	None	+Pitch
+Vertical	+Roll	−Pitch	None

The methodology used in car crash analysis, which often involves dynamic finite element analysis corroborated by data from well-instrumented experiments, can be applied to the evaluation of flywheel containment in the event of a burst. It is crucial to establish standards that provide clear guidelines during the developmental phase to ensure that FESS used for automotive applications is safe [200].

The flywheel can be mounted on several gimbals to keep its axis of rotation irrespective of the vehicle's motion. The mechanical transfer of power can be a fundamental design challenge with such an assembly. The two counter-rotating flywheels [201] are an alternative method for cancelling gyroscopic torques as shown in Fig. 12. In this configuration, the gyroscopic torque from each flywheel would counteract the gyroscopic torque produced by the other flywheel.

7.3. Driver experience

One of the main challenges in the adoption of FESS in vehicles is its impact on the driver experience. Modern vehicles, due to their complex technical architecture, require a significant understanding of the intricacies of energy and mobility. However, for the average consumer, energy usage remains highly non-intuitive, with little awareness of how much energy is consumed during daily driving activities [76].

7.3.1. Psychoacoustic and performance perception

One of the key challenges in the adoption of FESS in vehicles is the psychoacoustic feedback experienced by drivers. The characteristic hum or vibrations generated by the system can create an unfamiliar or undesirable sensory experience, particularly when the low-frequency noise differs from the typical sound patterns of internal combustion engine vehicles. This disconnect between the sound of the vehicle and its actual performance can lead to misperceptions, where drivers feel the vehicle is underperforming or operating inefficiently, even though the system is functioning optimally [202].

Psychoacoustics, the study of how sound is perceived by the brain,

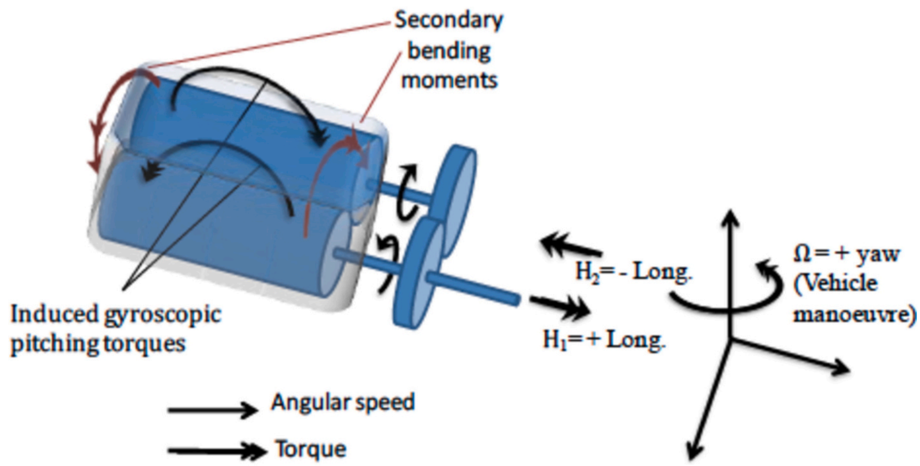

Fig. 12. The schematic diagram of counter-rotating flywheels [201].

plays a significant role in shaping consumer perceptions of vehicle performance. In FESS-equipped vehicles, the absence of the familiar engine sounds and the introduction of low-frequency hums, particularly at low speeds, may affect driving experience. This phenomenon is similar to the psychoacoustic rejection often observed with CVT, where the lack of a linear relationship between engine speed and vehicle acceleration can lead to feelings of inefficiency, even when the system is performing effectively [203]. In serial hybrid systems, where both electric motors and internal combustion engines are used, this non-intuitive auditory feedback is more pronounced. Drivers accustomed to traditional auditory cues may struggle to adjust to FESS-equipped vehicles, potentially leading to consumer rejection despite the efficiency gains offered by these systems. The integration of FESS, particularly when combined with regenerative braking and energy recovery systems, must be carefully designed to align with driver expectations to mitigate these negative psychoacoustic effects [202].

