Flywheel Energy Storage Systems: A Review

WP4.3

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Abbreviations

Abbreviation	Meaning
AMB	Active Magnetic Bearing
BES	Battery Energy Storage
BJT	Bipolar Junction Transistor
BTB	Back-To-Back
CAES	Compressed-Air Energy Storage
CS	Capacitor Storage
ESS	Energy Storage System
FESS	Flywheel Energy Storage System
ESS	Hybrid Energy Storage System
GTO	Gate Turn Off Thyristor
HIL	Hardware In Loop
HSS	Hydrogen Storage System
HV	High Voltage
IGBT	insulated gate bipolar transistor
IM	Induction Machine
KESS	Kinetic Energy Storage Systems
LV	Low Voltage
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NPC	Neutral Point Clamped
PHS	Pumped Hydro Storage
PMB	Permanent Magnetic Bearing
PMM	Permanent Magnetic Machine
PSB	Polysulfide Bromine (flow battery)
RES	Renewable Energy System
RPM	Revolutions Per Minute
SCES	Super Capacitor Energy Storage
SCR	Silicon Controlled Rectifier
SoC	State of Charge
SMB	Superconducting Magnetic Bearing
SMES	Superconducting Magnetic Energy Storage
TES	Thermal Energy Storage
THD	Total Harmonic Distortion
VRM	Variable Reluctance Machine

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Contents

1. Introduction

Fossil fuels are being phased out as part of the current energy transition. Instead, Renewable Energy Sources (RES) such as solar PV and wind turbines will be used to provide the required energy. However, these sources provide intermittent energy based on weather conditions [1]. Other technologies are required to increase the flexibility of the electrical grid, whereby flexibility is defined as the capability of a power system to maintain energy balance between generation and load under uncertainty [2]. Energy Storage Systems (ESS) can provide much of the flexibility required to meet the energy mismatch created by the introduction of renewables.

There are many types of Energy Storage Systems: Pumped Hydro Storage (PHS), Compressed-Air Energy Storage (CAES), Battery Energy Storage (BES), Capacitor Storage (CS), Super Capacitor Energy Storage (SCES), Superconducting Magnetic Energy Storage (SMES), Thermal Energy Storage (TES), Hydrogen Storage System (HSS), and new advances in energy storage technologies are made every day [3]. One of the oldest technologies is the Flywheel Energy Storage Systems (FESS). Basic flywheel mechanisms have existed for more than a thousand years. The use of flywheels increased during the industrial revolution where they were used as a short-term ESS solution to stabilize the power output of steam engines. However, nowadays, the flywheel has become a competitive option for electric ESS [4], more research is being conducted into potential uses of FESSs in microgrids. One of these projects is the EFRO QuinteQ project, where a new type of flywheel is produced, and potential uses in current and future microgrids is examined.

This report, as part of the EFRO project QuinteQ WP 4.3, is an introduction into the area of flywheels. Chapter 2 examines flywheel components, characteristics and losses, and makes comparisons with other storage technologies. Next, Chapter 3 investigates the applications of flywheels in microgrids, with a more in depth look at power quality mitigations as well as when flywheels are used in combinations with other storage technologies. Finally, Chapter 4 briefly looks at flywheel producers currently supplying to the energy market.

2. Flywheel Energy Storage System

This chapter presents a short introduction into FESS technology. First, the working principles are discussed. Next, the FESS components are investigated. Finally, characteristics of the FESS are presented.

2.1. Working Principles

A FESS is a device which stores kinetic energy by rotating a large mass at speed. At any moment, the FESS is in one of three states: 1) charging, 2) standby/idle and 3) discharging. During charging, the electrical energy is converted into kinetic energy through the electric motor. The mechanical energy is then stored in the flywheel rotor as kinetic energy of a rotating mass. After charging, the FESS will remain in the standby/idle state and the kinetic energy remains stored in the rotating flywheel. During discharge of the FESS, the mechanical energy is converted back into electrical through the electric motor [5].

Common ways to improve the performance of FESSs are by increasing the rotor operating speed, using high strength materials, and by optimizing the rotor shape and dimensions [6]. The following characteristics influence the total capacity of the kinetic energy that would be possible to store in the flywheel:

- Amount of flywheel rims: 1 or 2
- Type of rotor, material: composite, metal or hybrid (2-rim flywheels)
- Speed in rpm
- Shape, radius and mass

2.2. Flywheel Components

The basic structure of a FESS consists of five primary components:

1. a flywheel rotor
2. a motor/generator
3. an electronic power converter
4. bearings
5. a housing

2.2.1. Flywheel & rotor

Flywheels are built from a solid or hallow cylindrical disk, ranging from short disk type to long drum type. There are four types of flywheels possible based on the material: composite (either 1 or 2 rim based), metal rims or a hybrid (2 rims, where one is made out of composite material and the other is metal based). The flywheel disk is then attached to the rotor of the motor/generator via shaft and is supported by a magnetic or mechanical bearings on the top and the bottom of the shaft, see Figure 1. For more on flywheel design specifications, see Appendix D.

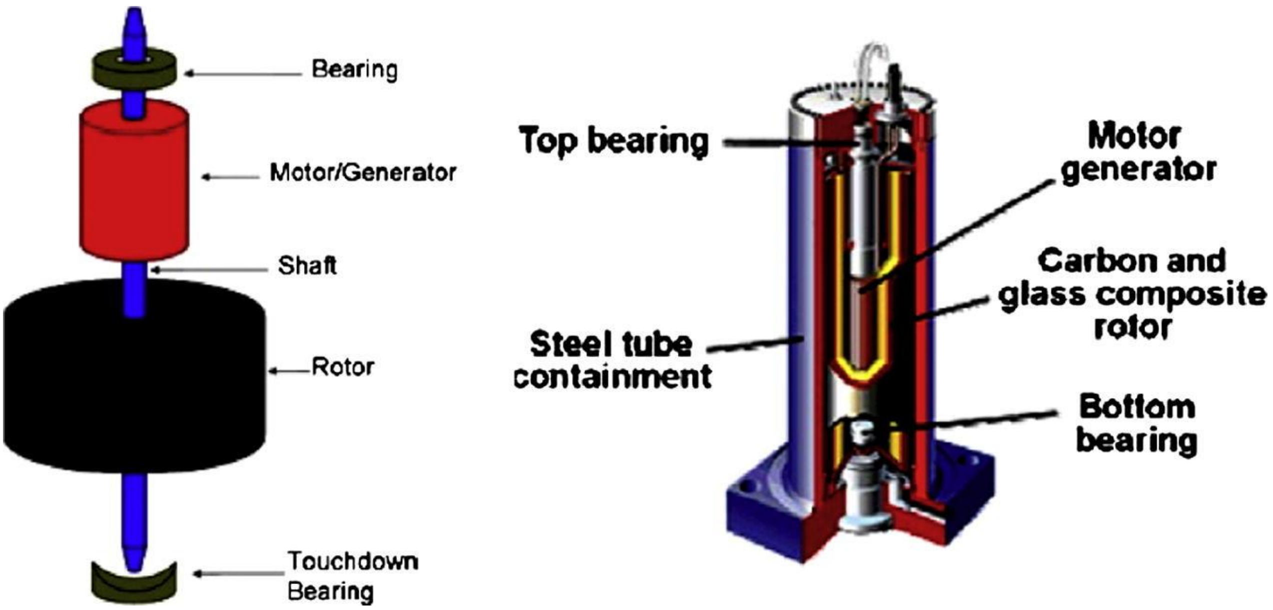

Figure 1 Rotor connection [40].

The energy which can be stored in the flywheel rotor is determined by the mass, shape of the flywheel disk and maximum speed. Equation (1) shows how the kinetic energy can be calculated, where E_{kin} is the amount of kinetic energy in joules, J is the flywheel's moment of inertia in kgm^2, and ω is angular velocity in rad/s. The useful energy stored in the flywheel (speed range) can be calculated using the following Equation (2). The moment of inertia for solid disk can be calculated with Equation (3), where m is the mass of the flywheel rotor and r is the radius. The moment of inertia for a hollow cylindrical flywheel can be calculated using Equation (4) Where b is the outer radius and a is inner radius.

$$E_{kin} = \frac{1}{2}J\omega^2 (1)$$

$$E_{kin} = \frac{1}{2}J(\omega^2 \max - \omega^2 \min) \ (2)$$

$$J = \frac{1}{2}mr^2 (3)$$

$$J = \frac{1}{2}m(b^2 - a^2) \ (4)$$

2.2.2. Motor/Generator

The motor/generator is coaxially connected with the flywheel as seen in Figure 1, hence controlling the speed of the motor/generator will also control the speed of the flywheel. During charging, the motor draws electrical energy from the energy source. During discharge, the generator will convert the kinetic energy stored into electrical energy [7]. The efficiency and power/density of a motor/generator should be high, and the idle and rotor losses should be low, in order to ensure the best working of the system.

There are three common types of motor/generator used in FESS: 1) Induction Machines (IM), 2) Variable Reluctance Machines (VRM) and 3) Permanent Magnetic Machines (PMM). Of these types

PMM has high efficiency, high power density and little rotor losses [8]. A more detailed overview of these types is shown in Table 1. Further information is given in Appendix A.

Table 1 Motor/Generator comparison [7]

Machine	Asynchronous	Variable Reluctance	Permanent Magnet Synchronous
Power	High	Medium and low	Medium and low
Specific power Rotor losses	Medium (~0.7 kW/kg) Copper and iron	Medium (~0.7 kW/kg) Iron due to slots	High (~1.2 kW/kg) Very low
Spinning losses	Removable by annulling flux	Removable by annulling flux	Non-removable, static flux
Efficiency	High (93.4%)	High (93%)	Very high (95.5%)
Control	Vector control	Synchronous: Vector Control. Switched: DSP	Sinusoidal: Vector control. Trapezoidal: DSP

2.2.3. Power Electronics

Power electronics are the main component in FESS for energy conversion. The conversion is accomplished with the use of an electrical machine (motor/generator) and a bi-directional power convert.

There are several topologies of power converters used in FESS: DC-AC, AC-AC, AC-DC-AC, or a combination of these can be used. Based on the operational characteristics and application, the switching devices of the power converter could be 1) Bipolar Junction Transistors (BJT) , 2) Metal Oxide Semiconductor Field Effect Transistor3 (MOSFET), 3) insulated gate bipolar transistors (IGBT) or 4) thyristors. The most common switches are IGBTs and thyristors of the types Silicon Controlled Rectifiers (SCR) and Gate Turn Offs (GTO) [7].

The commonly used topology configuration of a power converter is AC-DC-AC, also known as back-to-back (BTB). Figure 2 shows the layout of a BTB configuration [3]. More topologies are shown in Appendix B.

