







MESFIA 

**MESFIA**




Co-funded by the Erasmus+ Programme of the European Union 

**ENERGY STORAGE SYSTEMS-OTHER STORAGE MEANS**

   
Co-funded by the Erasmus+ Programme of the European Union  INSTITUTO TECNOLÓGICO DE CANARIAS

MESFIA 

**ULTRACAPACITORS  
SUPERCAPACITORS**


Co-funded by the Erasmus+ Programme of the European Union   

## MESFIA SUPERCAPACITORS (or ultracapacitors)

High-capacity capacitor (capacitance value much higher than other capacitors), that **bridges the gap between electrolytic capacitors and rechargeable batteries.**

Compete with rechargeable batteries, especially lithium-ion batteries:

- It can accept and deliver charge **much faster than batteries**
- It tolerates many **more charge and discharge cycles** than rechargeable batteries
- Feature **higher peak currents**
- **Low cost per cycle**
- No danger of overcharging
- The lifetime of supercapacitors, **can reach 10 to 15 years** or more at room temperature.
- **Specific power is typically 10 to 100 times greater than for batteries** and can reach **values up to 15 kW/kg**



| Specific energy                |   |
|--------------------------------|---|
| Supercapacitors                | 0.5 to 15 Wh/kg   |
| Conventional lead-acid battery | 30 to 40 Wh/kg  |
| Modern lithium-ion batteries   | 100 to 265 Wh/kg  |
| <b>Petrofuel</b>               | <b>12,300 Wh/kg (resulting in 3,700 Wh/kg if efficiency of 30 % in ICE is considered)</b> |

Co-Funded by the Erasmus+ Programme of the European Union

itc

Gobierno de Canarias


## MESFIA SUPERCAPACITORS (or ultracapacitors)

Although the specific energy of supercapacitors is lower than batteries, they offer the **advantage of the specific power** (the speed at which energy can be delivered to/absorbed from the load).

**Li-ion batteries** offer lower purchase cost and stable voltage under discharge, but **require complex electronic control** and switching equipment, with consequent energy loss and spark hazard given a short.

Supercapacitors have **advantages** in applications:

- Where a **large amount of power is needed for a relatively short time**
- where a very **high number of charge/discharge cycles**
- Where a **longer lifetime** is required.
- Where **many rapid charge/discharge cycles**, rather than long term compact energy storage



Supercapacitors can stabilize voltage fluctuations for powerlines by acting as dampeners

- They **can be implemented as an interface between the load and the grid** to act as a buffer between the grid and the high pulse power drawn from the charging station.
- Due to its tens of thousands of cycles of charge and discharge cycle life and high current charge and discharge characteristics, **supercapacitors can adapt to high current fluctuations of RES**

Co-Funded by the Erasmus+ Programme of the European Union

itc


Gobierno de Canarias

**MESFIA** SUPERCAPACITORS (or ultracapacitors)

Ultracaps rapid charge-discharge features, **can absorb and energy conveniently under fluctuating RES** generation and achieve better grid connection.

They **temporarily store a large amount of energy and power provided by the cyclical nature of RES**. They also **provide peak power delivery when combined with a low-cost lead-acid battery, extending battery life by a factor of four**.

The **UltraBattery is a hybrid rechargeable lead-acid battery and a supercapacitor**. The resulting cell performs with characteristics beyond either a lead-acid cell or a supercapacitor, with **charge and discharge rates, cycle life, efficiency and performance all enhanced**.



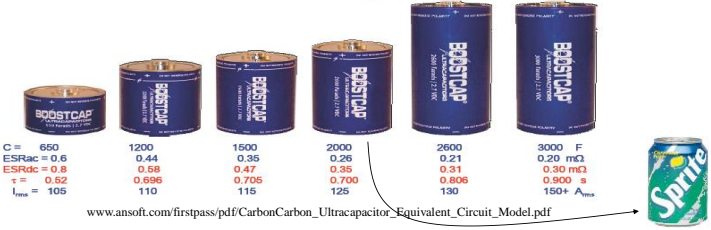
- Supercapacitors buffer power to and from rechargeable batteries, **mitigating the effects of short power interruptions and high current peaks**.
- Batteries kick in only during extended interruptions, e.g., if the mains power or a fuel cell fails, which **lengthens battery life**.
- **This combination reduces the cost per cycle, saves on replacement and maintenance costs, enables the battery to be downsized and extends battery life**

