UNIVERSITÀ DI TRENTO

DIPARTIMENTO DI

INGEGNERIA INDUSTRIALE

Batteries

Renewable Energy Conversion Systems Course

Lecture 3

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Academic Year 2024-2025

Electrical Energy Storage – Lecture III

Outline

- Parameters and Key Performance Indicators
- Equivalent Circuits for Battery modelling
- Lithium-ion Batteries
    - Working principle
    - Types and characteristics
    - Architecture of a battery pack/system
- Redox Flow Batteries
    - Working principle
    - Types and characteristics
    - Architecture of a battery storage system

Parameters and Key Performance Indicators

C → Current to charge/discharge the cell in 1 hour, corresponding to C-rate=1C

C-Rate → Rate at which the battery is charged/discharged expressed in multiples or fractions of C (ex: 2C discharge in ½ hour, C/10 discharge in 10 hours) ⟶ **Discharge Duration**

Charge Capacity → Maximum amount of charge that the battery can deliver in a full discharge process (Ah)

Energy Capacity → Maximum amount of energy that the battery can deliver in a full discharge process (J, Wh, kWh)

Power Capacity → Power that the battery can deliver during a discharge process (W, kW)

Coulombic Efficiency → $\eta_C = \frac{\int \boldsymbol{I_{dch} dt}}{\int \boldsymbol{I_{chr} dt}}$

State of Charge → Charge available in the battery / Charge Capacity

Voltage Efficiency → $\eta_V = \frac{\int \boldsymbol{V_{dch} dt}}{\int \boldsymbol{V_{chr} dt}}$

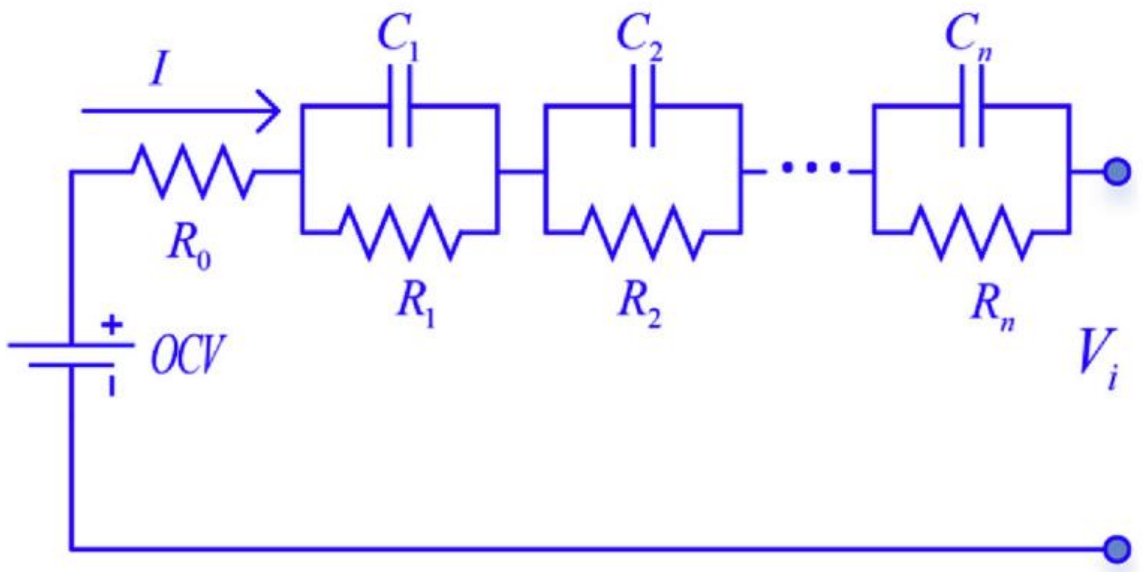
State of Health → Available Charge Capacity / Nominal Charge Capacity

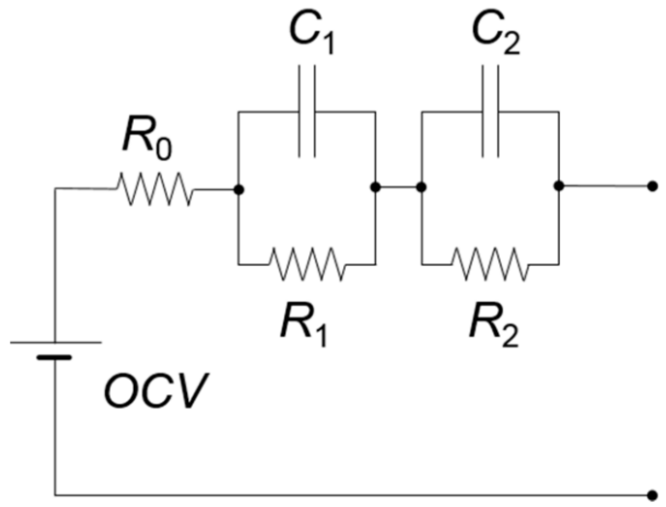
Energy Efficiency (round-trip) → $\eta = \frac{\int \boldsymbol{P_{dch} dt}}{\int \boldsymbol{P_{chr} dt}} = \eta_C \, \eta_V$

Energy Density → Energy Capacity / Battery mass or volume (Wh/kg or Wh/L)

Power Density → Power Capacity / Battery mass or volume (kW/kg or kW/L)

Equivalent Circuits for Battery modelling





Equivalent Circuits for Battery modelling

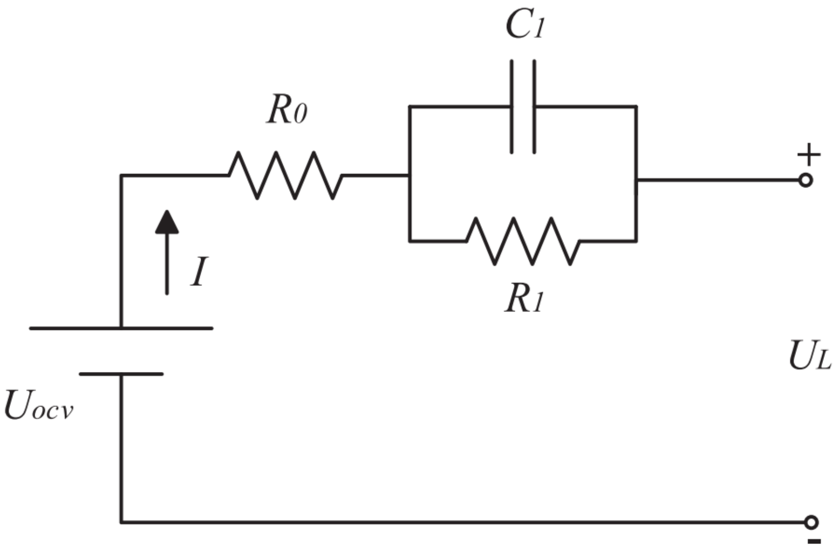


Fig. 1. Schematic presentation of the 1-RC equivalent circuit model.

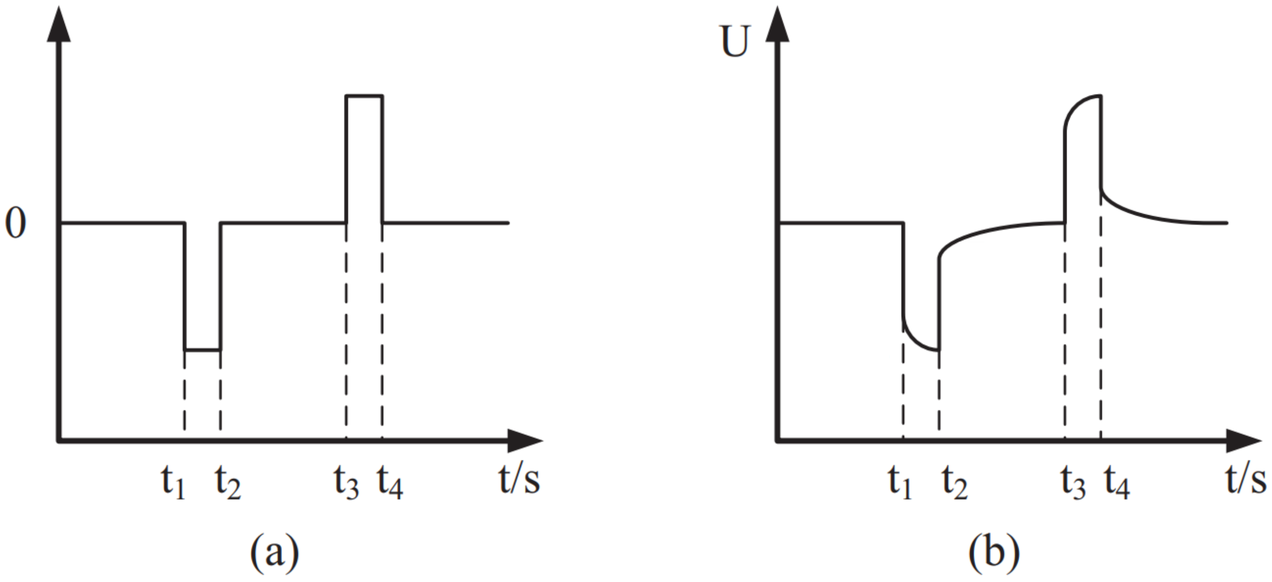
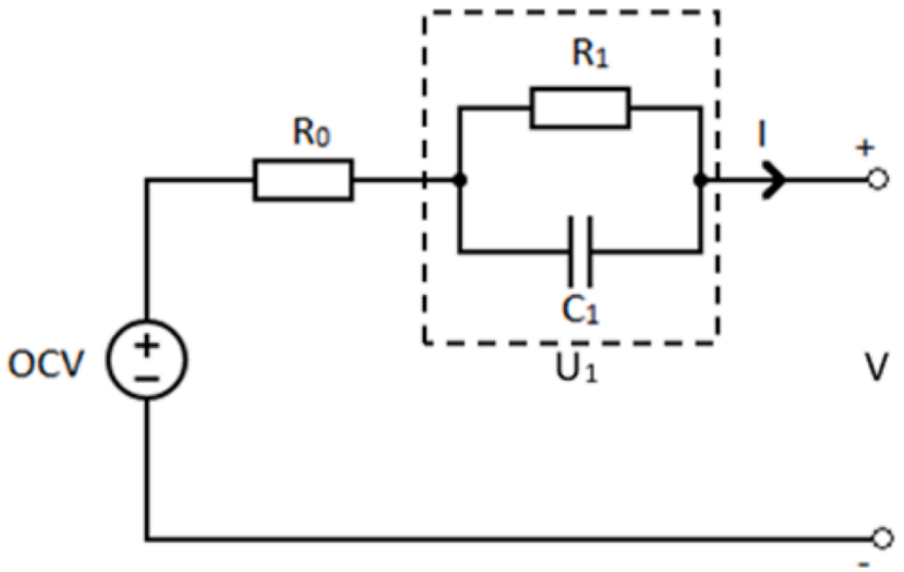


Fig. 6. (a) Current response curve. (b) Voltage response curve.

Source: Wang, Jianfeng, et al. "Precise equivalent circuit model for Li-ion battery by experimental improvement and parameter optimization." Journal of Energy Storage 52 (2022): 104980.

Equivalent Circuits for Battery modelling



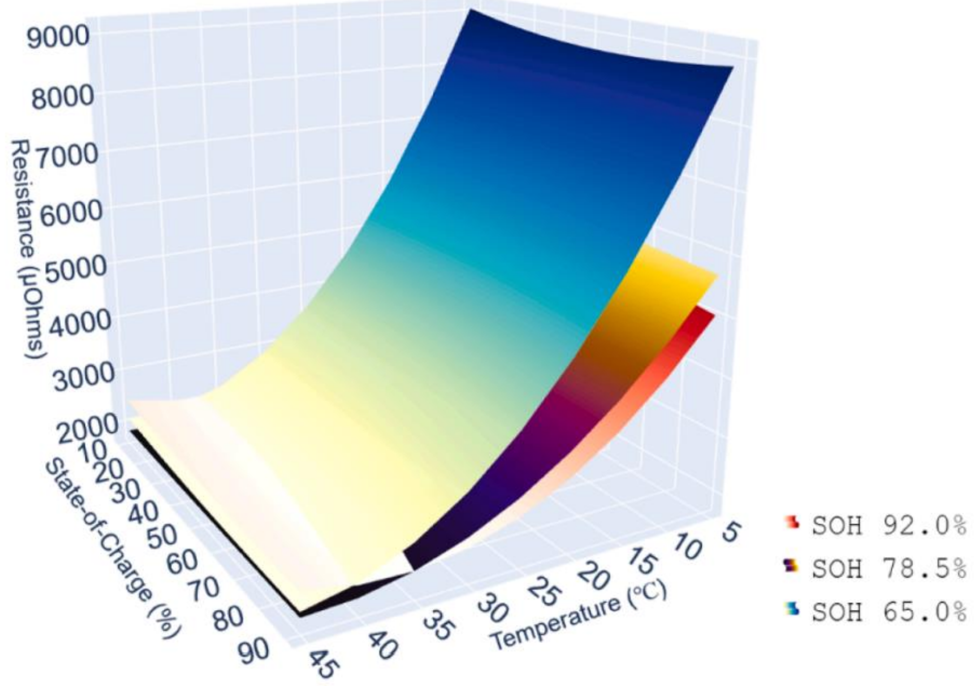


Fig. 5. Effect of SOH, SOC, and temperature on R_0.

Source: Tran, Manh-Kien, et al. "A comprehensive equivalent circuit model for lithium-ion batteries, incorporating the effects of state of health, state of charge, and temperature on model parameters." Journal of Energy Storage 43 (2021): 103252.

Equivalent Circuits for Battery modelling

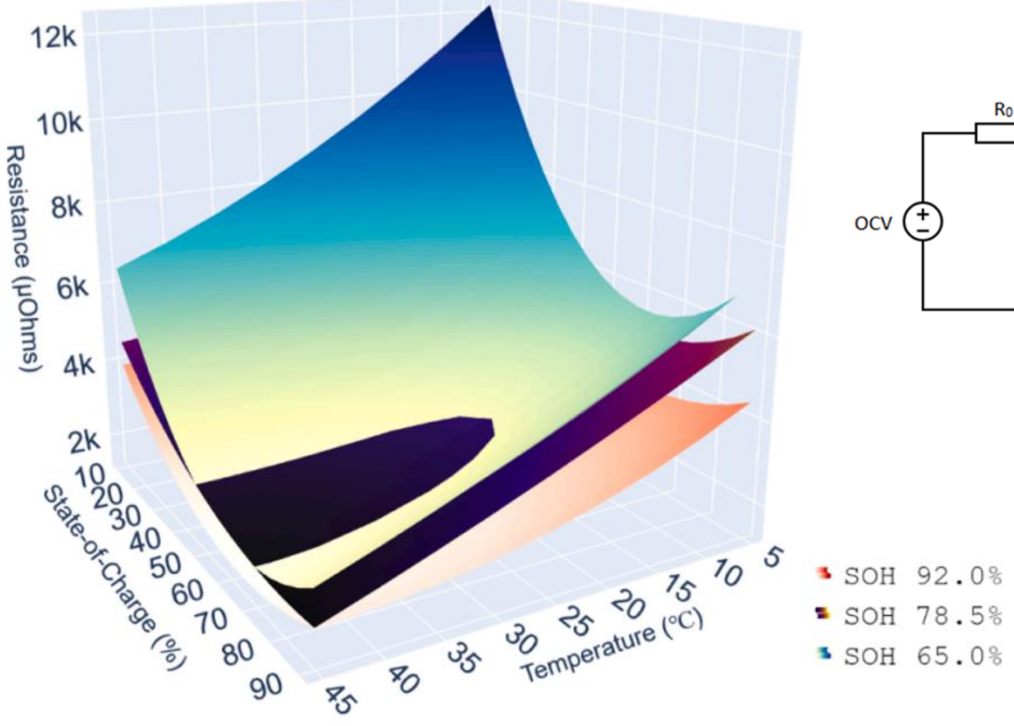
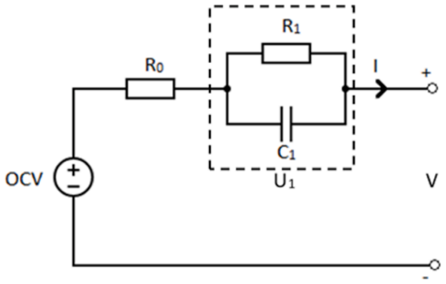


Fig. 6. Effect of SOH, SOC, and temperature on R_1.