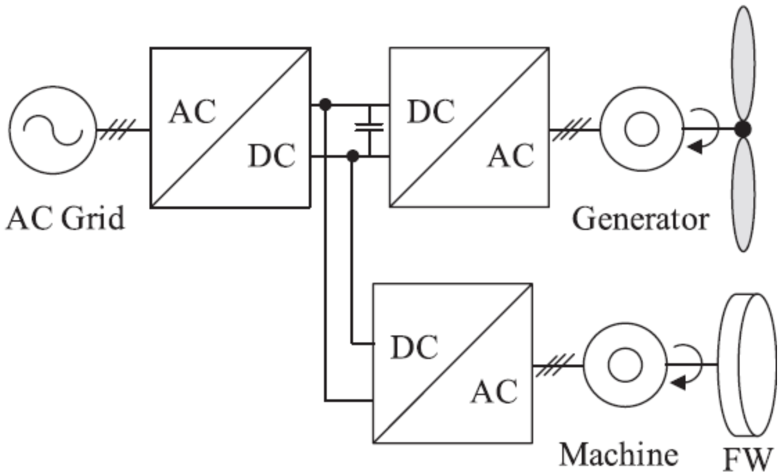

Figure 2 Back-To-Back power converter [3]

2.2.4. Bearings

The main function of the bearings is to keep the rotor in place with very low friction while proving support for the flywheel. Depending on the weight, lifecycle and lower losses, there are be three types of bearing systems which can be used: 1) mechanical, 2) magnetic and 3) gas [9].

Mechanical bearings have higher friction and require maintenance due to lubricant deterioration. Magnetic bearings, whilst having no friction and lubricant maintenance, require power to energize them. A hybrid system can be used to mitigate some of the problems [7]. Furthermore, when there is a vacuum within the encloser of the FESS (such as the QuinteQ FESS has), gas bearings cannot be used.

There are three main types of magnetic bearing system. These are 1) Permanent (passive) magnetic bearings (PMB), 2) Active magnetic bearings (AMB) and 3) Superconducting magnetic bearings (SMB). PMB has low cost and losses, but is limited in its stability and cannot be controlled. Usually, PMB is considered an auxiliary bearing system [10]. The operation of AMB (Figure 3) is done through the magnetic field produced from current carrying coils controlling the rotor position. AMB has high cost, consumes energy to operate adding to system losses. AMB affects FESS's standby losses [7]

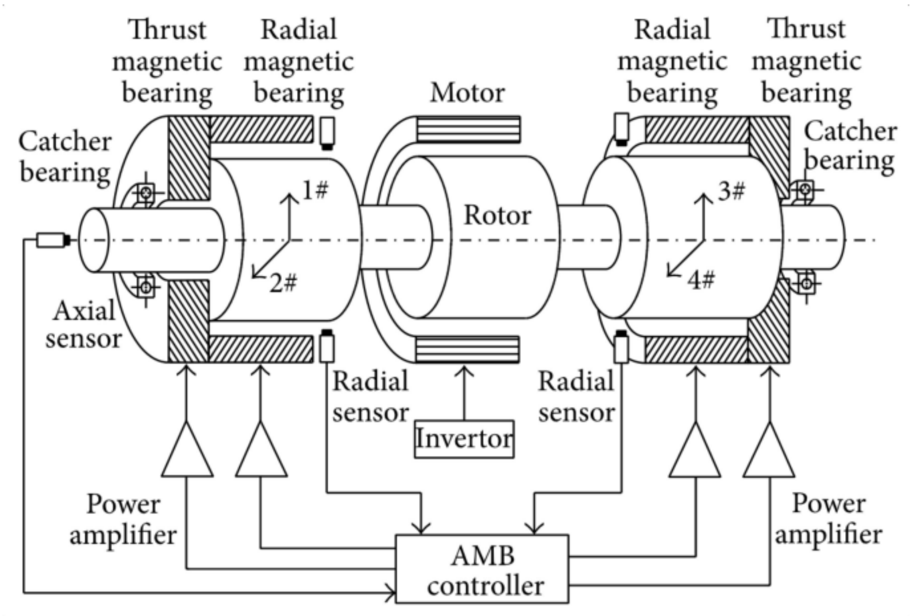

Figure 3 Active magnetic bearings system [11] [12]

SMB (Figure 4) has high speed, frictionless, long life, compact and stable operation. It is considered the best magnetic bearing system for high speed operations. SMB can stabilize the flywheel without the use of electrical energy or a positioning system, but also has high costs [13].

Hybrid bearings systems can reduce the losses and complexity of the control system as well as provide stable and cost effective solution. Here, the magnetic bearings could maintain the magnetic levitation in the vertical orientation; mechanical bearings would control the translational and rotational levitation.

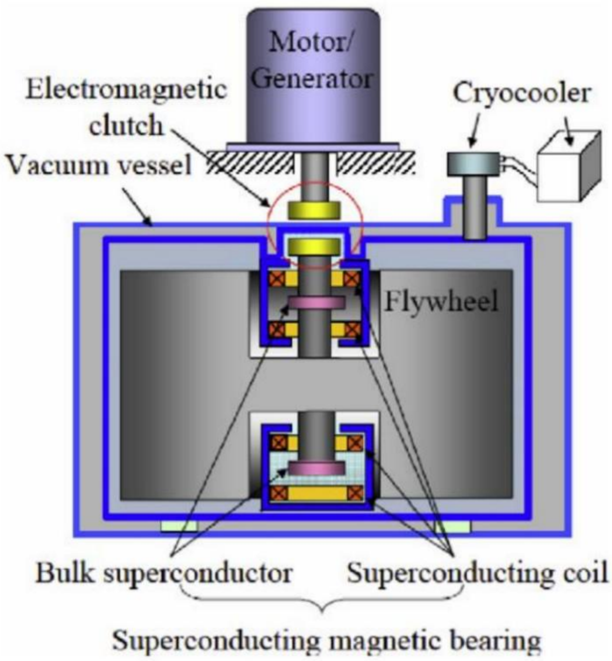

Figure 4 Superconducting magnetic bearings system [11] [14]

2.2.5. Housing

The housing or enclosure is the stationary part of the flywheel that is made out of high strength materials (thick steel or composites). The two main purposes of the housing are 1) to provide an environment for low gas or vacuumed drag and 2) to protect the surroundings in the event of a rotor failure or break.

The housing holds the rotor in a vacuum. This setup is used to control rotor aerodynamic drag losses with the low pressure inside the housing. Operating in low pressure requires FESS to have vacuum pump and an efficient cooling system to handle the heat generated from Motor/Generator and other parts of FESS. As there are no rotary seals and leakage can be very small, the pump can be eliminated with sufficient sealing of the housing . Additionally, the operation of the pump does depend on the type of the rotor [7].

One of the main safety criteria regarding FESS systems is the assurance of physical and operational safety when the FESS experiences off-normal conditions. This includes assuring the containment of a loose but largely intact rotor that would occur in the event of failure [15]. In the event of failure, composite rotors can break into numerous small fragments. As they rotate inside the casing their energy is dissipated by frication. Metal rotors burst into several bigger fragments, whereby a larger containment system is required to withstand this [7].

2.3.Flywheel Characteristics

This section detail ESS characteristics, FESS characteristics, power and energy ratings and operational losses.

2.3.1. ESS Characteristics and Flywheels

When examining ESSs, including FESSs, several characteristics are of importance. Most characteristics can be divided into five categories. These are 1) ratings, 2) dynamics, 3) space requirements, 4) performance and 5) cost. Table 2 gives an overview of the most important ESS characteristics.

Table 2 Energy Storage System Characteristics [16]

Category	***Name***	***Unit***
Rating	Power Rating	kW
	Energy Rating (Capacity)	kWh
Dynamics (Timescale)	Response Time	ms or s
	Ramp Rate	kW/s
	Self-Discharge	%
Space Requirements	Specific Energy or Energy Density	Wh/kg or Wh/L
	Specific Power or Power Density	W/kg or W/L
	Dimensions (l*b*w)	m
Performance	(Round trip) Efficiency	%
	Discharge Efficiency	%
	Charge Efficiency	%
Cost	Total Investment Costs / Total Energy Delivered During the System's Lifetime	€/kWh
Other	Manufacturer	
	Lifetime / Number of Cycles	
	Maturity of Technology	

Further definition for some characteristics which are open to interpretation are:

- Self-discharge, which defines energy dissipation in the form of various losses, e.g. heat transfer losses in thermal storages, air leakage losses in CAES, electromechanical losses in batteries.
- Round trip efficiency or cycle efficiency, which is the percentage (or ratio) of the complete ESS system energy output to the system energy input.
- Lifetime and Number of Cycles, which is defined as the number of times an ESS can be discharged before falling below a given depth of discharge. This affects the investment costs of an ESS.
- The maturity of an ESS technology, which is linked to its commercialization, technical risk and related economic benefits. According to [17], there are five classification of technology

maturity, 1) Developing (e.g. Advanced Adiabatic-CAES, Polysulfide Bromine (PSB) flow battery and Solar Fuel), 2) Demonstration (e.g. SCES and TES), 3) Early Commercialized (e.g. Over-ground small CAES and FESS), Commercialized (e.g. Conventional CAES), Mature (e.g. PHS and Lead-acid batteries).

FESS characteristics for the technical characteristics are shown Table 3. See Section 0 for a comparison between flywheels and other storage technologies.

Table 3 Flywheel Energy Storage System Characteristics [7] [16] [18]

Name	***Value***	***Unit***
Power Range	0.1-20, <0.25, 0-0.25, 0.01-0.25	MW
Response Time	< 4	ms-s
Self-Discharge	100 24-100	%
Energy Density	20-80	Wh/L
Power Density	1000-2000	W/L
Round trip efficiency	93-95, 90-95, 90-93,	%
Discharge Time	ms-15min	ms-min
Lifetime	15 +	years
Technology Maturity	Mature/Commercializing	

2.3.2. Power and Energy Ratings

Both power and energy ratings of a flywheel are independent of each other and individually optimizable. The power rating of a flywheel is related to the size of motor/generator and its related power electronics, whereas the energy rating is related to the rotational speed and size and dimensions of a rotor. The flywheel State of Charge (SoC), the percentage of the storage device that is charged at any moment, can be measured from the rotational speed of the flywheel. In contrast to other storage technologies, the SoC is in principle not affected by the lifetime or temperature of the flywheel.

