Microgrids

Electricity storage

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What we will do in this lecture

We will review the main storage technologies and get an overview of their main properties.

- short electrochemistry and physical analysis
- mostly how specific characteristics of each particular technology affect microgrid design, planning, and operation.

Introduction

A storage system is an object or device allowing to capture energy at a given point in time and restore some of it at a later time.

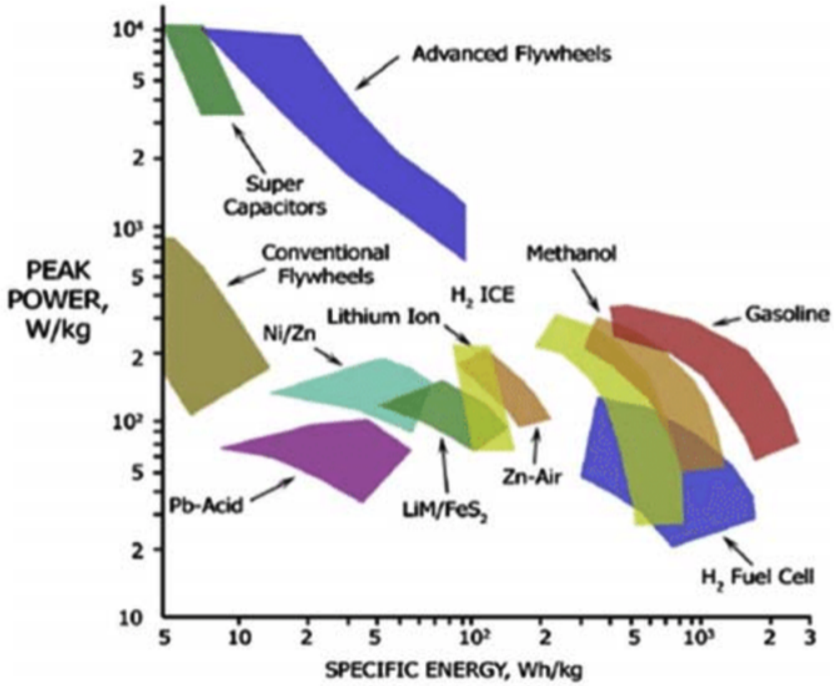
Ideally, the amount of energy restored should be as close as possible to the amount of energy captured initially, the ratio of the two defining the efficiency of the system.

Sources and forms of energy vary widely, leading to the emergence of many different storage system technologies.

Currently available technology

- Batteries
- Capacitors
- Supercapacitors
- SMES (super conducting magnetic energy storage)
- Fuel cells
- Flywheels
- Compressed Air Storage
- Pumped Hydro-Power
- Pumped Heat Storage

Power delivery vs energy delivery



High power/energy ratio required to compensate lack of dynamics for load and generation following.

Physical constitution of a battery

- Electrodes: cathode and anode
  - cathode: from where conventional current (+ charges) leaves -> + electrode if generator.
- Electrolyte
- case / enclosure

Voltage and current rating are function of material and construction.

The surface area of each cell determines factors such as

- the total energy stored,
- the maximum rates of charge and discharge

Example: standard 12V lead-acid battery: six 2V cells in series within an enclosure, that is either vented or sealed; the electrolyte can be a liquid or a gel.

Lead-acid batteries

Composition

- Lead Pb (negative electrode)
- Lead dioxide PbO_2 (positive electrode)
- Sulfuric acid H_2SO_4 and water in the electrolyte

Chemical reactions in the next video.


How a lead-acid battery works
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What limits the cycle-life?

During discharge, both electrode reactions create PbSo4 (lead sulphate) that coats the electrodes

- Lead sulphate is not totally removed when charging
- it accumulates with cycles

Sulfuric acid concentration dereases (as a consequence of the above phenomenon)

- flooded lead-acid batteries can be replenished
- sealed lead-acid batteries cannot

To avoid accelerating the sulfation process, batteries need to be fully charged after every discharge and they must be kept charged at a float voltage higher than the nominal voltage (2V).

Nernst equation recap

The relationship between battery-stored energy or capacity and electrolyte solution concentration is given by Nernst equation

$$E = E^0 + \frac{kT}{q} \ln(Q)$$

- E^0 is the energy at a standard 1 molar concentration
- k is the Boltzmann constant,
- T is the temperature in kelvin
- q is the charge of an electron.