7.3.2. *Driving dynamics and regeneration*

In terms of driving dynamics, FESS offers significant advantages, especially in hybrid vehicles, by allowing energy recovery during braking. However, the regeneration potential of such systems, especially in rear-wheel drive configurations, may feel counterintuitive to drivers used to traditional braking systems. Regenerative braking, if not properly integrated, may cause a disconnect between the driver's input and the vehicle's response, further complicating the adoption of FESS [204]. Additionally, flywheel systems can create gyroscopic effects during cornering or rapid directional changes, impacting vehicle stability. These effects must be carefully managed to avoid adverse impacts on vehicle's handling and driver control, particularly in high-performance or sports vehicles [125].

FESS excels at energy recuperation, which is highly advantageous in stop-and-go urban environments where frequent deceleration and braking occur. The system captures otherwise lost kinetic energy and stores it for later use, improving overall energy efficiency. However, this can also lead to an unusual driving dynamic that may not align with the expectations of drivers accustomed to conventional systems. For instance, the braking and acceleration patterns with FESS might feel different, as the system stores and redistributes energy in ways that affect the traditional mechanical feel of the car [76].

7.3.3. *Optimising FESS for the passenger experience*

To mitigate these challenges, manufacturers are increasingly looking to integrate FESS with advanced vehicle technologies, such as intelligent driver-assistance systems and predictive control strategies, which can smooth out the transition between different operational modes. Technologies such as the EO Smart Connecting Cars are examples of how intelligent networking can be used to enhance the driver experience while optimising energy storage and utilisation. By predicting and adjusting to real-time driving conditions, these systems ensure that energy flows are distributed in the most efficient manner, allowing the vehicle to maintain a more traditional driving feel while benefiting from the energy-saving advantages of FESS [76].

8. Optimisation of FESS standby losses

The main drawback of FESS is the high mechanical losses, which originate from bearing and aerodynamic “windage” losses [79]. Bearing losses, which are influenced by the flywheel's mass and the choice of lubricant, tend to increase linearly as a function of flywheel speed. On the other hand, windage losses, which are due to friction between the rotor and the fluid within the housing, constitute a significant proportion of total losses, particularly in high-speed applications [205]. These losses not only contribute to increased self-discharge but also adversely affect the overall efficiency of FESS [64]. Windage losses result from the frictional interaction between the rotor and the fluid surrounding it, dissipating energy as heat. Mitigating these losses is essential for enhancing FESS performance [79]. With the high peripheral speeds, the frictional windage losses of a flywheel system become notably substantial. These losses occur due to both skin friction on the rotor's surface and the radial outward movement of air caused by the rotor's motion. This can lead to significant energy depletion and excessive heat generation, potentially causing the rotor to overheat [206]. Gurumurthy et al. [207] conducted experiments at atmospheric pressure and determined that mechanical losses, primarily from drag, were the major contributors to power losses in FESS, accounting for 72 % of the total losses at high speeds.

Calculating windage loss is complex and is influenced by the skin friction coefficient, a parameter that is a function of the rotor radius ratio and Reynolds number [208]. For high-speed electric motors, several researchers have studied windage losses and presented methods to reduce them [209], such as those by Okada et al. [210], who demonstrated that shrouding the rotor could significantly decrease windage loss while preserving motor efficiency. Eltaweel et al. [211] developed a CFD model to estimate windage losses in high-speed FESS. Their study demonstrated that increasing air gap size and reducing rotor cavity pressure could lower windage losses by up to 45 %.

Computational Fluid Dynamics (CFD) has been utilised to model flow within the flywheel housing, aiming to develop ways to improve efficiency [208,212]. Anderson et al. [213] used commercial CFD software to analyse windage losses in high-speed motors, offering a method for designers to quickly assess the thermal impact of windage losses. Recent studies have combined CFD simulations with experimental data to advance the fundamental knowledge in this area [214–218]. Walton et al. [219] investigated the windage losses of a rotor supported by gas foil bearings, but they did not consider the fluid field's impact near the bearing journal. In the following section, the effects of various geometrical and operating conditions on FESS standby losses are discussed.

