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# State-of-the-Art of the Flywheel/Li-ion Battery Hybrid Storage System for Stationary Applications

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*Ai miei genitori, Leandro e Roberta,*

*e a mio fratello, Alessandro.*

# Abstract

This thesis presents the State-of-the-Art related to a Hybrid Energy Storage System (HESS) that combines flywheels and Li-ion batteries for stationary applications. As the number of Renewable Energy Sources (RES) increases in the grid, the environmental improvements are more and more evident. On the other hand, the penetration of these technologies, due to their intermittency and uncertainty, causes major problems to the stability of the electrical grid by generating fluctuating power outputs. Here comes the importance of Energy Storage Systems (ESSs) that, by converting electrical energy into other forms and then storing it, aim at enhancing the reliability of RES, improving the resilience of the grid, realizing the benefits of smart grids and optimizing generation to suit demand. After a presentation of the grid services that the ESSs can provide, a detailed description of the characteristics of Li-ion batteries and flywheels is proposed. The complementary operating features of these two devices in terms of power, energy and discharge time, allow their combination in a single hybrid technology in order to achieve specific requirements, provide many grid services and overcome the limitations of the single storage device. The performance of this system is analyzed and some possible control strategies are presented. In conclusion some technical data from companies that are implementing this hybrid technology is provided.

# Sommario

Questa tesi presenta lo stato dell'arte relativo ad un sistema ibrido di accumulo di energia costituito da batterie agli ioni di litio e volani a servizio della rete elettrica. Con l'aumentare del numero di fonti rinnovabili, i miglioramenti in ambito ambientale sono sempre più evidenti. D'altra parte però, la penetrazione di queste tecnologie, a causa della loro intermittenza e incertezza in termini di fornitura di energia, causa una serie di problemi alla stabilità della rete, generando potenze fluttuanti. E' qui che acquistano importanza i sistemi di accumulo energetico che, convertendo l'energia elettrica in altre forme di energia e poi immagazzinandola, mirano ad aumentare l'affidabilità delle fonti rinnovabili, migliorare la resilienza della rete, realizzare i benefici delle smart grids e ottimizzare la generazione in funzione della domanda. Dopo una presentazione dei servizi di rete che questi sistemi di accumulo forniscono, una descrizione dettagliata delle caratteristiche delle batterie agli ioni di litio e dei volani è proposta. Le caratteristiche complementari di funzionamento di queste due tecnologie in termini di potenza, energia e tempo di scarica, permettono la loro combinazione in un unico sistema ibrido allo scopo di raggiungere determinati requisiti, fornire svariati servizi di rete e sormontare le limitazioni del singolo dispositivo di accumulo. La prestazione di questo sistema è analizzata e alcune possibili strategie di controllo sono presentate. In conclusione vengono forniti alcuni dati tecnici da aziende che stanno implementando questa tecnologia ibrida.

# Contents

# Definitions

Here are presented some important definitions related to Energy Storage Systems:

- **State of Charge (SoC)**, [%]: is the ratio between remaining capacity and the full charge, where capacity is defined as the quantity of electrical charge in the cell from the fully charged state to the discharge state. The SoC is equal to 100% for full charge and 0% for full discharge. The variation in SoC (*dSoC*) is based on time and its relation to capacity ($C_i$) is outlined as it follows:

$$dSoC = \frac{idt}{C_i}\,, \qquad SoC = SoC_i - \int \frac{idt}{C(i)}$$

- **Depth of Discharge (DoD),** [%]: is the quantity of charge erogated by the cell. It's actually the complementary of the SoC, as one increases, the other decreases. 100% indicates full charge and 0% full discharge. It's equal to:

$$DoD = \left(1 - \frac{SoC}{100}\right) \cdot 100$$

- **Specific Energy and Specific Power**, [Wh/kg] and [W/kg]: refers to the maximum available energy and power per unit mass respectively.

- **Energy Density and Power Density**, [Wh/L] and [W/L]: refers to the maximum available energy and power per unit volume respectively.

- **Response Time**, [s]: is the length of time for the storage device to release power.

# Introduction

Globally, sustainable development is currently a crucial issue. Its most common and simplest definition is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [9]. Many factors can contribute to achieve a sustainable development and one of them is to be able to supply energy sources that are fully sustainable. This is not the only goal: energy is expected to be readily available all the time, at reasonable costs, and without causing negative social impacts.

Conventional energy sources based on oil, coal and natural gas have contributed the most towards the development we have achieved today. However, excessive use of these sources is causing depletion of these reserves, as well as damaging the environment and humans’ health. These so-called *dirty sources* are facing increasing pressure from environmental advocates, becoming targets of Kyoto Protocol greenhouse gas reduction. The 2015 United Limited Nations Climate Change Conference in Paris set the framework for a rapid global shift to a sustainable energy system in order to avoid the risk of catastrophic climate change. The challenges in meeting energy demand whilst limiting greenhouse gasses have prompted the idea of integrating Renewable Energy Sources (RES) into power systems.

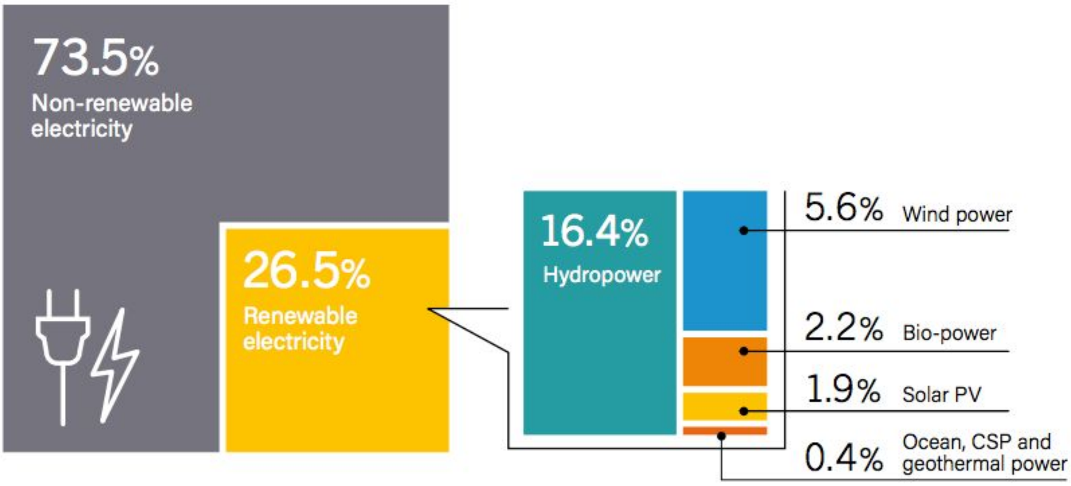


Figure 1 - RES share of global electricity production 2018 - Source [19]

RES have been growing rapidly over the last few years, as Figure 2 shows, and the environmental improvements are many. On the other hand, the penetration of these technologies, due to their intermittency and uncertainty, causes major problems to the stability of the electrical grid by generating fluctuating power outputs. The electricity generated from RES can rarely provide immediate response to demand as these sources don't deliver a regular supply easily adjustable to consumption needs. In fact, they rely on weather conditions, such as sunlight and wind. Here comes the importance of Energy Storage Systems (ESSs) where electrical energy is converted into other forms of energy that can be stored and then converted back into electricity when needed. EESs allow energy production to be decoupled from its supply, self generated or purchased. Furthermore, they can help improving the system reliability, whilst optimally maintaining sensible operational costs, by mitigating power variations and functioning as storage for flexible dispatch of RES. Services offered by ESSs are numerous, their main three targets are:

- enhancing the *reliability* of RES
- improving the *resilience* of the grid
- realizing the benefits of *smart grids* and optimizing generation to suit demand [1]

In the electric utility industry, power outage is the main concern because consumers are expecting a continuous ready supply throughout the year. This ready supply is termed as *reliability*, which is further defined as the reliability of a power system to provide adequate output to consumers. Moreover, energy storage can increase the *resilience* of the system during weather variations, natural disasters… and still guarantee a certain level of safety. All of this, aiming at an efficient distribution of electricity throughout the grid with less centralized generation and more distribution of the sources, making the overall system *smart*.

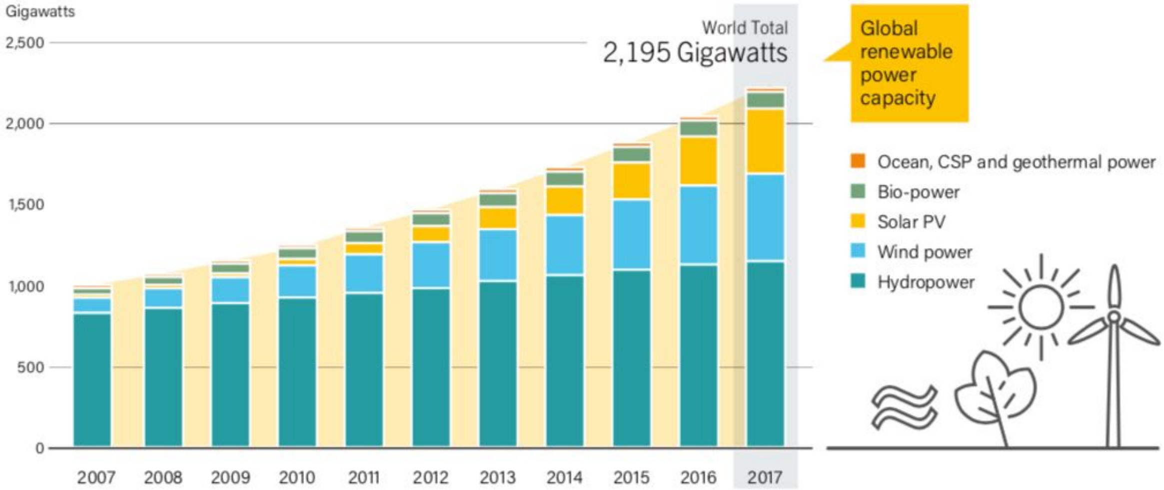


Figure 2 - Growth of RES capacity over the years - Source [19]

# Chapter 1 - Energy Storage Systems (ESSs)

## 1.1 Applications and Technical Benefits of ESSs

Energy Storage along with the fluctuations caused by RES plays a role in power and voltage smoothing but is also important for energy management, frequency regulation, peak shaving and load leveling, load following, seasonal storage, black start and helps with the integration of RES. [1], [2] and [9] identify four different types of applications of ESSs in modern grids:

- *Bulk Energy Application*
- *Ancillary Service*
- *Customer Energy Management*
- *Renewable Energy Integration*

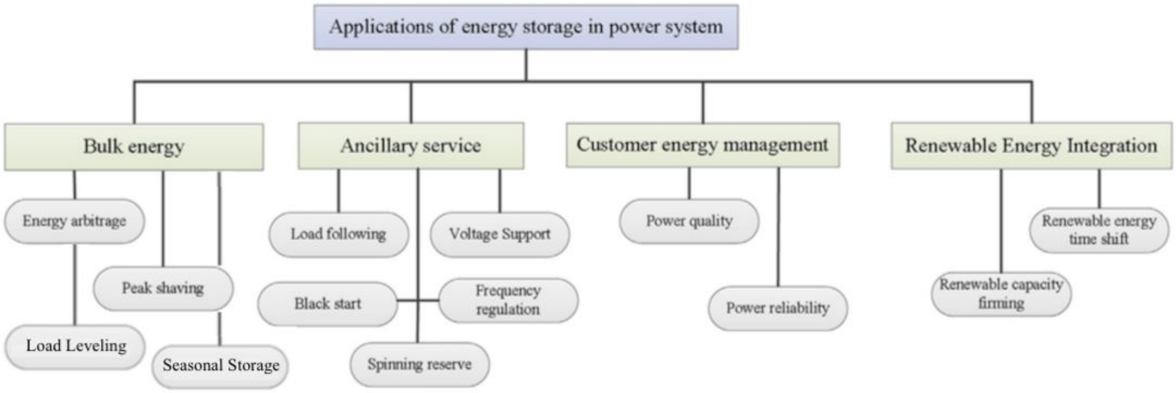


Figure 3 - Classification of ESS applications - Source [1]

### 1.1.1 Bulk Energy Application

Bulk Energy Application refers to the idea of storing large amounts of energy when there is a surplus of it in the electrical grid due to an increase of generation or a reduction of demand.

#### 1.1.1.1 Energy Arbitrage

Generating energy is quite expensive, storing it can both increase the efficiency of a system and optimize it economically. The main goal of *energy arbitrage* (or *energy shifting*) is to store energy during lower-priced hours and to sell it during higher-priced hours. Figure 4 shows that prices tend to change throughout the day and are correlated with the amount of demand. Of course by storing energy, there is a loss due to round-trip efficiency of the ESS, the inverter and transmission lines. The size of the installations for this application is usually between 10 MW and 1,000 MW with a energy-to-power ratio (E/P) bigger than 5. Indeed, this application requires storage technologies with high E/P at a reasonable cost. [12]

Figure 4 - Example of arbitrage cycle - Source [21]

#### 1.1.1.2 Peak Shaving

*Peak shaving* is installed to cover the peak load, and so reducing peak demand, and does not have an economic target, as *energy arbitrage* does. In a grid where the amount of RES is solid, the energy is stored when the generation exceeds demand (off-peak period) and it is injected during periods of shortages. Integrating energy storage system to the grid is the most potential strategy of peak shaving (two other strategies can be used: electric vehicles and the so-called demand side management [18]). The storage technology must be able to provide energy for some minutes to some hours and it's usually installed at the consumer. The goal is to avoid the installation of capacity to supply the peaks of a highly variable load. The typical size of the installations for this application is between 50 kW and 5 MW and the selected storage systems should present high power and low-to-moderate energy throughput.

Benefits of using peak shaving in the system are many and actually some of them result in improvements of other applications as well [18]:

- Improvement of the power quality (1.1.3.1) as peak load shaving techniques can mitigate the generation-demand imbalance.
- Efficient energy utilisation which can be estimated by measuring the *load factor* of a plant. It is a useful technique to measure the variability of consumption in a plant by determining how efficiently electricity is being used. A low load factor means that load is highly variable while a high load factor is essential for the economic feasibility of the plant. It can be determined by the following equation:

  $$LF(\%) = \frac{P_{AVG}}{P_{Peak}}$$

  $LF$ is load factor, $P_{AVG}$ is average real power demand and $P_{Peak}$ is peak real power demand. From the equation, high *LF* results in low energy cost, so an improvement of it is obligatory to reduce the energy cost and make the plant economically feasible.
- System efficiency. In order to mitigate the peak load, supply current needs to be increased significantly. However, increasing the supply current will reduce the system efficiency, as current is non-linearly related to the power loss, which can be calculated as:

  $$P_{LOSS} = I^2 x\, R$$

  where $P_{LOSS}$ is the power loss, *I* is current flowing through the transmission line and *R* is ohmic resistance in the transmission line.

  As the power loss is proportional to the square of the current, it is necessary to reduce the supply current by reducing peak demand to improve the system efficiency.
- Cost reduction by matching supply and demand perfectly. Since peak occurs occasionally, it is economically not feasible to design a generation system much bigger than the capacity needed. With peak shaving the efficient of the system is increased, as it allows plants to save in fuel and maintenance costs, as well as the

use of the transmission and distribution (T&D) system. The grid operator will so save in capital cost expenditure.

- RES integration (1.1.4) as their intermittent nature causes problems with the stability and reliability of the power network and peak shaving can help with the general stabilization of the grid.
- Improvement of the power reliability of the grid (1.1.3.2) that is affected by the significant peak load, which is increasing day by day, experienced by distribution systems.
- Benefits for end-users. In order to meet the time varying peak demand, sometimes less efficient (in terms of economy and environment) generators (peaking generators) are required. Therefore, the per kWh electricity generation cost increases during the peak period and this high cost is ultimately passed onto the consumer during peak hours. That’s why peak shaving is also important for end users as residential and industrial customers can save their electricity bills by shifting peak load from peak period (when energy price is high) to the off-peak period (when energy price is low). They may also save in connection charges and capital cost for the distribution system.
- Carbon emission reduction since that with peak demand, power plants consume extra fuels resulting in the production of more emissions. Peak load shaving ensure more efficient operation of power plants and reduce the variability in load.

Figure 5 describes *peak shaving* using an energy storage system (ESS).

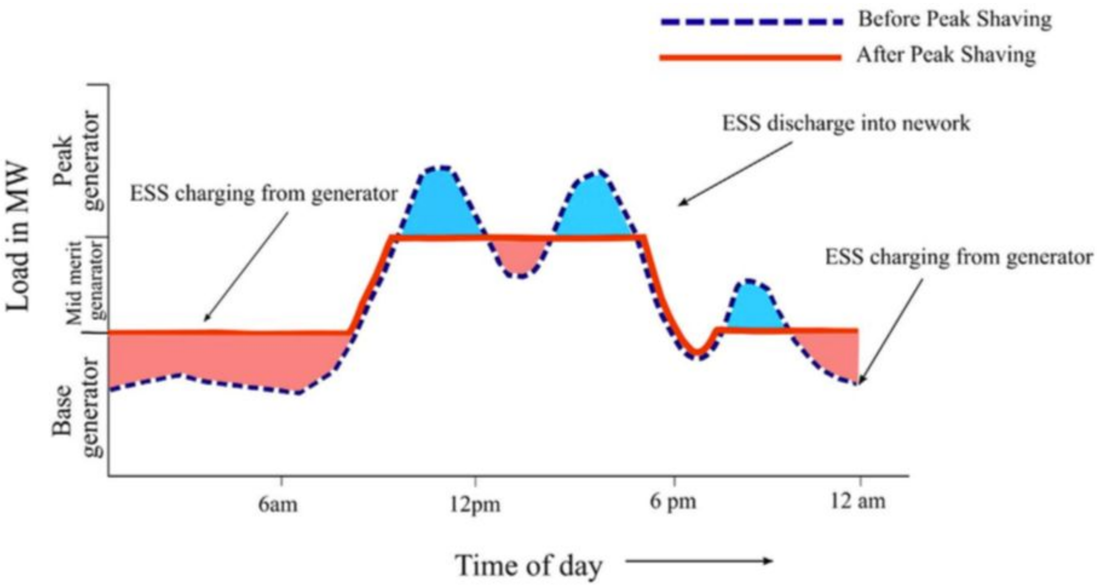


Figure 5 - Energy storage load profile in peak shaving - Source [18]

### 1.1.1.3 Load Leveling

*Load leveling* is the rescheduling of the loads to limit the consumption during periods of high demand and to increase the production of energy during off-peak periods. During these periods of high demand, the energy storage system supplies power, reducing the load on less economical peak-generating facilities. Load leveling allows for the postponement of investments in grid upgrades or in new generating capacity. This application may seem equal to *peak shaving* but there’s a slender difference: the main goal of *peak shaving* is to mitigate peaks while *load leveling* aims to level and flatten the entire load curve.

The typical size of installations for this application is between 5 MW and 100 MW with a energy-to-power ratio (E/P) of 3 to 6.

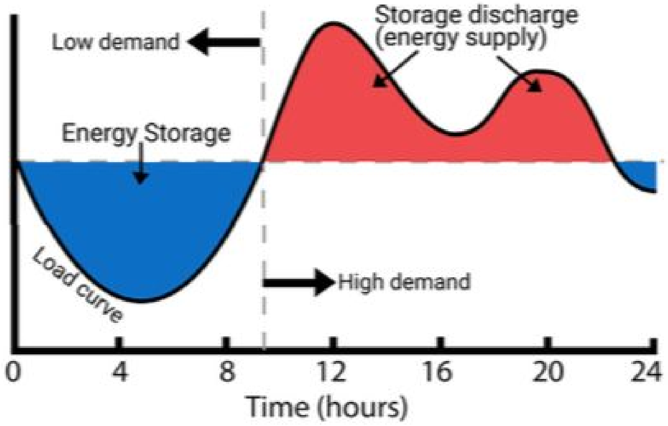


Figure 6 - Energy Storage Load Profile in Load Leveling - Source [2]

#### 1.1.1.4 Seasonal Storage

*Seasonal storage* requires high energy capacity and low self-discharge rates. The selected storage technology should be able to store energy for days to months and its efficiency and power density are considered a plus.

### 1.1.2 Ancillary Service

The term Ancillary Service refers to a variety of operations beyond generation and transmission that are required to maintain grid stability and security.

#### 1.1.2.1 Load Following

ESSs have a rapid response to changes in load compared to generation types (e.g. most types of storage can respond much more quickly than typical rotary generators) and, since the load can undergo frequent variations, energy storage is more suitable in the *load-following* applications, e.g when power sources adjust their power output as the demand for electricity fluctuates throughout the day. The aim is to create a balance between the generation part and the load. On the downside, ESSs can not supply power indefinitely: the duration of the supply is limited by the storage capacity.

For timescales of minutes to hours, load following matches relatively slow but large magnitude swings in daily electricity demand and mesoscale wind or PV variations.

Electricity demands are typically low at night and high during the day. On the load-following timescale, RES can affect economic dispatch since priority is usually given them due to their low cost and non-dispatchability, but can also increase the strain on the regulation unit since RES does not actually follow the load. For an EES used for this purpose, ramp rate requirements are less important than stored energy and power capacity; a 0.3–1 MW/s could be sufficient. In order to be profitable when participating in electricity markets, energy must be stored and charged/discharged over periods of hours to justify the use of EES. In the case of wind generation, paper [23] states that the amount of EES required to manage generation forecasting errors is 2–6% power (6–10% energy) of the wind rated capacity for a 20% wind penetration level, and 3–8% (10–15% energy) for 30% wind penetration; penetration is defined as the wind capacity over the system peak demand. These results evaluate the need for back-up power requirement based on unforecasted load and wind variations in addition to generator forced outages to fulfill the reliability criterion.

#### 1.1.2.2 Frequency Regulation

When the power consumption exceeds the generated power, due to increased customer usage or reduced generating capacity in the grid, the increased load on the generators will cause them to slow down and since the generators are synchronous machines, the grid frequency will also decrease. In the same way, if the consumption falls below the power generated or more generating capacity is injected into the network, the generator will speed up and the grid frequency will increase. To maintain the stability of the grid it is necessary to keep the grid frequency and voltage within strict limits. This requires access to very fast response means and requires power to be delivered for a very short duration.

The ESS in a *frequency regulator* serves power systems by correcting the frequency deviations to within the permissible limits: $\pm 0.1$ Hz in North of Europe or $\pm 0.2$ in Continental Europe.

Primary, secondary and tertiary frequency regulations occurs. The primary to balance generation and demand; it restores the frequency within 20-25 seconds. The secondary is a backup for the primary and sets the frequency at 50 (or 60) Hz and lasts up to 100-150 seconds. The tertiary is manual and has the same purpose of the secondary, plus helping to keep the system synchronized.

#### 1.1.2.2.1 Primary Frequency Control

*Primary frequency control* is a provision of Frequency Containment Reserve (FCR) and requests energy storage systems to modulate the active power output ( $\Delta P$ in MW) proportionally (depending on the droop parameter, $\sigma$, expressed in % and fully configurable) to the deviations of the grid frequency ( $\Delta F$ in HZ) around its nominal value of 50/60 Hz [17]:

$$\Delta P_{FCR} =- \frac{1}{\frac{\sigma}{100}} \cdot \frac{\Delta F}{50} \cdot P_{rated}$$

Figure 7 shows the FCR regulation patterns.

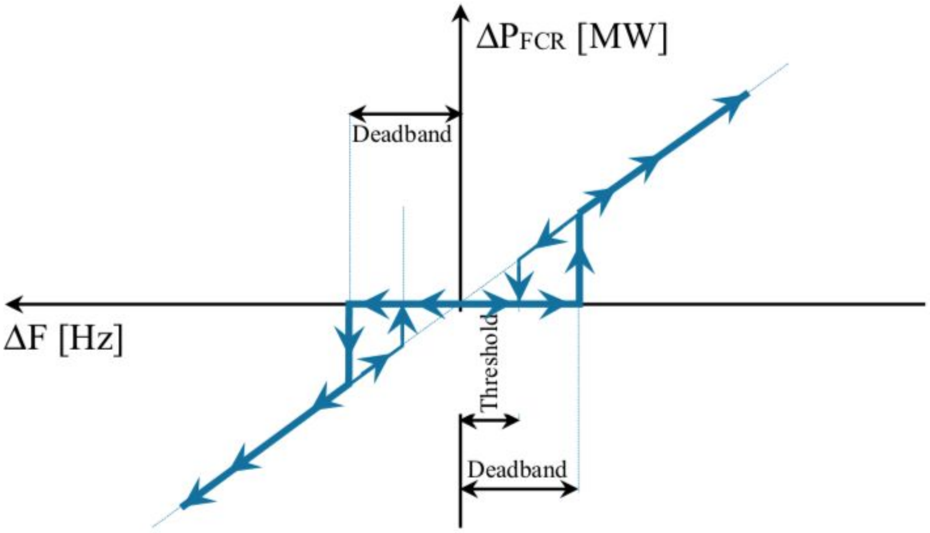


Figure 7 - FCR ancillary regulation pattern - Source [17]

ESSs are able to shift the active power flow direction continuously and take less than 100 ms for a complete inversion (full inversion from maximum discharge active power to maximum charge one). The value of the droop parameter $\sigma$ may be set to a small value to allow ESSs to perform a greater active power contribution in case of wide frequency deviations. This service plays a key role in the grid as it provides regulating energy, a resource that is slowly decreasing due to the increase of generation by RES.

[12] states that the general size of this type of installations is between 1 and 50 MW with a 1-1.5 (approximate) energy-to-power ration (E/P) achieved by pooling smaller units. This application requires high to very high power dynamics and relatively small energy throughput (∼1 cycle per day).

#### 1.1.2.2.2 Secondary Frequency Control

*Secondary frequency control* aims to provide a Frequency Restoration Reserve (FRR) performing active power output variation $\Delta P_{FRP}$ as requested by an external control signal (L% whose percentage range is 0-100%). FRR regulation is a power plant service. A reserved regulation band (half-band, HB, expressed in MW) around the active power set-point (the actual balancing program or the stand-by-mode) is dedicated in accordance with:

$$\Delta P_{FRP} = 2 \cdot HB \cdot \frac{(L\% - 50\%)}{100\%}$$

Set-point signal is updated and forwarded every 8 seconds to the plant with a maximum variation within the total regulation band of 4%. [17]

The typical size for this application is between 10 to 1,000 MW with E/P ratio bigger than 5, which can be achieved by pooling of smaller units. It's required moderate power and energy throughput that strongly depend on the current composition of the electricity supply system and demand variations, market design (e.g spot market regulation, tendering periods) and soft factors such as weather prognosis, quality or demand-side management potentials. [12]

#### 1.1.2.2.3 Synthetic Rotational Inertia (SRI)

As paper [17] states, in addition to FCR, ESSs can be equipped with SRI (operated independently from FCR) in order to reduce the fastest frequency transient phenomena, from its beginning. The high rapidity of ESSs in varying the generated or absorbed active power P has made feasible several scenarios that were not possible with traditional power plants. These characteristics may provide the grid some rotational inertia: ESSs may be requested to deliver an active power proportionally to the measured derivative frequency, i.e to the rate of change of frequency (*df/dt*). However, it is crucial to implement robust control blocks for a reliable frequency rate of change sampling. This could be fulfilled by feeding the control block numerical algorithm with a proper and adequate frequency sampling, insuring on one hand computational accuracy and on the other fast solution times. The result must be available within a time frame assessable in tens of milliseconds. The faster the active power response, the more effective the mitigation of frequency variation is. Such a $P$ response should not be confused with a fast FCR regulation set with low droop value because its contribution depends linearly on the instantaneous measured frequency deviation. By assuming both FCR and SRI committed together, each contributions must be distinguished: the ESS may be engaged in FCR with droop not sufficient to let the plant fill the active power capability though still guaranteeing fast response, and at the same time SRI may provide the ESS full $P$ capability access just in case of sudden frequency deviation. The ESS has to deliver $\Delta P_{SRI}$ (in MW) proportionally (depending on a parameter, $K_W$, expressed in MW $\cdot$ s / Hz and fully configurable) to the filtered derivative frequency measurement ( $\Delta f / \Delta t$, in Hz/s):

$$\Delta P_{SRI} =- k_w \cdot \left(\frac{\Delta f}{\Delta t}\right)_{Butterworth-filtered\ value}$$

Figure 8 shows the SRI service regulation patterns.

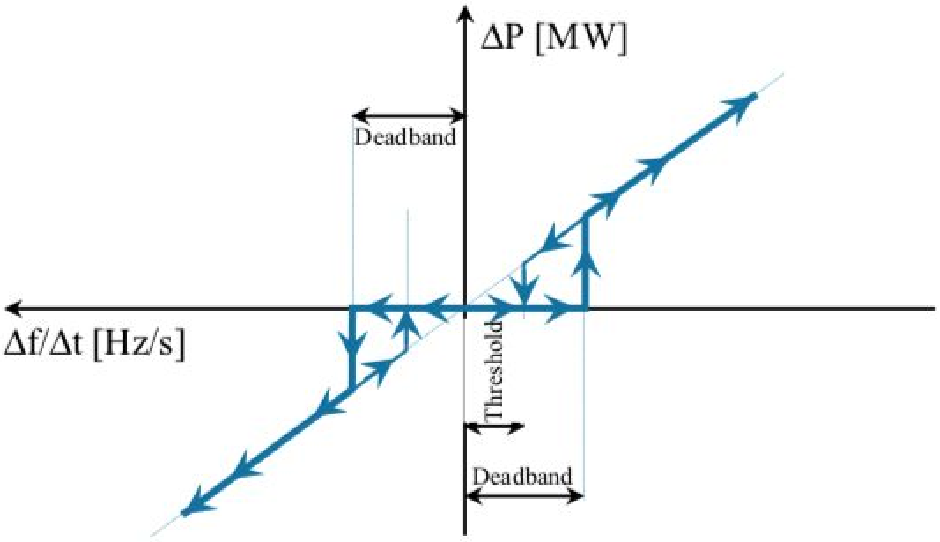


Figure 8 - SRI ancillary service regulation patterns - Source [17]

It is necessary to implement this service in order to emulate the stabilizing contribution to frequency deviations guaranteed by the rotating masses, in prevision of an ever-growing passage from traditional power plants (with rotating synchronous generators) to static inverter-equipped power generation. For a prompt SRI response, it has been crucial to implement a reliable, accurate and fully configurable digital filter or grid frequency for feeding the regulator: Infinite Impulse Response filters (IIR, e.g Butterworth filters) have been selected as the best solution for speed and accuracy of response. IIR filters are fully configurable in terms of filter order and cut-off frequency to adjust filtering to the effective harmonic content inside grid frequency and to achieve an adaptive filtering by means of high stopband attenuation and effective noise cancellation. In addition, IIR filters enable the achievement of low-rate phase delays and may be designed as inherently stable.

#### 1.1.2.2.4 Additional Functionalities

In addition paper [17] describes how ESSs can be equipped with advanced functionalities. A functionality represents the capability of ESS to perform a specific service, either in addition to the aforementioned ones or in a mutually exclusive way and it can either be demanded through automatism or on request of the operator.

- Local Frequency Integrator (LFI): this functionality is operated in background and is automatically activated (and fully configurable) in emergency conditions (high frequency transient) for restoring nominal frequency value through an integral control loop feedback. It is used when isolated grid conditions are detected.
- Defense plan (switch opening and active power modulation): the task is handling the shedding of load/production in order to keep the integrity of the grid, in case of abnormal conditions resulting from occurrence of extreme contingencies. This may be obtained through the following commands:
  - Switch opening
  - Active power (*P*) modulation within 300 ms

  ESS’ rapidity of varying the active is also used for these additional commands:

- Instantaneous maximum *P* feeding into the grid;
- Instantaneous maximum *P* absorption from the grid;
- Instantaneous *P* exchange stop.

The extremely fast response recorded for active power modulation (less than 300 ms from the request to the full activation) leads to considering, when including an ESS in system defense plan, the utilization of this command (maximum power feeding or maximum power absorption, depending on the desired direction) instead of switch opening (mostly used in hydro pumped storage). In this regard, in some operational conditions, the effectiveness of ESSs as a defense plan is doubled.

#### 1.1.2.3 Black Start

Some particular events can lead to interruptions in power throughout the whole system or in a single part and these can lead to a black-out. The system is restored through a process called *black start*, which takes care of power management, voltage control and balancing. Black start service is the ability of a generating unit to start without an outside electrical supply, or is the demonstrated ability of a generating unit with a high operating factor to automatically remain operating at reduced levels when disconnected from the grid. ESS generates active power that can be used for energizing distribution lines or as a start up power for large power plants. This happens in case the system fails to provide energy as units are unable to restart.

#### 1.1.2.4 Spinning Reserve

The *spinning reserve* is a part of the capacity of the source that is not used in normal operation but it's instead used for the prevention of unexpected problems in the grid. It's the unused capacity that can be activated by decision of the system operator and that is provided by the devices that are synchronized to the grid and can affect the active power. Such sources must respond immediately to cover a power shortage in the system, with the ability to maintain the output for some minutes up to a few hours. In other words, it's an extra operation mode. To provide effective spinning reserve, the ESS is maintained at a level of charge ready to respond to a generation or transmission outage. Depending on the application, the system can respond within milliseconds or minutes and supply power to maintain network continuity while the back-up generator is started and brought on line. This enables generators to work at optimum power output, without the need to keep idle capacity for spinning reserves. It can also eliminate the need to have backup generators running idle.

#### 1.1.2.5 Voltage Support

The stability of the grid is achieved also through maintaining the voltage within the permissible limits, which means controlling the reactive power. Since reactive power can not be transferred over long distances, a *voltage support* application is used locally to manage the problem. Two operating modes are available and they are mutually exclusive [17]:

- Local Bus Bar Voltage Regulator: the aim of this service is to adjust local substation voltage (High Voltage bus bar). If a voltage ($U$) error is measured, a reactive power contribution ($Q$) will occur in accordance to a predetermined $U$-$Q$ curve, fully configurable, to reduce the deviation between actual voltage and its set value.
- Regional Voltage Regulator (RVR): the aim of this regulation is to adjust relevant substation voltages (pilot substations with high faults levels) through a coordinated plant reactive power regulation. The remote controller is in charge of computing the exact amount of reactive power that has to be requested to the plant to reach the substation voltage set value. The remote controller aims at nullifying voltage deviations between the measured value and set value of each High Voltage pilot substation.

#### 1.1.2.6 UPS

In the case of a power interruption, ESS works as an *UPS (Uninterruptible Power Supply)* system by providing energy for some minutes up to two hours and it’s used to reduce or avoid negative effects and costs associated with electrical service outages and/or poor power quality (1.1.3.1). They are designed to automatically provide emergency power without delay. They are used especially in fire protection systems, security systems and in computer and servers. More specifically, UPSs provide stable and reliable power to:

- Serve critical safety-related loads such as emergency lighting and medical equipment
- Reduce or avoid lost productivity
- Reduce or avoid production damage (i.e. for manufactures)
- Reduce or avoid product or facilities damage
- Reduce or avoid electricity-using equipment damage.

