Battery Energy Storage Systems

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- Battery Equivalent Circuit
- Battery Technology (Pb, Lithium ion)
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- BESS (Use Cases, Grid Services)
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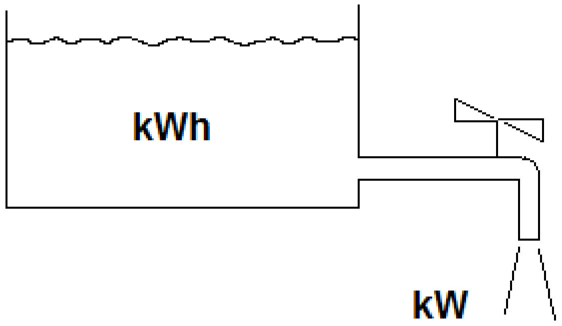
Battery Energy vs Power

Battery is an energy storage device, when charged it contains energy in electrochemical form. Energy is expressed in kWh.
The discharge rate can be expressed by current (A) or power (kW).
Energy and power are related by a simple approximated formula

Energy (kWh) = Power (kW) x Time (hours)

A simple hydraulic example helps to clarify the relationship between energy, power and time.

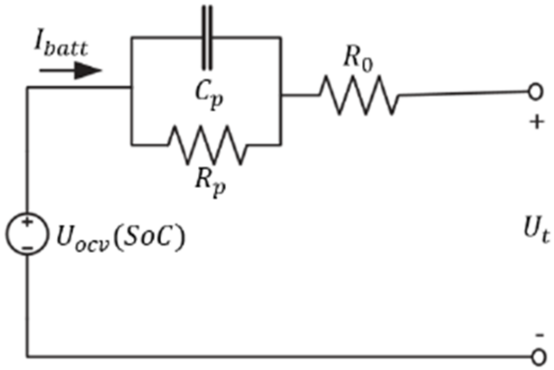


The energy content corresponds to the volume of water in the tank. The discharge power relates to the water flow. It is controlled by the tap (valve).

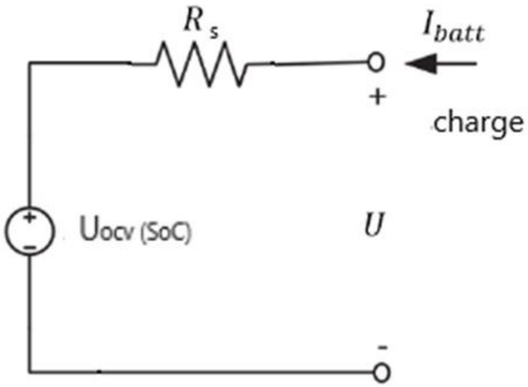
100kWh = 10kW x 10 hours
100kWh = 20kW x 5 hours

The higher the discharge rate, the shorter the time to empty the tank (or to discharge the battery)

Battery Equivalent Circuit



Thevenin equivalent circuit model of a battery



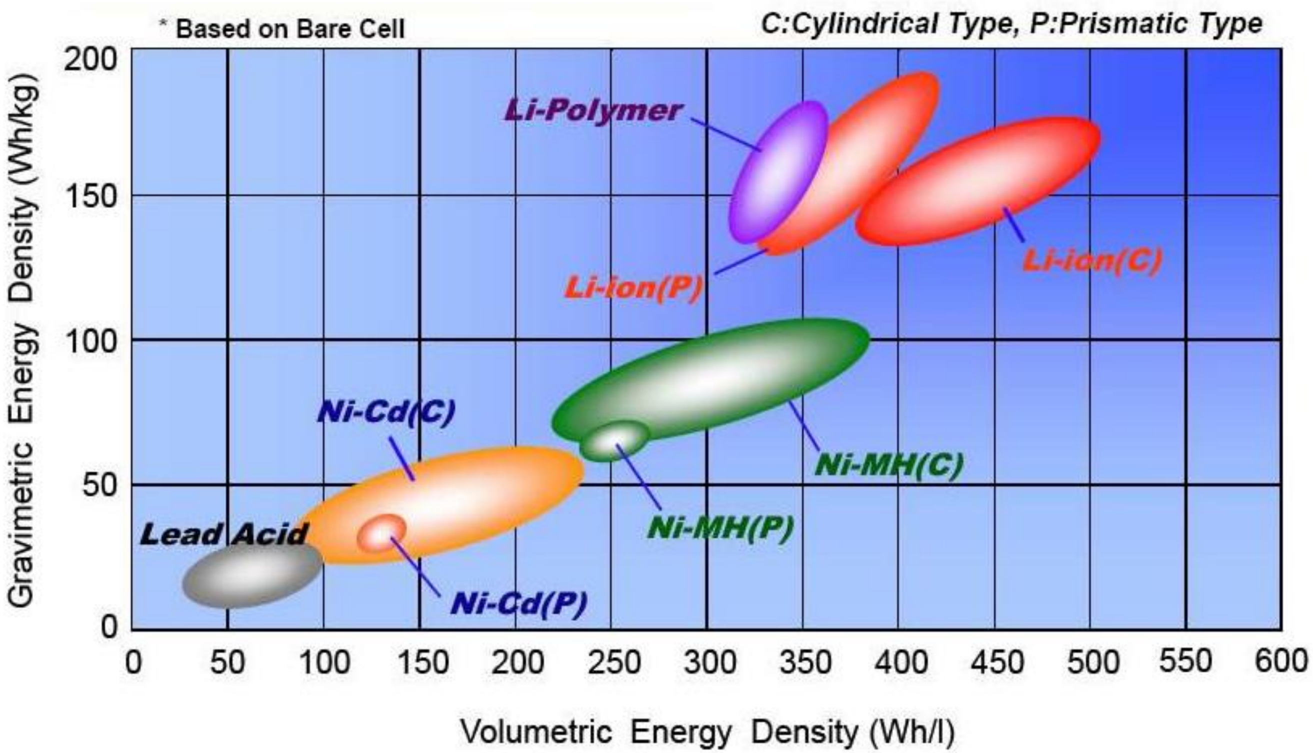
Equivalent circuit of battery (simplified)

The simplest equivalent circuit of a battery is the **series connection of a voltage generator and a resistance** to take into account power losses and voltage drop when a discharge (or charge) current is flowing.

More advanced models include RC elements to describe dynamic behaviour of battery.

Battery Technologies

Batteries built with different electrochemistry present a wide range of energy density expressed by Wh/kg (energy to weight) and Wh/dm3 (energy to volume).
Lithium-ion battery has much higher energy density compared to conventional lead-acid.



Battery Technologies

Battery Energy Storage System (BESS) performance depends upon the technology chosen

- **Lead Acid Batteries** (Pb) – conventional, proven technology
- **Lithium ions Batteries** – with different electrochemistry
- **Sodium Nickel Chloride** – salt batteries, operating at high temperature (300°C)
- Others (NiCd, NaS, flow batteries, etc)

Pb Battery is a conventional technology, the most utilized and it can be classified in

- Flooded, open type, with liquid electrolyte (acid and water solution)
- Hermetically sealed, with Gel electrolyte (VRLA type)
- Hermetically sealed AGM type, Absorbed Glass Mat

Hermetically sealed batteries are maintenance free
Flooded batteries require periodic maintenance, which consists of
- Check electrolyte level/concentration, add distilled water if needed
- Check voltage on battery string and replace damaged units, due to aging

BESS – Battery Technologies – Pros, Cons

Different electrochemical technologies have advantages and disadvantages

- **Lead-acid** or advanced Lead-acid
  - ✓ Low purchase cost
  - ✓ Power applications
  - × Small usable capacity
  - × Low energy density
  - × Temperature affected lifetime

- **Lithium-Ions** (Lithium-Titanate, LiFePO4, others)
  - ✓ High power density
  - ✓ Great usable capacity
  - ✓ No gas emissions
  - × Need of a periodical complete charge/discharge cycle
  - × Need of an external cooling system
  - × High purchase cost

- **Sodium-Nickel-Chloride** ($NaNiCl_2$)
  - ✓ High energy density
  - ✓ Fully recyclable
  - ✓ External cooling system not needed
  - × Long time needed for warm-up process
  - × High value of operating voltage

Lead Acid Battery

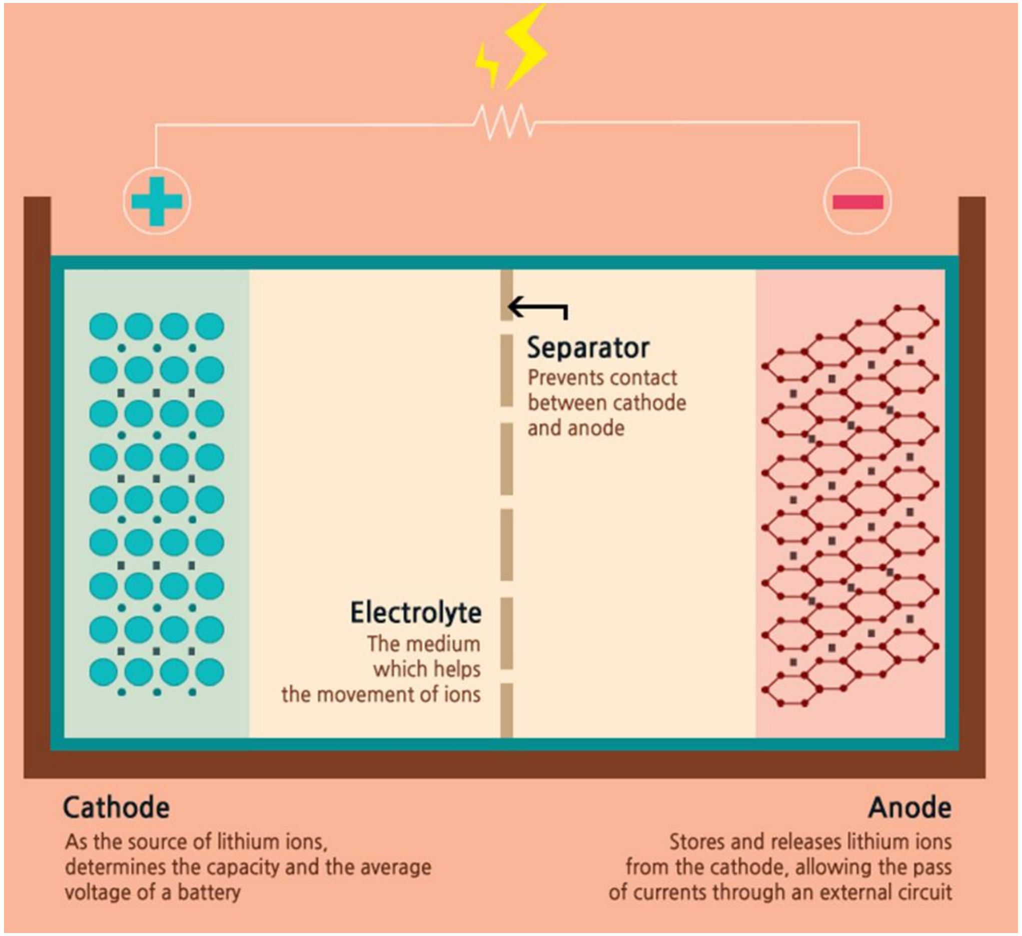
Hermetic Pb Gel Battery (VRLA – Valve Regulated Lead-Acid)

Typical parameters of OPzV cells	
Rated Voltage [V]	2
Rated Capacity [Ah]	100 – 3,000
Gravimetric Power Density [W/kg]	70 ÷ 80
Gravimetric Energy Density [Wh/kg]	15 ÷ 30
Round Trip Efficiency [%]	80 ÷ 90
Monthly self-discharge [%]	<2
Life-cycle expected @80% DoD [cycles]	1,200÷1,400
Typical C_{rate} [h^{-1}]	C_{10}
Maximum C_{rate} [h^{-1}]	1C for discharge e C_4 for charge
Operating temperature [°C]	-40 ÷ +60°C (recommended range +15°C÷+25°C)
Cost [€/kWh]	100÷300

Lithium ion Battery

Typical parameters of Lithium Ion cells	
Rated Voltage [V]	2.3 ÷ 4.1
Rated Capacity [Ah]	20 ÷ 100
Gravimetric Power Density [W/kg]	140 ÷ 4,000
Gravimetric Energy Density [Wh/kg]	30 ÷ 220
Round Trip Efficiency [%]	90 ÷ 98
Monthly self-discharge [%]	<1
Life-cycle expected @80% DoD [cycles]	4,000 ÷ (>12,000)
Typical C_{rate} [h^{-1}]	1C ÷ 4C
Maximum C_{rate} [h^{-1}]	1C ÷ 10C in discharge, 1C ÷ 4C in charge
Operating temperature [°C]	-20 ÷ +55°C
Cost [€/kWh]	200÷700

