Battery Energy Storage

ELEC2005 Electrical and Electronic Systems - Week 12

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Advantages and disadvantages: discussion

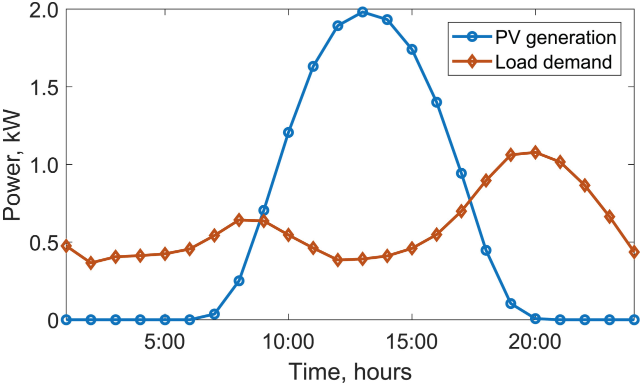
- Advantages
  - Storage allows using electricity at a different time than when it was generated
  - Using your own (stored) energy when electricity from the grid is expensive
  - Support grid stability (e.g. frequency regulation)
  - Others?
- Disadvantages
  - Some energy is lost due to inefficiencies
  - Additional investment costs
  - Safety requirements (e.g. fire hazard)
  - Others?

Storage to compound intermittency of renewable sources

Photovoltaic energy

Example of solar power generation and load demand for a South Australian home[1]

- peak PV generation does not match peak load demand

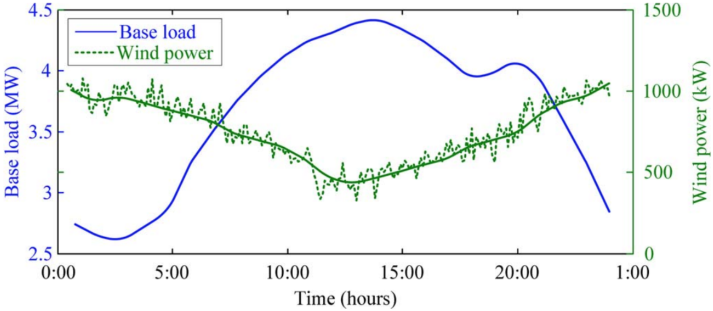


[1] source: V. Sharma et al., PV generation and load profile data of net zero energy homes in South Australia, *Data in Brief*, Vol. 25, paper 104235, 2019,https://doi.org/10.1016/j.dib.2019.104235

Storage to compound intermittency of renewable sources

Wind energy

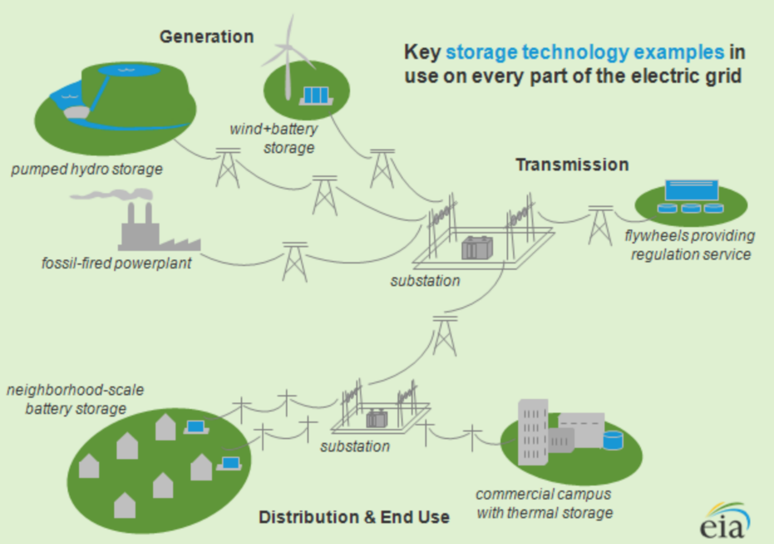
Another instance showing that at times of peak load demand there is not enough renewable energy production