Stored energy is heavily dependent not only on the molar concentration but also on the temperature.

Efficiency

The overal efficiency

$$\eta = \eta_V \eta_C$$

is the product of

- a voltage efficiency, ratio of the charge and discharge voltages, and technology dependent (VRLA = 88%)
- a coulombic efficiency, usually 92 %

Efficiency varies with usage

Battery capacity is indicated in Ah (ampere-hour) (or Wh) for a given discharge rate, which at full capacity is often 8 or 10 hours.

The internal resistance typically varies with different discharge rates, hence the capacity is less if the battery is discharged faster (Peukert's Effect).

Efficiency and technologies, from Victron's website:

1. VRLA technology: stands for Valve Regulated Lead Acid, which means that the batteries are sealed. Gas will escape through the safety valves only in case of overcharging or cell failure. VRLA batteries are maintenance free for life.
2. Sealed (VRLA) AGM Batteries: AGM stands for Absorbent Glass Mat. In these batteries the electrolyte is absorbed into a glass-fibre mat between the plates by capillary action. (...) more suitable for short-time delivery of high currents than gel batteries.
3. Sealed (VRLA) Gel Batteries: the electrolyte is immobilized as gel. Gel batteries in general have a longer service life and better cycle capacity than AGM batteries.

Discharg time (constant current)	End Voltage V	AGM 'Deep Cycle' %	Gel 'Deep Cycle' %	Gel 'Long Life' %
20 hours	10,8	100	100	112
10 hours	10,8	92	87	100
5 hours	10,8	85	80	94
3 hours	10,8	78	73	79
1 hour	9,6	65	61	63
30 min.	9,6	55	51	45
15 min.	9,6	42	38	29
10 min.	9,6	38	34	21
5 min.	9,6	27	24	
5 seconds		8 C	7 C	

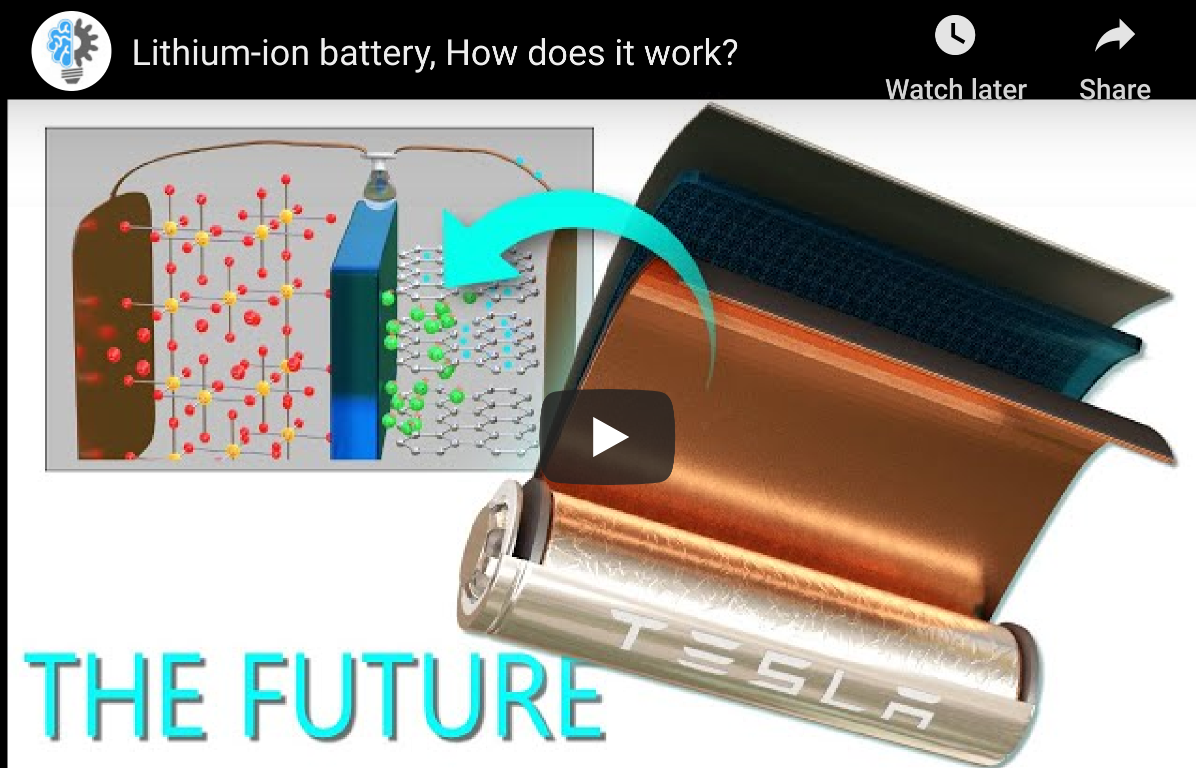
Table 1: Effective capacity as a function of discharge time
(the lowest row gives the maximum allowable 5 seconds discharge current)