Shorter duration UPSs are designed to:

- Carry the load during startup of backup electrical generators, typically diesel engine driven generators
- Enable a smooth transition to the generator as the power source

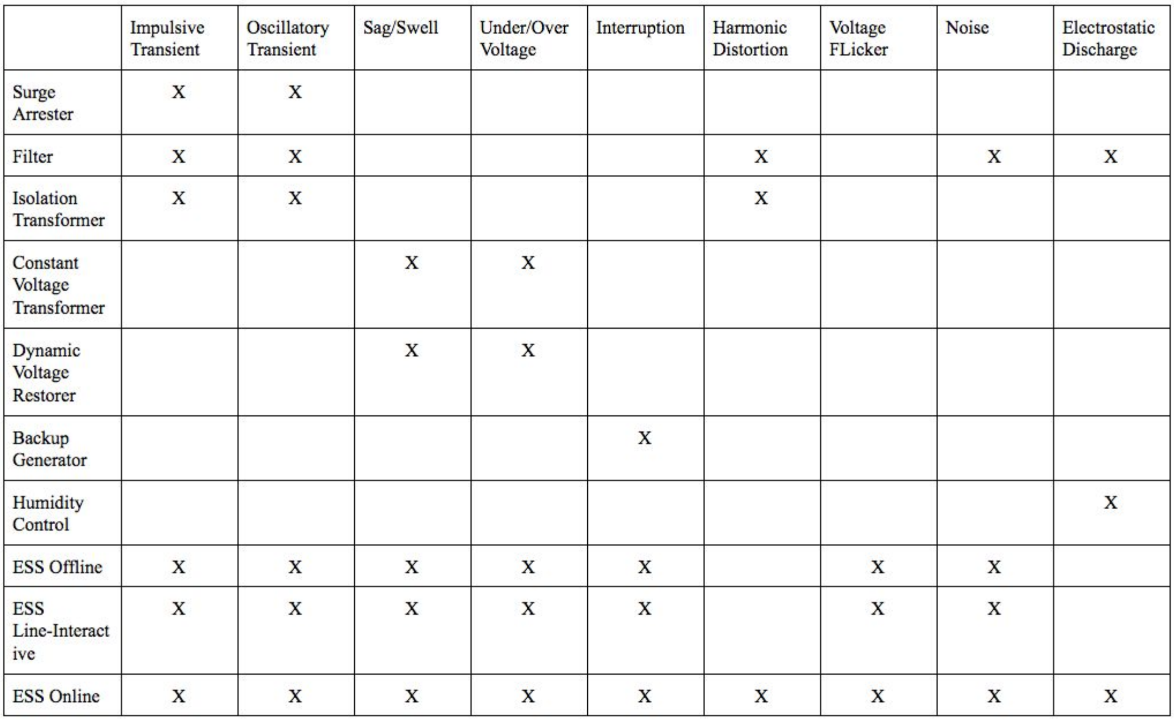
UPS power rating range from a few hundred Watts for a computer to a computer to a few MegaWatts (MW) for entire facilities.

### 1.1.3 Customer Energy Management

Customer Energy Management refers to the idea of providing the consumers with the best version of electricity in terms of quality and reliability, avoiding damages in some sensitive equipments that might be connected to the grid.

#### 1.1.3.1 Power Quality

The fluctuations in power generation systems lead to concern about *power quality* and the ability of the grid to supply a clean and stable power flow, especially in terms of voltage harmonics and voltage variations. The flow of reactive power and the presence of transients in the network are the common contributors to voltage instability and interference on the voltage waveform that can eventually affect the sensitivity of some power electronic devices and microprocessor-based controls. ESSs can ensure a power quality improvement with a fast response time, high cyclability and a reasonable cost as they take care of voltage sags, under-voltages, interruptions and many other possible events. [20] Indeed, Figure 8 points out the efficiency of ESS in mitigating most power quality events compared to any other protection device.



| | Impulsive Transient | Oscillatory Transient | Sag/Swell | Under/Over Voltage | Interruption | Harmonic Distortion | Voltage FLicker | Noise | Electrostatic Discharge |
|---|---|---|---|---|---|---|---|---|---|
| Surge Arrester | X | X | | | | | | | |
| Filter | X | X | | | | X | | X | X |
| Isolation Transformer | X | X | | | | X | | | |
| Constant Voltage Transformer | | | X | X | | | | | |
| Dynamic Voltage Restorer | | | X | X | | | | | |
| Backup Generator | | | | | X | | | | |
| Humidity Control | | | | | | | | | X |
| ESS Offline | X | X | X | X | X | | X | X | |
| ESS Line-Interactive | X | X | X | X | X | | X | X | |
| ESS Online | X | X | X | X | X | X | X | X | X |

Figure 9 - Mitigation capabilities of protection devices - Source [20]

These events can be described as follows:

- Spike or Impulsive Transient: a high, short duration (milliseconds or microseconds) voltage increase. Most spikes are caused by lightning or when electrical service is restored after an outage. Spikes are especially damaging to electronic equipment.
- Swell or Surge: electrical service voltage exceeds the nominal voltage for one second to one minute. A common cause is high power equipment shutting off. Common examples of such high power equipment include large pump motors, air conditioning equipment and manufacturing processes.
- Sag or Undervoltage: electrical service voltage exceeds the nominal voltage for one second to one minute. A common cause is high power equipment turning

on. If the sag lasts long enough and/or is severe enough then electricity using equipment will shut off and may be damaged.

- Noise: disturbance of the smooth flow of electricity in the form of Electromagnetic Interference (EMI) or Radio Frequency Interference (RFI). Common sources of noise are motors and electronic devices. Noise can affect performance of some types of electricity using equipment and can affect software operation and electronic data.
- Current Harmonics: distortions of the normal sine wave form of the alternating current electricity provided by the utility at 50 Hz (or 60 Hz) or cycles per second. Harmonics tend to exist in multiples of the 50 Hertz grid frequency, such as 3x (150 Hz) and 6x (300 Hez). Some types of electricity using equipment cause harmonics, especially electronics, by distorting the current waveform. Harmonics can cause significant voltage distortion and in a three-phase system harmonics may cause overheating of the neutral line which can lead to damage or fire.

The typical size of installations for this application is between 50 kW and 5 MW and the selected storage systems should present high power and low-to-moderate energy throughput. [12]

### 1.1.3.2 Power Reliability

Similar to power quality, the *power reliability* follows it in order. So, the time for restoring power with this application is longer than the time needed with the power quality application. It is under customer control and installed at the consumer. It’s the degree of performance of the elements of the electric system that results in electricity being delivered to customers within accepted standards and in the amount desidered. Paper [22] shows the effects of ESS in the power reliability of a system with wind turbine generators (WTGs). It’s important to define the Expected Energy Not Supplied (EENS) and the Expected Energy Not Used (EENU), two commonly used reliability indicators, as the first one is used to investigate the impacts of the rated capacity of ESS and the number of WTGs on system reliability while the second is used to present energy wasted from a generic wind farm:

$$EENS = \sum_{j=1}^{N_j} \sum_{i=1}^{N_i} p_{ji} \times \left(A_{dj} - AG_{ji}\right) \times t_j \text{ [MWh/year]}$$

where $p_{ij}$ is the individual probability of state *i* at time step *j*, $A_{dj}$ is the load level at step *j*, $AG_{ji}$ is the available capacity of state *i* at step *j*, $t_j$ is the step duration at step *j* and $N_j$, $N_i$ are the number of steps and states, respectively. $p_{ij}$ and $AG_{ji}$ are calculated considering the availability of generating units, the availability of WTGs and the unavailability of both.

$$EENU = \sum_{j=1}^{N_j} \sum_{i=1}^{N_i} \left[p_{ij} \times \left(AG_{ij} - A_{dj} - AG_{s\,limit} + AG_{s(j-1)}\right)\right] \text{ [MWh/year]}$$

where $AG_{s\,limit}$ is the storage capacity limit and $AG_{s(j-1)}$ is the left energy stored in storage at step *(j-1)*.

It is assumed in this case that there is no initial stored energy in the energy storage. When the rated storage capacity increases from 0 MWh to 300 MWh, the corresponding EENS and EENU are shown in Figure 10. The EENS drops sharply from 6.74 MWh/year to 0.21 MWh/year when storage capacity is increased from 0 MWh to 40 MWh. The EENS reduction begins to slow down when storage capacity is more than 40 MWh. When the storage capacity exceeds 60 MWh, the EENS is very close to 0 MWh/year. From these data, it is obvious that energy storage can significantly improve system reliability by shifting extra wind energy form one operating time step to others. It can also conclude that the energy storage capacity 60 MWh should be chosen to achieve a low enough EENS in this case. From the bottom curve in Figure 10, it can be seen that the EENU decreases slowly when storage capacity is increasing.

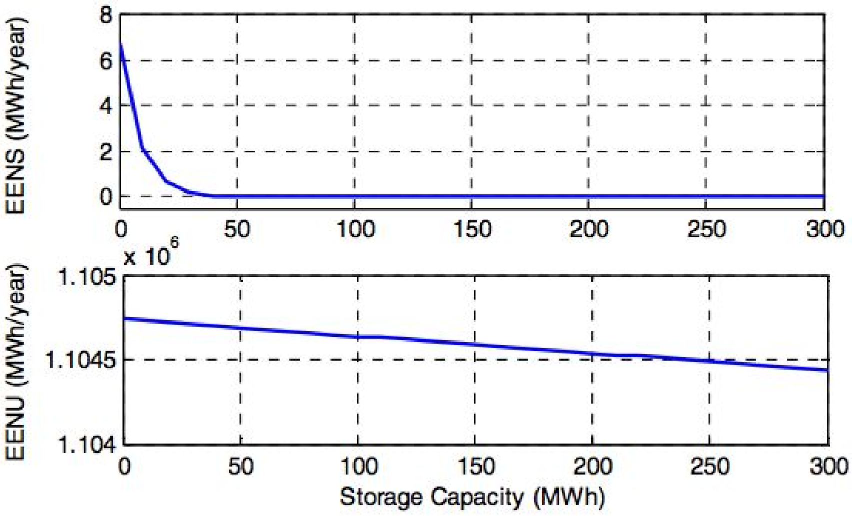


Figure 10 - Impact of storage capacity on EENS and EENU - Source [22]

When the system load increases 29.7 percent from its original value, i.e. the annual peak load is equal to the total system install capacity of the conventional generating units. In this case, the impact of energy storage capacity on EENS and EENU are shown in Figure 11. It can be seen that energy storage can reduce EENS significantly from 580.32 MWh/year without energy storage to 0.05 MWh/year with 100 MWh energy storage. The EENU values are decreased to about 8.16×105 MWh/year.

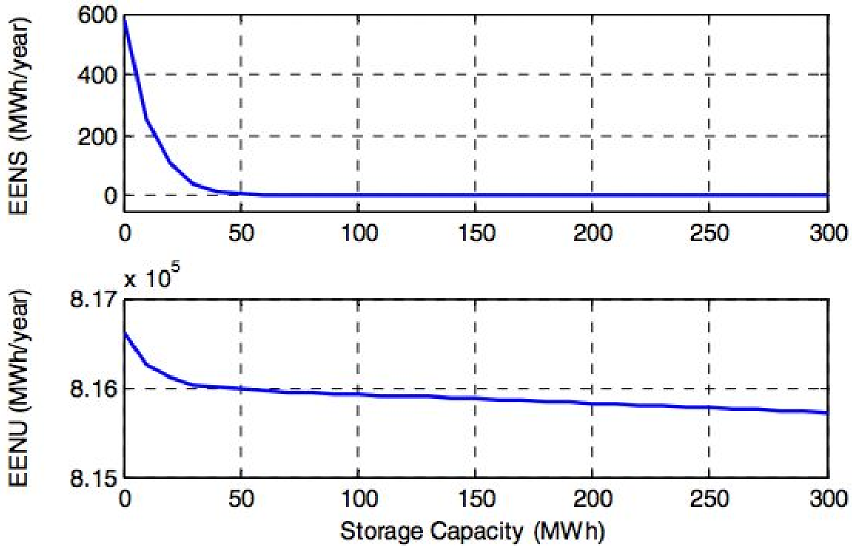


Figure 11 - Impact of storage capacity on EENS and EENU with increased load - Source [22]

### 1.1.4 Renewable Energy Integration

The RES integration is the idea of integrating sustainable sources in the grid. The main problem with RES is that they are intermittent and may be available when not needed (or vice versa). Moreover there are many fluctuations in the power generated by renewable sources. That's why the support of ESSs is needed and two different categories of them are identified: *time shifting* and *capacity firming*. The *time shift* application stores energy when demand is lower than generation and injects it during shortages. In this application, energy storage can be installed anywhere in the system, whether near to the source or to the load. Instead, the responsibility of the *capacity firming* application is to smooth the power and voltage output from renewable energy over a short period of time. The ESS smoothes the output and controls the ramp rate (MW/min) to eliminate rapid voltage and power swings on the electrical grid.

In order to analyze the penetration level and the effect of large-scale grid-tied wind, solar and other RES, the net load ($P_{net}$) is an important parameter to take in consideration. The characteristics of $P_{net}$ is significantly different from conventional load ($P_{load}$) which needs to be considered for operation planning of the grid. It's possible to define the following equation:

$$P_{net} = P_{load} - P_{g(non-dispatchable)}$$

where the last term is the non-dispatchable generation. This net amount of load must be supplied by dispatchable generator. With large-scale integration of wind and solar power, for example, the net load patterns change significantly as shown in Figure 12. Increasing amounts of non-dispatchable generation in grid increases the variability of net load which needs to be taken into account for the design and mechanism of the electrical grid. For an instant, when solar and wind is integrated to the grid, the net load demand reduces in the middle of the day and the highest peak shifts to the evening. [18]

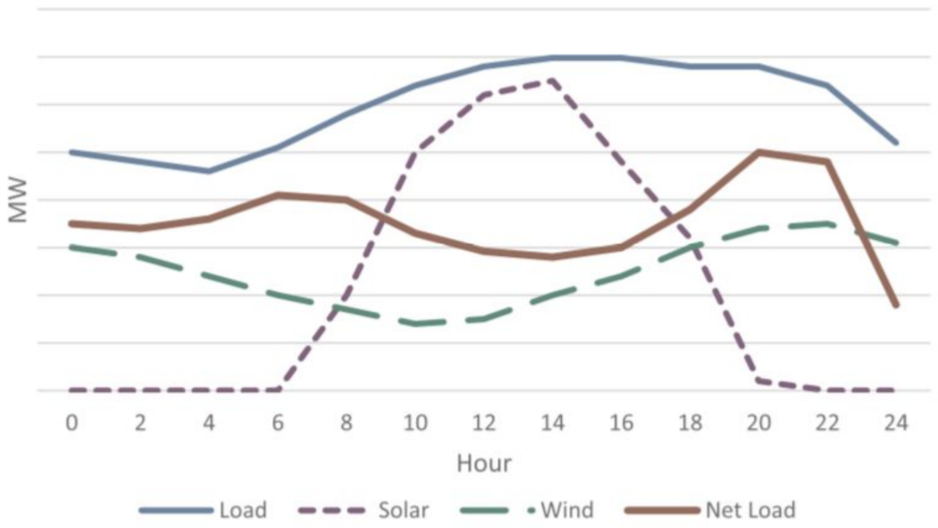


Figure 12 - Net load curve with integration of solar and wind - Source [18]

## 1.2 Economic Benefits of ESSs

All the applications of the Energy Storage Systems described above mostly results in technical benefits for the grid. Storing energy can have economic benefits as well [3]:

- It can cut costs for customers of electricity
- Off-peak electricity is cheaper compared to high-peak electricity and this is convenient for the seller ot it
- It stabilizes the electricity market price freeing the power sector from speculations and the volatility imposed by fossil fuels
- It contributes to the economic development and employment opportunities for many countries
- It overrides the need for peak generation, avoiding additional costs for generators
- It allows more efficient use of RES and off-peak generation capacity, encouraging more investment opportunities on these technologies
- It may help avoiding transmission congestion charges, which are expensive. Most utilities actually try to cut them out in a deregulated market environment

- It reduces the need for transmission and distribution capacity upgrades avoiding unnecessary investments
- It increases and improves the availability of ancillary services, reducing penalties to generators and the cost of over dimensioning infrastructures
- It allows a market-driven electricity dispatch, fostering proactive participation of the customers to secure their benefits and creates a cost sharing scheme in the power system
- It helps the environment reducing emissions and carbon cost (even though this depends on the different technology chosen)
- It is relatively inexpensive compared to an average value for power-related installations under construction today

## 1.3 Duration of the Storage

The suitability of ESS for different applications is also influenced by the duration ranges of the continuous charging and discharging of the storage system required. [12] In this respect, they can be classified as:

- Short-term storage: it's typically defined as an application where charging and discharging processes last no longer than a few minutes before power flow changes direction. Usually for this application devices with very high power capabilities are used.
- Mid-term storage (daily storage): it generally features charge and discharge times of several minutes to a number of hours. Generally Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES) and all types of electrochemical energy storage systems are suitable for this type of storage (as Chapter 2 and 3 will show).
- Long-term storage (or seasonal storage): it usually stores energy over periods of weeks and months. It is typically achieved using power-to-gas converters in combination with gas storage systems or large mechanical storage systems such as PHS and CAES. Additionally, redox flow batteries and NaS batteries may be

able to deliver reasonable weekly storage as their energy-related investment cost declines.

## 1.4 Efficiency of ESS

Energy storage consists of three different steps [1]:

- Charge: absorbing electrical energy from sources
- Storage: converting electrical energy to other types of energy and storing it
- Discharge: injecting the stored electrical energy back into the system

Moreover, ESS can be divided into three different parts:

- Central storage: the repository in which the energy is stored after conversion
- Power transformation: the interface between the central storage and the power system with bidirectional transfer
- Control: it uses sensors and other measuring devices to determine the level of charge or discharge of the stored energy.

Since energy storage is not an ideal energy source, but just a repository of energy, there are always losses at each step of the storage process. The energy generated by the sources given the energy delivered to the system during shortages is:

$$E_{generate} - \Delta E_{loss} = E_{out}$$

And the energy losses in this process are:

$$\Delta E_{loss} = \Delta E_{ch} + \Delta E_{st} + \Delta E_{disch}$$

A significant parameter in electrical storage is the efficiency of each step. Taking into account Figure 13, which shows the energy flow in a storage system, the efficiency of the charge step can be calculated as:

$$\eta_{ch} = \frac{E_{st}}{E_{ch}}$$

The storage period can be expressed as:

$$\eta_{st}(t) = \frac{E_{st}^{*}}{E_{st}}$$

It should be noted that the energy losses and also the efficiency of the storage depend on the storage time: for this reason, the time $t$ between charging and discharging need to be considered. Finally, the discharge step can be obtained:

$$\eta_{disch}(t) = \frac{E_{st}^{*}}{disch}$$

Moreover, the total energy storage efficiency ( $\eta_{st}^{total}$ ) is:

$$\eta_{st}^{total} = \frac{E_{out}}{E_{generate}} = \eta_{ch} \times \eta_{st}(t) \times \eta_{disch}$$

In these equations and Figure 13, the losses of energy are shown by $\Delta E_{loss}$ and the energy losses during storage, charge and discharge are presented as $\Delta E_{st}$ , $\Delta E_{ch}$ and $\Delta E_{disch}$ respectively. The stored energy in the central part, represented by $E_{st}$ and $E_{st}^{*}$ , is the existing energy from this part. $E_{generate}$, $E_{out}$ , $E_{ch}$ and $E_{disch}$ are the generated, output, charging and discharging energy respectively. The efficiencies of charging, discharging and storage are represented by $\eta_{ch}$ , $\eta_{disch}$ and $\eta_{st}$ .

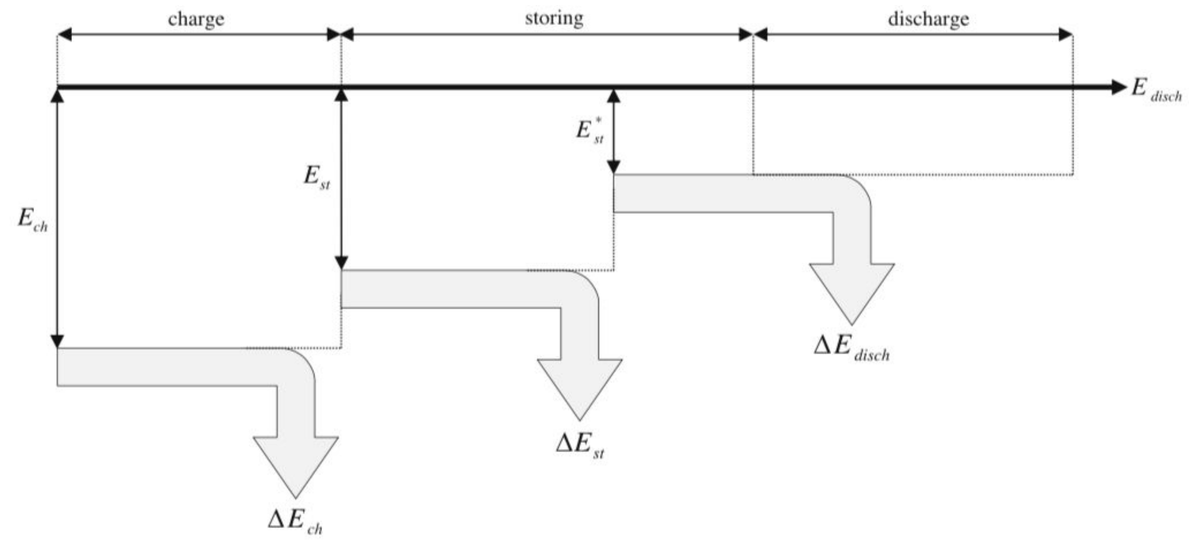


Figure 13 - Energy equilibrium in ESS - Source [1]

## 1.5 The Location and Characteristics of Each ESS

As Figure 14 shows, each Energy Storage System according to its application is placed in a specific area of the grid, where the abbreviations HV, MV and LV stand for high, medium and low voltage. From the figure it's important to point out how applications such as *energy arbitrage, frequency regulation, load following and RES integration* are obviously set at a high voltage since they are regulated at production level. Applications that regard *power quality and reliability, voltage support and peak shaving* at medium and low voltage, mainly because they mostly affect end-users.

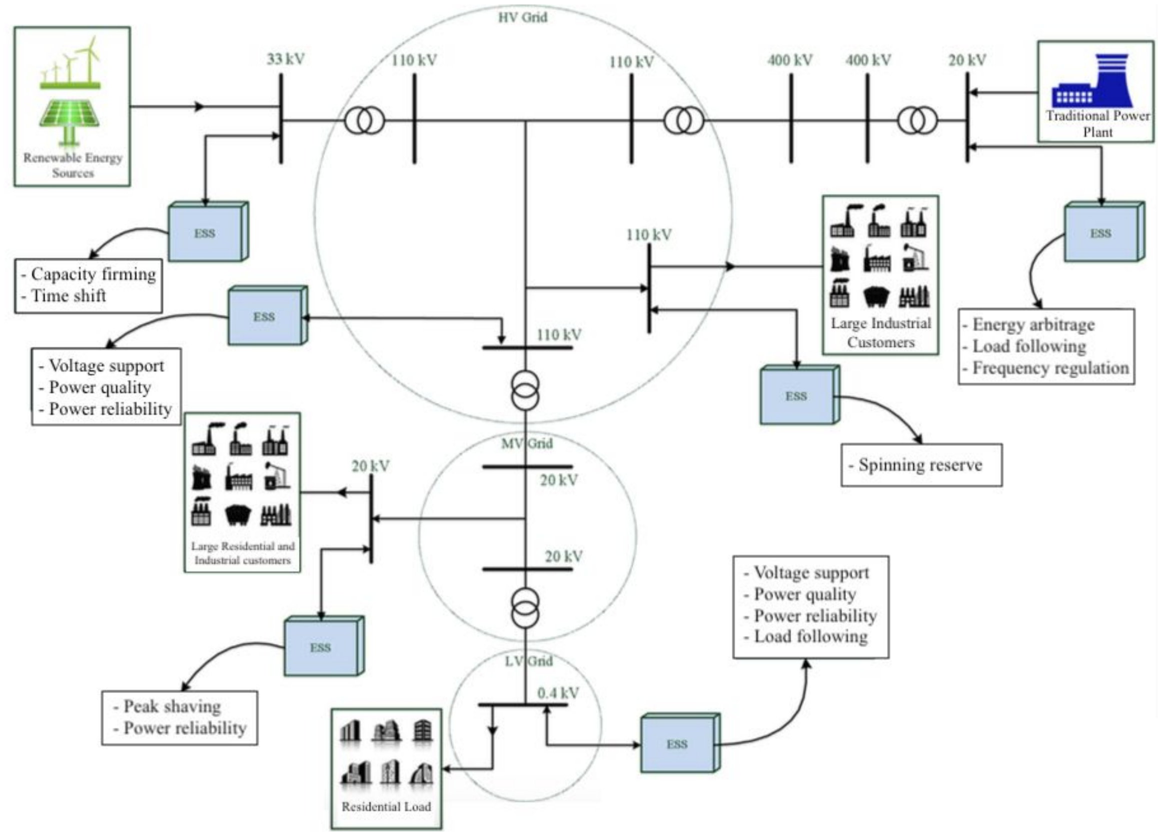
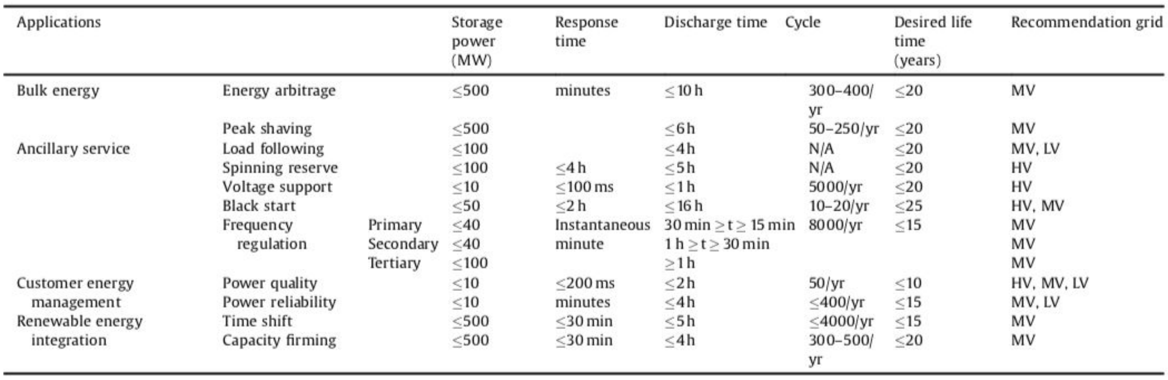


Figure 14 - Location of each ESS application in the power system - Source [1]

Figure 15 gives details about the characteristics of each energy storage application in modern grids.



| Applications | | | Storage power (MW) | Response time | Discharge time | Cycle | Desired life time (years) | Recommendation grid |
|---|---|---|---|---|---|---|---|---|
| Bulk energy | Energy arbitrage | | ≤500 | minutes | ≤10 h | 300–400/yr | ≤20 | MV |
| | Peak shaving | | ≤500 | | ≤6h | 50–250/yr | ≤20 | MV |
| Ancillary service | Load following | | ≤100 | | ≤4h | N/A | ≤20 | MV, LV |
| | Spinning reserve | | ≤100 | ≤4 h | ≤5h | N/A | ≤20 | HV |
| | Voltage support | | ≤10 | ≤100 ms | ≤1 h | 5000/yr | ≤20 | HV |
| | Black start | | ≤50 | ≤2 h | ≤16 h | 10–20/yr | ≤25 | HV, MV |
| | Frequency regulation | Primary | ≤40 | Instantaneous | 30 min ≥ t ≥ 15 min | 8000/yr | ≤15 | MV |
| | | Secondary | ≤40 | minute | 1 h ≥ t ≥ 30 min | | | MV |
| | | Tertiary | ≤100 | | ≥1 h | | | MV |
| Customer energy management | Power quality | | ≤10 | ≤200 ms | ≤2h | 50/yr | ≤10 | HV, MV, LV |
| | Power reliability | | ≤10 | minutes | ≤4h | ≤400/yr | ≤15 | MV, LV |
| Renewable energy integration | Time shift | | ≤500 | ≤30 min | ≤5h | ≤4000/yr | ≤15 | MV |
| | Capacity firming | | ≤500 | ≤30 min | ≤4h | 300–500/yr | ≤20 | MV |

Figure 15 - Characteristics of Energy Storage Applications in Modern Grids - Source [1]

Figure 16 also gives a general view of the distribution of energy storage systems according to their main applications.

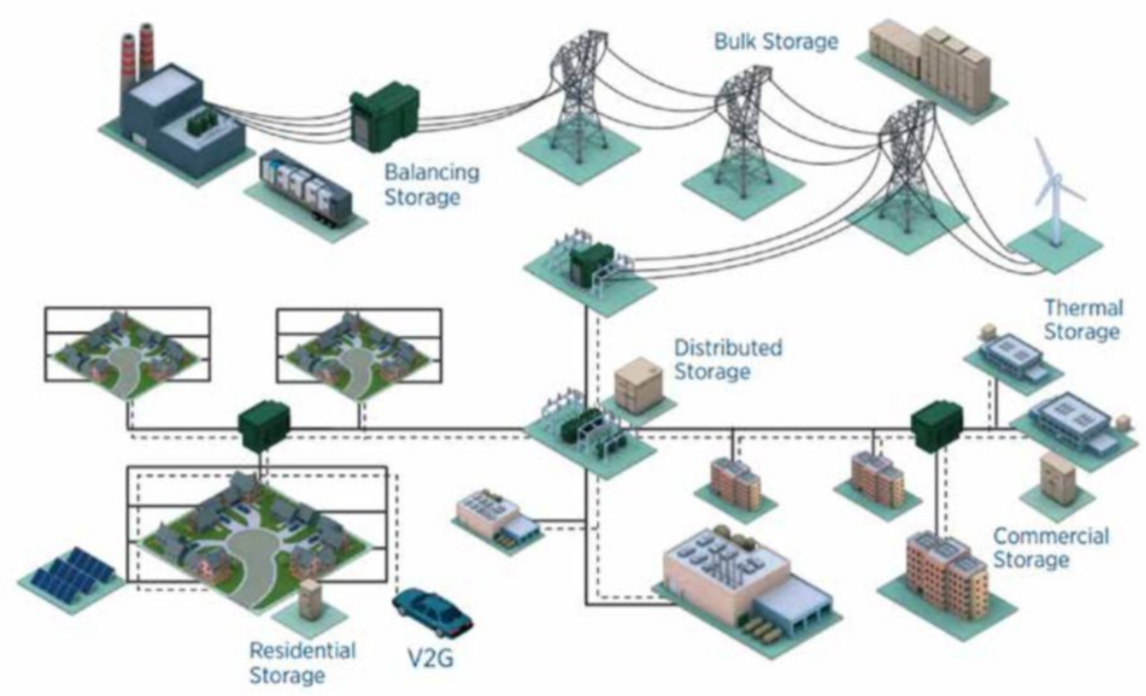


Figure 16 - Potential locations and applications of electricity storage in the power system - Source [12]

# Chapter 2 - Li-Ion Battery and Flywheel

Five main types of Energy Storage Technologies can be identified:

- Electrochemical Storage
- Mechanical Storage
- Electrical Storage
- Thermal Storage
- Chemical Storage

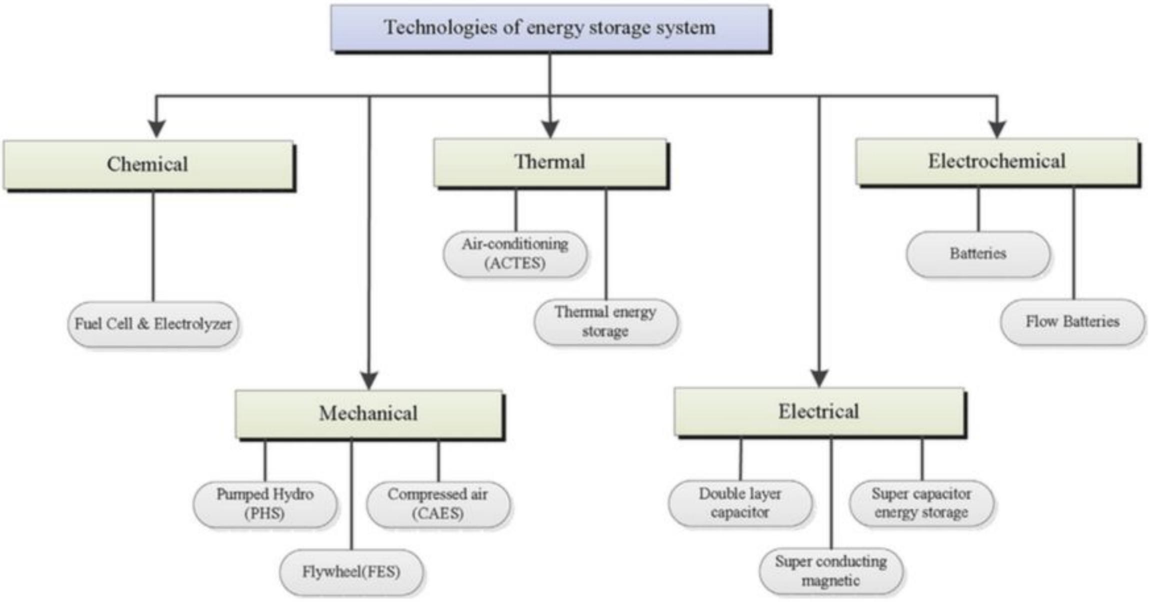


Figure 17 - Classification of ESS Technologies - Source [1]

In this thesis the attention will be focused on Electrochemical and Mechanical Systems such as batteries, in particular lithium-ion, and flywheels combined together in order to create a Hybrid Energy Storage System (HESS) able to achieve specific requirements and improve the grid performance.

[2] states that electrochemical batteries are the third most developed storage technology with 1.63 GW global power capacity, followed by electromechanical storage with 1.57 GW global installed power capacity. Lithium-ion batteries account for the largest share

of the installed power capacity with 1.12 GW in operation. Regarding the electromechanical storage, flywheels are one of the most developed technologies with storage capacities of 930 MW.