Based on the rotational speed, flywheels can be categorized into three types [17] [19]:

- Low Speed Flywheel (LSF):
  - Rotating between 1000 – 10.000 RPM, they are mostly made of steel,
  - Short-term and medium/high power applications,
  - Energy density around ~5 Wh/kg,
- High Speed Flywheels (HSF):

- Rotating above 10.000 RPM, they are made of composite material,
    - High power quality and ride-through power service in traction and the aerospace industry,
    - Energy density around ~100 Wh/kg,
- Micro High Speed Flywheels (MHSF):
    - Also rotates above 10.000 RPM but is much smaller and mostly used as kinetic recovery system in vehicles/transportation.

A FESS is capable of outputting large amounts of power in seconds while having a high self-discharge rate and little energy storage capacity. In addition, flywheels can typically make a large number of cycles over their lifetime. The aforementioned leads to flywheels being generally more suitable in situations where a high amount of power is required often for short periods of time.

2.3.3. Operational Characteristics and Losses

As stated in Section 2.1, FESS has three operational characteristics: 1) charging, 2) standby/idle and 3) discharging. Charge and discharge losses are shown in Figure 5 and Figure 6 respectively. During charge and discharge, FESSs experiences so called motor and converter losses. Motor losses can be further divided into copper, hysteresis, eddy current, bearing friction and wind resistance losses. Converter losses consists of switching and conduction losses. During standby/idle, FESS experience bearing friction and wind resistance loss [10] [20].

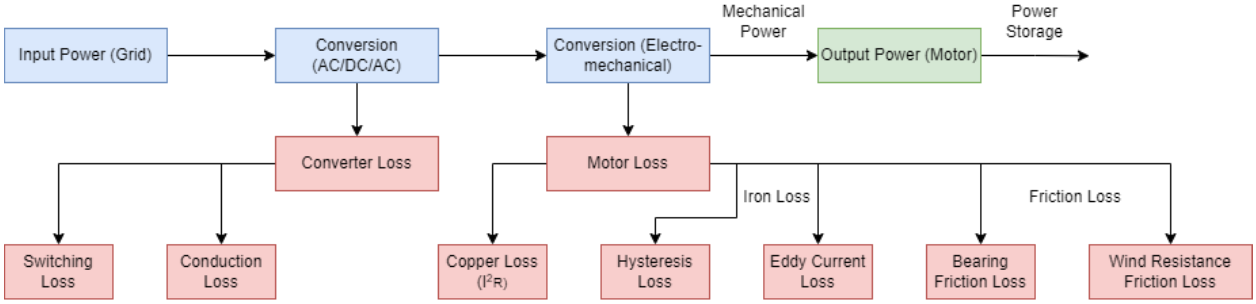

Figure 5 Charge energy conversions and losses [20]

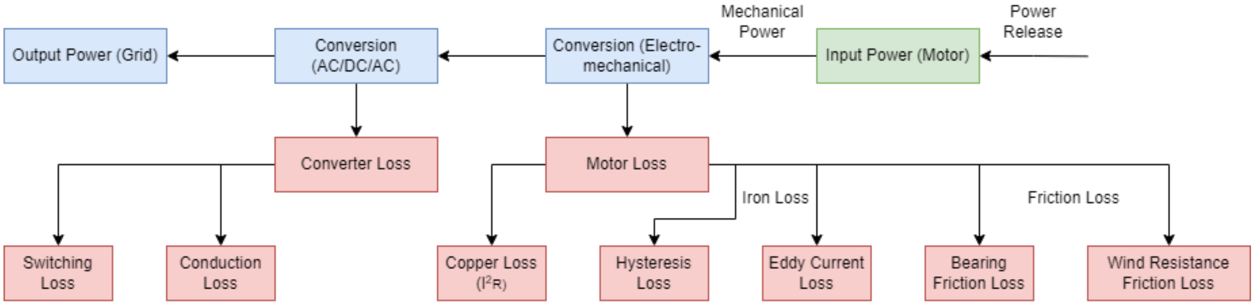

Figure 6 Discharge energy conversions and losses [20]

2.4.Storage Comparison

Storage technologies can be compared using various criteria. For a broader overview see Table 4. However, many times it is necessary to show key criteria in graphs, in order to gain better insight into the relationships between these criteria in relation to storage technologies. One such overview is shown in Figure 7. Here, a number of relevant storage technologies are shown, with the relationship between the duration of storage and the scale of the storage given. The duration of storage shows a preferred storage time per technology. Technologies can often operate outside of these bounds, but then sub-optimally. What is also of note here is the size of each technologies circle. This shows how mature a given technology is. Depending on the application, a more or less proven technology will be preferable.

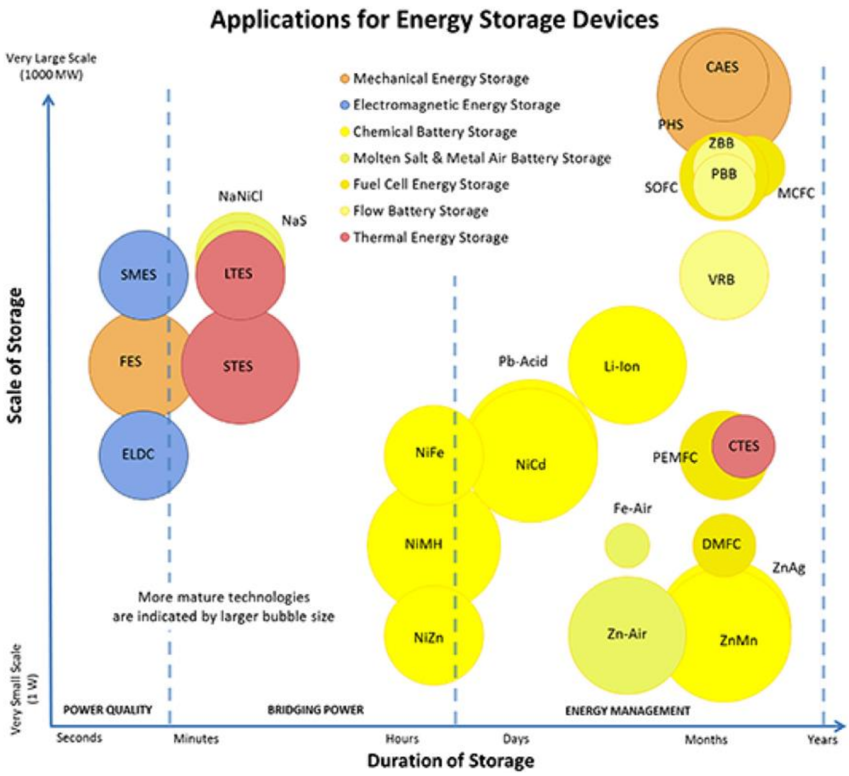

Figure 7 Comparison of scale of storage vs duration of storage [21]

Figure 8 shows the estimated global operational energy storage capacity for the planet in 2020. Of note here is the small market share of flywheels, just 0.2%. However, this is expected to increase greatly in the coming years, due in part to the growing need in developing countries for access to reliable and sustainable energy systems [22].

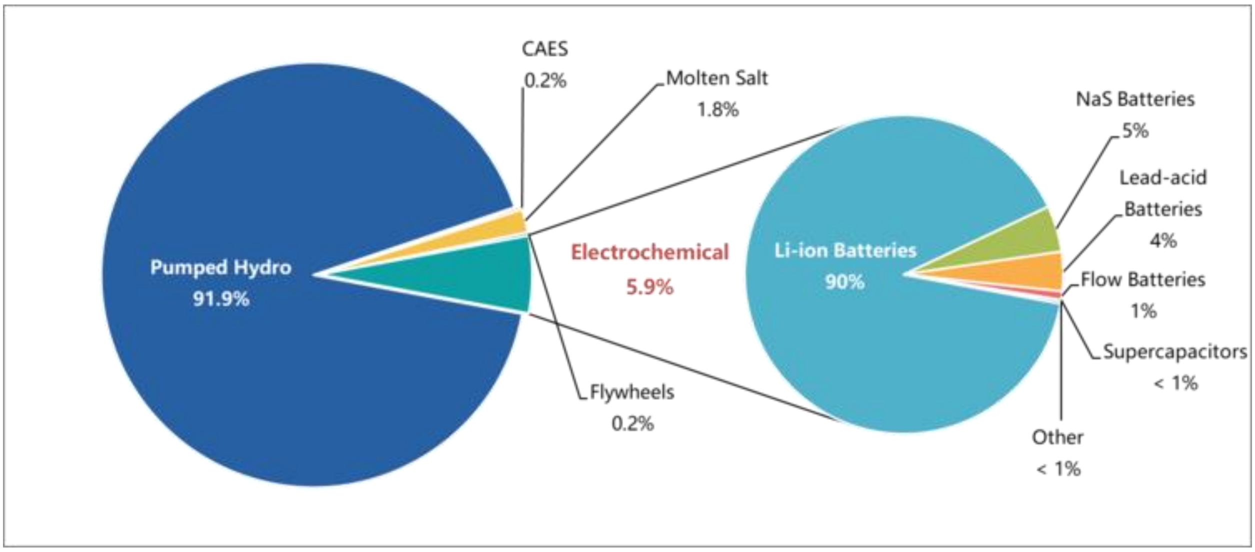

Figure 8 Global operational energy storage capacity [23]

Further useful overviews are included in Appendix E. From those overviews and other sources, the following can be noted about FESSs in relation to other ESSs [7] [17] [24] [25]:

- FESSs have a fast response rate of < 1 cycle, meaning it can respond within (milli-)seconds to demands
- FESSs have high power and energy densities, meaning they do not required much space in volume, unlike to PHS and CAES and some battery energy storage systems
- FESSs have high round trip efficiencies
- FESSs have high charge and discharge rates
- FESSs have a long component lifetime, with low maintenance and repairs requirement.
- FESSs have long lifetimes and high cycle life
- FESSs generally have a low environmental impact considering both system creation and system operation