Lithium Ion batteries

Lithium-ion (Li-ion) batteries have many advantages over lead-acid batteries:

1. Lighter than lead-acid batteries because lithium and carbon are lighter than lead.
2. Do not build up deposits every charge/discharge cycle, so their efficiency is about 99% -> cycle-life much bigger
3. Allow deeper discharges (although cycle-life dependes on DoD)

Also, higher cell voltage means fewer series-connected cells for a same string voltage.


Lithium-ion battery, How does it work?
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(and better)
100 Amp Hour 12 Volt
LiFePO4 Battery
$
VS
$$$
UB121000
UNIVERSAL BATTERY
Than Lead Acid

Battery Management System

- Modern battery storage systems are equipped with a battery management system (BMS).
- The BMS serves two main purposes:
  - Monitoring: harvest data to be fed to control systems and graphical user interface.
  - Safety: ensure battery does not operate in dangerous regimes, e.g. severe overvoltage or high temperature. Cell balancing.
- Old BMSs used inaccurate heuristics to estimate operating parameters and stop operation if needed whereas new generations exploit - high-fidelity electrochemical models solved in real-time.

Comparison of Li-Ion Battery Technologies

Lithium Nickel Manganese Cobalt Oxide: $LiNiMnCoO_2$. cathode, graphite anode Short form: NMC (NCM, CMN, CNM, MNC, MCN similar with different metal combinations) Since 2008	
Voltages	3.60V, 3.70V nominal; typical operating range 3.0–4.2V/cell, or higher
Specific energy (capacity)	150–220Wh/kg
Charge (C-rate)	0.7–1C, charges to 4.20V, some go to 4.30V; 3h charge typical. Charge current above 1C shortens battery life.
Discharge (C-rate)	1C; 2C possible on some cells; 2.50V cut-off
Cycle life	1000–2000 (related to depth of discharge, temperature)
Thermal runaway	210°C (410°F) typical. High charge promotes thermal runaway
Applications	E-bikes, medical devices, EVs, industrial
Comments	Provides high capacity and high power. Serves as Hybrid Cell. Favorite chemistry for many uses; market share is increasing.

