Energy Storage Technologies

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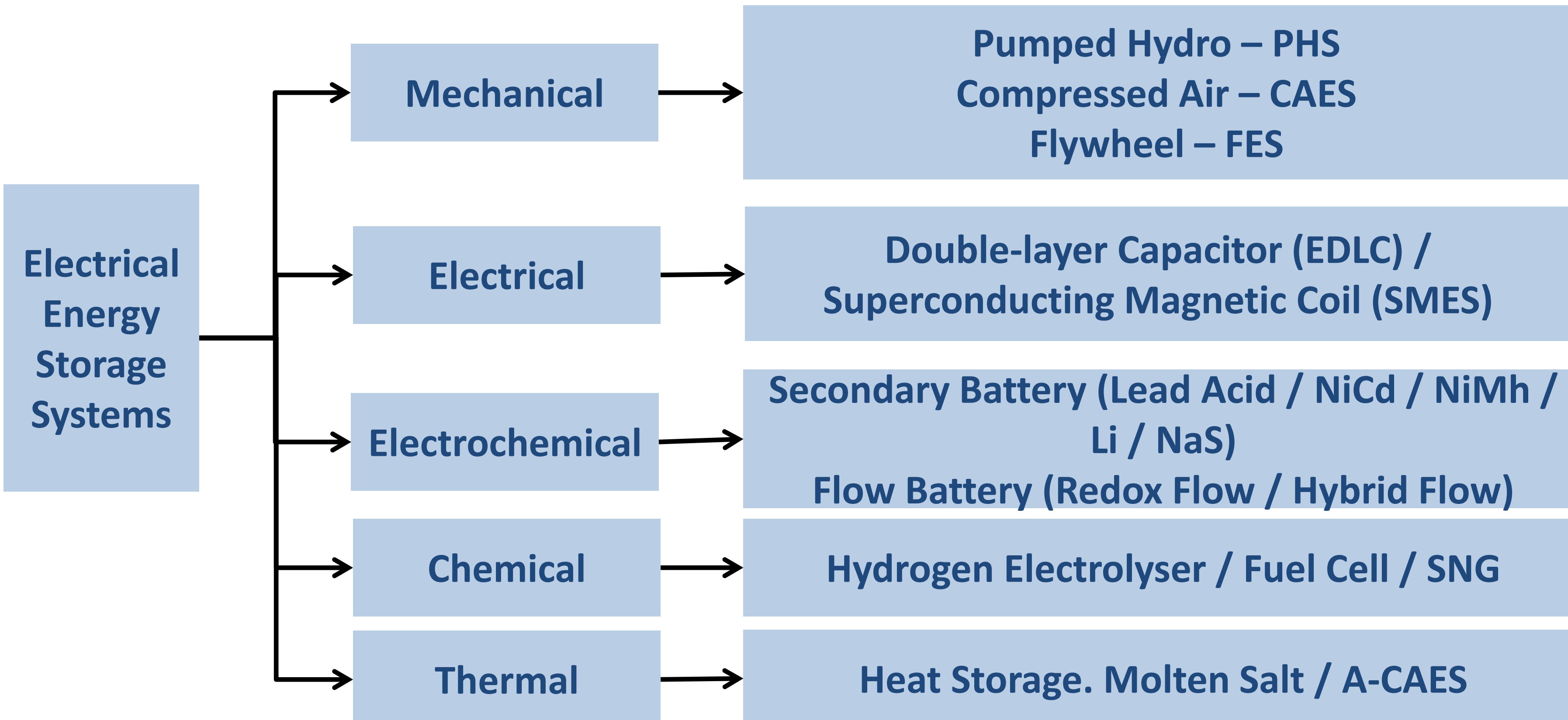
EE6509 – "Renewable Energy Systems in Smart Grids"

Lecture Objective

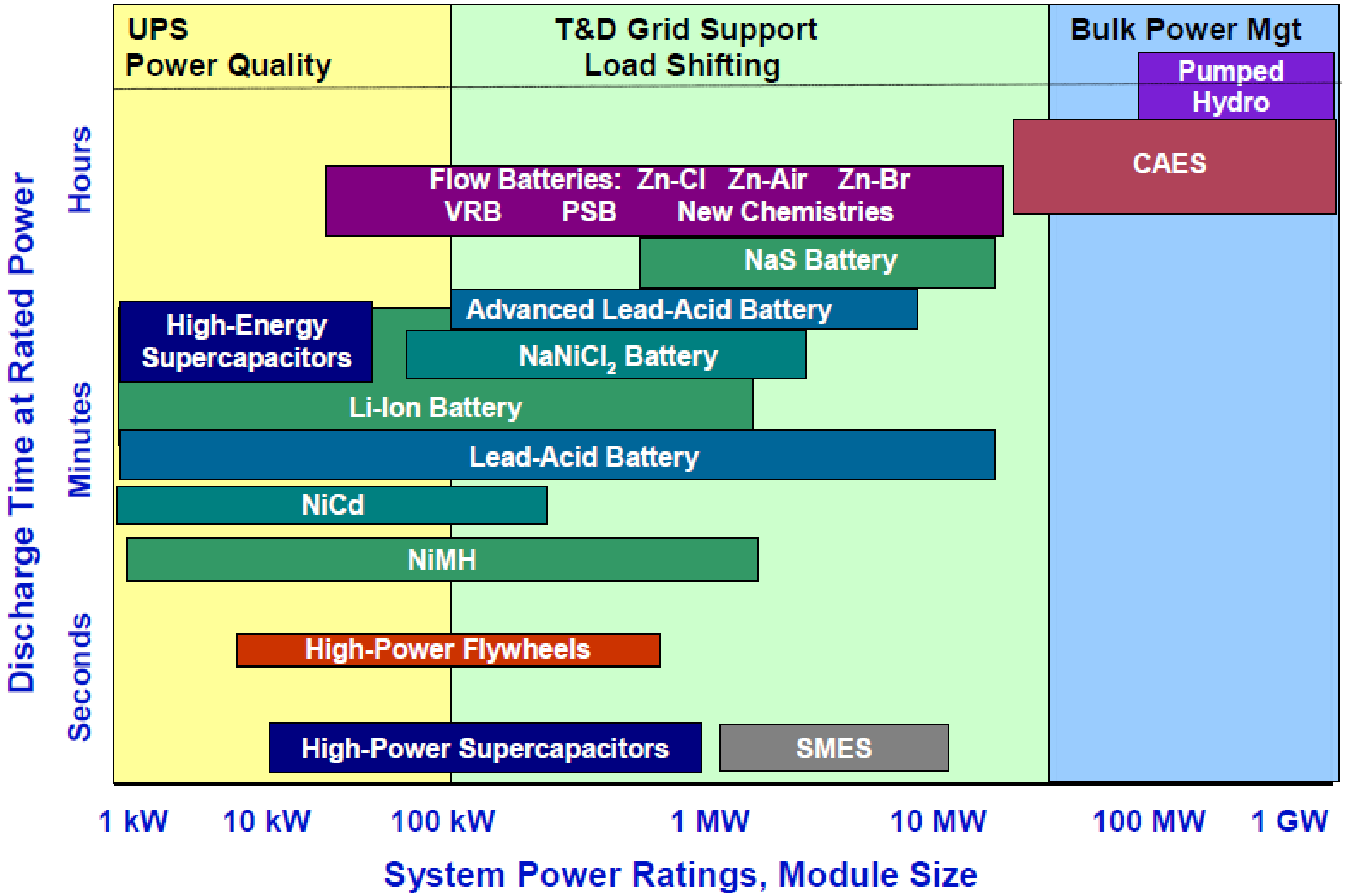
1. Review common energy storage system technologies.
2. Health Monitoring of Li-ion Batteries

ESS Classification

- Classified by fundamental technology (for power grid applications)

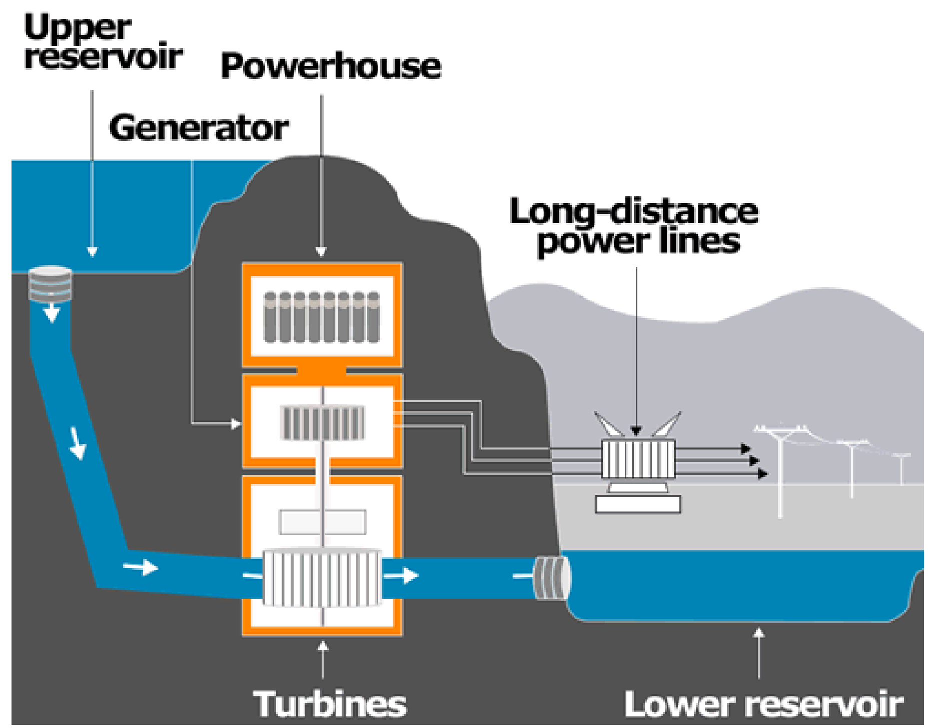


Power Rating and Energy Capacity



Mechanical - Pumped Hydro Storage

- Flow of water from low to high altitude reservoir and vice versa
- Advantages: Low Cost and Unlimited Charge-Discharge Cycle
- Efficiency: 70% - 85%
  - Pump, generator losses and water evaporation



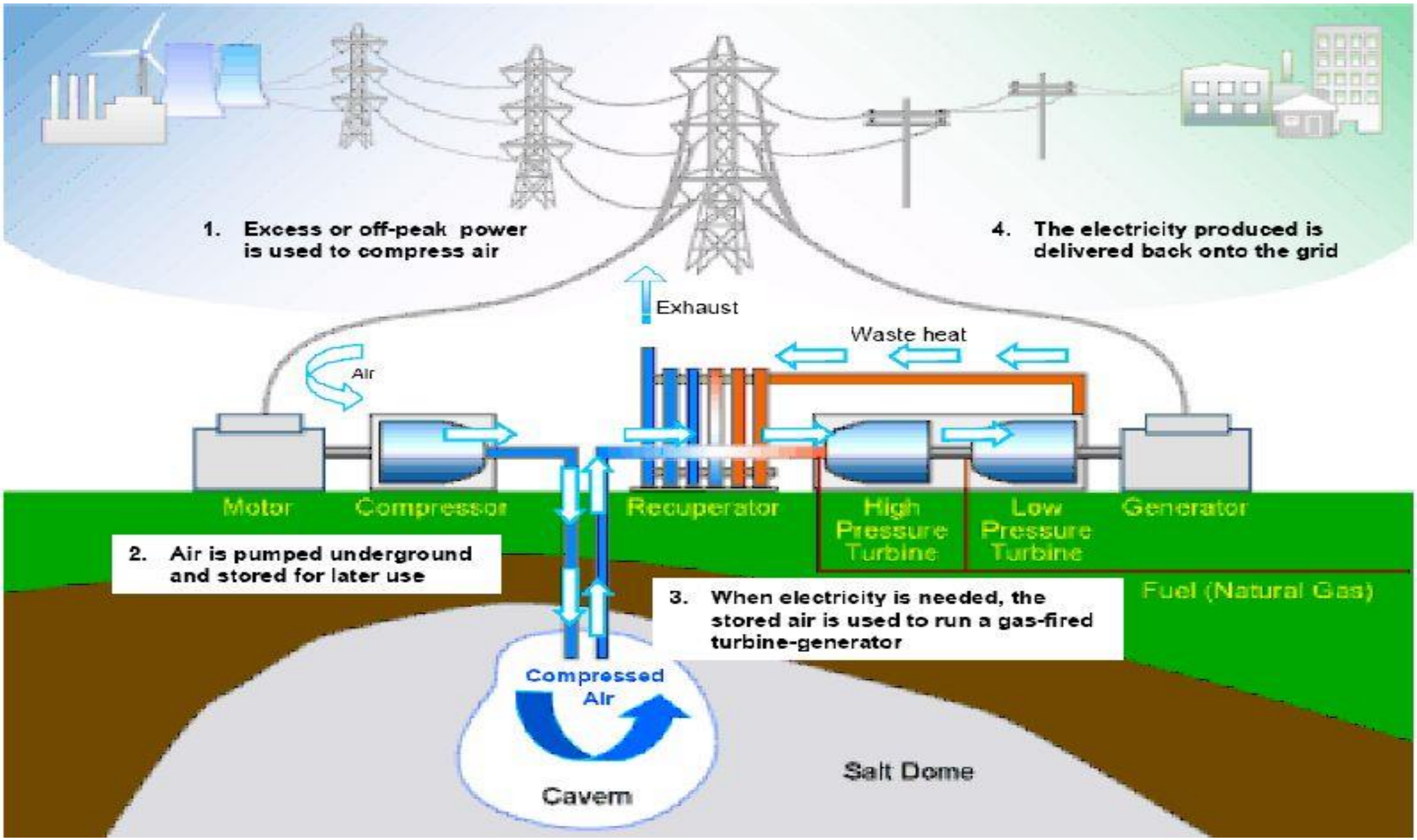
Mechanical - Pumped Hydro Storage

- Largest-capacity form of grid energy storage
- Disadvantage: Depends on geographic locations.
- Underground reservoir, salt water and smaller PHS on stream and within built environment is considered.
- Same concept for hydroelectric dams.
  - Strictly speaking, it is not pump hydro as there is no pumping.