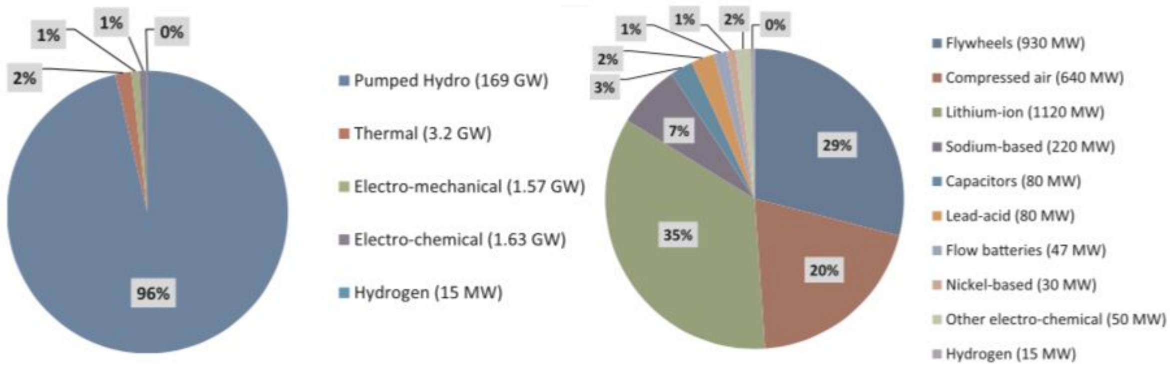


Figure 18 - Global Energy Storage Power Capacity until 2017 - Source [2]

## 2.1 Li-Ion Battery

Storage batteries are rechargeable electrochemical systems used to store energy. They are called secondary batteries, as primary ones are not rechargeable, and are the ones used for power grid applications. They both deliver the chemical energy generated by electrochemical reactions in the form of electric energy. [9]

Secondary batteries can be further classified into conventional (or Battery Energy Storage Systems BESSs) and flow batteries. Conventional storage batteries that are used extensively today include lead-acid batteries, nickel-based batteries, high temperature (sodium-based/sulfur) batteries and the lithium-ion batteries. [12]

| Lithium-ion Batteries | Lead-acid Batteries | High-temperature Batteries | Nickel-based |
|---|---|---|---|
| NMC/LMO<br>NCA<br>LFP<br>LTO | Flooded<br>VRLA | NaNiCl<br>NaS | NiCd<br>NiMH<br>NiFe |

Figure 19 - Types of Conventional Batteries - Source [12]

A graphic representation of a BES system is shown in Figure 20. It's a composition of cells and groups of cells (packs), connected in series and/or parallel combination to increase their power capacity in order to be compatible with different applications, a control system, a power conditioning system (PCS) and protection devices.

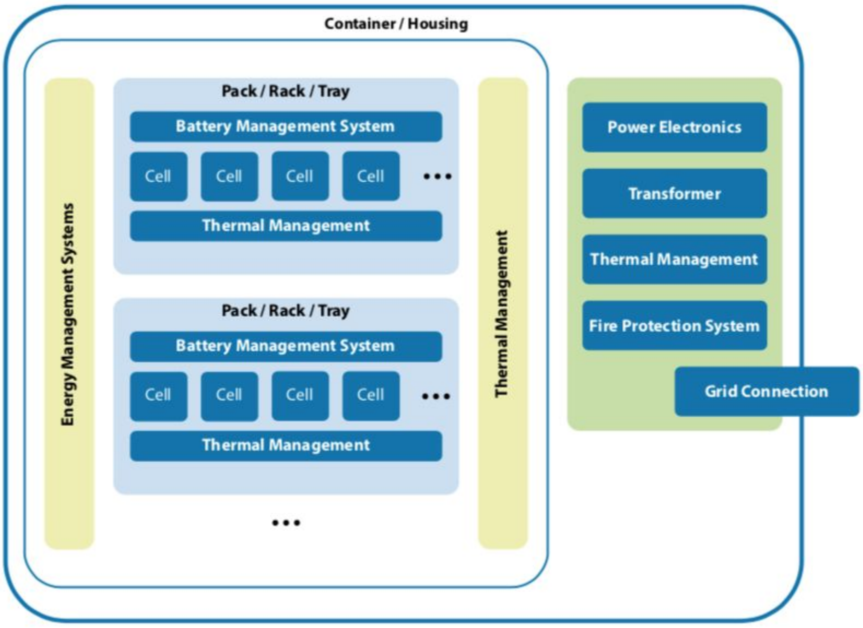


Figure 20 - Scheme of the different components of the BESS - Source [12]

In this thesis, Li-ion batteries are analyzed in detail and in comparison with other types of BESSs, resulting in a critical description that will explain the choice of this particular battery storage system among all the others.

### 2.1.1 General Description of the Li-ion Battery

Lithium-ion batteries, first proposed in the 1960s, came into reality when Bell Labs developed a workable graphite anode to provide an alternative to lithium metal. [13] The first commercial Li-ion batteries were produced by Sony in 1991 and the demand for these has grown exponentially in several markets. [2] The cathode is composed of a lithium metal oxide ($LiCoO_2$, $LiMn_2O_4$, $LiFePO_4$...) and the anode is made of graphitic carbon (C). Despite the fact that earlier polymer electrolytes were designed in the 1970s and are still being improved on, the most common electrolyte used is generally a non-aqueous liquid organic solvent mixed with dissolved lithium salts, such as $LiClO_4$. When the battery is charged, the lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited between the carbon layers as lithium atoms. This process is reversed during the discharge. The chemical reactions of the Li-ion battery with, for example, lithium cobalt oxide cathode ($LiCoO_2$) are:

Anode: $LiC_6 \rightleftharpoons Li+ \ + e^- + 6C$

Cathode: $CoO_2 \ + Li+ \ + e^- \rightleftharpoons LiCoO_2$

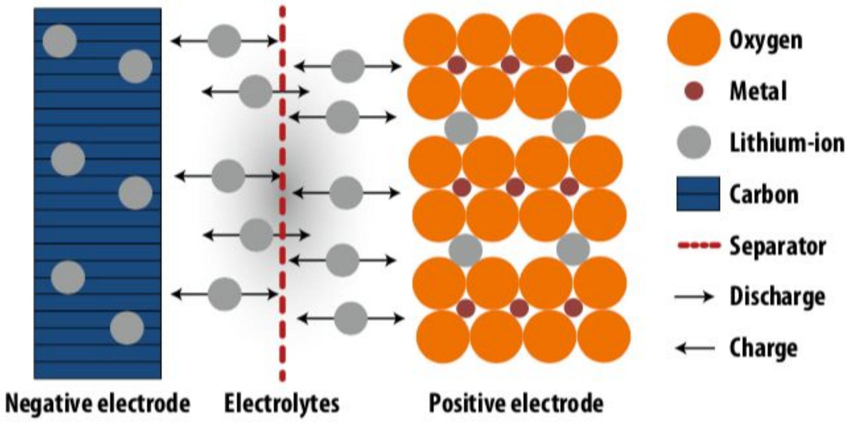


Figure 21 - Main Components of a Li-ion Battery - Source [12]

### 2.1.2 Types of Li-Ion Batteries

While Li-ion batteries are often discussed as a homogeneous group, this is far from reality. The various material combinations (i.e. chemistries or sub-chemistries) of the Li-ion Battery Energy Storage System (BESS) yield unique performance, cost and safety characteristics. The chemistry choice often relates to the desire to optimise the BESS to meet various performances or operational objectives, and such considerations may lead to a different electrode (or electrolyte) material selection. For example, some Li-ion BES systems may be designed for applications where high power or high energy density is required, while for other applications prolonged calendar life or the lowest capital cost possible may be the goal. Each set-up has its own economical, electric performance and safety characteristics.

In terms of materials, graphene has been considered a promising substance that will bring improvements in their performance. It's flexible, almost transparent, lightweight, environmentally friendly and the most impermeable and strongest material ever tested. By adding graphene to the anode the overall performance improves and its energy density and cycle life increase. Moreover, many other characteristics of the battery can be enhanced incorporating hybrid material with graphene at the cathode: faster charge and discharge, increase of the battery's storage capacity, improvement of the charging time and decrease of its weight. In general, the current research for the Li-ion battery focuses on the possible increase of the power capability with the use of nanoscale materials and the enhancement of the battery specific energy by developing advanced electrode materials and electrolyte solutions. [5]

It's possible to identify five main types of Li-ion batteries suitable for stationary applications [12]:

- Lithium nickel manganese cobalt oxide (NMC)
- Lithium manganese oxide (LMO)
- Lithium nickel cobalt aluminium (NCA)
- Lithium iron phosphate (LFP)
- Lithium titanate (LTO)

Given that lithium cobalt oxide (LCO) batteries are not typically used in the stationary applications market, they are not discussed here.

#### 2.1.2.1 Lithium Nickel Manganese Cobalt Oxide (NMC)

The Nickel-Manganese-Cobalt cells have as anode $LiNi_xMn_yCO_{1-x-y}O_2$ and cathode the usual $C\ (graphite)$ and they are a common choice for stationary applications, as well as the electromobility sector. They emerged as a way to reduce the high costs of LCO cells by combining cobalt with less expensive metals while still maintaining structural stability. It's a layered crystal-structural material generally composed by equal parts of nickel, cobalt and manganese (1/1/1) but structures with different ratios are present as well: (5/3/2) and (4/4/1). The NMC cathode material provides a good combination of energy, power and cycle life and actually has better thermal stability than LCO cells due to its lower cobalt content. They can operate at high voltages but unfortunately they encounter patent issues in some countries.

### 2.1.2.2 Lithium Manganese Oxide (LMO)

LMO cells are composed by a $LiMn_2O_4$ and graphite. They have high power capabilities and have the advantage of relying on manganese, which is about five times less expensive than cobalt. Their three-dimensional spinel crystal structure favours the positive Li+ ion flow which provides the LMO cells with high-current discharging capabilities. However, this type of cells has lower energy performance and only moderate life cycle properties, that's why usually LMO cells are not the best solution for stationary applications. Instead, a blend of NMC and LMO cells is preferred: it's a combined BESS that provides balance between performance and cost.

### 2.1.2.3 Lithium Nickel Cobalt Aluminium (NCA)

Another progression of LCO cells are the ones that use nickel instead of cobalt, maintaining the same crystal structure. These cells, based on lithium nickel oxide, benefit from higher energy density and lower costs compared to the early cobalt-based structures. They also present a good power capability as well as a long storage calendar life. Unfortunately, they are likely to have lithium diffusion issues even though their thermal stability is comparable to LCO cells. That's why small quantities of aluminium are added in order to improve their electrochemical and thermal stability properties, while still maintaining their benefits. These advantages have led to the rise of lithium cobalt aluminium (NCA) battery chemistries, mostly used in the mobility market (e.g. notably in Tesla Motors EVs). NCA cells tend to rely on a nickel cobalt aluminium cathode ($LiNiCoAlO_2$) with 5% aluminium doping. They have higher energy density than NMC cells with the additional advantage that aluminium increases performance and is more cost effective than cobalt. Their main drawback is the fact that operating with higher voltage leads to a degradation of the electrolyte of these cells but a solution of this problem may create an increased presence of NCA cells in other applications beyond mobility. Moreover, their capacity can fade at temperature between 40° and 70°C.

### 2.1.2.4 Lithium Iron Phosphate (LFP)

The olivine crystalline structure of the LFP chemistry with $LiFePO_4$ as the cathode ensures better thermal stability compared to other Li-ion cells and, while they still require single-cell management systems, they may be marketed as “inherently safe”. LFP cells have relatively high power capability, low costs, the environmental advantage of an inexpensive and non-toxic cathode material and a long lifetime. These properties, as well as a relative low discharge rate, makes LFP BESS a very attractive technology for stationary applications. Suddenly, the iron phosphate in the cell leads to a lower-rate cell voltage and, hence, lower achievable energy density due to the lower electrical and ionic conductivity of the material structure. A way to reduce such impacts is to bring the material particle size to a nano dimension and improve particle conductivity through carbon coating. In addition, doping metals such as vanadium or titanium may results in increased performances of the LFP cell.

### 2.1.2.5 Lithium Titanate LTO

In the LTO cell, the anode is no more made out of carbon $C$ but $Li_4Ti_5O_{12}$ and the cathode can vary: this can bring some advantages that can be relevant in stationary applications. In particular, it shows benefits in terms of power and chemical stability and the increased ion agility enables fast charging (i.e. high rate operation). It’s also very stable thermally in the charge and discharge states. Unfortunately, due to the higher reference potential of titanate compared to graphite, the cell voltage is reduced to approximately 2-2.5 V from the general rate of 3.7 V, which implies a lowering of its maximum energy density, although it is still higher than lead acid and nickel-cadmium batteries. Despite its lower energy density restriction, LTO is safer compared to other Li-ion technologies since the anode high potential prevents issues that relate to electrolyte material decomposition, which can result in the growth or breakdown of the solid electrolyte interphase and its related tendency to overheat and see capacity fade and other ageing issues. This is a significant advantage since solid electrolyte interphase challenges are the main disadvantage of all the other Li-ion technologies.

Another benefit of the high potential of the LTO anode is that even at high rates, the issue of microscopic fibres of lithium (dendrites) sprouting onto the anode surface does not occur. These properties make the LTO the most durable Li-ion technology so far and extremely high cycle lifetimes of 20,000 equivalent full cycles or more can be reached. Due to a low worldwide production volume, however, cell prices remain high.

Figure 22 summarizes the features of all the typologies of the Li-ion battery.

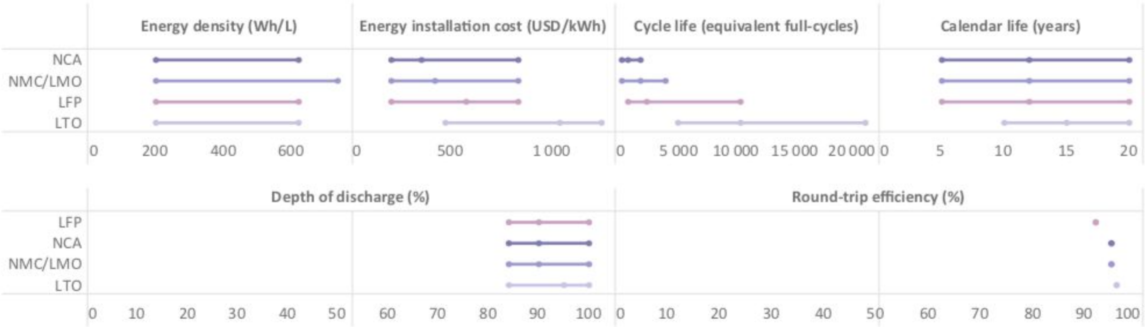
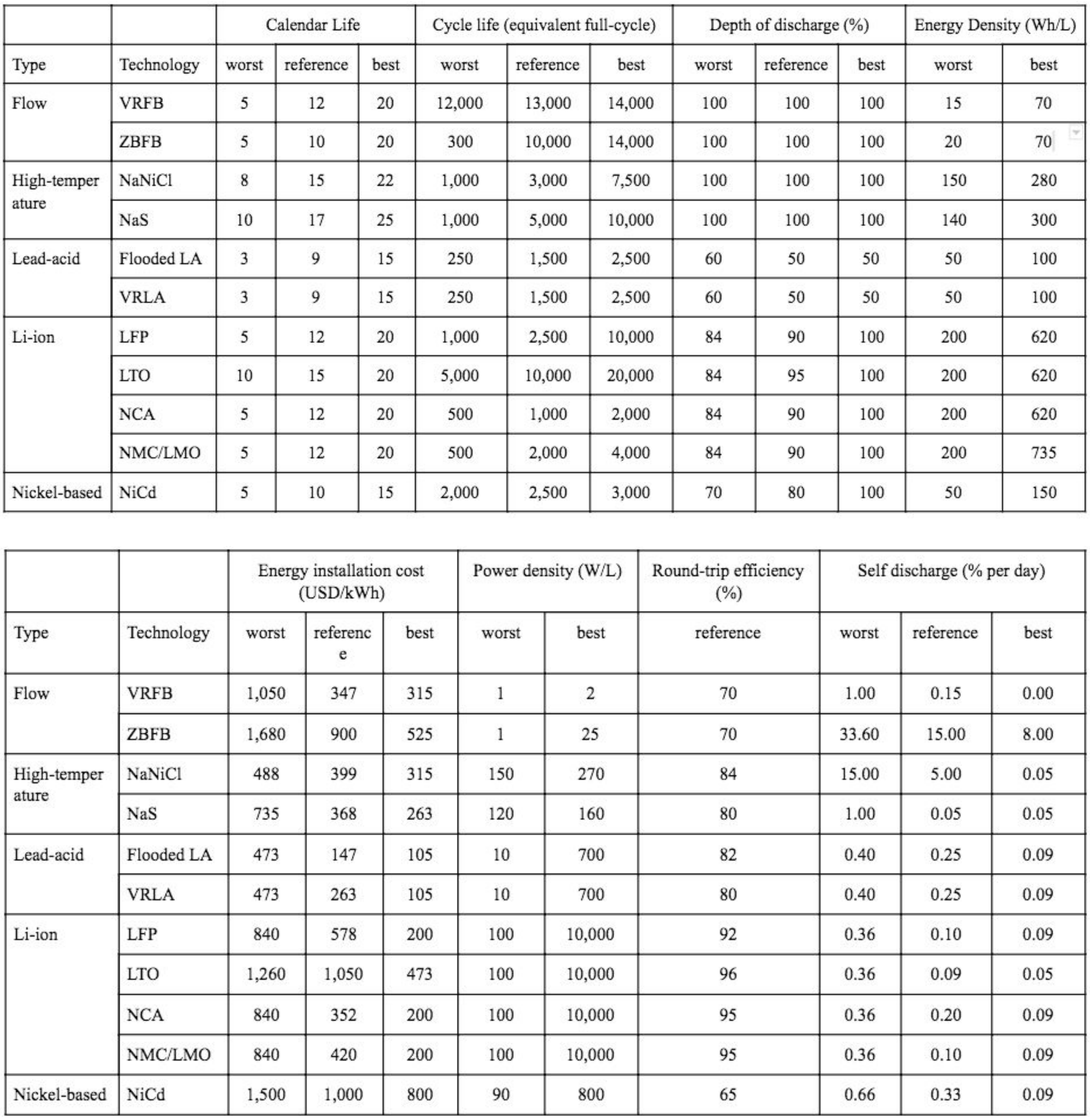


Figure 22 - Properties of selected chemistries of Li-ion ESS - Source [12]

### 2.1.3 Properties of the Li-ion Battery

Lithium ion cells have a nominal voltage of around 3.7 V at 25°C. [2] They present a high energy density (200-620 Wh/L) compared to any other type of BESS and flow batteries and high power density (100-10,000 W/L). In terms of specific energy and specific power, they are accounted to be 80-200 Wh/kg and 500-2,000 W/kg. Great energy efficiency (92-97%), low self-discharge rate (<5%/month) and extremely low maintenance required. Lithium-ion batteries have a fast response time (<5ms), wide operating temperatures (-20 to 65°C for discharge) and more than 1,000-10,000 life cycles, in some cases even 20,000. Figure 23 with data from [12] sums up all these qualities and compared them with the ones from other batteries, including the flow type.



| | | Calendar Life | | | Cycle life (equivalent full-cycle) | | | Depth of discharge (%) | | | Energy Density (Wh/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type | Technology | worst | reference | best | worst | reference | best | worst | reference | best | worst | best |
| Flow | VRFB | 5 | 12 | 20 | 12,000 | 13,000 | 14,000 | 100 | 100 | 100 | 15 | 70 |
| | ZBFB | 5 | 10 | 20 | 300 | 10,000 | 14,000 | 100 | 100 | 100 | 20 | 70 |
| High-temperature | NaNiCl | 8 | 15 | 22 | 1,000 | 3,000 | 7,500 | 100 | 100 | 100 | 150 | 280 |
| | NaS | 10 | 17 | 25 | 1,000 | 5,000 | 10,000 | 100 | 100 | 100 | 140 | 300 |
| Lead-acid | Flooded LA | 3 | 9 | 15 | 250 | 1,500 | 2,500 | 60 | 50 | 50 | 50 | 100 |
| | VRLA | 3 | 9 | 15 | 250 | 1,500 | 2,500 | 60 | 50 | 50 | 50 | 100 |
| Li-ion | LFP | 5 | 12 | 20 | 1,000 | 2,500 | 10,000 | 84 | 90 | 100 | 200 | 620 |
| | LTO | 10 | 15 | 20 | 5,000 | 10,000 | 20,000 | 84 | 95 | 100 | 200 | 620 |
| | NCA | 5 | 12 | 20 | 500 | 1,000 | 2,000 | 84 | 90 | 100 | 200 | 620 |
| | NMC/LMO | 5 | 12 | 20 | 500 | 2,000 | 4,000 | 84 | 90 | 100 | 200 | 735 |
| Nickel-based | NiCd | 5 | 10 | 15 | 2,000 | 2,500 | 3,000 | 70 | 80 | 100 | 50 | 150 |

| | | Energy installation cost (USD/kWh) | | | Power density (W/L) | | Round-trip efficiency (%) | Self discharge (% per day) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Type | Technology | worst | reference | best | worst | best | reference | worst | reference | best |
| Flow | VRFB | 1,050 | 347 | 315 | 1 | 2 | 70 | 1.00 | 0.15 | 0.00 |
| | ZBFB | 1,680 | 900 | 525 | 1 | 25 | 70 | 33.60 | 15.00 | 8.00 |
| High-temperature | NaNiCl | 488 | 399 | 315 | 150 | 270 | 84 | 15.00 | 5.00 | 0.05 |
| | NaS | 735 | 368 | 263 | 120 | 160 | 80 | 1.00 | 0.05 | 0.05 |
| Lead-acid | Flooded LA | 473 | 147 | 105 | 10 | 700 | 82 | 0.40 | 0.25 | 0.09 |
| | VRLA | 473 | 263 | 105 | 10 | 700 | 80 | 0.40 | 0.25 | 0.09 |
| Li-ion | LFP | 840 | 578 | 200 | 100 | 10,000 | 92 | 0.36 | 0.10 | 0.09 |
| | LTO | 1,260 | 1,050 | 473 | 100 | 10,000 | 96 | 0.36 | 0.09 | 0.05 |
| | NCA | 840 | 352 | 200 | 100 | 10,000 | 95 | 0.36 | 0.20 | 0.09 |
| | NMC/LMO | 840 | 420 | 200 | 100 | 10,000 | 95 | 0.36 | 0.10 | 0.09 |
| Nickel-based | NiCd | 1,500 | 1,000 | 800 | 90 | 800 | 65 | 0.66 | 0.33 | 0.09 |

Figure 23 - Summary of batteries characteristics - Source [12]

Flow batteries have much lower energy density, power density and efficiency in general than any other type of Li-ion batteries, but they have the advantage of operating at close to ambient temperatures and are able to independently scale their energy and power characteristics. Furthermore, although they present at the moment high upfronts investment costs compared to other technologies, these batteries often exceed 10,000 full cycles, enabling them to make up for the high initial cost through very high lifetime energy throughputs. Their long-term electrolyte stability, however, is the key to this longevity. High-temperature batteries (sodium sulphur and sodium nickel chloride batteries) have relatively high energy density, higher than flow, lead-acid batteries and nickel-based batteries but at the low end of Li-ion batteries as shown in Figure 24 and Figure 25. They also are not made out of toxic materials. Corrosion issues though are a major ageing mechanism of high-temperature cells. Nickel-based batteries have a quite high power density compared to lead-acid, high-temperature and flow batteries but it’s still lower than the lithium-batteries as well as in terms of energy density. Efficiency is another parameter where Li-ion cells excel.

Lithium-ion batteries’ high power and energy density (as shown in Figure 24) explain, in part, their use and consideration for a wide variety of applications, such as portable applications, electromobility and as stationary storage devices to support the grid.

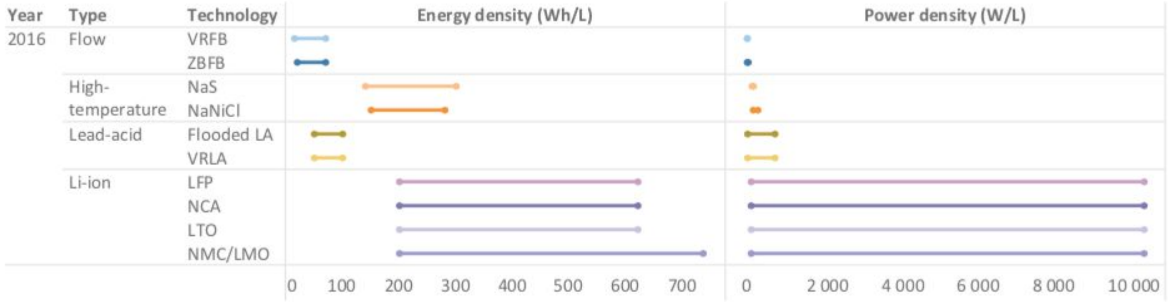


Figure 24 - Energy and power density of batteries - Source [12]

The Li-ion battery is considered as a good candidate for applications where the response time, small dimension (Figure 25 shows how they tend to have reduced storage volume) and/or weight of equipment are important.

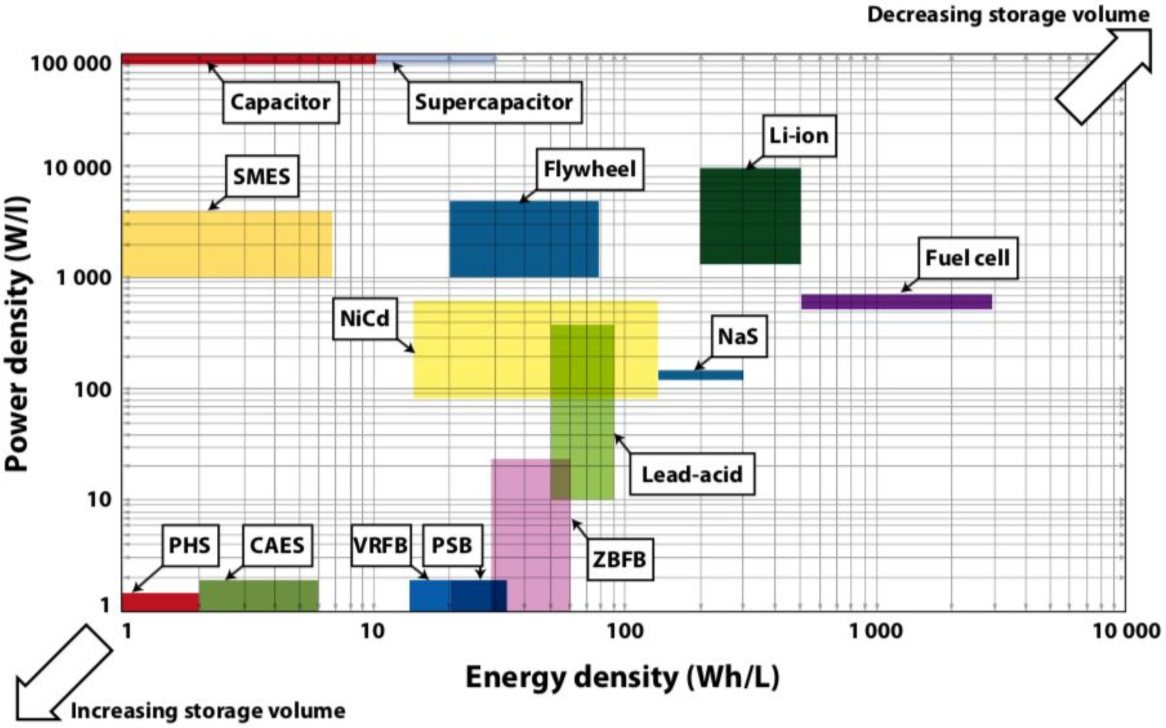


Figure 25 - Comparison of energy density and power density for selected energy storage technologies - Source [12]

Li-ion cells' main disadvantages regard their lifetime which depends on temperature and so their performance can decrease at high thermal grades, ranging between 5 and 20 years. A protective circuitry is needed as well as a monitoring unit to avoid over-charging and discharging since they can present some safety issues due to the metal oxide electrodes; they can decomposed at raised temperatures, releasing oxygen and thermal energy. [2] This increases the overall cost of the battery. In general, every temperature increase of approximately 10°C over the design operating temperature lowers the calender lifetime by 50%. This is because the rate of unwanted chemical reaction inside the battery increases with temperature, degrading the cells and resulting in reduced battery cycle life. The best lifetime performance for most Li-ion batteries is achieved at moderate temperatures of between 20°C and 30°C. In hot climates, this means that cooling of the battery storage location is often necessary. At the other extreme, operation at very low (e.g. below zero °C temperatures) may lead to severe power loss. [12]

In terms of energy installation cost they present higher numbers compared to the other batteries: it ranges between USD 473 and 1260/kWh for LTO-based systems and between USD 200 and 840/kWh for the other chemistries. However this cost is continuously decreasing, especially benefitting the growth in scale of Li-ion battery manufacturing for electric vehicles (which is a huge market for these cells), and it’s forecasted to reduce by 54-61% by 2030 as paper [12] predicts. This would reflect a drop in the total installed cost for Li-ion batteries for stationary applications (none of these costs are referred to those used in electric vehicles) to between USD 145 per kilowatt-hour and USD 480/kWh depending on the battery chemistry.

Figure 26 shows the decrease of the installation cost of each battery by 2030 and even though Li-ion cells will still present a higher cost compared to the others they experience a greater reduction.

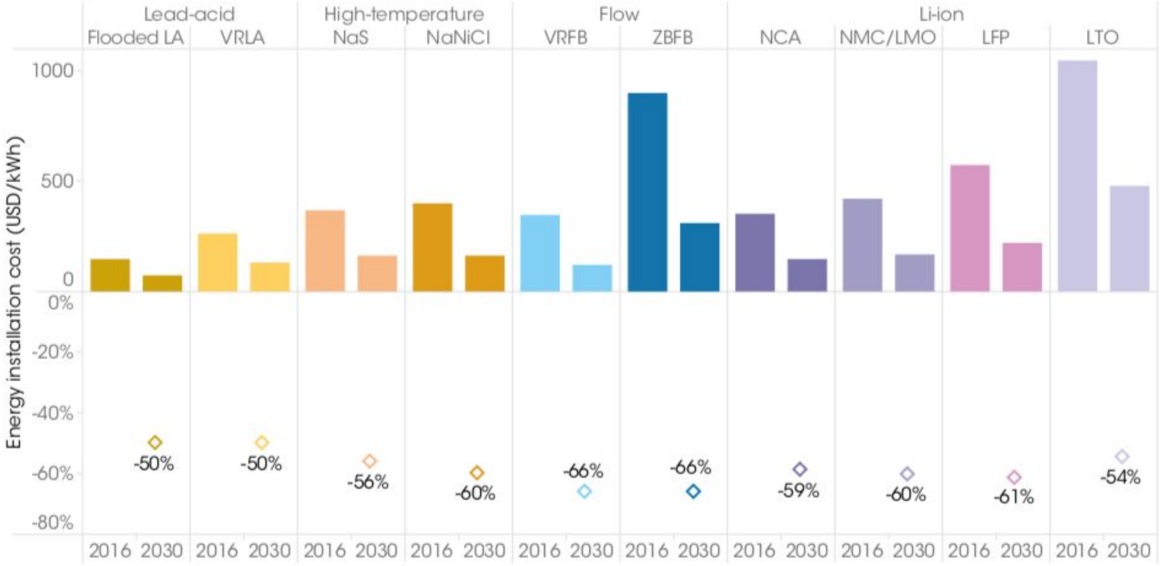


Figure 26 - BESS installed energy cost reduction potential 2016-2030 - Source [12]

It’s important to point out how the higher investment cost, especially for LTO cells, compared to other battery storage systems is not for its own sake: it actually results in a longer cycle life meaning that, considering a fixed amount of full-cycles, the overall lifetime of the battery appears to last longer.

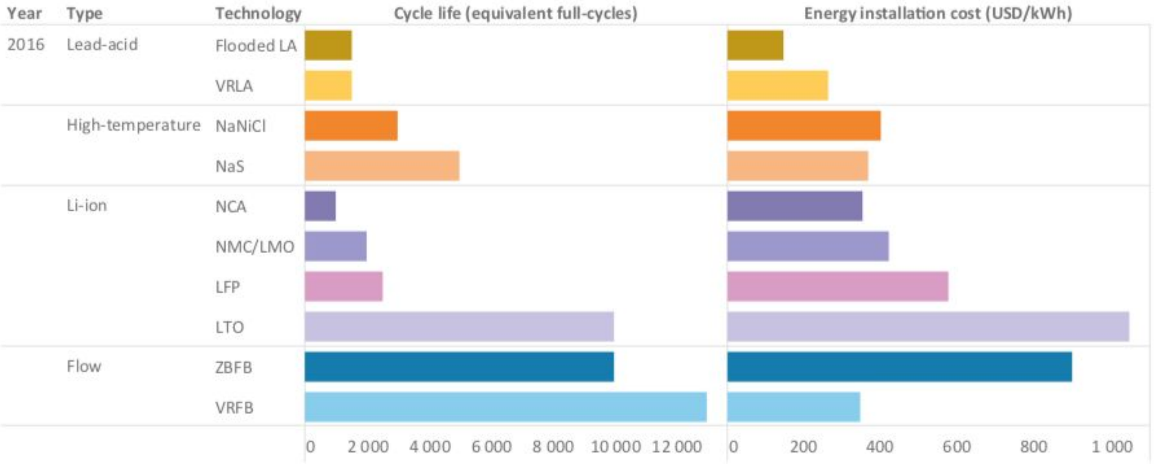


Figure 27 - Reference cycle life and energy installation cost of selected BES systems - Source [12]

As a matter of fact, Figure 28 shows how, by looking at the cost/performance (energy, life and efficiency) ratio, Li-ion batteries don't distance themselves too much from other BES systems such as lead-acid, nickel-based and also flow batteries meaning that their higher energy investment cost actually results in optimal outcomes and general results.

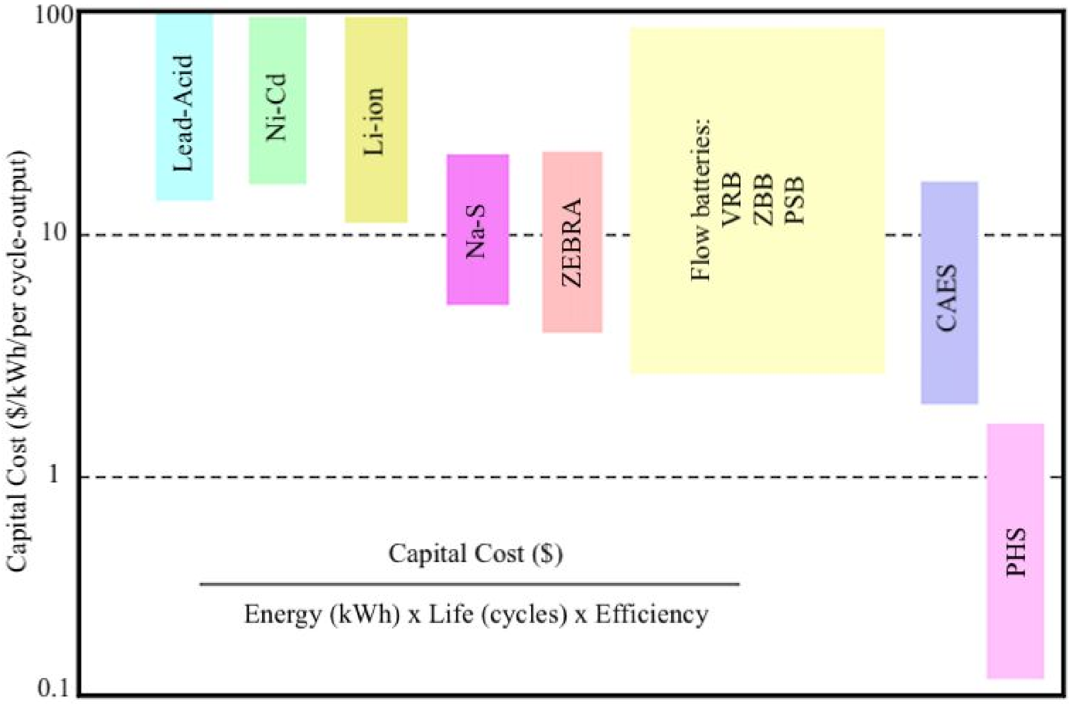


Figure 28 - Capital Cost/Performance ratio - Source [15]

The overall performance of this battery makes it a perfect match with flywheels in the construction of an hybrid energy storage system at the service of the electrical grid. Their high power and especially energy density intertwines perfectly with the flywheel's characteristics as Chapter 3 will show.