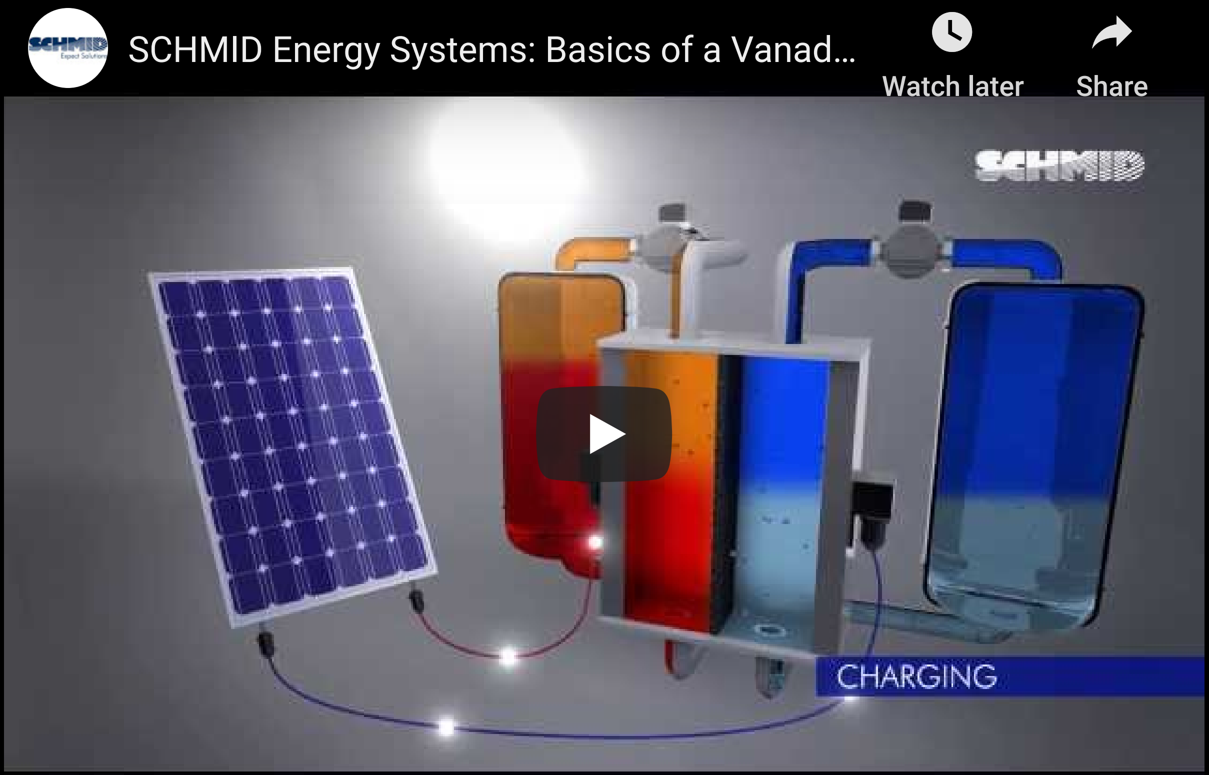
Lithium Iron Phosphate: $LiFePO_4$ cathode, graphite anode Short form: LFP or Li-phosphate Since 1996	
Voltages	3.20, 3.30V nominal; typical operating range 2.5–3.65V/cell
Specific energy (capacity)	90–120Wh/kg
Charge (C-rate)	1C typical, charges to 3.65V; 3h charge time typical
Discharge (C-rate)	1C, 25C on some cells; 40A pulse (2s); 2.50V cut-off (lower that 2V causes damage)
Cycle life	1000–2000 (related to depth of discharge, temperature)
Thermal runaway	270°C (518°F) Very safe battery even if fully charged
Applications	Portable and stationary needing high load currents and endurance
Comments	Very flat voltage discharge curve but low capacity. One of safest Li-ions. Used for special markets. Elevated self-discharge.

Lithium Manganese Oxide: $LiMn_2O_4$ cathode. graphite anode Short form: LMO or Li-manganese (spinel structure) Since 1996	
Voltages	3.70V (3.80V) nominal; typical operating range 3.0–4.2V/cell
Specific energy (capacity)	100–150Wh/kg
Charge (C-rate)	0.7–1C typical, 3C maximum, charges to 4.20V (most cells)
Discharge (C-rate)	1C; 10C possible with some cells, 30C pulse (5s), 2.50V cut-off
Cycle life	300–700 (related to depth of discharge, temperature)
Thermal runaway	250°C (482°F) typical. High charge promotes thermal runaway
Applications	Power tools, medical devices, electric powertrains
Comments	High power but less capacity; safer than Li-cobalt; commonly mixed with NMC to improve performance.