Mechanical – Compressed Air Energy Storage (CAES)

- Ambient air is compressed and stored under pressure in an underground cavern
- Pressurized air is heated using natural gas fired combustion turbine which will drive a turbine generator
- Advantages: Fast Startup
- Disadvantage: Geological Structure Reliance
- Efficiency: 50% - 75%

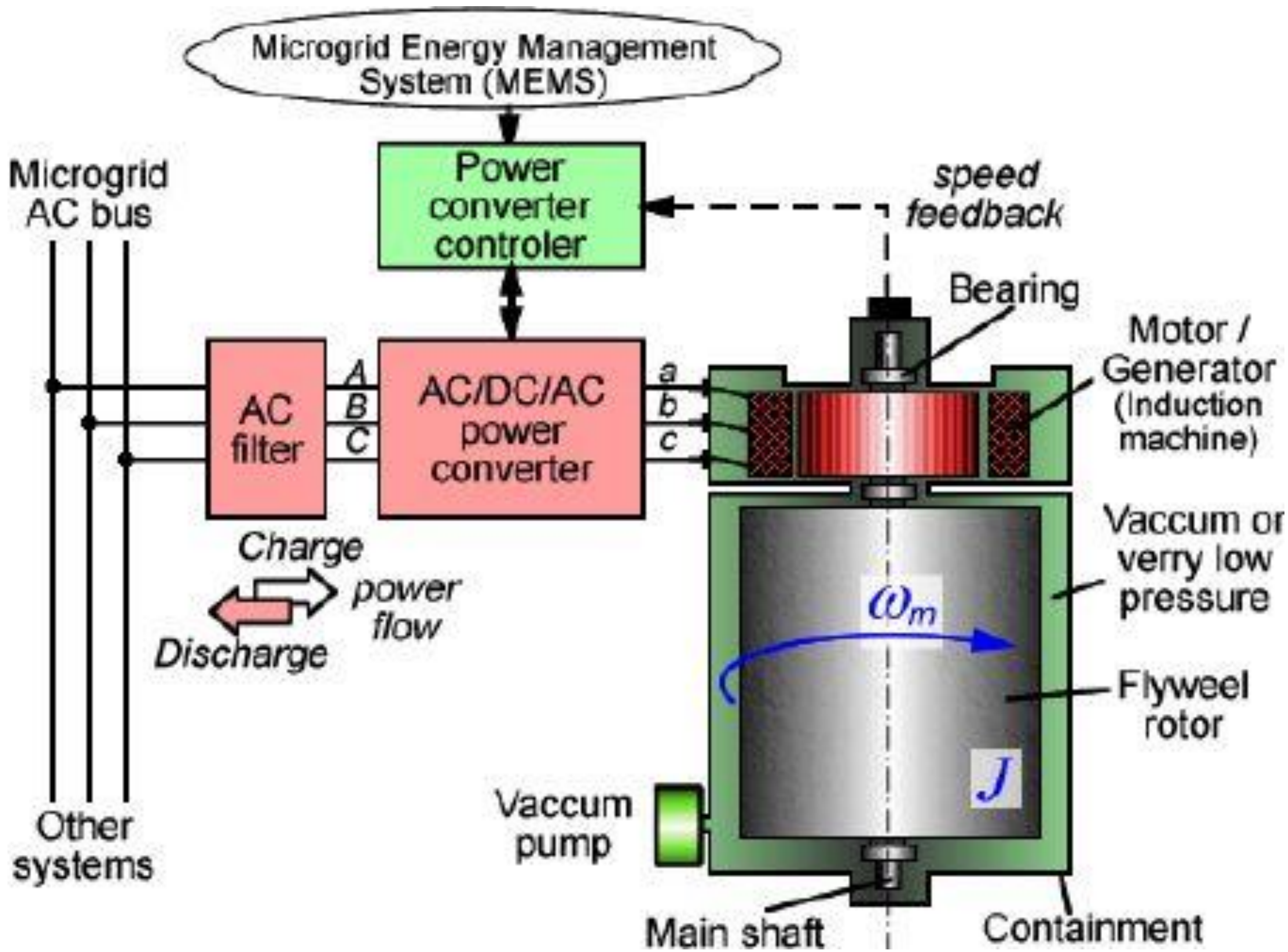
Mechanical – Compressed Air Energy Storage (CAES)



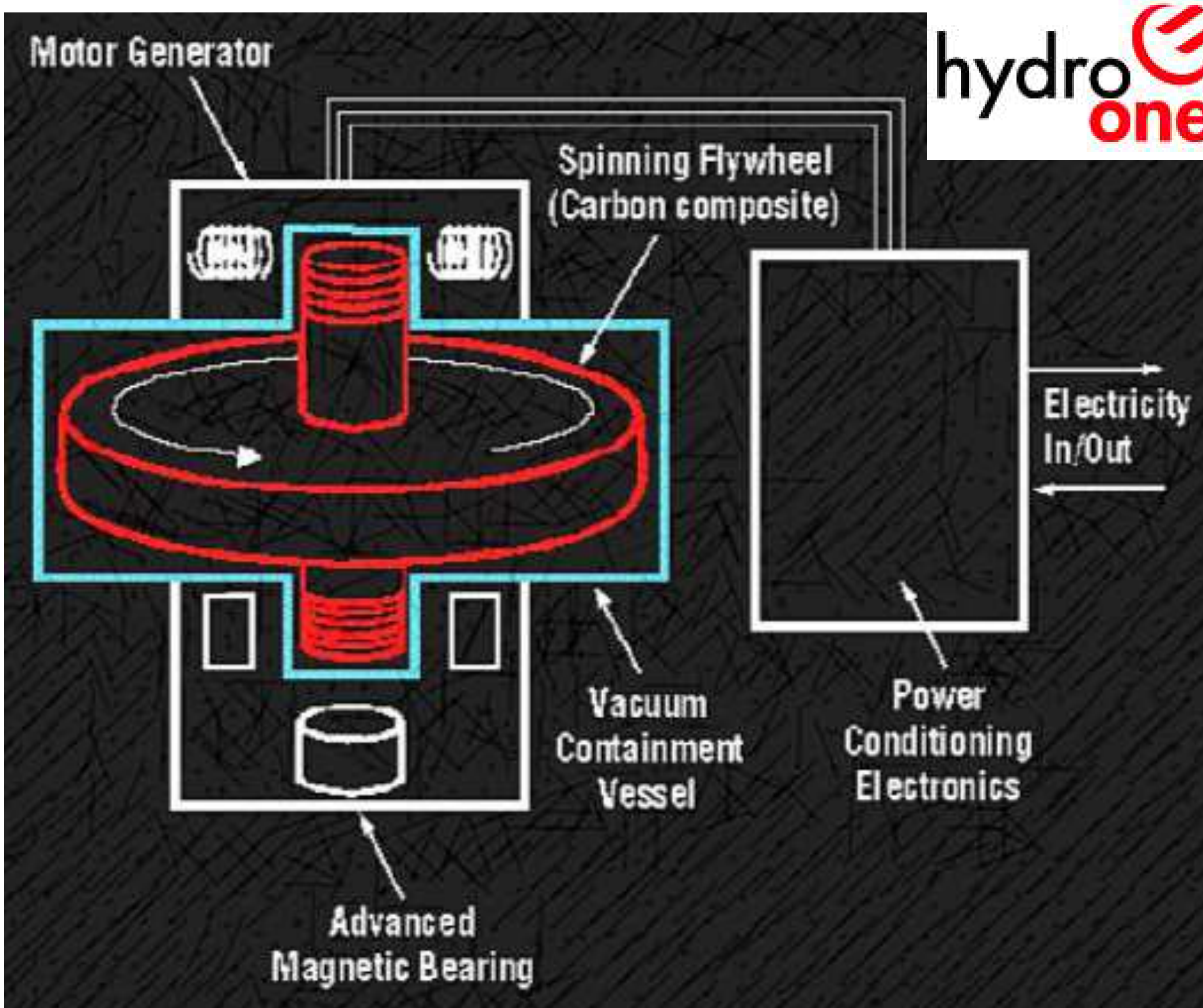
Mechanical – Flywheel Energy Storage (FES)

- Stores energy in the form of mechanical energy of a spinning wheel or tube which drives the generator.
- Has fast dynamic responses, a long life and require little maintenance.
- Used for power quality enhancement such as UPS, capturing waste energy in electric vehicle applications and dampen frequency variations.
- Efficiency: 85% - 90%

Mechanical – Flywheel Energy Storage (FES)



Mechanical – Flywheel Energy Storage (FES) Case Study



Mechanical – Flywheel Energy Storage (FES) Practical Issues

- Efficiency – Where are the losses?
- Bearing losses
- Windage losses
- Angular Momentum Effects
- Containment
- Tensile Strength of Flywheel (Mechanical)

Electrochemical – Rechargeable Batteries

- 3 main types. 1) Lead Acid, 2) NiCd, NiMH, Li-ion, 3) Sodium Sulphur (NaS)
- Operation requires two electrodes in an electrolyte to allow a chemical reaction to take place to produce current.

Lead Acid	Lithium Ion	Sodium Sulphide
Due to its maturity, relatively low cost, long lifespan, fast response, and low self discharge rate, Used for both short-and long (Up to 8 hours) term applications	Due to its ability to withstand harsh conditions and being light weight, Used in many consumer electronics, aircraft and hybrid electric vehicles	Due to its high energy density, longer life span and low maintenance, Used in application such as energy management and power quality

Electrochemical – Lead Acid Battery Introduction

- A very old technology, it is viable for large scale energy storage due its low cost and well understood technology;
- Also has high surge current capability
- Disadvantages are very low energy-to-weight ratio and low energy-to volume ratio, and maintenance issues;
- Large format lead-acid battery designs have made it viable for back-up power supplies and for isolated micro-grids;

Electrochemical – Lead Acid Battery Typical Values

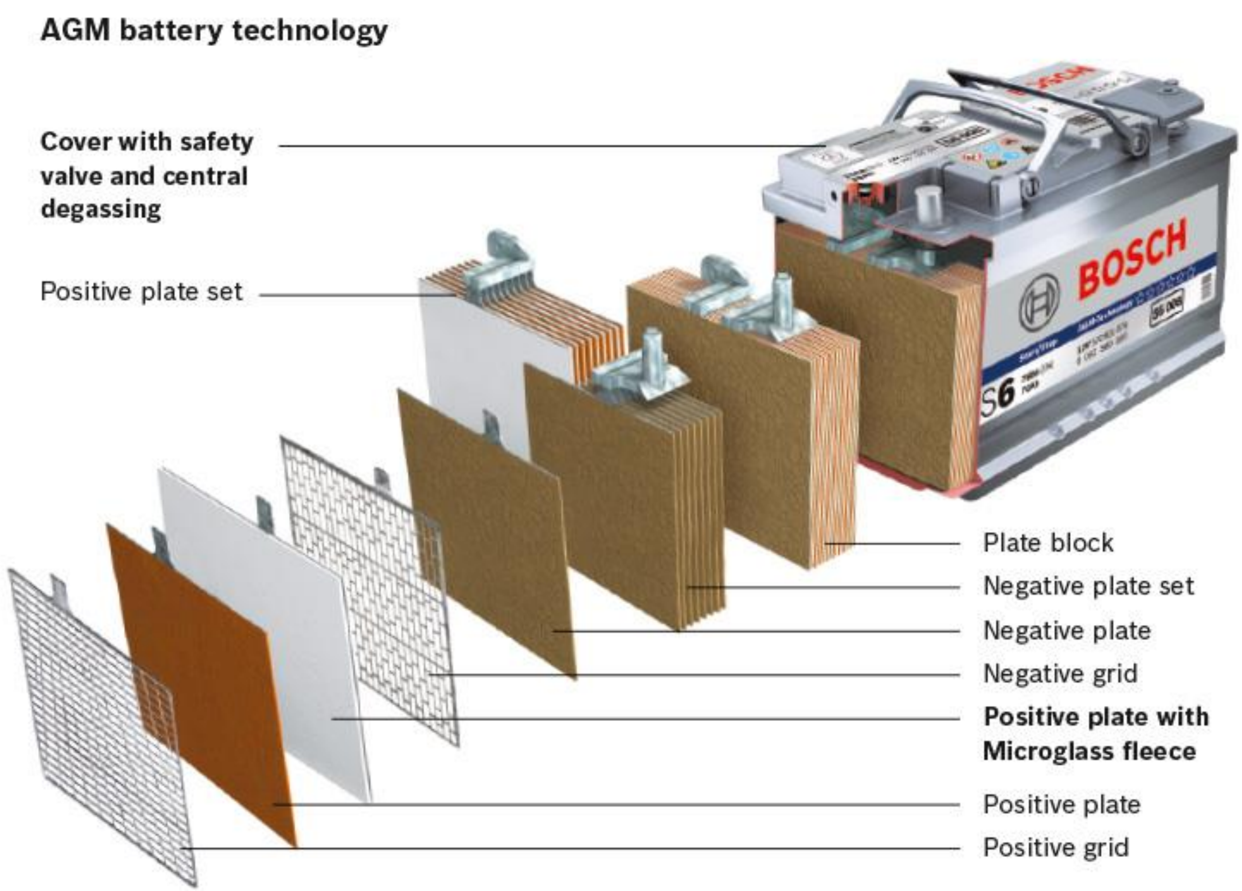
Specific energy	33–42 Wh/kg
Energy density	60–110 Wh/L
Specific power	180 W/kg
Charge/discharge efficiency	50–95%
Energy/consumer-price	7 (sld) to 18 (fld) Wh/US$
Self-discharge rate	3–20%/month
Cycle durability	<350 cycles
Nominal cell voltage	2.1 V
Charge temperature interval	Min. −35 °C, max. 45 °C

Electrochemical – Lead Acid Battery, Large Format Versions

- Modified design to improve storage capacity and reduce maintenance requirements; Known as **deep cycling batteries**; Also known as **Valve-regulated lead-acid (VRLA)** batteries
- Two types: gel-cells and absorbed glass-mat (AGM);
- VRLA cells have their acid electrolyte solution immobilized, either by soaking a fiberglass mat in it (hence: glass-mat batteries), or by turning the liquid into a paste-like gel by the addition of silica and other gelling agents (hence: gel batteries).