8.1. Airgap size

FESS optimisation involves careful consideration of various design parameters to minimise energy loss and enhance system performance. The intensity of the windage losses is a function of the flywheel rotational speed, airgap (annulus) size and operating pressure. The size of the airgap is an important factor when designing a FESS which is dependent on various parameters including flywheel speed and expansion rate at high speeds. The rotation of an enclosed flywheel creates a complex flow within the FESS cavity, resulting in heat generation due to frictional losses. The flow characteristics are dependent on the flywheel speed, outer rim surface roughness, airgap size, and properties of the working fluid [220]. Couette and Taylor determined flow viscosity and flow stability in the annulus of two concentric cylinders; consequently, this type of flow is commonly referred to as Taylor-Couette flow. The stability of Taylor-Couette flow, which occurs between two concentric cylinders within the FESS, is a key factor in controlling windage losses. This type of flow is a well-studied phenomenon in fluid mechanics, particularly in applications such as FESS and electric motors, where both windage loss and heat transfer are critical considerations [216]. Previous studies have shown that by understanding and managing the parameters affecting the flow characteristics within the airgap, such as rotor speed and surface roughness, windage losses can be substantially reduced [221,222]. The Taylor-Couette flow effect on performance is significant, and controlling this flow demonstrated how reducing windage losses and improving heat transfer can significantly improve FESS efficiency, especially at high rotational speeds [223].

In their pursuit of reducing windage losses, researchers such as Chirita [224] have explored design optimisations for flywheel components made from materials such as titanium alloys. Findings indicated that the flywheel outer diameter greatly impacts energy storage, more so than rim width and height. Similarly, Nakane et al. [225] and Pfister and Perriard [226] have proposed methods and models to lower windage losses in high-speed applications, reporting that certain configurations, such as the inclusion of rotor shrouds or adjusting the airgap size, can lead to improved torque and power efficiency.

The airgap size is a crucial design element, with small gaps defined by a gap-to-diameter ratio of <0.005 to 0.02 [219]. Larger airgaps have been extensively studied, particularly under atmospheric conditions, with findings highlighting the sensitivity of windage losses to airgap size [227]. Awad and Martin [228] investigated windage losses on both the disc and cylinder sides of pulse generator rotors. For the disc and cylinder sides, the skin friction coefficient is a function of the Taylor Number which is typically used to calculate the flow characteristics inside the annulus of concentric cylinders.

Windage losses are influenced by heat transfer within the FESS, and heat transfer within these systems is influenced significantly by Taylor-Couette flow. Gazley [229] was among the early researchers who examined the heat transfer in the annulus of concentric cylinders. Many researchers have studied heat transfer in the annulus of concentric cylinders both theoretically and experimentally. Becker and Kaye [230] studied heat transfer in concentric cylinder annuli without axial cross flow. Tachibana and Fukui [231] examined how airgap size affects electric motor heat generation and dissipation. In the annulus of high-speed electric motors, Howey et al. [232] examined how airgap size affects convective heat transfer of laminar and turbulent swirling air flows. The authors calculated surface convective heat transfer coefficients using non-dimensional parameters for the thermal modelling of radial-flux and axial-flux electrical machines.

8.2. Working pressure

Research and development in the field of FESS have primarily concentrated on optimising the design of crucial components such as housing and rotors, given the substantial safety considerations involved due to the high rotational speeds these components endure [55]. Among these considerations, windage losses are significant, especially if the flywheel operates at atmospheric pressure [209]. To minimise such losses, FESS can operate at lower working pressures, medium to hard vacuum, to reduce aerodynamic losses due to drag [79]. However, this solution introduces increased system complexity and necessitates additional components such as vacuum pumps and cooling systems. The vacuum pump used in the system should use minimal energy so that it does not affect the overall efficiency of the system [233]. The power the vacuum pump uses to maintain the working pressure and the power needed to overcome drag is known as standby power. Standby power, along with the power needed to keep the flywheel rotor at a specific state of charge, is a crucial factor in determining the overall efficiency of the FESS [234,235].