Example of wind power generation vs load profile[2]

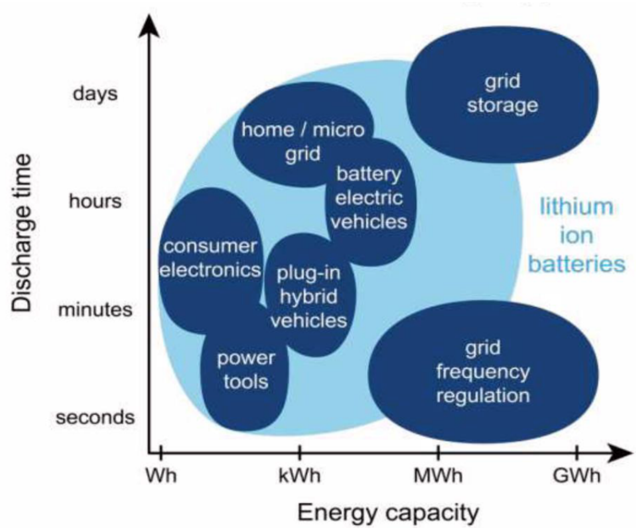
[2] S. Gao, *et al.*, "Integrated Energy Management of Plug-in Electric Vehicles in Power Grid With Renewables," in IEEE Trans. Veh. Technol., vol. 63, no. 7, pp. 3019-3027, Sept. 2014, doi: 10.1109/TVT.2014.2316153.

Energy storage location



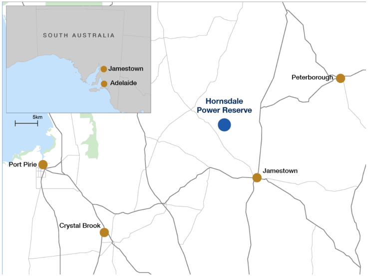
source: US Energy Information Administration website:
`https://www.eia.gov/todayinenergy/detail.php?id=6910#tabs_ElecStorage-1`, retrieved Sept. 17, 2020

Battery energy storage by application



South Australia Hornsdale power reserve

Example of large scale battery storage



Rated 100 MW/129 MWh, it was the largest Li-Ion battery in the world at the time of installation. When dispatching at peak output, the battery provides enough electricity to power the equivalent of 45,000 homes[3]

[3] source: https://hornsdalepowerreserve.com.au/learn/, retrieved 17 Sept, 2020

Small scale energy storage and portable power

1 Overview

2 Electrochemical energy storage

- Primary, secondary cells, galvanic cell principle
- Comparison among battery storage technologies
- Cell characteristics and discharge curves

3 Battery specifications

Some terminology

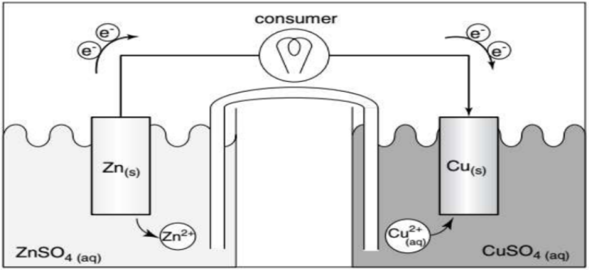
- *Electrochemistry* is a branch of chemistry dealing with the conversion of chemical energy into electricity and *vice versa* Energy conversion occurs through reduction-oxidation **Redox** reactions inside **electrochemical cells**
  - OXIDATION ~~Reduction:~~ loss of electrons (anode)
  - ~~Oxidation:~~ REDUCTION acquisition of electrons (cathode)
- Types of electrochemical cells:
  - *Galvanic*: chemical energy → electricity (dry cells, Pb-acid, Ni-Cd)
  - *Electrolytic*: electricity → chemical energy (Nelson's cell, Down's cell)
- An electrochemical cell is typically formed by two electronic conductors (*electrodes*) and one proton conductor (*electrolyte*)