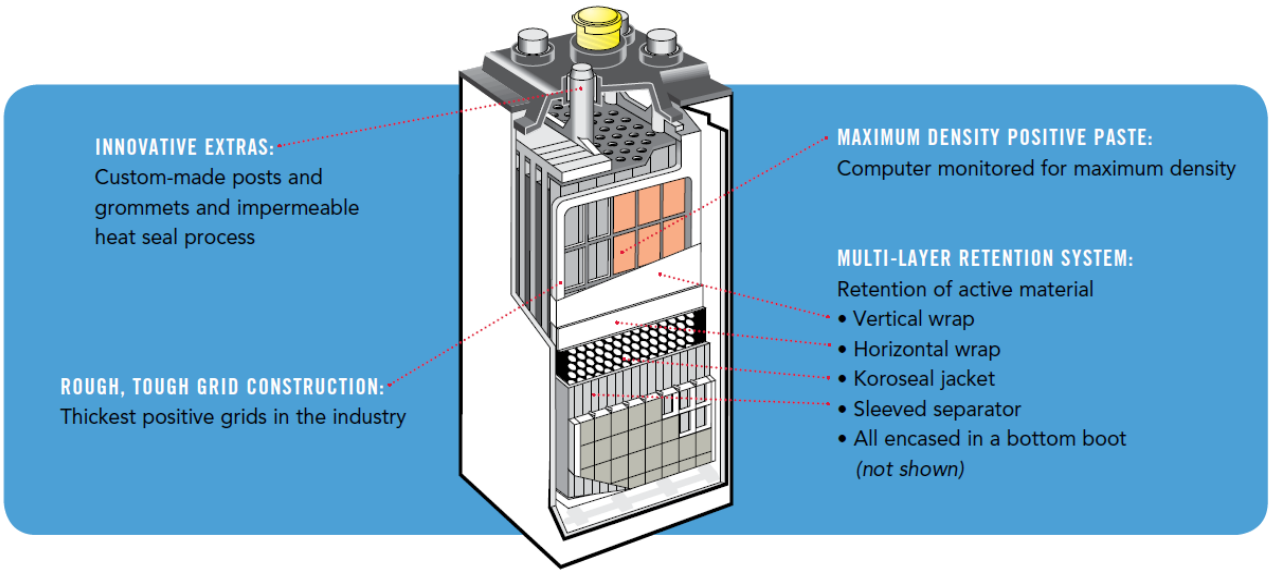
Electrochemical – Valve Regulated Type (VRLA)

- Need less maintenance but need valve regulation



Electrochemical – Deep Cycling Type

- Main difference: have thicker plates that deliver less peak current, but can withstand frequent discharging
- Can be used as automotive battery as they are designed to deliver short, high-current bursts for cranking the engine, thus frequently discharging only a small part of their capacity.

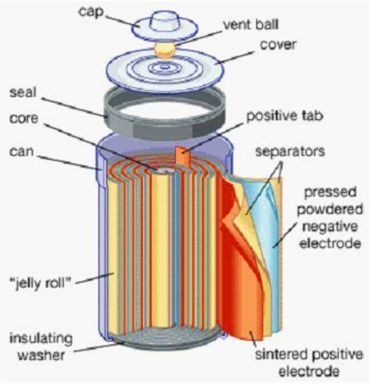


Electrochemical – Nickel-Cadmium Battery Introduction

- A familiar technology used in consumer appliances before replaced by NiMH battery cells.
- Have been available as wet-type large format versions used successfully in standby power, UPS, aircrafts and other micro-grid applications.
- Ni-Cd batteries have higher energy densities, higher power densities, longer cycle life and better performance at low temperatures compared to lead-acid batteries.
- A major concern is the toxic nature of cadmium, which requires careful disposal and recycling

Electrochemical – Nickel-Cadmium Battery Typical Values

Specific energy	40–60 W·h/kg
Energy density	50–150 W·h/L
Specific power	150 W/kg
Charge/discharge efficiency	70–90%
Self-discharge rate	10%/month
Cycle durability	2,000 cycles
Nominal cell voltage	1.2 V



Electrochemical – Lithium Ion Battery

- Lithium-ion battery uses an intercalated lithium compound as electrode material.
- Intercalation is the reversible inclusion or insertion of ions into compounds waith layered structures.
- Can be dangerous under some conditions since they contain flammable electrolyte and are also kept pressurized.

Electrochemical – Lithium Ion Battery Typical Values

Specific energy	100–265 W·h/kg (0.36–0.875 MJ/kg)
Energy density	250–693 W·h/L (0.90–2.43 MJ/L)
Specific power	~250-~340 W/kg
Charge/discharge efficiency	80–90%
Energy/consumer-price	2.5 W·h/US$
Self-discharge rate	2% per month
Cycle durability	400–1200 cycles
Nominal cell voltage	NMC 3.6 / 3.85 V, LiFePO4 3.2 V

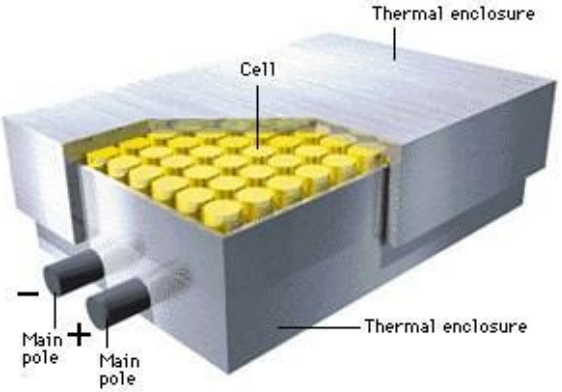
Electrochemical – Lithium Ion Battery Types

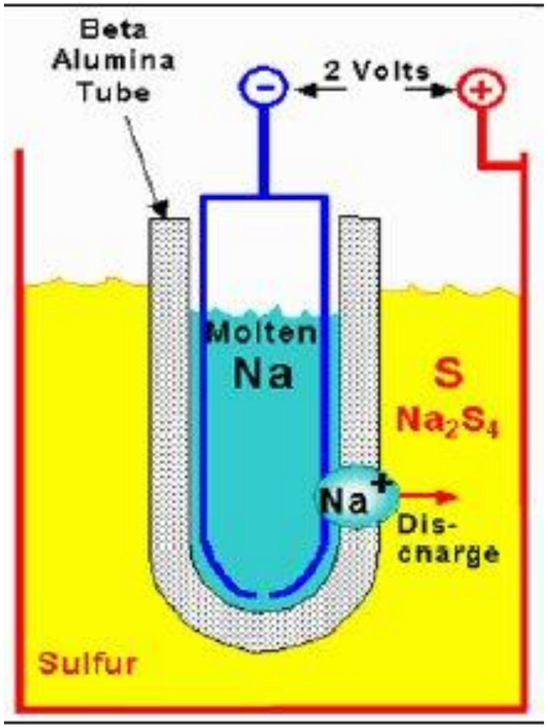
Type	Brief Description
LiBs, $LiCoO_2$	High energy density but present safety risks when damaged.
$LiFePO_4$, LMO, NMC	Lower energy density, longer lives and inherent safety. Used for electric tools and medical equipment. NMC for automative applications.
NCA, LTO	Used for niche applications
LiS	Highest performance to weight ratio

Lithium ion technology area is very research intensive at present, with many new variants being reported every week. Few will be commercially successful.

Electrochemical – Sodium Sulphur Battery

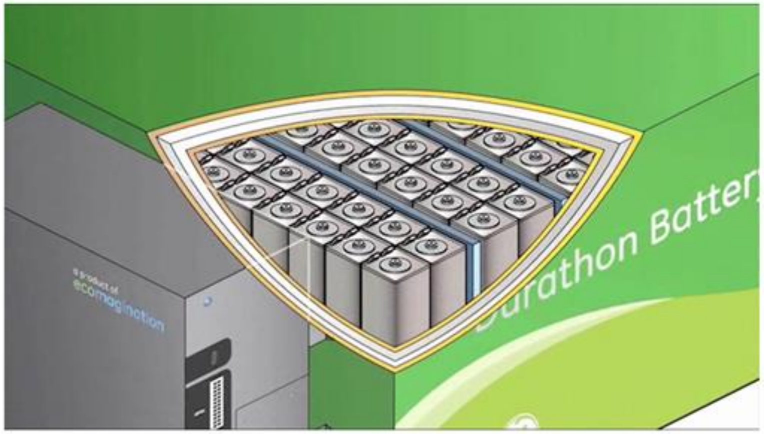
- A molten-salt battery using liquid sodium (Na) and sulfur (S).
- High energy density, high charge/discharge (89–92%) efficiency and long cycle life,
- High operating temperatures of 300 to 350°C and corrosive nature of the sodium polysulfides
- Suitable for large-scale stationary applications such as grid energy storage.