Table 4 Comparison of Energy Storage Systems

Energy Storage System	Cycles	Component Life Spam (years)	Response Rate	Cycle efficiency (%)	Discharge efficiency (%)	Storage Duration	Power Density (W/L)	Energy Density (Wh/L)	Power Rating (MW)	Rated Energy Capacity (MW h)
FESS [17]	20.000+ / 21.000+	~15-20	< 1 cycle, seconds,	~90 – 95 %	90 – 93 %	Seconds – Minutes (Short-term)	1.000 – 2.000, ~5.000	20 – 80	~0.25 – 20	0.0052, 0.75, up to 5
PHS [25]	10.000 – 30.000	25+	Minutes	75 – 85 %	Turbine and Pipe efficiencies (87%)	Hours – Months (Long-term)	0.5 – 1.5	0.5 – 1.5	30 – 5.000	500 – 8.000
CAES [17]	8.000 – 12.000	20 – 40	Minutes (large scale CAES), Seconds – minutes (over-ground CAES)	42%, 54%	~70 – 79 % (large scale), ~75 – 90 % (over-ground)	Hours – Months (Long-term)	~0.5 – 2	2 – 6	110 – 1.000 (large scale), 0.003 – 10 (over-ground)	~580 – 1.000 (large scale), ~0.0083 – 0.01 (over-ground)
BES [17] [24] [25]	1.000 – 20.000 (Li-ion), 2.500 – 4.500 (NaS), 2.000 – 3.500 (NiCd)	3 – 15	< ¼ cycle, Milliseconds,	70 – 95 %	~90 – 97 % (Li-ion), ~75 – 90 % (NaS), ~60 – 83 % (NiCd)	Minutes – Days (Short-to-Medium term)	1.500 – 10.000 (Li-ion), ~140 – 180 (NaS), 80 – 600 (NiCd)	150 – 500 (Li-ion), 150 – 300 (NaS), 15 – 180 (NiCd)	0 – 100 (Li-ion), <8, 34 (NaS), 0 – 47 (NiCd)	0.024, ~0.004-10 (Li-ion), 0.4 – 244.8 (NaS), 6.75 (NiCd)
CS [17]	50.000+	~5	< ¼ cycle, Milliseconds,	~60 – 70 %	~75 – 90 %	Seconds – hours	100.000+	2 – 10	0 – 0.05	-
SCES [17]	50.000 – 100.000+	10 – 30	< ¼ cycle, Milliseconds,	~84 – 97 %	95 – 98 %	Seconds – hours (Short-term)	100.000+	~10 – 30	0 – 0.3	0.0005
SMES [17]	100.000+	20+	< ¼ cycle, Milliseconds,	~95 – 98 %	95%	Minutes – hours (Short-term)	1.000 – 4.000	0.2 – 2.5, ~6	0.1 – 10	0.0008 – 0.015
TES [17]	-	10 – 30	-	~30 – 60 %	-	Minutes – Days – Months	-	80 – 500	0.1 – 300	-
HES [17]	1.000 + / 20.000+	5-20+	< ¼ cycle, Seconds	~20 – 66 %	59%	Hours – Months	500+	500 – 3.000	< 10, < 50	0.312

3. Applications in Microgrids

This chapter presents possible flywheel applications in microgrids. First, flywheel applications are more generally examined. Next, the effects of implementing FESS on power quality, as well as a definition of power quality, is given. Finally, the role of flywheels in Hybrid Energy Storage Systems (HESS) is discussed based on previously published case studies.

3.1. Flywheel Applications

In [7], a comprehensive list of applications where flywheels have an added benefit is given:

- **Power Quality Improvement**: This is the application that FESSs are currently mostly used for. FESS can quickly add or take power from the grid, to keep to these systems an acceptable level of power quality. For more see also Section 3.3. As FESSs have a high response rate and have a high power output, they are suitable for voltage sag control and frequency regulation.
- **Uninterruptible Power Supply (UPS)**: FESS serves as a UPS when power outage occurs in the grid. However, these outages must be short in order or some other backup generator must start up, otherwise a FESS will not be. For outages of longer duration a HESS can be used.
- **Transportation**: FESS can be used in hybrid or Electrical Vehicles (EVs). EVs can recuperate energy when the vehicle is slowing down through regenerative braking and then store the energy in a FESS for later use.
- **Spacecraft**: With satellites mainly powered by solar panels (PV), there is a need for energy when the sun is not present. In this case, a FESS can be used to supply power to satellites when the device passes an area inaccessible by sunlight.
- **Renewable Energy**: RESs like wind turbines and solar panels are influenced by the weather. The power supplied to the electrical grid from RESs oscillates and create an unstable system. FESS's fast response characteristics makes it a suitable candidate for grid frequency balancing in microgrids with a high RES penetration.
- **Military**: FESS is used as a rapidly responding and reliable power to supply the various energy demands of several military applications (e.g. ships, military bases, navigation and communication). In the case of military bases, FESSs can provide energy security using renewable energy and storage systems.
- **Railway**: FESS can be used in railway settings application to improve the quality of the railway and utilize the regenerative braking energy.

3.2. Power Quality Definition

As power quality is a broad term, it is first useful to define it further for the purposes of this report. Power quality here is taken to mean how well the power characteristics fit within the system requirements. More concretely, it is taken to mean how well the voltage, current, frequency and waveform of a system adhere to the system standards and guidelines. When power quality is ensured, the system characteristics are within acceptable boundaries as stipulated within net standardization [26].

Common power quality problems are:

- Voltage Dips: According to the NEN-EN 50160, a dip is a sudden lowering of the voltage to a value between 90% and 1% of the original value, followed by a restoration of the voltage, within a period of 10ms to 60s. Dips are caused by sudden changes in loads or generators.
- Harmonic Distortion: Caused typically by non-linear loads, harmonic distortions are the voltage and current variations which alter the structure of a sinewave. A measurement of this is Total Harmonic Distortion (THD). Frequency regulation can counteract harmonic distortion effects [27].
- Unbalanced 3-phase systems: When the phases of a three phase system are not even (i.e., each phase does not have exactly an equal amplitude and there is not 120 degree phase-shift between two adjoining phases), the system is deemed asymmetric and unbalanced. This is caused by an uneven division of loads between the phases.
- Transients: Caused by shorts in networks, switch operation or lightning strikes, transients are a sudden increase in the voltage of a system lasting a period of microseconds to milliseconds.
- Voltage level reduction or increase: When voltages are higher or lower than a range over a longer period of time (10 minute average values are used). In the case of the Netcode for the Netherlands, a deviation from the agreed upon voltage level of more than 10-15%. An undervoltage of 15% is permissible while an overvoltage of 15% is not.
- Flicker: One of the larger complaints from clients of a LV net, flicker is a visible alteration of the intensity of a lighting fixture. A type of transient, it is caused by rapid changes in loads or generators.

Although not strictly considering power quality, the Power Factor (PF) of a system is also a method of evaluating system health. The PF is defined as the ration between the real (useful) power and the reactive (not useful) power. Reactive power is caused by inductive loads (such as motors) in a network.

3.3. Power Quality and Flywheels

Flywheels are useful in mitigating power quality problems [13]. As part of a Flexible Power Conditioner (FPC) architecture, flywheel technology is useful for storing energy as well as generation active and reactive power [28]. Additionally, FESSs are suitable and well researched when used for frequency regulation and voltage sag compensation [29] [30] [31].

Two studies are examined in which larger scale FESSs are used to mitigate power quality issues. First, a case study [32] of an off grid microgrid on an island in Scotland consisting of 30 households studied the potential power quality improvement through the use of a 4kWh/200kW flywheel, which is comparable to the QuinteQ flywheel. This microgrid consists of two interconnected networks (one heating and one service network) with two wind turbines and two diesel generators. Hardware In Loop (HIL) testing was carried out to investigate 1) using the flywheel to smooth service load frequency and 2) reducing the danger of a power cut when switching from wind turbines to diesel generators when wind speed is low. Using a flywheel to smooth the frequency (Figure 9) was shown to not have an effect on the average frequency, but reduce the deviation by about 50% (from 0.32Hz to 0.2Hz). Figure 10 shows that the flywheel keeps the frequency at about 45Hz at changeover, which was desired.

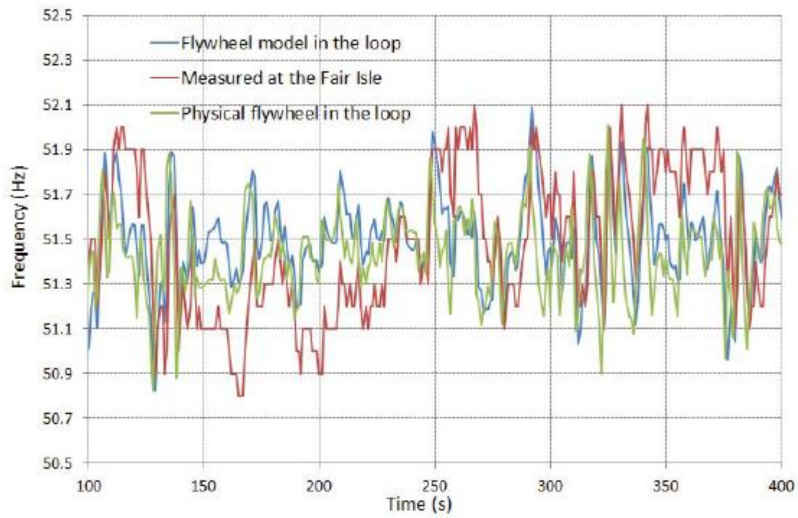

Figure 9 Service load frequency with and without Flywheel [32]

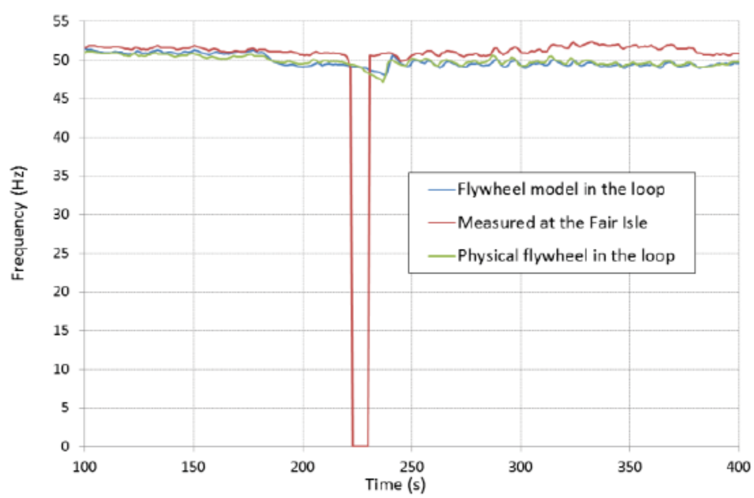

Figure 10 Service load frequency [32]

Next, a similar yet less comprehensive simulation study by [33] investigates a case study where a flywheel is added to a rural residential grid. A scaled simulation is carried out with a smart charging algorithm, whereby it is shown that a large enough flywheel can compensate for the intermittent nature of wind energy.

Furthermore, two studies were found where power quality issues are investigated in a residential setting. Although no FESS technology is currently used here, there is the potential to use smaller scale FESSs to mitigate certain power quality issues. First, an investigation into the power quality issues created by several types of loads commonly found in residential settings is conducted by [34]. Here combinations of non-linear loads fans, lighting, and both AC and DC drive systems are tested in a laboratory setting in order to ascertain the effect of each system on power quality. The findings are:

- The voltage on the source side is unbalanced.
- Voltage and Current variations are caused by changing loads.
- Both THD and harmonics in source current increased to outside of recommended standards due to variable speed drive systems.
- PF is reduced.