Co-Funded by the Erasmus+ Programme of the European Union

itc Gobierno de Canarias

**MESFIA** Ultracapacitors-Size

• Some typical Maxwell's ultracapacitor packages:



|                  |      |       |       |       |       |                       |
|------------------|------|-------|-------|-------|-------|-----------------------|
| C =              | 650  | 1200  | 1500  | 2000  | 2600  | 3000 F                |
| ESRac =          | 0.6  | 0.44  | 0.35  | 0.26  | 0.21  | 0.20 mΩ               |
| ESRdc =          | 0.8  | 0.58  | 0.47  | 0.35  | 0.31  | 0.30 mΩ               |
| τ =              | 0.52 | 0.696 | 0.705 | 0.700 | 0.806 | 0.900 s               |
| I <sub>max</sub> | 105  | 110   | 115   | 125   | 130   | 150+ A <sub>max</sub> |

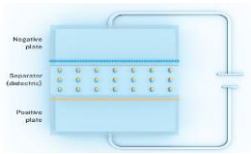
[www.ansoft.com/firstpass/pdf/CarbonCarbon\\_Ultracapacitor\\_Equivalent\\_Circuit\\_Model.pdf](http://www.ansoft.com/firstpass/pdf/CarbonCarbon_Ultracapacitor_Equivalent_Circuit_Model.pdf)

- At 2.7 V, a BCAP2000 capacitor can store more than 7000 J in the volume of a soda can.
- In comparison a 1.5 mF, 500 V electrolytic capacitor can store less than 200 J in the same volume.

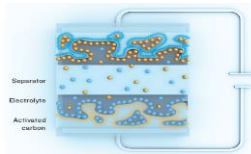
Co-Funded by the Erasmus+ Programme of the European Union

## MESFIA Ultracapacitors-Construction

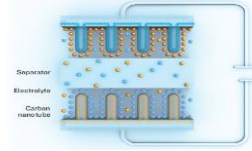
Traditional standard capacitor



Double layer capacitor (ultracapacitor)



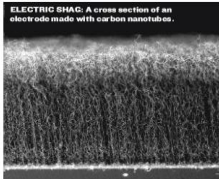
Ultracapacitor with carbon nano-tubes electrodes



The charge of ultracapacitors, IEEE Spectrum Nov. 2007

- Key principle: area is increased and distance is  $\epsilon \frac{A}{d}$  decreased
- There are some similarities with batteries but there are **no reactions** here.

Co-funded by the Erasmus+ Programme of the European Union



## MESFIA Ultracapacitors vs Capacitors

• Comparison with other capacitor technologies

| Capacitor Type                                | Current (pk/rms) (A) | Voltage (V) | Energy (Wh/liter) | Energy (Wh/kg) | Mass 1 MJ (kg) | Response Time (seconds) |
|---|----------------------|-------------|-------------------|----------------|----------------|-------------------------|
| Electrostatic<br>Polymer Film<br>Ceramic MLCC | 200,000/300          | 900         | 0.03              | 0.024          | 12,000         | 10 <sup>-9</sup>        |
| Electrolytic<br>Aluminum electrolytic         | ?/40                 | 450         | 0.087             | 0.019          | 15,000         | 10 <sup>-4</sup>        |
| Electrochemical<br>Carbon ultracapacitor      | 4,800/150            | 2.7         | 6.4               | 5.5            | 51             | 1                       |
| Electrochemical<br>Lithium-Ion                | 2,000/150            | 3.8         | 286               | 123            | 2              | 10 <sup>3</sup>         |

www.ansoft.com/firstpass/pdf/CarbonCarbon\_Ultracapacitor\_Equivalent\_Circuit\_Model.pdf