Electrochemical – Sodium Sulphur Battery

Japan NaS Battery



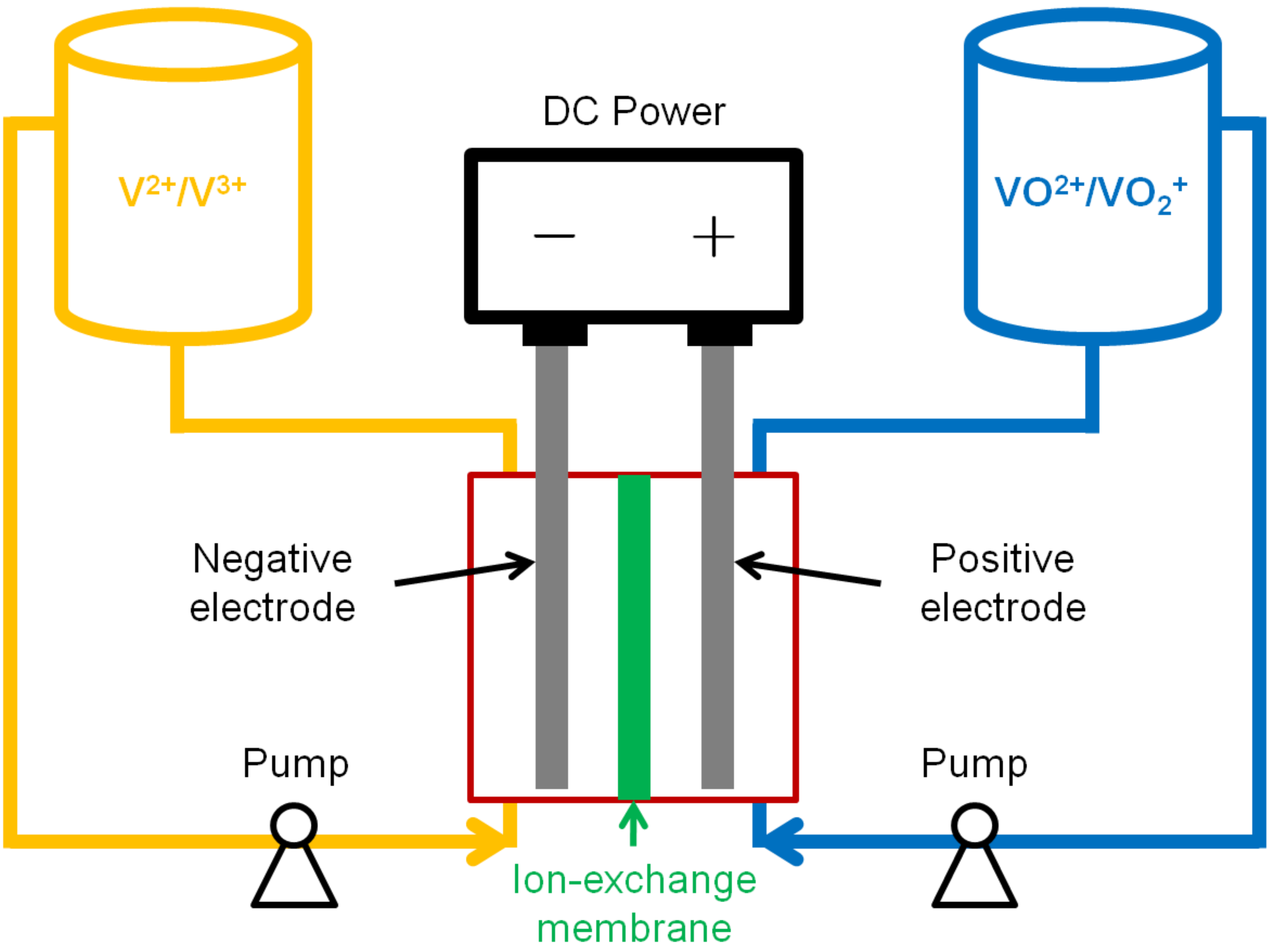
GE Durathon Battery

Electrochemical – Flow Battery Introduction

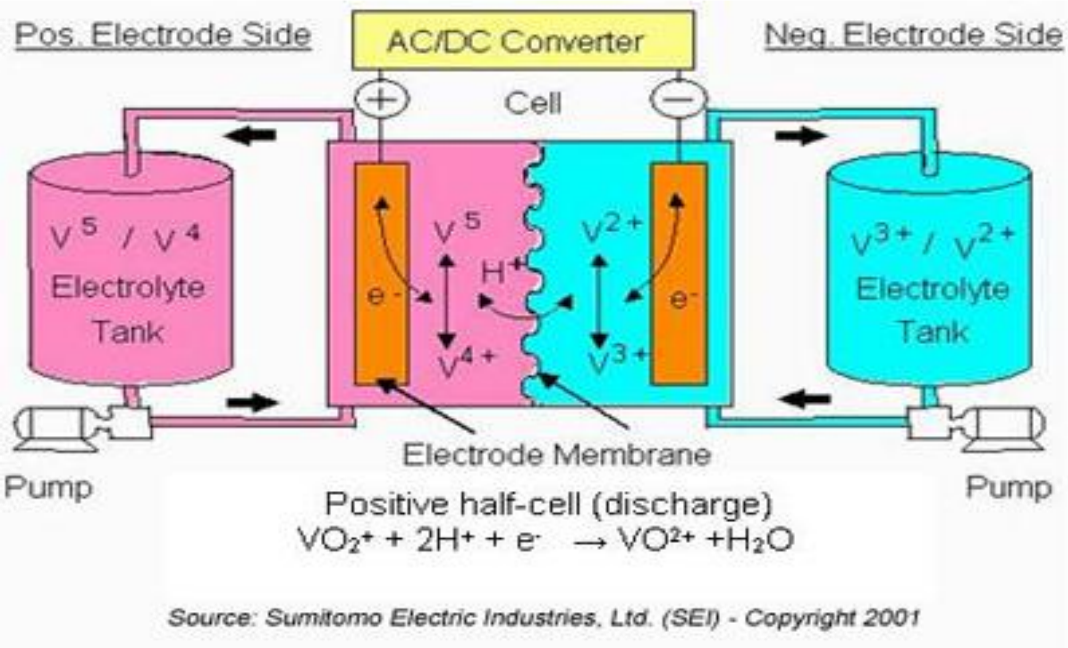
- 3 main types: Vanadium Redox (VR), Polysulphide Bromide & Zinc Bromine; Operates in a similar fashion
- Vanadium Redox is successfully commercialized

Vanadium Redox	Polysulphide Bromide	Zinc Bromide
Redox Type; Versatile energy storage. Used for every energy storage requirement (UPS, load levelling, peak-shaving, telecommunications, electric utilities and integrating renewable resources	Redox Type; fast response time Used for all energy storage requirements (load levelling, peak shaving, and integration of renewable resources)	Hybrid type; high energy density and relatively light in comparison to other batteries, Used in the renewable energy backup for smoothing the output fluctuation and providing frequency control

Electrochemical – Flow Battery



Electrochemical – Flow Battery



Electrochemical – Flow Battery Introduction

- Energy is stored in liquid electrolyte which flows through a reaction chamber,
- In redox flow batteries, two chemical components are dissolved in liquids and separated by a membrane. Ion exchange occurs through the membrane and provides flow of electric current.
- Energy available is related to the electrolyte volume (amount of liquid electrolyte) and the power to the surface area of the electrodes.

Electrochemical – Vanadium Redox Flow Battery Typical Values

Specific energy	10–20 Wh/kg (36–72 J/g)
Energy density	15–25 Wh/L (54–65 kJ/L)
Charge/discharge efficiency	75–80%<.
Time durability	20-30 years
Cycle durability	>100,000 cycles
Nominal cell voltage	1.15–1.55 V

Chemical Storage – Hydrogen

- Hydrogen can be generated by electrolysis and stored in compressed or liquefied form;
- Stored hydrogen can be converted back to electricity by fuel cells;
- Hydrogen has a high energy density by weight but has a low energy density by volume when not highly compressed or liquefied.
- Hydrogen can also be converted directly to mechanical power in vehicles by combustion engines without conversion to electricity.

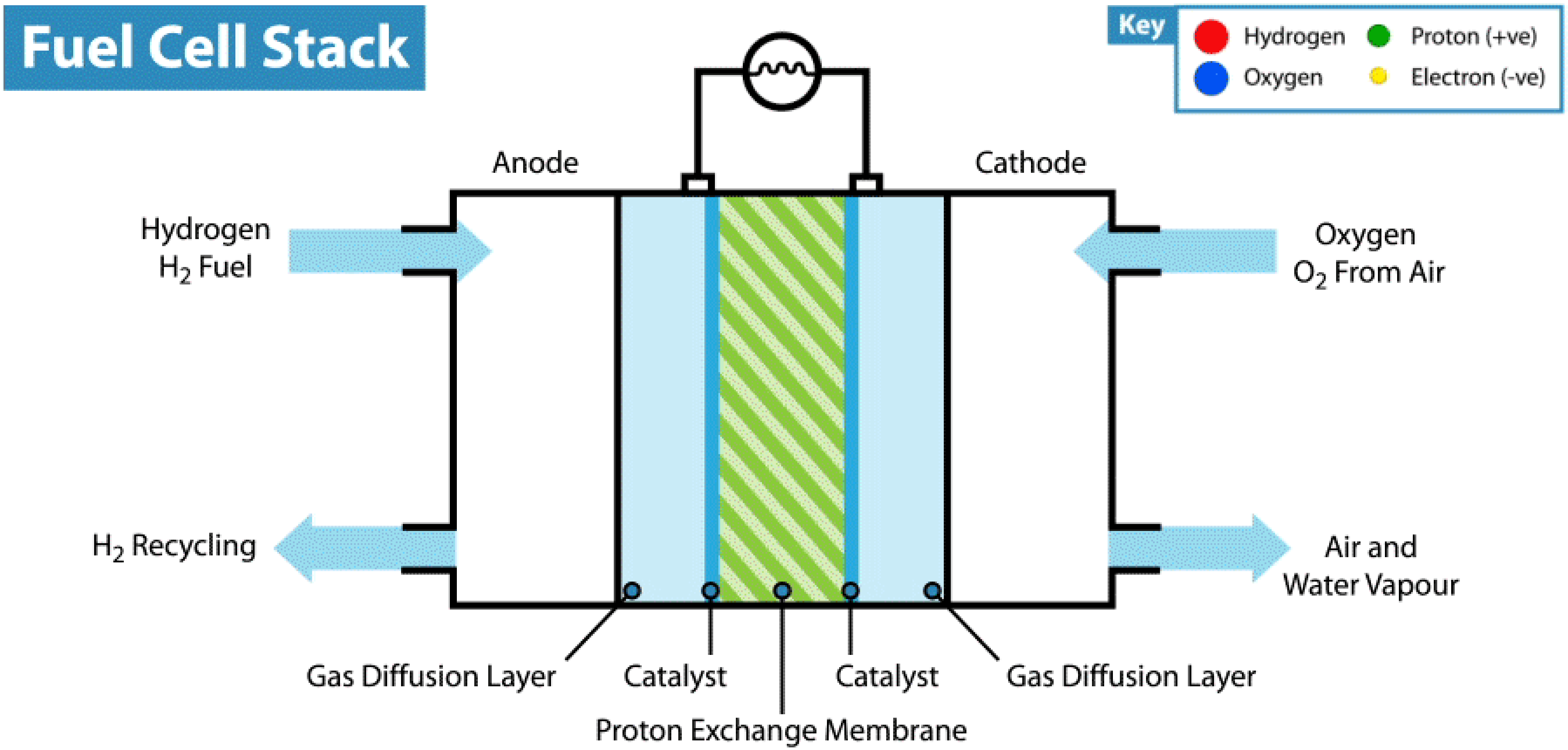
Chemical Storage – Hydrogen

FILE PHOTO - The Toyota Mirai, an hydrogen fuel cell vehicle, is displayed on media day at the Paris auto show, in Paris, France, September 29, 2016. REUTERS/Benoit Tessier/File Photo

OHIO STATE UNIVERSITY

Ohio State University added a single hydrogen fuel cell bus to its fleet in early 2017. It's on loan from Stark Area Regional Transit Authority in Canton.

Chemical Storage – Hydrogen and Fuel Cells

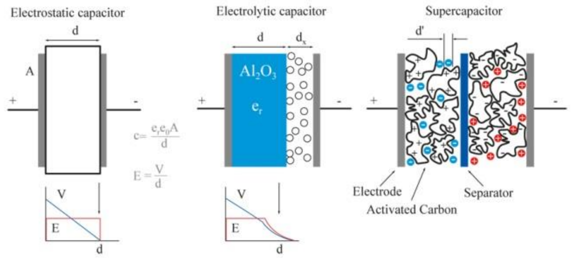


Chemical Storage – Hydrogen and Fuel Cells

- A fuel cell converts stored chemical energy directly into electrical energy
- In this case, hydrogen is passed over the anode (negative) and oxygen is passed over the cathode (positive), causing hydrogen ions and electrons to form at the anode
- When the electrons flow through an external circuit to produce electricity, whilst the hydrogen ions pass from the anode to the cathode and form water molecules
- Various types of fuel cells exist, such as solid-oxide fuel cell and permeable membrane fuel cell.

Electrical Storage – Electro-Static Devices

- Electro-Static Device also called Supercapacitors or Ultracapacitors
- It consist of two parallel plates that are separated by dielectric insulator . The plates hold opposite charges which induces an electric field in which energy is stored
- Due to its fast charge and discharge ability, combined with its extremely long life of approx. $1x10^6$ cycle, it is made to replace small-scale power quality application.



Electrical Storage – Electro-Static Devices

Function	Supercapacitor	Lithium-ion (general)
Charge time	1–10 seconds	10–60 minutes
Cycle life	1 million or 30,000h	500 and higher
Cell voltage	2.3 to 2.75V	3.6V nominal
Specific energy (Wh/kg)	5 (typical)	120–240
Specific power (W/kg)	Up to 10,000	1,000–3,000
Cost per kWh	$10,000 (typical)	$250–$1,000 (large system)
Service life (industrial)	10-15 years	5 to 10 years
Charge temperature	–40 to 65°C (–40 to 149°F)	0 to 45°C (32°to 113°F)
Discharge temperature	–40 to 65°C (–40 to 149°F)	–20 to 60°C (–4 to 140°F)

Table 3: Performance comparison between supercapacitor and Li-ion.
Source: Maxwell Technologies, Inc.