## 2.2. Flywheel Energy Storage System (FESS)

Flywheel, as the main component of the Flywheel Energy Storage System (FESS), is a rotating disk around an axis that is used as a mechanical energy storage device. Depending on the inertia and speed of the rotating mass, a given amount of kinetic energy is stored as rotational energy. [5]

The rotor is placed inside a vacuum cylindrical chamber (or in a chamber filled with helium) to eliminate friction-loss from the air and it is suspended by magnetic bearings for a stabile operation. Kinetic energy is transferred in and out of the flywheel with an electrical machine that can function either as a motor or a generator depending on the load angle (phase angle). In motor mode, electric energy supplied to the stator winding is converted to torque and applied to the rotor, causing it to spin faster and gain kinetic energy. In generator mode, kinetic energy stored in the rotor applies a torque, slowing down the flywheel, which is converted into electric energy. The faster the flywheel rotates the more energy it stores.

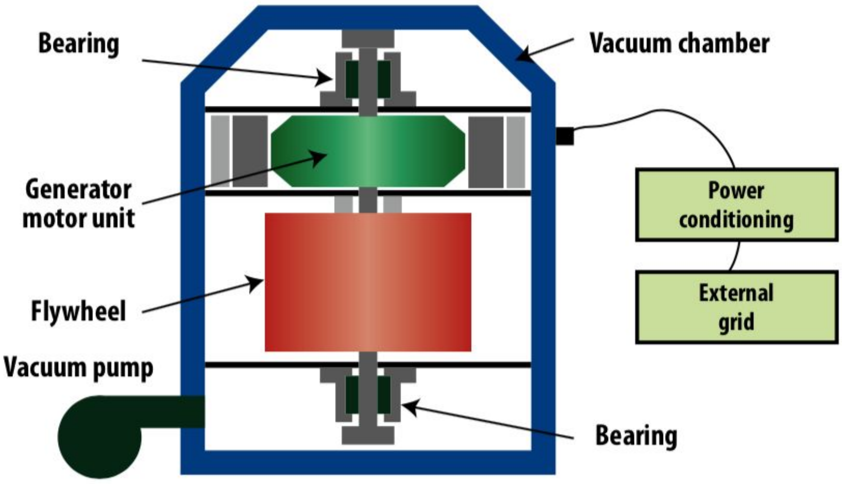


Figure 29 - Basic Structure of a Flywheel - Source [12]

The kinetic energy stored in a flywheel is proportional to the moment of inertia of the rotor and the square of its angular velocity [1]:

$$E = \tfrac{1}{2} I \omega^2 \qquad\qquad I = mr^2$$

The second equation shows that the total mass of the flywheel ( $m$ ) and the angular velocity ( $\omega$ ) squared have a direct impact on the energy stored by this device. ( $r$ ) is the radius of the disk. As the equation shows, increasing the speed of the disk is much more effective than increasing the mass of it in order to increase the energy capacity of the flywheel.

There are two types of FESS:

- low speed FESS (<10,000 rpm)
- high speed FESS (>10,000 rpm up to 100,000 rpm). [5]

Low speed flywheels are usually made of steel rotors and conventional bearings and typical specific energy achieved is around 10-30 Wh/kg; high speed ones use advanced composite materials for the rotor with ultra-low friction bearing assemblies and the specific energy can achieve 100-130 Wh/kg. Low speed FESS is typically used for short-term and medium/high power applications and is in general much more popular in industry, whilst high speed FESS is mainly used in high power quality and ride-through power service in traction and the aerospace industry.

As pointed out in [1] and [2], the main advantages of the flywheel storage system are the very low maintenance required and the fact that it can be charged and discharged at high power rates for many cycles without losing efficiency. Indeed, they have a long life, 15-20 years, capable of providing several hundreds of thousands of full charge–discharge cycles (100,000-200,000 cycles even reaching 1,000,000 in some cases [12]). Their instant response time and high power density (5,000-10,000 W/L) compared to any other storage device are the features that make them suitable for short-term/high-power applications. Energy efficiency is quoted to be between 90 and 95% . [16] No carbon emissions or toxic components involved set them as a green solution.

Figure 30 - Properties of flywheel energy storage systems - Source [12]

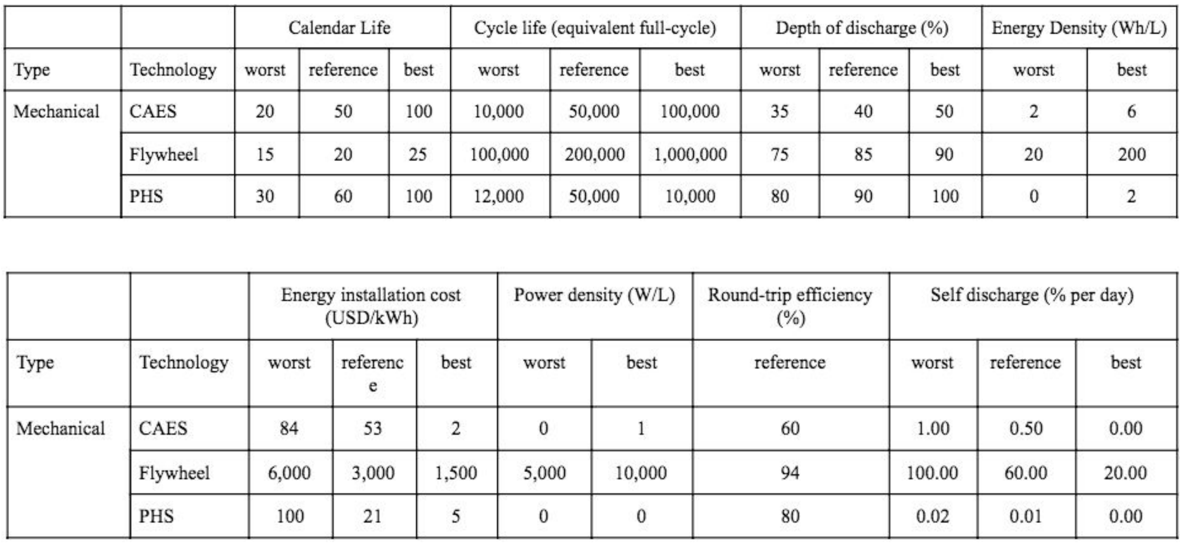
The main disadvantages regard their high energy installation cost that is between USD 1,500 and USD 6,000/kWh and the relatively high standing losses. As a matter of fact, their self discharge rate is quite solid: 3-20% of the stored capacity is lost per hour. These high rates have the effect of deteriorating energy efficiency when cycling is not continuous. The overall storage capacity is low: the range of energy storage is 0.2-25 KWh. These last few features reinforce the notion that flywheels are not an adequate device for long-term energy storage but only to provide reliable standby power. Their best outcome occurs when integrated with other storage systems. To keep in consideration the noise they make and the vibrations when working at very high speed.

There are many ongoing developments that aim to improve the performance of flywheels for energy storage. [12] The most important ones include:

- New materials with high strength and low density that can allow higher energy densities.
- Superconducting bearings that will reduce friction losses in order to increase the rotating speed and decrease self-discharge rates.
- Innovative concepts for electric machines with fewer permanent magnets that could reduce the dependency on materials such as rare earths.

This is believed to result in a reduction of energy installation costs that will get to USD 1,000 and USD 3,900/kWh as cycle and calendar lifetimes substantially improve.

Compared to any other BES system, flow battery or mechanical energy storage system, such as Compressed Air Energy Storage (CAES) and Pumped Hydro Storage (PHS), flywheels account the higher power density as Figure 23 and 31 show. This characteristic allow them to serve the grid in many aspects, as Chapter 3 will show, in a way that is not achievable by any other mechanical storage system. Only Li-ion batteries can compete with them in this feature but what mainly differentiate them is the charge/discharge sequence that, if implemented at high power rates for many cycles, can affect the efficiency and so the overall lifetime of the battery; plus flywheels present a very much lower energy density (20-200 Wh/L).



| | | Calendar Life | | | Cycle life (equivalent full-cycle) | | | Depth of discharge (%) | | | Energy Density (Wh/L) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type | Technology | worst | reference | best | worst | reference | best | worst | reference | best | worst | best |
| Mechanical | CAES | 20 | 50 | 100 | 10,000 | 50,000 | 100,000 | 35 | 40 | 50 | 2 | 6 |
| | Flywheel | 15 | 20 | 25 | 100,000 | 200,000 | 1,000,000 | 75 | 85 | 90 | 20 | 200 |
| | PHS | 30 | 60 | 100 | 12,000 | 50,000 | 10,000 | 80 | 90 | 100 | 0 | 2 |

| | | Energy installation cost (USD/kWh) | | | Power density (W/L) | | Round-trip efficiency (%) | Self discharge (% per day) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Type | Technology | worst | reference | best | worst | best | reference | worst | reference | best |
| Mechanical | CAES | 84 | 53 | 2 | 0 | 1 | 60 | 1.00 | 0.50 | 0.00 |
| | Flywheel | 6,000 | 3,000 | 1,500 | 5,000 | 10,000 | 94 | 100.00 | 60.00 | 20.00 |
| | PHS | 100 | 21 | 5 | 0 | 0 | 80 | 0.02 | 0.01 | 0.00 |

Figure 31 - Properties of all mechanical storage systems - Source [12]

Although flywheels are not yet widespread in the power industry, they are slowly penetrating the market, mostly for uninterruptible power supply, power conditioning and pulse power, and are starting to be used with RES.

# Chapter 3 - Hybrid Energy Storage System (HESS)

Hybrid Energy Storage System (HESS) refers to the integration of two or more different storage technologies into a system. This is possible by combining the characteristics and advantages of different ESSs to achieve specific requirements, improve the whole system performance and at the same time overcome the single technology's limitations producing a device that is more efficient and more robust compared to a stand-alone storage solution. A HESS is better in terms of durability, practicality and cost-effectiveness for the overall system implementation. [14]

## 3.1 Basic Parameters

### 3.1.1 High Power Density and High Energy Density

The choice of the energy storage technique depends directly on the applications. To correctly choose the perfect ESS, it is first necessary to distinguish two important parameters: energy (kWh) and power (kW). So, to design the perfect hybrid storage system, the power and the energy of the each system should be determined in the first instance. [1]

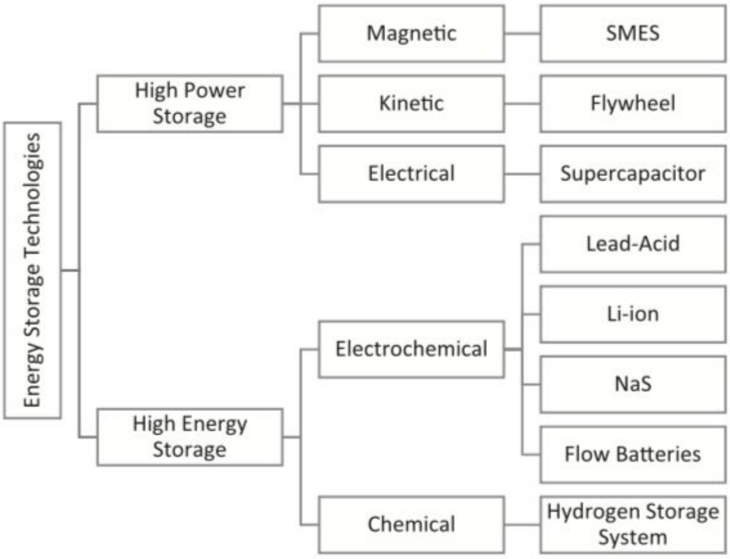


Figure 32 - Classification of ESSs - Source [14]

The idea of HESS lies on the fact that heterogeneous storage devices have complementary characteristics in terms of power and energy density [7]. High energy storage systems would help improving profitability, so it secures economic benefits to the power system stakeholders, and high power systems provide reliability, safety and productivity, characteristics that lead to technical benefits. This hybridization is proved to provide excellent characteristics not offered by a single ESS unit.

The high power device should supply short term power needs, while the high energy device should meet the long-term energy needs. In a first general explanation, we can say that flywheels provide high power for a short period of time with high efficiency and high cycle life so they are suitable for applications with rapid charge and discharge requirements whilst Li-ion batteries with their high energy density, solid capacity and low self discharge rate work as a long-term storage system. It's important to point out that Li-ion batteries can be employed either as high power or high energy devices due to their extensive characteristics range but in the case they are coupled with flywheels they act as high energy suppliers mainly in order to preserve their lifetime. Indeed, charging and discharging Li-ion batteries with high power rates for many cycles will eventually cause a faster ageing and overall a worse performance in terms of efficiency, economy and environmental impact; in fact, in stationary applications, costs and lifetime are often more important than energy density, power density or specific energy since the applications are not as volumetrically or weight constrained as mobile or portable applications.

Figure 25 in Chapter 2 shows the collocation of flywheels and Li-ion batteries in a chart as function of power density and energy density.

### 3.1.2 The Length of Discharge

Another important parameter to consider is the length of discharge [1], which can be divided into three categories: seconds-minutes, minutes-hours and hours. It is obvious that the first two categories are related to customer energy management and to the ancillary services of energy storage applications. The "hours" category can be used for long-term storage and discharge, such as for bulk energy or in RES integration applications.

Flywheels fall in the “seconds-minutes” discharge time category, Li-ion batteries in the “minutes-hours”. Figure 33 sums up the position of each storage technology as a function of the discharge time at rated power and also of the module size which is relevant too when discussing the suitability of a technology for a specific stationary application. Figure 34, instead, offers a view of all the technologies’ discharge time as a function of their rated power.

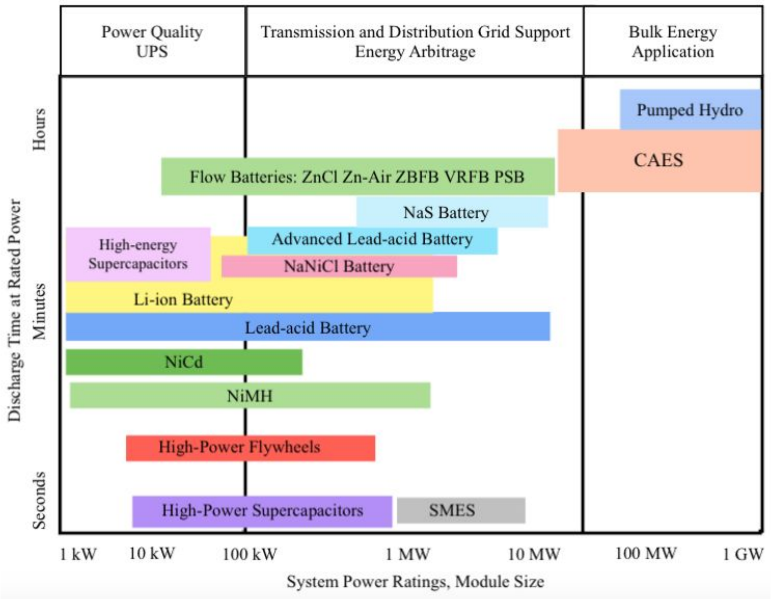


Figure 33 - Positioning of ESSs per their power rating and discharge times at rated power - Source [12]

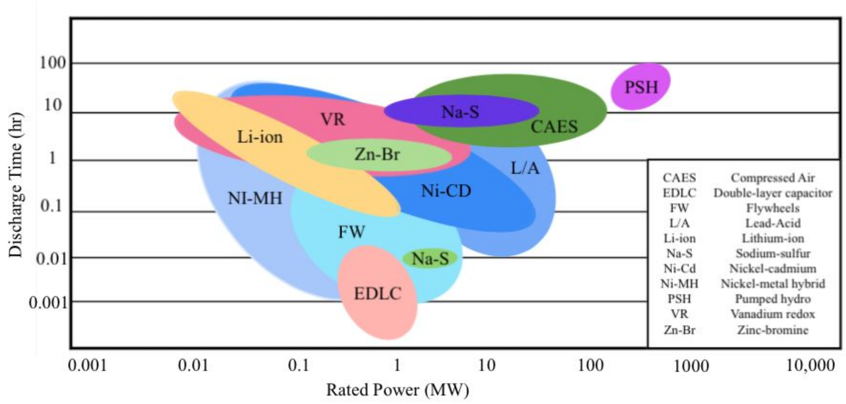


Figure 34 - Power ratings and discharge times of different technologies - Source [15]

## 3.2 Stationary Applications of the HESS

As explained in [1], Flywheel Energy Storage Systems benefit the electrical grid mainly in terms of customer energy management, in other words they assure power quality and power reliability. Indeed, high power density technologies bring improvements to the grid resilience. Ancillary service is another application of theirs as they take care of voltage support and load following, but still can be possibly applied to help with the primary frequency regulation and act as a spinning reserve. Quite important their role in transient smoothing and control of the reactive power, as well as their utility as UPS devices. This is a result of their very short discharge duration (seconds). With the integration of RES into the grid they can work as a capacity firming application. In other words, the flywheel is used for low-energy applications, emergency devices and load levelers giving an overall economic advantage.

Lithium-ion batteries are more versatile as they guarantee voltage support, frequency regulation, black start and power reliability, but still can possibly help with RES integration, power quality and load following. Overall they can support the system in ancillary service and customer energy management applications.

None of the two technologies though can act as bulk energy sources but they both cover the system in terms of voltage support and power reliability. This results into a power quality improvement.

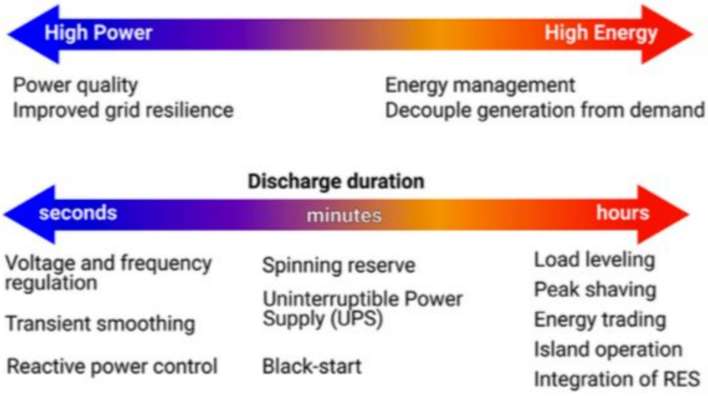
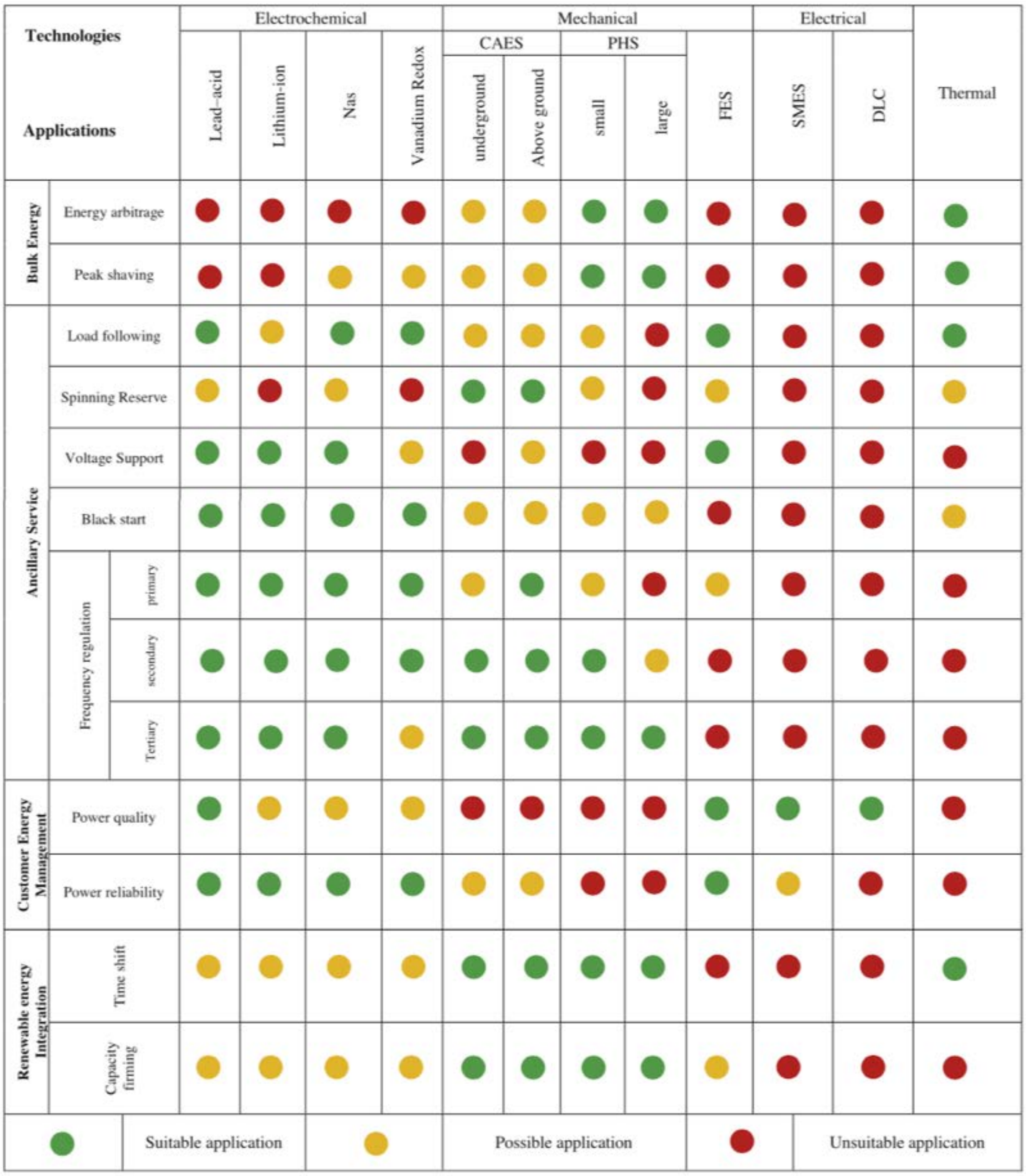


Figure 35 - EESs by the needs in energy, power and discharge duration - Source [2]

Figure 36 sums up all the applications covered by each storage device, including electrical and thermal storage technologies.



| **Technologies** / **Applications** | | | Electrochemical | | | | Mechanical | | | | | Electrical | | Thermal |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | CAES | | PHS | | | | | |
| | | | Lead-acid | Lithium-ion | Nas | Vanadium Redox | underground | Above ground | small | large | FES | SMES | DLC | |
| **Bulk Energy** | | Energy arbitrage | 🔴 | 🔴 | 🔴 | 🔴 | 🟡 | 🟡 | 🟢 | 🟢 | 🔴 | 🔴 | 🔴 | 🟢 |
| | | Peak shaving | 🔴 | 🔴 | 🟡 | 🟡 | 🟡 | 🟡 | 🟢 | 🟢 | 🔴 | 🔴 | 🔴 | 🟢 |
| **Ancillary Service** | | Load following | 🟢 | 🟡 | 🟢 | 🟢 | 🟡 | 🟡 | 🟡 | 🔴 | 🟢 | 🔴 | 🔴 | 🟢 |
| | | Spinning Reserve | 🟡 | 🔴 | 🟡 | 🔴 | 🟢 | 🟢 | 🟡 | 🔴 | 🟡 | 🔴 | 🔴 | 🟡 |
| | | Voltage Support | 🟢 | 🟢 | 🟢 | 🟡 | 🔴 | 🟡 | 🔴 | 🔴 | 🟢 | 🔴 | 🔴 | 🔴 |
| | | Black start | 🟢 | 🟢 | 🟢 | 🟢 | 🟡 | 🟡 | 🟡 | 🟡 | 🔴 | 🔴 | 🔴 | 🟡 |
| | Frequency regulation | primary | 🟢 | 🟢 | 🟢 | 🟢 | 🟡 | 🟢 | 🟡 | 🔴 | 🟡 | 🔴 | 🔴 | 🔴 |
| | | secondary | 🟢 | 🟢 | 🟢 | 🟢 | 🟢 | 🟢 | 🟢 | 🟡 | 🔴 | 🔴 | 🔴 | 🔴 |
| | | Tertiary | 🟢 | 🟢 | 🟢 | 🟡 | 🟢 | 🟢 | 🟢 | 🟢 | 🔴 | 🔴 | 🔴 | 🔴 |
| **Customer Energy Management** | | Power quality | 🟢 | 🟡 | 🟡 | 🟡 | 🔴 | 🔴 | 🔴 | 🔴 | 🟢 | 🟢 | 🟢 | 🔴 |
| | | Power reliability | 🟢 | 🟢 | 🟢 | 🟢 | 🟡 | 🟡 | 🔴 | 🔴 | 🟢 | 🟡 | 🔴 | 🔴 |
| **Renewable energy Integration** | | Time shift | 🟡 | 🟡 | 🟡 | 🟡 | 🟢 | 🟢 | 🟢 | 🟢 | 🔴 | 🔴 | 🔴 | 🟢 |
| | | Capacity firming | 🟡 | 🟡 | 🟡 | 🟡 | 🟢 | 🟢 | 🟢 | 🟢 | 🟡 | 🔴 | 🔴 | 🔴 |

| 🟢 | Suitable application | 🟡 | Possible application | 🔴 | Unsuitable application |
|---|---|---|---|---|---|

Figure 36 - Technologies vs applications - Source [1]

Being more specific, paper [12] highlights the efficiency of the main Li-ion technologies as well as the flywheels' and the most important electrochemical and mechanical ones in some particular stationary applications, highlighting their main pros and cons and possible future scenarios for these technologies. Many informations can be extracted:

- **Frequency containment reserve**: due to the very high power ability and relatively low electricity storage capability, flywheel are a natural choice for this application and have been used accordingly for many years. Since this application present constant fluctuations, the high self-discharge of flywheels is not an obstacle.

  Generally, all types of batteries are suitable to provide this service. Li-ion chemistries are well suited from a technical point of view and Li-ion BES systems have accounted for most installations in this application during the last couple of years. Even lead-acid batteries are used sometimes but in combination with other high-power storage technologies, such as Li-ion batteries or flywheels, to create cost-efficient HES systems that work well. In addition, high-temperature batteries are technically well suited to FCR and have been commercially used for many years.
- **Frequency restoration reserve**: Li-ion batteries are technically suitable for this application but, as well as lead-acid batteries, are actually uneconomic due to the high energy costs. Instead the pooling of many small installations, particularly electrical vehicles, is proposed as a technically feasible and economically interesting business concept for the near future. Similar considerations would apply for the utilisation of high-temperature batteries. Nowadays, the most used technologies for this service are PHS and CAES.
- **Load Leveling**: as the demand for load levelling usually occurs in densely built areas, large-scale storage systems such as PHS and CAES are unsuitable. Flywheel is technically perfect for this solution, even though it's not always competitive in terms of costs. Sodium sulphur batteries and high-temperature batteries are a proven technology but lead-acid and Li-ion, or even a

combination of both, are considered to be the future for this application. Actually, in a multi-use scenario (e.g. combination of frequency control, load levelling, UPS functionality) their profitability largely increase. The choice of subtechnologies will depend on the use case: if high power capabilities for short time periods (such as to boost EV charging) are required, LTO could be used; if the use case leans towards load levelling combined with for example solar self-consumption, the less expensive NMC or LFP are more likely to be used.

- **Energy Arbitrage**: energy shifting has always been the major-use case for PHS an CAES. Due to the relatively low energy cost of these storage technologies, with low discharge rate at idle they can perform optimally and economically if charged and discharged over many hours (e.g. from 4 to 40 hours is common). Flywheels are technically capable of delivering energy arbitrage services but are today still economically unsuitable due to their high energy cost compared to PHS and CAES. However, they may feature other technical advantages (modularity, fast deployment, almost no geographical constraints) that make them interesting for those applications.
- **Power quality and peak shaving**: all types of lead-acid and Li-ion batteries are well suited to both these applications due to their high power dynamics (e.g. fast response), scalability and existing operating experience. Integrating ESS to the grid is the most potential strategy of peak shaving and actually BESS in particular is promising to provide it for mid-term time scale (minutes to few-hours < 5h). High-temperature batteries are also suitable for both services. Depending on the individual load profile, flywheels can be a very attractive technology. They are, nevertheless, only feasible if there are predictable periodic power peaks in the grid. Typical applications for flywheels are metro stations with underground trains that regularly brake and accelerate. In this case, the flywheel system takes up the recuperated energy and supplies it following the stop, thus increasing significantly the energy efficiency of the transport system. If, however, load peaks occur only a few times a day (or over a week), as in the case of many industrial sites, low-speed flywheels are not suitable due to their

very high self-discharge. New high-speed flywheels, however, have lower discharge rates that may make them attractive in these applications in the future. Due to their size, PHS and CAES are not suitable for these small applications.

- **Island Electrification**: in this application the storage technologies (ranging from 100 kW to 100 MW) should provide the services of a traditionally connected grid. An island system designed to operate predominantly on renewable energy requires many services that could be supplied by storage systems: frequency containment reserves, frequency restoration reserves and energy shifting. Additionally, a number of island grids are now incorporating storage systems for residential self-consumption that are pooled to deliver some of the services listed above and this trend is likely to grow over time. To date, CAES installations are too large for islands and require a complicated balance of system. PHS if available, can provide a low-cost source of power and also inexpensive energy shifting capacity. By adding a BESS such as Li-ion batteries, a versatile storage system can be achieved. However, if PHS is not available, only BESS can provide the services. A typical island electrification system, for example, could comprise a high-power storage system (e.g. a 5 MW Li-ion battery container system) to frequency containment reserves, as well as parts of the frequency restoration reserve. However, other high-power ESS could be used, such as flywheels in conjunction with a high-energy technology, such as lead-acid or Li-ion batteries. It should also not be forgotten that solar and wind technologies can provide part of the flexibility needs themselves. In most cases, cost efficiency will be achieved with a mix of generation service supply and storage assets.

In a more general and current connotation, Figure 37 presents the global power capacity shares at the beginning of 2018 of PHS, electrochemical storage, electromechanical and thermal storage for each stationary application.

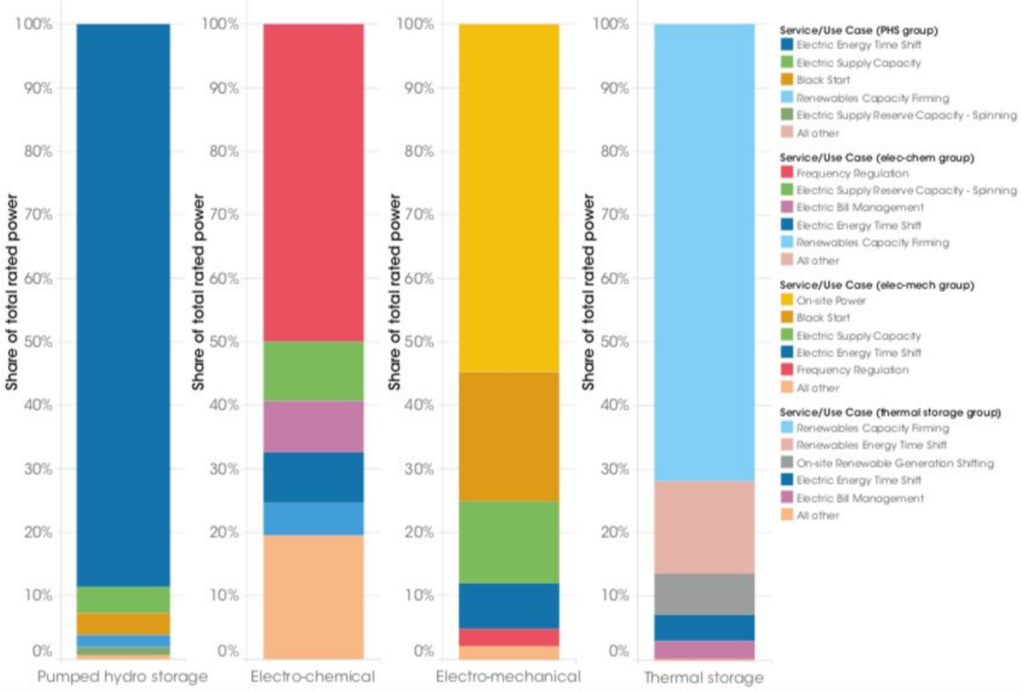


Figure 37 - Global energy storage power capacity shares by main-use case and technology group - Source [12]

## 3.3 Advantages of the HESS

It’s important to point out the reason why an hybrid storage system is preferred among a single storage unit, otherwise without a real convenience the hybridization results in just an useless spending. The main and most important reason of combining a flywheel with a Li-ion battery is to preserve the lifetime of the second avoiding its premature ageing. As already said before, some grid applications, due to the many cycles per day they require, cause a stress on the battery shortening in this way its lifetime and so resulting in economic expenditures and even environmental issues related. Hence, flywheels, because of their excellent cycling behavior, should act as a filter to reduce battery cycling and provide enough time for the battery cells to cool when switching from charging to discharging.

It’s now fair to analyze the ageing rate of the battery when combined or not combined with flywheel in providing grid services.

### 3.3.1 General Ageing Test With/Without Flywheel

Generally speaking, paper [24] present a scenario where the impact cell current and cell temperature have on the cell lifetime is analyzed in the case of a renewable firming application including frequency regulation at a 98% yearly operating time. The data used is the following:

- *100 Ah NMC Li-ion battery*
- $R = 10\ m\Omega$
- $Cp = 950\ \frac{J}{kg\,K}$
- $\lambda = 0.8\ \frac{W}{m\,K}$
- *Air cooling flow =* $1\ \frac{m}{s}$

Integrating the battery with a flywheel results in a significant impact on the battery performance. Cycles are reduced and even more important the average cell temperature is reduced as less power flows through the cell. Figure 38 presents how much the temperature of the cell increases when a flywheel is not hybridized with the battery. In the same way, Figure 39 shows the different values the cell current reaches when the battery in connected with a flywheel and when it’s not.