Second, a comprehensive measurement and simulation study examining multiple typical household loads is conducted by [35]. Here, numerous loads are grouped based on common characteristics (AC/DC conversion, heating elements, motors, waveform shapes etc.). The conclusion of this study is that household appliances show high waveform distortions and are a large source of harmonics, but that they vary depending on the type of appliance. In addition, PF is decreased by the existence of harmonics in the system. Variable speed appliances have less distorted waveforms at higher speeds than at lower speeds. Finally, although the amount of distortion per device is manageable, the power quality effect is larger in networks with high amount of these devices. The suggestion [35] proposes it to use filtering techniques to improve power quality.

3.4. Hybrid Energy Storage Systems

An increasingly interesting option to increase the flexibility in microgrids is to combine multiple ESSs into a single system, a so called Hybrid Energy Storage Systems (HESS). These HESSs combine characteristics of each separate energy system, in order to create a system capable of dealing with situations where a single type of storage system would be sub-optimal. In other words, HESSs accentuate the advantages of each individual storage technology, while trying to mitigate each storage's disadvantages. Often times, one or more storages are used to handle power peaks, while the other storages are used to provide energy capacity (see Figure 11). HESSs have the potential to be more cost efficient and effective than their single storage type counterparts. Location, storage space availability and how well the specific storage devices complement each other's power and energy ratings should be examined when designing a HESS.

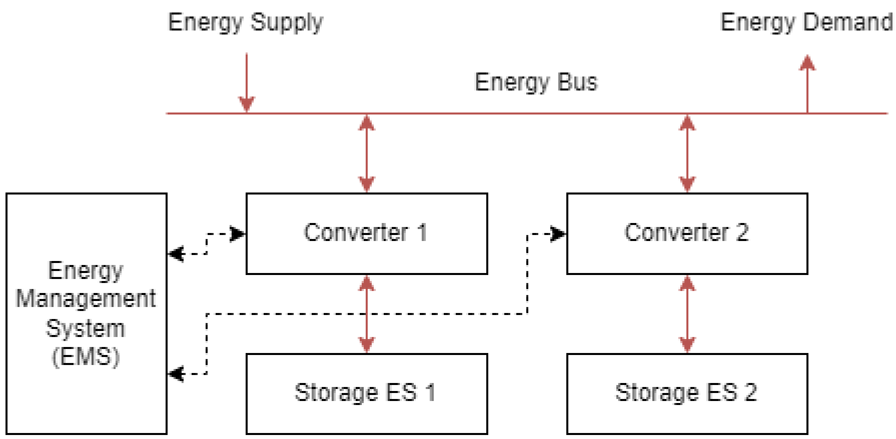

Figure 11 Possible HESS topology with two storage devices

In spite of the benefits of HESSs with flywheels, there is still a lack of larger scale HESS pilots in the EU currently. Also, the specific combination of flywheel storage and traditional chemical battery storage (for example, lithium-ion or lead-acid) has been largely overlooked in recent years, in favour of combinations between chemical battery storages and supercapacitors. However, two HESS-flywheel studies were conducted by [36] and [37], both focussing on the lifetime of the HESS. Additionally, [37] approaches battery life from a perspective of how a battery is negatively affected while operating under stress conditions, while [36] analyses battery life only from a perspective of storage cycles.

First, [36] examined the possibility of reducing the aging of a lithium battery through the use of a FESS. The results of the created Simulink simulations, which use a simplistic power management scheme to use a flywheel for frequency regulation cycles, point to an increase of battery life of more than 20%. More optimistic results are found in [37], which examines potential energy performance and battery life improvement. Simulations were created using MATLAB to ascertain the influence of using HESSs in a microgrid situation, while verification was also carried out of the battery life improvement using accelerated aging tests. The results show that for HESSs, the ratio between self-consumption and global PV production increases in respect to an equivalent battery only systems, with 8% for lead-acid and 15% for lithium-ion based systems. The ratio between purchased electricity and global request drops by 17% for lead-acid systems, and by 21% for lithium-ion systems. Therefore, we can conclude that hybrid batteries are able to add to the potential for microgrids to be less dependent on the main grid. Most surprising though is the projected increase of the life of the battery. For lead-acid batteries, the projected life is 3 times as high when used as part of a HESS, and 3.6 times as high for lithium-ion based HESSs.

4. Flywheel market availability

As of 2023, there are several key players in the FESS market, shown in [17] [6] (see also Appendix C). They are :

- Active Power [38] operates in more than 50 countries with Flywheel-based UPS systems and power solutions. Their CleanSource flywheel consists of a motor with an input power of about 1kW that keeps the rotor spinning at 7.700 RPM (stores up to 10.5 MJ of energy). The rotor is supported by a magnetic unloading technology and the housing uses a vacuum pump that keeps the air pressure under 2 mTorr.
- Beacon Power [39] focuses on developing and commercializing fast response flywheel-based energy storage systems. Beacon Power operates three commercial flywheel plants in the United States. Their application area is frequency regulation, power quality and voltage support. Their flywheel systems can be configured to meet the power capacity demand from 100 kW to multi-MW systems while their high-performance rotor flywheel can spin up to 16.000 RPM. The flywheel is enclosed in the sealed vacuum chamber. This flywheel assembly can perform more than 175.000 full charge and discharge cycles.
- Amber Kinetics [40] manufactures grid-scale kinetic energy storage systems (KESS). They provide long-duration flywheel energy storage solutions. Their flywheel is a four-hour discharge, long-duration KESS powered by a 32kWh of energy in a two-ton steel rotor with a response time of less than 1 second.
- Piller Group [41] is a German based manufacturing and Research and Development company with subsidiaries across Europe, the Americas and Australasia. Their application area is ride-through power and sources of backup power. Their KESS POWERBRIDGE offers frequency stability under dynamic load conditions with an energy storage capabilities of 60MJ+. The unit can deliver power above 3MW and sustain 1MW of power for 60 seconds.
- French based Energiestro is currently developing a cement based flywheel which is intended for storing residential solar PV energy [42], as well as bridging (small) gaps in solar energy supply (see Figure 12). Although heavier in weight, it is thought that this cement flywheel will greatly reduce costs in comparison to both carbon and steel flywheels. The cement flywheels are intended to be installed underground outside of the adjoining residence, for example in a garden. Two variants are proposed: one with a higher power and lower capacity which is useful for storing energy for an hour, and one with a lower power higher capacity which is useful for storing energy for 24 hours. The plan is to deploy the flywheels in Madagascar and Mauritius first, before moving towards global deployment [43].

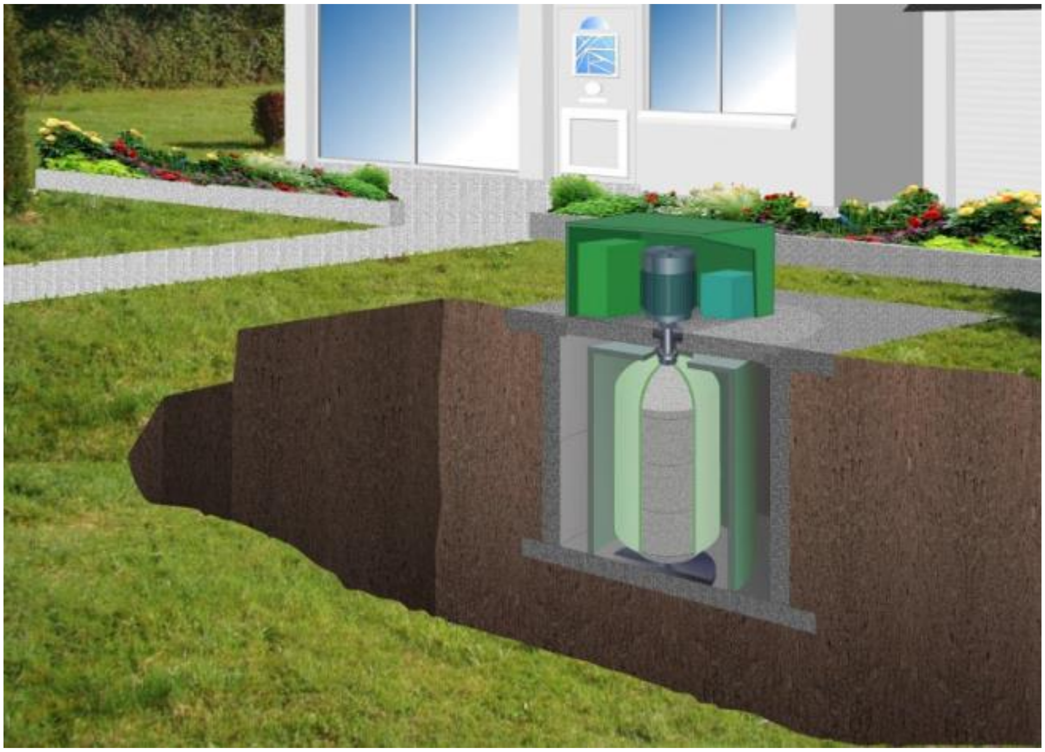

Figure 12 Energiestro cement flywheel, 10kWh, 1 hour of storage [42]

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Appendix A – Motor/Generator Comparison

Table 5 Motor/Generator comparison [7]

Machine	Asynchronous	Variable Reluctance	Permanent Magnet Synchronous
Size	1.8 L/kW	2.6 L/kW	2.3 L/kW
Tensile strength	Medium	Medium	Low
Torque ripple	Medium (7.3%)	High (24%)	Medium (10%)
Maximum/base speed	Medium (>3)	High (>4)	Low (<2)
Demagnetization	No	No	Yes
Cost	Low (22 €/kW)	Low (24 €/kW)	Low (38 €/kW)
Advantages	Low cost	Robustness of temperature overheat	Low loss, high efficiency
	Simple manufacture	Overcurrent capability	High power density
	Technology-matured	Excitation coil can repeat adjustment	High load density
	Adjustable power factor	Lower loss at starting torque	High torque density
	No demagnetization	Easy to dissipate heat	Small volume, light quality
	High energy storage	Lower loss, higher efficiency	low rotor resistance loss
	No running loss	High power density	No field winding loss
			Flexible shape and size
			Simple control mode
			High reliability
Disadvantages	High slip ratio of rotor	Complex structure	poor robustness of temperature
	Limited speed	Difficult to manufacture	Demagnetisation
	Larger volume	Low power factor	High cost
	Low power to quality ratio	Torque ripple, vibration and noise	Materials fragile
	High losses, low efficiency	More outlet from machine	Difficult air gap flux-
		Difficult to regulate speed	field adjustment