Complementary advantages - hybrid ESS

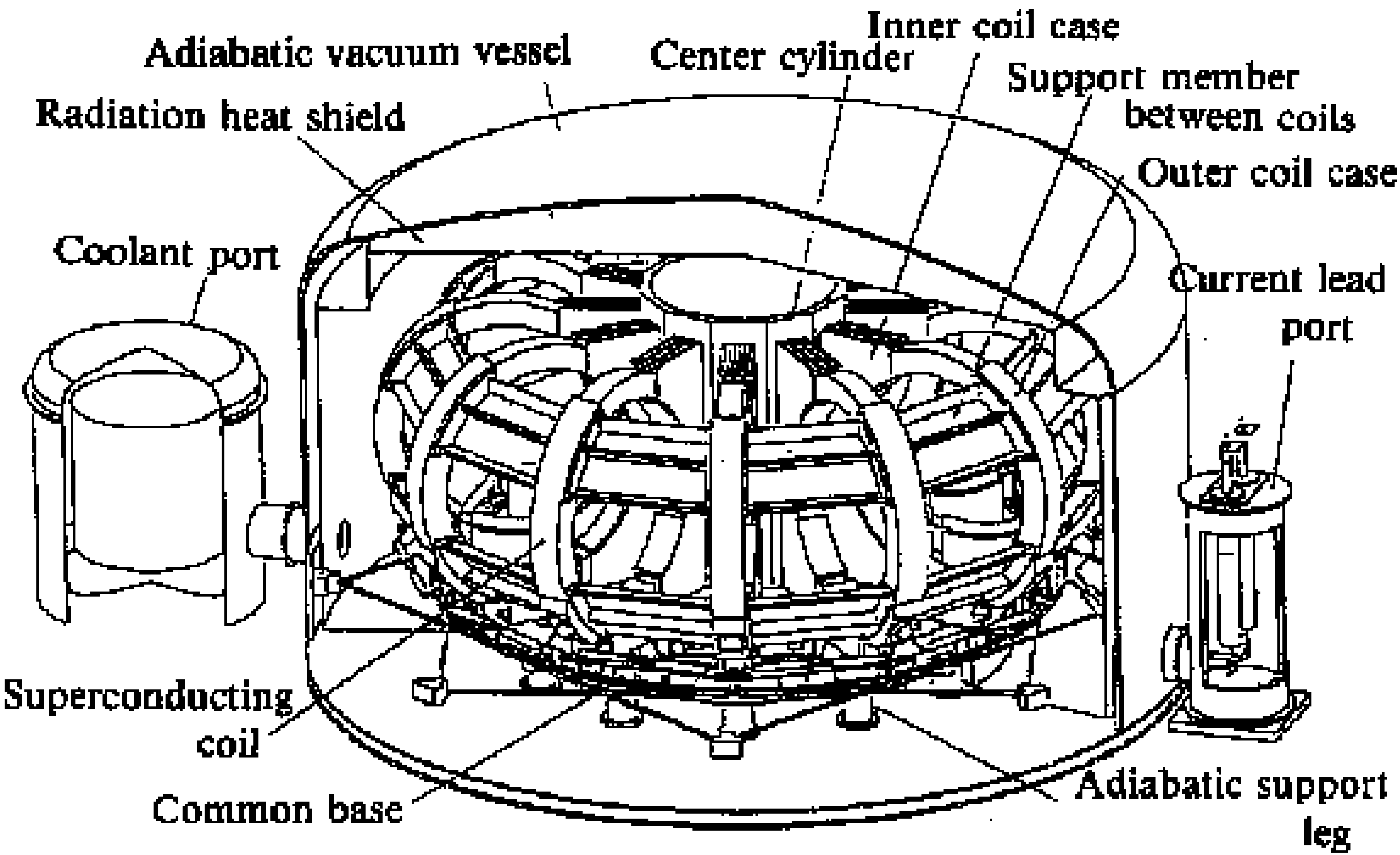
Electrical Storage – Electro-Static Devices

- Not a battery replacement for long-term energy storage. (>60s)
- Supercapacitors are ideal when a quick charge is needed to fill a short-term power need
- Combining the two into a hybrid battery satisfies both needs and reduces battery stress, which reflects in a longer service life.

Electrical Storage – Magnetic Devices

- A SMES unit consists of a large superconducting coil, maintained at cryogenic temperature by a cryostat containing liquid helium or nitrogen.
- Energy is stored in the magnetic field created by the flow of direct current in the coil wire.
- Two types of superconductors: 1) low temperature superconductors (range from 0K to 7.2K) 2) high temperature superconductors (range from 10K to 150K)
- High power capacity and instantaneous discharge rates. For industrial power quality market

Electrical Storage – Magnetic Devices



My trip to ITER (International Thermonuclear Experimental Reactor), France, 2022.

https://www.iter.org/


Powerful magnets to maintain the shape
and stability of ITER plasma
Four Poloidal Field coils (PF 2-5)
to be manufactured on-site
because of their weight
and size
The largest
PF coil to be
around 25 m
Weights range
between
200 T and 400 T
CONDUCTORS
• Made of niobium-titanium (Nb-Ti)
• ITER uses "cable-in-conduit conductors"
superconducting strands mixed with coppe
cabled together and contained in a steel ja
• Cooled by liquid helium at 4 K (-269 °C)
to become superconducting


FUSION FOR ENERGY
BRINGING THE POWER OF THE SUN TO EARTH
iter
CMU 40t / 30t
NFM
WATER


FUSION FOR ENERGY
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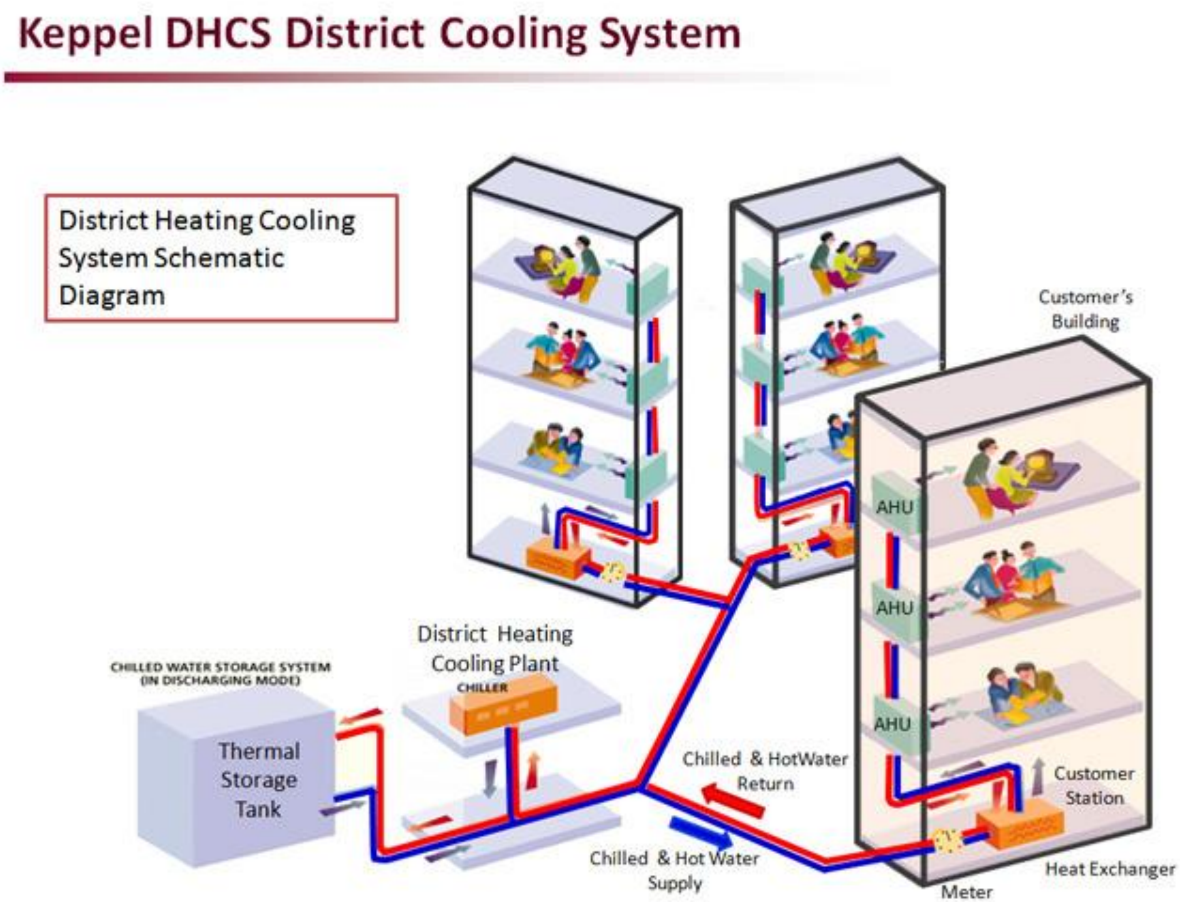
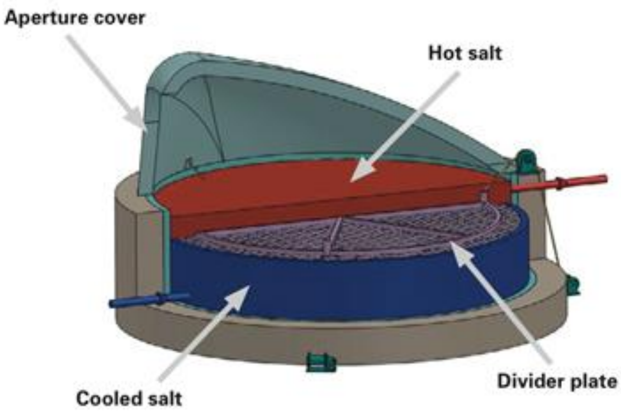
ls will be cooled in a
at at -196°C
s will be performed in
ee stages:
before cool-down
• at cryogenic temperature
• after warm-up of the
PF coil
Three Cryostats to test the
different PF coils
• Cryostat A (36 t, 12m
diameter) to test PF6
• Cryostat B (57 t, 20m

Thermal Electric ESS

- Thermal ESS store available heat by various means in insulated containers for subsequent use in heating or cooling applications. These systems may or may not involve conversion from or to electricity.
- For example, solar energy falling on heat pipes may be converted to heat to be stored in water tanks, to be used for heating applications.
- Another present application is the storage of chilled water for building and district cooling.
- A near-future application may the thermal storage using molten salt which can drive steam turbines to generate electricity.

Thermal Electric ESS





World's biggest underground district cooling network now at Marina Bay

BY LIYANA OTHMAN

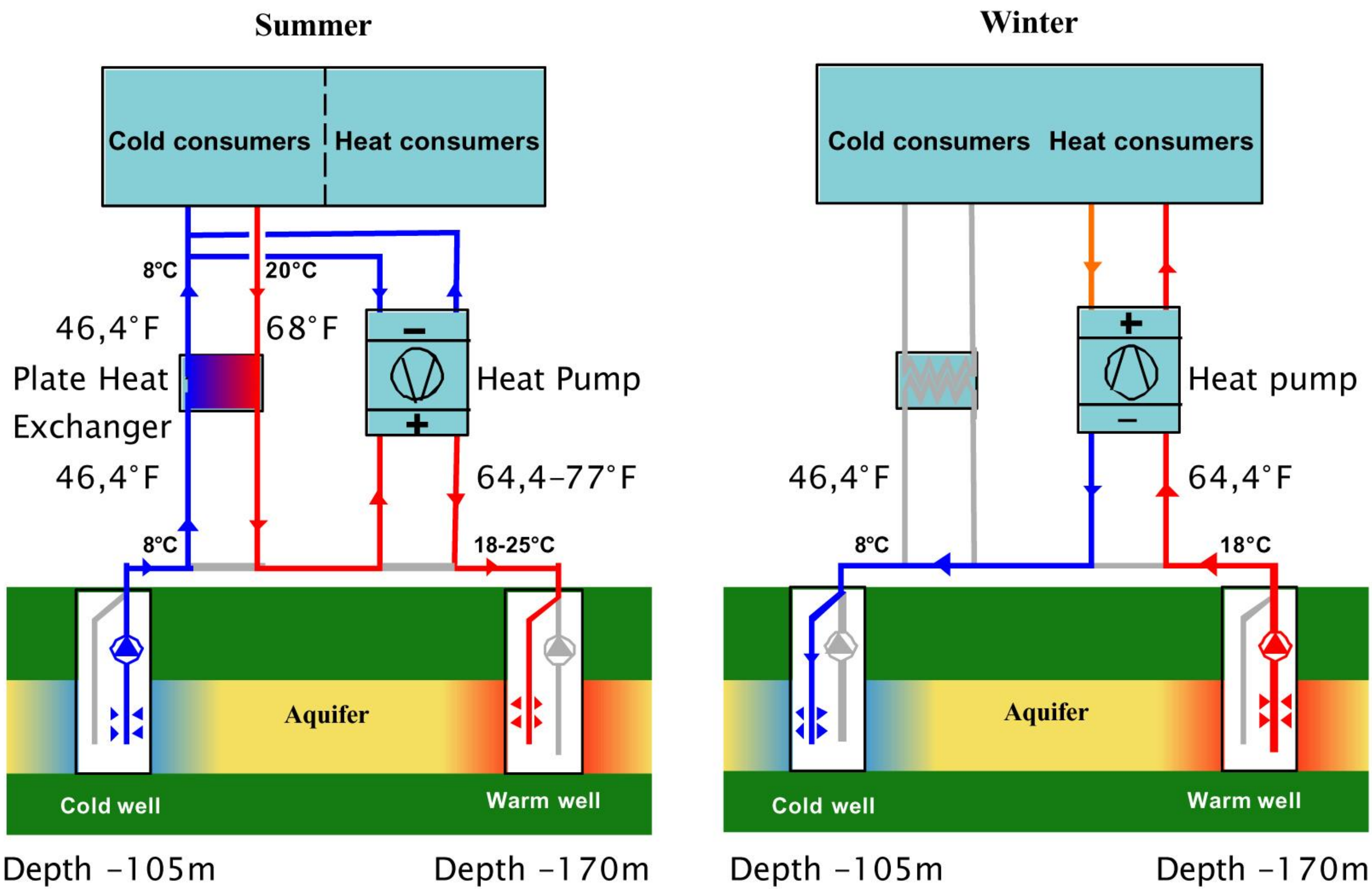
Published March 3, 2016
Updated March 3, 2016

https://www.todayonline.com/singapore/plant-underground-district-cooling-network-marina-bay-commissioned

Marina Bay district cooling network to be expanded

https://www.spgroup.com.sg/about-us/media-resources/energy-hub/sustainability/marina-bay-district-cooling-network-to-be-expanded-with-new-partnerships

Thermal Electric ESS



ESS Technologies – Summary

- Large grid energy storage – Pumped Hydro and Compressed Air; Economically viable solutions but uncommon
- Flywheel is used for niche application requiring very high power, long life and fast response
- Electro-chemical batteries are difficult to be scaled up because of costs and limited charge-discharge cycles.