Lithium Ion Battery (LIB) - Schematic



State of the art
Liquid electrolyte LIBs
State of the art LIBs use

Oxide Cathodes
(particularly NMC and NCA),

Liquid electrolytes
with additives
to improve coulombic efficiency

Carbon Anodes
with 3-5% silicon added
to improve energy density

Current LIB achieve a gravimetric energy density of 200-260 Wh/kg
By improving same technology it can reach up to 400 Wh/kg

Lithium Ion Battery (LIB)

Types of Lithium ion batteries with different chemistry

- Lithium Cobalt Oxide ($LiCoO_2$)
- Lithium Nickel Oxide ($LiNiO_2$)
- Lithium Manganese Oxide ($LiMn_2O_4$)
- Lithium Iron Phosphate ($LiFePO_4$)
- Lithium Nickel Manganese Cobalt Oxide (NMC)
- Lithium Nickel Cobalt Aluminum Oxide (NCA)
- Lithium Titanate ($Li_4Ti_5O_{12}$)

(In red the most commonly used types on Electrical Vehicles and Stationary Energy Storage Systems)

Main international suppliers
- CATL (China)
- BYD (China)
- LG Chem (Korea)
- Samsung (Korea)
- Panasonic (Japan)

Future Trends in Lithium Battery Technology Development

Objectives

- Increase the energy density of battery cell (from 200 to >500Wh/kg)
- Improve the energy conversion efficiency
- Improve safety (reduce and eliminate fire hazard)
- Extend battery lifetime (number of cycles, energy throughput)
- Extend Electrical Vehicle range (from 200km up to 700km)
- Reduce manufacturing cost (at 100 US$/kWh EV in parity with ICE car)

Technology Steps

- **State of art** : Li-Oxide cathode (NMC), liquid electrolyte, Carbon anode
- From 100% Carbon Anode to **Silicon-Carbon Anode**
- From Liquid to **Solid State Electrolyte**, with all lithium anode (no fire hazard)
- Lithium-Sulphur Cathode
- Lithium air (Li-O2)

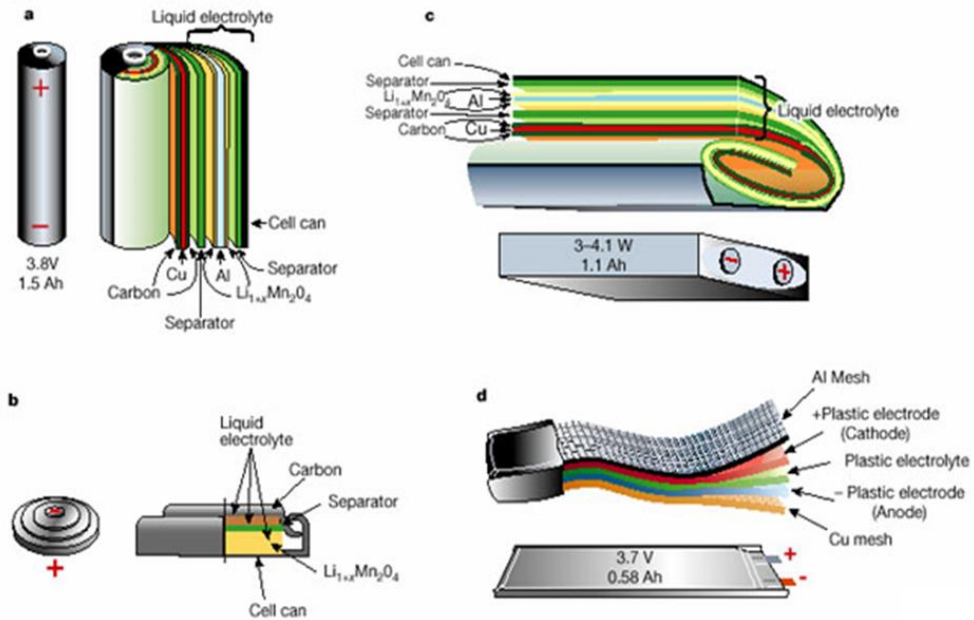
Formula E Power train / Battery

The progress of LIB technology is demonstrated by the big improvement of performance of battery utilized by Formula E cars, in few years.
Almost double energy capacity , a 60% increse of energy density, higher power, allowed to switch from two-session race to one session in 2018-2019 season.

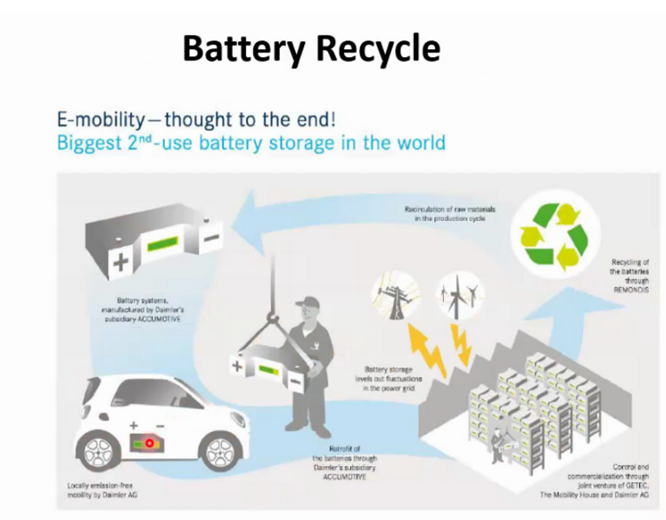
	Gen1	Gen2
Lithium ion – NMC / Nickel Manganese Cobalt electrochemistry	NMC	NMC
Stored energy	32 kWh	
Available energy	28 kWh	54 kWh
number of battery cells	165	209
Battery weight	320 kg	385 kg
Min weight of car (including driver)	880 kg	900 kg
Energy density, available energy/weight Wh/kg	87,5	140,3
Cooling method	liquid cooled	liquid cooled
Dc Voltage nominal	610 Vdc	
Peak permitted regenerative power	150 kW	250 KW
Peak permitted power (race mode)	170 kW	200 kW
Peak permitted power (qualifying mode)	200 kW	250 kW

Battery Gen1 was supplied by Williams Advanced Engineering to all Formula E racing teams
Battery Gen2 is supplied by McLaren dvanced Engineering to all Formula E racing teams

Li-ion Battery Cell Shapes



a) Cylindrical
b) Button
c) Prismatic
d) Pouch



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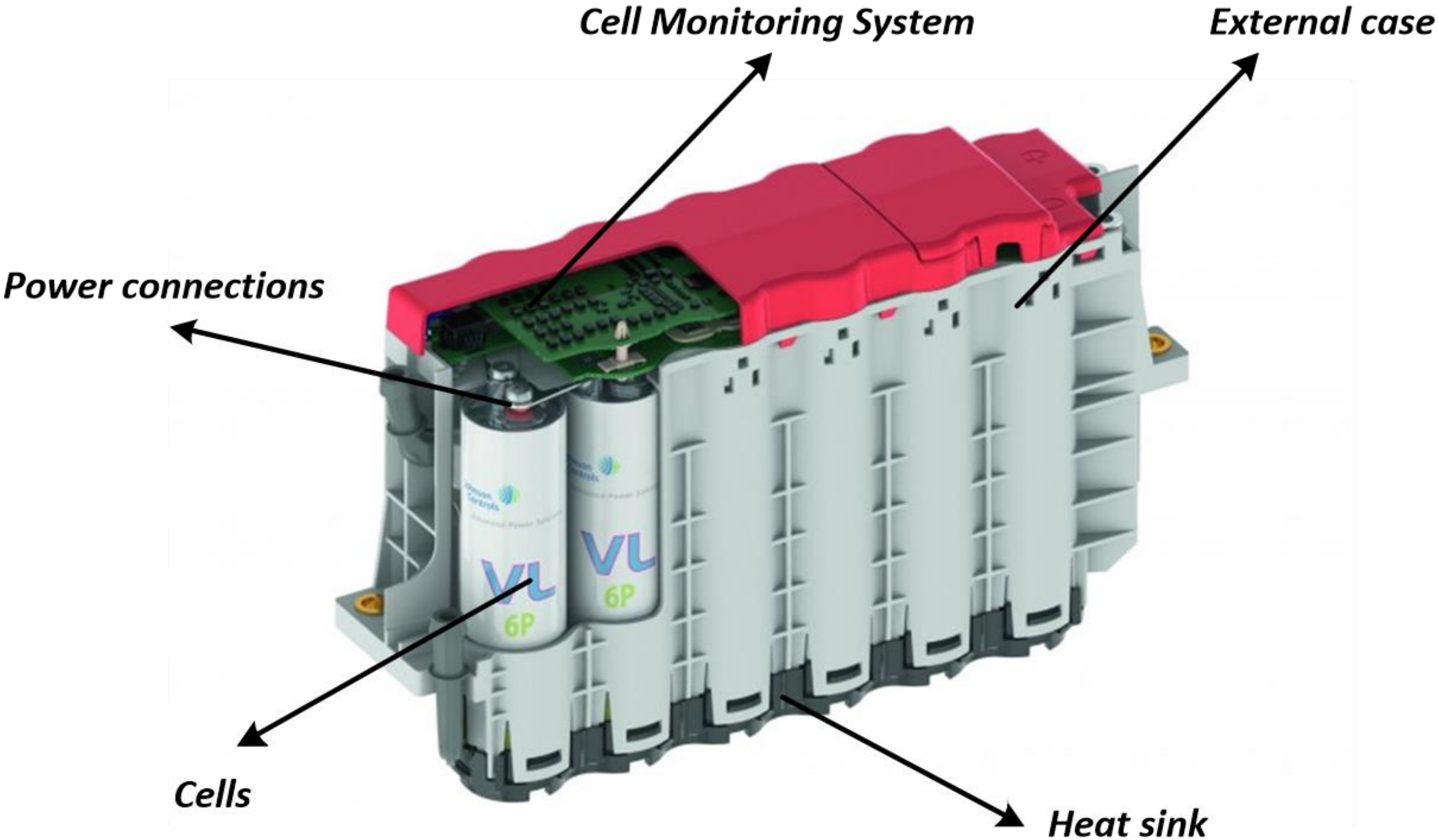
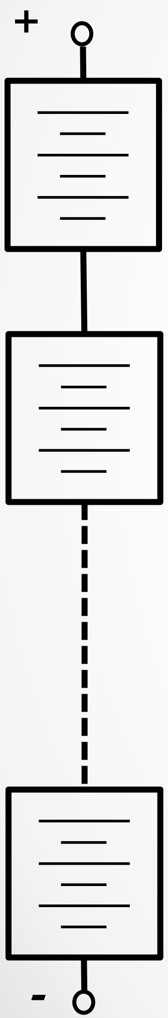
Battery Module

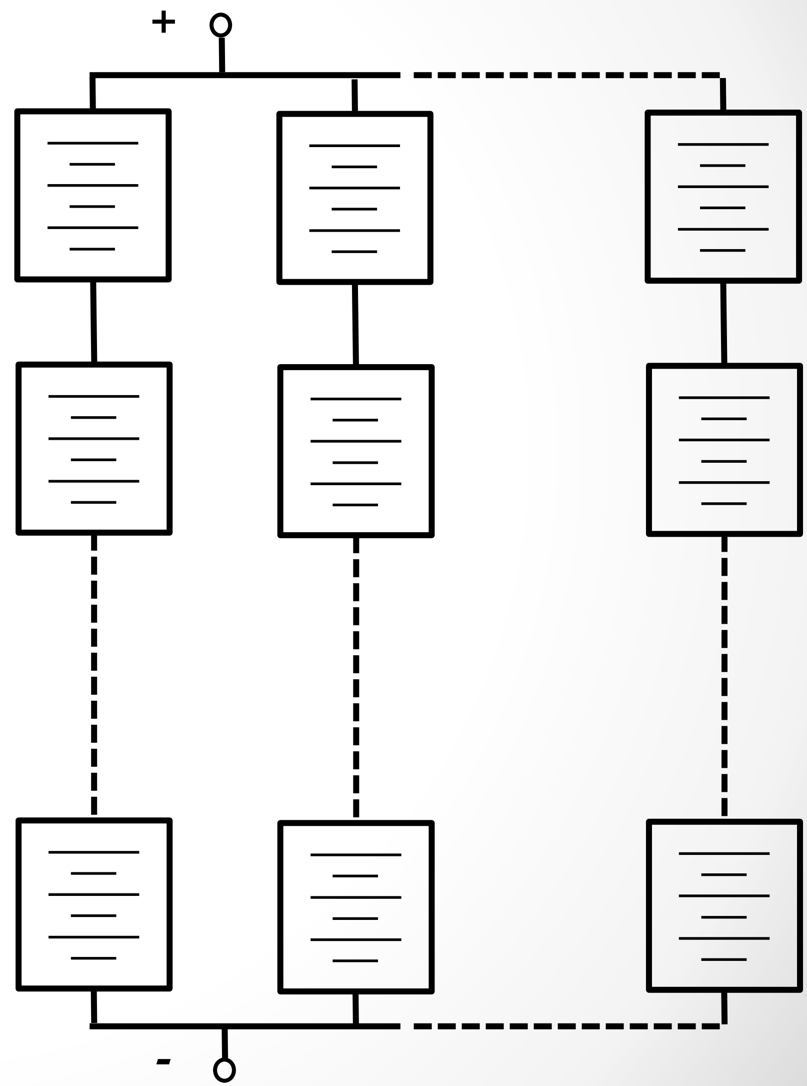


Battery Configurations



STRING (RACK): series connection of **battery modules** to achieve the DC link voltage.