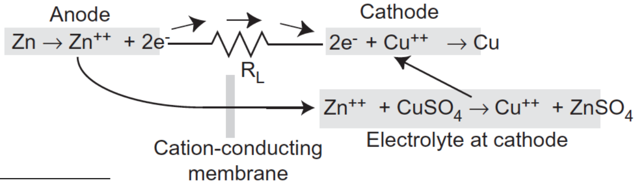
Galvanic cells

- Primary cells: conversion of chemical energy into electricity is not reversible (non rechargeable cells/batteries)
- Secondary cells: conversion of chemical energy into electricity is reversible (rechargeable cells/batteries)

Primary cells: Deniell's cell principle (1836)

Chemical energy $\rightarrow$ electricity conversion is non reversible, resulting in non rechargeable cells[4]





[4] De Rosa, A. V., Fundamentals of Renewable Energy Processes, 3rd edn, Elsevier, 2013, pp. 830-831 (ebook available from MQ library)

Secondary cells

- Electrochemical reactions are reversible: chemical energy $\leftrightarrow$ electricity
- After a cell is discharged, an external electrical force is applied to reverse the flow of electrons and re-establish the charged condition
- One discharge and charge operation is called *cycle*
- A secondary cell can endure hundreds or thousands of charge/discharge cycles, before loosing its original properties

Secondary cells

- Reversible chemical reactions are quite more complicated that non-reversible ones. Example of reversible reactions in Lead-acid batteries:
  - see De Rosa, A. V., Fundamentals of Renewable Energy Processes, 3rd edn, Elsevier, 2013, pp. 833-834 (ebook available from MQ library)

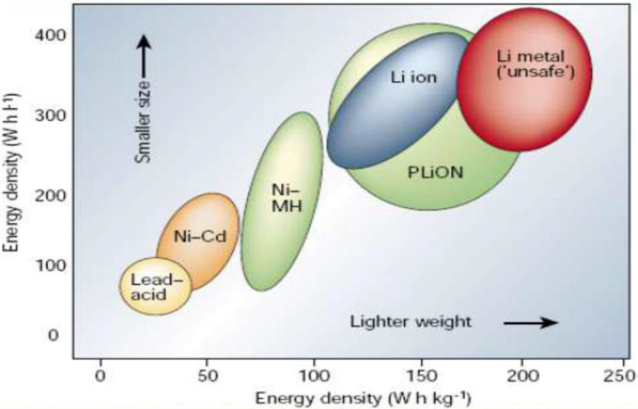
Electrochemical energy: key attributes

- **Energy density**: energy stored per unit of mass or volume, in Wh/kg or Wh/m^3
- **Power density**: max *rate of* energy discharge per unit of mass or volume, in W/kg or W/m^3
- **Capacity**: amount of charge deliverable by a battery in a discharge cycle, in A h
- **Life**: number of discharge/recharge cycles at the rated capacity
- **Electrical efficiency**: ratio of the energy required to charge a battery compared to the available energy during discharge is referred to as the efficiency: e.g. 95% efficiency for Li-Ion, 75% efficiency for Lead-acid[5]
- **Safety**: behaviour at high temperature, fire risk
- **Cost**

[5] https://batterytestcentre.com.au/project/lithium-ion/

Comparison between electrical storage technologies

Ragone plot for electrochemical batteries



Comparison among popular battery technologies

	Lead VRLA	Ni/Cd	Ni/MH	Lithium ion
voltage (V)	2.0	1.2	1.2	3.7
Specific energy (Wh/kg)	35	50	90	165
Energy density. (Wh/L)	80	170	330	330
Cost /kWh	50	200	200	500
Cycle number	200	600 - 1000	300-500	500

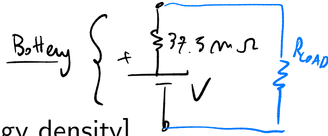
Also note that:

- charging rate of valve-regulated Lead-Acid (VRLA) batteries is constrained and is much smaller than discharging rate, resulting in long charging time
- charging rate of Li-ion batteries is not constrained, allowing fast charging

Energy density and power density example

- Lead-acid battery

$Q = 80\,\mathrm{A\,h}$, $V = 12\,\mathrm{V}$, $m = 31\,\mathrm{kg}$, $v = 10\,\mathrm{dm}^3$, $R_{\mathrm{int}} = 37.5\,\mathrm{m\Omega}$



$$W = 12\,\mathrm{V}\,80\,\mathrm{A\,h} = 960\,\mathrm{W\,h}$$

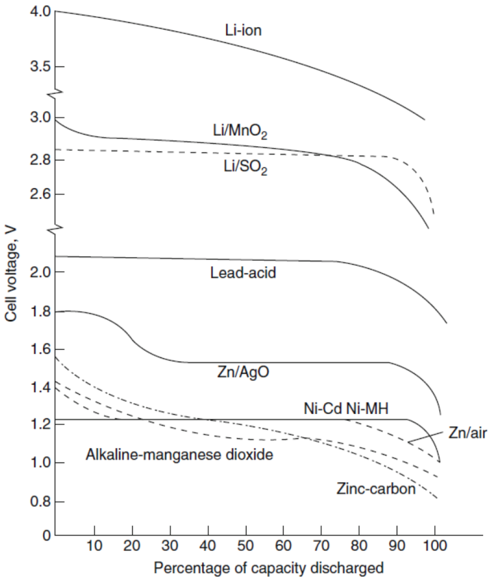
$$\frac{W}{m} = \frac{960\,\mathrm{W\,h}}{31\,\mathrm{kg}} = 31\,\frac{\mathrm{W\,h}}{\mathrm{kg}} \quad \text{specific energy [energy density]}$$

$$P_{\max} = \frac{(V/2)^2}{R_{\mathrm{load}}} \cong 1\,\mathrm{kW} \quad \text{theoretical max power when } R_{\mathrm{load}} = R_{\mathrm{int}}$$

$$\frac{P_{\max}}{m} = 32\,\frac{\mathrm{W}}{\mathrm{kg}} \quad \text{specific power [power density]}$$

Storage system	Energy density $[\frac{\mathrm{W\,h}}{\mathrm{kg}}]$	Power density $[\frac{\mathrm{W}}{\mathrm{kg}}]$
Supercapacitor	4.2	8900
Battery (Pb-acid)	31	32

Typical battery cell voltages and discharge curves



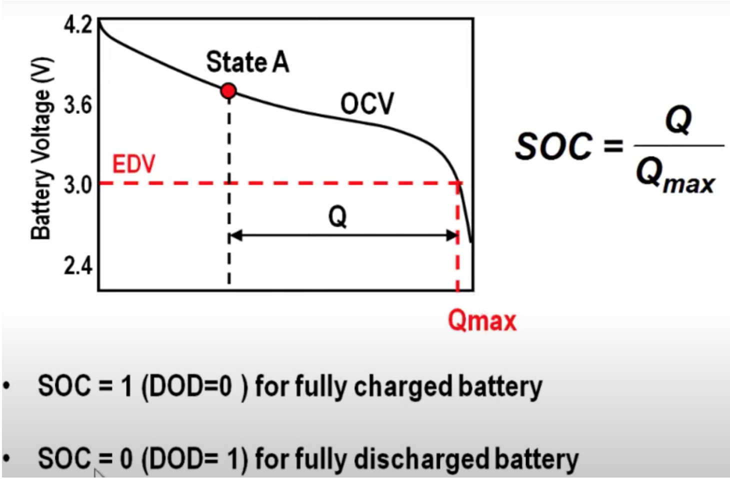
- cell voltage depends on chemistry
- cell voltage is not constant
  - cell voltage depends on capacity discharged (state of charge, SoC)

$$SoC\,(t) = SoC\,(t_0) - \frac{1}{Q_\mathrm{r}} \int_{t_0}^{t} i_\mathrm{b}\, dt$$