Appendix B – Power Electronics

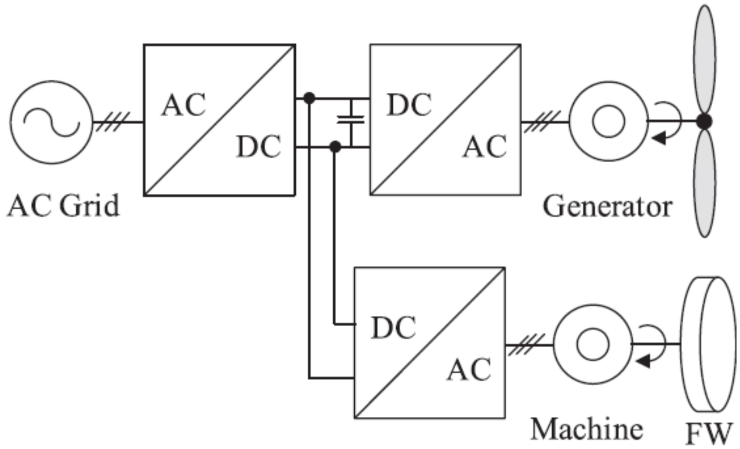

Figure 13 Back-To-Back power converter [3]

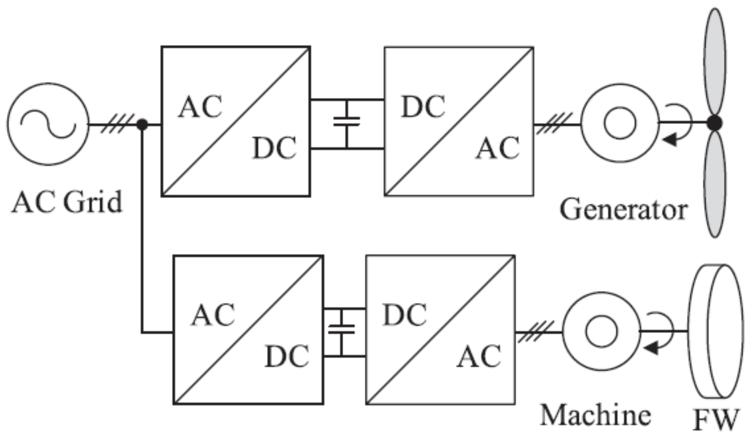

Figure 14 Back-To-Back power converter connected directly to the grid [3]

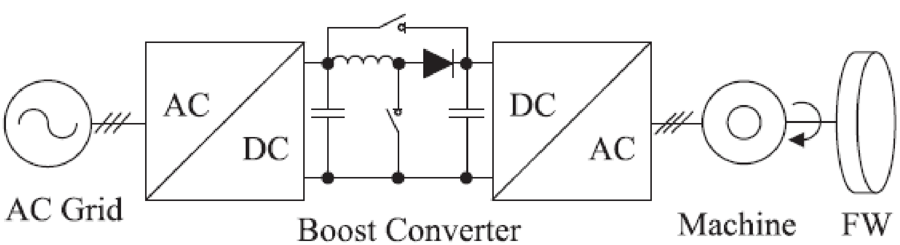

Figure 15 Boost Converter [3]

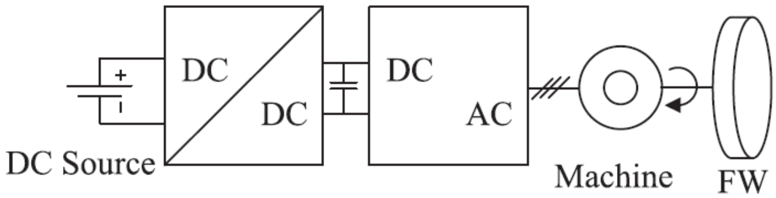

Figure 16 DC/DC plus AC/AC configuration [3]

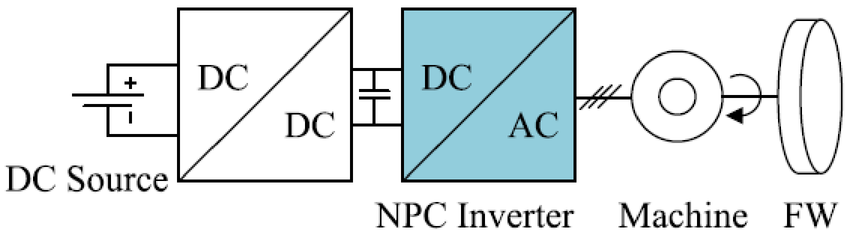

Figure 17 DC/DC plus Neutral Point Clamped (NPC) inverter [3]

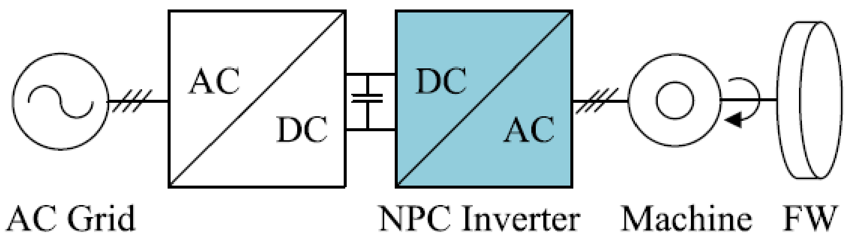

Figure 18 AC/DC plus NPC inverter [3]

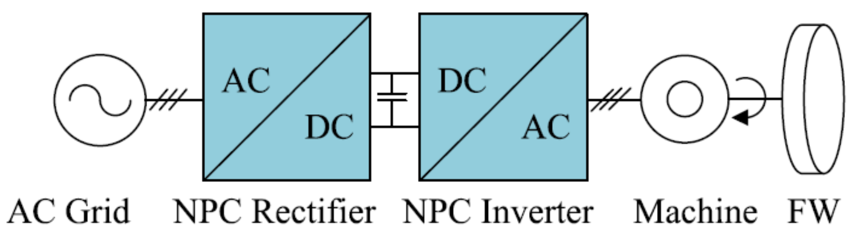

Figure 19 BTB NPC topology [3]

Appendix C – Flywheel Storage Solutions

Table 6 Flywheel storage facilities [17]

Firms/Institutes	Characteristics	Application area
Active Power Company	Clean Source series 100–2000 kW	Backup power supply, UPS systems
Beacon Power Company	100/150 kW a unit, 20 MW/5 MW h plant	Freq. regulation, power quality, voltage support
Boeing Phantom Works	100 kW/5 kW h, HT magnetic bearings	Power quality and peak shaving
Japan Atomic Energy Center	235 MVA, steel flywheel	High power supply to Nuclear fusion furnace
Piller power systems Ltd.	3600–1500 rpm, 2.4 MW for 8 s	Ride-through power and sources of backup power
NASA Glenn research center	2×10^4–6×10^4 rpm, 3.6 MW h	Supply on aerospace aviation & other transports

Table 7 Flywheel storage solutions [6]

Flywheel storage solutions deployed at utility scale applications.

Flywheel model	Rotor type	Power capacity kW	Energy storage kWh	Mass kg	Specific energy Wh/kg	Speed rpm	Self-discharge W	η %
Beacon Power, LLC (BP400)	Carbon composite	100	25	1133	22.06	8000–16000	4500	85
LEVISYS	Carbon composite	10–40	10	–	–	–	–[a]	–
Stornetic GmbH (EnWheel)	Carbon composite	22–80	3.6	–	–	<45000	–	–
Flywheel Energy Systems Inc.	Composite	50	0.75	135	5.55	15500–31000	500–1000	86
Powerthru / Pentadyne	Carbon composite	190	0.528	590	0.89	30000–53000	250–300	–
Calnetix (VDS-XE)	4340 Aerospace steel	300	1.11	821	1.35	24500–36750	–	–
Amber Kinetcis (M32)	Low-carbon Steel	8	32	2268	14.10	<8500	65	88
Temporal Power	Steel	100–500	50	3500	14.28	<10000	500	85
ActivePower	Steel	50–250	0.958	272	3.55	7700	2500	–
ABB (PowerStore)	Steel	100–1500	5	2900	1.72	1800–3600	12000	–
Piller	–	2400	5.833	–	–	1500–3600	–	–
Energiestro	Concrete	5	5 kWh	1700	2.94	–	–	–

[a] Three weeks standby time.

Appendix D – A overview of flywheel design specifications

Table 8 Flywheel rim material comparison [6]

Flywheel	Material	Kinetic Energy, kJ	Speed, rpm	Rim radii, mm	Mass, kg
Metal, 1-rim	Al-6061-T6	418.86	15,713	(110–200)	11.87
Metal, 1-rim	Al-2024	637.04	19,167	(110–200)	12.13
Metal, 1-rim	Carbon-Steel-1020	685.47	11,818	(110–200)	34.35
Metal, 1-rim	Al-7075-T6	709.56	20,156	(110–200)	12.22
Metal, 1-rim	Steel-4340	749.61	12,351	(110–200)	34.40
Metal, 1-rim	Stainless-Steel-15–7	1180.80	15,682	(110–200)	33.61
Metal, 1-rim	Steel-18Ni-300	1203.03	15,46	(110–200)	35.23
Metal, 1-rim	Stainless-Steel-440C	1947.44	20,1	(110–200)	33.74
Metal, 1-rim	Stainless-Steel-455	2369.82	22,087	(110–200)	34.00
Composite, 1-rim	T300-BSL914C	786.48	28,388	(110–200)	6.83
Composite, 1-rim	Kevlar49-Epoxy	885.49	31,97	(110–200)	6.06
Composite, 1-rim	E-Glass-Epoxy	1060.36	28,565	(110–200)	9.09
Composite, 1-rim	S2-Glass-Epoxy	1355.19	32,958	(110–200)	8.73
Composite, 1-rim	AS4-3501–6	1360.29	36,957	(110–200)	6.97
Composite, 1-rim	T300-PR319	1403.14	37,877	(110–200)	6.84
Composite, 1-rim	AS4–8552	2404.63	49,343	(110–200)	6.91
Composite, 1-rim	IM7-8551–7	2452.16	49,883	(110–200)	6.89
Composite, 1-rim	IM7–8552	3150.50	56,292	(110–200)	6.96
Composite, 2-rim	EGlass-Epoxy, IM7-8551–7	3154.54	56,263	(110–119.32–200)	7.06
Composite, 2-rim	EGlass-Epoxy, AS4–8552	3224.14	56,74	(110–120.48–200)	7.10
Composite, 2-rim	Kevlar49-Epoxy, T300-BSL914C	2213.79	48,459	(110–155.64–200)	6.49
Composite, 2-rim	Kevlar49-Epoxy, AS4-3501–6	2532.95	51,162	(110–146.72–200)	6.66
Composite, 2-rim	Kevlar49-Epoxy, IM7-8551–7	3716.71	61,814	(110–134.25–200)	6.72
Composite, 2-rim	S2-Glass-Epoxy, AS4-3501–6	2798.60	52,233	(110–133.60–200)	7.33
Composite, 2-rim	S2-Glass-Epoxy, IM7–8552	4072.10	63,65	(110–120.22–200)	7.11
Composite, 2-rim	AS4-8552, IM7-8551–7	3302.65	57,882	(110–137.42–200)	6.90
Composite, 2-rim	T300-BSL914C, T300-PR319	1738.68	42,169	(110–134.62–200)	6.84
Hybrid, 2-rim	Al-6061-T6, Kevlar49-Epoxy	441.64	17,006	(110–190–200)	11.06
Hybrid, 2-rim	Al-2024, IM7–8552	719.87	21,325	(110–190–200)	11.41
Hybrid, 2-rim	Steel-4340, IM7–8552	760.70	13,598	(110–190–200)	30.56
Hybrid, 2-rim	Stainless-Steel-15-7, T300-PR319	1153.48	16,937	(110–190–200)	29.87
Hybrid, 2-rim	Stainless-Steel-440C, Kevlar49-Epoxy	1804.94	21,208	(110–190–200)	29.87
Hybrid, 2-rim	Stainless-Steel-455, Kevlar49-Epoxy	2188.32	23,265	(110–190–200)	30.10
Hybrid, 2-rim	Stainless-Steel-455, IM7–8552	2274.63	23,644	(110–190–200)	30.22