ESS Technologies – Summary

- Lead acid and Ni-Cd have been used successfully for small microgrid applications
- Lithium ion have issues of high costs and safety
- Flow batteries and sodium sulphur have been experimented on, but yet to achieve market acceptance.

ESS Technologies – Summary

- Chemical technologies such as power-to-gas, hydrogen and fuel cells are not commercially viable yet and require substantial infrastructure investment.
- Electro-static supercapacitors are very costly and are used only to hybridize cheaper energy storage devices to achieve higher power capabilities.
- Magnetic and thermal energy storage technologies are still very experimental.

ESS Technologies – Summary

- Different types of ESS technologies suits different applications. Some applications require higher percentage of certain factors such as safety, cost, power density or energy density.

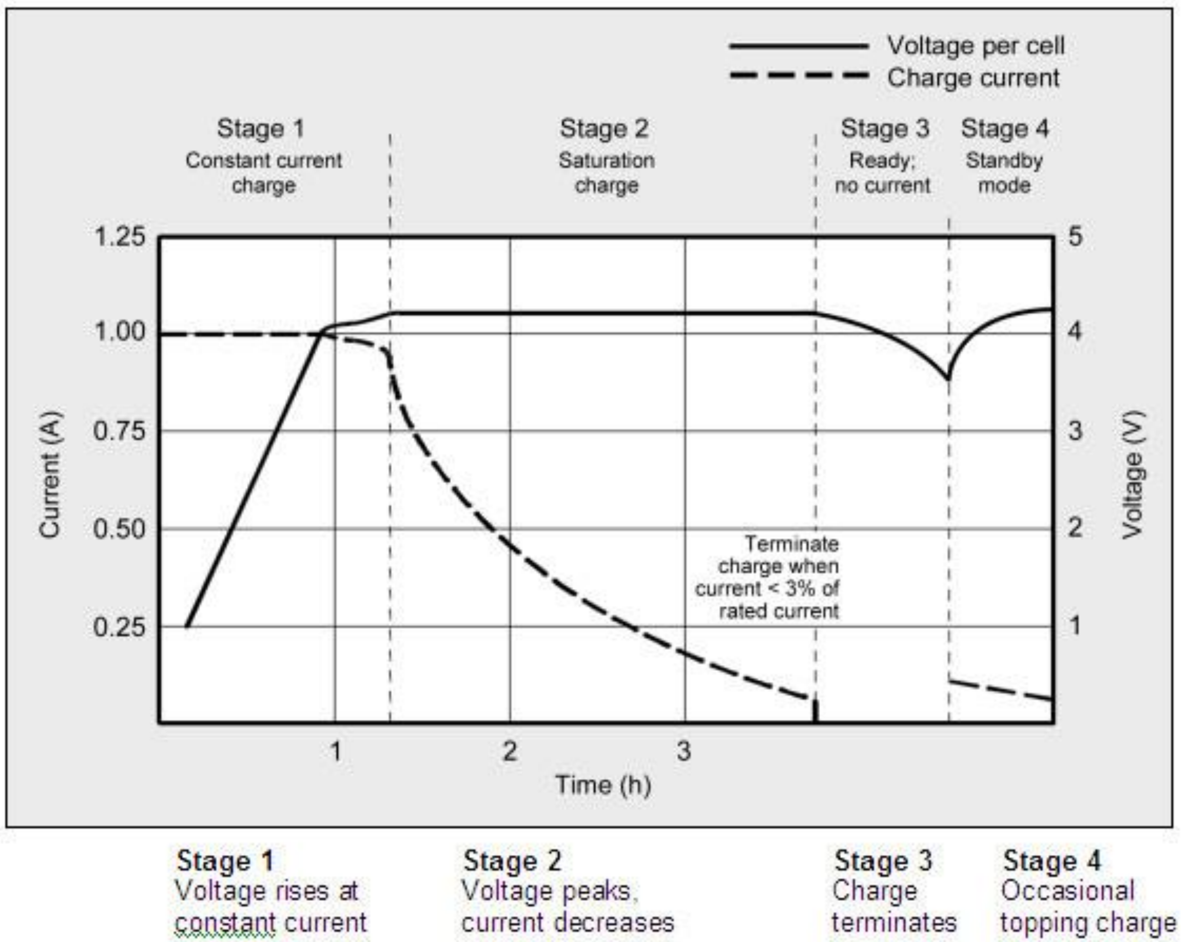
Table 5: Energy, power, and cost comparison of BES, SCES, FES, and SMES [42, 43, 53, 57]

Storage type	Power density (W/kg)	Power density (MW/m^3)	Power cost ($/kW)	Energy density (Wh/kg)	Energy density (kWh/m^3)	Energy cost ($/kWh)	Cycle efficiency (%)	Life cycles (-)
Li-ion	150-500	0.4-2	686-4000	70-200	200-600	240-2500	90-97	up to 20000
SCES	1000-10000	0.4-10	100-400	0.5-5	4-10	500-15000	90-97	50000-1000000
FES	500-4000	1-2.5	150-400	10-50	20-100	1000-14000	90-95	20000+
SMES	500-2000	1-4	200-500	1-10	0.2-2.5	1000-10000	95-98	20000-100000

Health Monitoring of Li-ion Batteries

1. Operation process of Lithium-ion (Li-ion) batteries: Charging and discharging profiles
2. Aging mechanism of Li-ion batteries: What causes Li-ion to die?
3. State of health (SOH) estimation
4. Health management: How to prolong the life of Li-ion batteries

Charging Profiles of Li-ion



Charge stages of lithium-ion. Li-ion is fully charged when the current drops to a set level. In lieu of trickle charge, some chargers apply a topping charge when the voltage drops.

Charging Profiles of Li-ion

- The advised charge rate of an Energy Cell is between **0.5C and 1C**; the complete charge time is about 2–3 hours.
- Manufacturers of these cells recommend charging at 0.8C or less to prolong battery life; however, most Power Cells can take a higher charge C-rate with little stress.
- Charge efficiency is about 99 percent and the cell remains cool during charge.
- Some Li-ion packs may experience a temperature rise of about 5ºC (9ºF) when reaching full charge. This could be due to the protection circuit and/or elevated internal resistance. Discontinue using the battery or charger if the temperature rises more than 10ºC (18ºF) under moderate charging speeds.

Charging Profiles of Li-ion

- Full charge occurs when the battery reaches the voltage threshold and the current **drops to 3 percent of the rated current**. A battery is also considered fully charged if the current levels off and cannot go down further. Elevated self-discharge might be the cause of this condition.
- Increasing the charge current does not hasten the full-charge state by much. Although the battery reaches the voltage peak quicker, the saturation charge will take longer accordingly. ***With higher current, Stage 1 is shorter but the saturation during Stage 2 will take longer.*** A high current charge will, however, quickly fill the battery to about 70 percent.

Charging Profiles of Li-ion

- Li-ion does not need to be fully charged as is the case with lead acid, nor is it desirable to do so. ***In fact, it is better not to fully charge because a high voltage stresses the battery.*** Choosing a lower voltage threshold or eliminating the saturation charge altogether, prolongs battery life but this reduces the runtime. Chargers for consumer products go for maximum capacity and cannot be adjusted; extended service life is perceived less important.
- Some lower-cost consumer chargers may use the simplified “charge-and-run” method that charges a lithium-ion battery in one hour or less without going to the Stage 2 saturation charge. “Ready” appears when the battery reaches the voltage threshold at Stage 1. State-of-charge (SoC) at this point is about 85 percent, a level that may be sufficient for many users.

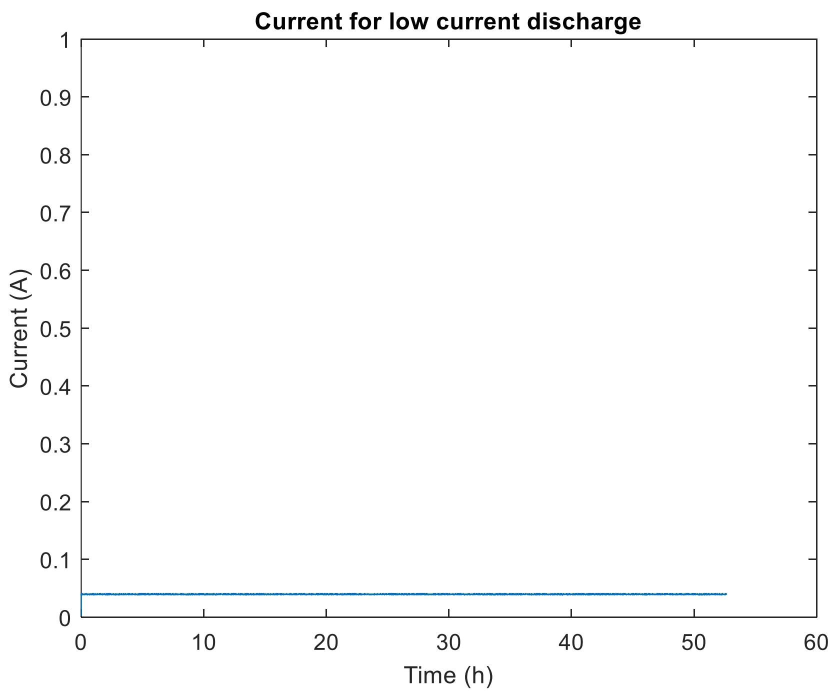
Simple Guidelines for Charging Lithium-based Batteries

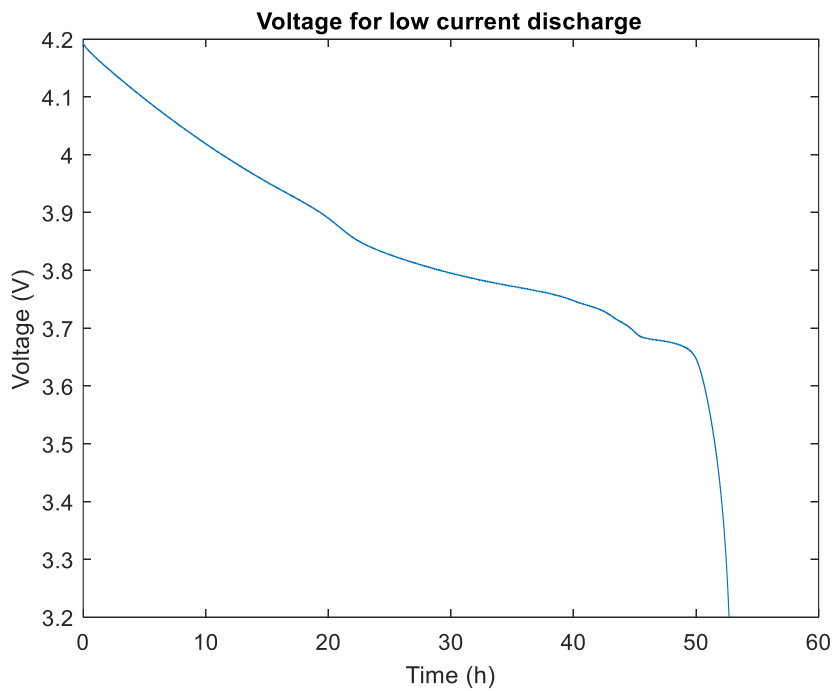
- Turn off the device or disconnect the load on charge to allow the current to drop unhindered during saturation. A parasitic load confuses the charger.
- Charge at a moderate temperature. Do not charge at freezing temperature.
- Lithium-ion does not need to be fully charged; **a partial charge is better**.
- Not all chargers apply a full topping charge and the battery may not be fully charged when the “ready” signal appears; a 100 percent charge on a fuel gauge may be a lie.
- Discontinue using charger and/or battery if the battery gets excessively warm.
- **Apply some charge to an empty battery before storing** (40–50 percent SoC is ideal).

Discharging Profiles of Li-ion

Depth of Discharge

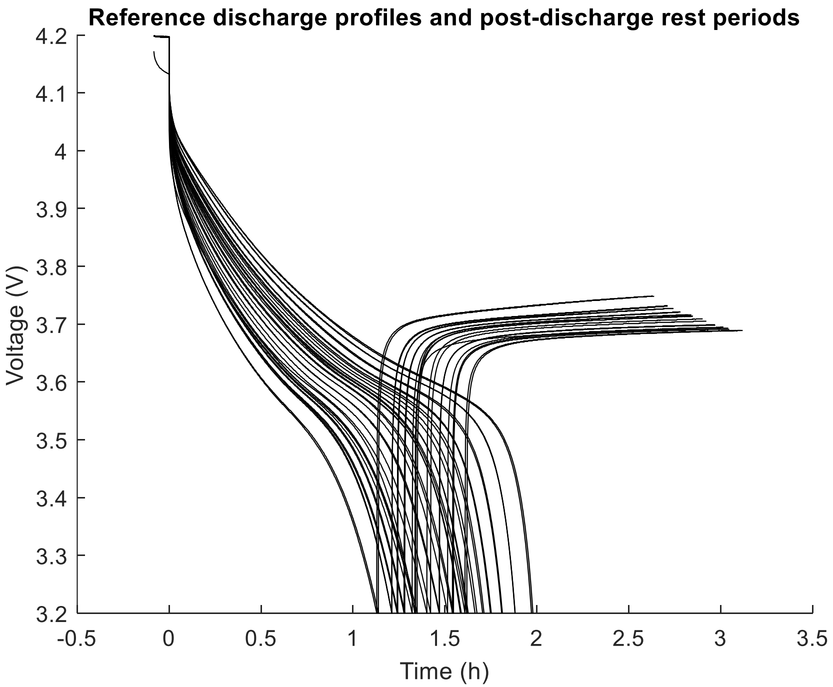
- Lead acid discharges to 1.75V/cell; nickel-based system to 1.0V/cell; and **most Li-ion to 3.0V/cell**. At this level, roughly 95 percent of the energy is spent, and the voltage would drop rapidly if the discharge were to continue. To protect the battery from over-discharging, most devices prevent operation beyond the specified end-of-discharge voltage.