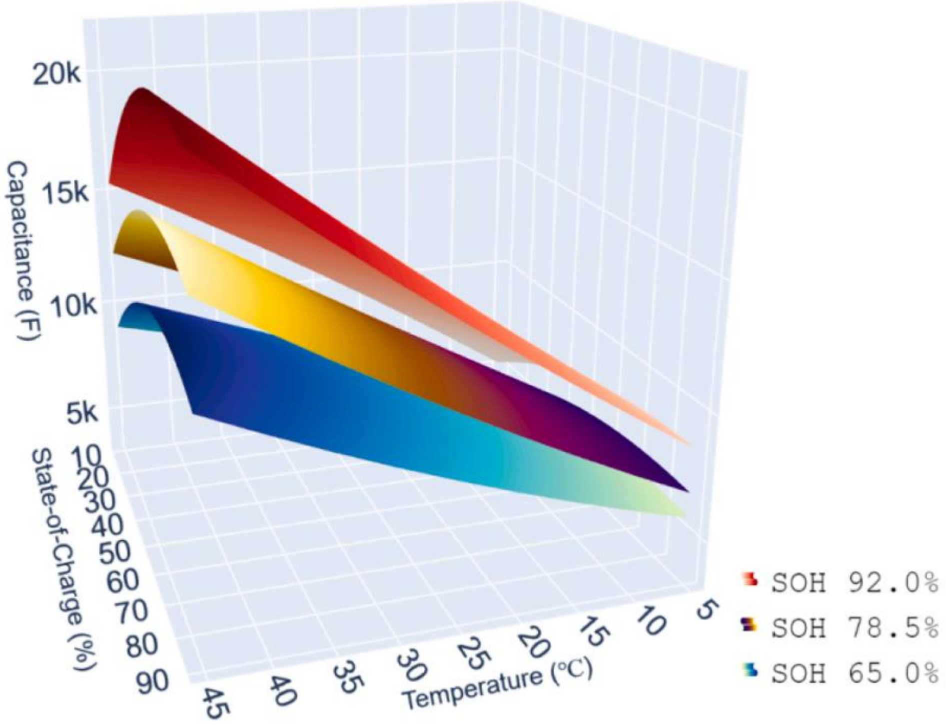


Fig. 7. Effect of SOH, SOC, and temperature on C_1.

Source: Tran, Manh-Kien, et al. "A comprehensive equivalent circuit model for lithium-ion batteries, incorporating the effects of state of health, state of charge, and temperature on model parameters." Journal of Energy Storage 43 (2021): 103252.

Equivalent Circuits for Battery modelling

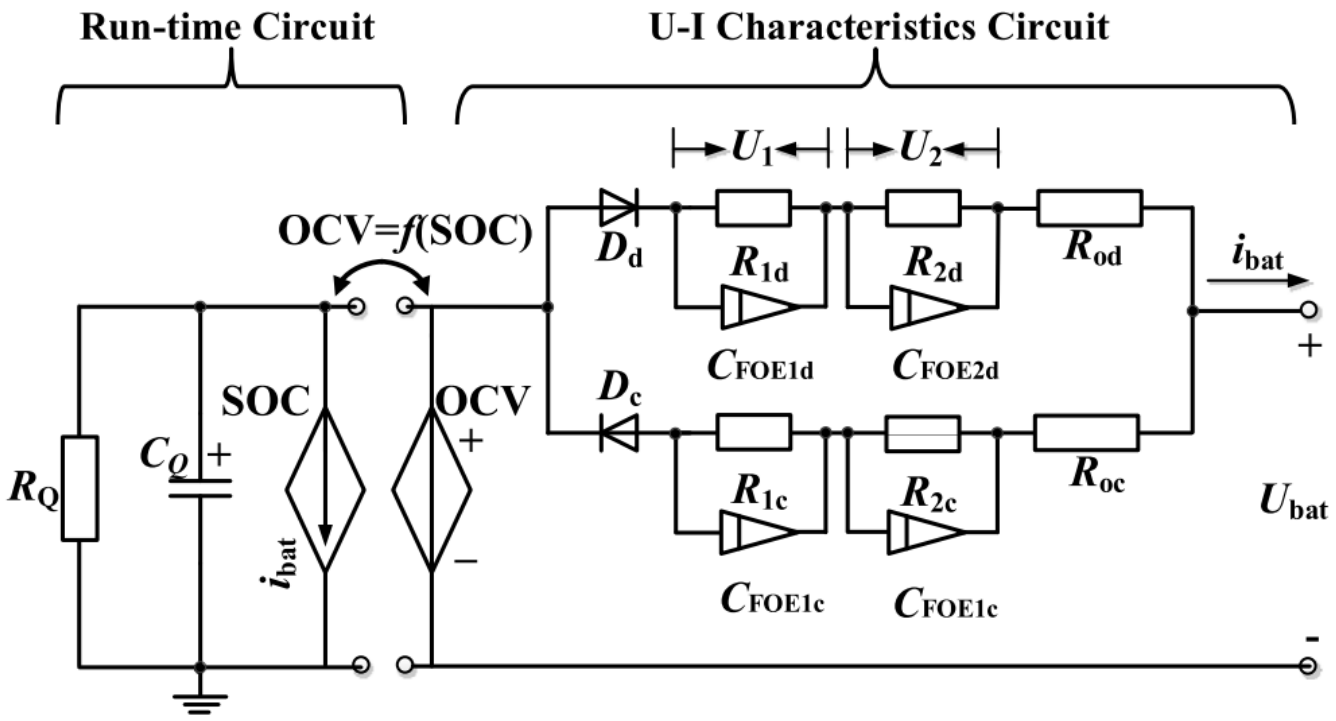


Fig. 1. Structure of proposed FVO-ECM of Li-ion batteries.

Source: Zhang, Qi, et al. "A novel fractional variable-order equivalent circuit model and parameter identification of electric vehicle Li-ion batteries." ISA transactions 97 (2020): 448-457.

Li-ion Batteries - Working Principle

Li-ion battery

Anode: The negative electrode, often based on graphite where lithium can intercalate, creating lithium carbonate LiC_6

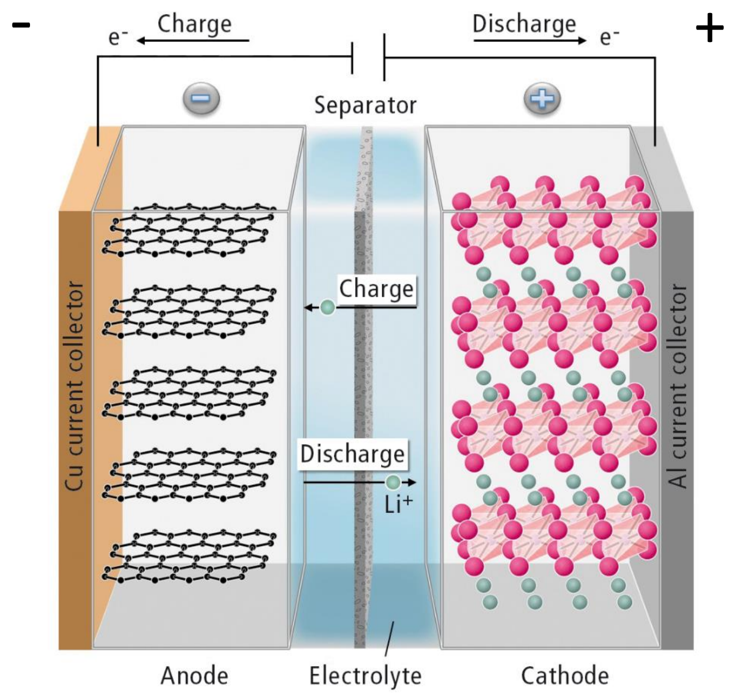
Cathode: The positive electrode, usually based on lithium metal oxides ($LiCoO_2$, $LiMnNiCoO_2$, LiFePO4), where Li^+ ions can be released, leaving simple metal oxides

Current collectors: Conductive foils at each electrode of the battery that are connected to the terminals of the cell. The cell terminals transmit the electric current from the battery to the external circuit

Electrolyte: An organic liquid or gel that conducts ionic current and increases the mobility of Li^+ ions

Separator: A porous polymeric film that separates the electrodes while enabling the exchange of Li^+ ions from one side to the other

$$C_6 + Li^+ + e^- \rightleftharpoons LiC_6 \qquad LiCoO_2 \rightleftharpoons CoO_2 + Li^+ + e^-$$



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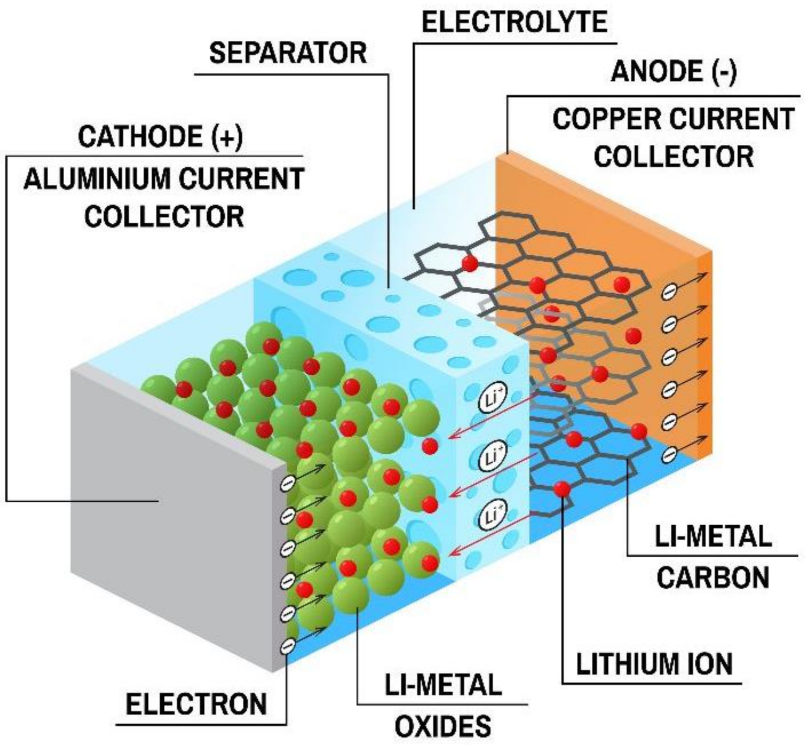
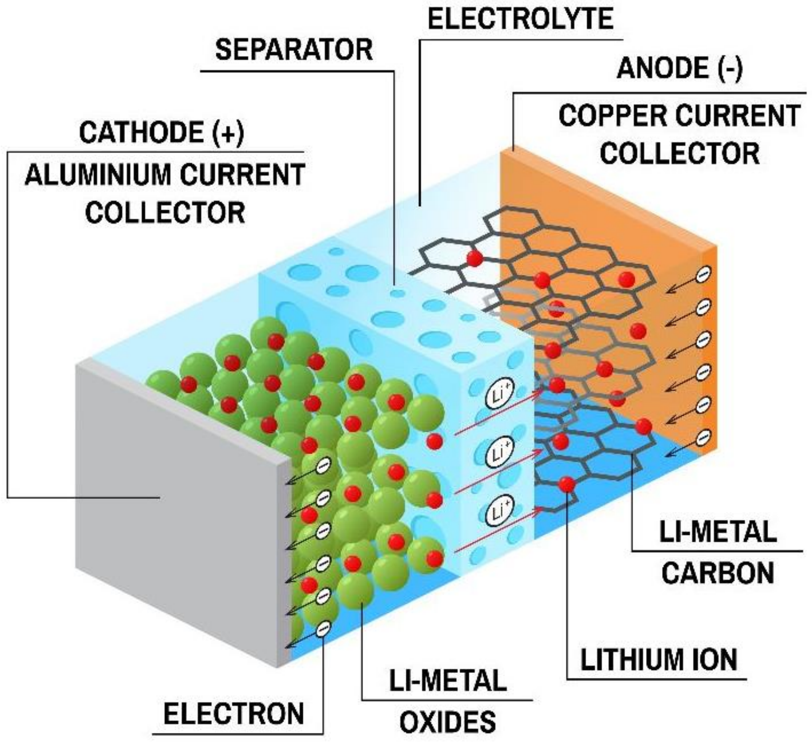
Li-ion Batteries - Working Principle

DISCHARGE

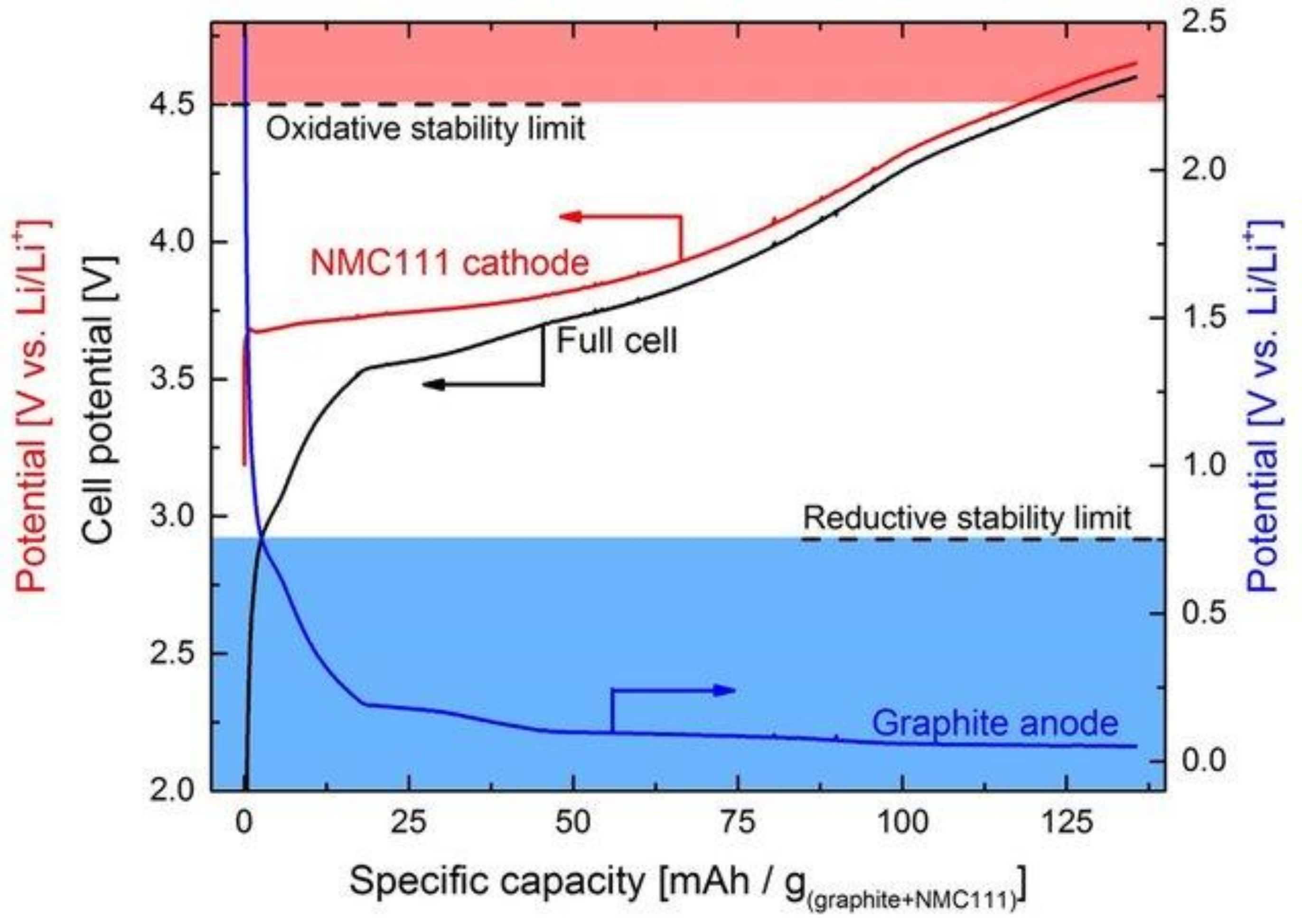


CHARGE



Li-ion Batteries - Working Principle

Open Circuit Voltage (OCV)