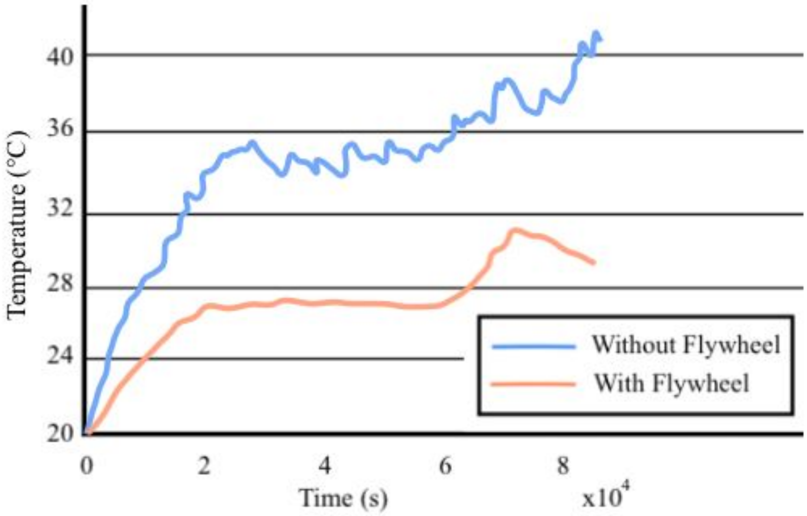


Figure 38 - Cell temperature with/without flywheel - Source [24]

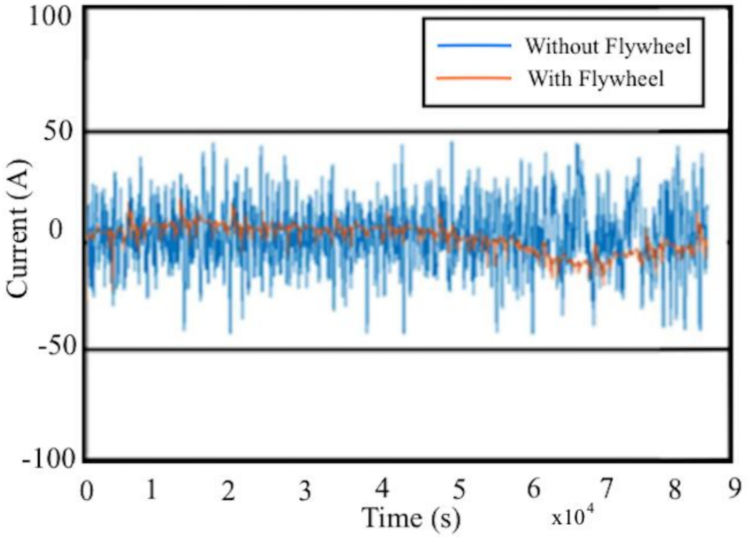


Figure 39 - Cell current with/without flywheel - Source [24]

Lastly Figure 40 shows the effects cell temperature has on the lifetime of the battery. Of course, it's clear how the reduction of temperature on the cell thanks to the connection with the flywheel generates a positive result in the time scale of the battery. Its lifetime shifts from 8 years without the flywheel to 10 full years with it.

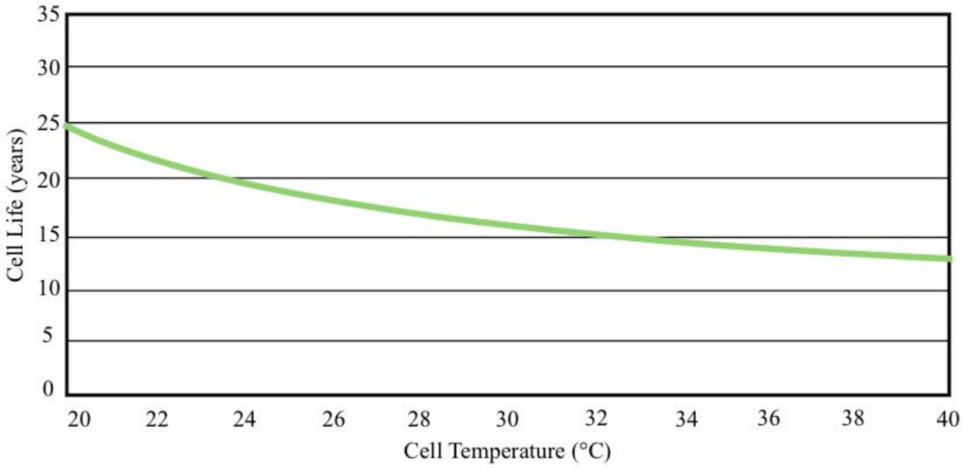


Figure 40 - Battery lifetime as a function of cell temperature - Source [24]

Extending the lifetime of the battery of even just two years, results in a substantial economic saving: the current installation energy cost of NMC Li-ion cells is circa 420

USD/kWh and this would occur two years prior when a flywheel is not used; plus the costs of the old battery disposal need to be added. And this is considering one of the cheapest lithium-ion chemistries: using LTO cells for example would highly enlarge these costs. It's also quite important to consider the environmental effects the battery has and for this reason they are analyzed in paragraph 3.3.3.

## 3.3.2 Ageing Test with Primary Frequency Regulation Without Flywheel

### 3.3.2.1 Ageing Tests

Paper [25] gives more specific details in terms of the ageing of different chemistries of Li-ion batteries when they are used alone for ancillary services, in particular for primary frequency regulation. The ageing tests are performed by Terna (the italian operator for the high voltage transmission) during the installations of the Storage Lab. They are executed on the basis of three different cycle typologies, namey:

- a standard cycle
- a frequency regulation cycle
- a current step cycle

#### The Standard Cycle

It is necessary to conceive a standard cycle in order to uniformly compare and rank the different Li-ion chemistries. The standard cycle consists of a discharge at nominal power $P_n$ up to a Depth of Discharge (DoD) equal to 80%, a complete charge at $P_n$ and no standby time between consecutive cycles. The daily equivalent cycles (i.e. the ratio between the daily energy discharged and the nominal energy) are 5-12 based on the battery charge/discharge times and the daily inversions of power are maximum 24. However, during these tests, it is clear that some chemistries are not able to withstand a continuous cycling without experiencing temperatures higher than the nominal ones. Thus, it becomes necessary to introduce a rest time of one or more hours between the consecutive cycles, in order to allow a safer battery operation.

#### The Frequency Regulation Cycle

The second cycle type is conceived in terms of the primary frequency regulation where the 24 hours long frequency variations in a real network bus are analyzed. The behaviour is modified to obtain a repeatable one, which could be representative of a long period (average value equal to 50 Hz with maximum mismatches up to 100 mHz) and the profile is composed of 86,400 set-points (one per each second of a 24 hours cycle duration). Then, every 10 days a full charge/discharge cycle is executed in order to determine some electrochemical parameters of the Li-ion batteries. The average power is equal to $0.4 P_n$, the daily equivalent cycles are about 5 and the daily inversions of power are over 1,000. A nil deadband is used to stress the battery, in order to accelerate the battery ageing upon testing. The frequency regulation tests are performed starting from 100% State of Charge as a conservative approach. In fact, to charge a battery near to 100% SoC (or to discharge it near 100% DoD) is even more stressful than the actual frequency regulation operations.

#### New Cycle with Current Steps

A third cycle is created to stress the batteries with an energetic exchange wider than that of a standard cycle and it's characterized by the steps of current. It consists of six phases of charge/discharge with a duration of 30 seconds each. The average power is equal to $0.6 P_n$, the daily equivalent cycles are about six and the daily inversions of power are over 1,000 (about 2,800).

### 3.3.2.2 Ageing Test Results

Here, a comparative overview of the results of the ageing tests based on the standard cycles and on the frequency regulation ones are presented. The following Figures 41-45 show the ageing of each Li-ion chemistries after the tests previously presented in terms of the battery residual energy after every cycle. The expected ageing of each technology, provided by the battery manufacturer in the tender phase, is compared with the experimental results obtained.

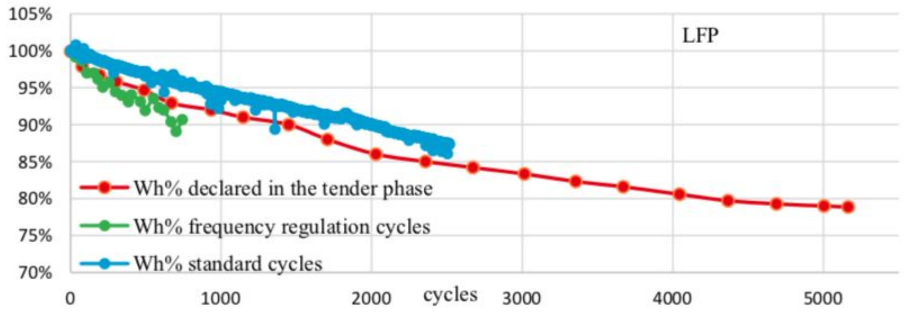


Figure 41 - Lithium iron phosphate (LFP) technology - Source [25]

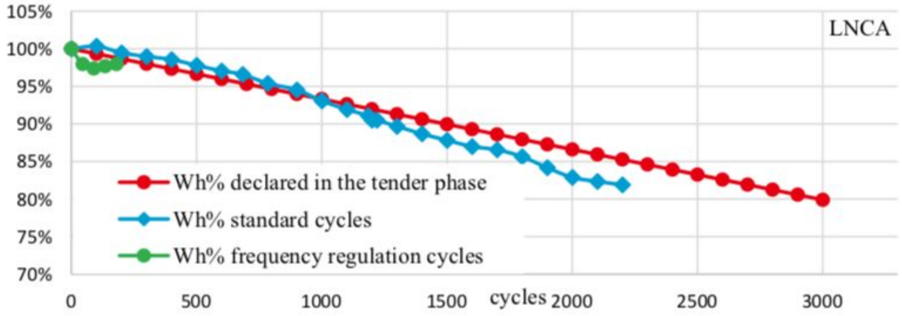


Figure 42 - Lithium nickel cobalt manganese (NCA) technology - Source [25]

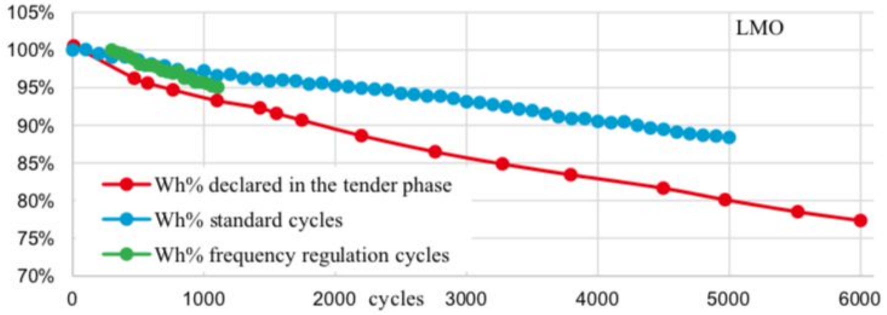


Figure 43 - Lithium manganese oxide (LMO) - Source [25]

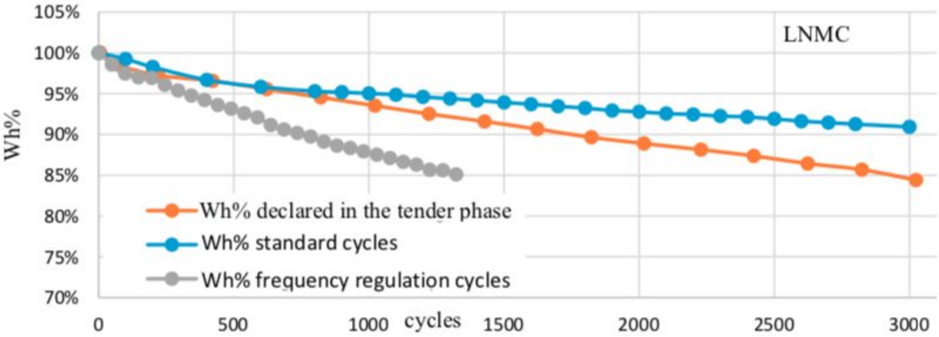


Figure 44 - Lithium nickel manganese cobalt (NMC) - Source [25]

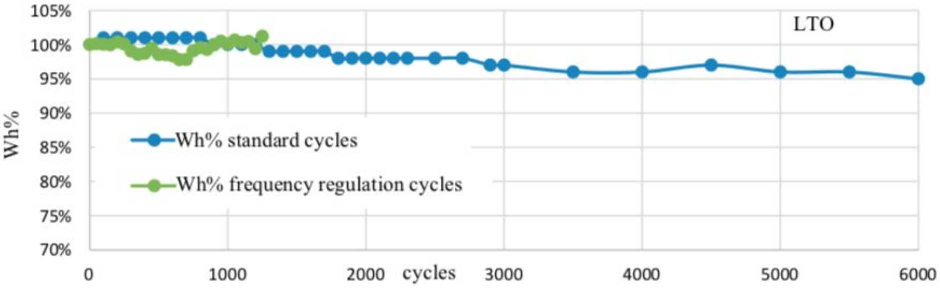


Figure 45 - Lithium titanate (LTO) - Source [25]

As it's possible to see, the number of cycles widely varies for each technology. This fact is due to the nominal charge/discharge time changes between the various battery technologies.

Figures 46 and 47 compare the ageing of the different Li-ion chemistries following the standard cycle test and the frequency regulation one.

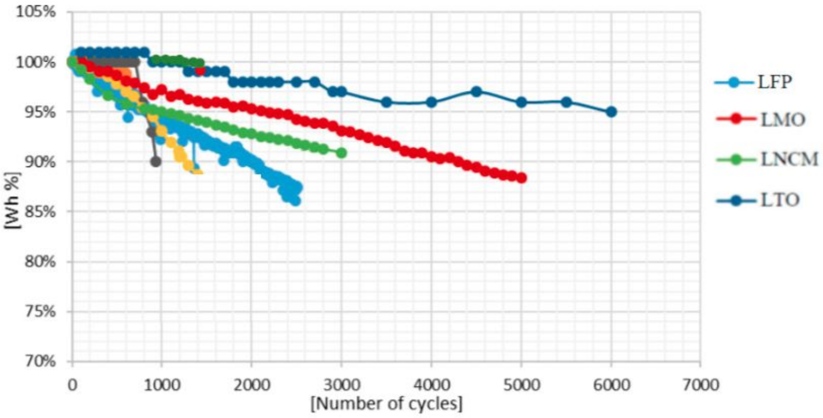


Figure 46 - Comparative curves of ageing for different Li-ion chemistries based on the standard cycle - Source [25]

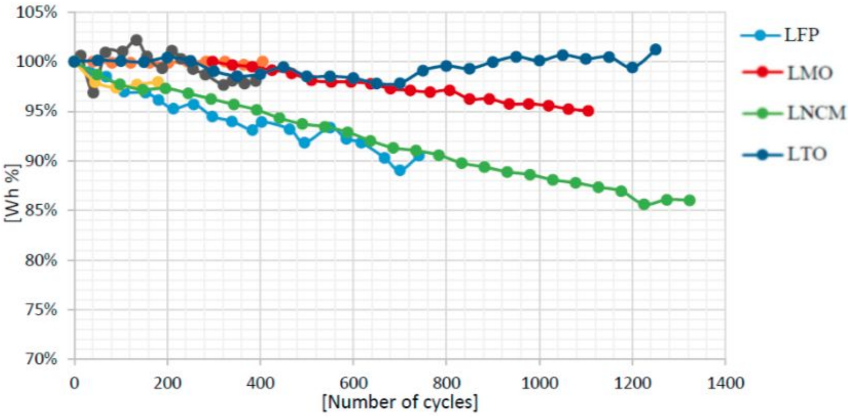


Figure 47 - Comparative curves of ageing for different Li-ion chemistries based on the frequency regulation cycle - Source [25]

For the LFP and NMC technologies, the ageing determined by the frequency regulation cycle is more pronounced. The NCA module suffered irreparable damage during the frequency regulation cycle test and, therefore, the test was interrupted after 180 cycles and it is not possible to draw any conclusion for this particular technology; its capacity decreased by 20% at the end of the test. LTO and LMO cells, instead, revealed a low ageing following the frequency regulation cycle, with respect to the standard one.

These tests are important to point out how much the lifetime of a battery can be drastically affected by the cycle rates it undergoes and the grid applications it provides, in this case primary frequency regulation. Once again, integrating a flywheel in this configuration would improve the overall battery performance elongating its lifetime resulting in many benefits in terms of economics and environment.

### 3.3.3 Environmental Impact and Economics

Every battery technology contains an amount of toxic components. However, Li-ion batteries are considered one of the most sustainable in terms of environment thanks to their higher round trip efficiency. [28], [40] Ni-NaCl batteries have actually the lowest environmental impact, from a recycling point of view to the chance of contamination in the case of faults or accidents and that's because they are an intrinsic safety technology made in Italy. Nevertheless, in relation to the available data regarding the effects that various types of batteries have on short-term and long-term health in the case of exposition and on the environment, Li-ion technology has as well one of the lowest impact. Its danger is related to lithium reacting with oxygen producing toxic products but lithium is not in heavy quantities in the battery, the main risk actually is associated with its electrolyte (a mix of an organic solvent and lithium salts), which is toxic and flammable. Being exposed to it can cause skin problems or intestine problems if eaten. However, the solvent volatizes when in air. Other types of batteries like lead-acid are more dangerous. Lead is a noxious element for human health and it accumulates in nature. Instead, lithium is not harmful towards flora and fauna. Plants easily absorb it and actually are indicators of its concentration in the environment. It's obviously also true that a huge concentration of it in the surroundings can be toxic.

Paper [27] presents a way to evaluate the effects these batteries have by building a Life Cycle Impact Assessment (LCIA). A detailed measurement (inventory analysis - LCI) of the amount of each component present in three Li-ion chemistries (LFP, NMC, LMO) and other battery technologies had previously been made and now, LCIA aims to assess the inventory analysis results and interpret them in terms of potential environmental threats associated with the product's value chain. In general, LCIA involves the following key steps:

- Selection of impact categories (e.g. climate change, terrestrial toxicity)
- Classification: attributing inventory results to impact categories (e.g. attributing carbon dioxide emissions to global warming potential - GWP)

- Characterization: selection of characterization models and expressing the contributions from all substances in the impact category into a common unit of the category indicator (e.g. using specific characterization models and summing up the impacts of all greenhouse gases - GHGs - into kg $CO_2$ equivalents - GWP - under the impact category of climate change)
- Normalization: normalizing the characterization results on a common scale that applies to all impact categories (e.g. normalizing GWP score to a product by the GWP from an average per capita European lifestyle)
- The final steps of LCIA may include grouping and weighting of impact categories.

The impact categories considered in this study are as follows:

- Cumulative Energy Demand (CED): it's the total energy used across the product's life cycle, both direct and indirect [MJ/MWh] or [MJ]
- Global Warming Potential: the total amount of GHGs emitted into the atmosphere across the life cycle of the product and uses a specific characterization model for time horizon of 100 years to estimate the global warming potential of the product [%]

In this thesis, it's fair to consider the impact of the batteries in stationary applications and not their use in other contexts (EVs, power electronics..), that's why four stationary application scenarios were chosen for this analysis:

- Energy management
- Frequency regulation
- Voltage support
- Energy arbitrage/Energy time-shift

Figure 48 presents a comparative CED impact assessment of the battery types for these four applications including the CED impact of the battery complete-life utilization but only in the *cradle-to-gate* stage of the lifetime of the battery (the production stage, described in Figure 49). Figure 50, instead, shows the results of the overall life cycle in terms of CED and Figure 51 in terms of GWP.

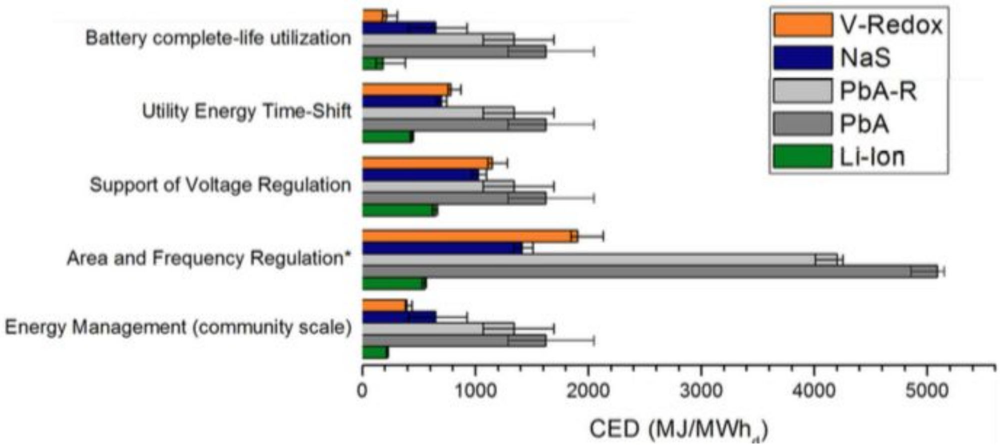


Figure 48 - CED impact assessment of different technologies in the *cradle-to-gate* stage - Source [27]

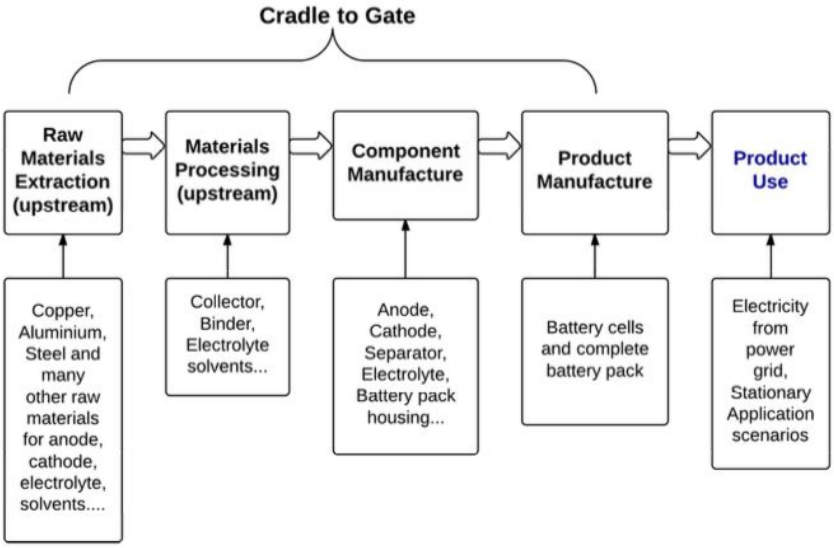


Figure 49 - Life cycle stages of a battery - Source [27]

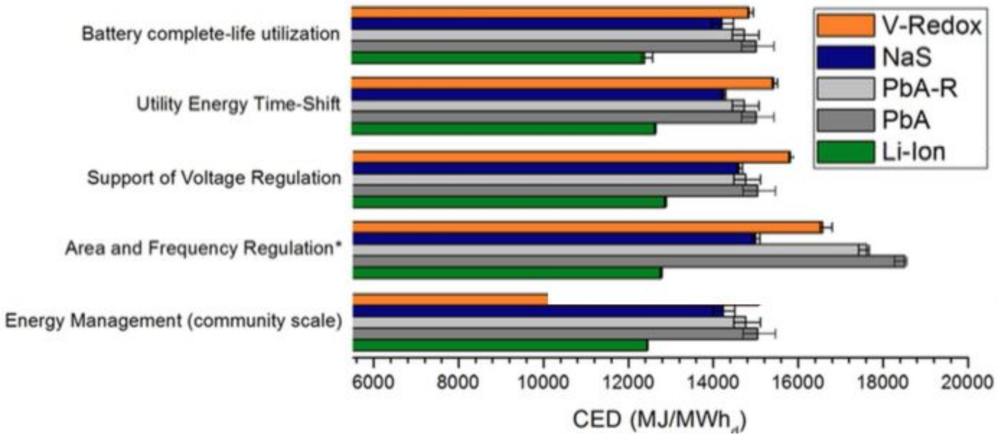


Figure 50 - CED impact assessment of different technologies in overall life cycle - Source [27]

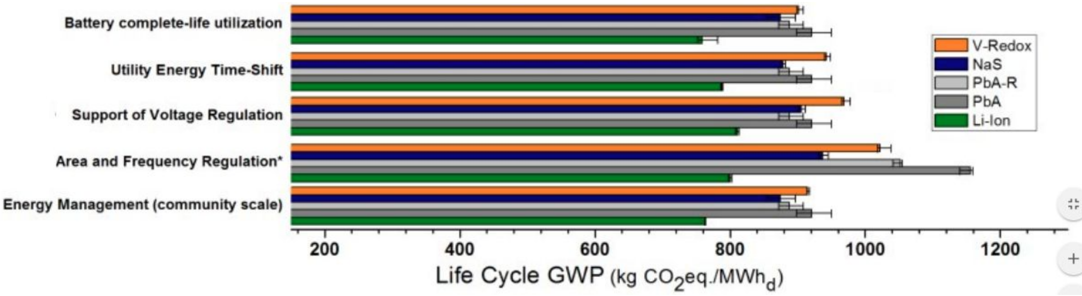


Figure 51 - GWP impact assessment of different technologies in life cycle - Source [40]

The results show how the lithium-ion technologies present one the lowest impact compared to other batteries technologies. The Ni-NaCl technology is not here considered, even though it’s the one that presents the lowest impact, and that’s because of the cost limitations it has: it is actually much higher than the average cost of other technologies and overall is not commercially competitive yet.

Comparing results from Figure 48 and Figure 59 it’s possible to see how in general the use stage of batteries dominates their life cycle impacts significantly; it is therefore misleading to compare the environmental performance of batteries only on a mass or capacity basis at the *cradle-to-stage* while neglecting their use stage impacts, especially when they have different characteristic parameters. Based on the results obtained, Paper

[40] recommend the deployment of batteries with higher round trip efficiency, such as Li-ion, for stationary grid operation in the first instance.

To provide a more detailed analysis, without considering the application, the general comparative results for the five batteries for complete utilization of their cycle life are presented in Figure 52 for the *cradle-to-gate* stage and Figure 53 for the overall life cycle impact. Figure 52 show how Li-ion and NaS have higher impacts per kilogram of battery mass in both the impact categories when compared to PbA, but have lower impacts when compared on MWh basis. In fact, Li-ion and NaS have cycle lives that are, respectively, nearly 8.2 times and 2.6 times longer than the cycle life of PbA. In addition, the mass of battery that would be required for a specific application size depends on its energy density and Li-ion and NaS have energy densities that are, respectively, 5.2 times and 4.3 times higher than the energy density of PbA. This means that Li-ion and NaS can deliver a lot more electricity per kilogram of battery mass than PbA across their lifetimes. This significant increase in lifetime electricity delivered for same mass of batteries ultimately results in the decreased *cradle-to-gate* impacts of Li-ion and NaS on MWh basis, even though they have greater impacts on mass basis.

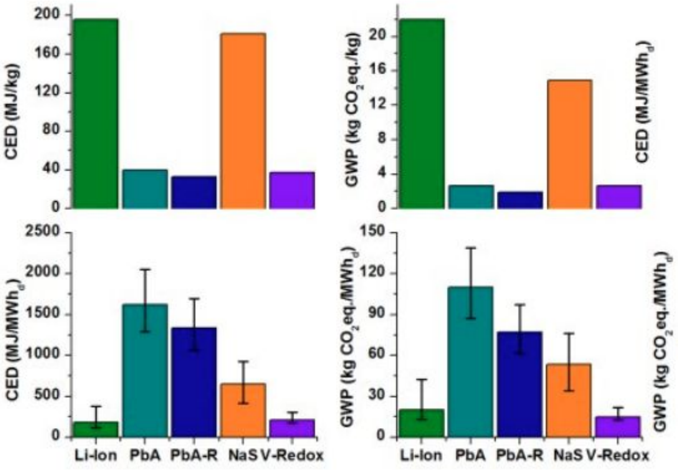


Figure 52 - *Cradle-to-gate* impacts - Source [40]

Figure 53 shows the comparison of the five battery technologies for their life cycle impacts. It can be seen that Li-ion has the least impact in both the impact categories and there is a close competition between the other three batteries. The contribution of the *cradle-to-gate* stage to the life cycle impacts, as previously said, is very small compared to the contribution of the use stage, with the impacts coming primarily from the battery losses and the power-grid mix used to charge the batteries. The proportions of *cradle-to-gate* impacts in the life cycle CED impacts for Li-ion, PbA, PbA-R, NaS and V-Redox are 1.4%, 10.8%, 9.1%, 4.6% and 1.4% respectively; the corresponding proportions for the GWP impacts are 2.7%, 11.9%, 8.7%, 6.1% and 1.6% respectively. PbA and NaS have higher proportions of *cradle-to-gate* values in their life cycle impacts compared to the other two because of their relatively low cycle life. Furthermore, the use stage impacts also vary across the five battery systems. These variations basically result from the differences in the round-trip efficiencies of the battery technologies, i.e. electricity wasted by batteries in each complete charge-discharge cycle. Li-ion with a round-trip efficiency of 92-95%, has the lowest use stage impacts. That is, the more efficient the battery system, the lower the losses and hence the lower the use stage impacts resulting from electricity consumption. Li-ion therefore becomes more competitive from a life cycle perspective.

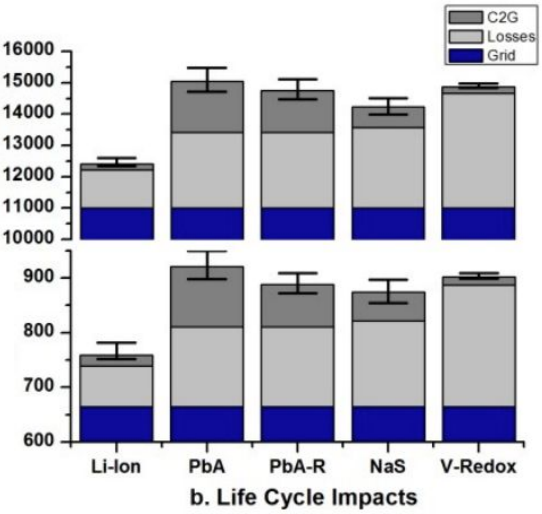


Figure 53 - Life cycle impacts - Source [40]

Overall, these outcomes lead to the consideration that a long lifetime for this technology not only provides economic savings but also prevents the impacts that the life cycle and the *cradle-to-gate* stage have on the overall energy consumption (on the CED) and so the environmental status caused by the production of this energy. If a battery lasts longer, its substitution is shifted and so the production and use of a new one.

Analyzing in details the *cradle-to-gate* stage, Figure 54 and 55 show how much energy and GPW is associated with the production of the Li-ion battery components. Suddenly, it was not possible to find data on the disposal stage of these batteries, but it seems obvious that a long battery lifetime shifts away the date of the disposal, shifting away as well the costs related to it.

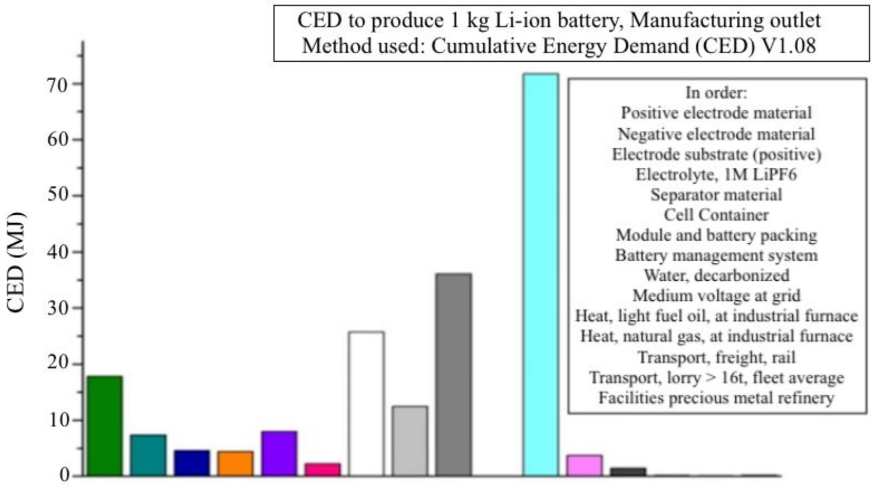


Figure 54 - CED impacts of the major processes during the *cradle-to-gate* stage of Li-ion battery life cycle - Source [27]

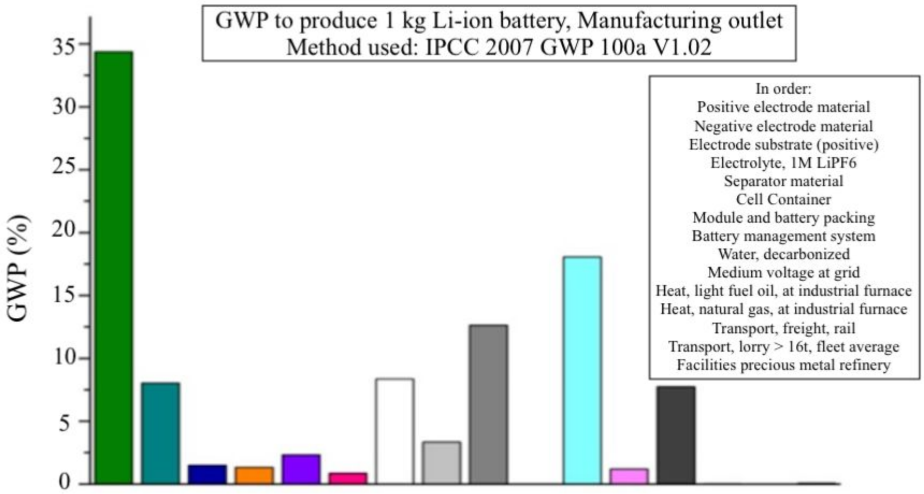


Figure 55 - GWP impacts of the major processes during the *cradle-to-gate* stage of Li-ion battery life cycle - Source [27]

Furthermore, Figure 56 shows in blue the contribution to the overall Li-ion battery cost of the components, according to five different sources. The contribution of material-related cost items ranges from less than one-third in one study to between 55% and 63% of total system costs in other four studies. It's obvious how solid this contribution is in the total cost of the battery and so it's fair to reaffirm how much money is going to be saved if the battery lasts longer and so the production of new batteries is shifted away in the future.

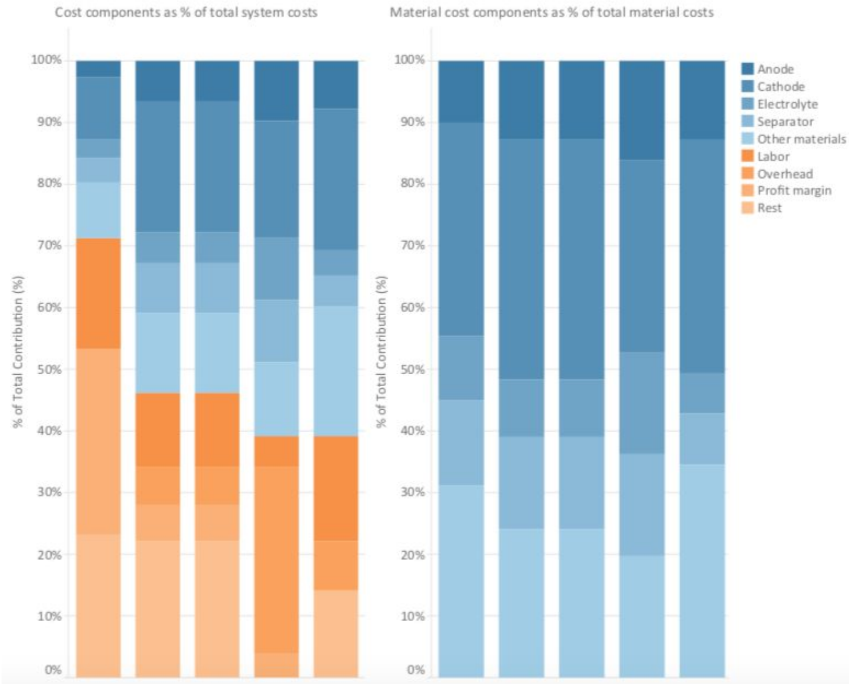


Figure 56 - Cost breakdown of Li-ion battery - Source [12]

The contribution of cell costs to the total BES system cost of course will vary, depending on the BES system size. A lower contribution of cell cost components as system size increases can be expected, since for larger systems, the power electronics and periphery costs become more relevant. For example, aggregated cost breakdown estimates for Li-ion BES systems in various market segments place cell costs at 35% for large systems, compared to 46% for residential systems (Figure 57).