BATTERY BANK: parallel connection of **battery strings**, to achieve the requested capacity.



Battery Management System - BMS

BMS is an electronic system managing a battery by the following main functions:

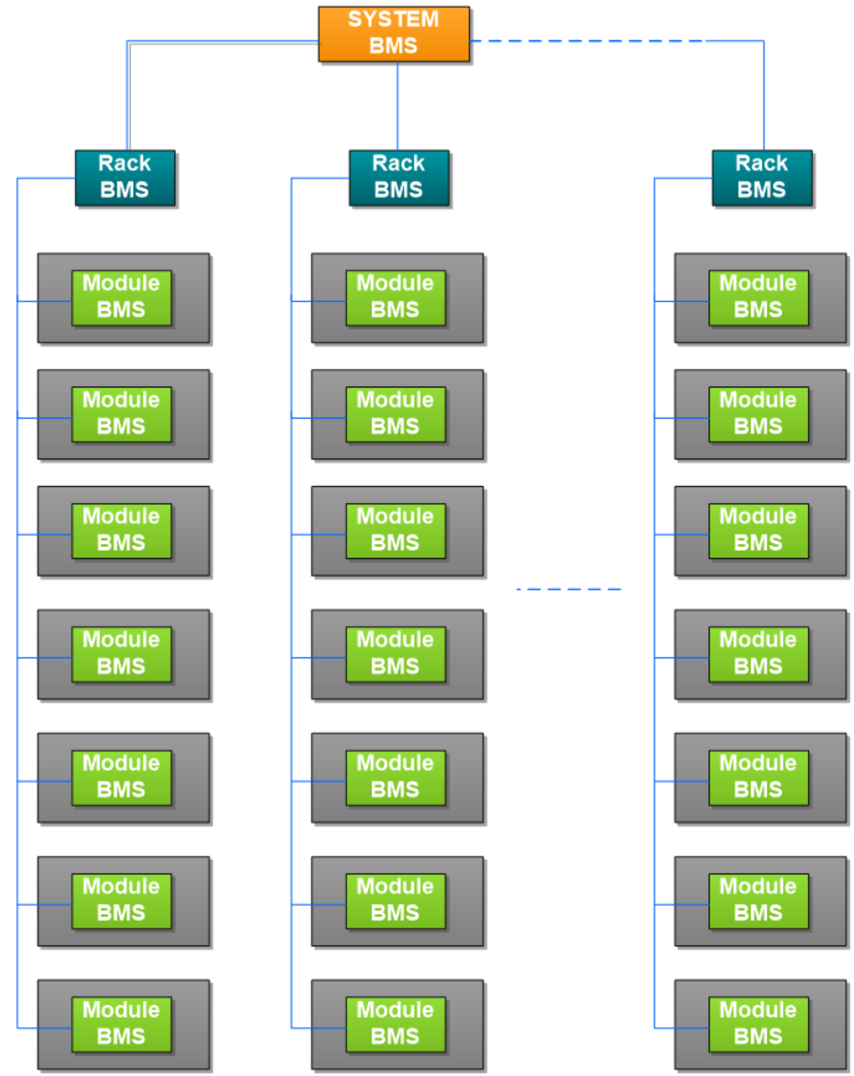
Monitoring state of battery, (voltages, currents, temperatures, SOC, DOD, cooling)

Calculations: charge, discharge, energy, internal impedance

Communication: with cell level HW and high level control HW (PC, server, HMI)

Protection: over/under voltage, temperature, current, by operating relay or switch and sending alarms

Optimization: cell balancing



Nominal and Available Energy / DoD%

The amount of energy stored in a fully charged battery is expressed by the product :

Battery Voltage (V) x Capacity (Ah) = kWh

Example. A string battery of 300 elements, each consisting of a 2V cell with a capacity C10 of 100Ah, has a **nominal energy capacity** of :

300 x 2V x 100Ah = 600V x 100Ah = 60 kWh

To maintain a long service life a recommended Depth of Discharge (DoD) shall not be exceeded, (40% for Pb, 80% for Lithium ion), which means that the **available energy** is:

40% x 60kWh = 24kWh (Pb)   80% x 60kWh = 48kWh (Lithium)

At EOL (End of Life) the battery capacity shall be reduced to 80% of the value at BOL (Beginning of Life). This is a widely accepted conventional criteria.

The number of cycles correspond to **battery service life** and are roughly inversely proportional to DoD . The cyclic ageing factor is the **"Energy Throughput"**, which is the product of charged/discharged energy multiplied by the number of cycles

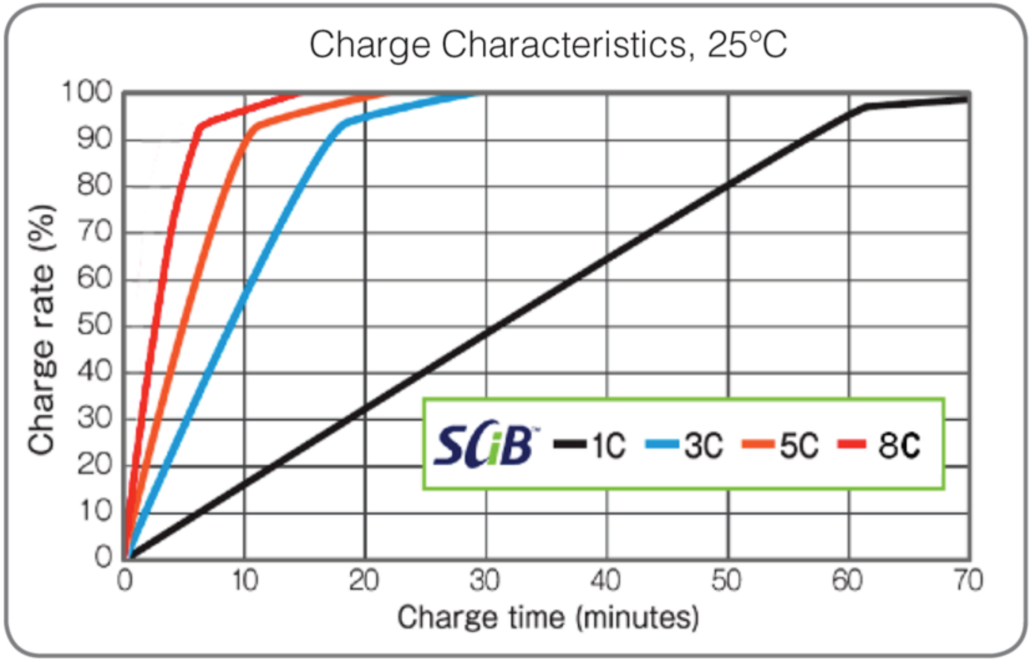
See an example in the table below, which shows **relationship between DoD and n. of cycles**

N. of Cycles	1250	2000	2500	5000
Depth of Discharge - DoD (%)	80	50	40	20

Battery C-rate

C-rate stands for "current rate" and indicates the ratio between the current flowing through the battery (both charging and discharging) and the nominal capacity of the battery itself.
It is expressed with the symbol C, followed or preceded by a number corresponding to a factor of division or multiplication, respectively.
For example, a battery operating at 2C is charging or discharging with a current twice the nominal capacity, so that it is completely discharged or charged in half the estimated time (30 minutes).
C10 means that the battery operates at a current equal to one tenth of its nominal capacity, so that it is discharged or charged in ten times the nominal time (10 hours).

$$\mathbf{C_{rate}} = \frac{\textbf{Corrente in carica(scarica) [A]}}{\textbf{Capacità di accumulo nominale [Ah]}}$$



SOC – State of Charge

It is the **quantity of discharge energy contained in the battery, referred to the nominal capacity**. It is usually expressed as a percentage. The SOC can be indicated as an absolute or relative value: the first is calculated with respect to the nominal capacity, the second with respect to the useful capacity.

The Ideal state of charge SoC (the actual measurement is influenced by temperature and C-rate) can be calculated with time integral of current :

$$\mathbf{SOC} = \mathbf{SOC(0)} - \frac{\mathbf{1}}{\mathbf{C_n}} \cdot \int \mathbf{i(t)dt}$$

Cn = nominal capacity (Ah)

The **depth of discharge (DOD - Depth of Discharge) is the complement to 1 of the SOC** and represents the amount of energy supplied by the battery, assessed at nominal capacity. It is usually expressed as a percentage.

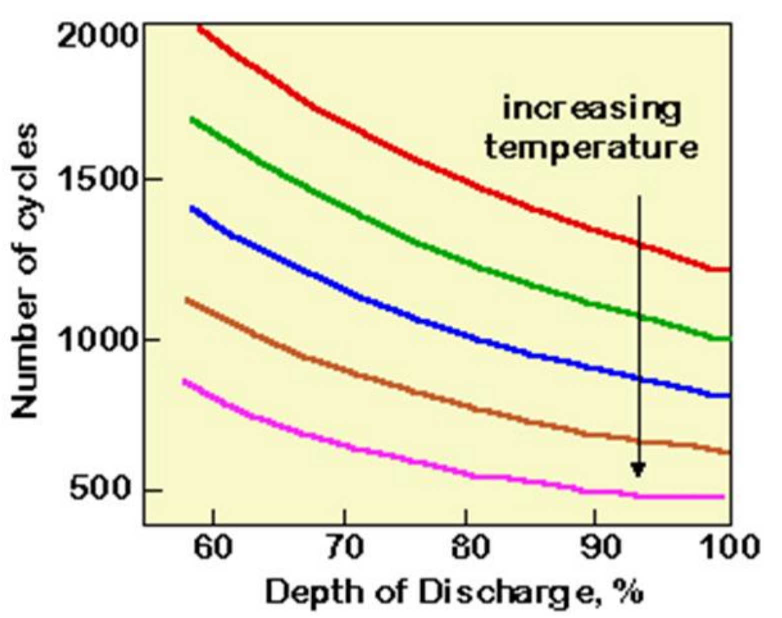
$$DOD = 1 - SOC$$

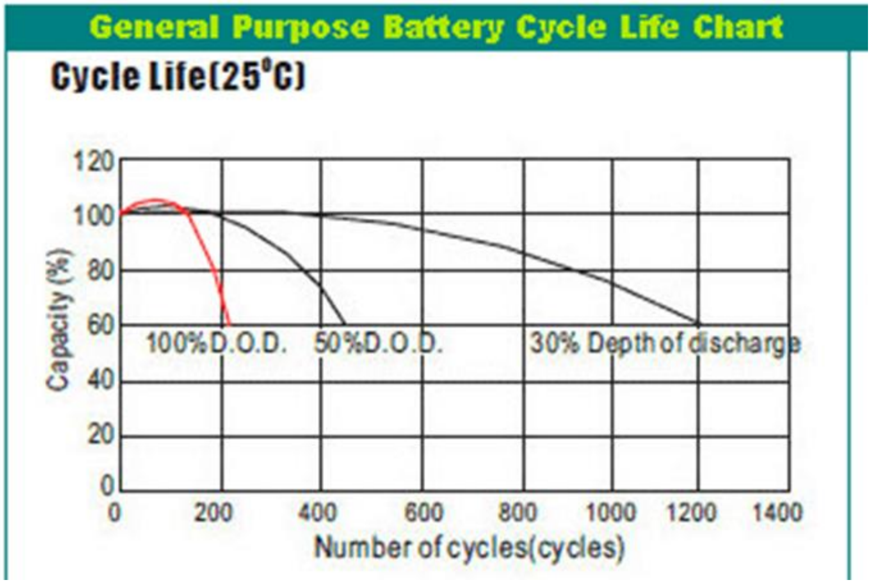
Life Cycles - SoH

Number of charge and discharge cycles of the battery before the storage capacity becomes lower than a fixed value with respect to the nominal value (typically 80%), at End of Life (EoL). Expected life cycles are typically indicated by the manufacturer for different DoD values.
The main factors that influence the actual number of life cycles of a battery are:

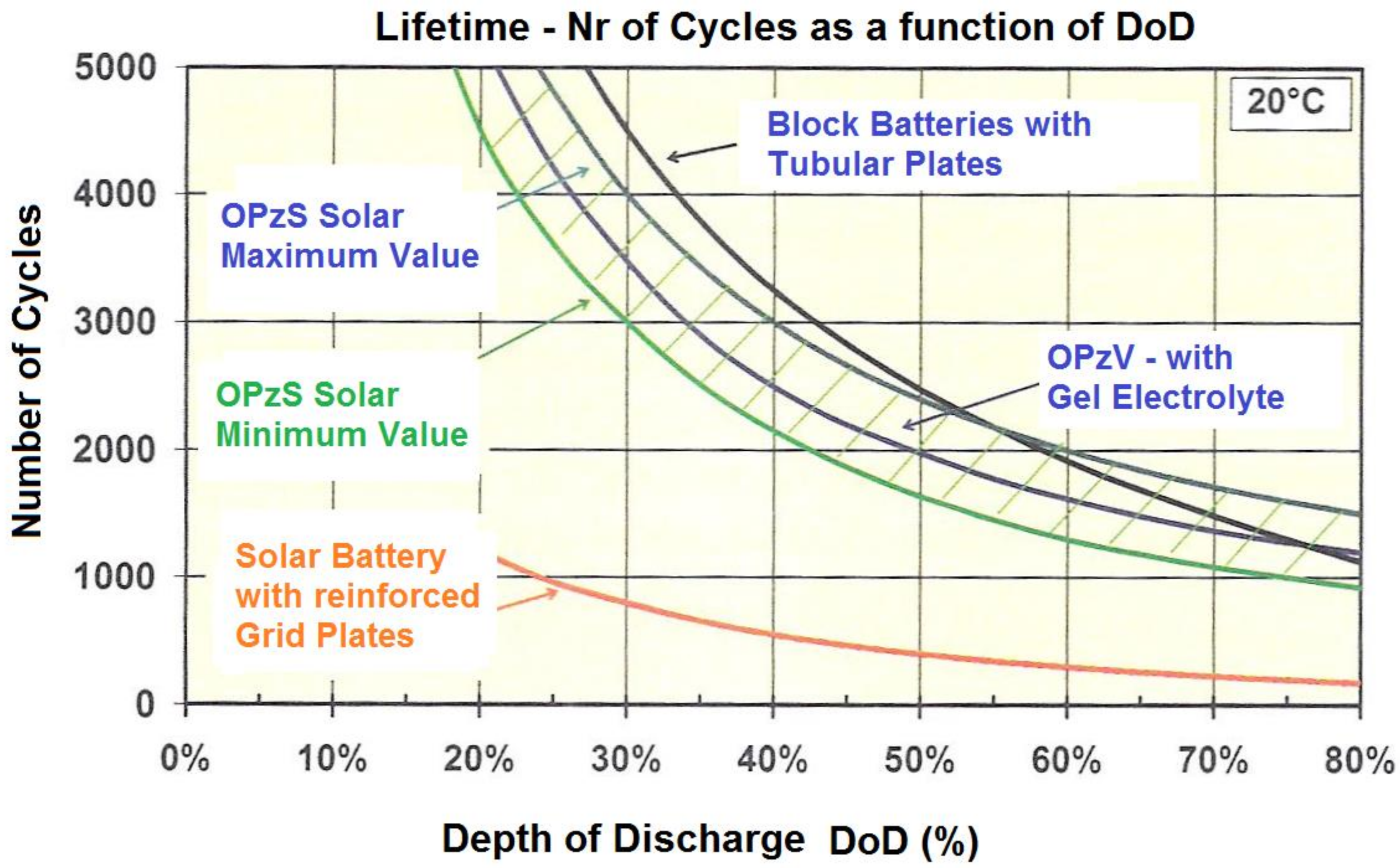
- DoD
- Temperature

The **State of Health (SoH)** is expressed in percentage of the ideal value of a battery parameter at Beginning of Life (BoL) . Normally it is referred to the capacity (Ah) of battery

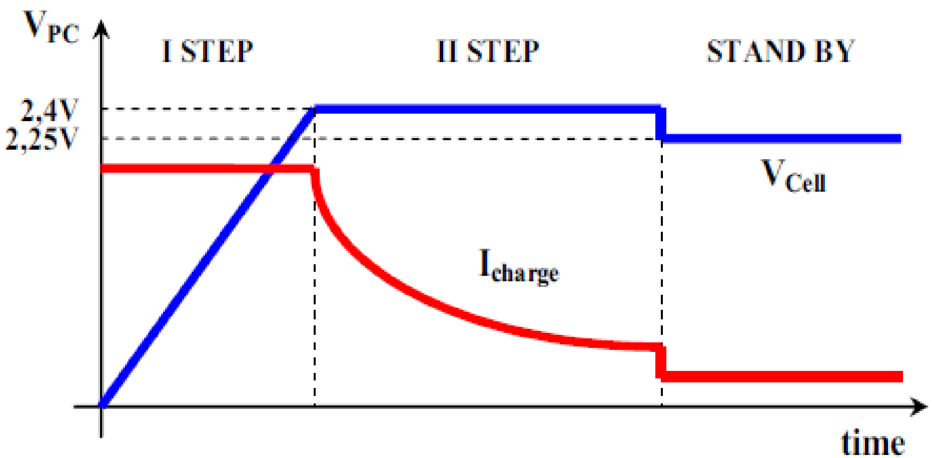




Pb Battery – N. of Cycles / DoD(%)



Recommended Charge Process



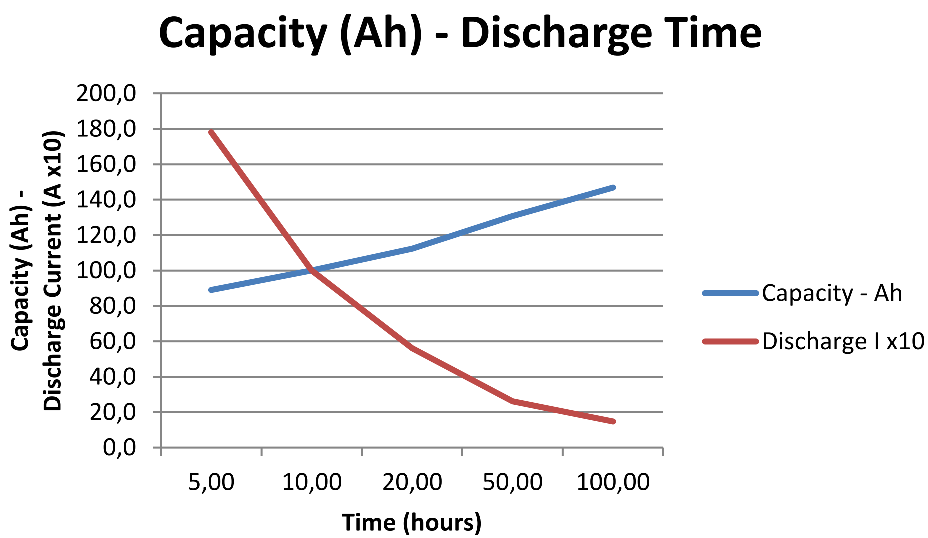
The Pb Battery in floating condition absorbs only a small current, which compensates the leakage current, due to self discharge

I step – charge at constant current, typically 20% of C10, up to 2.4V/cell;
Ex) If C10 = 100Ah, 20 A is the charge current

II step – boost (rapid) charge at 2.4V/cell, until I charge is below 2-3% of C10

III step – stand by
The battery is kept in a floating condition, at 2.25V/cell

Discharge Rate



Discharge time	hours	5,00	10,00	20,00	50,00	100,00
Discharge current	A	17,8	10,0	5,6	2,6	1,5
Capacity	Ah	89,1	100,0	112,2	130,8	146,8

The amount of **"useful" energy** that can be extracted from a battery depends on the **discharge rate.**

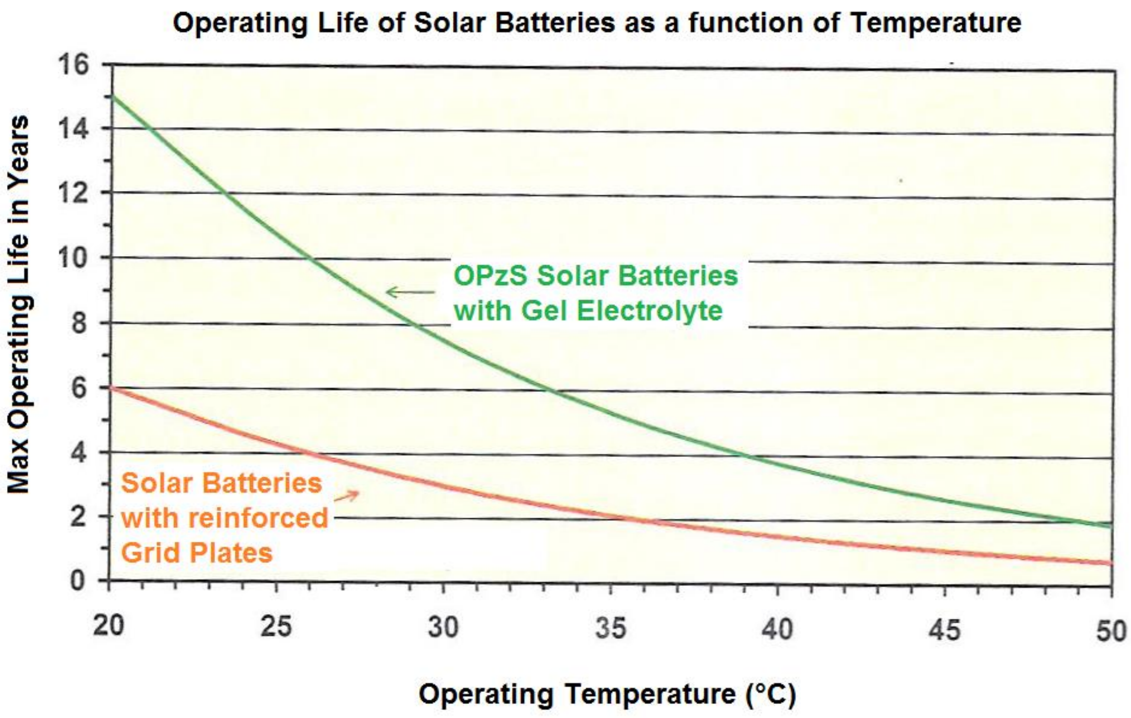
The higher the discharge current , the lesser the withdrawn energy.

This is due to **internal losses, which depends on the series resistance** of battery and electrochemical reactions.

This effect is well expressed by the capacity C (Ah) related to discharge time.

C10 is about 70% of C100, for example

Pb Batteries
Operating Life - Temperature



Operating temperature is an aging factor, affecting lifetime of battery.
Recommended operation is at 20°C.
As a "rule of thumb" every 10°C rise, the service life is reduced by 50%

Battery Cyclic Operation

Batteries utilized in BESS work in a cyclic mode and have severe operating requirements :

- High operating temperature
- High C-rate
- Deep discharge (DoD)
- High number of cycles during service life
- High round trip efficiency → **Lithium-ion shows highest RTE**

Battery Technology		Lead acid	Lithium ions	Sodium Nickel
Continuous power	W/kg	50 - 100	200 - 1000	160
Deliverable energy	Wh/kg	10 - 20	60 -100	120
Round trip efficiency	%	80	95	75
Cycles		2000	4000	3000
Max recommended DoD	%	40	80	80
Max ambient temperature	°C	35	40	no limit
DoD = Depth of Discharge				

Cell, Module, Rack, Battery Bank, Container

The table refers to a **Virtual Battery (BV),** which presents typical data of a **Lithium-Ion Battery**.
The configuration defines the number of elements in parallel (P) and in series (S).