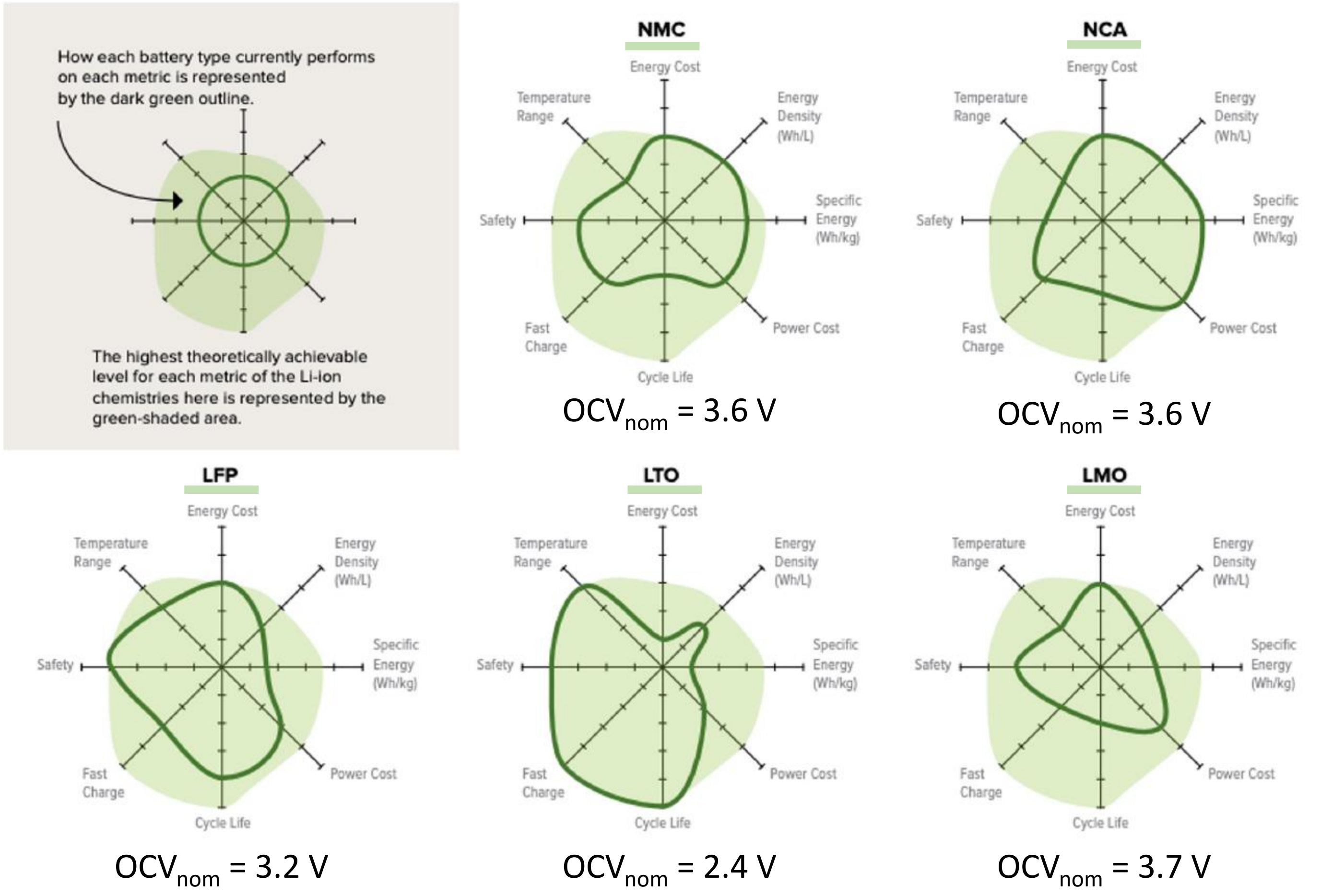
Li-ion Batteries - Types and Characteristrics

The good and the bad of different chemistries

Automotive

$x+y+z=1$

- NMC→ Cathode $Li\ Ni_x\ Mn_y\ Co_z\ O_2$
  Anode $Li\ C_6$
- NCA → Cathode $Li\ Ni_x\ Co_y\ Al_z\ O_2$
  Anode $Li\ C_6$
- LFP → Cathode $Li\ Fe\ P\ O_4$
  Anode $Li\ C_6$
- LTO → Cathode $Li\ Ni\ Mn\ Co\ O_2$
  Anode $Li_4\ Ti_5\ O_{12}$
- LMO → Cathode $Li\ Mn_2\ O_4$
  Anode $Li\ C_6$



Li-ion Batteries - Types and Characteristrics

	Primary Use Cases	Representative Manufacturers
NMC	Power tools, electric vehicles	CATL, Sanyo, Panasonic, Samsung, LG Chem, SK Innovation
NCA	Electric vehicles	Tesla/Panasonic
LFP	Electric buses, grid storage	BYD, K2, Lishen, Saft, GS Yuasa, A123, Valence, BAK
LTO	Personal electronics, UPS, some electric vehicles	Altairnano, Toshiba, Yabo
LMO (Li-manganese oxide)	Power tools, some electric vehicles (often combined with NMC)	Hitachi, Samsung, LG Chem, Toshiba, NEC

SPECIFIC CAPACITY OF ANODE AND CATHODE MATERIALS:

Anode	- C:	350 – 360 mAh/g
	- Si(SiOX)/C:	400 – 900 mAh/g
	- LTO:	150 mAh/g
Cathode	- NMC 111:	160 mAh/g
	- NMC 532:	175 mAh/g
	- NMC 622:	180 mAh/g
	- NMC 811:	175 – 200 mAh/g
	- NCA:	200 mAh/g
	- LFP:	150 mAh/g
	- LMO:	105 – 120 mAh/g

- LFP and NMC are the most common solutions for EV applications
- LTO is used in niche markets to due its advantages (cycle life, safety, high C-rate) but it’s more expensive and has low energy density.
- Customized NMC for high energy or high-power application are also available

Li-ion Batteries - Types and Characterestrics

Generation	1	2		3		4			5
		2a	2b	3a	3b	4a	4b	4c	
Type	Current	Current	State of the Art	Advanced Li-ion HC	Advanced Li-ion HV	Solid State			Beyond Li-ion
Expected Commercialzzation	Commercialized			2020	2025	> 2025			
Cathode	NMC/NCA LFP LMO	NMC111	NMC424 NMC523	NMC622 NMC811 NMC910	HE NMC Li-rich NMC HVS	NMC		HE NMC	O_2 S
Anode	Graphite LTO	Graphite		Graphite + Si (5-10%)	Si/C		Li metal		Li metal Mg, Na, Ca, Al
Electrolyte	Organic $LiPF_6$				Organic + Additives	Solid electrolytes (polymer, inorganic, hybrid)			

current

90-300 Wh kg^{-1}
200-700 Wh L^{-1}

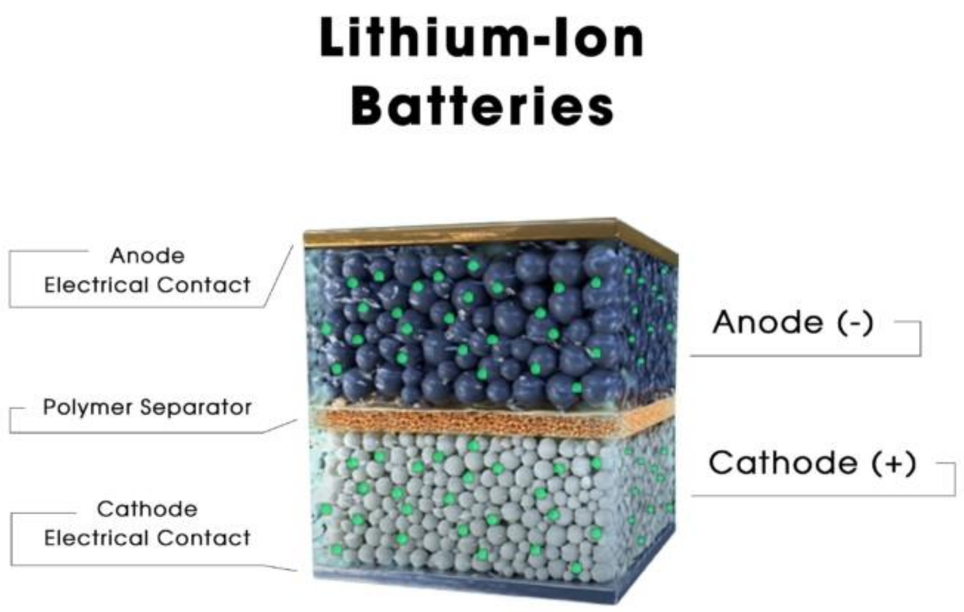
near future

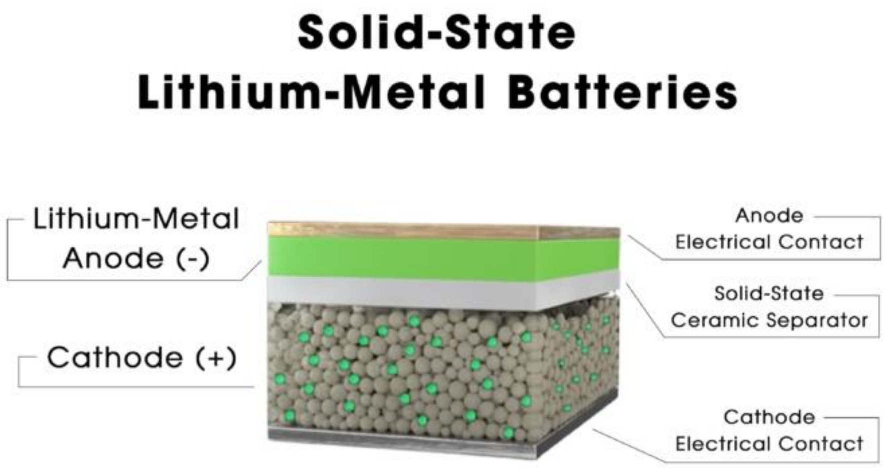
350 Wh kg^{-1}
750 Wh L^{-1}

long-term (post 2025)