Appendix E – Comparison overviews between storage technologies

The following figures in this appendix show several characteristic comparisons for several energy storage systems. These are

- Figure 20 Comparison of power rating vs rated energy capacity
- Figure 21 Comparison of power rating vs discharge time
- Figure 22 Comparison of specific power vs specific energy
- Figure 23 Comparison of power density vs energy density
- Figure 24 Comparison of Power output vs energy stored

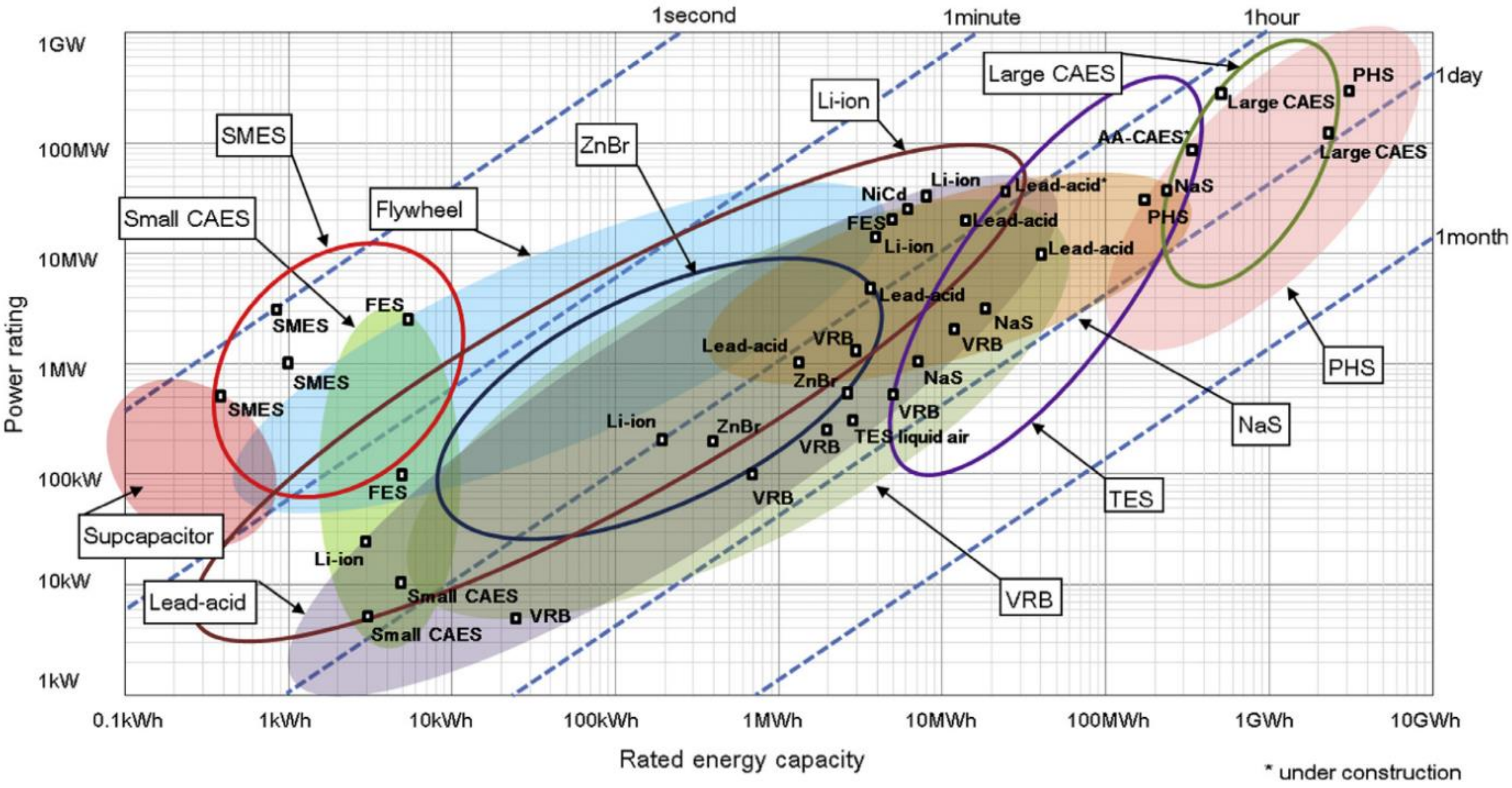

Figure 20 Comparison of power rating vs rated energy capacity [17]

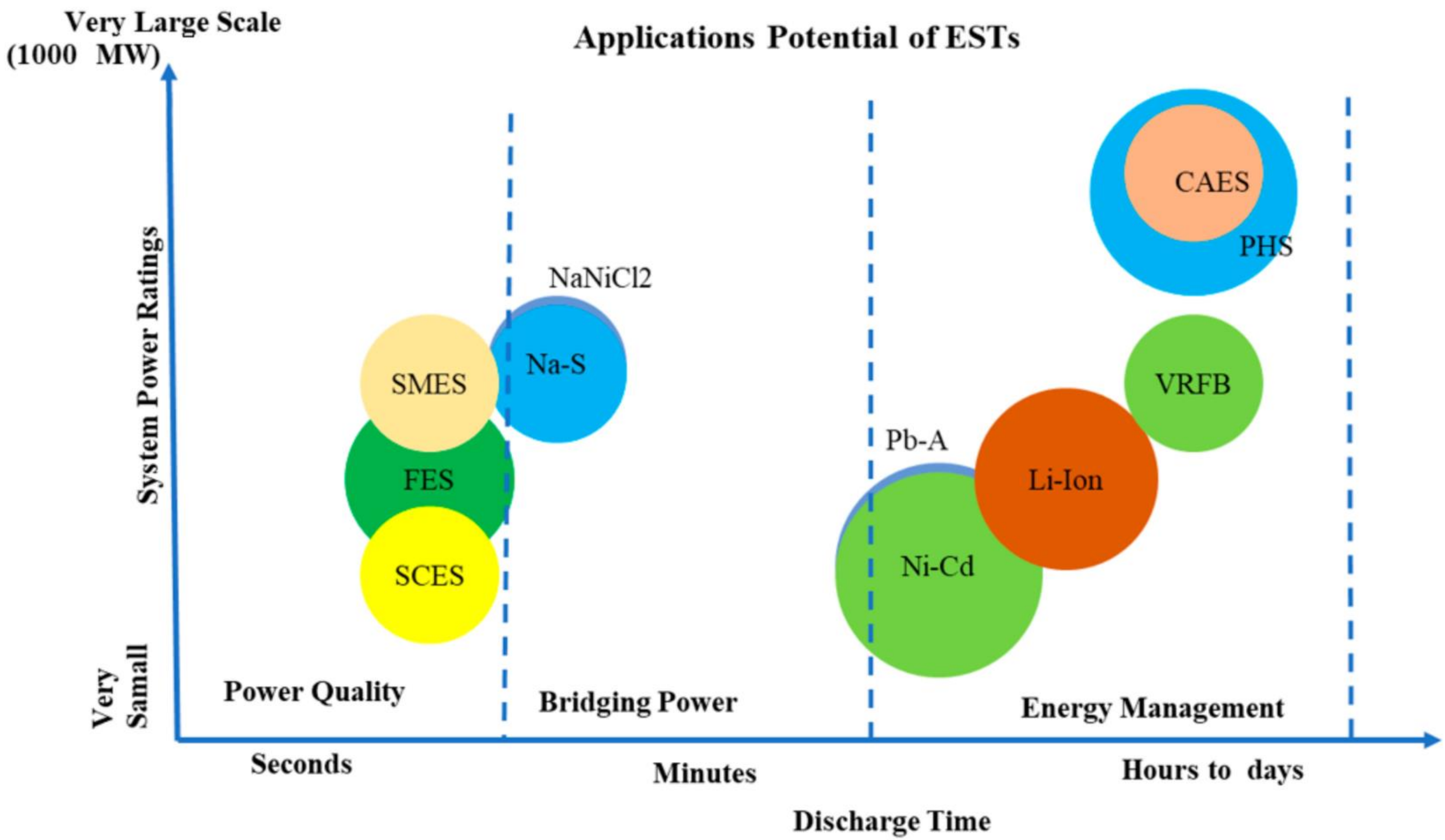

Figure 21 Comparison of power rating vs discharge time [18]