Q_r rated battery capacity, in A h

sometimes specified as Q_max

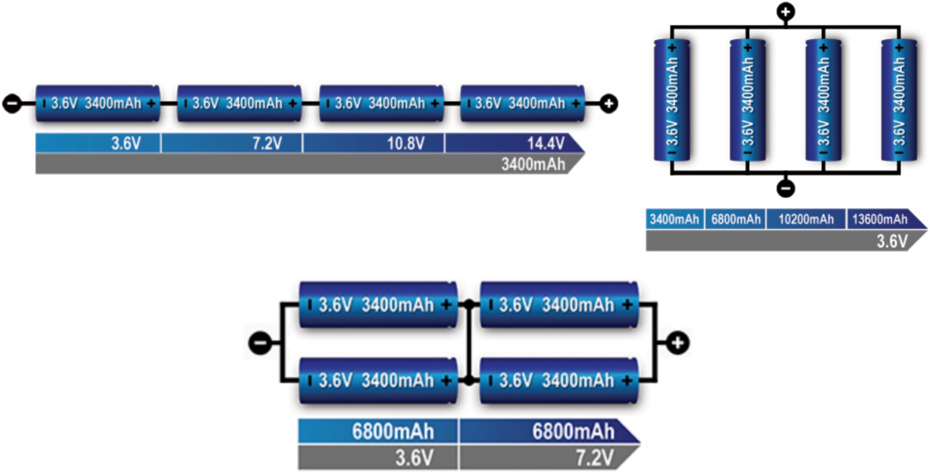
State of Charge



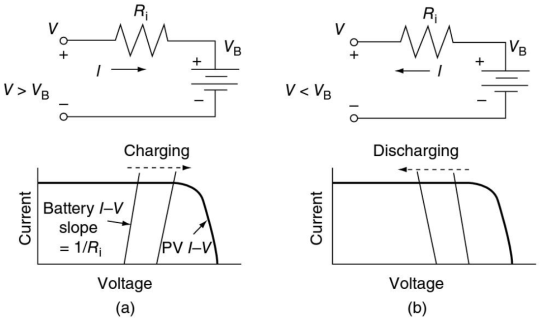
EDV is the lowest voltage that the battery/cell can be discharged to, without damage (figure sourced from Texas Instruments `https://youtu.be/6CFRjEZVXI8`)

Electrochemical batteries

- Batteries are groups of cells connected in series or parallel. E.g. a 12 V car battery is made of 6 series-connected 2 V cells



Equivalent circuit



- Battery equivalent circuit: ideal voltage source in series with small resistance
- Current changes direction depending on charging/discharging operation
  - Fig. (a): battery charges ($V_B \nearrow$) its tilted characteristic slides right
  - Fig. (b): battery discharges ($V_B \searrow$) its tilted characteristic slides left

Energy stored in a battery

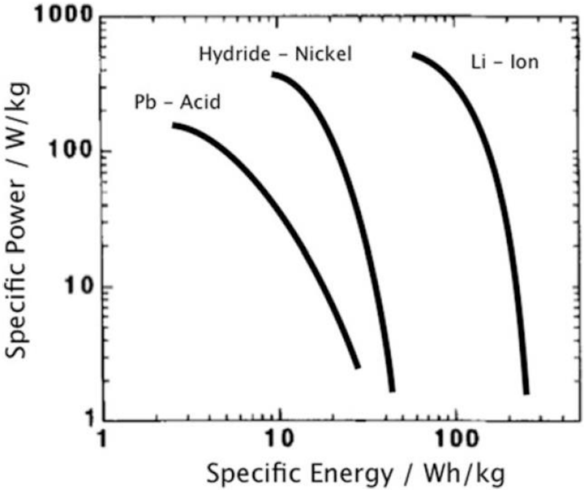
$$E = \int_0^Q V dQ$$

However, it is more intuitive:

$$E = \int_{t_1}^{t_2} V I dt$$

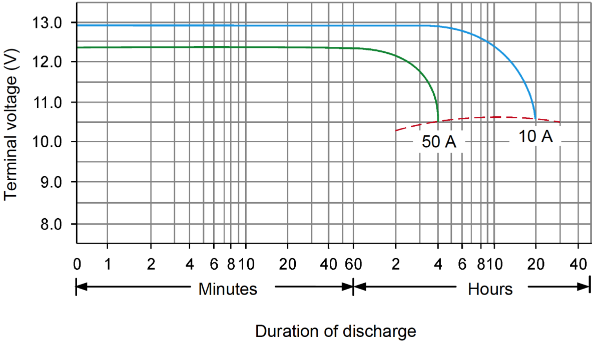
- A battery is usually specified in Ah or Wh
- A 12 V lead-acid battery may be specified as a 165 Ah battery. What is the energy deliverable by the battery?

Ragone plot for rechargeable battery technologies



Battery capacity

- electric charge Q delivered by the battery when fully charged
  - $Q = I \times t$, i.e., constant current delivered for a certain time
- it is a measure of the energy delivered by the battery



A 200 A h battery

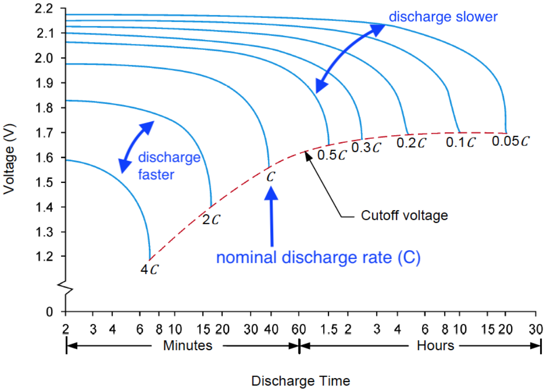
- delivers 10 A for 20 h
- delivers 50 A for 4 h

according to the discharge curves presented

Battery capacity is determined discharging the battery at a constant current, for a fixed time, until allowed minimum voltage is reached

Discharge rate

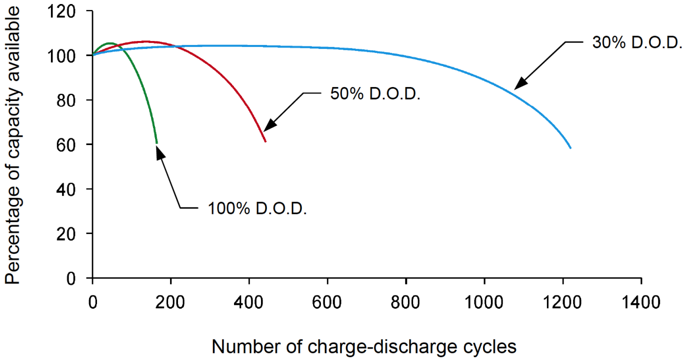
- the rate a which the charge is taken out of the battery (time) $i = \dfrac{dQ}{dt}$
- example: discharge rate for a 200 A h battery discharged in:
    - 1 h is $1C = 200$ A ($1C \rightarrow 1 \times 200$ A $= 200$ A, in 1 h)
    - 10 h is $0.1C = 20$ A ($0.1C \rightarrow 0.1 \times 200$ A $= 20$ A, in 10 h)
    - 0.5 h is $2C = 400$ A ($2C \rightarrow 2 \times 200$ A $= 400$ A, in 0.5 h)



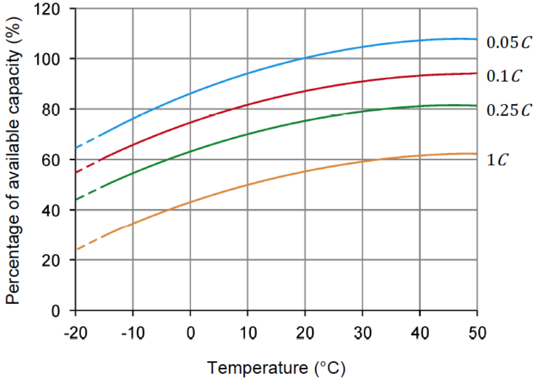
- min voltage depends on discharge rate
- higher discharge rates imply lower min voltage
- higher discharge rates imply lower discharge times