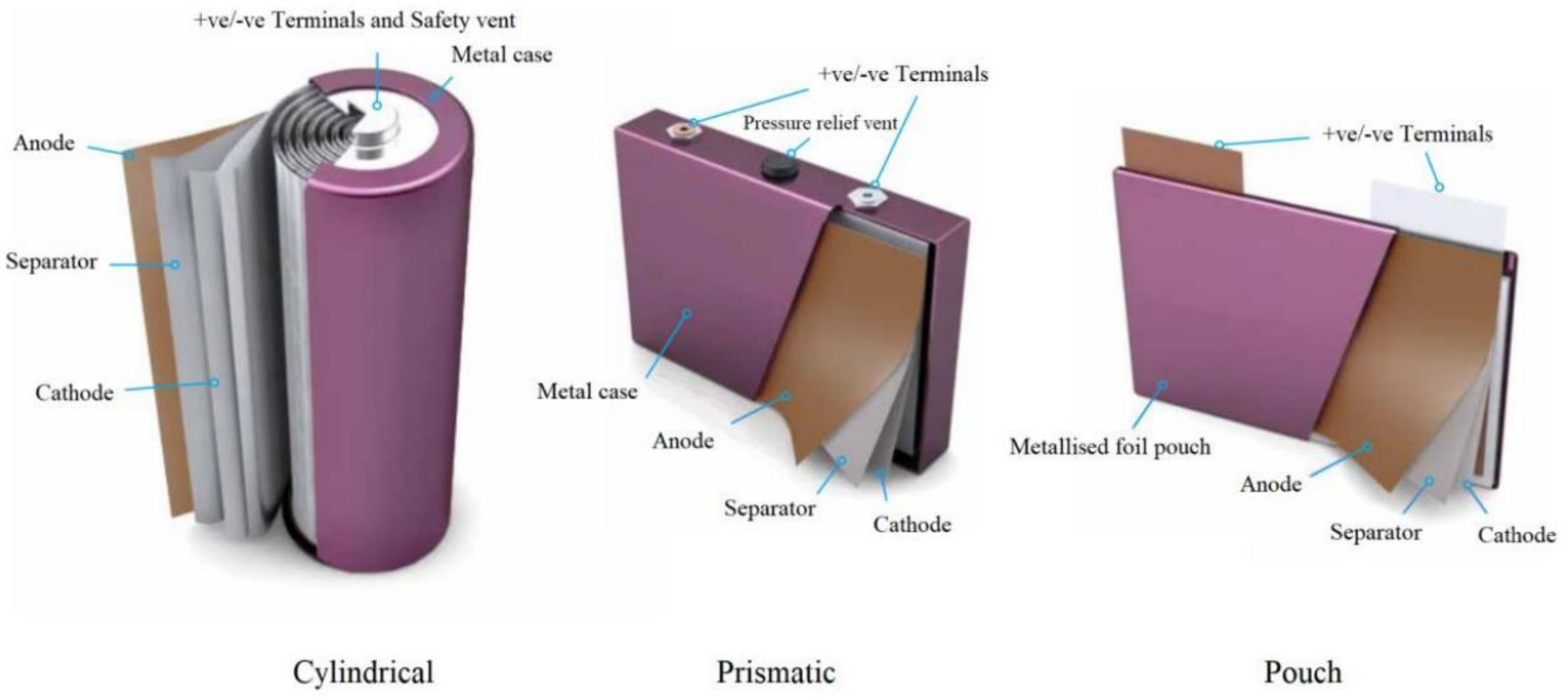
500 Wh kg^{-1}
1000 Wh L^{-1}

Li-ion Batteries - Types and Characterestrics

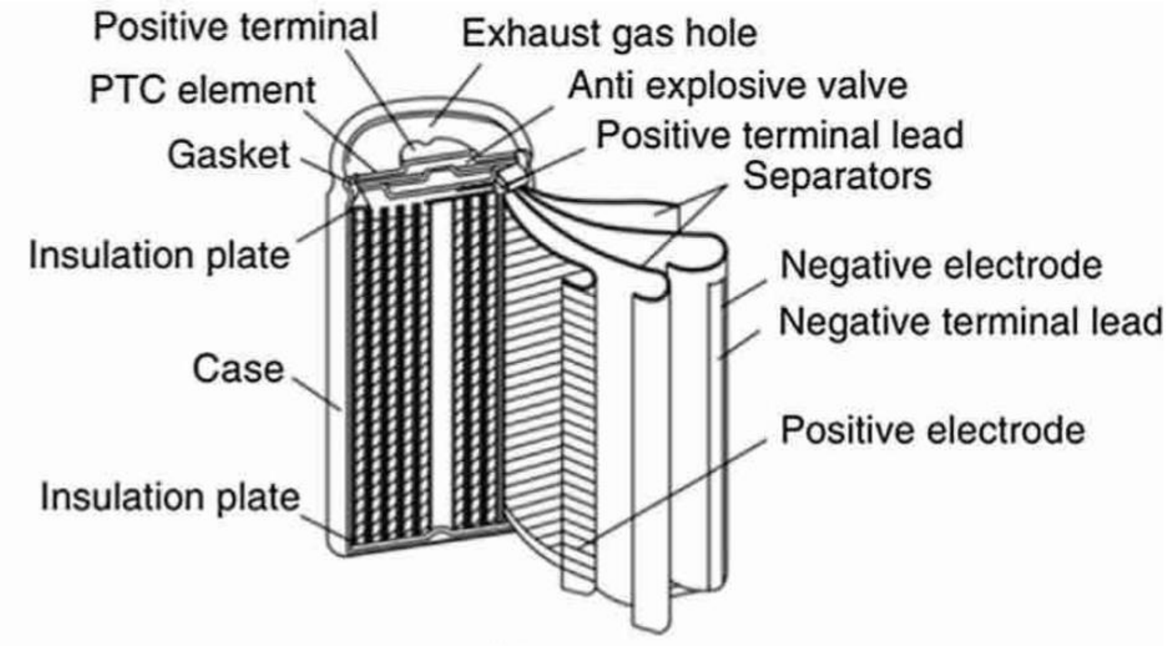


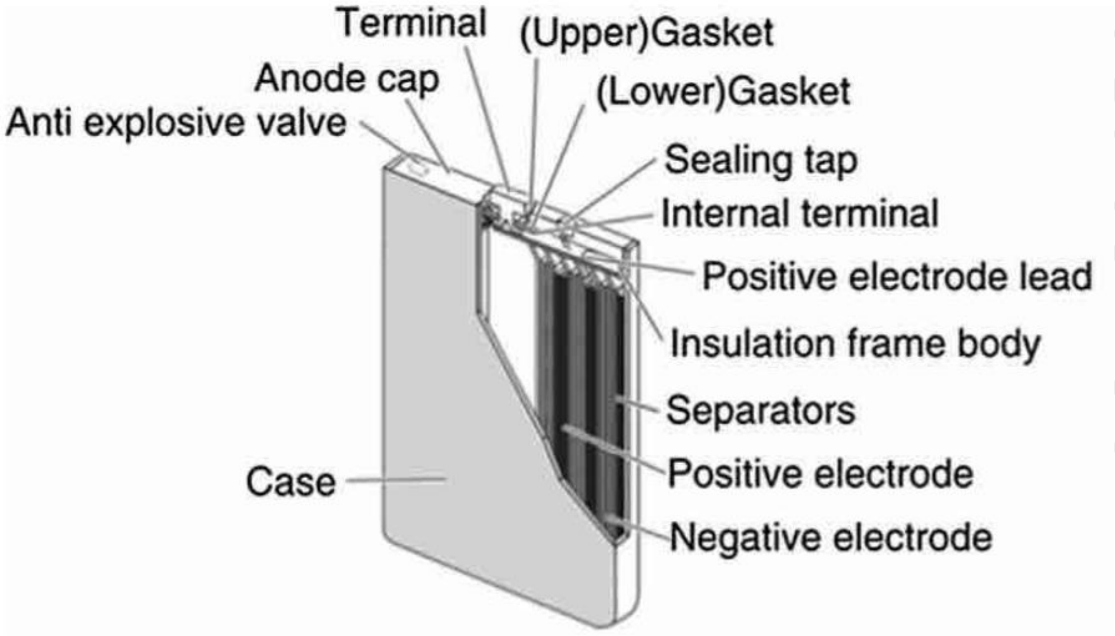


Li-ion Batteries - Architecture of a Battery Pack



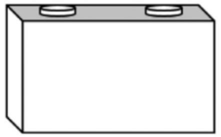
Li-ion Batteries - Architecture of a Battery Pack

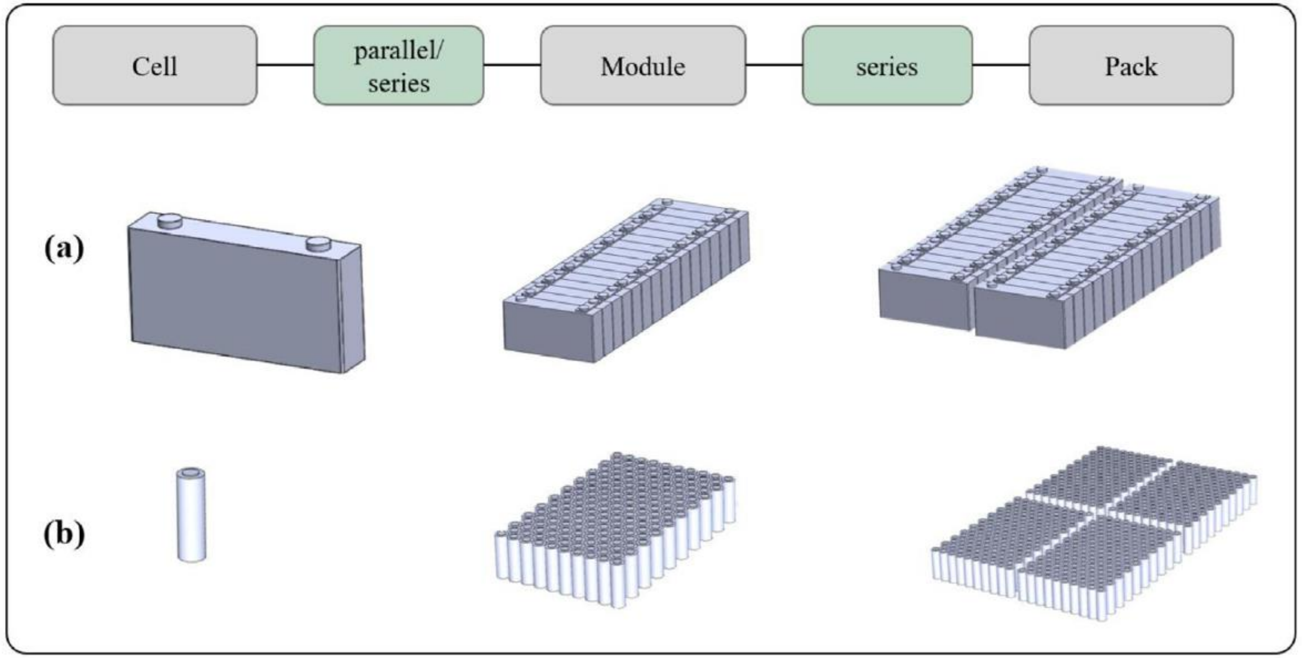




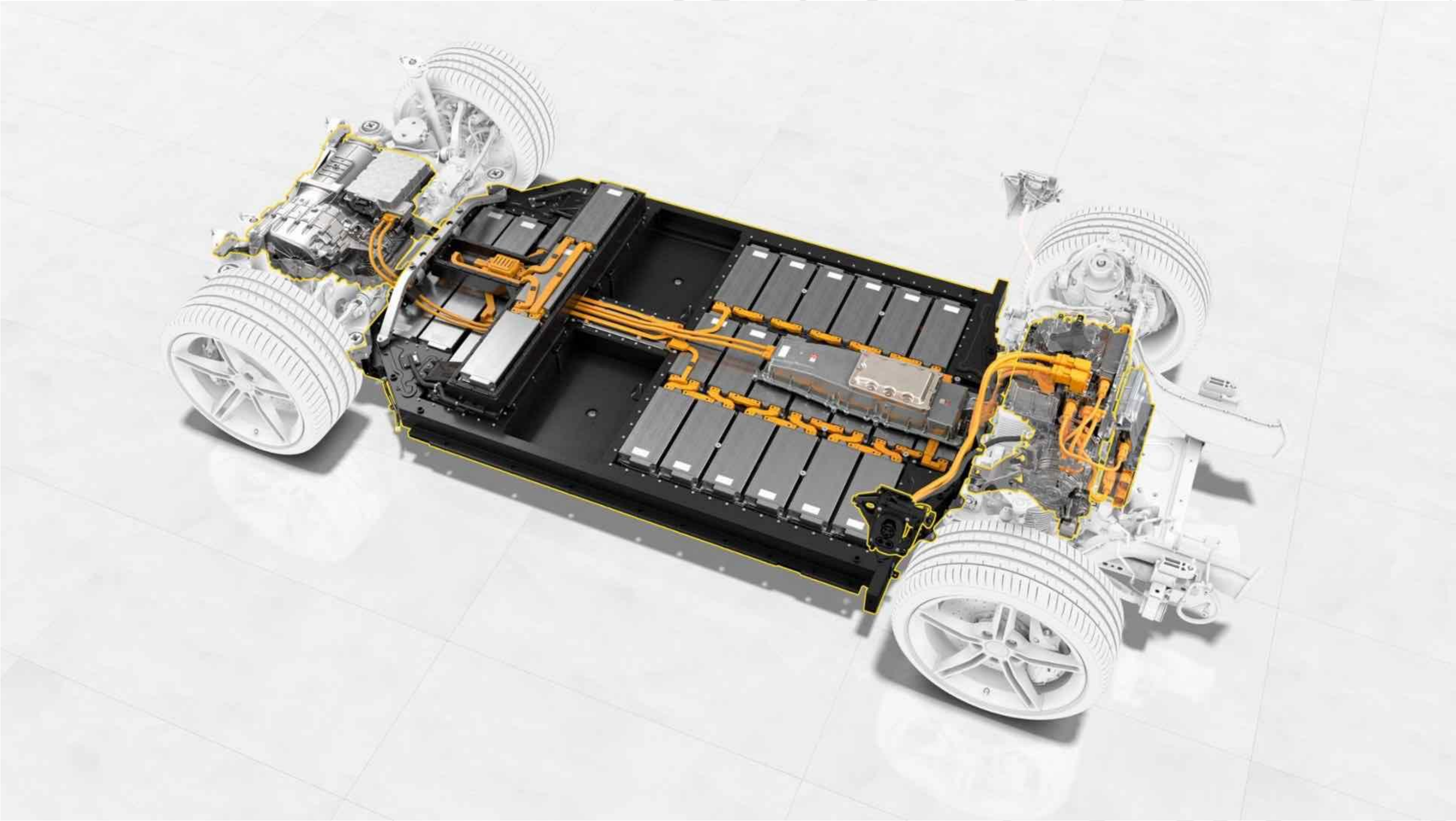
Li-ion Batteries - Architecture of a Battery Pack

From Cell to Pack - Mobility

Cylindrical cell	Prismatic cell	Pouch cell
		
• Small size (e.g. 18650 type (ø 18 mm, height 650 mm)) • Hard casing • Low individual cell capacity • Build in safety features • Comparably cheap	• Hard casing • Large size • High individual cell capacity	• Soft casing • Large size • High individual cell capacity • Geometrical deformation during (dis-)charging