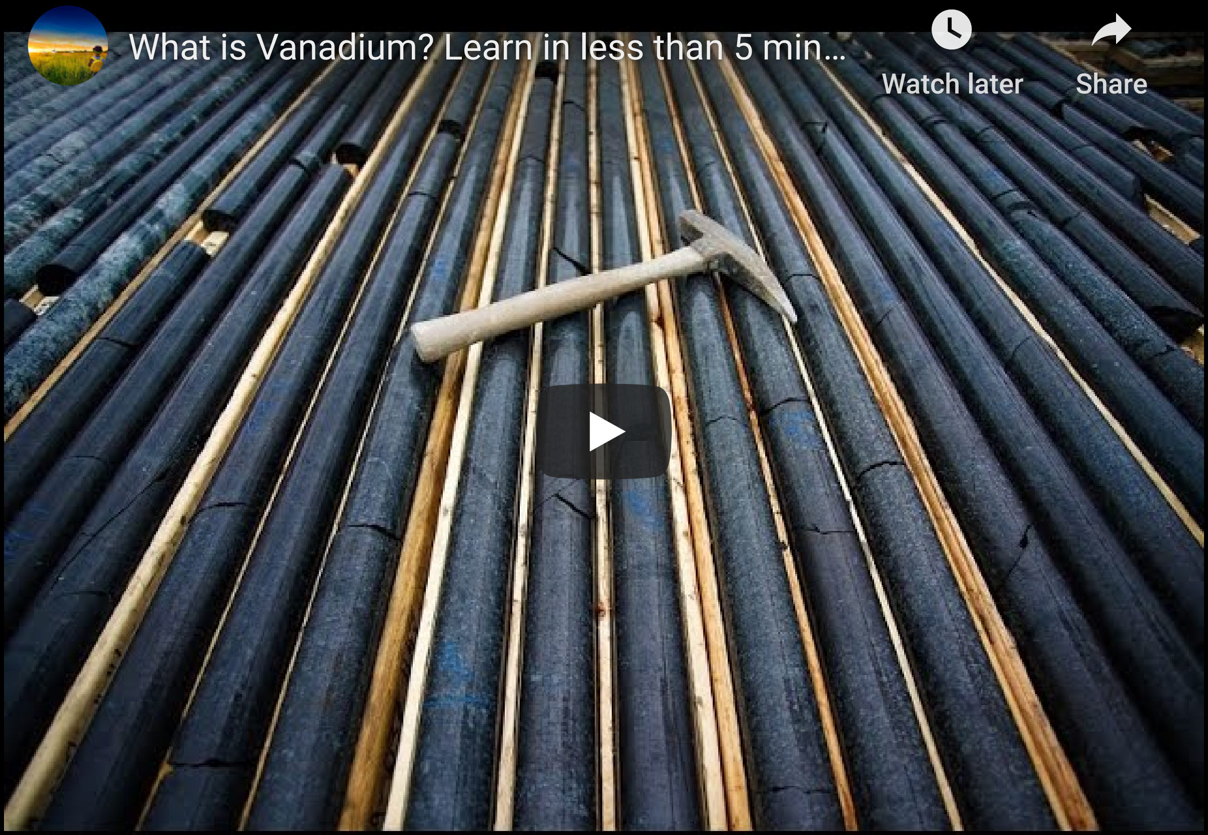
Lithium Nickel Cobalt Aluminum Oxide: $LiNiCoAlO_2$ cathode (~9% Co), graphite anode Short form: NCA or Li-aluminum. Since 1999	
Voltages	3.60V nominal; typical operating range 3.0–4.2V/cell
Specific energy (capacity)	200-260Wh/kg; 300Wh/kg predictable
Charge (C-rate)	0.7C, charges to 4.20V (most cells), 3h charge typical, fast charge possible with some cells
Discharge (C-rate)	1C typical; 3.00V cut-off; high discharge rate shortens battery life
Cycle life	500 (related to depth of discharge, temperature)
Thermal runaway	150°C (302°F) typical, High charge promotes thermal runaway
Applications	Medical devices, industrial, electric powertrain (Tesla)
Comments	Shares similarities with Li-cobalt. Serves as Energy Cell.

Victron's lithium batteries

Flow batteries



Don't do it yourself ;)



What is vanadium (with Barack Obama!)

Other chemistries under development.

Essential Battery Parameters

Capacity, SOC & Voltage

- Capacity reflects total amount of charge (Ah) that can be theoretically stored in device.
- State of charge (SOC) reflects amount of charge available at given time instant, usually expressed as percentage of capacity.
- Voltage (V) at cell/pack terminals is measurable operating parameter providing indirect information about SOC.