Co-funded by the Erasmus+ Programme of the European Union

**MESFIA** Ultracapacitors-Construction

•Double-layer technology

*A. Burke / Journal of Power Sources 91 (2000) 37-50*

<http://www.ultracapacitors.org/img2/ultracapacitor-image.jpg>

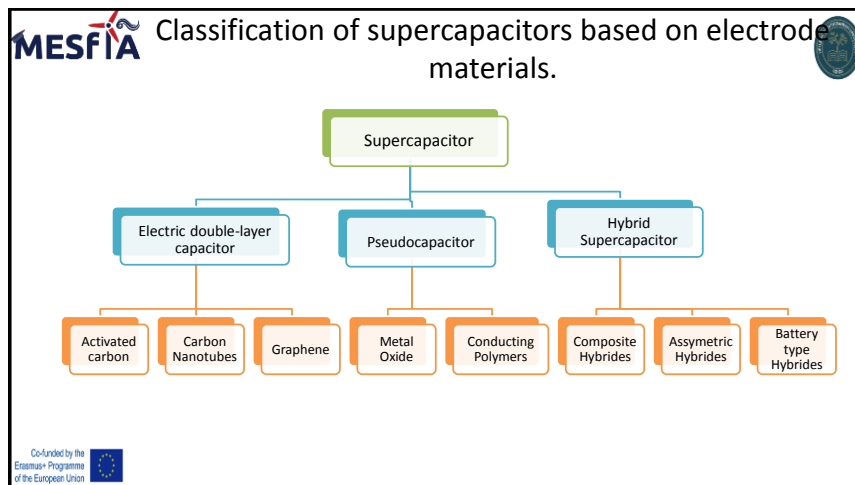
- Electrodes: Activated carbon (carbon cloth, carbon black, aerogel carbon, particulate from TiC, particulate from TiC)
- Electrolyte: KOH, organic solutions, sulfuric acid.

Co-funded by the Erasmus+ Programme of the European Union

**MESFIA** Ultracapacitors-construction

[www.ansoft.com/firstpass/pdf/CarbonCarbon\\_Ultracapacitor\\_Equivalent\\_Circuit\\_Model.pdf](http://www.ansoft.com/firstpass/pdf/CarbonCarbon_Ultracapacitor_Equivalent_Circuit_Model.pdf)

Co-funded by the Erasmus+ Programme of the European Union



**MESFIA** Classification of supercapacitors based on electrode materials.

➤ **supercapacitors Types**

1. Double layer electric capacitors (EDLC)
  - They usually use KOH, H<sub>2</sub>SO<sub>4</sub> as a liquid electrolyte between the electrodes..
  - Helmholtz bilayer formation at the interface between conductive electrodes / electrolyte.

Figure 3. Schematic illustrating a basic EDLC supercapacitor.

Co-funded by the Erasmus+ Programme of the European Union

## MESFIA Classification of supercapacitors based on electrode materials.

### 2. Pseudo-capacitors

- They are made using metal oxides / hydroxides / sulfides or conductive polymers or compounds with C and N functional groups.
- They operate on the basis of the rapid Faradaic redox reaction that occurs at the electrode.

### 3. Combination of an EDLC electrode and a pseudo-capacitor electrode

- Combination of high power density of EDLC & high energy of pseudo-capacitors.
- Good stability between cycles.



## MESFIA Ultracapacitors-Modelling

- Capacitors store energy in its electric field.

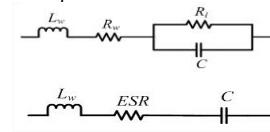
- In ideal capacitors, the magnitude that relates the charge generating the electric field and the voltage difference between two opposing metallic plates with an area  $A$  and at a distance  $d$ , is the capacitance:

$$C = \epsilon \frac{A}{d}$$

- In ideal capacitors:

$$C = \frac{Q}{V}$$

- Equivalent model of real standard capacitors:

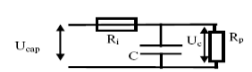


$$ESR = R_w + \frac{1}{\omega^2 R_l C^2}$$

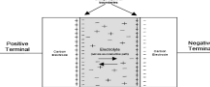
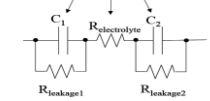


**MESFIA** **Ultracapacitors-Modeling**

- Model (sometimes similar to batteries)



Mierlo et al., Journal of Power Sources 128 (2004) 76-89

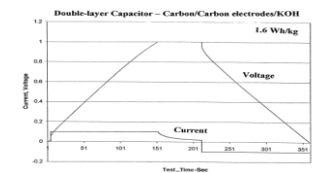



Ultracapacitors for Use in Power Quality and Distributed Resource Applications, P. P. Barker

Co-Funded by the Erasmus+ Programme of the European Union

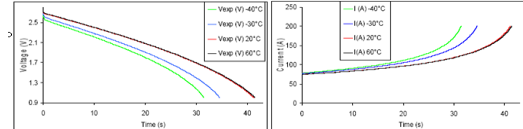
**MESFIA** **Ultracapacitors- Charge and discharge**

- With constant current, voltage approximate a linear variation due to a very large time constant:



Double-layer Capacitor - Carbon/Carbon electrodes/KOH  
1.6 W/kg

- Temperature affects the output (discharge on a constant power load):