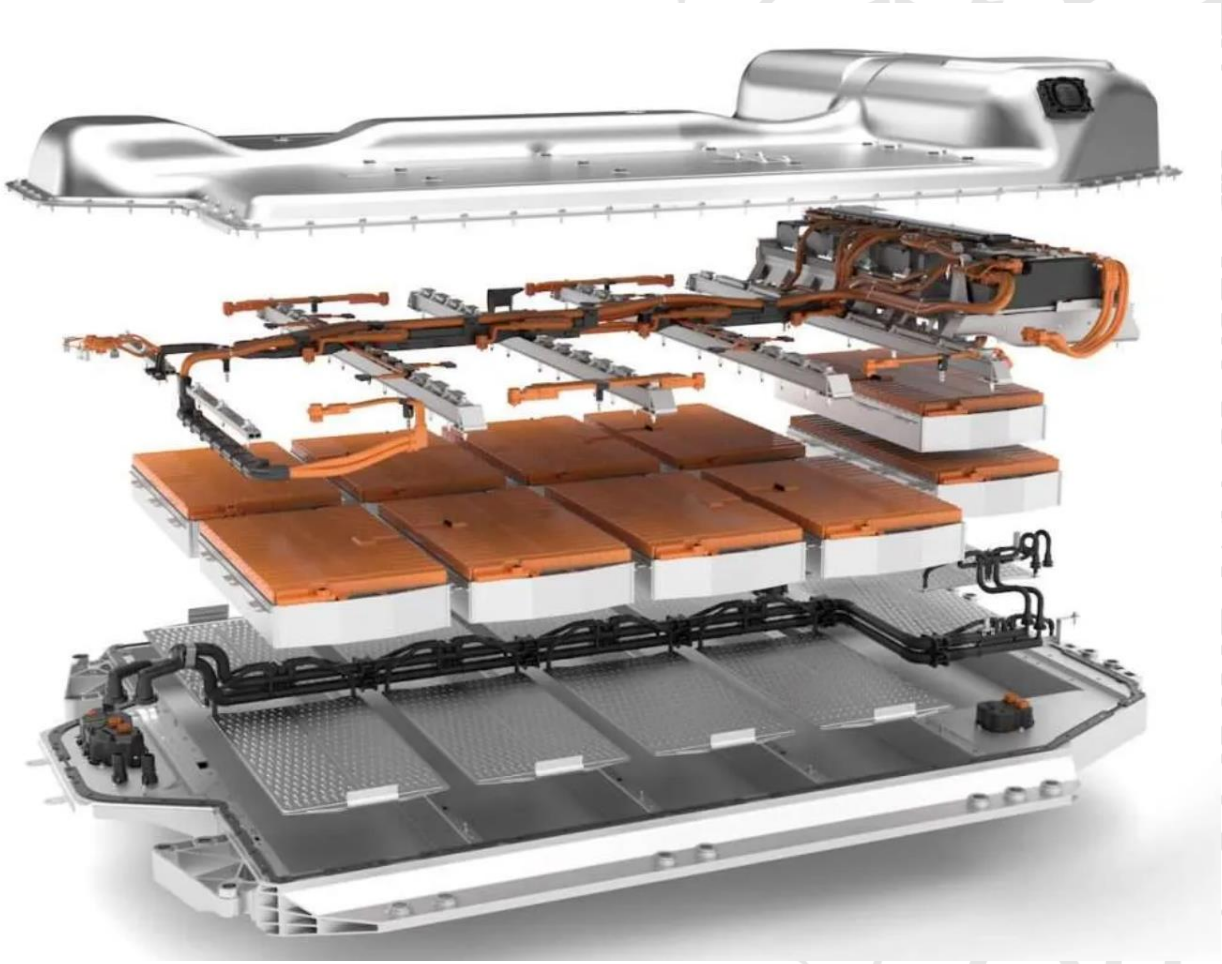


Li-ion Batteries - Architecture of a Battery Pack



Li-ion Battery Pack – Tesla Model S

Li-ion Battery Pack – BMW iX3



Li-ion Battery Pack – Hyundai Kona

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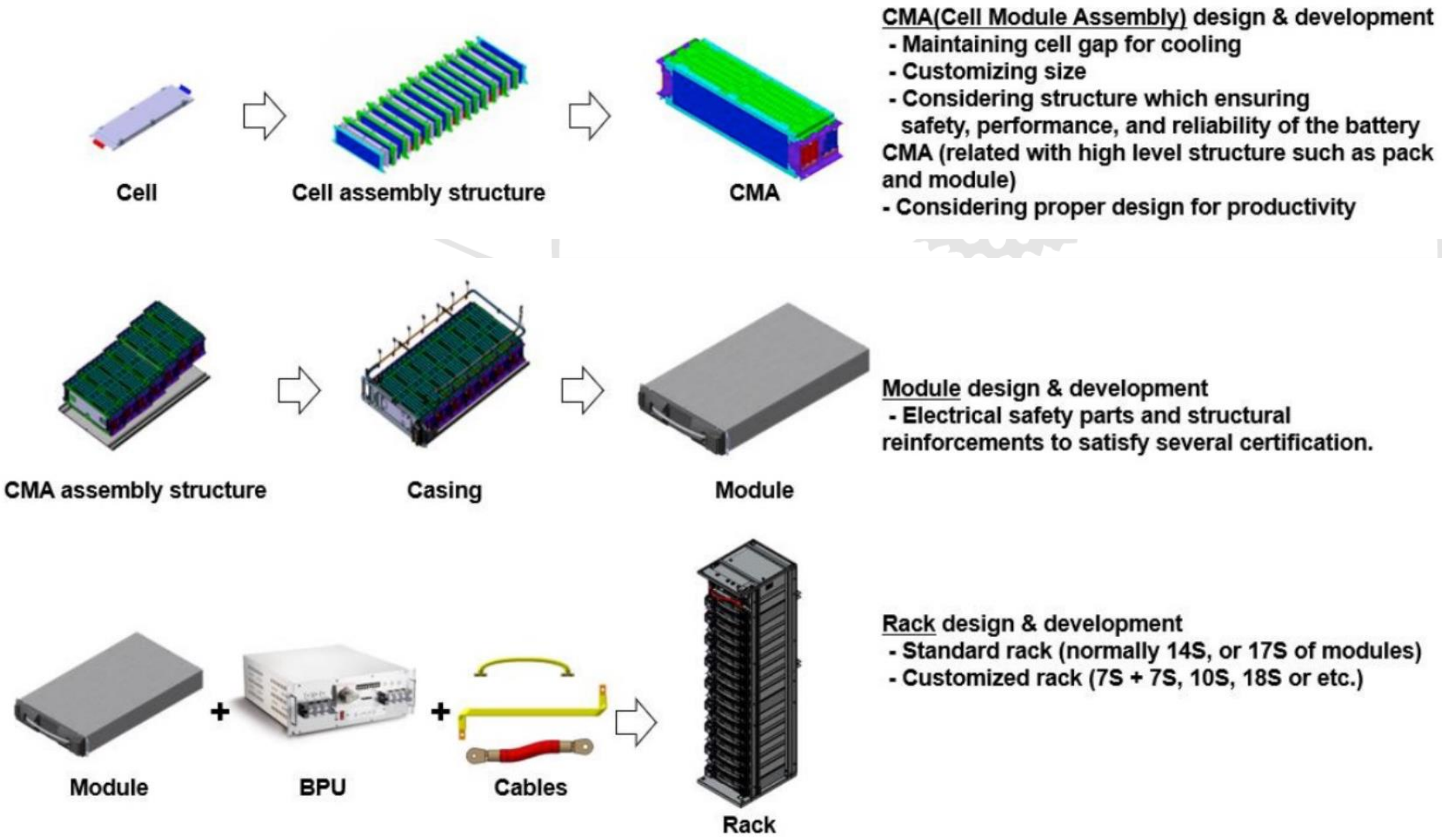
Li-ion Batteries - Architecture of a Battery System

From Cell to Pack

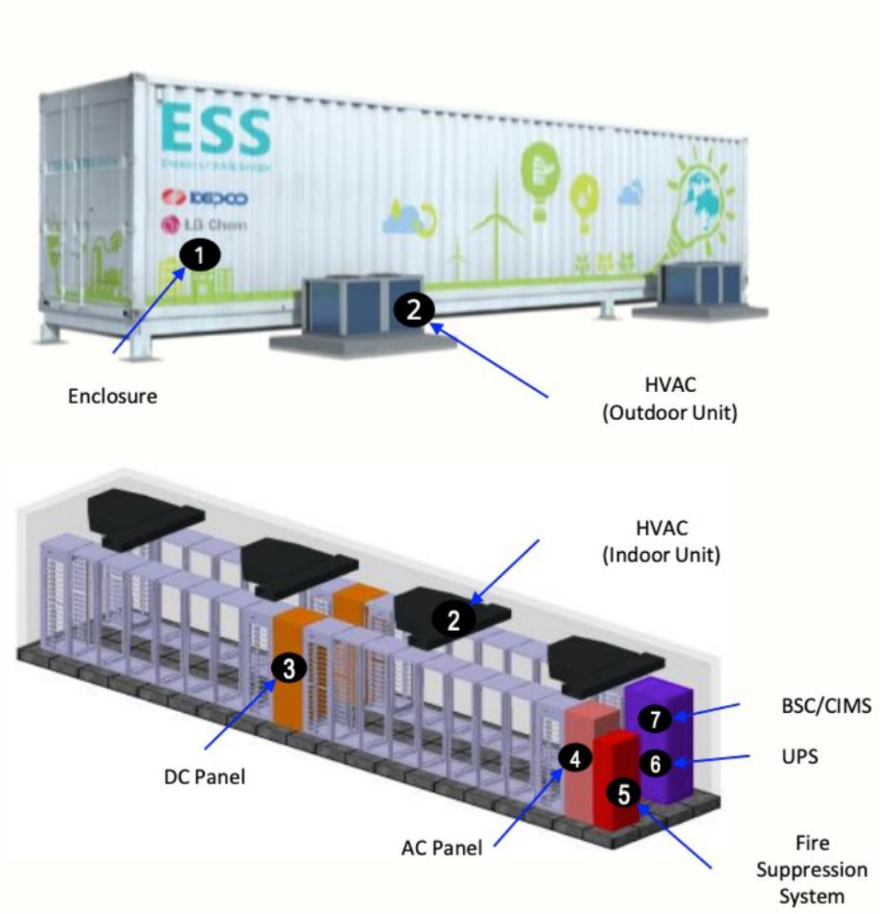
–

Stationary

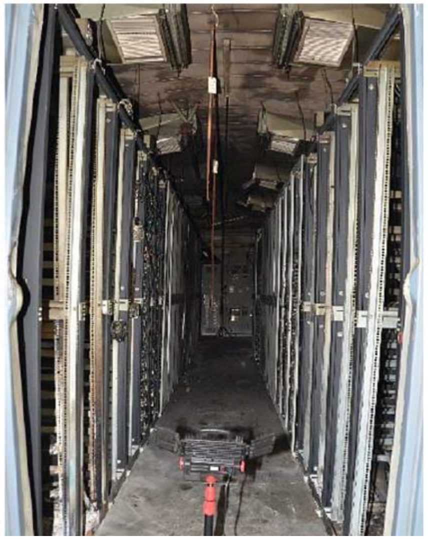


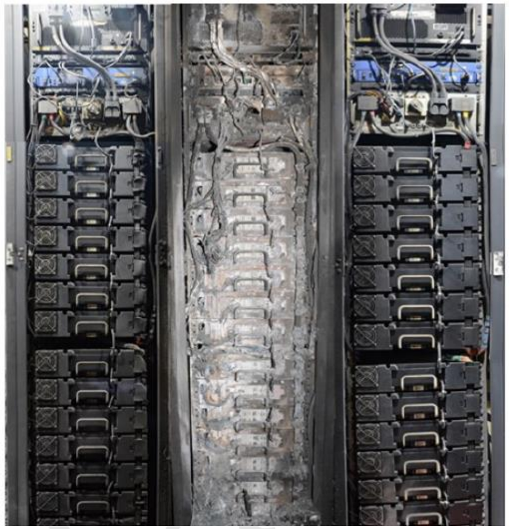
Li-ion Batteries - Architecture of a Battery System

No	Item	Function
1	Enclosure	• Battery Protection against external environment and providing interface for external equipment • ISO Standard type or Structured Insulated Panel type
2	HVAC	• Battery Temperature Management • Wall Mount, Roof Top, Packaged or Duct type
3	DC Panel	• DC Protection and interface for PCS connection • DC Power Junction for various racks
4	AC Panel	• Distribution for AC Power Load like BSC, HVAC and FSS (Fire Suppression System) • SMPS for battery racks • Protection for AC Load equipment
5	Fire Suppression System	• Fire detection and suppression system • Fire Strobe and Siren
6	UPS	• BSC & BMS Power Back-up when outage
7	BSC / CIMS	• BSC : Battery System Controller to communicate with PCS or EMS • CIMS : ESS Container Integrated Management System



Li-ion Batteries - Architecture of a Battery System





Redox Flow Batteries - Working Principle

Redox Flow Battery

Bipolar plates: Carbon-based plates connecting the electrodes to the copper current collectors at each pole of the battery

Electrodes: Anode and cathode, usually made with a carbon-based porous media, such as felts or cloths

Electrolytes: Water-based solution conducting ionic current and containing supporting chemicals that increase the mobility of charged species

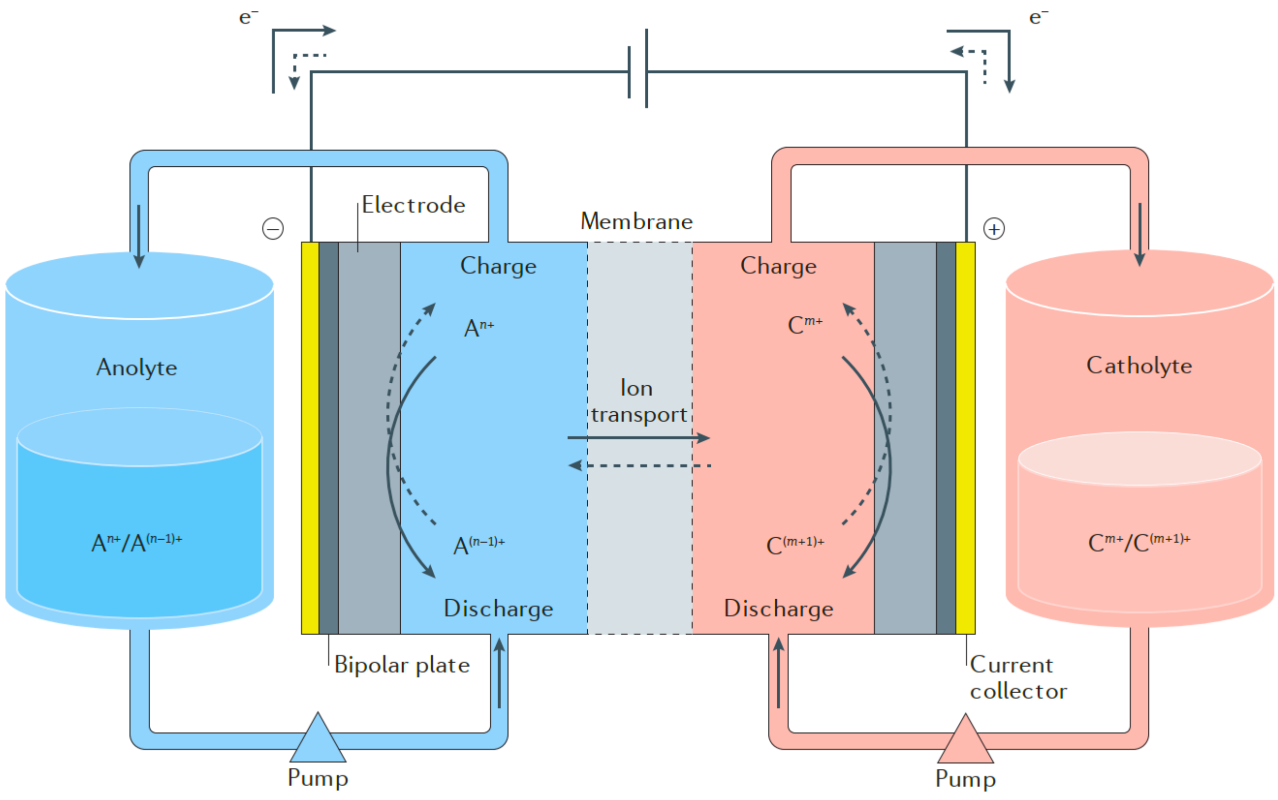
Anolyte: The electrolyte on the negative side, containing a supporting electrolyte and the active species reacting at the anode

Catholyte: The electrolyte on the positive side, containing a supporting electrolyte and the active species reacting at the cathode

Separator: A porous polymeric film that separates the electrolytes while enabling the exchange of specific ions from one side to the other

Tanks: Large containers from which the catholyte and the anolyte are pumped into the cell

Pumps: Induces the motion of the electrolyte, guaranteeing continuous exchange of active species in the porous electrode

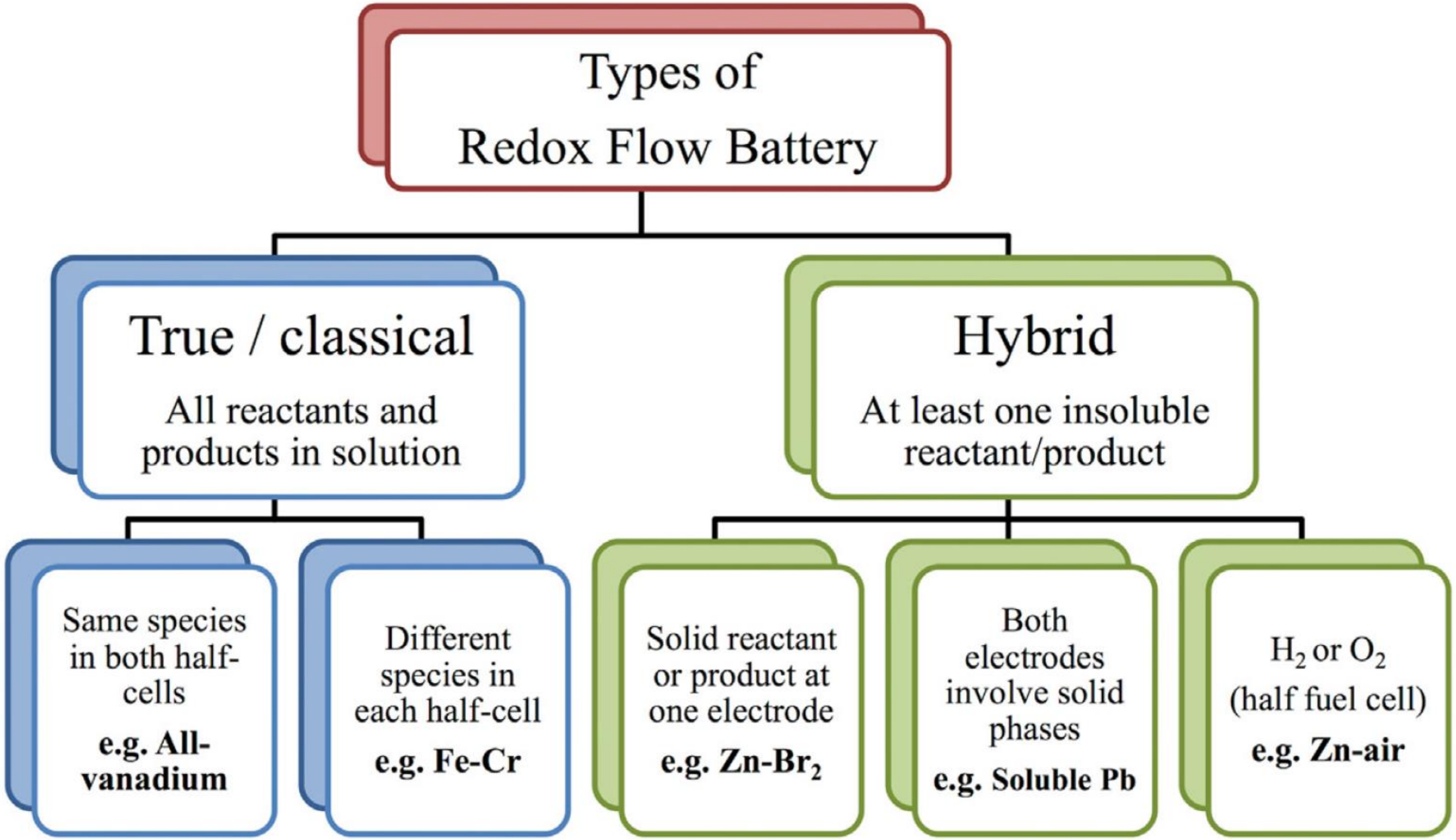


Redox Flow Batteries - Types and Characteristrics

TECHNOLOGY	DEVELOPMENT	REACTION TIME	TYPICAL DURATION OF DISCHARGE AT MAX POWER CAPACITY	ROUND TRIP EFFICIENCY	CYCLE LIFE (CYCLES)	ADVANTAGES	DISADVANTAGES
Lithium-ion	Widely commercialised	Subsecond to seconds	Minutes to a few hours	86-88%	1,000-2000	Established technology; Lower maintenance costs	Safety considerations: thermal runaway
Flow	Initial commer-cialisation	Subsecond to seconds	Several hours	65-80%	12,000-14,000	High intrinsic safety; capable of deep discharges	Low energy and power density
Lead-acid	Widely commercialised	Seconds	Minutes to a few hours	79-85%	500-1,000	Low cost	Short cycle life; toxicity of components