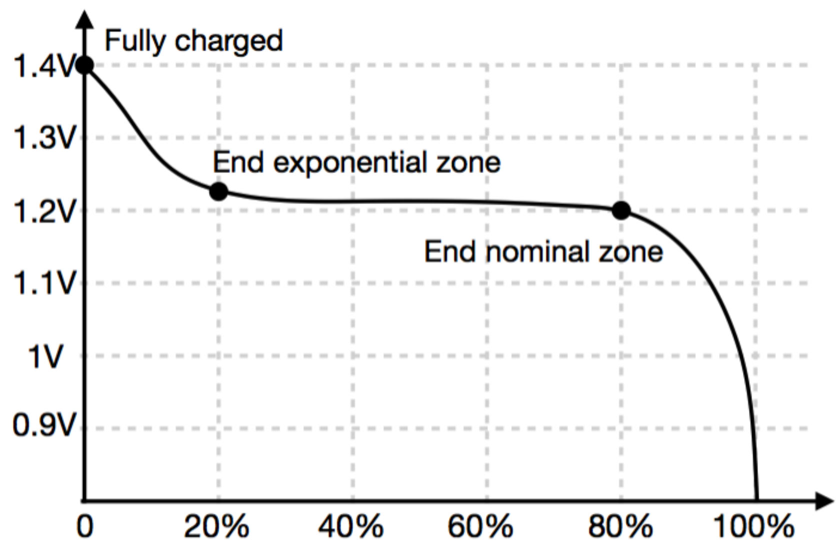


Figure 2.2: Discharge curve example.

Current & C-rate

- Current (A) is the main excitation signal in batteries as voltage is imposed by system physics.
- C-rate is a standardized metric quantifying applied current intensity. This alternative scale is derived from the constant current intensity needed to fully charge/discharge the battery over a given time period, usually 1h.
- Battery charge/discharge behaviors vastly differ across C-rate range.
- In particular, in Li-ion cells, much less charge can be retrieved from discharge at high C-rates. This phenomenon is called the rate - capacity effect.

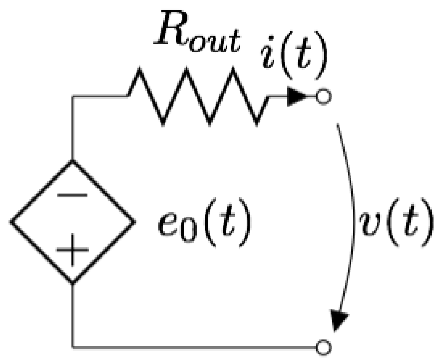
Degradation & Health

- Battery performances typically decrease over lifetime, in a process known as degradation.
- Main degradation types:
  - Power fade: peak power decreases over time.
  - Capacity fade: capacity decreases over time.
- Several metrics quantifying degradation exist, e.g. remaining capacity or internal resistance. Those quantities then allow to define state of health indicator in fashion similar to SOC.

Battery models in practice

Highly dependent of the application :

- for sizing or planning problems, a simple tank model may be enough (for sizing, see how to evaluate capacity degradation on the next slide)
- a more detailed model can represent the current-voltage dependance and thus the efficiency as a function of the power charged or discharged:



Parameters can be obtained from a data sheet, or from voltage (dis)charge curves experiments

Simple model of energy capacity degradation as a function of the number of cycles

For Li-ion batteries, a simple throughput model is in general enough to evaluate the number of cycles:

cycles(t) = amount of Ah charged(t) / initial_capacity

Actual capacity(t) = initial capacity - a * cycles(t)

a is a parameter determined experimentally.

Charging strategies

Charging strategies refer to the way current and voltage are controled over time to charge a battery.

Complex strategies exist to maximize the efficiency and the safety of the process

- constant current CC is the simplest, but can lead to over voltage if not stopped fast enough
- constant voltage CV is a bit more complex, but avoids over-voltages (since it is regulated). But leads to high currents when the battery is near empty and tiny currents when it is almost charged.
- more advanced techniques combining CC and CV or regulating a function of C and improve the process.