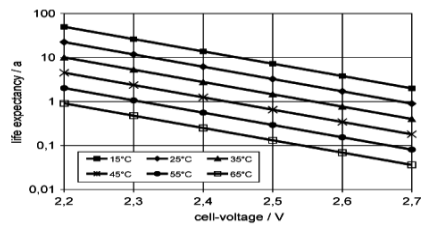


www.ansoft.com/firstpass/pdf/CarbonCarbon\_Ultracapacitor\_Equivalent\_Circuit\_Model.pdf

Co-Funded by the Erasmus+ Programme of the European Union

## MESFIA Ultracapacitors- Aging process

- Life not limited by cycles but by aging
- Aging influenced by temperature and cell voltage
- Overtime the materials degrade, specially the electrolyte
- Impurities reduce a cell's life.



Linzen, et al., "Analysis and Evaluation of Charge-Balancing Circuits on Performance, Reliability, and Lifetime of Supercapacitor Systems"

## MESFIA Ultracapacitors-Power electronic interface:

- It is not required but it is recommended
  - It has 2 purposes:
    - Keep the output voltage constant as the capacitor discharges (a simple boost converter can be used)
    - Equalize cell voltages (circuit examples are shown next)

LINZEN *et al.*: ANALYSIS AND EVALUATION OF CHARGE-BALANCING CIRCUITS

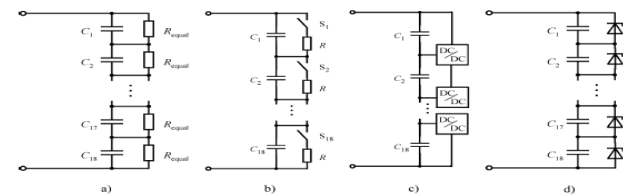


Fig. 2. Cell equalization circuits. (a) Resistor. (b) Switched resistor. (c) DC/DC converter. (d) Zener diodes.

MESFIA

FLYWHEELS



Co-funded by the Erasmus+ Programme of the European Union

itc Gobierno de Canarias

MESFIA

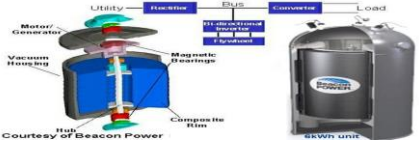
FLYWHEEL

Flywheel Energy Storage (FES) works by accelerating a rotor (flywheel) to a very high speed and maintaining the energy in the system as rotational energy.

When energy is extracted from the system, the flywheel's rotational speed is reduced as a consequence of the principle of conservation of energy. Adding energy to the system correspondingly results in an increase in the speed of the flywheel.

Key Characteristics:

- Modular sizes of few kW
- Short term applications
- High Charging/Discharging capacity



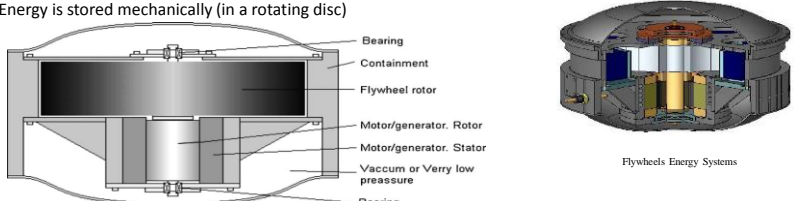
Co-funded by the Erasmus+ Programme of the European Union

itc Gobierno de Canarias

**MESFIA**

## Flywheels-Operation

- Energy is stored mechanically (in a rotating disc)



Bearing  
Containment  
Flywheel rotor  
Motor/generator. Rotor  
Motor/generator. Stator  
Vacuum or Very low pressure  
Bearing

*B. Boland et al. / Renewable and Sustainable*

**Configuration**  
Vertical for optimum efficiency

**Magnetic Bearing**  
Fully active 5-axis

**Rotor**  
Integral with hub

**Stator**  
Dual Mode Motor / Generator

**Hub**  
Aerospace high performance steel

**Housing**  
Vacuum environment

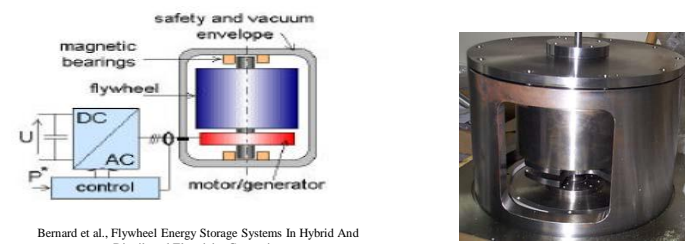
Flywheels Energy Systems

Co-funded by the Erasmus+ Programme of the European Union

**MESFIA**

## Flywheels-Components

- In order to reduce the friction (hence, losses) the disc is usually in a vacuum chamber and uses magnetic bearings.