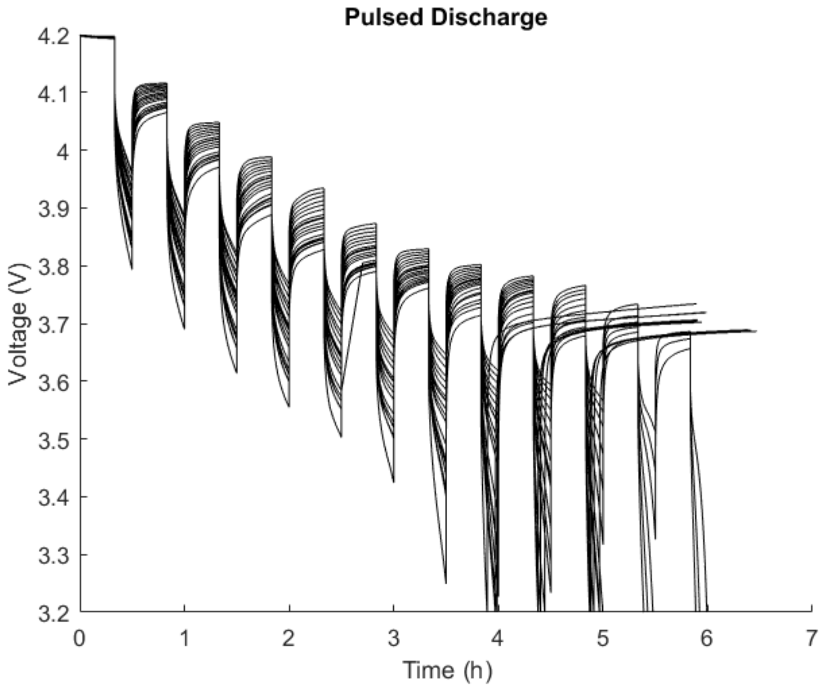




Discharging Profiles of Li-ion

- When removing the load after discharge, **the voltage of a healthy battery gradually recovers and rises towards the nominal voltage.** Differences in the affinity of metals in the electrodes produce this voltage potential even when the battery is empty. A parasitic load or high self-discharge prevents voltage recovery.



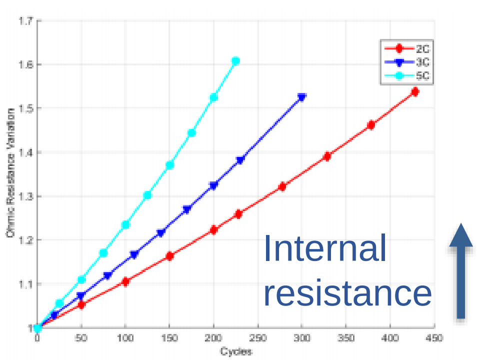


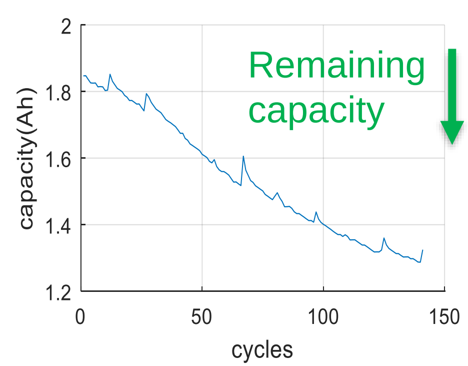
What Causes Li-ion to Die?

The charging/discharging will lead to capacity loss, and when the capacity is below 80% of the original capacity, the battery is considered dead.

Four suspected reasons responsible for capacity loss and the eventual end-of-life of the Li-ion battery :

- Mechanical degradation of electrodes or loss of stack pressure in pouch-type cells. Careful cell design and correct electrolyte additives minimize this cause.
- Growth of solid electrolyte interface (SEI) on the anode. A barrier forms that obstructs the interaction with graphite, resulting in an increase of internal resistance. SEI is seen as a cause for capacity loss in most graphite-based Li-ion when keeping the charge voltage below 3.92V/cell. Electrolyte additives reduce some of the effect.
- Formation of electrolyte oxidation (EO) at the cathode that may lead to a sudden capacity loss. Keeping the cells at a voltage above 4.10V/cell and at an elevated temperature promotes this phenomenon.
- Lithium-plating on the surface of the anode caused by high charging rates.





SOH Estimation

What is the State of Health (SOH) ?

- Capacity quantifies the available energy stored in a fully charged ESS and is often applied to indicate the SOH of ESS.
- The SOH is defined as the ratio of the current practical capacity to the nominal capacity of the ESS as follows:

$$\mathrm{SOH} = \frac{C_{\mathrm{P}}}{C_{\mathrm{N}}} \times 100\%$$

where C_P denotes the current practical capacity and C_N is the nominal capacity of the ESS.

1. Direct assessment
2. Model-based approach
3. Data-driven approach

SOH Estimation Methods

1. Direct assessment

Direct assessment methods are to calculate the capacity or impedance of battery cells based on the direct measurements.

- Coulomb counting

The coulomb counting (CC) method is used in common to estimate SOH. Firstly, the battery is discharged corresponding to the state of charge (SOC) value of 0%. Secondly, SOH is calculated dividing the discharge value by the rated capacity.

- Open circuit voltage

Extensive laboratory tests are conducted to obtain a **relationship between SOH and OCV**. The charging curves at different lifespan of battery is monitored to evaluate the capacity fade and model parameters for predicting SOH.

- Impedance spectroscopy

Impedance spectroscopy uses wide frequency spectrum to determine SOH. The easiest way to estimate SOH with impedance spectroscopy is to compute ECM parameters.

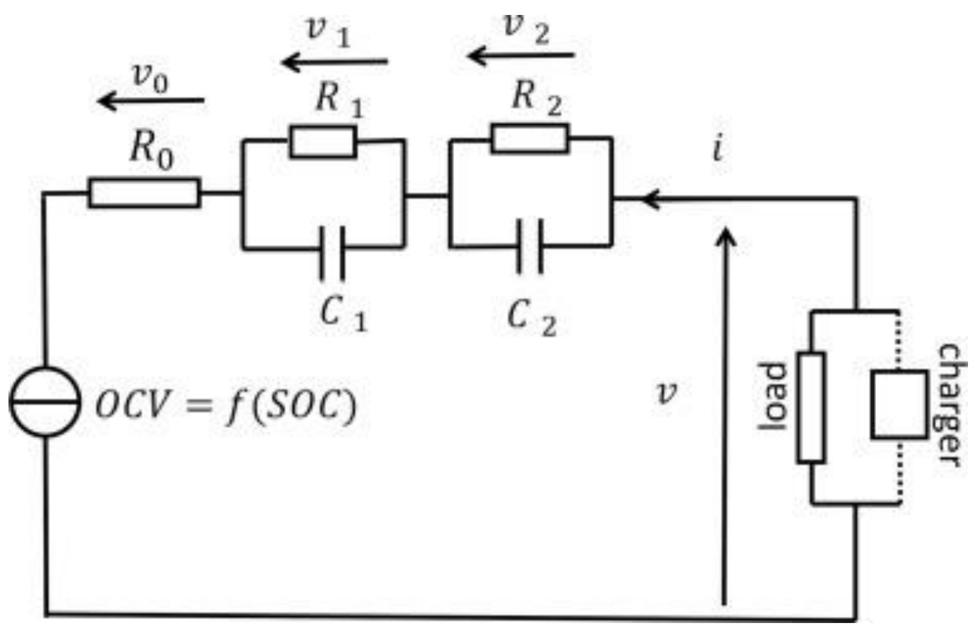
SOH Estimation Methods

2. Model based method

The model-based methods use the electrochemical mechanism or equivalent electrical circuit to emulate the mathematical or stochastic models of battery degradation phenomenon. The capacity or impedance of the battery is one of the model parameters. Health estimation is achieved by identifying the model parameters.

Parameter identification:

- Kalman filter
- Particle filter

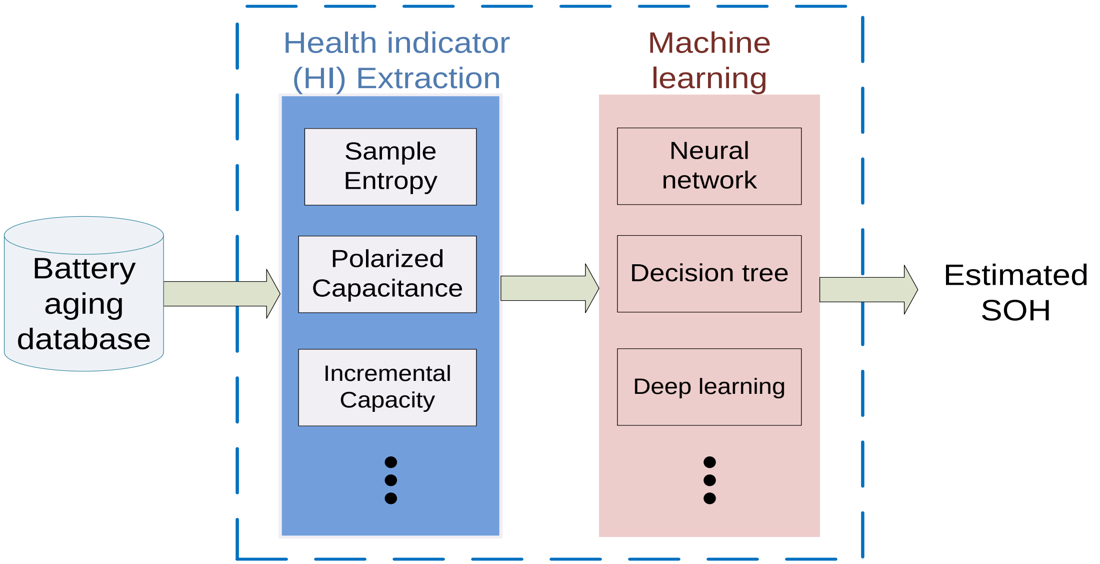


battery equivalent circuit model (ECM)

SOH Estimation Methods

3. Data-driven approach

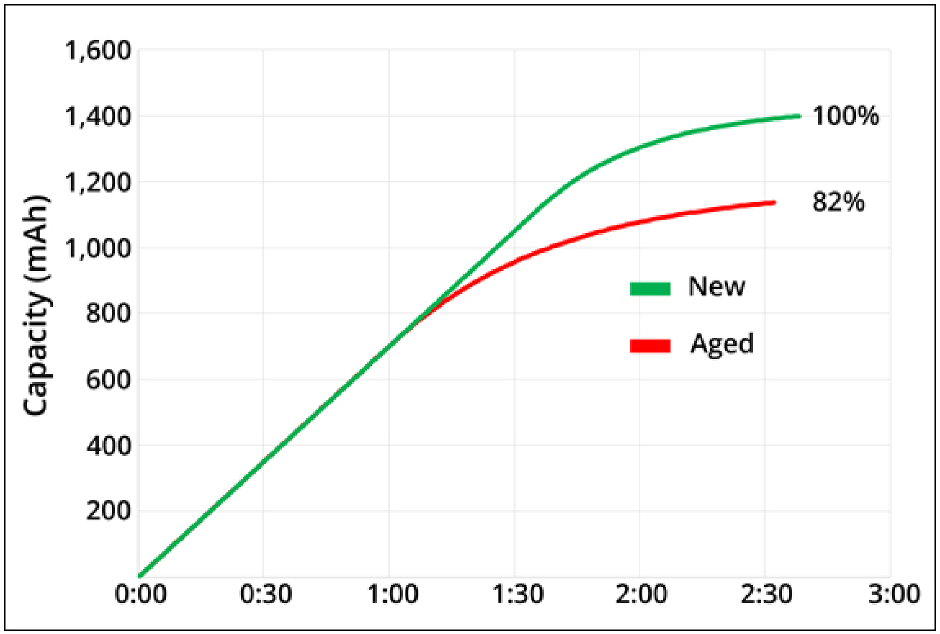
The basic idea of the data-driven method is to extract the mapping relationship knowledge between the health indicator (HI) and the battery SOH from learning a database. Thus, the battery is considered as a black box rather than a practical mathematical model.



B. Gou, Y. Xu*, et al, "State-of-Health Estimation and Remaining-Useful-Life Prediction for Lithium-ion Battery Using A Hybrid Data-driven Method," IEEE Trans. Vehicular Technology, accepted in Aug. 2020.

Health Indicator Extraction

Battery users often ask: “Why does an old Li-ion take so long to charge?”