Establishing a medium to hard vacuum presents various challenges such as potential leaks, lubricant vaporisation at low pressures, and outgassing, where materials release trapped gases. These issues can lead to environmental contamination and a decline in the material's properties. Moreover, such an environment can lead to elevated flywheel temperatures due to diminished convective heat transfer, making it necessary to evaluate the trade-offs between reduced windage loss and the energy savings potential of the system [79]. A hermetically sealed flywheel containment can maintain a vacuum while minimising the need for continuous pump operation, thus preserving energy [236]. Asami et al. [234] have proposed a novel structure combining an aerodynamic step thrust bearing with a spiral-grooved viscous vacuum pump to reduce windage losses in high-speed motors.

Investigations by Liu et al. [237] into various vacuum levels show the impact on windage heating within a high-speed flywheel. Motaman et al. [238] conducted a numerical analysis of FESS for low-carbon powertrains, showing that a 40 % reduction in operating pressure can decrease surface temperatures by 20 % and windage loss by 30 %. An innovative approach to further reduce aerodynamic losses involves the use of a helium-air mixture, as studied by Suzuki et al. [239], who found that a 50 % helium mixture could lower losses by 43 %, with greater reductions at higher helium concentrations.

Analysis of mechanical and electrical losses, such as those by Skinner [240] on cylindrical composite rotor FESS, indicate that both flywheel speed and working pressure can influence mechanical losses. Similarly, Amiryar and Pullen [79] examined how different vacuum pressures and airgaps can affect windage and bearing losses, emphasizing the significant role of design parameters on power losses. Complementing this, Anderson et al. [213] used commercial CFD software to model windage loss in high-speed motors, providing valuable insights on mitigating thermal performance issues.

Ensuring a vacuum-tight seal is critical for maintaining the low-pressure environment within a FESS. Various seals, including mechanical, magnetic, and labyrinth seals, offer different advantages in terms of cost, reliability, and suitability for handling high-speed rotations [215,216,241]. The role of the vacuum pump is also vital, with a variety of types available, each with specific benefits and suited for different vacuum levels and applications [218,246].

FESS often employ air or magnetic bearings to support the rotor, with each offering benefits in terms of friction reduction and operational longevity. While air bearings provide low-friction levitation with an extended lifespan, magnetic bearings are known for their high precision, though they come at a higher cost and complexity [247]. Integrating these bearings with the appropriate seals can help achieve the desired vacuum tightness and system durability [248].

8.3. Rotor material

Metallic rotors represent a crucial subset of flywheel technology, using dense metals such as steel to store kinetic energy. Due to their robustness, metallic flywheels offer greater durability and cost-effectiveness compared to composite flywheels [221]. Their high density allows for a more compact energy storage solution, capable of storing substantial energy at lower rotational speeds. This inherent attribute means that metallic flywheels face lower centrifugal forces, which in turn simplifies the design requirements [60].

The relationship between the windage loss and the physical characteristics of flywheels is a critical consideration. Windage loss is heavily dependent on the flywheel diameter and velocity, scaling with the fifth power of diameter and the cube of velocity, as well as the 3/4 power of working pressure [239]. This principle dictates that for a given energy storage capacity, a composite flywheel, which typically operates at a higher peripheral speed than its metallic counterpart, requires a more substantial vacuum to mitigate losses.