The rack in the table consists of **12 modules in series**, but it is possible to build racks with a lower number of modules.
Data referring to BOL (beginning of life)

VIRTUAL BATTERY - LITHIUM ION - NCM TYPE			
	cell	**module**	**rack**
Capacity (Ah)	80	80	80
Energy (Wh)	296	6512	78144
Voltage max (V)	4,1	90,2	1082,4
Voltage nominal (V)	3,7	81,4	976,8
Voltage min (V)	2,7	59,4	712,8
Weight (kg) *	2	57,2	755
Density gravimetric (Wh/kg)	148	114	103
Configuration	1P1S	1P22S	1P264S
Power @1C (kW)	0,296	6,51	78,14
RTE round trip efficiency @1C	94%	94%	94%
Number of cycles	10000	10000	10000
Modules series connected		1	12

A **container** contains one or more **battery banks.** A battery bank consists of a number of parallel connected **racks.**

To increase the **battery capacity**, several **racks** are connected in parallel

To increase the **battery voltage**, several **modules** are conneccted in series

* Weight of one module = +30% of cells weight
* Weight of one rack = +10% of modules weight

Numeric Examples – Battery Energy Storage Systems

Battery Energy Storage Systems, questions
Refer to the data in the Virtual Battery table

6A.1 - Build a rack with 10 modules in series (max voltage about 900V) and fill in a new column of the BV table
6A.2 - what is the capacity (or energy) of a Virtual Battery (BV) module worth when SoH = 85%,?
6A.3 - If the discharge rate is C = 0.7 what is the current supplied by a BV module?
6A.4 - If the discharge rate is C = 0.7 what is the power supplied by a BV module?
6A.5 - If RTE = 94%, what is the loss of energy in a full charge and discharge process of a 10 BV module rack?
6A.6 - Calculate the Energy Throughput of a BV module that has carried out 2000 charge and discharge cycles, with DoD = 80%

	cell	module	rack		rack
Capacity (Ah)	80	80	80		80
Energy (Wh)	296	6512	78144		65120
Voltage max (V)	4,1	90,2	1082,4		902
Voltage nominal (V)	3,7	81,4	976,8		814
Voltage min (V)	2,7	59,4	712,8		594
Weight (kg) *	2	57,2	755		629
Density gravimetric (Wh/kg)	148	114	103		103
Configuration	1P1S	1P22S	1P264S		1P220S
Power @1C (kW)	0,296	6,51	78,14		65,12
RTE round trip efficiency @1C	94%	94%	94%		94%
Number of cycles	10000	10000	10000		10000
Modules series connected		1	12		10

Numeric Examples – Battery Energy Storage Systems

6A.2 - what is the capacity (or energy) of a Virtual Battery (BV) module worth when SoH = 85%,?

$$C = 0{,}85 \cdot 6512Wh = 5535Wh$$

6A.3 - If the discharge rate is C = 0.7 what is the current supplied by a BV module?

$$I = 0{,}7 \cdot 80A = 56A$$

6A.4 **-** If the discharge rate is C = 0.7 what is the power supplied by a BV module?

$$P = P_{1C} \cdot 0{,}7 = 6{,}5 \cdot 0{,}7 = 4{,}56kW$$

6A.5 - If RTE = 94%, what is the loss of energy in a full charge and discharge process of a 10 BV module rack?

$$P_L = 65012Wh \cdot (1 - 0{,}94) = 3{,}9kWh$$

6A.6 - Calculate the Energy Throughput of a BV module that has carried out 2000 charge and discharge cycles, with DoD = 80%

$$E_{thr} = 0{,}8 \cdot 2000 \cdot 6512Wh = 10419kWh$$

Numeric Examples – Battery Energy Storage Systems

A **lithium-ion battery energy storage system** has the following characteristics:
initial energy capacity = 100 kWh
rated voltage = 400V
Number of cycles guaranteed by the manufacturer = 2000 (*)
(*) With depth of discharge (DoD) = 80%
Round Trip Efficiency RTE = 94% (**)
(**) referred to complete charge and discharge cycles, from 0% to 100% SoC, with 1C speed of charge/discharge
SoC = State of Charge

Calculate:
6B.1 The Energy Throughput available at the beginning of life (in MWh)
6B.2 The charge and discharge current at 1C
6B.3 The energy losses during a full cycle from SoC = 0% to SoC = 100% and back to zero, at 1C speed
6B.4 The energy losses during 100 charge and discharge cycles (it is assumed that the battery capacity does not degrade during these cycles), going from SoC = 10% to SoC = 90% and back, again at 1C
6B.5 The time required to charge the battery from 10% to 90%, with a slow charge at C4 and the charge current
Note: C4 means a C rate equal to one quarter of the nominal charging current
6B.6 The time required to charge the battery from 20% to 80%, with a fast charge at 2C and the charge current

Numeric Examples – Battery Energy Storage Systems

Energy capacity at BOL	kWh	100
Voltage	V	400
Capacity at BOL	Ah	250
Current @1C	A	**250**
N.cycles with DoD 80% to EOL	n.	2000
EnergyThroughput at BoL	MWh	**160**
RTE @ 1C	pu	0,94
Losses of one full cycle @ 1C	kWh	6
N of cycles with DoD 80%	n.	100
Losses on 100 cycles @DoD 80%	kWh	480
Time of slow charge C4	h	3,2
Energy to charge SoC 10-90%	kWh	80
Slow charge power	kW	25
Current in slow charge C4	A	62,5
C rate slow charge C4	pu	0,25
Time of fast charge 2C	h	0,3
Energy to charge SoC 20-80%	kWh	60
Fast charge power	kW	200
Current in fast charge 2C	A	500
C rate fast charge 2C	pu	2

6B.1 - Energy Throughput available at the beginning of life (in MWh)

$$E_{thr} = 0,8 \cdot 2000 \cdot 100kWh = 160MWh$$

6B.2 - The charge and discharge current at 1C

$$I = 100000 / 400 = 250A$$

6B.3 - The energy losses during a full cycle from SoC = 0% to SoC = 100% and back to zero, at 1C speed

$$P_L = 100kWh \cdot (1 - 0,94) = 6kWh$$

6B.4 - The energy losses during 100 charge and discharge cycles (it is assumed that the battery capacity does not degrade during these cycles), going from SoC = 10% to SoC = 90% and back, again at 1C

$$E_L = 100kWh \cdot (0,9 - 0,1) \cdot (1 - 0,94) \cdot 100 = 480kWh$$

Numeric Examples – Battery Energy Storage Systems

Energy capacity at BOL	kWh	100
Voltage	V	400
Capacity at BOL	Ah	250
Current @1C	A	**250**
N.cycles with DoD 80% to EOL	n.	2000
EnergyThroughput at BoL	MWh	**160**
RTE @ 1C	pu	0,94
Losses of one full cycle @ 1C	kWh	6
N of cycles with DoD 80%	n.	100
Losses on 100 cycles @DoD 80%	kWh	480
Time of slow charge C4	h	3,2
Energy to charge SoC 10-90%	kWh	80
Slow charge power	kW	25
Current in slow charge C4	A	62,5
C rate slow charge C4	pu	0,25
Time of fast charge 2C	h	0,3
Energy to charge SoC 20-80%	kWh	60
Fast charge power	kW	200
Current in fast charge 2C	A	500
C rate fast charge 2C	pu	2

6B.5 - The time required to charge the battery from 10% to 90%, with a **slow charge** at C4 and the charge current
Note: C4 means a C rate equal to one quarter of the nominal charging current

$$I_{C4} = 250A \cdot 0,25 = 62,5A$$

$$P_{C4} = 400V \cdot 62,5A = 25kW$$

$$T_{C4} = 100kWh \cdot (0,9 - 0,1) / 25kW = 3,2h$$

6B.6 - The time required to charge the battery from 20% to 80%, with a **fast charge** at 2C and the charge current

$$I_{2C} = 250A \cdot 2 = 500A$$

$$P_{2C} = 400V \cdot 500A = 200kW$$

$$T_{2C} = 100kWh \cdot (0,8 - 0,2) / 200kW = 0,3h$$

Pb Battery Room – Safety Requirements

Pb batteries must be installed in suitable rooms, according to standard **CEI EN 50272-2 which sets Safety requirements for installation of stationary batteries**

Battery rooms must be **properly ventilated**, to avoid dangerous concentration of hydrogen, which is released by electrolysis during charge of battery (4% concentration is the threshold)

A temperature of 25°C should be kept not to reduce the **lifetime of battery**

Air ventilation according to formula : **Q = 0.05 * n * Igas *C10 *10-3 (m3/h)**

Refer to standard for more details

When using vented type batteries (open, flooded) the floor must be chemically resistant to electrolyte.

To **protect against explosion hazards** a safety distance in air must be observed between batteries and glowing devices, arcs, sparks and flames.

Battery Aging

Battery aging process depends on **calendar aging** and **cycle aging**.
Consequence of aging is reduction of capacity (Q) and increase of resistance

Main aging influence factors are:

- Time (t)
- Temperature (T)
- State of Charge (SoC)
- Depth of Discharge (DoD)
- Charge/discharge current (C-rate)
- Charge (or Energy) Throughput (Ah or kWh)

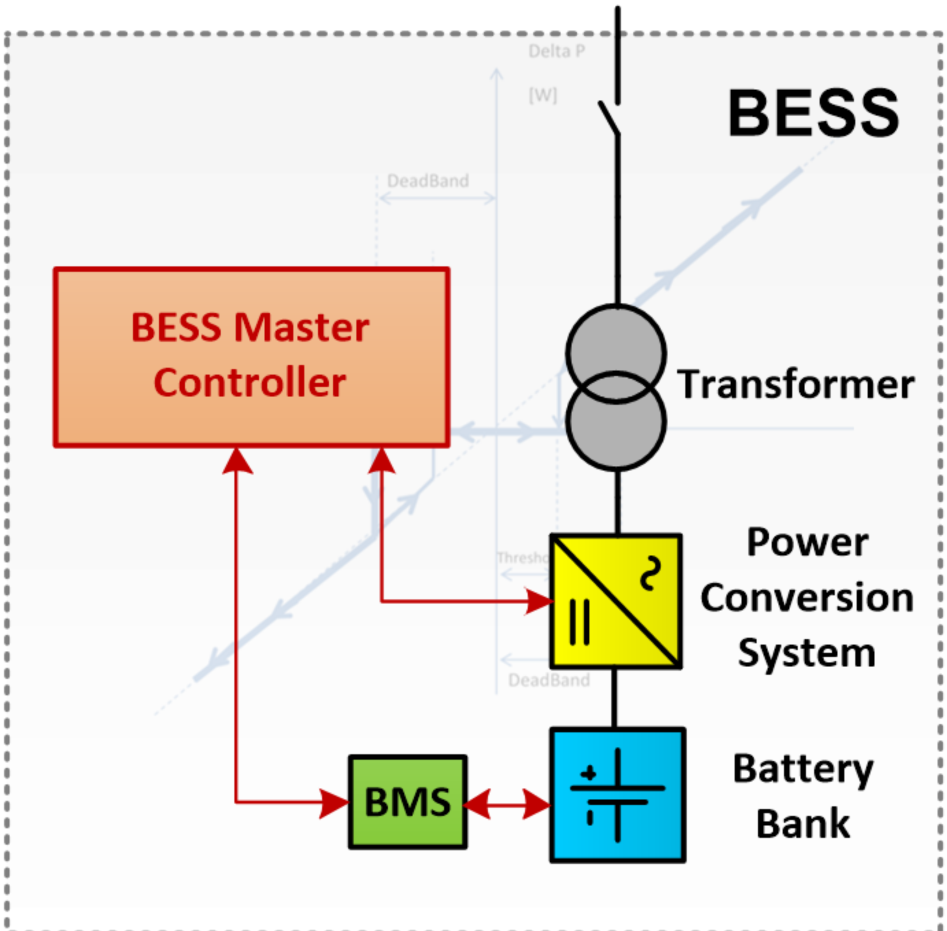
Cycling

$$Q_{loss\%} = B(SOC, T, C-rate)e^{-\frac{E_a(SOC,T,C-rate)}{RT}} Ah^z$$

Calendar

$$Q_{loss\%} = A(SOC, T)e^{-\frac{E_a(SOC,T)}{RT}} t^z$$

BESS – Main Components



Battery Energy storage system

Power Conversion System (Inverter)
interface between battery (DC system) and network (AC system)
bidirectional (energy storage and production)
active / reactive power regulation

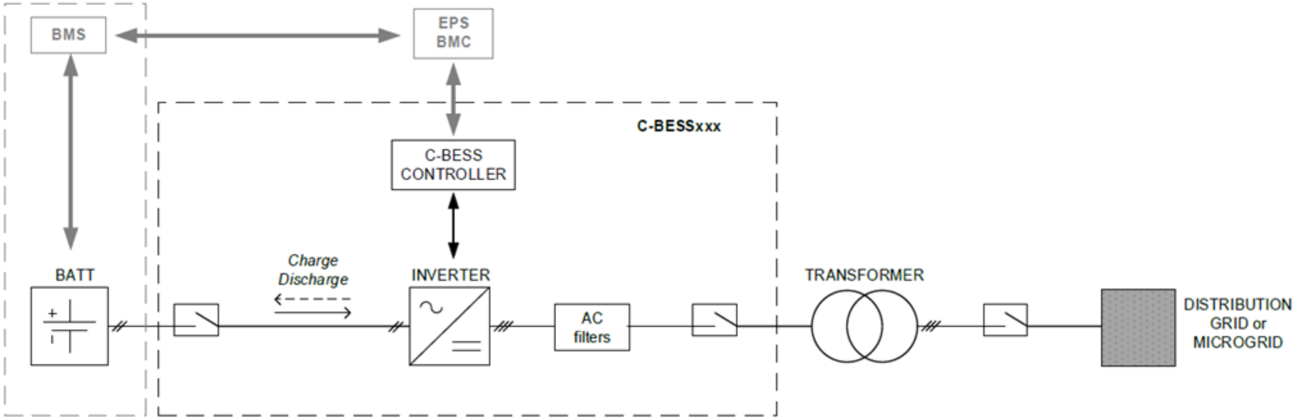
Battery Management System (BMS)
battery control system

Central Control System
coordinates the controllers of the BESS subsystems (inverters, batteries)

BESS – Inverter

BESS inverters are used to interface battery bank with the surrounding electrical system and mainly to perform the following functions:

- Convert the DC voltage of the battery bank to match the AC output (DC up to 1100V)
- Modulate active and reactive power, in response to set points from a superior level control system.
- Charge the batteries according to recommended charging profiles.