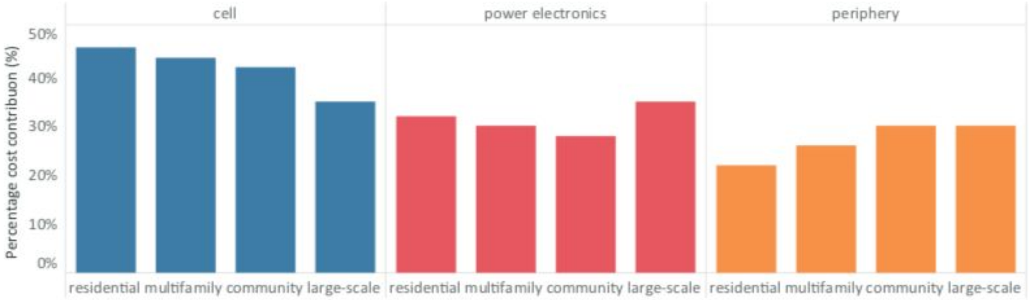


Figure 57 - Cost component distribution of Li-ion of different storage sizes - Source [12]

In conclusion the benefits offered by the combination of a flywheel with a Li-ion battery can be here summarized:

- Each technology is suitable to some specific stationary applications; the combination of two technology provides more grid services not achievable by one single storage system. Furthermore using storage technologies in applications for which they are not the best fit can result in performance degradation and can have cost implications and sometimes also lead to safety issues around charging and discharging batteries.
- The complementary operating characteristics of the two technologies allow the system to deliver power capacity, energy duration and cycle life in a single hybrid that is not achievable by any single energy storage technology.
- The presence of the flywheel can possibly preserve the lifetime of the Li-ion battery (as generally seen in 3.3.1) by reducing the stress on it caused by high rates of charge/discharge. It's this a subject of studies at the University of Padua, Italy: using a specific control strategy the flywheel can help the battery in terms of lifetime. Overall, assuring a long lifetime to the battery leads to economic savings and a reduced environmental impact caused by the production and disposal of the battery.
- The choice of integrating flywheels avoids the use of more batteries and so reducing the environmental impacts caused by their production, use and also disposal.

It's this a particular energy solution still under development and has recently be chosen as a subject of many studies. The idea of integrating different energy storage devices though has been considered and implemented in the last years and is progressively developing: according to a white paper from Navigant Research, global installed hybrid energy storage system power capacity is expected to grow from 78.6 MW in 2017 to 2.1 GW in 2026 as Figure 58 shows.

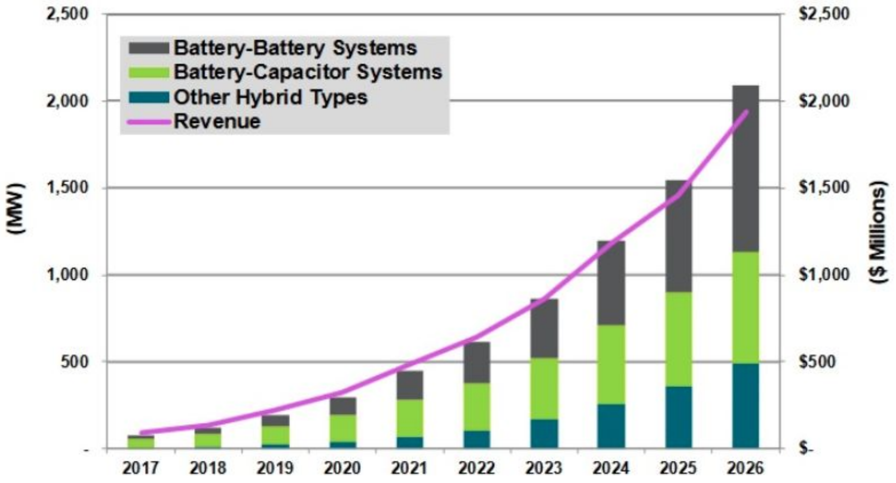


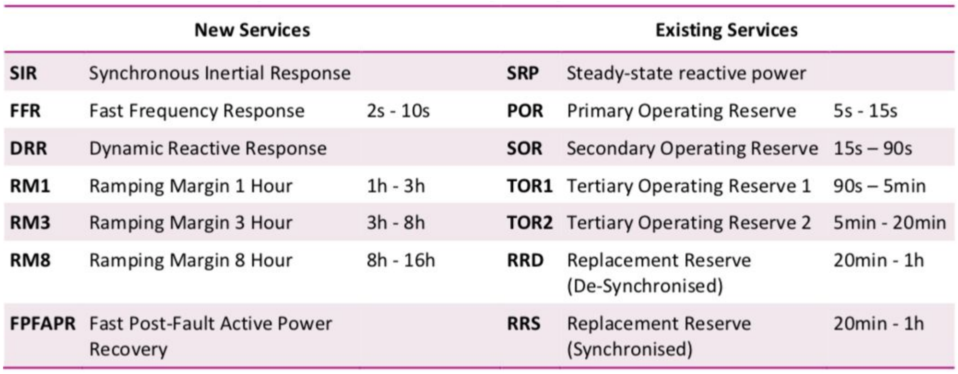
Figure 58 - Installed HESS power capacity by technology, world markets: 2017-2026 - Source Navigant Research

## 3.4 The HESS Performance

Schwungrad Energie is an Irish company established in 2013 that firstly developed an hybrid storage system at the service of the electrical grid combining batteries and flywheels. The project will be described in details in Chapter 5 but it seems fair to present now an overview of the tests the company has done to evaluate the performance of the HESS as well as the reflections made towards the benefits of it and the reasons why this particular system is going to have major success in the next years.

### 3.4.1 The Tests and Results

Report [26] presents the results from demonstration project, showing how the flywheel/battery hybrid solution responded to real frequency events over the period of nine months. The metrics used to classify the quality of performance are: *response time* and *sustainability of power output*, both of which are time based measurements. The DS3 Programme (Delivering a Secure Sustainable Electricity System) has defined 14 system service products which in general are categorised in sequential timeframes. This project was set up to demonstrate the capability of flywheels and batteries to provide system services in the timeframe of 500 ms up to 20 minutes without participating in the energy market. Figure 60 shows the existing and the new services defined by DS3.



| | **New Services** | | | **Existing Services** | |
|---|---|---|---|---|---|
| **SIR** | Synchronous Inertial Response | | **SRP** | Steady-state reactive power | |
| **FFR** | Fast Frequency Response | 2s - 10s | **POR** | Primary Operating Reserve | 5s - 15s |
| **DRR** | Dynamic Reactive Response | | **SOR** | Secondary Operating Reserve | 15s – 90s |
| **RM1** | Ramping Margin 1 Hour | 1h - 3h | **TOR1** | Tertiary Operating Reserve 1 | 90s – 5min |
| **RM3** | Ramping Margin 3 Hour | 3h - 8h | **TOR2** | Tertiary Operating Reserve 2 | 5min - 20min |
| **RM8** | Ramping Margin 8 Hour | 8h - 16h | **RRD** | Replacement Reserve (De-Synchronised) | 20min - 1h |
| **FPFAPR** | Fast Post-Fault Active Power Recovery | | **RRS** | Replacement Reserve (Synchronised) | 20min - 1h |

Figure 60 - System service products defined by DS3 - Source [26]

In this way the HESS can contribute in providing the required stability to the grid to allow RES to rise while not displacing any of it as would be the case with conventional plant running at minimum generation just to provide system services. That's what occurs when many non-synchronous generators (aka RES) are installed into the grid: due to their inability to provide rotational inertia, traditional generators are runned specifically for that reason without having to also provide energy and when that happens the RES generators need to be curtailed. Now, flywheels and batteries will do this, providing synthetic inertia and other system services such as for example voltage control.

#### 3.4.1.1 Test Methodology

##### Response to Real Events

The hybrid is a 422 kW demonstration plant connected to the distribution network in a rural area in Ireland. In conjunction with the Distribution Network Operator it was decided that the operation of the plant would only include the *Active Power* capabilities of the plant to minimise the risk of breaching power quality standards. Three different control modes were used in order to test the frequency response of the HESS but their full description, as well as the one for the voltage response control modes, is not relevant for the purpose of this Chapter; every modes will be analyzed in Chapter 4. However, it's fair to name them as they will be mentioned in the following tests' results:

1. Frequency response:
    - Mode 1 - Static Response Mode
    - Mode 2 - Feedback Response Mode
    - Mode 3 - Droop Mode
2. Voltage response:
    - Mode 4 - Power Factor Control Mode
    - Mode 5 - Voltage Control Mode
    - Mode 6 - Reactive Power Control Mode

### Manual/Simulated Testing

A series of manual tests were designed to monitor the response of the plant to simulated normal grid conditions, low frequency events and simulated Rate of Change of Frequency (RoCoF) events. Manual control overrides the automated control system, stopping it from monitoring live grid conditions. The plant delivers *Real Power* to the grid when manual response is selected, proving a physical response to a simulated input. This was typically used to validate any modifications to the plant or the control algorithms. Before any events were experienced a test signal was generated to simulate a rapid change in the system frequency. A grid induced RoCoF trigger occurs when the frequency suddenly drops as a result of the loss of a large generator and a typical frequency curve for a frequency event is shown in Figure 61.

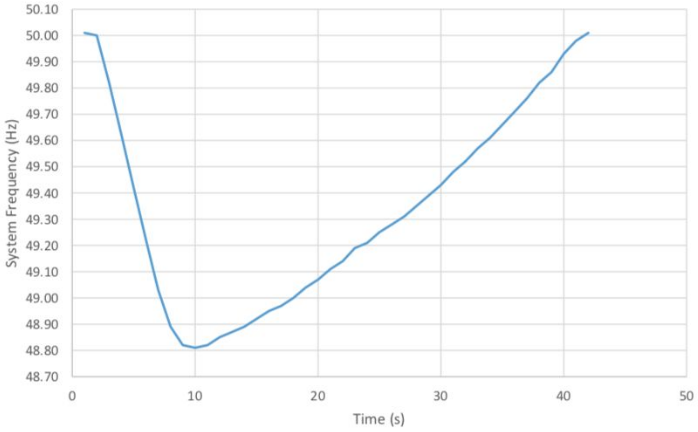


Figure 61 - Low frequency curve - Source [26]

### 3.4.1.2 Performance Results

#### Target Performance

Schwungrad Energie plans to deploy the HESS pending the results of the demonstration. For a commercial installation the target is to deliver the following DS3 products: FFR, POR, SOR, TOR1 and TOR2. In order to maximize revenue generation, the following performance metrics were set:

- Response time: 0,5 seconds
- Output Sustainability: flywheels (480 V) 5 minutes, batteries (400 V) 20 minutes

Meeting these performance metrics will deem the technology commercially viable. Voltage control will also be provided.

#### Output Sustainability Tests

- Flywheels: they have proven their capability of sustaining full output for over 5 minutes after which the output power reduces gradually as the flywheel loses its remaining kinetic energy over an additional period of 10 minutes
- Batteries: they recharge by absorbing power from the network. Recharging is achieved in two ways:

  1) during normal operation the batteries will receive a periodic equalisation charge, this is a low current charge sustained over a long duration and occurs every couple of weeks

  2) if the State of Charge of the battery falls below a set point, as a result, for example of discharging for a frequency event, the controls will recharge the batteries at 10% of nominal power capacity if the frequency is healthy and is in the 0.05 deadband.
- Hybrid: the output from it is the combined output from the two devices. The result is the plant can deliver full power for 5 minutes and sustain an output from the batteries for a further 15 minutes.

### Reaction Time Tests

The events displayed are real frequency events where the frequency changed due to a mismatch between generation and demand, probably due to a trip of a generator of the interconnector. The system is able to go into full output in under 0.5 seconds. This is measured from the time of system frequency falling through 49.80 Hz until the flywheels and battery first reach 320 kW and 160 kW respectively. Figure 62 shows a physical response to a simulated RoCoF command. Both flywheels and batteries go into full blast and sustain that for 5 seconds.

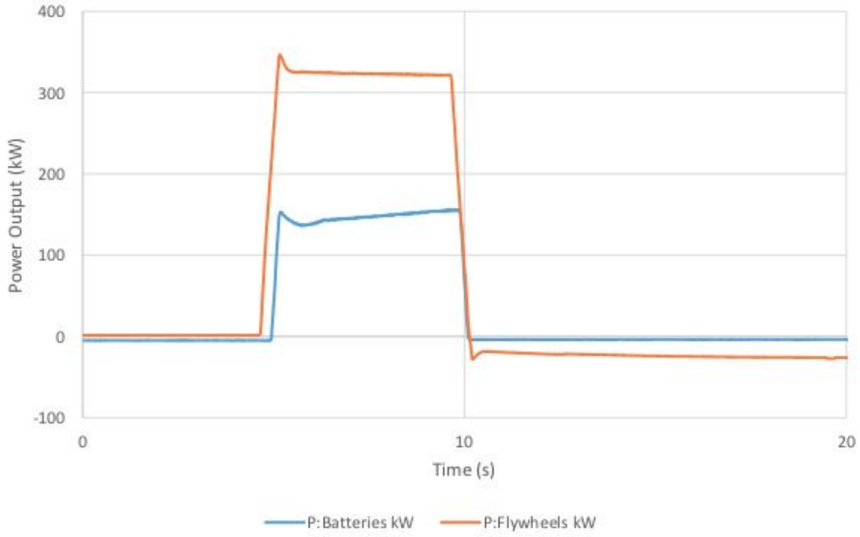


Figure 62 - HESS response to simulated RoCoF event - Source [26]

The result shows that the command reaches the flywheels inverter sooner than the batteries. However, once received the batteries ramp up more quickly than the flywheels and both reach maximum power output at circa the same time.

In Figure 63 the controller was in Droop Mode. As the RoCoF was detected, the hybrid was requested to deliver full power: 320 kW achieved in 0.5 seconds by the flywheel before the frequency went below 49.80 Hz and 160 kW from batteries achieved after the frequency fell through 49.80 Hz. Full power was maintained for 5 seconds. The flywheels discharged by 0.75% for the event and the batteries by approximately 0.038%.

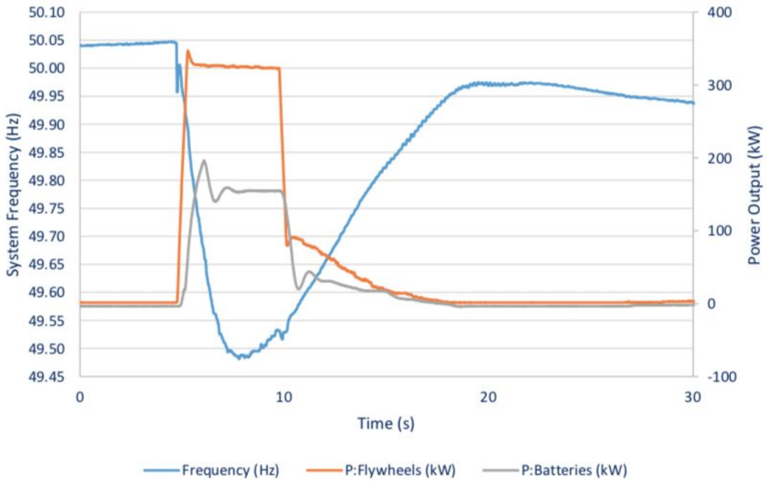


Figure 63 - Plant response to RoCoF event and reverting to Droop Mode - Source [26]

In Figure 64 the controller was again in Droop mode when the frequency fell from 50.05 Hz to 49.80 Hz over a period of circa 5 seconds. Both flywheels and batteries adjust their power output to the fall and rise of grid frequency. This provided a very smooth output from the plant as the frequency recovered but then fell again. For each value of the frequency, the system delivered a certain amount of *Active Power* and both flywheels and batteries were discharged by a negligible amount.

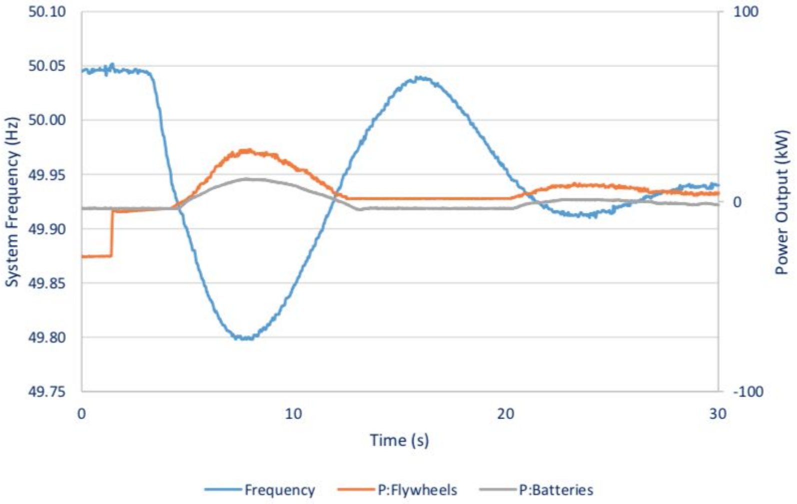


Figure 64 - Plant response to Droop mode - Source [26]

In Figure 65, it is believed that the interconnector tripped while Ireland was exporting energy into the national grid. As a result, there was an over frequency event, followed by a small under frequency event. The HESS is able to assist the grid in this type of situations, by absorbing the excess power while the frequency is high and releasing it while it's low. The hybrid was in Droop mode during this over frequency event, flywheels and batteries started absorbing power when the frequency reached 50.05 Hz and changed the slope at 50.40 Hz. For each value of the frequency, the system delivered a certain amount of *Active Power* and both flywheels and batteries were discharged by a negligible amount, smaller than 0.5% of the State of Charge.

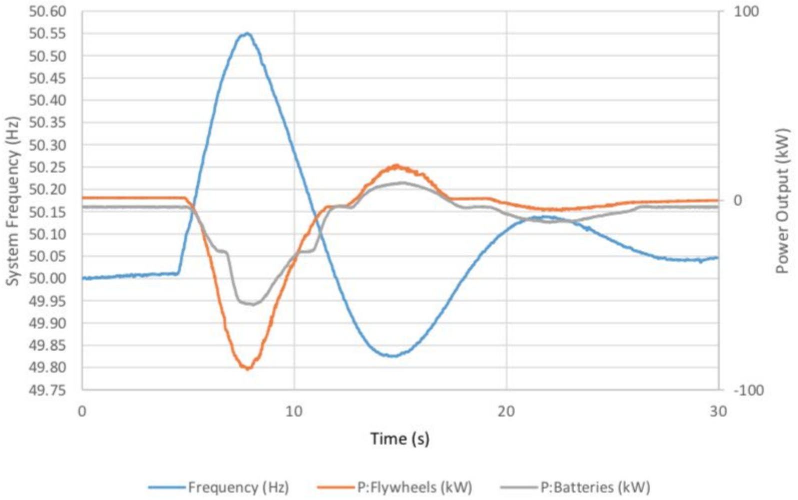


Figure 65 - Plant response an over frequency in Droop mode - Source [26]

In Figure 66, the frequency event is believed to be a consequence of the loss of a large generator and here the plant is in Feedback Response mode. Again the system detected a sudden change in the rate of frequency and sent the full blast command anticipating the dip in frequency before it passed below 49.8 Hz. Full blast was then maintain for 5 seconds, after that, the system reverted into Feedback Response mode. As the frequency recovered, the output of the HESS decreased. Once the system reverted back to Feedback Response mode the frequency was already recovering so the hybrid calculated a droop from full blast to the total recovery of the frequency assigning a value of power output for each value of frequency; under this circumstances the flywheels reach the desired output rapidly.

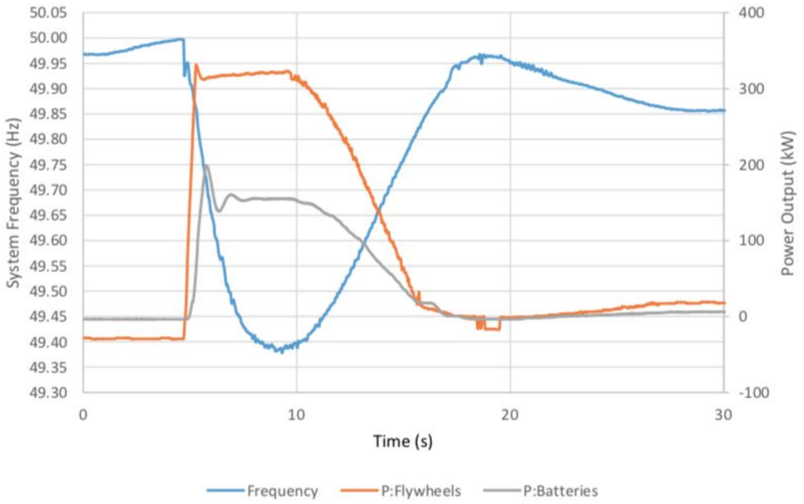


Figure 66 - Plant response to RoCoF event and reverting to Feedback Response mode - Source [26]

In Figure 67, the plant was in Static Response Mode. During the event, the frequency fell gradually and when the frequency fell below 49.80 Hz the controller sent the full blast command to both flywheels and batteries. The sudden change in power output created some momentary disturbance in the frequency readings provided by the disturbance recorder. However the device recovered in a few cycles and continued to provide accurate readings after that.

The flywheels were recharging prior of the start of the frequency event, once the frequency reached 49.95 Hz, the flywheels stopped charging and started to gradually increase the power export as the frequency continued to fall, as mentioned earlier, once the frequency reached 49.80 Hz the system sent the full blast command. The ramping time of the flywheels was < 500 ms, the full output was sustained until the frequency recovered above 49.90 Hz.

The hybrid is designed to be available to assist the grid given that it has enough energy to do so, there is no recovery time needed, as soon as the frequency recovers from a frequency event the plant is ready again.

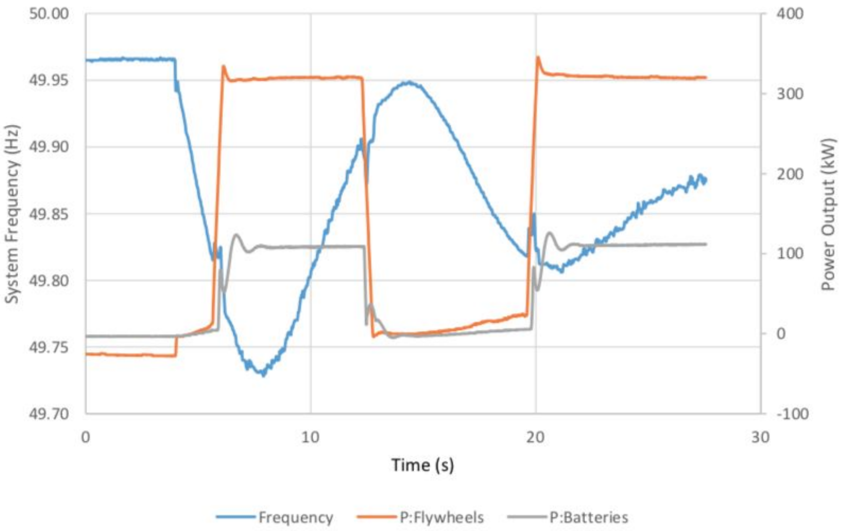


Figure 67 - Plant response to frequency event in Static Response mode - Source [26]

### 3.4.2 Future Trends for HESS

The results obtained in the tests proved the efficiency of the system in supporting the grid and guaranteeing an optimal use of both technologies in order to preserve their lifetime. The presentation conference that Schwungrad Energie staged in October 2016 and whose video is available online aimed to highlight these results as well as offer an overview of the attual grid situation of Ireland anticipating the trends that every nation will encounter in the next years.

Ireland is an island electricity system with a peak demand of 6,878 MW, which is relatively small on a global scale. The Irish grid has a limited interconnection capacity of 1000 MW representing an import/export capability of 15% of peak demand. All the interconnection is DC and there is no synchronous AC interconnection. In addition to this, the grid is undergoing significant change due to a large increase in renewable generation driven by government objectives to reach 40% renewable generation by 2020. The majority of this will be delivered from wind generation, which currently accounts for 21% of Ireland's electricity demand. The combination of low interconnection capacity and high renewables results in periods of very high system non-synchronous penetration (SNSP).

The problems that Ireland is facing these years in having to guarantee the right support to the grid are believed to be the ones that other Nations will face in the next 5-10 years. RES number will increase worldwide aiming at the environmental targets of 2020, 2030 and 2050 leading to a point where interconnections won't be enough to sustain the single national grid, as it's for now. That's when systems like the one proposed in this thesis will become fondamental to guarantee the efficiency of the electrical grid as well as stabilizing it. As a matter of fact, the Irish company has already attracted interest from UK, Europe, Vietnam and China.

Other possible applications for this technology refer to their possible integration with:

- existing or new built conventional generators: HESS can enhance their performance as they sometimes struggle to provide the grid with all the systems it needs and many times conventional generators need to adapt themselves in order to provide grid services
- renewable generators: HESS can improve their firmness as storage can help them provide what they had previously predicted since renewable sources are not stable. There are actually different kinds of dynamic storage that are useful depending on what type of RES is present: for example, the variation in output from PV is much more rapid than the one from wind as this one tends to vary slowly and there's a certain amount of inertia in the wind machines whereas for PV, due to clouds, the output dips down and comes back up in instants.

In these announced scenarios, what gains importance is the duration of the supply contracts. Since RES is evolving and the number of installations is constantly increasing, long term supply contracts are much needed as they are believed to be the cheapest way to provide these sorts of services. In Ireland, when renewable generation came in it was through Alternative Energy Requirement Contracts which were long-term 15 years contracts. People started bid in and more and more followed them biding very competitively and knowing they got a long-term contract they were able to raise the funds from the banks. Furthermore, Ireland has extremely cheap renewable generation compared to other countries where different mechanisms for supporting it are applied. So overall, long-term contracts appear to be very important to bring in new technologies in new plants that are required in order to allow the amount of renewable energy into the system that's going to be needed to meet the environmental targets of the next years. Moreover, storage system is different to a plant and requires specific grid codes and permits and at the moment has been lumped in with winds and other technologies that use power electronics between it and the grid.

# Chapter 4 - HESS Management

## 4.1 Hybridization Architectures

In Hybrid Energy Storage Systems, the architecture of the system has a considerable effect on the control and energy management strategy as well as a variety of characteristics like modularity, flexibility, efficiency and especially costs. The more flexibility the more choices in implementing control and energy management strategies, characteristics that lead to the most possible enhanced performance at the expense of complexity and cost.

Generally, there are three main types of architectures [7], [8]:

- Passive Parallel
- Cascade
- Active Parallel

Figure 68 shows their graphic representation.

### 4.1.1 Passive Parallel

The *passive parallel* architecture is also known as *direct parallel*. The two ESS technologies are connected in parallel and coupled to the DC bus directly without any power conditioning circuit (Power Electronic Device PED) between them, meaning that the output voltage of the two must be the same. It’s a simple and easily implementable structure that doesn’t need a control system or power electronic converters. It’s the cheapest architecture out of the three.The disadvantages though are quite a few:

- the two systems are not insulted, meaning that the failure of one could lead to the failure of the other one
- the distribution of the current between the two devices is not controlled and it varies with the voltage
- there’s a lack of possibilities for power flow control and energy management
- there is no flexibility in the choice of the ESSs nominal voltage

- the DC bus voltage varies as the HESS charges and discharges because the voltages of both ESSs and the DC bus voltage are required to be matched

### 4.1.2 Cascade

The *cascade* architecture is more efficient, yet more expensive than the previous one and that's because of the converter placed between the two ESSs, that are now decoupled. This aspect allows active energy management: the converter controls the power output of the first ESS allowing the voltage to vary, while the second ESS delivers the remaining power requirement of the load. Usually the first ESS is the one with higher voltage variations or the more sensitive one in order to increase the lifetime of the overall system by controlling the power output of it. The biggest drawback is the lack of freedom in the control policy and is restricted in terms of scalability since it suffers from more conversion losses as the number of power conversion steps increases.

### 4.1.3 Active Parallel

In the *active parallel* architecture, each ESS is connected to a PED. The highest level of flexibility is here achieved and the advantages are many:

- the scalability is higher because the number of power conversion steps between every ESS and load is always two and the power conversion loss doesn't increase as the heterogeneity increases
- The DC bus voltage can be maintained at constant value with minimum ripples
- each storage system can operate at its specific voltage so that the specific power and energy are optimized using the best available technology.
- the two ESSs are decoupled, meaning that the failure of one does not lead to the failure of the other
- many control and energy management strategies can be implemented

The only drawback is the high cost.

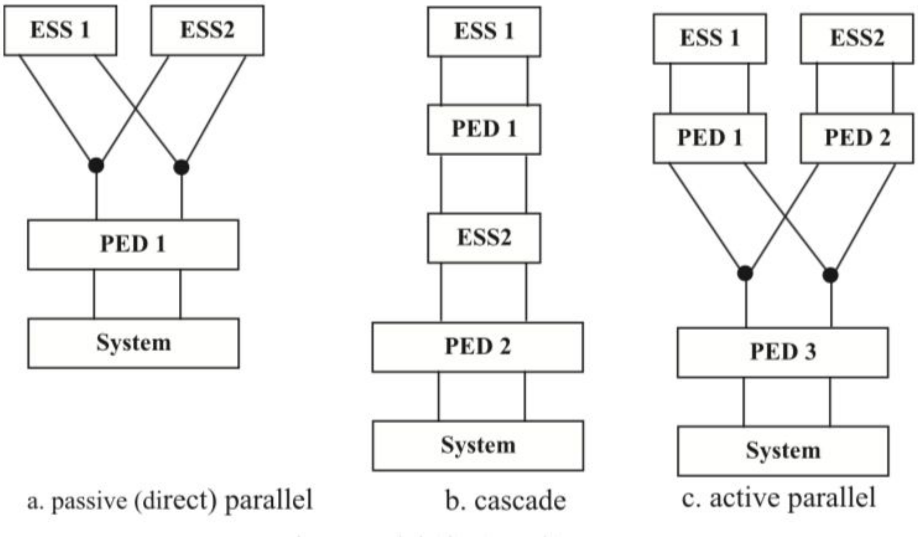


Figure 68 - HESS hybridization architectures - Source [7]

Figure 69-71 show a more visual representation of the architectures proposing a passive parallel, a semi-active parallel and an active parallel for a stand-alone configuration involving a renewable energy source, a load and the HESS where the units are distinguished as the high specific energy one (ESS-E) and the high specific power one (ESS-P).

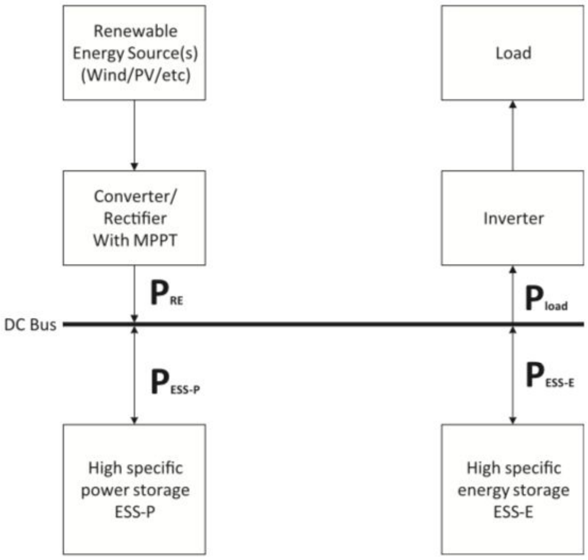


Figure 69 - Stand-alone RES with passive parallel - Source [29]

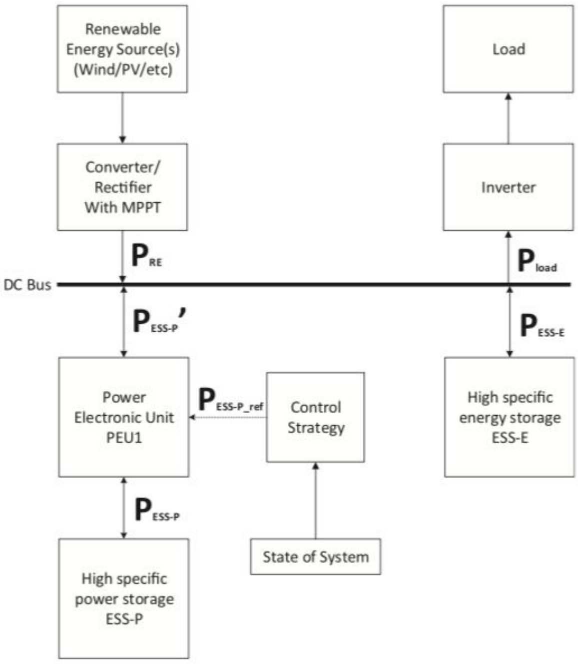


Figure 70 - Stand-alone RES with semi-active parallel - Source [29]

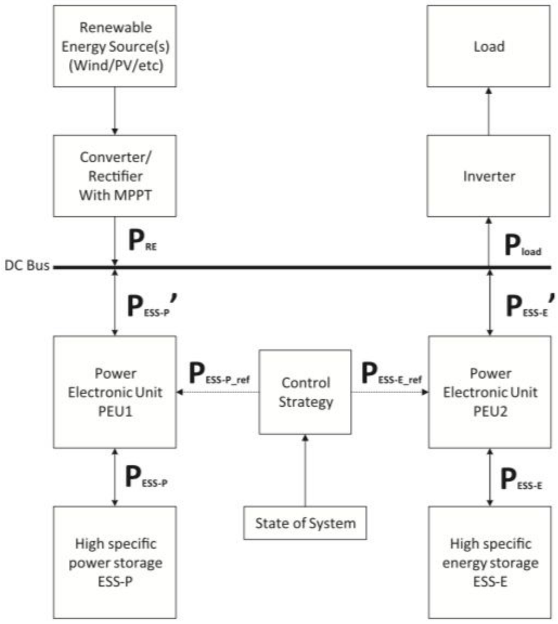


Figure 71 - Stand-alone RES with active parallel - Source [29]

Generally, the dynamic power balance of the stand-alone RES with passive load (Figure 69) is the following:

$$P_{RES} + P_{HESS} = P_{load}$$

where these are the power flows of the RES, HESS and the load. The power flow of the HESS can also be expressed as the sum of the power flows of each ESS composing it:

$$P_{HESS} = P_{ESS-E} + P_{ESS-P}$$

In the semi-active configuration (Figure 70), where just one ESS is connected to a power electronic unit (PEU), composed by a converter and a control circuitry, the role of the ESS-P in the system is to satisfy the peak power and the high dynamic power demand. With the presence of the PEU, a control strategy can be employed to regulate the power flow of ESS-P depending on the state of the system such as $P_{RES}$, $P_{load}$, State of Charge of the ESSs, voltage level of the ESSs and other parameters. PEU controls the power flow of ESS-P and allows the variation of ESS-P voltage while the ESS-E supplies the remaining load demand. This topology not only offers the decoupling of the ESS-P to the DC bus, it also optimizes the utilization of ESS-P and the durability of the HESS by relieving the dynamic stress of ESS-E. The general power equation of the system is expressed here:

$$P_{HESS} = P_{ESS-E} + P'_{ESS-P}$$

where $P'_{ESS-P}$ refers to the power flow of ESS-P after the power conversion. Practically, the efficiency of the converter ($\eta_{CON}$) is below 100%, hence the relationship between $P_{ESS-P}$ and $P'_{ESS-P}$ can be expressed as:

$$P_{ESS-P} = \eta_{CON} + P'_{ESS-P}$$

In the case of the stand-alone RES with active parallel, the general power equation of the system can be expressed as:

$$P_{HESS} = P'_{ESS-E} + P'_{ESS-P}$$

where the reasoning behind $P'_{ESS-E}$ is the same behind $P'_{ESS-P}$ in the previous case.