The high-speed operation of flywheels, especially those made from composite materials, presents additional challenges. Increased rotational speeds can lead to significant frictional losses, which manifest as heat within the flywheel housing. For composite flywheels, which might include materials such as graphene composite rims, this heat can compromise the mechanical integrity of the material by softening the epoxy and reducing its tensile strength [249]. Similarly, the mechanical properties of a steel hub can be adversely affected by localised thermal stresses, leading to deformation, crack formation, and ultimately, the risk of premature failure [250]. Therefore, the implementation of a cooling system is imperative to manage the heat in these high-performance, non-vented systems, although this increases complexity and costs.

8.4. Slit wall design

The Taylor-Couette flow, which involves fluid motion between two rotating coaxial cylinders, has garnered significant attention from researchers due to its complex dynamics and applications in heat transfer enhancement [251]. The manipulation of cylinder surfaces through structures such as ribs and slits has been a focal point of previous investigations to improve heat transfer efficiency [252]. Tsukahara et al. [253] examined how ribs on the rotor surface influence the frictional drag coefficient and pressure drag. They found that ribs increase pressure drag, but this is somewhat mitigated by the strong adverse pressure gradient caused by the Taylor vortices' in-flow motion. The overall resistance due to ribs is a factor in their orientation and spacing.

Studies have focused on optimising the geometric design of the housing, such as incorporating concave, convex, or slit wall shapes. For example, Eltaweel and Herfatmanesh [254] investigated how concave and convex casings with reduced pressure can reduce windage losses by influencing the airflow dynamics within the annulus, allowing for up to 90 % reduction in energy dissipation compared to standard cylindrical designs. Similarly, another study demonstrated the effectiveness of slit walls—particularly triangular and rectangular designs—within the housing, which improved both heat transfer and windage loss reduction [255].

Investigations into heat transfer within grooved channels have shown varied results based on the groove designs. Karakas [256] reported on the heat transfer properties of the Taylor-Couette flow affected by longitudinal and oblique slits. Notably, slanting counterclockwise slits had better heat transfer capabilities compared to clockwise slits. Similarly, Hayase et al. [257] conducted numerical research on grooved channels within electric motors, reporting that inner grooved cylinders increase heat transfer more significantly than outer grooved cylinders.

Research by Gokul and Deepu [258] indicated that helical fins outperform longitudinal fins in terms of enhancing heat transfer and thermal performance due to the increased vorticity and turbulence intensity they induce. Tzeng et al. [259] demonstrated that the addition of axial ribs to rotating machines facilitates heat transfer, a finding that has practical implications for the design of high-speed rotating machinery. Kim et al. [260] explored the effects of airgap fans on the cooling of induction motors. They found significant improvements in heat transfer coefficients at the winding surface and airgap, leading to enhanced total winding cooling performance.

Liu et al. [261] provided a numerical analysis of turbulent Taylor-Couette flow within a slit model. Their results highlighted the relationship between velocity in the slit area and wall shear force, noting a contrasting behaviour in heat flux. Building upon this, Liu et al. [262] investigated the role of slit number and width on flow distribution and heat transfer in an annulus. Their findings suggested that the number and width of slits positively affect convection between the inner and outer walls, thus augmenting heat transfer. The study also revealed that the Reynolds number significantly influences the slit wall structure, affecting both flow field and heat transfer, with slit width playing a more pivotal role than the number of slits. In this research, Liu et al. [263] focused on the role of axial slit walls in Taylor-Couette flow, adjusting the rotating Reynolds number and applying a negative temperature gradient. Their comprehensive study, which tested six different models with up to 18 slits, found that these slits improved the Taylor vortex flow and minimised its azimuthal fluctuation. Significantly, the study concluded that more slits and higher Reynolds numbers facilitate better heat transfer and accelerate flow transition across both laminar and turbulent regimes.