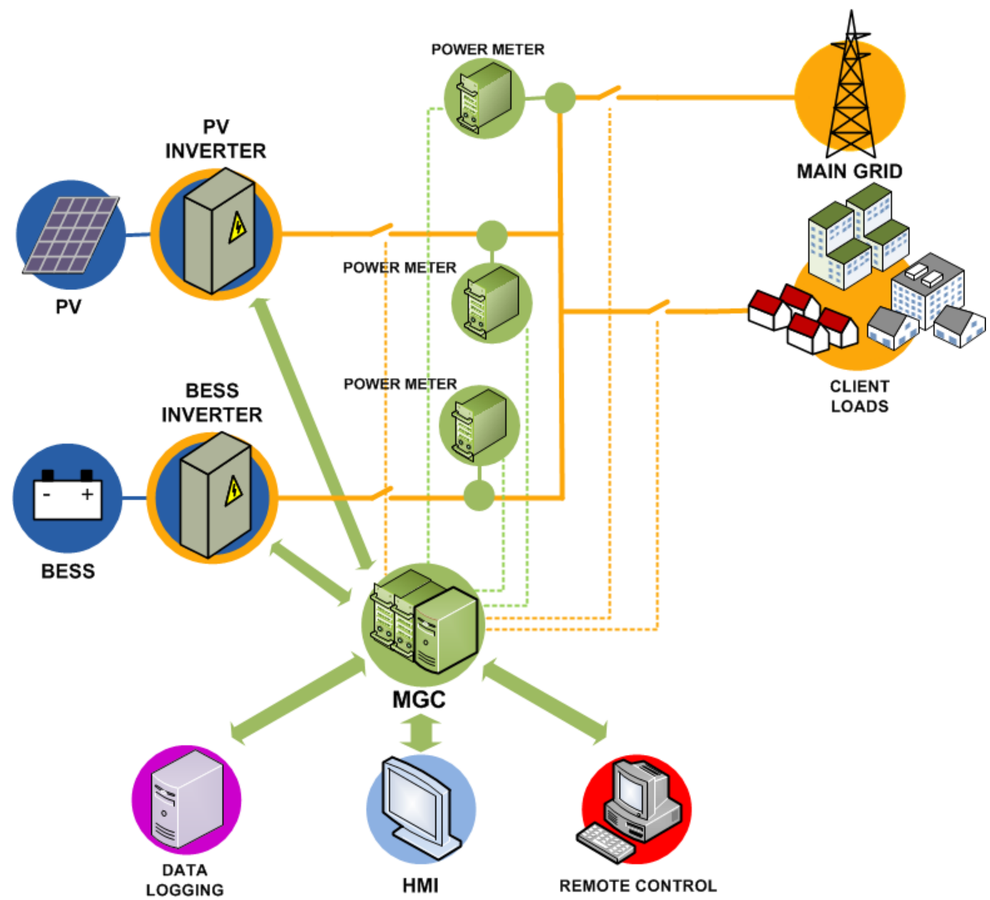


BESS - Battery Energy Storage System

A Battery Energy Storage System (BESS) includes three main elements: a **battery bank,** a **DC/AC inverter and a BESS Master Controller (BMC)**.

The converter allows the BESS to control **P and Q set points**, when the system is **grid-connected**, or **V and f set points**, when the system is **isolated**.

The **BMC manages the BESS control functions** and is interfaced with the Battery Management System (BMS) and with a higher hierarchical control level, which can be a MGC (if present), a SCADA, an external supervision system



Standard References :

- CEI 0-16; CEI 0-21 – Italy
- VDE AR-N 4105 – Germany
- IEC 62933-2

Definition of DER

Distributed Energy Resources (DER) are defined as "generation, storage, and controllable load interconnected at the low or medium voltage distribution level"

Examples of DERs:

- Renewable energy sources (solar, wind, hydro, geothermal)
- Energy storage systems (batteries, capacitors, flywheels, electrical vehicles)
- Fossil fuel (diesel generators, gas microturbines)
- Controllable load (air conditioners, pumps, cooling sytems, etc.)

Most DERs are connected to grid by "**smart inverters**" which convert power between DC and AC.

Inverters are controlled by firmware and can change voltage, frequency, active and reactive power.

Smart Inverters can be used to support the grid – either as mandatory or through market-based functions

DG/DER - Benefits and Challenges

- DERs Improve reliability and resilience of electrical power network (back up, microgrids)
- Renewable DERs minimize use of fossil fuels
- Deferral of new power generation and transmission construction since unmet load grows more slowly and DER can provide both energy and ancillary services
- DERs decrease power transmission losses
- DERs reduce energy costs
- DERs allow to shift energy usage as prices vary over time

- Renewable DER are intermittent and not dispatchable.
- PV provides power only during the day and in presence of sunlight, power fluctuations happen when clouds pass over or as the wind changes speed
- Owners of DER systems are interested in meeting their own energy requirements first and when selling energy back to the grid, they do not want power generation curtailment by utilities
- DER systems may cause voltage problems on feeders
- Disconnection of DER systems under brief voltage or frequency fluctuations may cause outages
- Management of several DER systems requires significant investments in communication equipment

Grid Codes

*A **grid code** is a technical specification which defines the parameters a facility connected to a public electric network has to meet to ensure safe, secure and economic proper functioning of the electric system. The facility can be an electricity generating plant, a consumer, or another network. The grid code is specified by an authority responsible for the system integrity and network operation. Typically a **grid code** will specify the required behavior of a connected generator during system disturbances. (source : Wikipedia)*

Italy
CEI 0-21 and CEI 0-16 define the connection rules to LV and MV distribution networks respectively

European Union - EU
CENELEC → EN 50549-1 and EN 50549-2: Requirements for generating plants to be connected in parallel with distribution networks / Part 1 → LV, Part 2 → MV distribution network
Generating plants up to and including Type B

USA
IEEE 1547:2018
IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces
UL 1741 – Inverter certification standard
California Rule21 → how to connect and operate generation facilities to be connected to a utility's distribution system

Ancillary Grid Services

Ancillary services *are necessary to support the transmission of electric power from seller to purchaser given the obligations of control areas and transmitting utilities to maintain reliable operations of the interconnected transmission system.*
These services generally include, ***frequency control, spinning reserves and operating reserves****.*
Traditionally ancillary services have been provided by generators, however, ***the integration of intermittent generation*** *and the development of* ***smart grid technologies*** *have prompted a shift in the equipment that can be used to provide ancillary services*. (Source : Wikipedia)

Most DERs are interfaced to grid by **smart inverters**, software controlled, with very fast response time. These DERs can execute functions associated to ancillary services autonomously, based on voltage, frequency, and other status and measurement inputs.
DERs can operate in response to these inputs in millisecond timeframes
In California-USA, a **SIWG (Smart Inverter Working Group)** has been established to develop standards on smart inverters, which is still active.

The most common functions associated to **ancillary services** are :

1. Disconnect / Connect Function
2. High/Low Voltage Fault Ride-Through
3. High/Low Frequency Ride-Through
4. P(f) → Active Power as a function of frequency / Power Balancing
5. Q(V) → Reactive Power as a function of Voltage / Voltage support

European Network Codes (by ENTSO-E)

Requirements for Generators

The Network Code on Requirements for Generators is harmonising standards that generators must respect to connect to the grid.
The published network codes have become regulation :
COMMISSION REGULATION (EU) 2016/631 of 14 April 2016
European Network Codes, developed by ENTSO-E, define as significant the following categories of power generators:

Type A: connection point below 110 kV and maximum capacity of 0,8 kW or more;

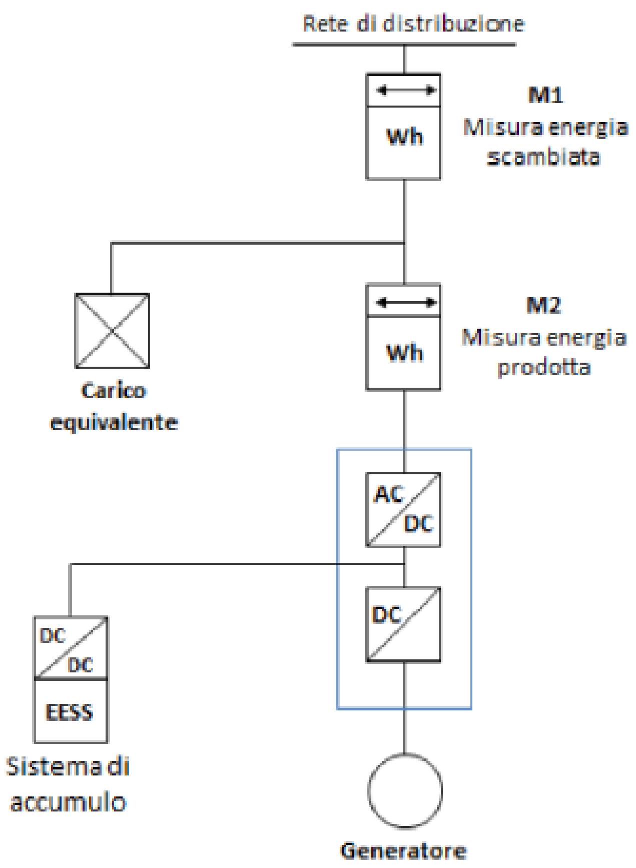
Type B: connection point below 110 kV and maximum capacity at or above a threshold and below the limit established by the relevant regulatory authority (Ranging between Baltic countries at 0.5 MW, Continental Europe at 1 MW, and Nordic countries at 1.5 MW);

Type C: connection point below 110 kV and maximum capacity at or above a threshold and below the limit established by the relevant regulatory authority
(Continental Europe = 50 MW)

Type D: connection point at 110 kV or above for all power generating modules

Each European country will specify requirements and parameter values, within these Codes

Connection to Grid of Energy Storage Systems



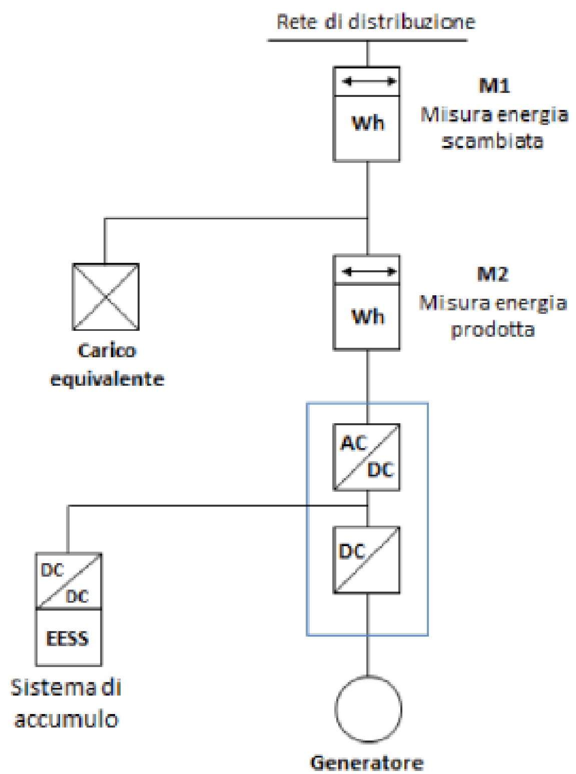
The ***Technical Connection Rules*** *provide the diagrams to be adopted for the grid connection of the Energy Storage System (ESS) within the user's plant, the characteristics of the measurement system necessary for the correct handling of the energy flows introduced by the storage, the positioning of protection systems.*

An ESS can be installed:

- *in the direct current part of the plant;*
- *in the part of the AC plant downstream of the generator energy production meter;*
- *in the part of the AC plant upstream of the generator energy production meter;*
- *with a passive user.*