State of charge estimation

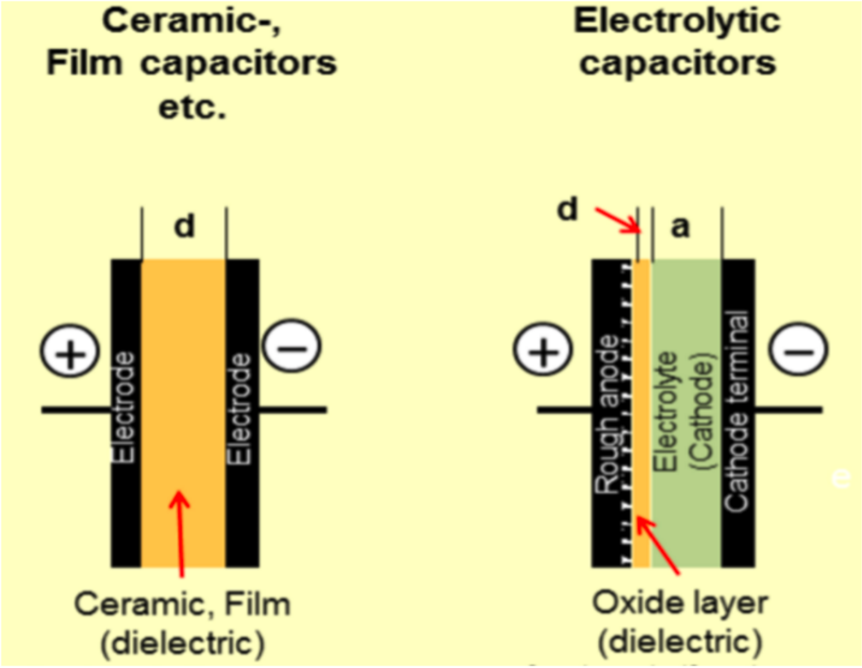
- Coulomb counting
- Voltage measurment
- Kalman filtering
- Technology specific methods.

Capacitors and supercapacitors

Capacitors

- Energy stored in electrostatic form (electrical field).
- Charge (electrons) stored on electrode surfaces.
- Dielectric inserted between electrodes to increase capacity.
- Two common designs: ceramic/film capacitors and electrolytic capacitors (with much higher capacity).

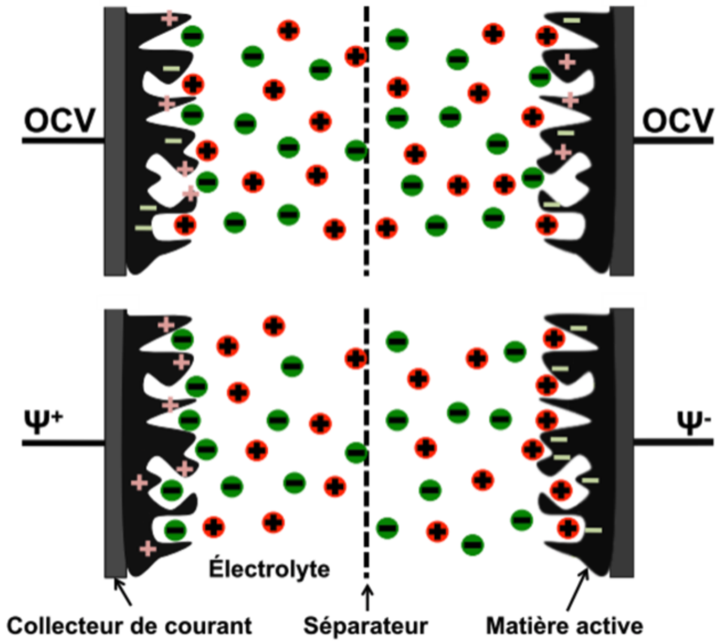
Schematic of common capacitor technologies



Supercapacitors

- Super and ultra capacitors are synonyms. Capacitors and super capacitors are different.
- Energy stored in electrostatic form (electrical field).
- Charge (ions) adsorbed on porous activated carbon electrode surfaces bound to current collector.
- Ions transferred through electrolyte from one electrode to the other.
- Porous separator inserted between electrodes.

Schematic & working principle of super capacitor technology



E.g. Maxwell ultracapacitors

Optimized for size and power in industrial, electronics, and consumer applications

POWER & ENERGY

Operating Temp. Range	Standard (-40°C to 65°C) at 2.7 V	Extended (-40°C to 85°C) at 2.3 V
Maximum Stored Energy, E_{max}[6,9]	3.0 mWh	2.2 mWh
Gravimetric Specific Energy[6]	2.1 Wh/kg	1.5 Wh/kg
Usable Specific Power[6]	8.9 kW/kg	6.4 kW/kg
Impedance Match Specific Power[6]	18.6 kW/kg	13.4 kW/kg

Description

Size comparison

Capacitor of 1F: cylinder with

- diameter = 7.6 cm
- length = 14.3 cm

Ultracapacitor of 3F: cylinder with

- diameter = 0.8 cm
- length = 2cm

References

- Kwasinski, Alexis, Wayne Weaver, and Robert S. Balog. Microgrids and other local area power and energy systems. Cambridge University Press, 2016.

The end.