Similarly, Sun et al. [251] employed large eddy simulations to assess the impact of slit structure on flow and heat transfer. By comparing slits of various shapes, including trapezoidal, rectangular, and elliptical, they determined that the elliptical model was superior. This shape not only prevented backflow but also maximised velocity-temperature interaction and energy utilisation, as evidenced by the lowest entropy generation and optimal field synergy angle. Sommerer and Lauriat [264] explored heat transfer in annular gaps with rectangular slits on the outer cylinder, underlining the significant influence of slit quantity on heat transfer enhancement. Zhu et al. [265], through direct numerical simulation, found that V-shaped slits impacted the flow field structure only when the slit depth exceeded the boundary layer thickness. Liu et al. [266] compared the effects of different slit wall cross-sections; triangle, rectangle, and trapezium, on turbulent flow and heat transfer. The trapezoidal cross-section was particularly effective, promoting the merging of vortices within the annular and slit areas, thereby intensifying fluid mixing, which has implications for the design of rotating machinery. The geometry of grooves also plays a pivotal role, as studied by Bilen et al. [267], who examined how various groove geometries affect heat transfer and pressure drop. Lorenzini-Gutierrez et al. [268] and Liu et al. [269] further contributed to this area by investigating the benefits of curved flow deflectors and rounded axial grooves, respectively. The latter research work concluded that rounded grooves significantly reduce pressure loss compared to square grooves.

In a similar vein, Joo and Kim [270] sought to optimise the shape of grooved tubes, particularly focusing on natural convection in vertical orientations. The optimisation of tube shapes is vital for improving heat transfer efficiency in various applications. Tachibana and Fukui [231] examined the influence of grooves on the critical Taylor number, which determines the stability threshold of the onset of Taylor vortices. Their research demonstrated that grooved layouts can effectively delay the appearance of these vortices, raising the critical Taylor number substantially.

Eiamsa-ard and Promvonge [271] provided evidence that all groove shapes significantly elevate the heat transfer rate in comparison to a smooth channel. Nouri-Borujerdi and Nakhchi [272] studied fluid flow and heat transfer in grooved channels, discovering that grooves substantially increased the average Nusselt number and overall heat transfer efficiency. They noted the Taylor number as a pivotal factor for enhancing heat transfer, with the wall temperature exerting the least influence. Their study also considered the buoyancy effects within rotating grooved channels, which positively contributed to heat transfer coefficients. Furthermore, Nouri-Borujerdi and Nakhchi [273] employed the response surface methodology to fine-tune the design parameters of annular flow with an exterior slit cylinder and a revolving inner cylinder. Their work underscored the slit aspect ratio (b/c) as having a more pronounced effect on heat transfer enhancement than the number of slits (N), suggesting that optimal slit geometry can be identified to maximise heat transfer in Taylor-Couette flows.

Complementing these findings, Sun et al. [252] also utilised the response surface methodology to optimise the influence of slit number and width on Taylor-Couette flow. Their research highlighted that higher Reynolds numbers lead to increased heat transfer, mainly attributed to intensified jet flow and temperature gradients near the inner cylinder wall. The study concluded that while the slit width and Reynolds number are significant factors affecting heat transfer, the slit number and Prandtl number play a lesser role. They achieved a 12.42 % improvement in heat transfer capacity at a Reynolds number of 4652. The role of slit walls in the outer cylinder of rotating machinery is crucial for enhancing fluid mixing and achieving a uniform temperature distribution. Liu et al. [274] specifically examined the influence of the slit wall depth-to-width ratio on flow distribution and heat transfer. Their findings indicated a strong correlation between the number of slits and heat transfer enhancement, providing insights into the structural design of rotating machines.

This collection of studies contributes to a better understanding of how changes to the physical geometry of the housing within the airgap can significantly advance heat transfer capabilities and reduce windage losses.

9. Future trends

As the automotive industry seeks more sustainable and efficient energy storage solutions, FESS are emerging as a promising technology. FESS offer high power density and rapid response, making them well-suited for applications in hybrid vehicles, EVs, and heavy-duty transport, where energy recovery and propulsion support are critical. Current research on advanced FESS focuses on improving energy density, enhancing specific power, reducing initial costs, and minimising standby losses. These advancements aim to make FESS more competitive compared to other energy storage technologies. Future developments in FESS for automotive applications are likely to continue along these lines, with ongoing research expected to drive further improvements in performance and cost-effectiveness.