Diagrams and descriptions (in italics) are taken from the technical guide
GUIDA TECNICA SUI SISTEMI DI ACCUMULO CONNESSI ALLA RETE ELETTRICA DI DISTRIBUZIONE
published by ANIE

Connection to Grid of Energy Storage Systems

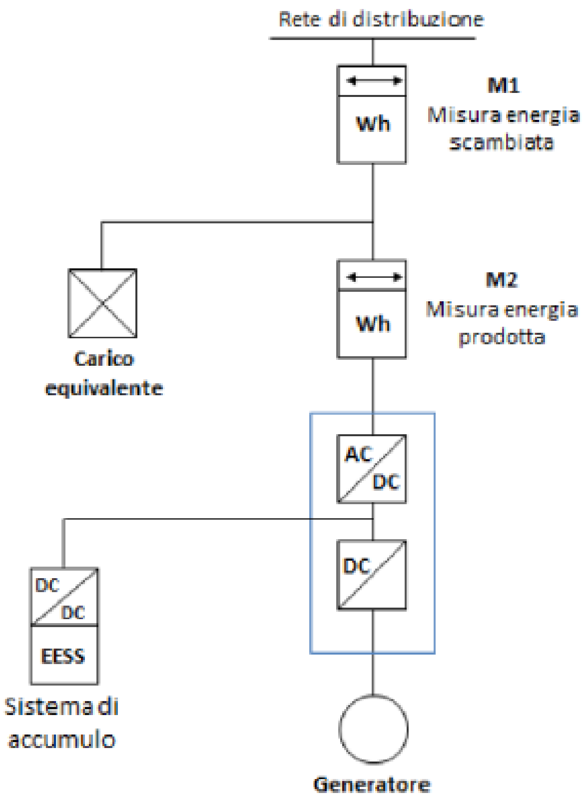


*The first way to install the ESS (connection in the **direct current part of the plant**) involves sharing with the generator (typically photovoltaic) of the AC / DC converter and transformer MV / LV (if the ESS is connected to MV grid).*

The batteries are connected to the DC bus through a further converter (DC/DC), necessary for decoupling the operation of the storage from the one according to MPPT logic of the photovoltaic generator.

*This configuration allows to achieve an **optimal Yield** of the overall system: the energy produced by the generator can be stored directly in the ESS, without passing through the AC side of the plant.*
On the contrary, if the ESS was connected to AC section it would require a double conversion (DC/AC in the generator inverter, and subsequently AC/DC in the ESS converter).

Connection to Grid of Energy Storage Systems



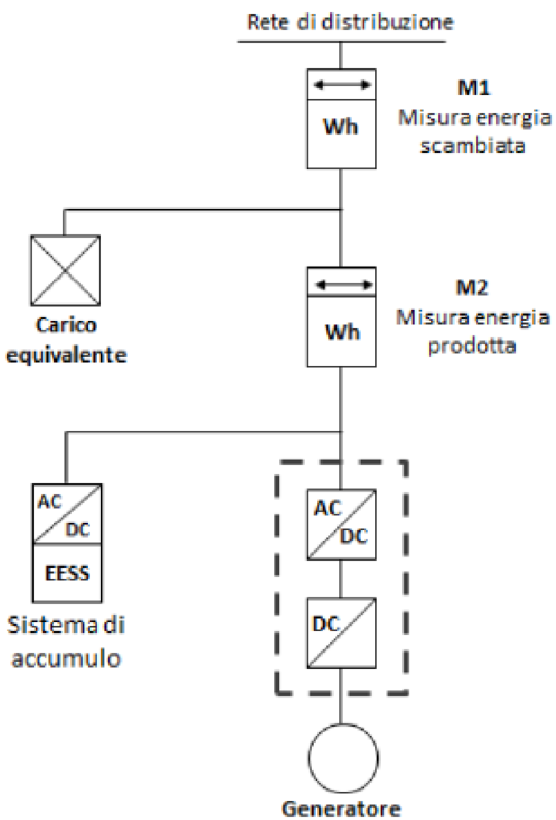
The AC / DC converter of the ESS and generator can be ***bidirectional or unidirectional****:*

in the ***bidirectional case****, the ESS can store both the energy produced by the generator and to take it from the grid;*

in the ***unidirectional case****, charging can only take place through production on the DC side.*
In this case, the ESS system + generator + converter is seen by the network as an overall equivalent generator.

The M2 energy production meter must be of the ***bidirectional*** *type, regardless of whether or not the ESS and or Generator have access to incentive schemes.*
In fact, the energy storage can allow to withdraw energy from the grid (not detected by a one-way M2 meter) and re-feed it into the grid as local production.
In the configuration under consideration, the ESS and generator behave as a single system for the purposes of the network, so they share both the Generator Protection and the Interface Protection (Dispositivo Di Generatore – DDG and Dispositivo Di Interfaccia – DDI, respectively).

Connection to Grid of Energy Storage Systems

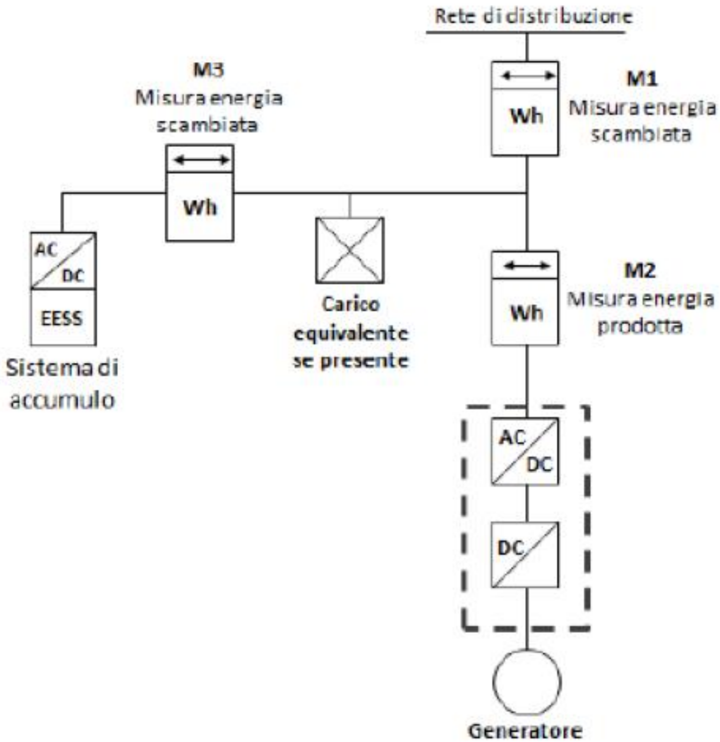


*The ESS can be connected on the **alternating current (AC) side** of the user's system, downstream or upstream of the M2 energy production meter.*

The figure illustrates the case of a one-way DC-AC converter, integrating the ESS in the alternating current section, upstream of the M2 energy meter)

Compared to the configuration with the ESS integrated in direct current section, it has the disadvantage of requiring the duplication of some devices (e.g., the AC / DC converter) and of involving an overall lower yield, due to the double conversion stage

Connection to Grid of Energy Storage Systems



The case of ESS connected on the ***alternating current side (AC),*** *downstream of the M2 meter, is ideal when you want to install the storage inside an existing system, as it does not require intervention on the generator power plant.*

BESS – Main Properties for Energy Systems

BESS applications in energy systems are classified in 2 major categories

- **Energy Intensive** : BESS autonomy higher than 6 hours
- **Power Intensive** : BESS autonomy less than 6 hours

Power intensive applications may require operation with C rate up to 4C

Service Life

is expressed by number of cycles with 80% residual capacity at the end of life. Best lithium-ion batteries show a long lifetime, up to 10.000 cycles with operation at 25°C, rate of charge/discharge 3C

Energy Efficiency

Round trip efficiency of Li-ion batteries : more than 96.5% at 1C

All BESS have excellent dynamic properties.

Response time to a complete charge/discharge reverse process is very fast, within 100msec. By far superior to any conventional power plant, which have much slower response times.

The high response speed makes BESS ideal for primary frequency regulation, creation of synthetic inertia, mitigation of RES intermittance, power balancing

BESS – Use cases

BESS can provide both

Energy Services (little variations of power for long periods) and

Power Services (fast response to large variations of power)

The Use Cases of BESS can be summarized :

Intermittent RES mitigation

Counteract the RES unpredictability, by compensating the power unbalances

Energy Time Shift

Peak shaving, load leveling

Ancillary Services

To grid operators, according to National Grid Codes

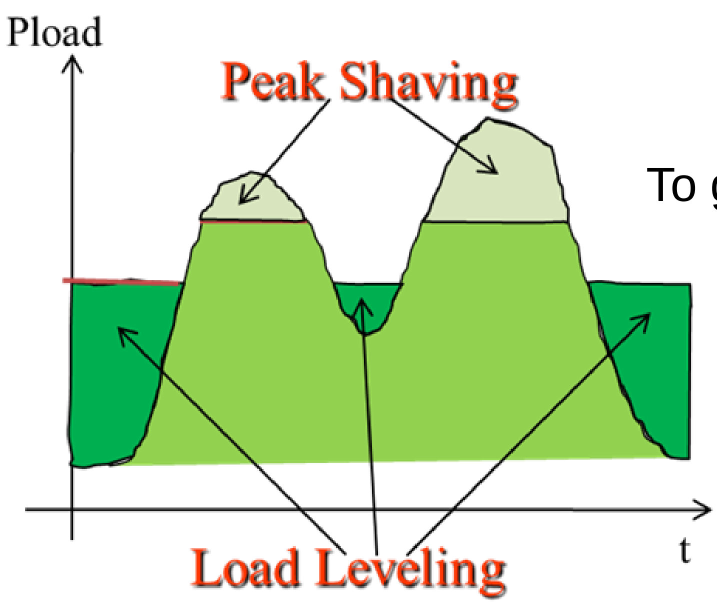
Voltage support

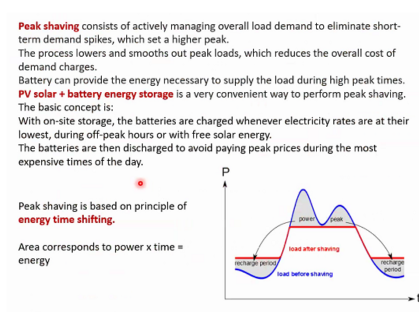
Frequency Regulation

Reactive Power Supply

LVFRT

Black Start





Peak shaving consists of actively managing overall load demand to eliminate short-term demand spikes, which set a higher peak.

The process lowers and smooths out peak loads, which reduces the overall cost of demand charges.

Battery can provide the energy necessary to supply the load during high peak times.

PV solar + battery energy storage is a very convenient way to perform peak shaving.

The basic concept is:

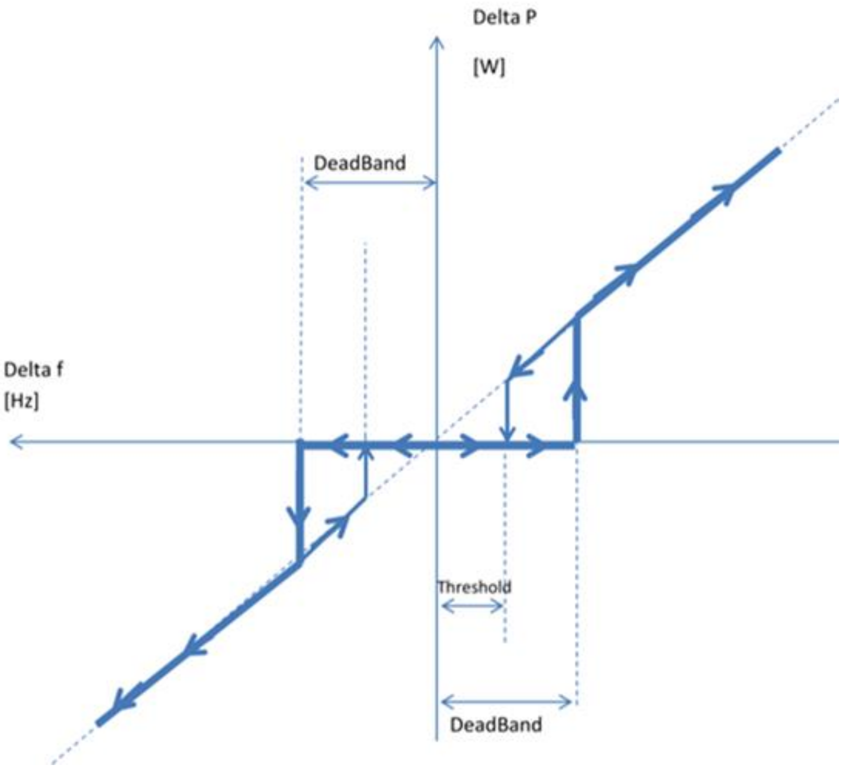
With on-site storage, the batteries are charged whenever electricity rates are at their lowest, during off-peak hours or with free solar energy.