safety and vacuum envelope  
magnetic bearings  
flywheel  
DC  
AC  
control  
motor/generator

U  
P

Bernard et al., Flywheel Energy Storage Systems In Hybrid And Distributed Electricity Generation

Co-funded by the Erasmus+ Programme of the European Union

**MESFIA** Flywheels-Motors

- Motor / generators are typically permanent magnet machines. There are 2 types: axial flux and radial flux. AFPM can usually provide higher power and are easier to cool.

*B. Boland et al. / Renewable and Sustainable Energy Reviews 11 (2007) 235-258*

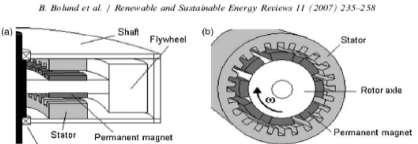


Fig. 3. (a) show an AFPM machine arrangement and (b) show an RFPM machine arrangement.

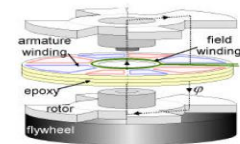


Fig. 20. Overview of the homopolar axial synchronous motor/generator

Bernard et al., Flywheel Energy Storage Systems In Hybrid And Distributed Electricity Generation

Co-funded by the Erasmus+ Programme of the European Union

**MESFIA** Flywheels-Kinetic energy

- Kinetic energy: 
$$E_k = \frac{1}{2} I \omega^2$$

where  $I$  is the moment of inertia and  $\omega$  is the angular velocity of a rotating disc.

$$I = \int r^2 dm$$
- For a cylinder the moment of inertia is 
$$I = \frac{1}{2} r^4 \pi a \rho$$
- So the energy is increased if  $\omega$  increases or if  $I$  increases.
- $I$  can be increased by locating as much mass on the outside of the disc as possible.
- But as the speed increases and more mass is located outside of the disc, mechanical limitations are more important.

Co-funded by the Erasmus+ Programme of the European Union

**MESFIA** Flywheels and Disc Dependence

- Disc shape and material: the maximum energy density per mass and the maximum tensile stress are related by:
- Typically, tensile stress has 2 components: radial stress and hoop stress.

$$e_m = K \sigma_{\max} / \rho$$

Table 1  
Shape factor  $K$  for different planar stress geometries

| Fly wheel geometry            | Cross section | Shape factor $K$ |
|-------------------------------|---------------|------------------|
| Disc                          |               | 1.000            |
| Modified constant stress disc |               | 0.931            |
| Contact disc                  |               | 0.806            |
| Flat unpierced disc           |               | 0.606            |
| Thin film                     |               | 0.500            |
| Shaped bar                    |               | 0.300            |
| Rim with web                  |               | 0.400            |
| Single bar                    |               | 0.333            |
| Flat pierced bar              |               | 0.305            |

Table 2  
Data for different rotor materials

| Material            | Density (kg/m <sup>3</sup> ) | Tensile strength (MPa) | Max energy density (for 1 kg) | Cost (\$/kg) |
|---------------------|------------------------------|------------------------|-------------------------------|--------------|
| Monolithic material | 7700                         | 1520                   | 0.19 MJ/kg = 0.05 kWh/kg      | 1            |
| 4340 Steel          |                              |                        |                               |              |
| Composites          |                              |                        |                               |              |
| E-glass             | 2000                         | 100                    | 0.05 MJ/kg = 0.014 kWh/kg     | 11.0         |
| S2-glass            | 1920                         | 1470                   | 0.76 MJ/kg = 0.21 kWh/kg      | 24.6         |
| Carbon T1000        | 1520                         | 1950                   | 1.28 MJ/kg = 0.35 kWh/kg      | 101.8        |
| Carbon AS4C         | 1510                         | 1650                   | 1.1 MJ/kg = 0.30 kWh/kg       | 31.3         |