9.1. Rotor materials in FESS

While composite materials offer significant advantages in terms of high energy density and safety characteristics, they present challenges related to manufacturing complexity and cost. The precision required in their production increases costs, limiting their widespread adoption, particularly in cost-sensitive vehicular applications. In contrast, steel rotors, though less efficient in terms of energy storage, are more economical and provide better thermal resistance and ease of balancing. These properties make steel rotors particularly well-suited for heavy-duty vehicles, where high temperature stability and low operational costs are essential [275].

Looking ahead, advancements in rotor materials for vehicular FESS will focus on increasing energy density without compromising safety. Research into nano-composite materials and advanced manufacturing techniques promises to make composite flywheels lighter, safer, and more thermally stable [276]. These developments are expected to enhance the viability of composite rotors for broader use in vehicular applications. In parallel, hybrid rotor materials could offer a promising solution by combining the cost-effectiveness and strength of steel with the superior energy density of composites. Such hybrid designs have the potential to overcome the limitations of both material types, achieving an optimal balance between performance, safety, and cost. This could lead to the development of more efficient and economically viable FESS, making them suitable for a wider range of vehicular applications.

9.2. Safety

Studies conducted between 1960 and 1990 focused on low-speed steel flywheels, with limited attention given to the behaviour of composite rotors. However, recent research has highlighted the complex fracture dynamics of fibre composites, which exhibit a higher degree of anisotropy compared to steel rotors. In particular, the kinetic energy of fragments in composite rotors tends to be lower due to the disintegration of the fibre material into smaller particles. This “good-natured” fracture behaviour provides an inherent advantage over steel, where failure typically results in large, high-energy fragments [277].

Several experimental designs have been proposed to better understand and manage the safety risks associated with the flywheel operation. One such design involves the use of rotatable liners, such as Kevlar rings, which are set into rotation within the housing to absorb the kinetic energy of rotor fragments. These liners have been shown to reduce the energy of projectile fragments, providing an additional layer of safety in the event of rotor failure [178].

Future developments in FESS safety will likely focus on the continued optimisation of containment solutions and the integration of advanced materials. The use of hybrid containment systems, which combine steel and composite materials, offers a promising direction for improving both safety and weight efficiency. Additionally, further refinement of rotor monitoring technologies will be crucial in ensuring early detection of potential failures, particularly in high-stress applications such as electric vehicles and hybrid transport systems [76].

9.3. Hybrid energy storage systems

The integration of FESS with traditional electrochemical batteries is gaining traction as a hybrid energy storage solution. In this configuration, FESS act as a buffer for high-power demands, providing short bursts of energy during acceleration and capturing energy during braking [278]. This reduces the strain on batteries, enhancing their lifespan and improving the overall system efficiency. For electric vehicles, FESS also support fast charging and improve the system's ability to handle high-power operations, such as regenerative braking [76].

9.4. Energy efficiency and cost reduction

One of the main factors limiting the widespread FESS adoption is its cost. Future research is aimed at reducing both manufacturing costs and operational losses, such as windage and bearing friction. Advances in magnetic bearings, which reduce friction and energy loss, will be crucial in making FESS more viable for automotive applications. Additionally, the use of less expensive materials, such as high-strength steel, will be key to improving the cost-performance ratio and expanding market adoption [76].

9.5. Autonomous and connected vehicle technologies

FESS are poised to play a significant role in future autonomous and connected vehicles by improving the energy management systems. They can supply power to advanced driver-assistance systems (ADAS), vehicle-to-everything (V2X) communication, and autonomous driving sensors. Furthermore, FESS could contribute to vehicle dynamics and stability control, particularly in electric trucks and buses, where energy requirements vary greatly depending on load and route [279].