The batteries are then discharged to avoid paying peak prices during the most expensive times of the day.

Peak shaving is based on principle of **energy time shifting.**

Area corresponds to power x time = energy

BESS – On grid – P(f)

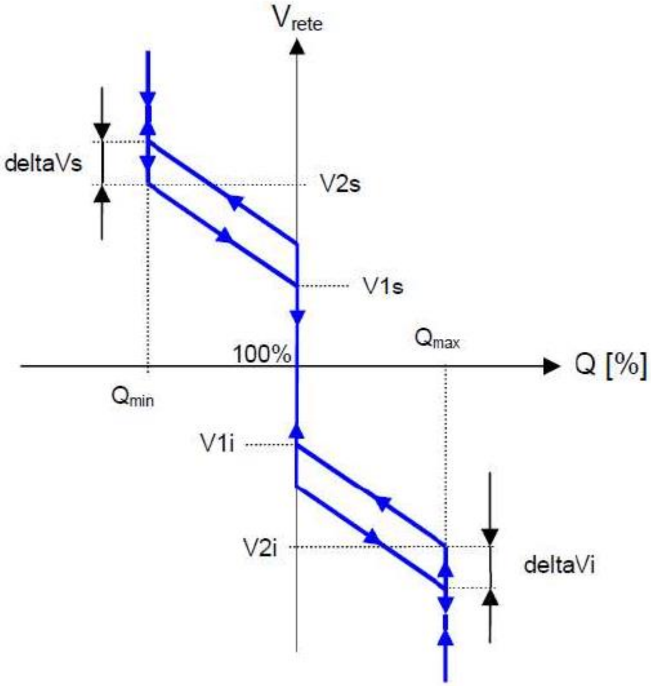


Primary frequency regulation:
the BESS contributes to the frequency regulation, to guarantee the stability of the network, behaving like a synchronous generator (correspondence to the CEI 0-16 standard).

Objective: to influence the frequency value at the connection point by supplying or absorbing active power

The control system based on the value of the frequency measured in the point of parallel with the network elaborates a set point of P according to the curve in the figure.
-DeadBand < Δf <+ DeadBand: frequency dead band (regulation not active);
Δf < -DeadBand: under-frequency (the BESS feeds active power into the network);
Δf > + DeadBand: overfrequency (the BESS absorbs active power from the network).

BESS – On grid – Q(V)

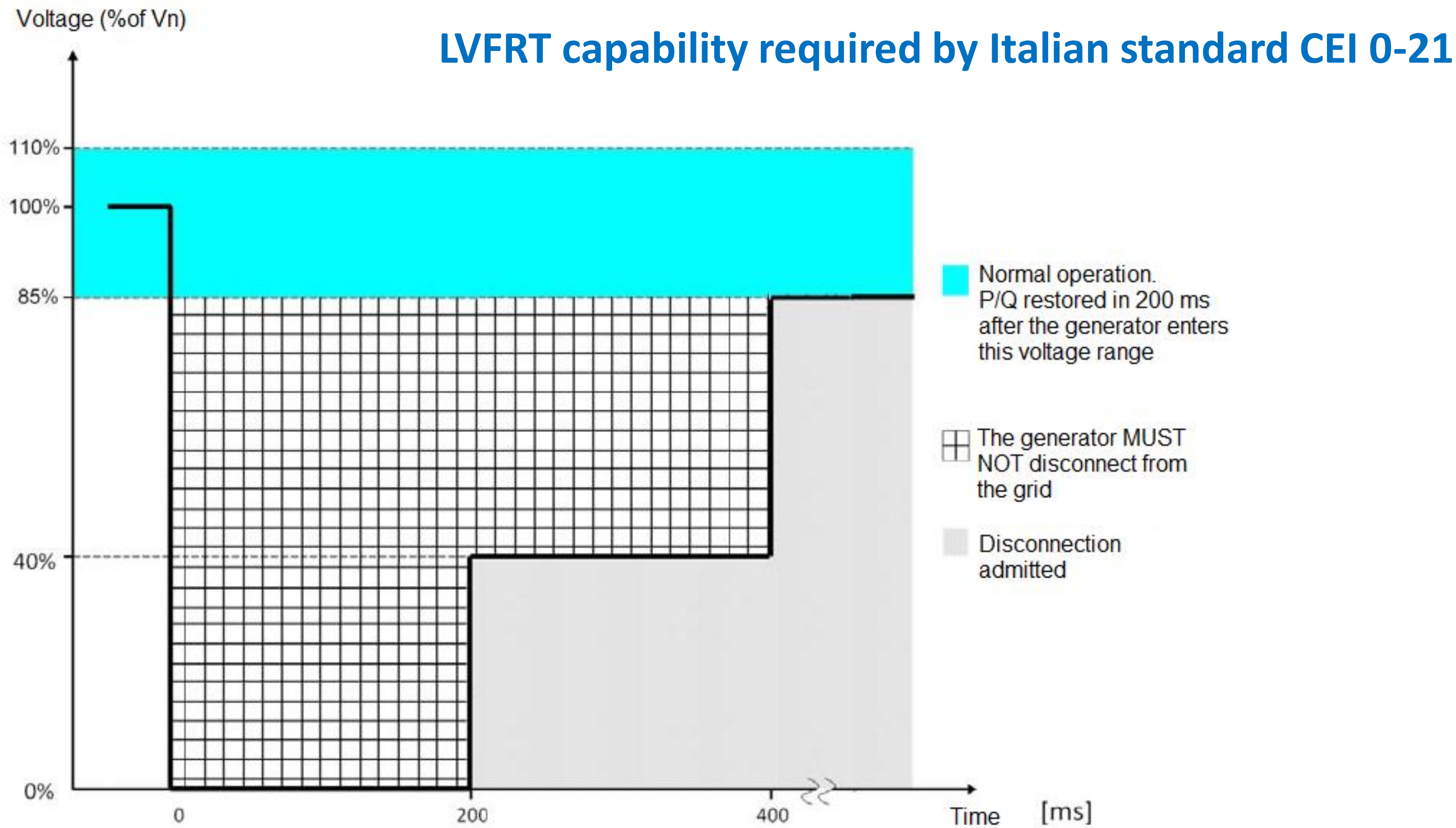


Voltage regulation: the BESS contributes to the voltage regulation, to guarantee the stability of the network, behaving like a synchronous generator (correspondence to CEI 0-21 and CEI 0-16).

Objective: to influence the value of the voltage at the point of delivery by injection or absorption of reactive power

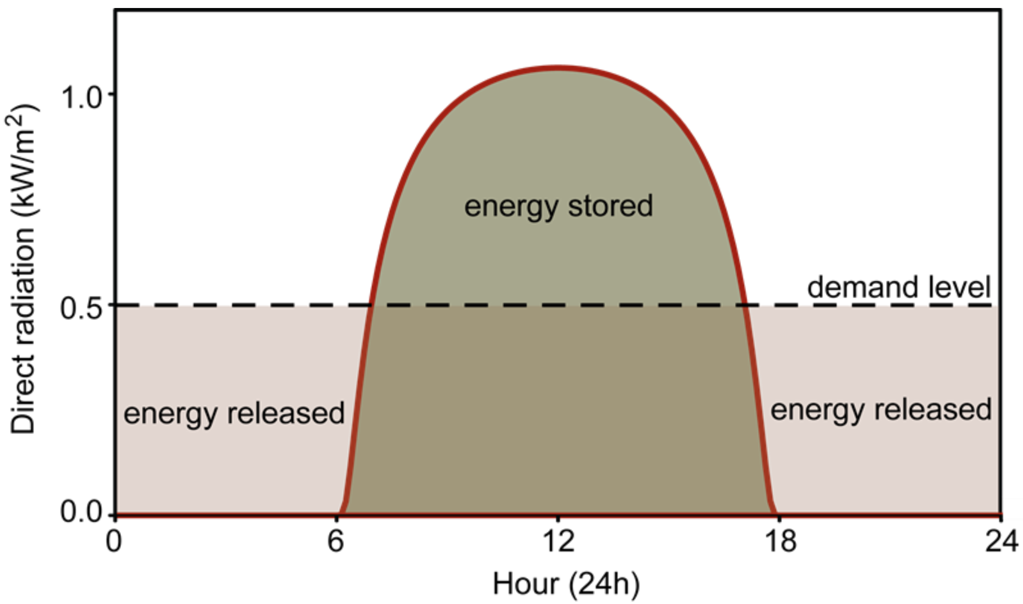
The control system based on the value of the voltage measured in the point of parallel with the network elaborates a set point of Q according to the curve in the figure.
V1i-V1s: voltage dead band (regulation not active);
V1i-V2i: undervoltage (the BESS feeds reactive power into the network);
V1s-V2s: overvoltage (the BESS absorbs reactive power from the network).

Low Voltage Fault Ride Through (LVFRT)



The **BESS** coupled to a RES generator allows the RES generator to remain connected to the grid in case of a fast voltage drop. This application is defined as "**LVFRT capability**".

BESS – On Grid – Time Shift



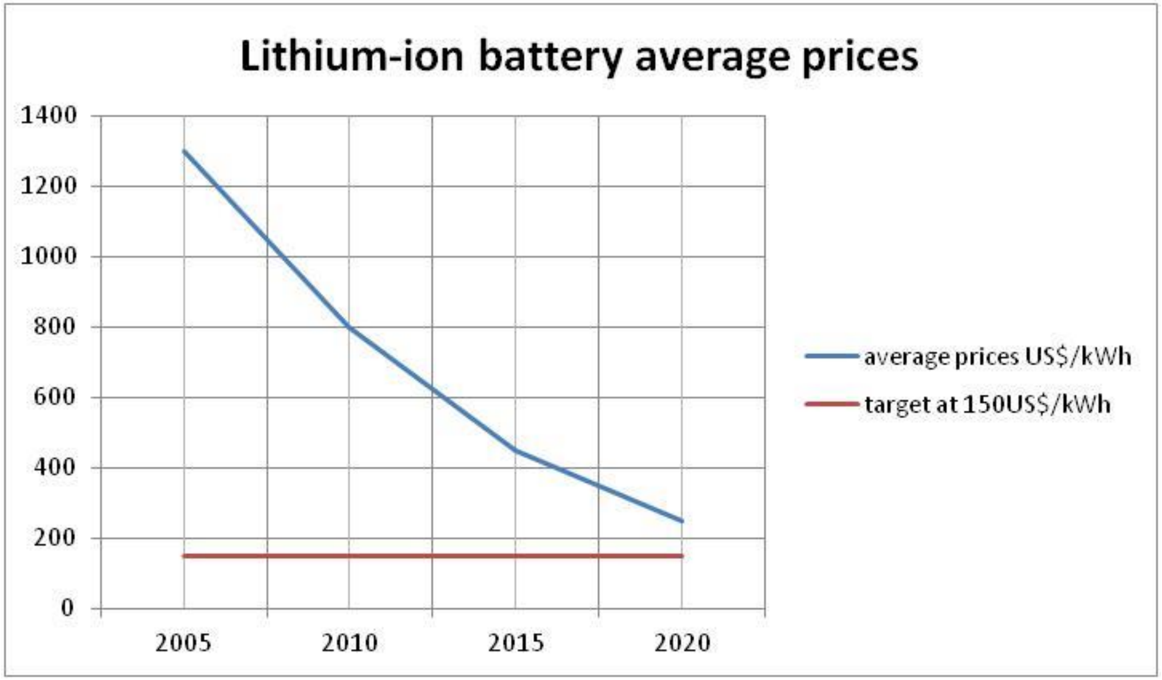
Energy time-shift:
transfer over time of the energy supplied / absorbed between BESS and network based on the needs of the load or at more convenient rates.

The BESS absorbs energy from the RES (or DER) when the cost of selling the energy is lower (eg over night, pumping plants) or when production is higher than the load demand.
BESS supplies energy when the cost of selling energy is higher or when production is lower than the load demand.

Objective: to increase energy independence of DER owner and obtain economic benefits.

BESS – Lithium–ion Battery Price Decline

Lithium-ion battery prices are declining faster than expected, probably due to high production growth by electric car manufacturers.
A cost of 200 US$/kWh has been achieved in 2018 by market leaders.



Automotive market.
EV Battery Cells/Packs
Price decline

Lowest prices in 2014
300 US$ per kWh

Time interval :
2005 – 2020.

Projection :
150 US$/kWh by 2020

Battery price reduction will transfer to the stationary energy sector. Probably the economy of scale will push cost down as it happened in solar business.
The PV power plant price dropped in less than 10 years to 1€/Wp (utility scale**)**