Depth of discharge (DoD)

- is a measure of how much the battery gets emptied for every cycle
- the deeper a battery gets discharged at every cycle, the shorter the number of cycles it can do (the shortest its lifetime)
- battery design takes into account cycling
  - batteries for stand-alone power systems are designed for deep discharging and need to endure a high number of cycles (to avoid frequent replacement)



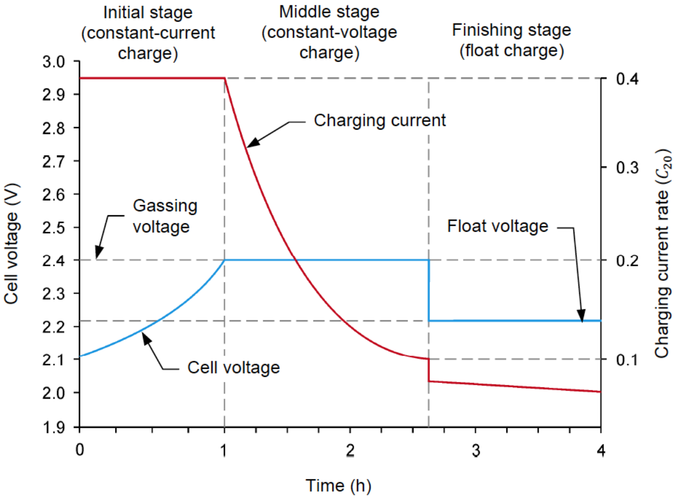
Effect of temperature on the available capacity



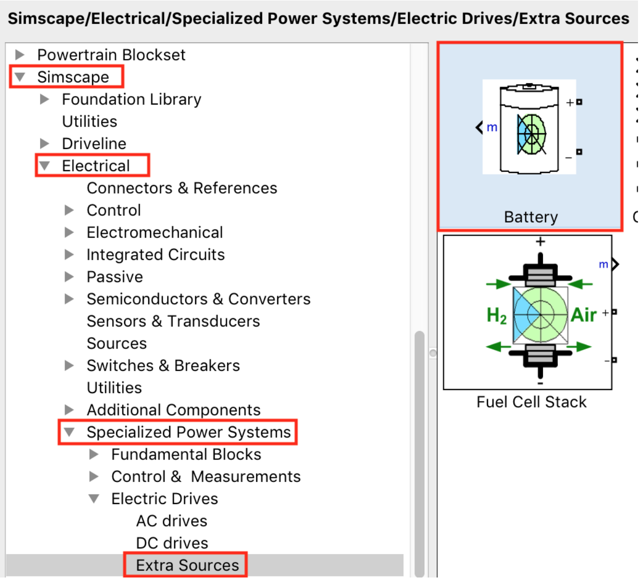
- lower temperature decreases available capacity

Typical charging profile

Constant current - constant voltage charging profile (CC-V)



Battery models used in simulation



- Battery model used in Simulink (Simscape Electrical)
- this model embeds all the characteristics explained in this lecture
- battery voltage dependence on SoC