## 4.2 Power Conversion Systems (PCSs)

As seen in paragraph 4.1, the most used and more efficient architectures of the HESS involve Power Conversion Systems (PCSs), previously named in a more general way as Power Electronic Devices or Units. Paper [30] gives a good introspective into these PCSs by considering an HESS, inclusive of a general BESS and a FESS, in the case of a wave generation system; however this particular structure is easily adaptable to any other grid arrangement and it serves just as an example.

### 4.2.1 General Structure (Wave Generation System)

The HESS and the wave-activated generator group work in *active parallel* operation, as shown in Figure 72. In this connection mode, charging and discharging of HESS is decided by the operation of the wave generator and power grid and, thanks to this arrangement, the impact of input power fluctuation to the external system is reduced and the scheduling ability of wave power is improved. Considering that the speed range of flywheel must be wide enough, a switched reluctance machine (SRM) has been chosen as the drive motor. The system consists of the battery, SRM flywheel, DC/DC converter, flywheel converter, wave-activated generator group, power grid, AC/DC and DC/AC converter. The HESS is composed by three parts: the FESS and BESS connected together to the DC bus through the HESC. The HESC can monitor the changes of DC voltage, input power and grid power and also convert charging and discharging state and strategies.

When the input power of wave energy is large enough, the HESC will switch HESS to charging state to absorb the peak of input power. When the input power is not enough to sustain the load demand, the DC voltage will drop. At this point, the HESC will respectively control FESS and BESS to discharge according to different conditions, so as to provide voltage support for load.

For the purposes of this thesis, only the PCS of each ESS is going to be analyzed in detail, the other converters shown here are related to the specific configuration of the chosen grid.

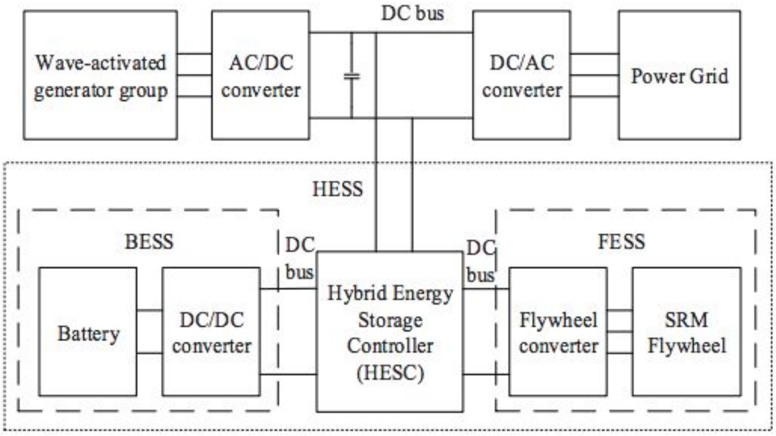


Figure 72 - The topology of wave generation HESS - Source [30]

### 4.2.1.1 DC/DC Converter

A Buck/Boost bidirectional DC/DC converter is used in the BESS, it has a simple structure and has a high work efficiency, as shown in Figure 73.

When charging BESS, drive signal is sent to $S_1$ and the converter works in the BUCK mode. On the contrary, drive signal will be sent to $S_2$ when discharging the BESS that will work in the BOOST mode.

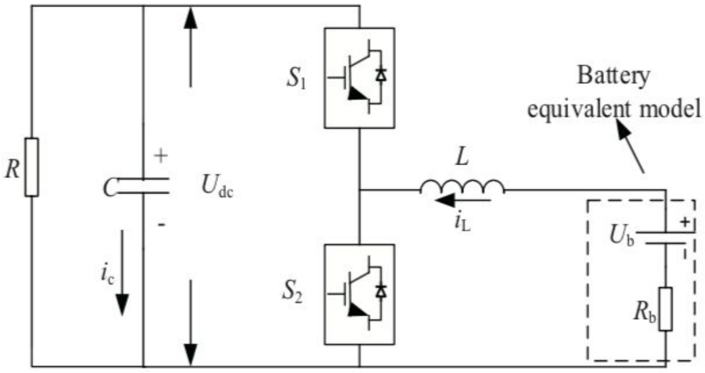


Figure 73 - DC/DC converter - Source [30]

In discharge mode the converter output voltage $U_{dc}$ can be expressed as a function of the battery voltage $U_b$ and of the duty cycle *D* of the DC-DC converter (i.e. of the $S_2$ switch) as [31]:

$$U_{dc} = 1/(1 - D) \cdot U_b$$

Being $0 \leq D \leq 1$, $U_{dc}$ is always greater than $U_b$. This condition enables electric power to flow from the battery into the network. As it's shown in Figure 74b, the battery current $i_b$ is unidirectional and equal to $i_L$.

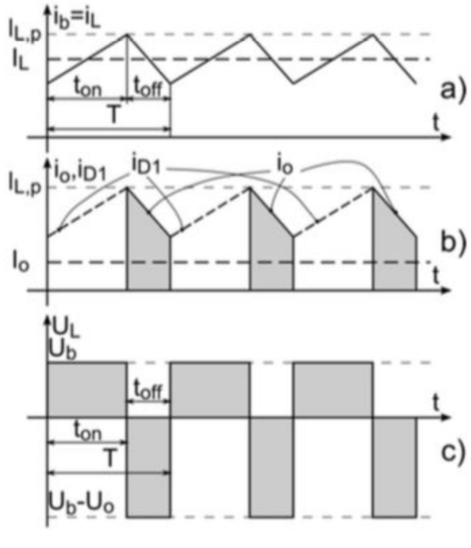


Figure 74 - Discharge operation: current and voltage waveforms - Source [31]

In charge condition, the output voltage (i.e. battery voltage $U_b$) still depends only upon the $S_1$ duty cycle *D,* and it is given by:

$$U_b = D \cdot U_{dc}$$

Consequently, the battery voltage $U_b$ is always lower than the input voltage $U_{dc}$. In the BESS charge mode this voltage behaviour has a key-role because the power flow from the grid to the battery is always guaranteed, so that the charge operation is possible directly from the grid. The battery current is unidirectional and non-impulsive.

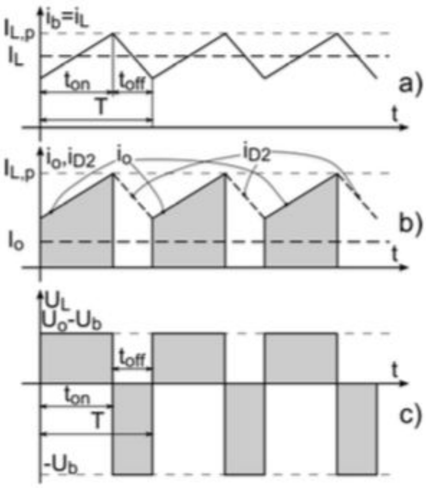


Figure 75 - Charge operation: current and voltage waveforms - Source [31]

Now, taking $i_L$ and $u_{dc}$ as state variables and using state space average method, there will be:

$$L\frac{di_L}{dt} = U_b - du_{dc} - R_b i_L$$

$$C\frac{du_{dc}}{dt} = di_L - \frac{u_{dc}}{R}$$

The small-signal model after adding the disturbance in the static working point ($d_0$, $u_{dc0}$, $i_{L0}$) will be:

$$L\frac{d\widehat{i_L}}{dt} = U_b - d_0\,\widehat{u}_{dc0} - R_b\widehat{i_L}$$

$$C\frac{d\hat{u}_{dc}}{dt} = d\widehat{i}_{L0} + d_0\widehat{i_L} - \frac{\hat{u}_{dc}}{R}$$

So, the transfer function of $\widehat{i_L}$ to $\hat{d}$ is:

$$\frac{\widehat{i_L}}{\hat{d}} = -\frac{RCu_{dc0}s + Rd_0 i_{L0} + u_{dc0}}{RCLs^2 + (RCR_b + L)s + R_b + Rd_0^2}$$

The poles of the system transfer function will be:

$$s_{1,2} = \frac{-(RCR_b + L) \pm \sqrt{(RCR_b + L)^2 - 4RCL\,(R_b + Rd_0^2)}}{2RCL}$$

There will obviously be:

$$(RCR_b + L) > 0$$

$$RCL\,(R_b + Rd_0^2) > 0$$

It appears that the poles are all on the left side of *s* plane. The structure of the DC/DC converter is stable.

#### 4.2.1.2 Flywheel converter

A three-phase full-bridge converter is chosen for FESS, where each bridge arm is constituted of one IGBT, one diode and one resistance. Both ends of the converter have direct access to the DC bus which input is $U_{dc}$ and the output is a three-phase six channels current; this current will be sent to the three-phase stator windings of the SRM in a square wave form. The windings will be excited and then the SRM flywheel will rotate according to minimum reluctance principle.

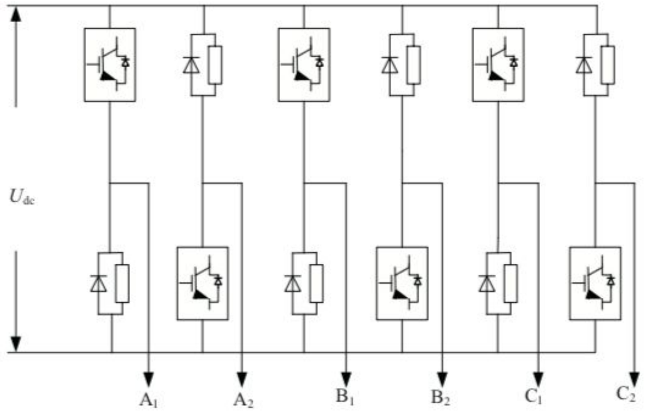


Figure 76 - Flywheel converter - Source [30]

This converter is controlled with a Pulse Width Modulation (PWM) technique in order to manage and give shape to the amplitude and the frequency of the output three-phase voltage, with $U_{dc}$ as input. [32] The PWM is done by comparing a triangular waveform with three control sinusoidal voltages with a difference of phase between them equal to 120°, as shown in Figure 77a.

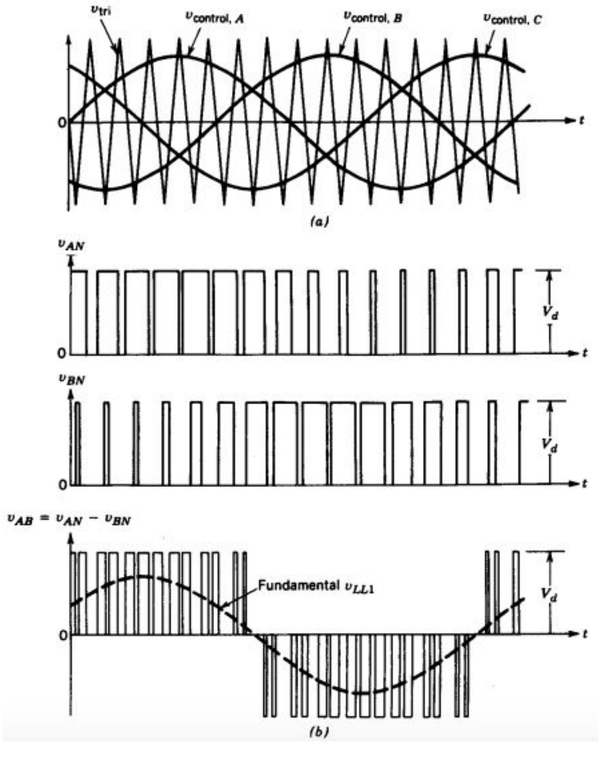


Figure 77 - Waveforms of a three-phase PWM - Source [32]

$v_{AN}$ and $v_{BN}$ are the voltages of phase A and B, and their difference results in the phase-to-phase voltage $v_{AB}$. When for a single phase $V_{control} > V_{tri}$ the phase voltage reaches the value of the input voltage $U_{dc}$, when $V_{control} < V_{tri}$ the phase voltage is zero.

Two parameters need to be defined:

- $m_a = \frac{\widehat{V}_{control}}{\widehat{V}_{tri}}$ : it's the *amplitude modulation ratio* and is the ratio between the peak value of the control voltage and the peak value of the triangular voltage.
- $m_f = \frac{f_s}{f_1}$ : it's the *frequency modulation ratio* and is ratio between the frequency of the triangular wave and the frequency of control voltage.

Now it's possible to identify PWM working strategies:

1) Modulation in linear zone $m_a \leq 1.0$: the first harmonica of the output voltage varies linearly with $m_a$. The peak level of the first harmonica of one branch of the converter is:

$$\left(\widehat{V}_{AN1}\right) = m_a \frac{U_{dc}}{2}$$

   Instead, the *rms* value of the one phase-to-phase output voltage at the fundamental frequency is:

$$V_{LL1}(phase - to - phase,\ rms) = \frac{\sqrt{3}}{\sqrt{2}}\left(\widehat{V}_{AN1}\right)$$

$$= \frac{\sqrt{3}}{2\sqrt{2}} m_a U_{dc} \approx 0.612\ m_a U_{dc}$$

2) Overmodulation $m_a \geq 1.0$: in this case, the peak value of the control voltage is higher than the one of the triangular voltage. The amplitude of the first harmonica of the output voltage does not depend on $m_a$.
3) Square wave operation: it occurs for a certain value of $m_a$ high enough. Here, every switch is closed for 180° and the converter can not control the amplitude of the output voltage. The *rms* value of the first phase-to-phase output voltage harmonica is:

$$V_{LL1}(phase - to - phase,\ rms) = \frac{\sqrt{3}}{\sqrt{2}} \frac{4}{\pi} \frac{U_{dc}}{2}$$

$$= \frac{\sqrt{6}}{\pi} U_{dc}$$

$$\simeq 0.78U_{dc}$$

Figure 78, sums up these working strategies.

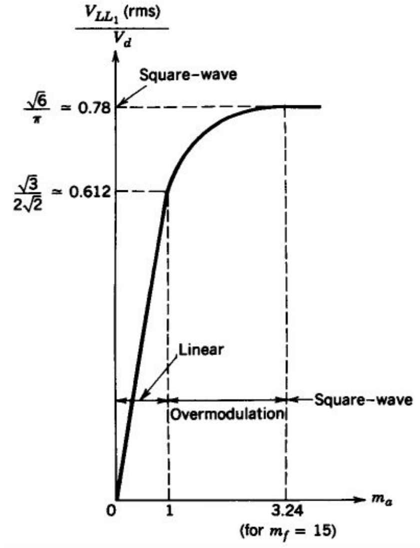


Figure 78 - Working strategies of the three-phase voltage converter - Source [32]

### 4.2.2 Other Possible Grid Configurations

The wave generation system was chosen as a general structure to analyze the PCSs of the hybrid energy storage system. However, other grid configurations have been designed and are available in papers [33], [34], [35] and [36]. The converters for each ESS in every configuration are the same as the ones analyzed in the previous paragraph. Paper [33] proposes an HESS coupled to a photovoltaic (PV) plant as shown in Figure 79.

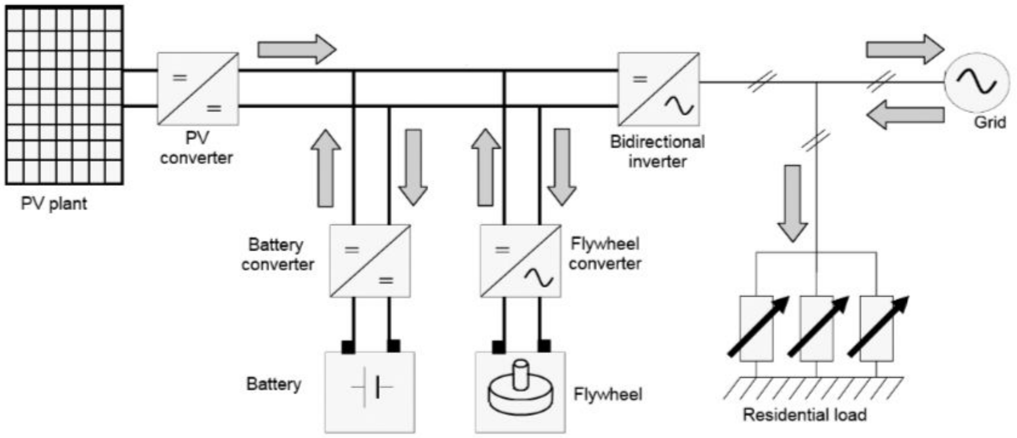


Figure 79 - Micro PV grid architecture - Source [33]

Paper [34] presents a grid configuration where the HESS is used to compensate the power fluctuation of a large scale wind farm in Cheju Island, Korea. The battery is connected to the system through the usual DC/DC converter coupled with a AC/DC inverter, as shown in Figure 80. The AC/DC inverter plays the role of the active rectifier, whereas the DC/DC operates as the charger. The FESS instead is connected to the grid through two full-bridge converters in cascade arrangement as in Figure 81. Plus, as Figure 82 shows the daily output power variability of the wind farm, Figures 83 and 84 show the power compensating operations of the BESS and the FESS.

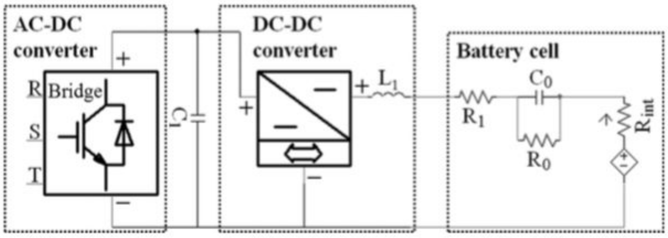


Figure 80 - Battery model and control set - Source [34]

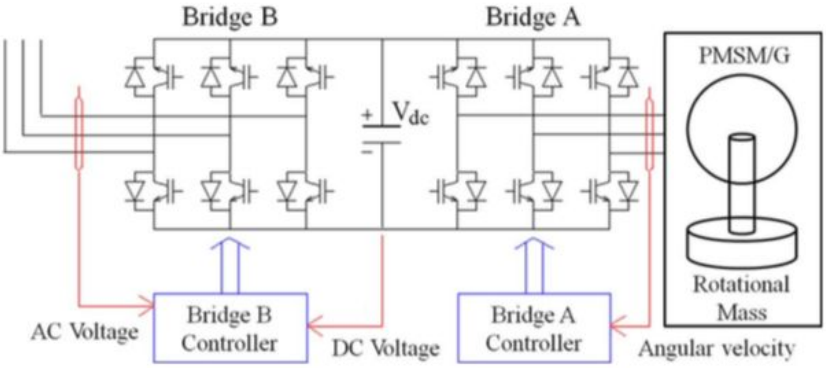


Figure 81 - Grid connection of the flywheel - Source [34]

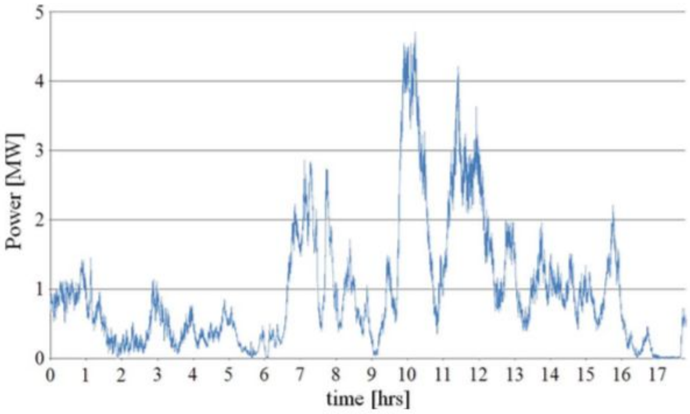


Figure 82 - Daily output power variability of the wind farm - Source [34]

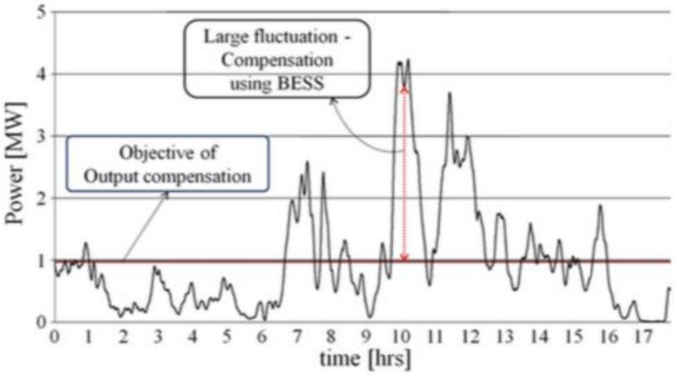


Figure 83 - Compensating operation of BESS - Source [34]

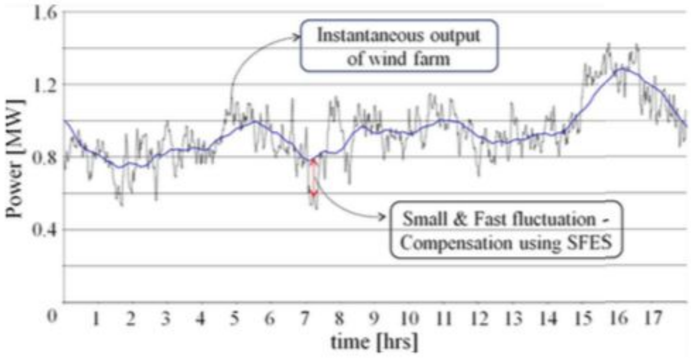


Figure 84 - Compensating operation of FESS - Source [34]

Figures 85 and 86 show the cumulative energy in each ESS.

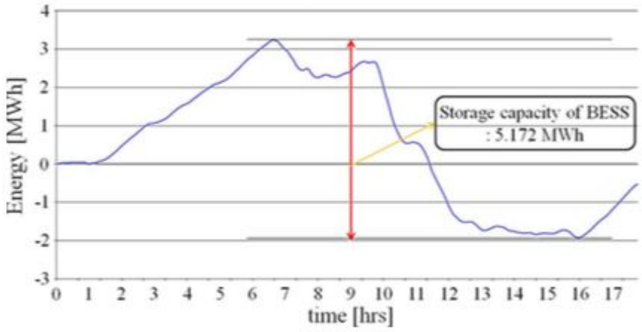


Figure 85 - Cumulative energy in the BESS - Source [34]

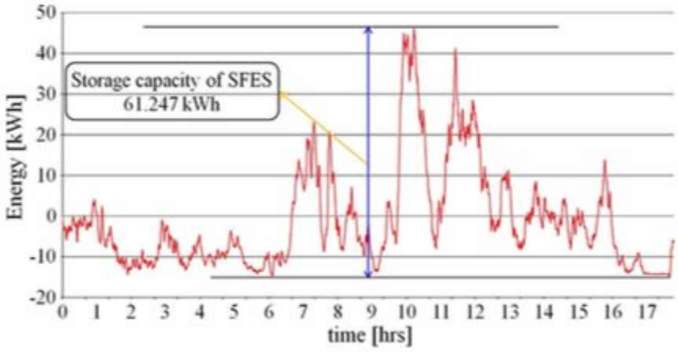


Figure 86 - Cumulative energy in the FESS - Source [34]

Paper [35] presents a HESS with Li-ion battery and flywheel for a wind generator based DC microgrid. Figure 87 shows the configuration.

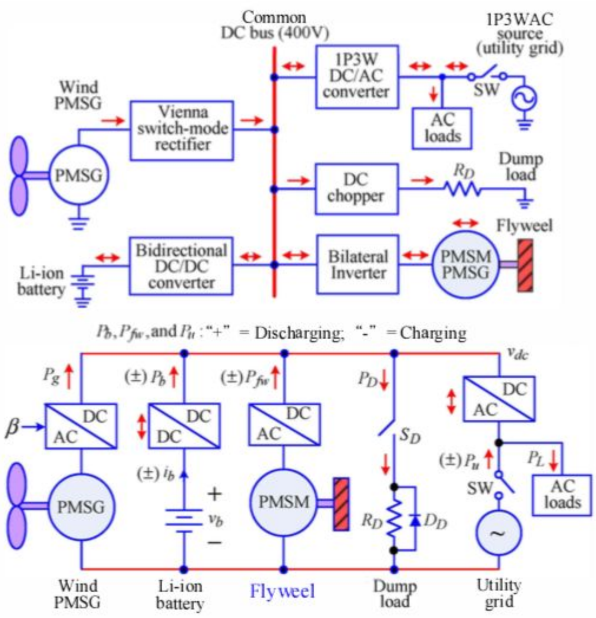


Figure 87 - System configuration of the DC micro-grid - Source [35]

Source [36] shows how it’s possible to integrate multiple HES systems: in this microgrid a FESS and a BESS are present as well as Fuel Cells, Diesel Engine Generators, Solar Photovoltaic generators, Aqua Electrolyser and Wind Turbine Generators (Figure 88).

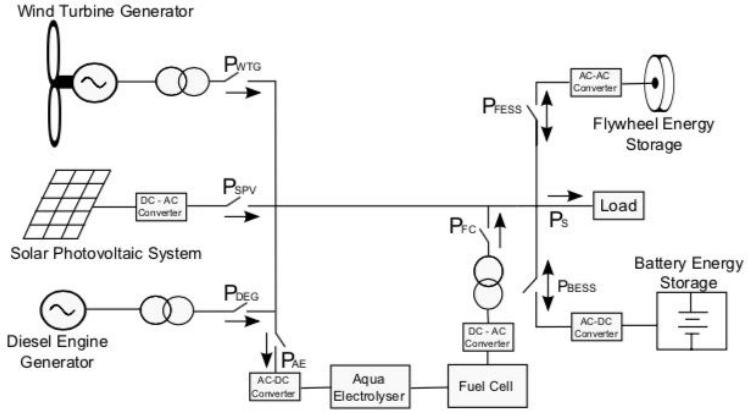


Figure 88 - A micro-grid configuration - Source [36]

## 4.3 Control System

In order to get the best outcome and the maximum advantages out of a Hybrid Energy Storage System and in general of each Energy Storage System involved, it is necessary to develop a sophisticated system management plan. The control and energy management strategy for a HESS is obviously more complicated than the one for a single ESS unit and that’s because of the heterogeneity of the system. And in order to take advantage of this heterogeneity, every aspect of each ESS should be taken into account, including power electronic devices and their efficiency, load, time frames and also non-linear and time-dependent characteristics like self discharge and memory effect.

The HESS architecture is the first and foremost factor governing control strategy design and implementation. As mentioned in paragraph 4.1, one of the properties of each architecture is its flexibility to plan various control strategies.

Generally, the aim of the control system is optimizing three tasks related to HESS utilization, which are *charge allocation, charge replacement* and *charge migration.* [7]

*Charge allocation* refers to the idea of optimizing the charging process by selecting the proper ESS taking into account technology’s type, State of Charge, voltage, current and time characteristics of the power source. *Charge replacement* strategy determines the most efficient ESS technology which can be discharged during power needs. It depends on load characteristics and capabilities and also on the State of Charge of the device. *Charge migration* is needed when the discharge rate of a specific storage system is quite high. If required, it can be appropriately carried out by precise forecasting of the future load demand as well as self discharge rate.

### 4.3.1 General Control Strategies

An intelligent control and optimizing management of the power flow distribution is essential for a good operation of any HESS. Generally two control and energy management concepts can be distinguished: *ruled-based* and *optimization-based.* [8]

The ***ruled-based*** concepts are well suited for real-time applications and the rules are created by an expert or mathematical models and can handle measurement imprecisions and component variations quite well. A simple ruled-based control strategy for HESS is the *thermostat* concept where the high energy storage system is switched on and off according to a lower and an upper State of Charge threshold applied to the high power storage system (as it will be in paragraph 4.3.2.2). A more advanced concept is the *state machine* control which can involve multiple rules defined on the basis of heuristic or expert experience. A further improvement is the *fuzzy logic* control where the power split between the two ESS is achieved in a smooth way without any switching involved by fuzzy-rules and membership functions. This strategy can be easily tuned to achieve nearly optimal operation.

The main characteristics of ***optimization-based*** approaches are the minimization of a cost function and they can divided into *global* (offline) and *real-time* (online) algorithms. Frequency decoupling is well suited for the second applications and it is usually accomplished by a simple low-pass filter or by advanced filter concepts based on wavelet or Fourier transform. The low frequency component supplies the set-point value of the power controller of the high energy storage system and the high frequency component is covered by the high power system (as it will be in paragraph 4.3.2.1). Another promising and widely used *optimization-based* energy management approach is the equivalent fuel consumption minimization strategy which aims to minimize an instantaneous cost-function (for example efficiency). Other approaches are based on classical PI controllers not requiring expert knowledge and allowing to be tuned easily on the basis of an online adaptation law.

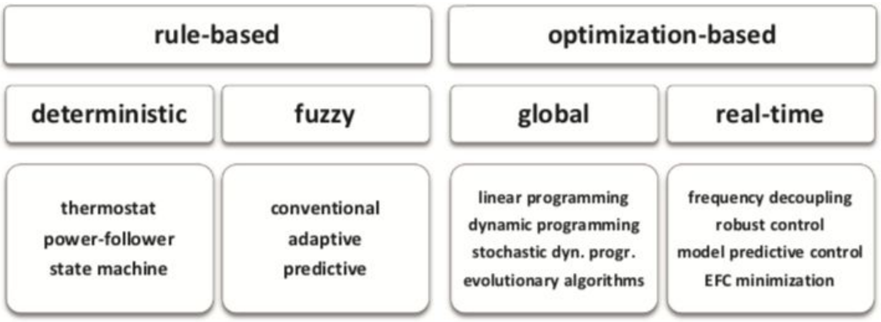


Figure 89 - Control and energy management concepts for HESS - Source [8]

### 4.3.2 Control Strategies of Charge and Discharge in a Fictitious Application

In this paragraph, the control strategies of the wave generation system mentioned in 4.2.1 are discussed as they represent a general yet efficient way to describe the charging and discharging processes of the HESS that can be applied to other, and perhaps more complex, grid configurations. It's fair to specify that this specific configuration has not been implemented in real life and has just been tested experimentally.

In this system, a Hybrid Energy Storage Controller (HESC) is designed to control the HESS and make decisions timely. The exceeding power is distributed to FESS and BESS through a low-pass filter algorithm at the charging state; at discharging state, FESS and BESS compensate the loss of power at different speed with the changes of coordinated coefficient *k*. Overall, the energy distribution of HESS is coordinated controlled to prevent the battery from overcharging and over-discharging.

The short response time and high-power discharging characteristics of the FESS allow to deal with voltage sag, inhibition of power system high frequency oscillation and instantaneous power failure. It can also make up for the shortcomings of short lifetime and low output capacity rate of battery.

### 4.3.2.1 The Charge Control Strategy of HESS

When the system is steady, the output *Active Power* and DC voltage are maintained at their reference values. If the input power is bigger than the output one, the spared part will increase the DC voltage and the output power as a consequence, resulting in a loss of control. So, the spared power must be absorbed by the HESS that works in charging state. The charge control strategy is shown in Figure 90.

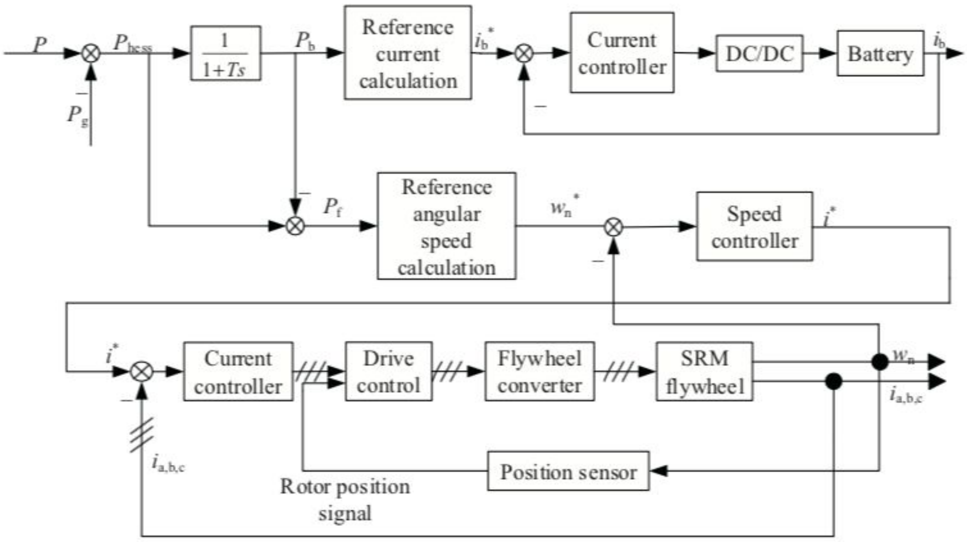


Figure 90 - Charge control strategy of HESS - Source [30]

When $P$ is larger than $P_g$, $P_{HESS} = (P - P_g) > 0$, HESS will operate in charging state. As the battery can not charge and discharge frequently while the flywheel can, a low pass filter is chosen to divide $P_{HESS}$ into an high frequency part $P_f$ and a low frequency one $P_b$. The two parts will be respectively absorbed by FESS and BESS.

$$P_b(s) = \frac{1}{1+Ts} P_{HESS}(s)$$

$$P_f(s) = P_{HESS}(s) - P_b(s) = \frac{Ts}{1+Ts} P_{HESS}(s)$$

The larger $T$ is, the lower cutoff frequency is. Then $P_b$ will be smaller and $P_f$ will be larger. Vice versa, the smaller $T$ is, the larger $P_b$ is. Choosing suitable time constant $T$ is important for distributing energy. There will be the following formulas for the reference current and reference angular speed calculation parts:

$$P_f = \frac{d}{dt}\left(\frac{1}{2}J\omega_n^{*2}\right) \Rightarrow \omega_n^* = \sqrt{\frac{1}{s}\frac{2P_f}{J}}$$

$$P_b = u_b i_b^* \Rightarrow i_b^* = \frac{P_b}{u_b}$$

The single closed loop control strategy is adopted for BESS. By sending the battery current error into current controller, the drive signal for DC/DC converter can be generated. The double closed loop control strategy with outer look of speed and inner loop of current is used for FESS. Because the motoring and braking states of SRM are closely related to the turn on and turn off angle, selecting right turn on and turn off angle in the motoring state is the first step to charge the FESS. Chopped current control strategy is used to control the SRM. After processing the output value of the current controller and the rotor position signal, the output results will be sent to the drive control step to generate drive signal. Finally, the drive signal will be transferred to flywheel converter to drive SRM flywheel accelerating and charging.