9.6. Expansion into commercial and public transport

FESS technology is expected to expand beyond passenger vehicles into commercial fleets and public transportation, where vehicles operate in highly dynamic environments with frequent stops and accelerations. The use of flywheels in buses, trucks, and delivery vehicles will enhance fuel efficiency and reduce emissions, as energy can be recovered during braking and reused for acceleration. This will be particularly beneficial in urban settings, where vehicles spend a considerable amount of time in stop-and-go traffic [280].

10. Conclusion

FESS hold significant potential for improving energy efficiency and sustainability in vehicular applications. This review has outlined key technological advancements such as the development of high-strength composite rotors, cryogenically cooled bearings, and advanced vacuum chambers, which contribute to the enhancement of the overall efficiency and reliability of FESS. These technologies enable FESS to offer high power density, rapid charge and discharge capabilities, and long cycle life, making them a promising alternative to conventional energy storage systems, especially in dynamic environments such as road transportation. In terms of key technologies, notable developments include:

- Composite rotor materials, which offer higher energy storage capacity and enhanced safety due to superior fracture characteristics compared to traditional steel rotors.
- Magnetic and cryogenic bearings, which minimise energy losses due to friction and improve system longevity and efficiency.
- Vacuum chambers, which reduce air resistance (windage losses), allowing the flywheel to operate at higher speeds with minimal thermal energy dissipation.
- Integration with hybrid systems, where FESS complements battery storage systems by handling peak power demands and regenerative braking, thus extending battery life and improving overall system efficiency.

Looking forward, the successful deployment of FESS in vehicles will require further innovation in several key areas:

1. Manufacturing and operational costs of FESS must be lowered through material innovations and improved production techniques.
2. Advances in containment strategies and real-time monitoring systems will enhance the safety of high-speed flywheels in automotive environments.
3. The continued development of hybrid energy systems, where FESS works alongside batteries and other storage technologies, will be crucial for widespread adoption.
4. Optimising control strategies, such as model predictive control and artificial neural networks, will enhance the responsiveness and adaptability of FESS in complex vehicular environments.

The review underscores the necessity for continued innovation and cross-disciplinary collaboration to overcome existing limitations and fully harness the capabilities of FESS. Flywheel technology represents a transformative technology for energy storage in vehicles, providing a sustainable and efficient alternative. Continued research and development will be essential in overcoming current challenges and realizing the full potential of FESS in decarbonization of road transportation.

CRediT authorship contribution statement

Mahmoud Eltaweel: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Mohammad Reza Herfatmanesh:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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.

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Data availability

No data was used for the research described in the article.

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Abbreviations

ABS: Anti-locking Braking System
BLDCM: Brushless Direct Current Machine
BM: Bearingless Machine
CMG: Control Moment Gyros
CVT: Continuously Variable Transmission
EMALS: Electromagnetic Aircraft Launch System
EMB: Electromechanical Battery
EV: Electric Vehicle
F1: Formula One
FESS: Flywheel Energy Storage System
FIA: Federation Internationale L'Automobile
FWB: Flywheel Battery
HEV: Hybrid Electric Vehicle
ICE: Internal Combustion Engine
IM: Induction Machines
ITS: Intelligent transport systems
IVT: Infinitely Variable Transmission
JET: Joint European Torus
KERS: Kinetic Energy Recovery System
MG: Motor/Generator
MIMO: Multiple Inputs Multiple Outputs
MPV: Multi-Purpose Vehicles
NEDC: New European Drive Cycle
NHTSA: National Highway Transportation and Safety Administration
OEM: Original Equipment Manufacturer
P: Proportional
PGS: Planetary Gear Set
PI: Proportional-Integral
PID: Proportional-Integral-Derivative
PMSM: Permanent Magnet Synchronous Machine
RDE: Real-Driving Emissions
RM: Reluctance Machine
RTG: Rubber-tired Gantry
SUV: Sport Utility Vehicles
TPBV: Two-point Boundary-value
UK: United Kingdom
UN/ECE: Economic Commission for Europe of the United Nations