Co-Funded by the Erasmus+ Programme of the European Union

*B. Boland et al. / Renewable and Sustainable Energy Reviews 11 (2007) 235–258*

**MESFIA** Flywheels-Maths

- Since

$$e_m = K \sigma_{\max} / \rho \quad (1) \quad \text{and} \quad E_k = \frac{1}{2} I \omega^2 \quad (2)$$

and "  $I = r^2 m$  " (3)

then, from (2) and (3) 
$$e_m = \frac{1}{2} r^2 \omega^2 = \frac{1}{2} v^2 \quad (4)$$

So, replacing (1) in (4) it yields 
$$v_{\max} = \sqrt{\frac{2K\sigma_{\max}}{\rho}}$$

Co-Funded by the Erasmus+ Programme of the European Union

**MESFIA** Flywheels-Velocity and Voltage

- However, high speed is not the only mechanical constraint
- If instead of holding output voltage constant, output power is held constant, then the torque needs to increase (because  $P = T\omega$ ) as the speed decreases. Hence, there is also a minimum speed at which no more power can be extracted
- If 
$$V_r = \frac{V_{\max}}{V_{\min}}$$
 and if an useful energy ( $E_u$ ) proportional to the difference between the disk energy at its maximum and minimum allowed speed is compared with the maximum allowed energy ( $E_{\max}$ ) then

Fig. 4: Evolution in useful energy vs.  $r$

$$\frac{E_u}{E_{\max}} = \frac{V_r^2 - 1}{V_r^2}$$

Bernard et al., Flywheel Energy Storage Systems In Hybrid And Distributed Electricity Generation

Co-funded by the Erasmus+ Programme of the European Union

**MESFIA** Flywheels-Electronics

Motor/Generator (MG) ac Inverter/Rectifier dc

Motor

Generator

RECTIFIER/INVERTER

Soft start

To UPS battery input

IGBT power converter

Flywheel module

DC monitoring Power conversion module controller (PCMC)

Motor-generator controls


Magnetic levitation module (MLM)

Control panel

Versatile Interface: Remote Monitoring, Diagnostics & Control

Co-funded by the Erasmus+ Programme of the European Union


**MESFIA** Flywheels-Compact solutions



<http://www.pentadyne.com>

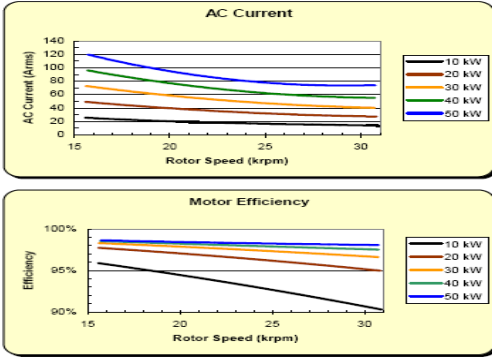
<http://www.vyconenergy.com>

**VYCON Direct Connect (VDC)**



Co-funded by the Erasmus+ Programme of the European Union

**MESFIA** Flywheels- Typical outputs



**AC Current**

| Rotor Speed (krpm) | 10 kW | 20 kW | 30 kW | 40 kW | 50 kW |
|--------------------|-------|-------|-------|-------|-------|
| 15                 | ~25   | ~35   | ~45   | ~75   | ~115  |
| 20                 | ~25   | ~35   | ~45   | ~70   | ~105  |
| 25                 | ~25   | ~35   | ~45   | ~65   | ~95   |
| 30                 | ~25   | ~35   | ~45   | ~60   | ~85   |


**Motor Efficiency**

| Rotor Speed (krpm) | 10 kW | 20 kW | 30 kW | 40 kW | 50 kW |
|--------------------|-------|-------|-------|-------|-------|
| 15                 | ~95%  | ~98%  | ~98%  | ~98%  | ~98%  |
| 20                 | ~95%  | ~97%  | ~97%  | ~97%  | ~97%  |
| 25                 | ~95%  | ~96%  | ~96%  | ~96%  | ~96%  |
| 30                 | ~95%  | ~95%  | ~95%  | ~95%  | ~95%  |

Co-funded by the Erasmus+ Programme of the European Union

**MESFIA** Flywheels-Compact solutions

Representative Flywheel Energy Storage Module




Labels in the diagram include: 480V Switchgear & Cluster Controller, 480V Step-up Transformer, Cooling System, Flywheel Foundation, Flywheel Dessicant Tank, Flywheel Assembly Bolted to Foundation, Power Control Module, and Flywheel Foundation (Flywheel inside).