Source: Adapted from NREL report USAID Grid-scale Energy Storage Technologies Primer (July 2021); and data from Maria Skyllas-Kazacos

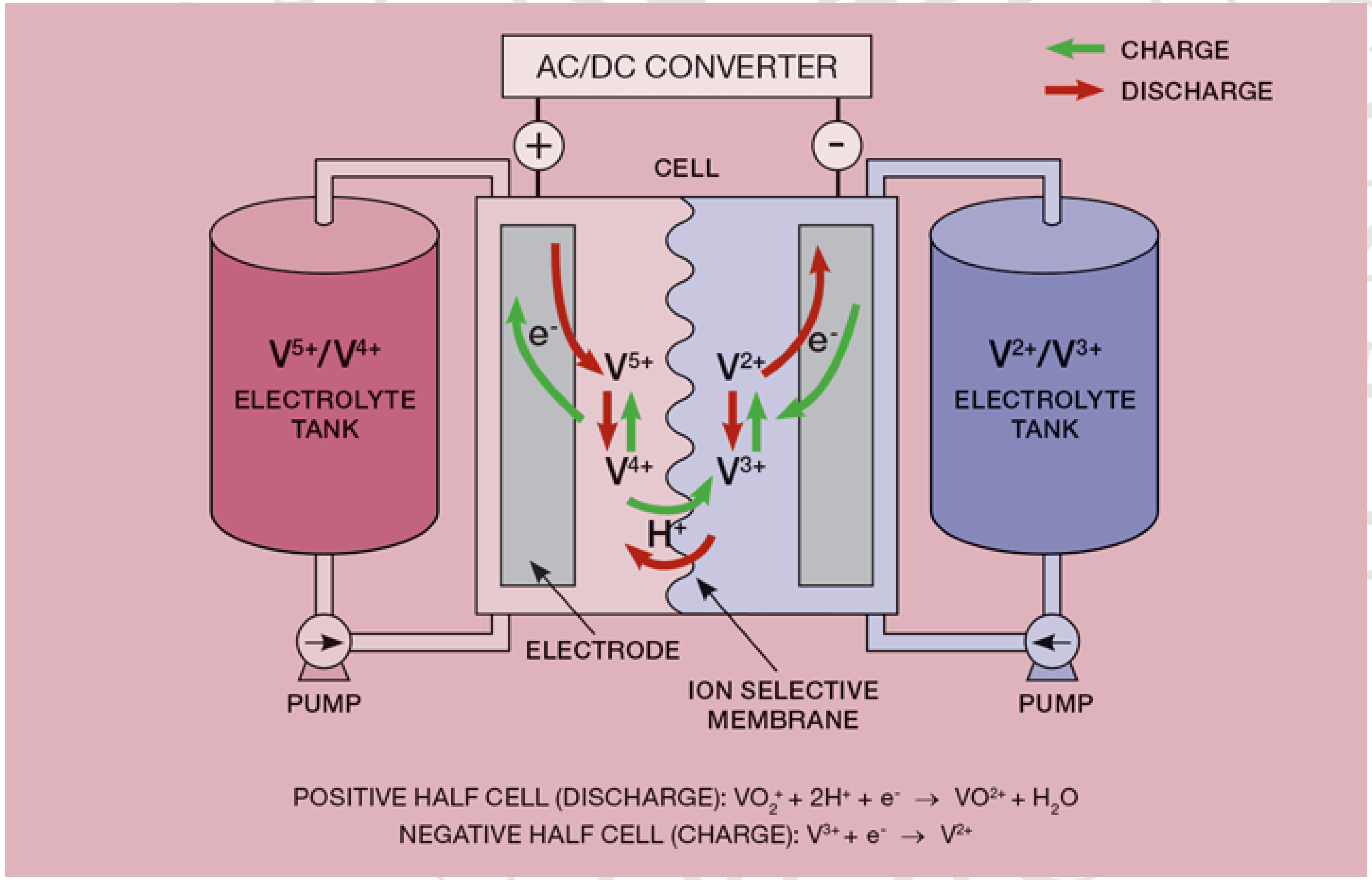
Redox Flow Batteries - Types and Characteristics



Redox Flow Batteries - Types and Characteristics

Vanadium Redox Flow Battery

$OCV_{nominal}$ = 1.2 V



Redox Flow Batteries - Types and Characteristics

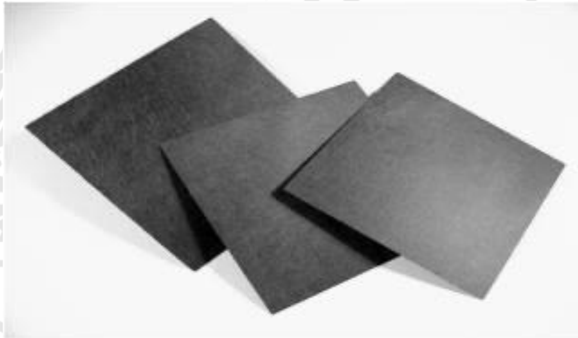
Storage Chemistry	AC Roundtrip Efficiency (%)	Storage Duration (Hours)	Capital Cost Range ($/kWh)	Life Span (Years)	System Architecture Notes
Vanadium Redox	70-80	4-12+	500-1,100	20+	Containerized, modular, and custom solution; two-tank system
Zinc Bromide	65-70	4-6	450-900	20+	Containerized; plating electrode; one-tank system
Iron-Salt	65-70	4-10	600-1,200	20+	Containerized. modular, and custom solutions; plating electrode; two-tank system
Lithium-ion Comparison	80-90	1-4	300-1,000	5-20	Containerized, modular, and custom solutions; consider degradation/ augmentation

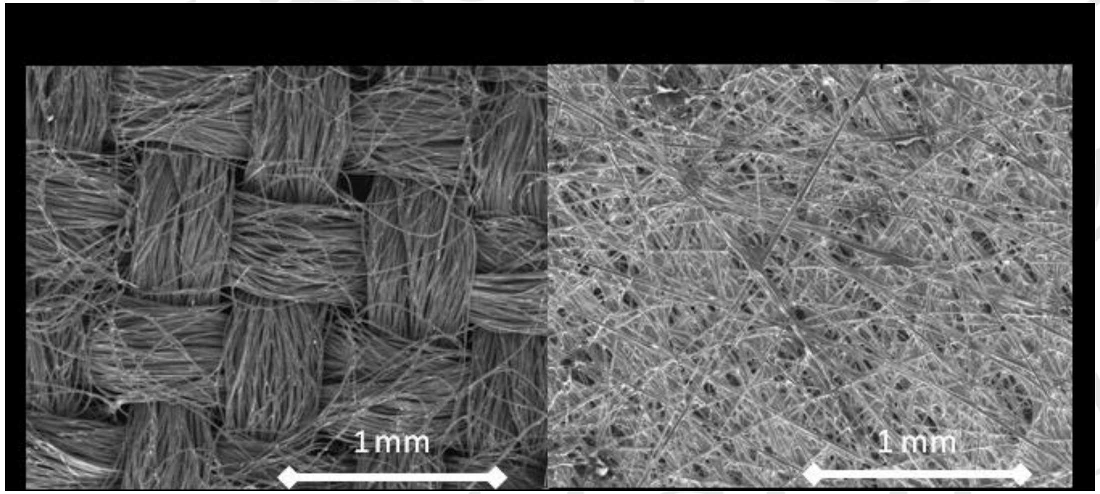
Redox Flow Batteries - Architecture of a battery storage system