### 4.3.2.2 The Discharge Control Strategy of HESS

When the input power cannot support the load demand ($P < P_g$, $P_{HESS} < 0$), the DC voltage will drop. That's where the HESS comes in and makes up for the loss of power. In the discharging state, constant DC voltage is selected as the control target. This method can provide voltage support for the power of the grid and, when the voltage is stable, will keep the output power constant.

When the difference between the input power and the output power ($\left|\Delta P_{HESS}\right|$) is small enough, the FESS will be connected to the system alone to reduce the work frequency of the battery to preserve its lifetime. When instead $\left|\Delta P_{HESS}\right|$ is large enough to a certain range, FESS and BESS will be accessed to the system at the same time. HESS will work in the hybrid discharging state. The structure of the discharge control strategy is shown in Figure 91.

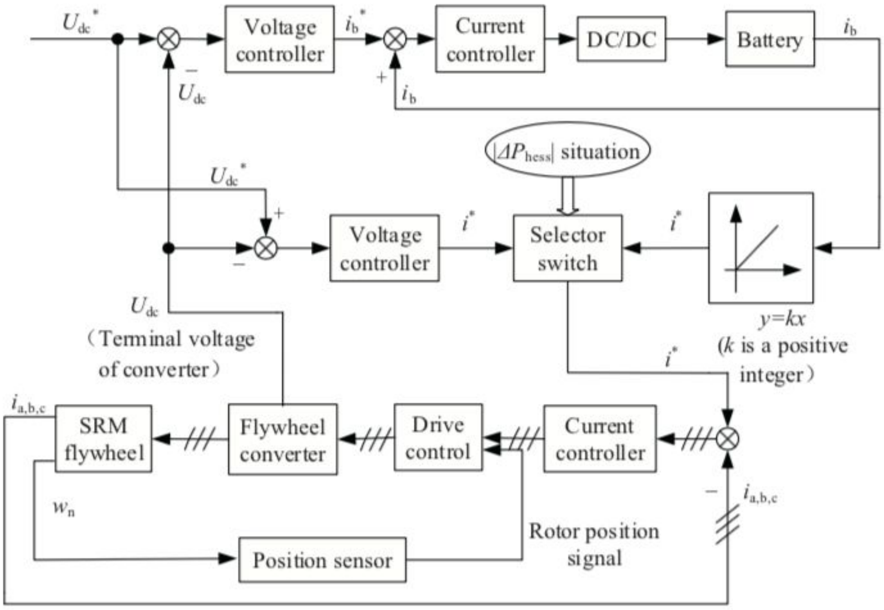


Figure 91 - The discharge control strategy of HESS - Source [30]

The selector switch can realize the switch between FESS alone discharging state and HESS discharging state according to $\left|\Delta P_{HESS}\right|$ and the State of Charge of the battery. At the HESS discharging state, the discharging current of the battery $i_b$ is linked to the reference control current of the flywheel $i^*$ via a linear function $y=kx$. $k$ is decided by the SoC and controlled by HESC. The single closed loop control strategy is also adopted for BESS discharging. The same control structure of the charge process for FESS is adopted at discharging state. At the same time, change the turn on and turn off angle or SRM to braking state to make the SRM flywheel decelerate and discharge.

#### 4.3.2.3 The Control Strategy of HESC

The HESC is the core part of the system as it can detect the changes of DC voltage, input power and grid power. On the other hand, it can make decisions to switch charging and discharging state and strategies as well as regulate the coordinated coefficient *k.* The control flow graph of HESC is shown in Figure 92.

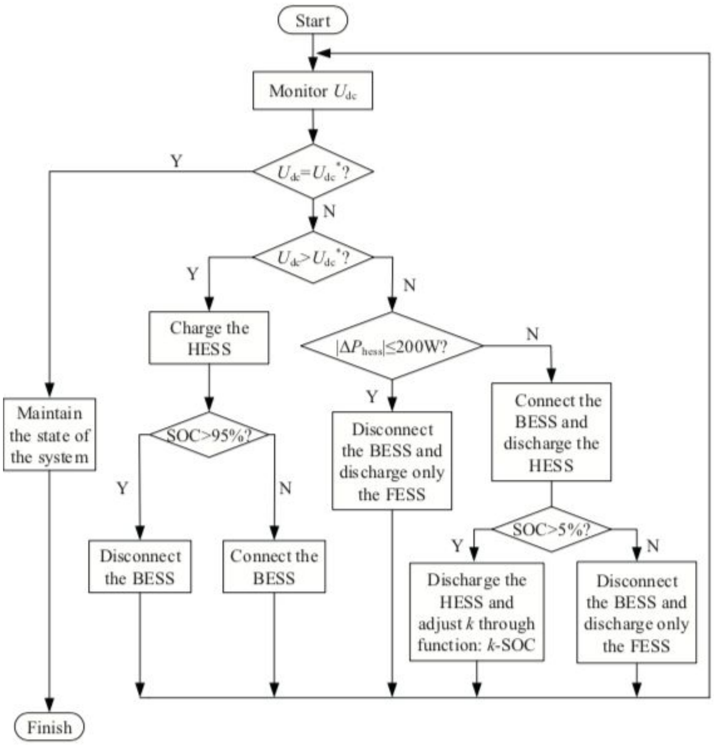


Figure 92 - The state flow graph of HESC - Source [30]

Three cases are presented:

- If $U_{dc} = U_{dc}^*$ the input and output are exactly balanced and the system should keep the original state.
- If $U_{dc} > U_{dc}^*$ , $P$ is larger than $P_g$ so the HESS should charge to absorb the redundant power. At charge state, if SoC > 95%, the BESS will be disconnected to prevent the battery from overcharging.
- If $U_{dc} \leq U_{dc}^*$ , energy storage unit will discharge to compensate the loss of power. If $\left|\Delta P_{HESS}\right| \leq a\ certain\ n°$, the power fluctuation will be small, so the FESS will discharge alone. Otherwise, FESS and BESS will discharge at the same time. At this stage, the coefficient *k* is adjusted on the basis of the SoC. The function relationship between *k* and SoC is shown in Figure 93. *k* will

increase with the decrease of SoC when there is a condition that 5%<SoC≤15%. The discharge velocity of FESS will also increase with the decrease of SoC and the power compensated by the FESS will be larger and larger. This process can reduce the depth of discharge of the battery. If Soc>15%, *k* will be constant because the SoC is at safe condition. At the discharge process, if SoC≤5%, the BESS should be disconnected to prevent the battery from over discharging.

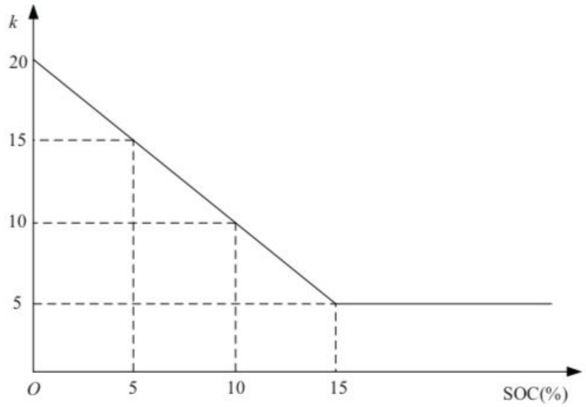


Figure 93 - The function of *k*-SoC - Source [30]

### 4.3.3 Control Strategies for Frequency or Voltage Events in a Existing Application

Some control modes and algorithms have been designed by Schwungrad Energie aiming to test the capability of a real existing HESS in Ireland to respond to some frequency or voltage events providing *Active* and *Reactive Power* outputs. [26] The results of these tests have already been covered in Chapter 3.

The inputs for the control system are provided by a high resolution frequency monitoring equipment, used to provide dynamic and smooth response in all operational modes enabling a different output for every 10 mHz. In addition to dynamic response, the plant can deliver full power in two situation:

- when the frequency dips below a particular threshold, typically 49.80 Hz

- on detection of a Rate of Change of Frequency (RoCoF) event

On detection of a high rate of RoCoF event the plant delivers full power for 5 seconds after which it reverts to monitoring the grid frequency and adjust the power output accordingly. The injected energy is replaced during the normal periodic equalisation charge or, in some cases following frequent usage, the system is charged when the frequency is within the $\pm 0.05\,\text{Hz}$ deadband. This maintains the State of Charge within present limits.

#### 4.3.3.1 Frequency Response

Imbalances in the power system, between generation and consumption can increase or decrease the desired nominal frequency of 50 Hz. One of the primary functions of the HESS is to provide frequency response so it will inject power as the frequency of the grid falls and can also absorb excess power if it rises. The frequency modes designed are three.

##### Mode 1: Static Response Mode

It's the least complex operational mode and was designed primarily for test purposes, but still considered relevant, minimising the processing and calculation requirements on the control system. This mode delivers a triggered MW response once a frequency threshold has been breached. The mode includes a deadband where the device will provide no frequency response and a droop characteristic between the edge of the deadband and the static trigger response. A frequency recovery trigger point is also included to trigger the device back down to the droop line. Recharging the flywheels and batteries after an event to return them to a preset State of Charge occurs only when the frequency has sufficiently recovered i.e. is within the deadband. If the frequency rises above the deadband (set at 50.05Hz for example) the control algorithm causes the flywheels and batteries to absorb power to reduce the frequency back towards 50Hz.

##### Mode 2: Feedback Response Mode

Response mode is the most intelligent mode and is designed to deliver an enhanced performance from the HESS. It has been designed to gradually reduce the power output as the frequency recovers from the fault. This mode delivers a triggered MW response once a frequency threshold has been breached. The mode includes a deadband where the device will provide no frequency response and a droop characteristic between the edge of the deadband and the triggered response point. The device then provides a droop response on frequency recovery. Recharging the flywheels and batteries after an event to return them to a preset State of Charge occurs only when the frequency has sufficiently recovered i.e. is within the deadband. If the frequency rises outside the deadband the control algorithm causes the flywheels and batteries to absorb power to reduce the frequency back towards 50Hz.

#### Mode 3: Droop Mode

In Droop Mode the HESS provides an output that is similar to the one provided by large traditional generators. The slopes get more pronounced as the frequency falls away from 50Hz. There is no large step in power output which increases gradually based on two slopes and can cover the full range of frequency becoming steeper as grid frequency deviates further from nominal. The mode includes a deadband within which the device does not provide frequency response. Outside the deadband the device provides a proportional droop response to frequency. Once the frequency breaches a pre-set threshold, the device provides a proportional droop response on a more aggressive droop slope. The slopes of both droop characteristics are settable.

Recharging the flywheels and batteries after an event to return them to a preset State of Charge occurs only when the frequency has sufficiently recovered i.e. is within the deadband. If the frequency rises outside the deadband the control algorithm causes the flywheels and batteries to absorb power to reduce the frequency back towards 50Hz.

### 4.3.3.2 Voltage Response

In the voltage response modes, the plant absorbs or injects *Reactive Power* as the substation network voltage increases or decreases. The voltage is referenced to the medium voltage distribution network which is currently set at 20 kV (variable). The hybrid plant is able to deliver *Reactive Power* in any point of the quadrant of the *Apparent Power* i.e. it can provide any combination of *Active* and *Reactive Power* which means it can separately provide frequency and voltage control. The control system prioritises the delivery of *Active Power* over the *Reactive*: for example, if the frequency drops and *Active Power* is required, this reduces the *Reactive Power* available to control the voltage. Three control modes are present here as well.

### Mode 4: Power Factor Control Mode

In Power Factor Control Mode, the *Power Factor* can be set between 0.95 and 1. The plant is capable of both leading and lagging but as it is connected at medium voltage to the distribution network there is a restriction that the plant is not allowed to export *Reactive Power*. This restriction would not apply if the plant was connected to the transmission grid. The *Reactive Power* is calculated to give the required power factor at the *Active Power* output at that moment. This algorithm also determines an offset if the voltage is outside a range between a minimum and maximum voltage setpoint. It adds/subtracts that offset to the *Reactive Power* needed, only when the voltage deadband thresholds are breached. It should be noted that the algorithm calculates a *Reactive Power* command which provides the required power factor for the *Active Power* command at that time i.e. the *Active Power* and *Reactive Power* commands to the flywheels and batteries yield the desired power factor. The actual *Active Power* and *Reactive Power* at the point of connection will be slightly different because of the effects of the transformer and also any house load.

### Mode 5: Voltage Control Mode

Voltage Control Mode is designed to bring the local voltage to the desired set point, based on a droop characteristic. If the local voltage is below the set point, the plant will export kVAR to increase the voltage. Conversely, if the local voltage is above the set point, the plant will absorb kVAR to reduce the voltage. In a commercial plant connected to the transmission grid, the TSO (Transmission System Operator) would send the voltage set point to the plant as a command. As this in particular is a demonstration plant of less than 0.5MW connected into the local distribution network, it is determined to be uneconomical to set up such communications with the TSO. Instead the set point is adjusted manually with the control system

### Mode 6: Reactive Power Control Mode

The Reactive Power Control Mode needs the TSO to send a command to the plant to provide kVAR exporting or importing. Again this is deemed unfeasible for a small demonstration plant. Instead such commands are given locally through the control system. The Reactive Power control algorithms are tested offline during commissioning.

# Chapter 5 - Applications

The HESS that integrates batteries and flywheels is a recent technology in stationary applications. All over the world just three companies have implemented or are implementing it and they are:

- Schwungrad Energie Ltd, Ireland
- Chugach Electric Association / ABB, Alaska
- Jamaica Public Service Ltd / ABB, Caribbean

## 5.1 Schwungrad Energie Ltd

Schwungrad Energie Limited is an Irish company founded in 2010 but formally established in 2013. Its 400 kW hybrid flywheel/battery pilot is set in Rhode, Co. Offaly, Ireland.

### 5.1.1 Background

As already anticipated in Chapter 3, Ireland is an island electricity system with a peak demand of 6,878 MW, which is relatively small on a global scale. The Irish grid has a limited interconnection capacity of 1000 MW (2 x 250 MW Moyle and 500 MW EWIC - the East West Interconnector) representing an import/export capability of 15% of peak demand. All the interconnection is DC and there is no synchronous AC interconnection. Furthermore the electrical grid is undergoing significant change due to a large increase in renewable generation driven by government objectives to reach 40% renewable generation by 2020. The majority of this will be delivered from wind generation, which currently accounts for 21% of Ireland’s electricity demand. The combination of low interconnection capacity and high renewables results in periods of very high system non-synchronous penetration (SNSP). The Delivering a Secure Sustainable Electricity System (DS3) programme was initiated by EirGrid (TSO in Ireland) and SONI to address the challenges of managing a power system with high levels of SNSP.

Challenges include, controlling system frequency and voltage for adverse system events and maintaining overall stability of the grid. Traditionally the grid frequency was set by the rotational speed of electrical machines spinning in synchronisation at 3,000 rpm. The output of these machines is controlled to accurately match the instantaneous system demand, which is relatively predictable. The deployment of non-synchronous machines, such as wind turbines whose output is dependent on the volatile wind speed, introduces two issues:

- lack of system inertia
- unpredictable power generation

the combination of which results in an imbalance between power supply and demand. New sources of fast acting frequency response, are required to continue maintaining the grid frequency at a nominal 50 Hz (± 0.20 Hz). Fast acting frequency response can be delivered as a rapid injection of Real Power (MW) from a non-synchronised source, of a magnitude dependent on the change in grid frequency, quickly reconciling momentary any imbalance between the supply and demand for electricity.

Schwungrad Energie Limited has developed a flywheel/battery hybrid on the grid at Rhode, Co. Offaly and have engaged in a demonstration project with EirGrid to trial the technology. The demonstration enabled performance validation in preparation for commercial deployment of the solution in Ireland and subsequently Great Britain and mainland Europe as their grids realise similar levels of non-synchronous renewable penetration. This was a Demonstration Project in conjunction with EirGrid who provided a Disturbance Recorder to validate the performance.

### 5.1.2 The Project

The plant has been designed specifically as a research facility which has added features to enable testing and monitoring. Figure 94 shows an actual picture of the plant.

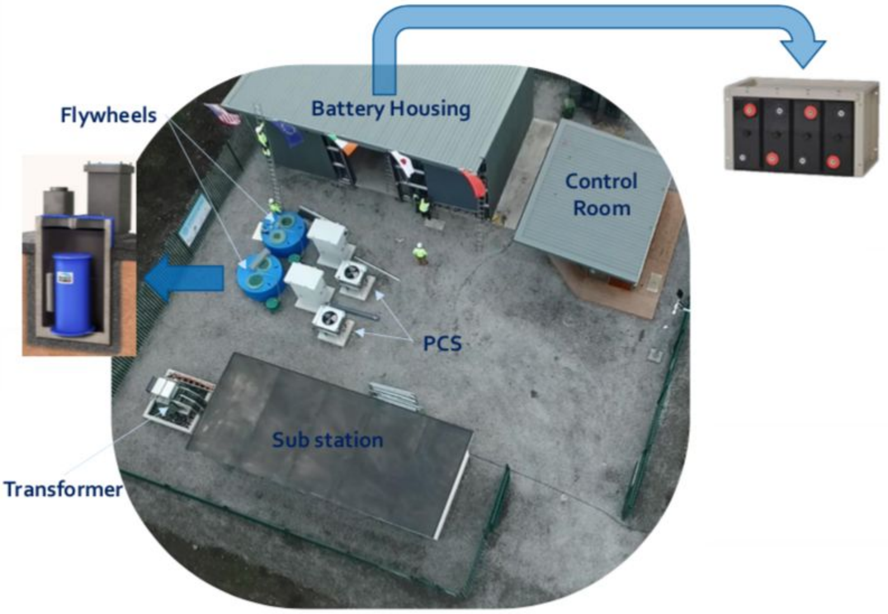


Figure 94 - Plant of the Irish project - Source [37]

The flywheels are two, 160 kW each and they are provided by Beacon Power, an American company that has great experience in the flywheel sector specifically for the power industry. Their technical description is in Figure 95. They can provide full output for 5 minutes and then a reduced output for the following 10 minutes. They speed at maximum 16,000 rpm and have magnetic bearings. Placed mostly underground to reduce noise pollution and stabilize the axis.

- Manufacturer: Beacon Power, LLC.
- Flywheel Model: Gen. 400 FESM
- Design life: 175,000 cycles (20 years)
- Supply Voltage: 480 VAC
- Power rating: 160 kVA
- Storage capacity: 30 kWh
- Response time: 100 ms
- Roundtrip efficiency: > 85%
- Power Control Module (PCM): Converts variable speed motor output into a clean and stable source of AC power.
- Dry Cooler: Fan power 480 VAC

Figure 95 - Flywheel technology - Source [26]

The batteries are 192 Hitachi Chemical lead-acid batteries that provide 160 kW and storage capacity of 576 kWh, more than what the Irish grid needs but that is how the batteries were set up. They can be worned for 1.1 hours and reach a Depth of Discharge of 30%. The choice of lead-acid chemistry is related to the fact that because the market in Ireland is looking for plants that are ready to inject power into the system when the frequency system falls, and that only happens 30-40 times a year, not a huge number of cycles are required. That obviously means that when different requirements and more challenging grid situations occur, the lithium-ion technology would be more suitable. Figure 96 gives a general description of the battery technology.

Hitachi Chemical
Working On Wonders

- Manufacturer: Hitachi Chemical Co., Ltd.
- Battery model: LL1500-WS
- Battery type: Valve Regulated Lead Acid (VRLA)
- Design life: 4,500 cycles (17 years)
- Number of cells: 192
- Number of parallel strings: 1
- Power rating: 160 kVA
- Battery capacity: 1500 Ah (576 kWh)
- DC voltage: 400 V
- Weight: 195 kg

Figure 96 - Battery technology - Source [26]

The flywheels and the batteries are connected to the 20 kV distribution network. The transformer though has two toppings since the flywheels are American and have a voltage of 480 V whilst the batteries are at 400 V. Both flywheels have a PCS which is managed by a Beacon system placed in the Control Room. The batteries have their own FREQCON power conversion system (Figure 97). The YOKOGAWA general control system manages the FREQCON and the Beacon (Figure 98).

- Manufacturer: Freqcon
- Model: NGC 160kW Converter
- IGBT type SKiiP 603 GD123-3DUW V3
- Rated AC voltage (Vr) 400 V, 3-phase system
- Rated AC current 232 A
- Rated power (Pr) 160 kW
- DC link voltage ±450 V (working range 200V to 700V)

Figure 97 - Batteries' PCS - Source [26]

- Manufacturer: Yokogawa
- FAST/TOOLS SCADA
- Exequantum data historian

Figure 98 - General control system - Source [26]

### 5.1.3 Performance of the Plant

As with the battery, the flywheel has operational constraints which were specified by Beacon Power. These constraints are very different for the flywheel than the battery as they are mechanical as opposed to chemical but refer to the same parameters such as State of Charge, charge/discharge rates etc. For example the State of Charge of the flywheel needs to be continuously conditioned, consuming power, as it has higher losses than the battery.

The Valve Regulated Lead Acid battery supplied by Hitachi Chemical Co., Ltd. has specific operational constraints for the battery. The constraints include maximum power output/input, maximum and minimum State of Charge and maximum depth of discharge etc. These were taken into account when designing the control system to ensure the optimum balance between conservation of battery life and delivery of DS3 system services.

Figure 99 shows the profile of power delivery during a four week period. It indicates that for the vast majority of the time the battery remained in standby mode where the power output was nearly zero (<5kW). The impact of this on the power system is that it can operate with a high penetration of renewables without the need for curtailment as the battery is a non-energy source of reserve. The graph also shows that the battery delivered full power during the course of the month but for a very short time, a fraction of a one hour.

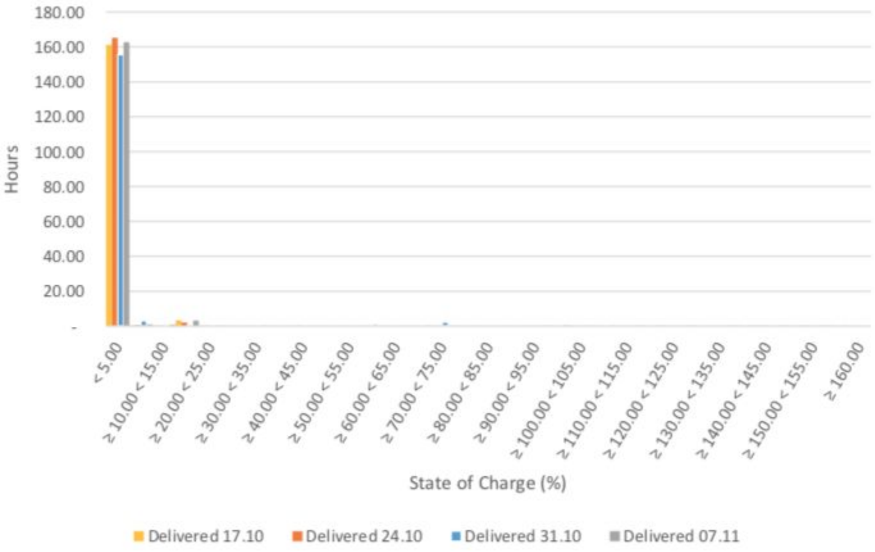


Figure 99 - Battery delivered kW distribution - Source [26]

Maintaining a high State of Charge ensures that the plant availability is maximised allowing for multiple successive responses to system frequency events without the need to recharge. The State of Charge of the battery is shown in Figure 100 to be between 85% and 90%. This is within the design specification of the lead-acid battery technology and also very suitable for the demands of unidirectional system services as for example provision of additional power output.

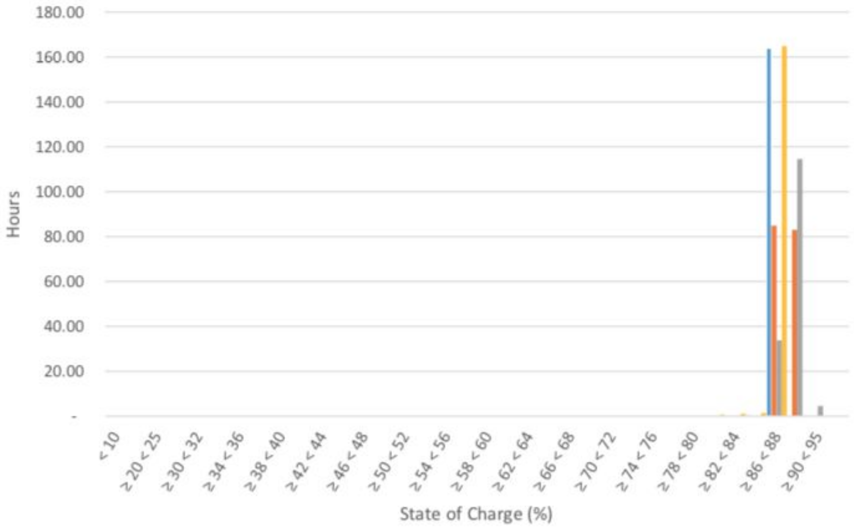


Figure 100 - Battery State of Charge distribution - Source [26]

## 5.2 Chugach Electric Association / ABB

Chugach Electric Association (Alaska) and ABB (Switzerland) are two companies working together to better manage the Alaskan transmission grid, specifically in Anchorage.

### 5.2.1 Background

Fire Island is a small island near the tip of Cook Inlet in the Municipality of Anchorage, Alaska. While it once served as an Air Force station, the island now sits vacant other than a privet FAA aviation airfield and a wind farm. The 11-turbine, 17.6 MW wind farm, built by Fire Island Wind LLC in 2012 (a subsidiary of island owner Cook Inlet Region Incorporated or CIRI), is the first megawatt-scale project in South-Central Alaska. According to Fire Island Wind, the aim of the project was to ease the strain on the natural gas supply in Cook Inlet. Although the wind farm can generate more than 50,000 MWh annually for the utility, Chugach Electric Association, leveraging the project's full capacity has been a challenge over the years. Power usage of this wind farm is relatively low: it sells roughly 4% of the retail capacity of Chugach Electric, so it is not a large proportion or quota of the overall electricity sold by the utility into the

Anchorage area. A problem for the utility is variability of the load and supply as Anchorage is served with a number of different energy sources: wind energy, hydropower, gas, and fire or thermal capacity. Transportation of fuel is another concern. The city has ports, which can mean heavy transportation loads coming from vessels and cranes. This can lead to further pressure on the utility to keep up with power demands. To better manage the load and demands, Chugach Electric needs to add regulatory capacity to the transmission grid, which, at only about 500 MW, is not a large grid.

### 5.2.2 The project

Chugach Electric Association is working with ABB on a *microgrid stabilization* project that will improve power scalability, test scalability and identify a system that enables the integration of more renewables. The project combines a 2 MW Li-ion battery with storage capacity of 500 kWh from Samsung and a PowerStore flywheel from ABB. The PowerStore system uses a flywheel for fast release and sync of power, which can go up to one megawatt per second and then back down again. These fast variations are managed by a flywheel, where it excels, and the slower variations are dealt with through battery storage. The overall system is controlled by The Microgrid Plus Control System which is responsible for coordinating the operation of different generation sources and loads. So it monitors the hybrid storage system to ensure proper load sharing between the two storage devices and is equipped for remote service and maintenance, which makes it ideal for use in Alaska. An example of its functionalities is shown in Figure 101.

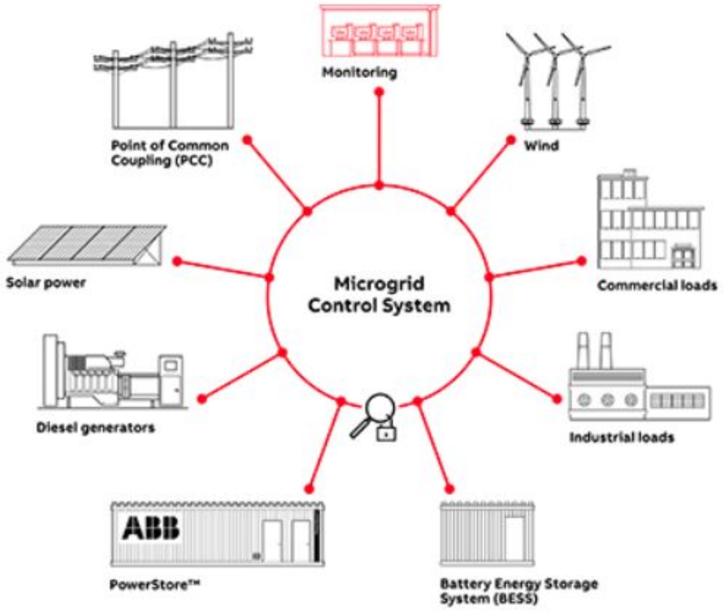


Figure 101 - Microgrid Plus control system - Source ABB

The PowerStore is a compact and versatile grid stabilizing generator. Its main purpose is to stabilize power systems against fluctuations in frequency and voltage. Stabilizing the grid needs highly dynamic power injection and absorption for short amount of time, while common energy storage solutions require slower response and discharge over longer time. It combines a low speed flywheel with solid state converters to provide reliable and high-performance grid stabilization. [38]

The PowerStore is able to inject and absorb power up to its nominal power rating and it is available in a range of models from 500 kW to 1.5 MW and can be configured to operate in either a grid support mode for use in multi-megawatt grids or as a virtual generator for use in smaller isolated microgrids. The PowerStore consists of:

- Flywheel spinning mass including motor/generator
- AC-DC-AC converter system
- Operator interface
- Container-based building (optional)

Figure 102 gives a simple visual representation of it.

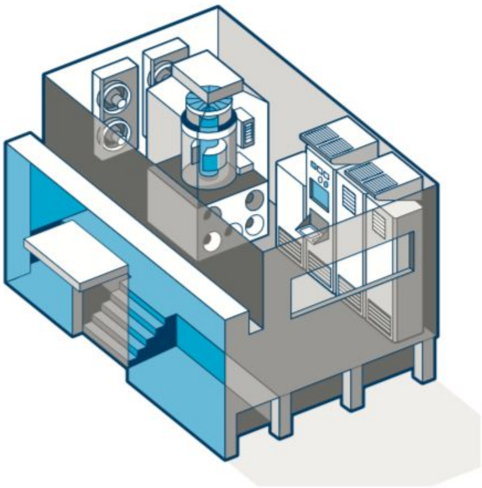


Figure 102 - PowerStore representation - Source [38]

The unit has a lifting magnet that holds the weight of the 3,000 kg flywheel during operation, ensuring a long bearing life, reduced losses and low maintenance. Oversized primary mechanical bearings are also included to hold the weight of the flywheel while it is stationary and below operational speed while catch bearings are installed to provide a fail-safe system. The design incorporates proven technologies in order to deliver worry free years of operation.

The AC-DC-AC converter system hardware is based on customized PCS100 insulated gate bipolar transistor (IGBT) power converters from ABB. Using these proven modules results in a highly reliable design with an installed base of thousands of units worldwide. The use of back-to-back IGBT converter pairs allows the flywheel to rotate at variable speed enabling the injection and absorption of power. Multiple converter pairs are paralleled to achieve the desired model rating. The PowerStore is able to export and import at maximum power ratings regardless of the state of charge, from 0% to 100% capacity; there is no need to derate the PowerStore for lower state of charge. For example, 100% of power injection until the PowerStore is completely empty, or 100% power absorption until the PowerStore is completely full is possible. This gives the PowerStore its unique fully symmetric power ratings, and the ability to charge with as much power as it can discharge. The converter modules are configured for redundancy which means that the PowerStore will continue to operate despite the failure of one module. An operator interface is used to monitor the flywheel and converter components and to provide access to historical data. Figure 103 presents a typical circuital scheme of the PowerStore.

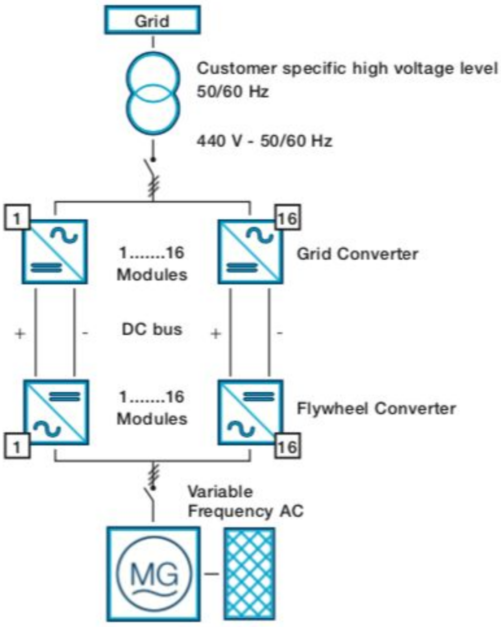


Figure 103 - PowerStore overview scheme - Source [38]

## 5.3 Jamaica Public Service, Ltd / ABB

Suddenly not many informations are available for this project (JPS Grid Stability) as it's realization is set for 2019. It's a collaboration between the Jamaica Public Service Limited and ABB to serve the Jamaican grid, in Hunts Bay, which involves a photovoltaic plant and a wind farm for a total of 160 MW of RES energy capacity. ABB will provide the Li-ion batteries as well as the flywheels. The technology of the flywheels is the same as the Alaskan project, so a PowerStore flywheel, and in this case a battery PowerStore is also provided. This last one is a containerized plug-and-play microgrid solution that includes Li-ion batteries, the PCS, a HMI (Human Machine

Interface), the Automation and a remote monitoring powered by ABB Ability. The Li-ion batteries provides 21.5 MW and have a storage capacity of 16.6 MWh, while the 3 flywheels provide each one 1 MW and have a storage capacity of 16.5 MWs.

The aims of this project are:

- Maximum utilization of wind and PV energy
- Provide reliable power to 5 million people in the island
- Provide power during intermittency of RES
- Reduce the dependency on fossil fuels and lower carbon footprint

Figure 104 shows a picture of the Jamaican wind farm.

Figure 104 - Jamaican wind farm - Source [39]

# Conclusions

The idea of integrating different energy storage technologies is progressively developing and many combinations are possible. The complementary operating characteristics in terms of energy, power and discharge time of the Li-ion battery and the flywheel candidate this particular hybrid system as an optimal solution to support future grids where the amount of RES involved will be quite solid. It's obviously a technology still under development and more and more institutions are considering it in their studies (the University of Padua and the University of Sheffield are some examples) but its possible benefits are already showing through. From the idea that this system can provide multiple grid services not reachable by a single technology to the hypothesis that flywheels could preserve the lifetime of the battery resulting in economic savings and reduced environmental impacts, the future of this technology seems very bright. Hopefully, this thesis gave an overview of its potentiality and also its limitations, providing a useful and compact source of informations to those who aim to study or develop this technology.

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*Padova, 7 Dicembre 2018*
*Laura*