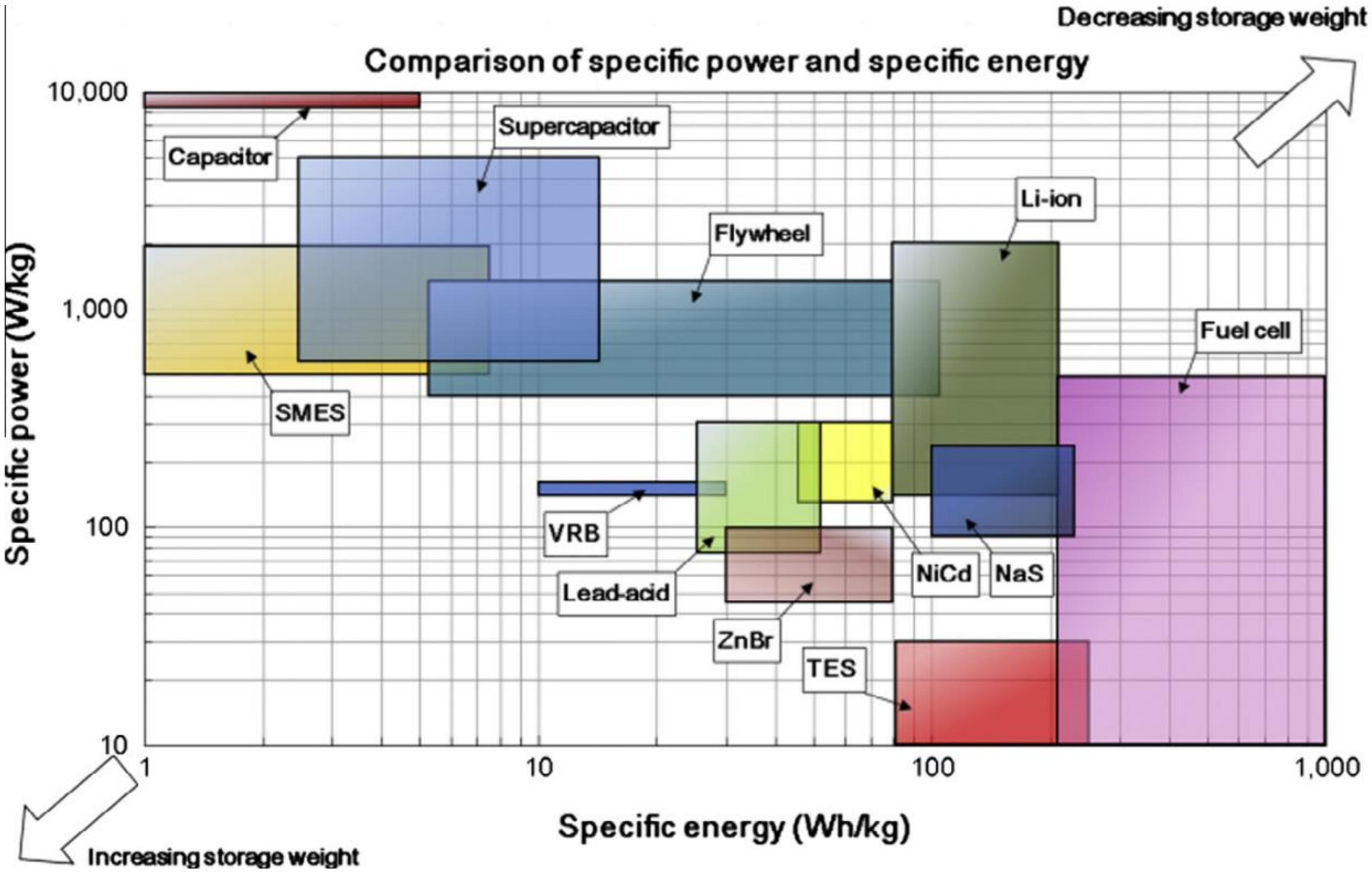

Figure 22 Comparison of specific power vs specific energy [17]

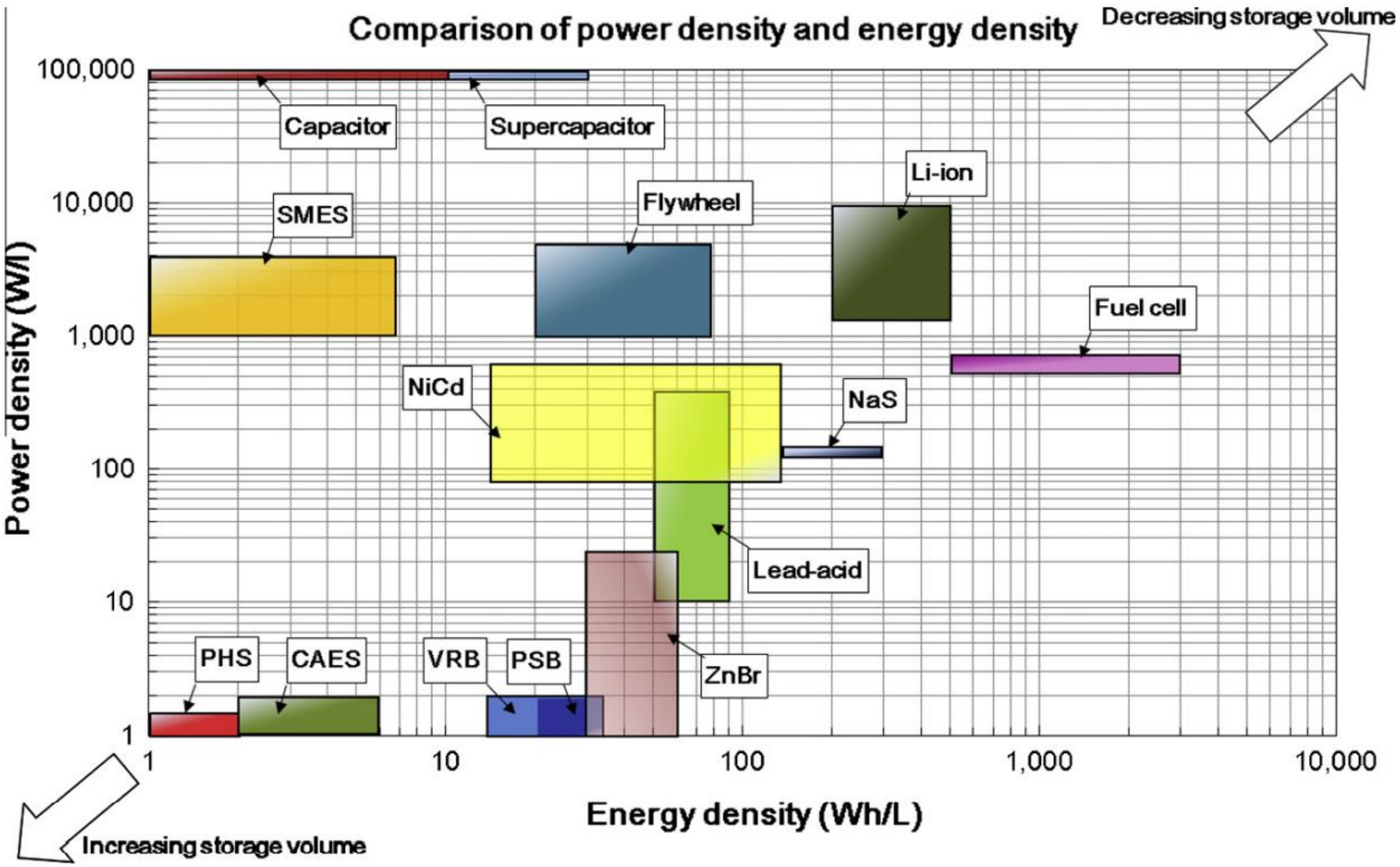

Figure 23 Comparison of power density vs energy density [17]

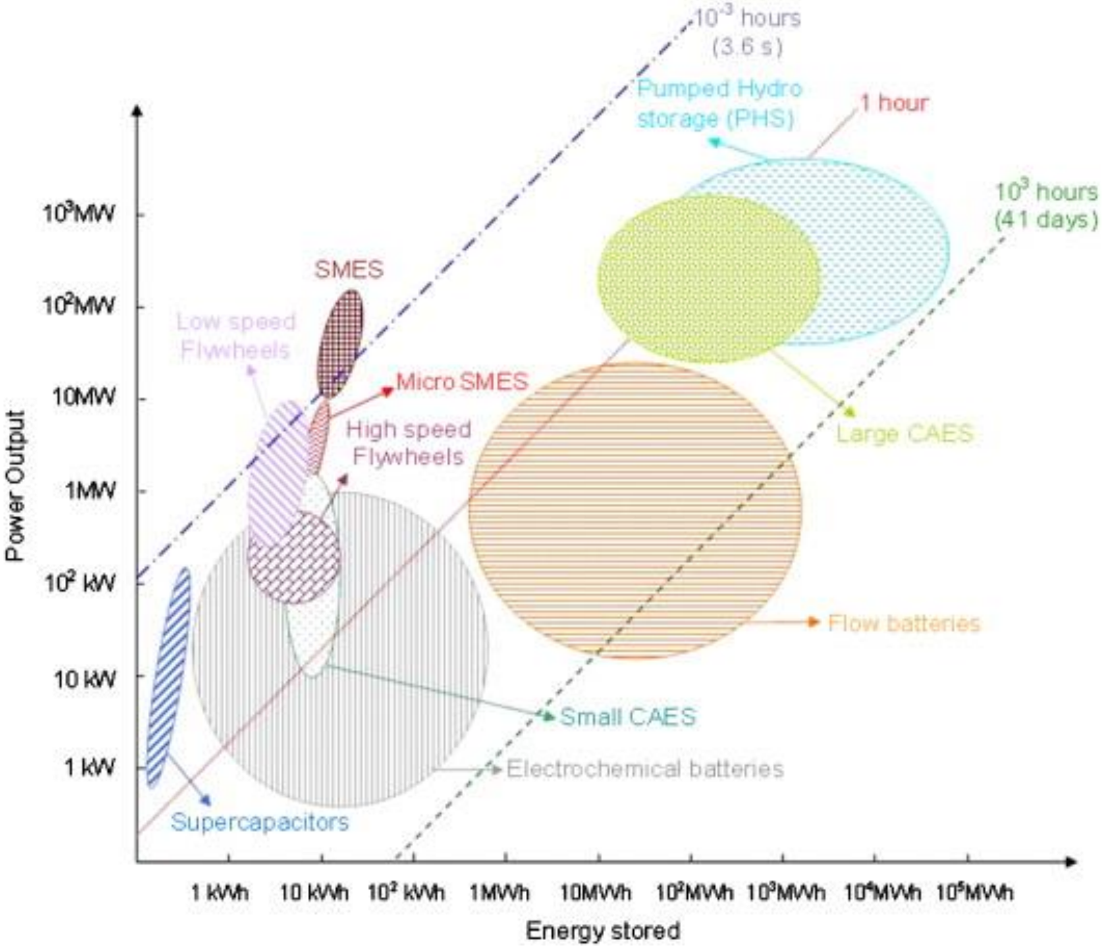

Figure 24 Comparison of Power output vs energy stored [44]