All-electric vehicle components

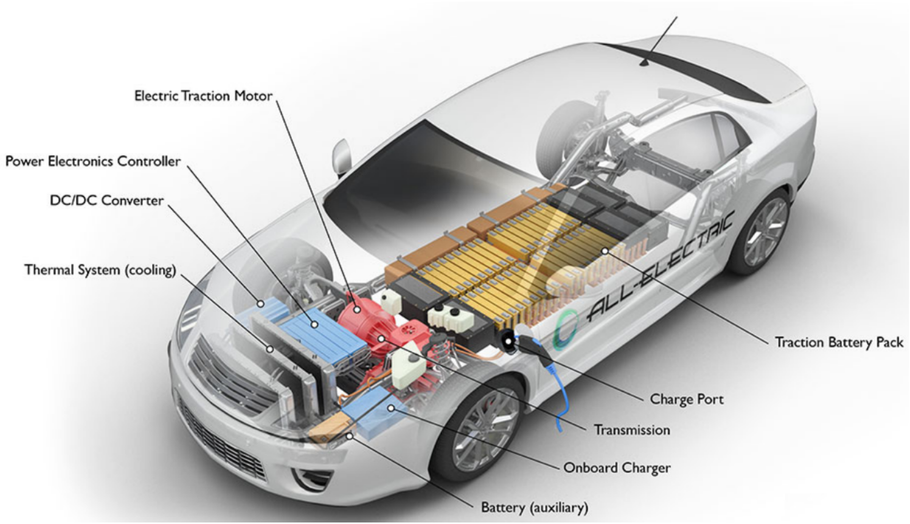


image from: `https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work`, accessed Sept. 29, 2020

Batteries and power electronics[7]

Traction battery pack

- stores electricity for use by the electric traction motor

Power electronic controller

- manages the energy flows to/from motor and batteries
- allows to control speed and torque of the electric motor
- increases reliability and battery lifetime

DC/DC converter → ELCT3005 Power Electronics

- converts higher-voltage DC power from the traction battery pack to the lower-voltage DC power needed to run vehicle accessories and recharge the auxiliary battery

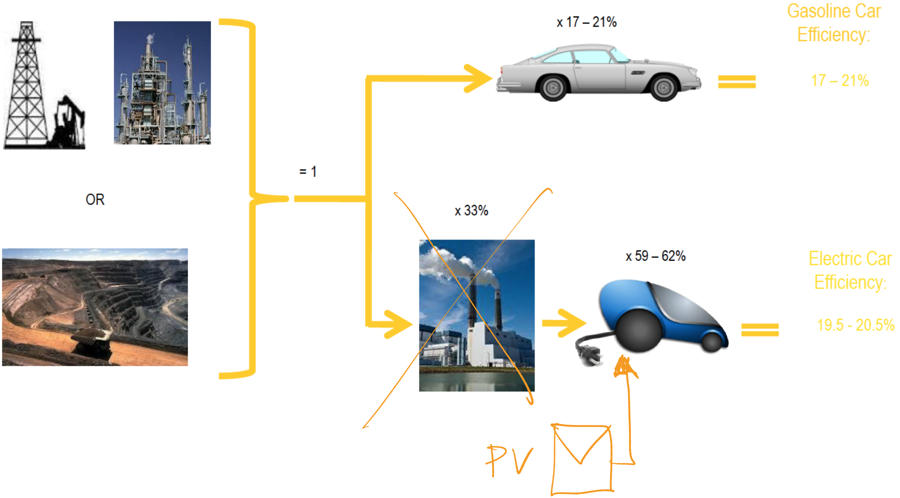
Charge port

- the charge port allows the vehicle to connect to an external power supply in order to charge the traction battery pack

[7] source: https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work, accessed Sept. 29, 2020

Final considerations on EV

Electric vehicles are ultimately powered by electric power plants - that's where the energy to recharge the batteries comes from



Readings

- *Masters (2004), Renewable and Efficient Electric Power Systems*
  - Chapter 9 (extract): Photovoltaic Systems (link)
    - 9.5.3 Batteries
    - 9.5.4 Basics of Lead-Acid Batteries
    - 9.5.5 Battery Storage Capacity
    - 9.5.6 Coulomb Efficiency Instead of Energy Efficiency
    - 9.5.7 Battery Sizing

- FESTO Didactic, Student Manual 579343: Lead-acid batteries (link)

References

- ELCT2005 S2 2020 lecture slides courtesy of Dr Binesh Puthen Veettil
- FESTO Didactic, *Lead-Acid Batteries*, Manual 579345