Electrodes


Carbon Felt

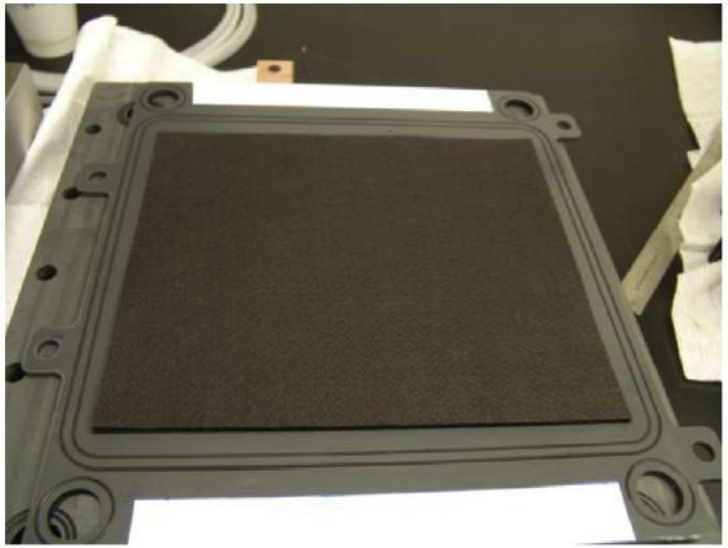

Carbon Cloth

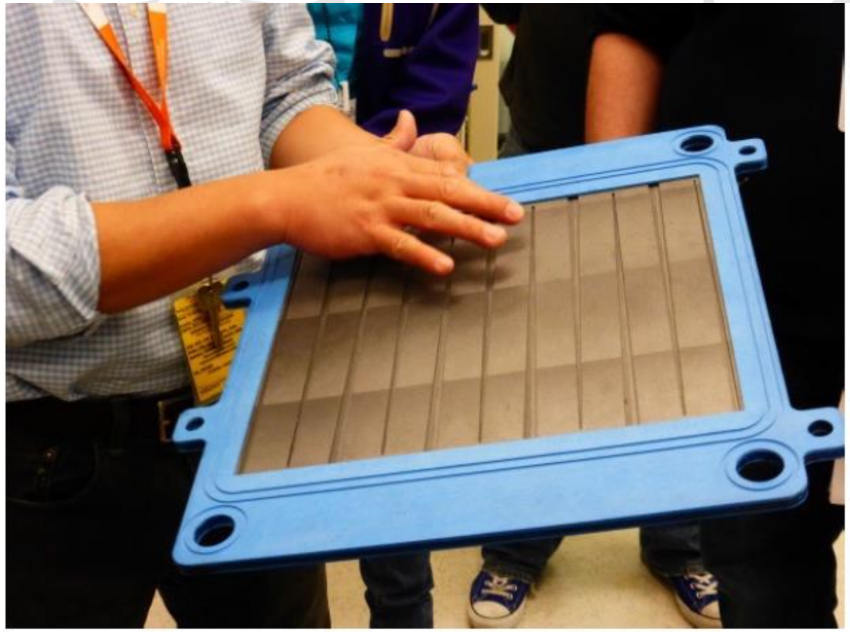

Carbon Paper



Redox Flow Batteries - Architecture of a battery storage system

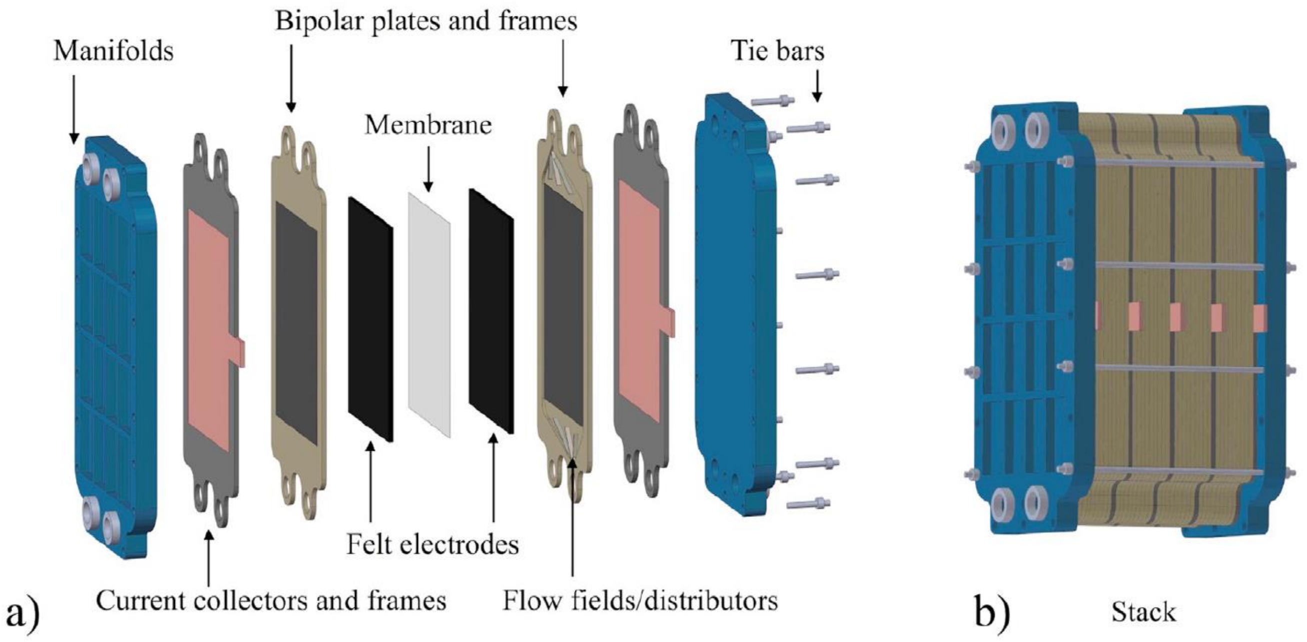
Cells – Frames – Bipolar Plates

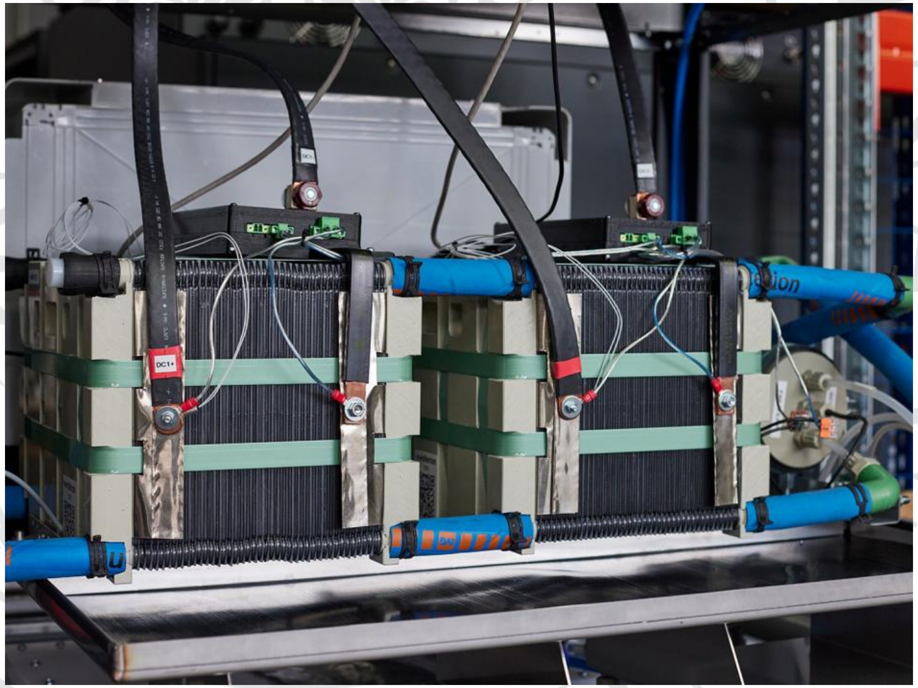




Redox Flow Batteries - Architecture of a battery storage system

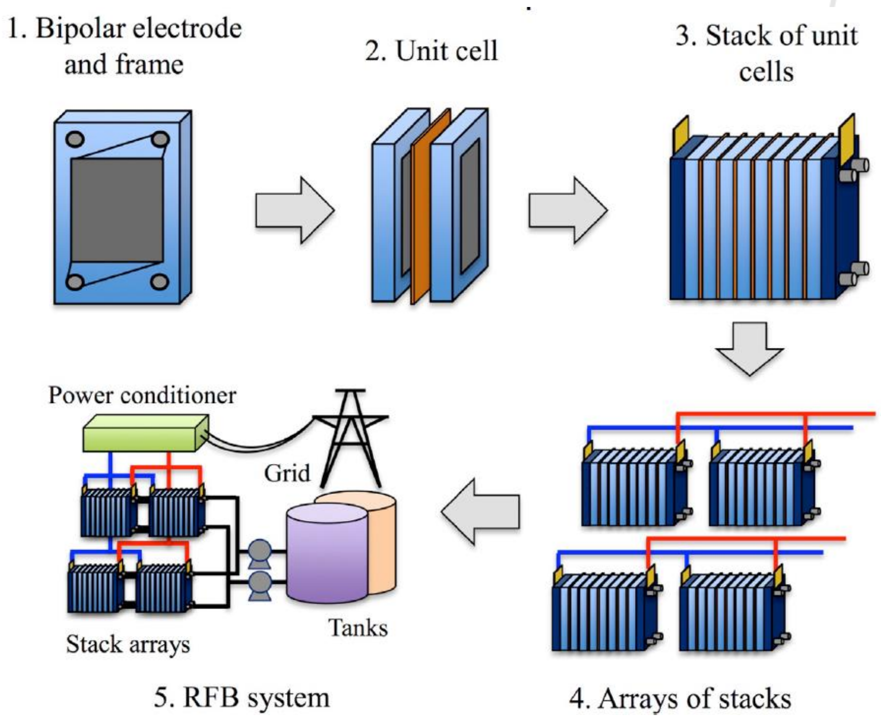
From Cell to Stack



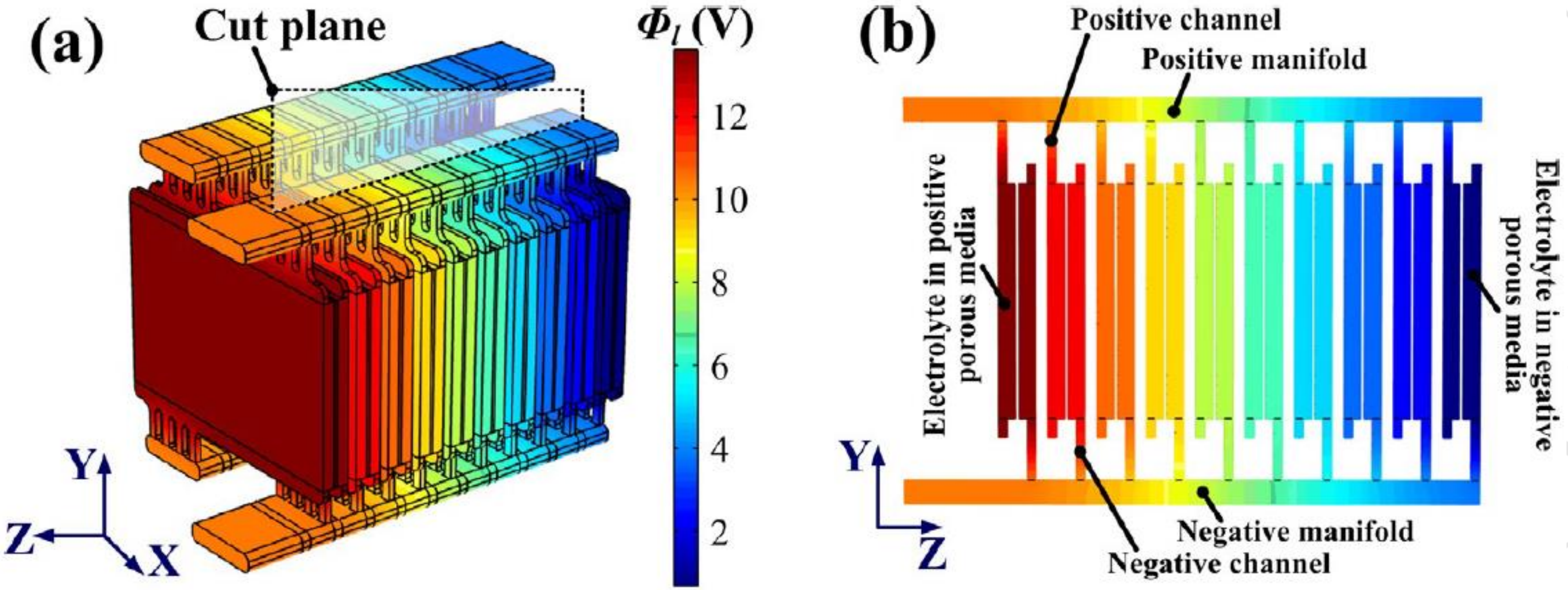


Redox Flow Batteries - Architecture of a battery storage system

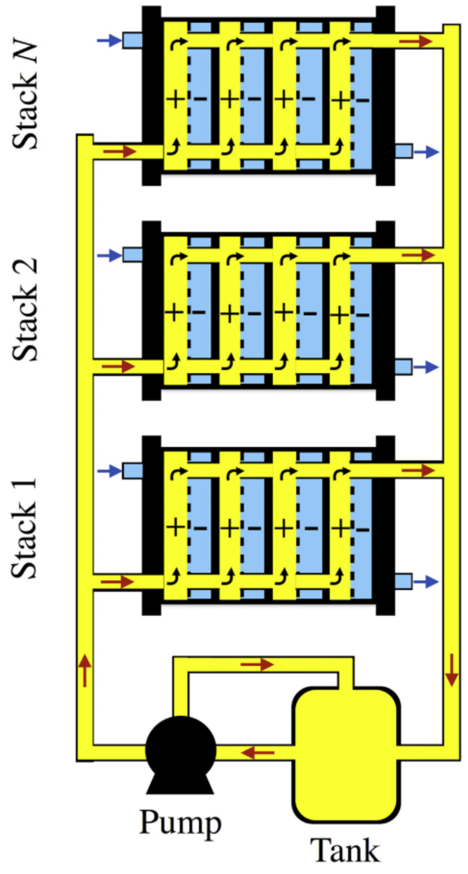
From Stack to System

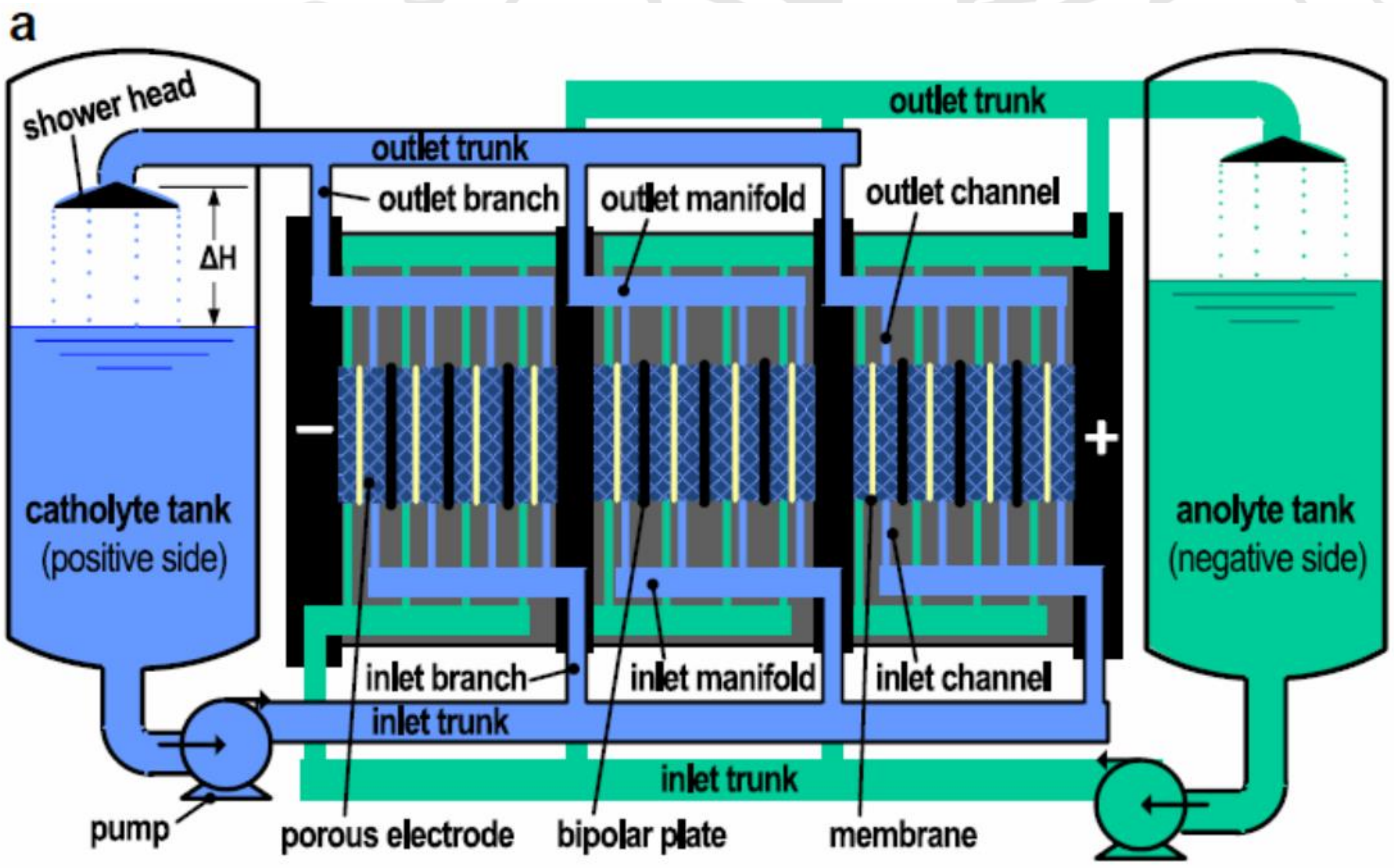


Redox Flow Batteries - Architecture of a battery storage system



Redox Flow Batteries - Architecture of a battery storage system

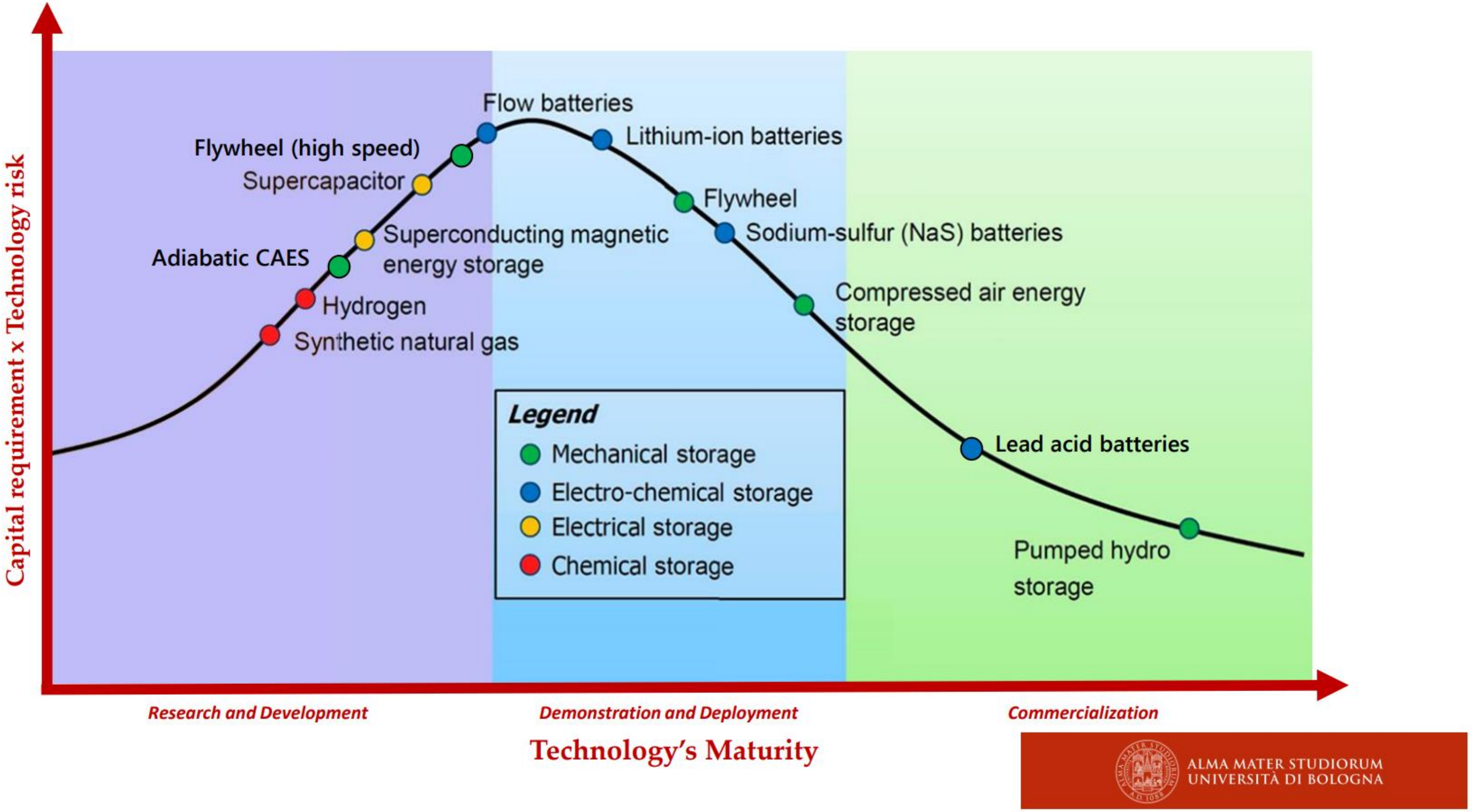




Redox Flow Batteries - Architecture of a battery storage system

Tanks

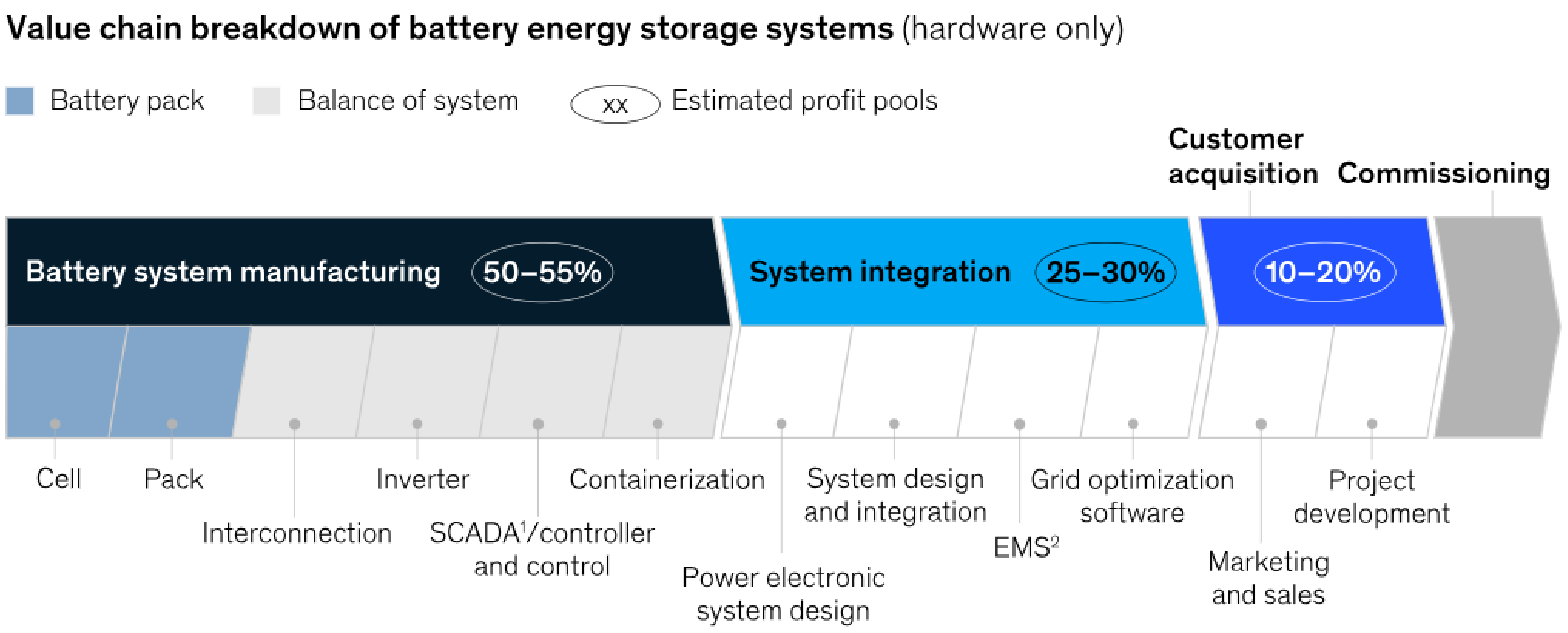
Development of Energy Storage Systems



Graph referring to 2015

Today many technologies have a larger level of maturity (e.g. Flow Batteries)