<http://beaconpower.com/resources/> 50" total height of which 27" above the ground-Weight 1660lb

Co-funded by the Erasmus+ Programme of the European Union


**MESFIA** FLYWHEEL vs Other storage means

- FES systems **have long lifetimes**, lasting decades with little or no maintenance;
- **High specific energy (100–130 W·h/kg)**
- **Large maximum power output.**
- The energy efficiency (ratio of energy out per energy in) of flywheels, also known as round-trip efficiency, can be as high as **90%**
- Typical capacities **range from 3 kWh to 133 kWh**
- Rapid charging of a system occurs in less than 15 minutes
- The high specific energies often cited with flywheels can be a little misleading as commercial systems built have much lower **specific energy, for example 11 Wh/kg**



Labels in the diagram include: Composite Rim, Magnetic Bearing, Vacuum Chamber, Shaft, Hub, and Motor.

Source: Beacon Power, LLC




Co-funded by the Erasmus+ Programme of the European Union


itc  
GOVERNIO DE CANARIAS

**MESFIA** FLYWHEEL vs Other storage means

- Flywheels can offer great power in a large number of cycles.
- They do not need air conditioning.
- They have no chemicals during their operation and maintenance is mainly for the electrical interface.
- 6kWh devices can provide approximately 250 kW in 1'
- Therefore for short duration applications with high power are ideal
- Especially for communication facilities ...
- 250kW-1MW are required for the transmission for a few seconds 12 (so around 4kWh) and other 4KWh for 1-2kW and for several hours ...
- A container can hold 250 kWh



Source: Beacon Power, LLC

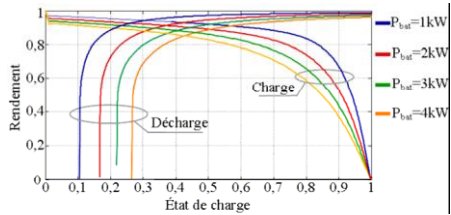


Co-funded by the Erasmus+ Programme of the European Union

itc Gobierno de Canarias

**MESFIA** Flywheels-Charge & Discharge

- Model BHES-6 6kWh providing 2kW of power at 22,500rpm.



Co-funded by the Erasmus+ Programme of the European Union

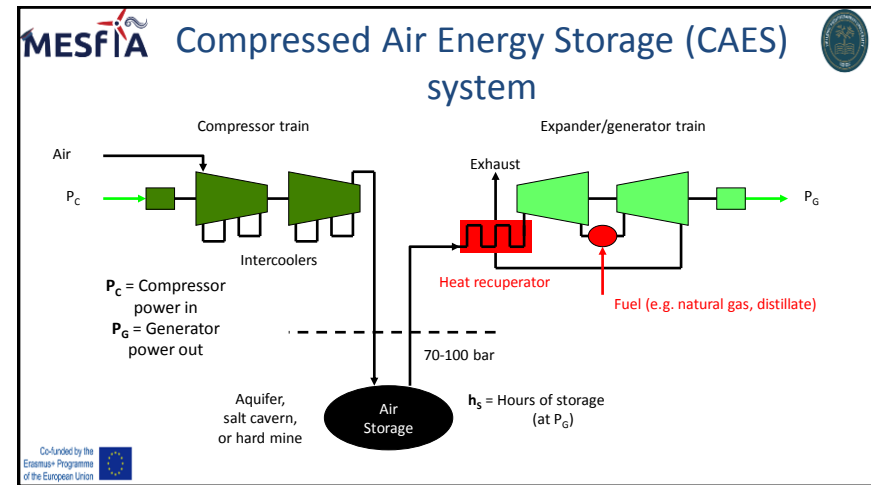
MESFIA

**OTHER STORAGE MEANS**

Co-funded by the Erasmus+ Programme of the European Union


itc

Gobierno de Canarias



**MESFIA** Compressed Air Energy Systems (CAES)

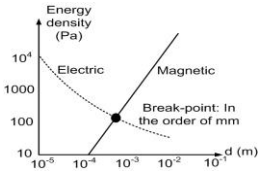
- Most Famous Application Example: Huntorf (1979) at 70 bar
  - 2 Cavities 310 000m<sup>3</sup>
  - 290MW within 2 hours
  - PG = Generator output
- T-CAES has been proposed quite recently
- Less storage capacity / power-portability.