Development of Energy Storage Systems



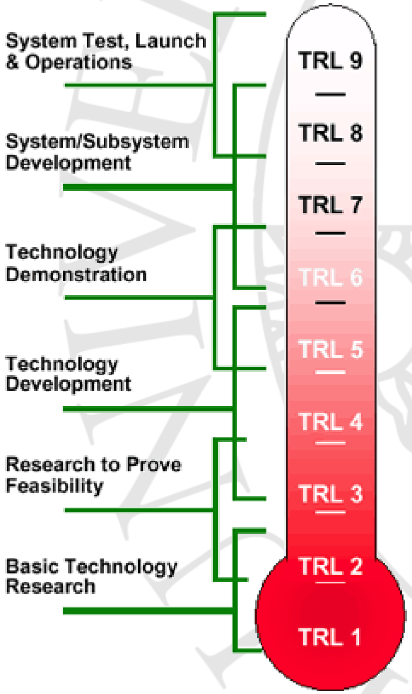
Development of Energy Storage Systems

Technology Readiness Level (TRL)

Scale to indicate the maturity of a technology with respect to the possibility of commercialization

Technology readiness level (TRL).

Stage	TRL	Description
Deployment	9	System deployed and operational in a real environment
	8	Complete validation and certification of system in real environment
	7	Prototype validated in real environment
Research	6	Technology demonstrated in relevant environment
	5	Technology validated in relevant environment
Development	4	Technology validated in lab
	3	Concept tested
	2	Concept/technology formulated
	1	Basic idea/concept

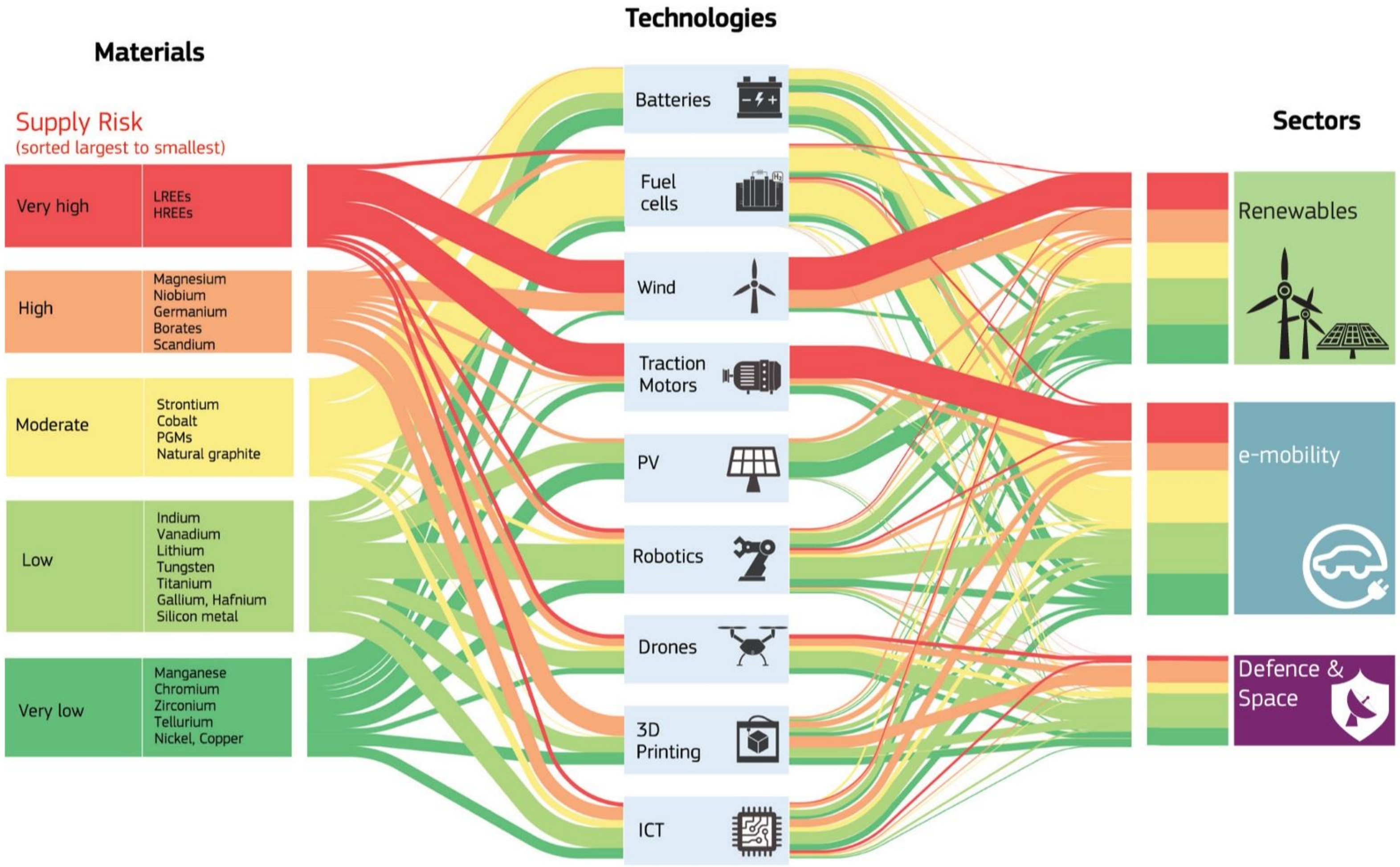


Current status of energy storage technologies [108,551,565,566].

Storage system	Current scenario	TRL
Lead-acid batteries	Mature technology, commercially available	9
Lithium-ion batteries	Commercial technology	9
Nickel-cadmium batteries	Mature technology	9
Sodium sulphur	Large-scale demonstration	8
Vanadium redox batteries	Mature technology	9
Polysulfide bromide batteries	–	4–5
Zinc bromine batteries	Demonstration	6
Electric double-layer capacitors	Early commercial technology	8–9
Hybrid energy storage system	–	7
Synthetic natural gas	Prototype testing to large scale demonstration	4–8
Pumped hydro energy storage system	Mature technology, commercially available	9
Compressed air energy storage system	–	7–8
Low speed flywheel energy storage system	–	9
High speed flywheel energy storage system	Prototype testing to small scale demonstration	5–7
Supercapacitors	–	6
Superconducting magnetic bnergy storage system	–	5–6

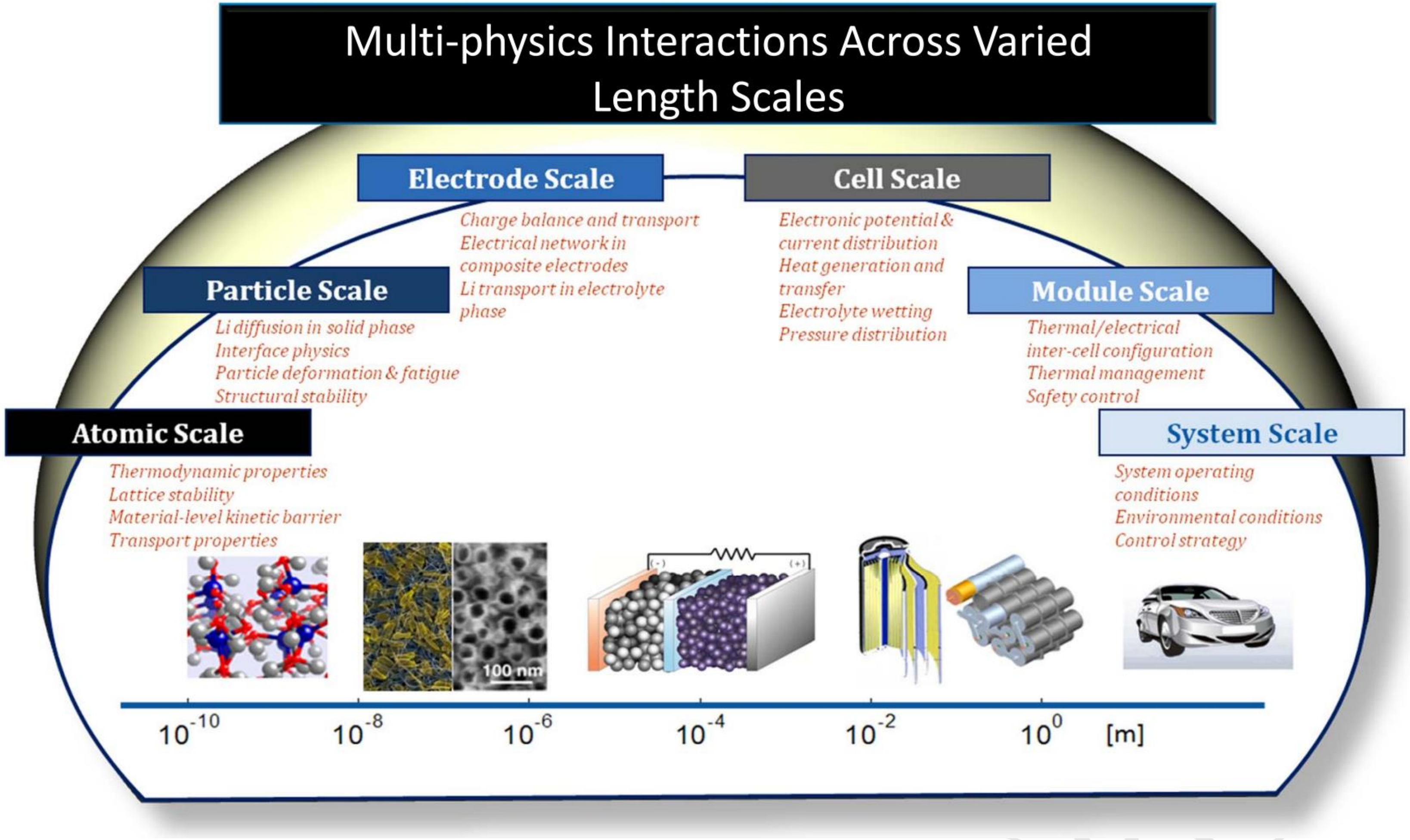
Source: Mitali, J., S. Dhinakaran, and A. A. Mohamad. "Energy storage systems: A review." Energy Storage and Saving (2022).

Critical Raw Materials



End of the Lesson

Cells Formats



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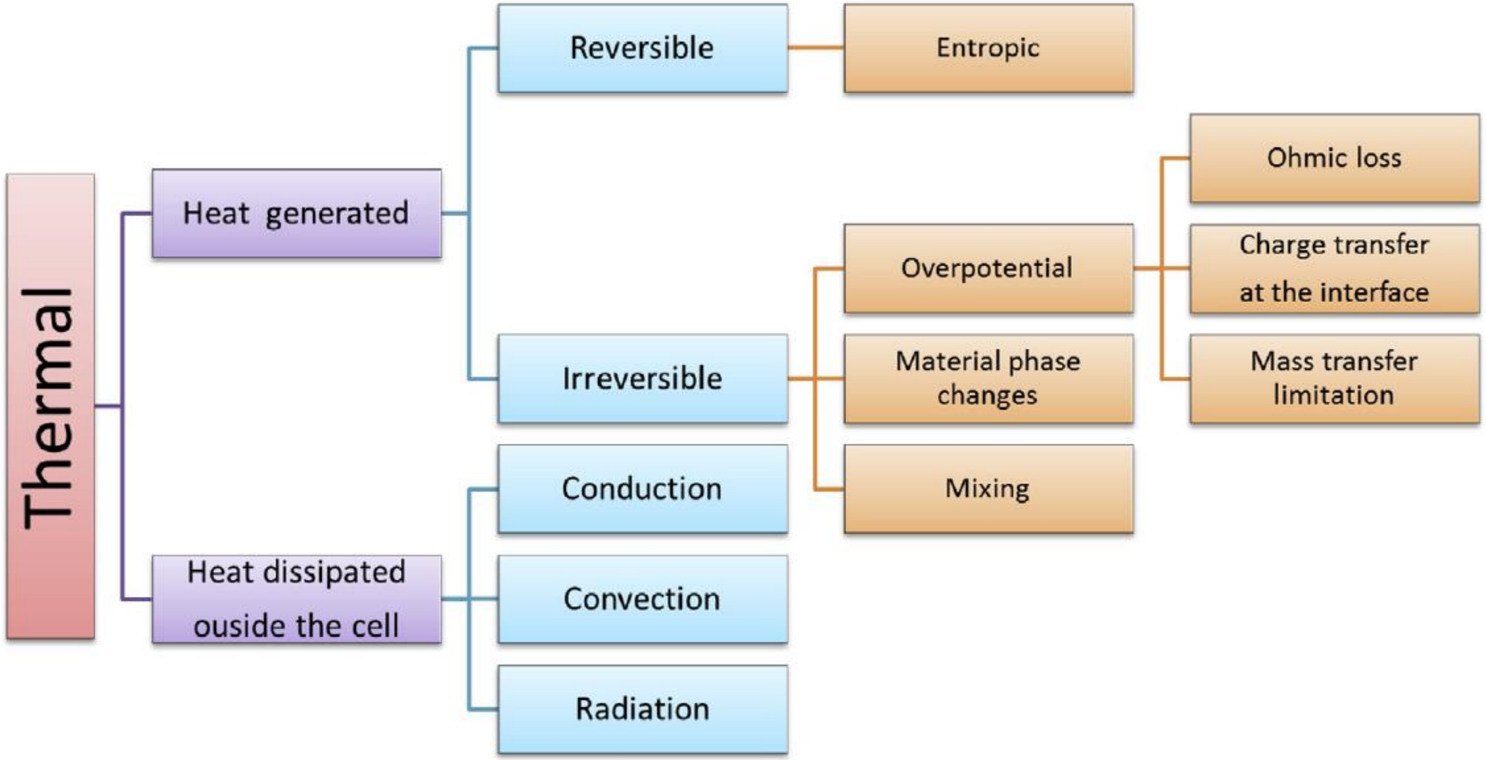

Fig. 4. Thermal modeling approaches of LIBs.