Co-funded by the Erasmus+ Programme of the European Union

**MESFIA** Electric vs. Magnetic energy storage


- Consider that we compare technologies based on energy density (J/m<sup>3</sup>)
 
$$[Energy] = [Work] = [F][d] = Nm = J$$

$$[Energy\ density] = \frac{J}{m^3} = \frac{Nm}{m^3} = \frac{N}{m^2} = Pa$$
- Plot of energy density vs. length scale (distance between plates or air gap):
 
- Hence, magnetic energy storage (e.g. SMES) is effective for large scale systems (higher power)

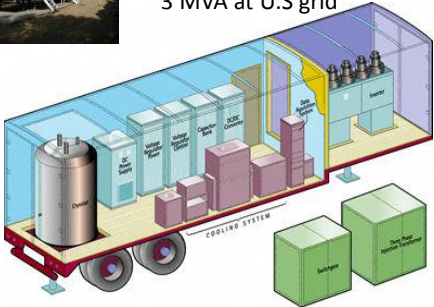
Co-funded by the Erasmus+ Programme of the European Union

**MESFIA Super-conducting Magnetic Energy Storage(SMES)**

- High performance
- Provisions for power quality improvement
- Convenience and installation flexibility
- Installation mainly at the distribution level



3 MVA at U.S grid



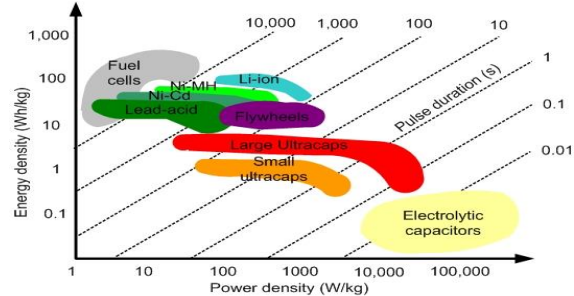
COOLING SYSTEM

39

Co-funded by the Erasmus+ Programme of the European Union

Εργαστηριακή άσκηση - Αποθήκευση ενέργειας

**MESFIA Ragone Chart and Flywheels**



Energy density (Wh/kg)

Power density (W/kg)

Pulse duration (s)

Technologies shown: Fuel cells, Ni-MH, Lead-acid, L-Ion, Flywheels, Large ultracaps, Small ultracaps, Electrolytic capacitors.

- More information and charts can be found in Holm et. al., "A Comparison of Energy Storage Technologies as Energy Buffer in Renewable Energy Sources with respect to Power Capability."

Co-funded by the Erasmus+ Programme of the European Union

**MESFIA** Power vs. energy delivery profile technologies

|                                      | Lead-Acid | Ni-Cd      | Ni-MH    | Li-ion     |
|--------------------------------------|-----------|------------|----------|------------|
| Cell voltage (V)                     | 2         | 1.2        | 1.2      | 3.6        |
| Specific energy (Wh/kg)              | 1-60      | 20-55      | 1-80     | 3-100      |
| Specific power (W/kg)                | < 300     | 150 – 300  | < 200    | 100 – 1000 |
| Energy density (kWh/m <sup>3</sup> ) | 25-60     | 25         | 70-100   | 80-200     |
| Power density (MW/m <sup>3</sup> )   | < 0.6     | 0.125      | 1.5 – 4  | 0.4 – 2    |
| Maximum cycles                       | 200-700   | 500-1000   | 600-1000 | 3000       |
| Discharge time range                 | > 1 min   | 1 min-8 hr | > 1 min  | 10 s-1 h   |
| Cost (\$/kWh)                        | 125       | 600        | 540      | 600        |
| Cost (\$/kW)                         | 200       | 600        | 1000     | 1100       |
| Efficiency (%)                       | 75 - 90   | 75         | 81       | 99         |

|                                      | Flywheel    | Ultracapacitor |
|--------------------------------------|-------------|----------------|
| System power ratings (kW)            | 2 – 500     | 5 – 1000       |
| Specific energy (Wh/kg)              | 15 – 150    | 0.5 – 4        |
| Specific power (W/kg)                | 900 - 20000 | 50 – 3000      |
| Energy density (kWh/m <sup>3</sup> ) | 6 – 100     | 0.8 – 4        |
| Power density (MW/m <sup>3</sup> )   | 0.3 – 40    | 0.3 – 1        |
| Maximum cycles                       | > 100 000   | > 100 000      |
| Discharge time range                 | 4 - 60 s    | 1 – 60 s       |
| Life expectancy (hours)              | 175 000     | 100 000        |
| Cost (\$/kW)                         | 300         | 500            |
| Efficiency (%)                       | 90 – 93     | 90 – 95        |

Co-funded by the Erasmus+ Programme of the European Union