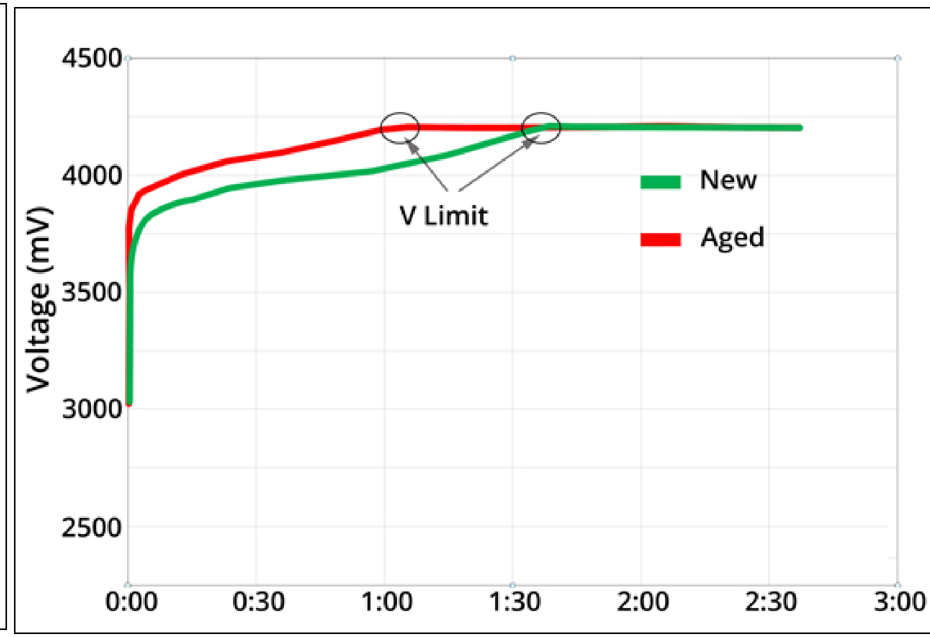


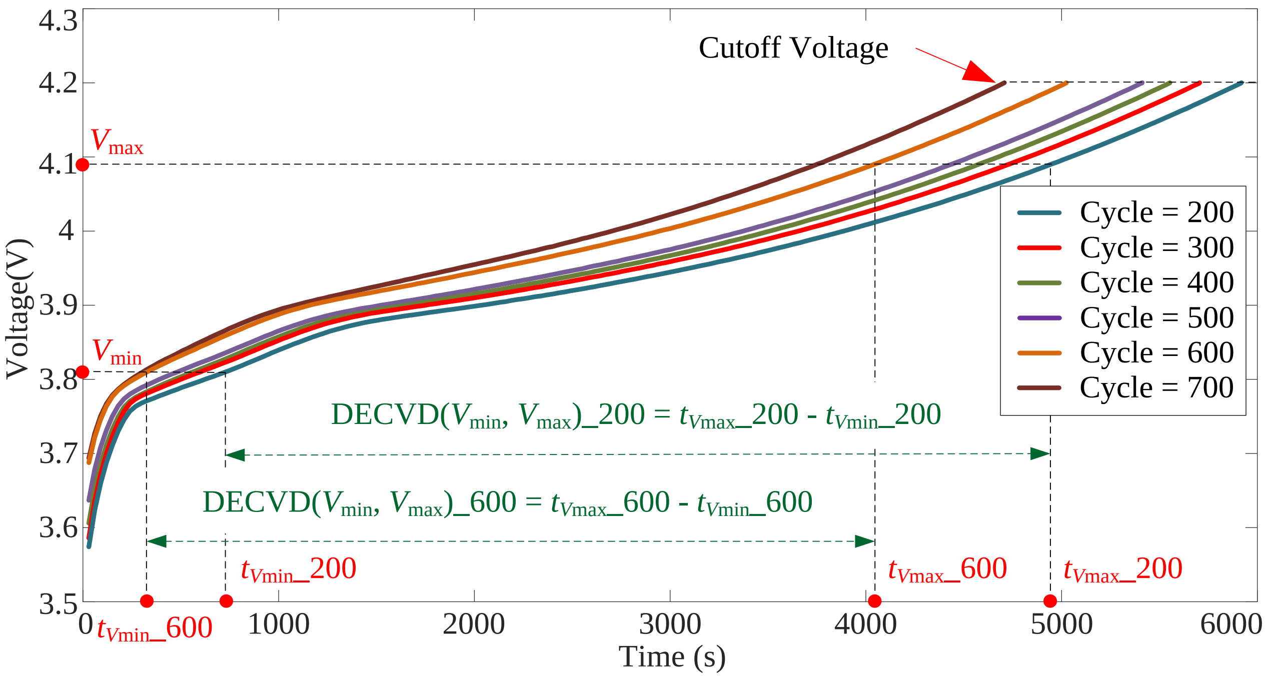
Figure 6: New and aged Li-ion batteries are charged. Both packs take roughly 150 minutes to charge. The new pack charges to 1,400mAh (100%) while the aged one only goes to 1,150mAh (82%).

Figure 7: Observing charge times of a new and aged Li-ion in Stage 1. The new Li-ion takes on full charge for 90 minutes while the aged cell reaches 4.20V/cell in 60 minutes.

W. Liu and Y. Xu, “A Comprehensive Review of Health Indicators of Li-ion Battery for Online State of Health Estimation,” IEEE 3rd Conference on Energy Internet and Energy System Integration (EI2), 2019.

Health Indicator Extraction

As the cycle number increases, the charging time in CC mode exhibits an overall decreasing trend due to the gradually aggravated polarization phenomenon as the battery ages. In other words, the **time duration of equal terminal voltage interval** gradually decreases as the cycle number increases in the CC charging step, and can be used for indicate the battery degradation trend.

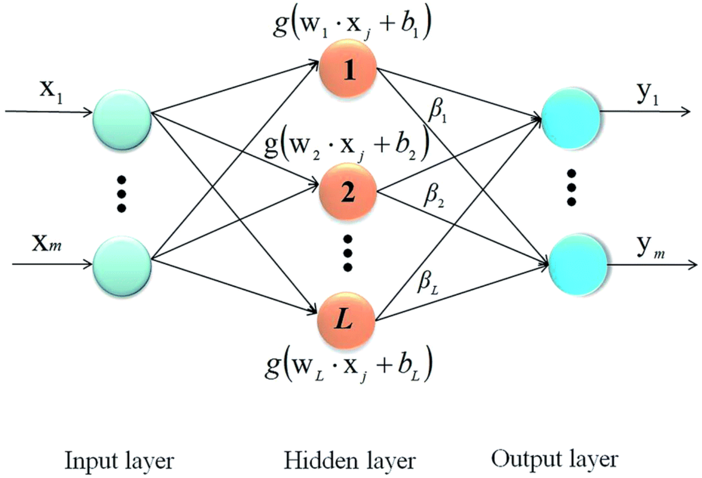


The voltage curves during CC charging step in different aging cycles.

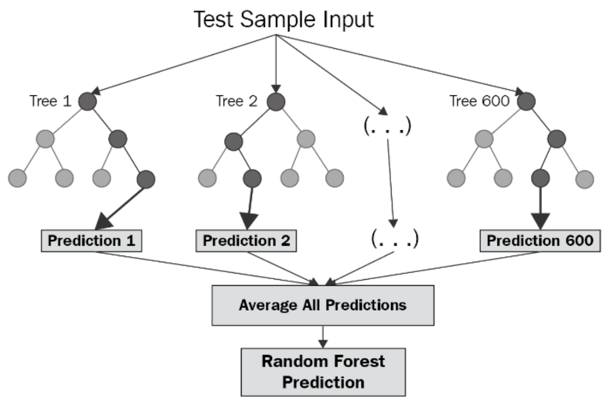
B. Gou, Y. Xu*, et al, "State-of-Health Estimation and Remaining-Useful-Life Prediction for Lithium-ion Battery Using A Hybrid Data-driven Method," IEEE Trans. Vehicular Technology, 2020.

Machine Learning Algorithms

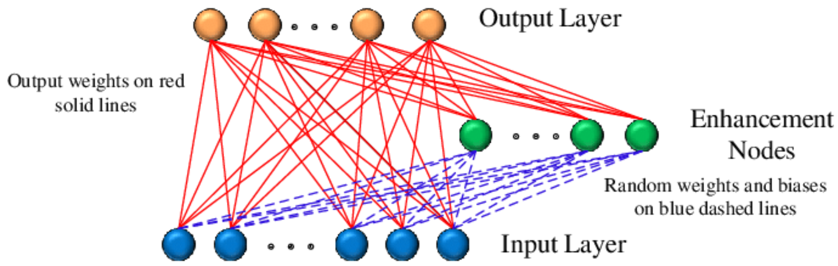
Machine learning algorithm is used for extracting the mapping knowledge relationship between the health indicator and the SOH of battery.



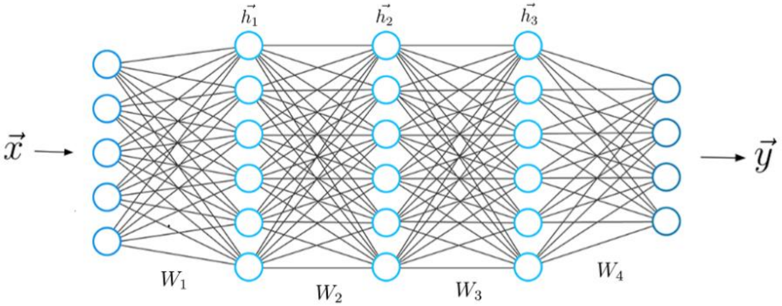
Extreme Learning Machine



Random Forests



Random Vector Functional Link (RVFL) Networks



Deep Learning

Some popular machine learning algorithms.

SOH Estimation Results

The SOH can be accurately estimated with a maximum absolute error of 3%.

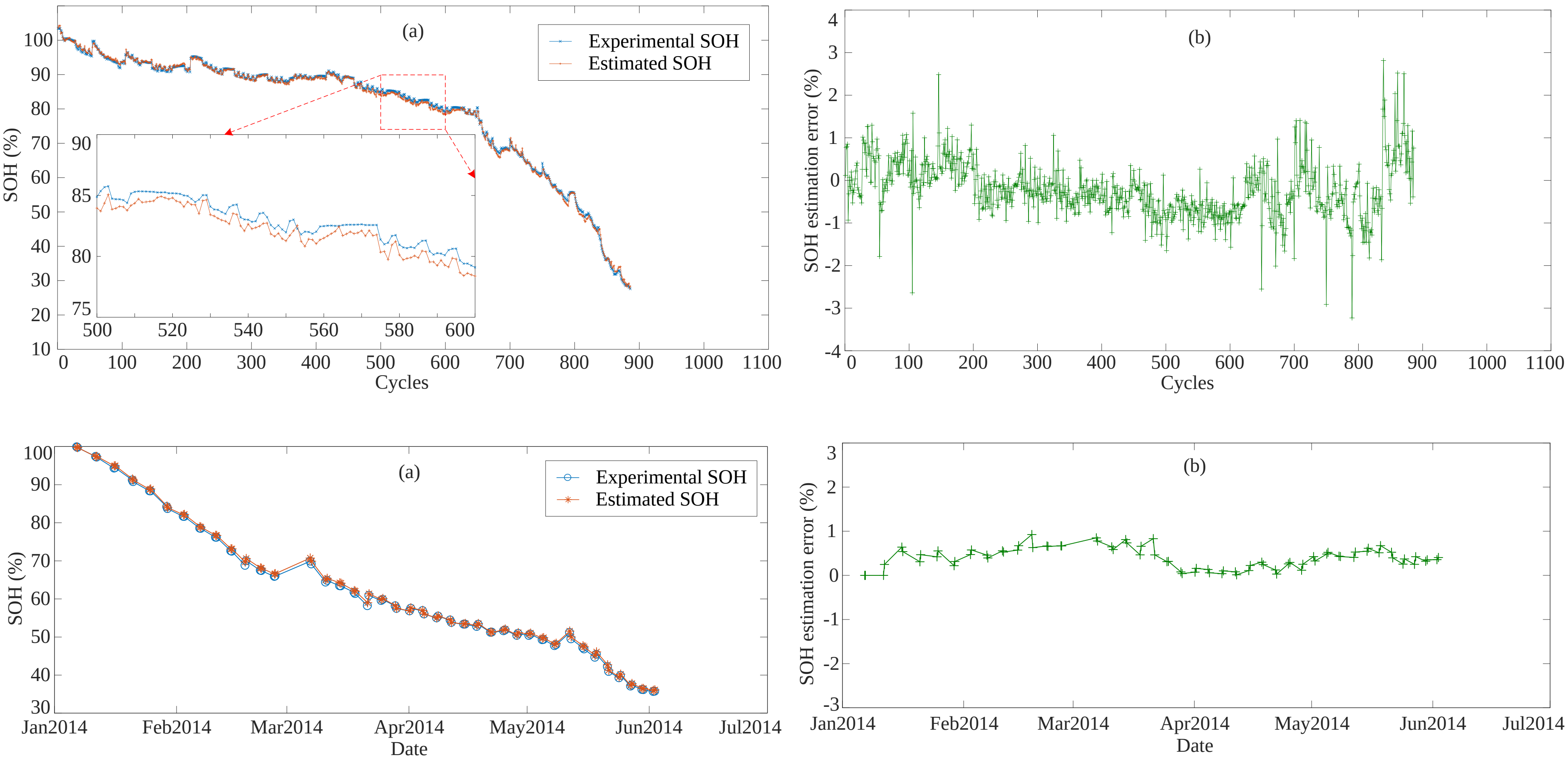
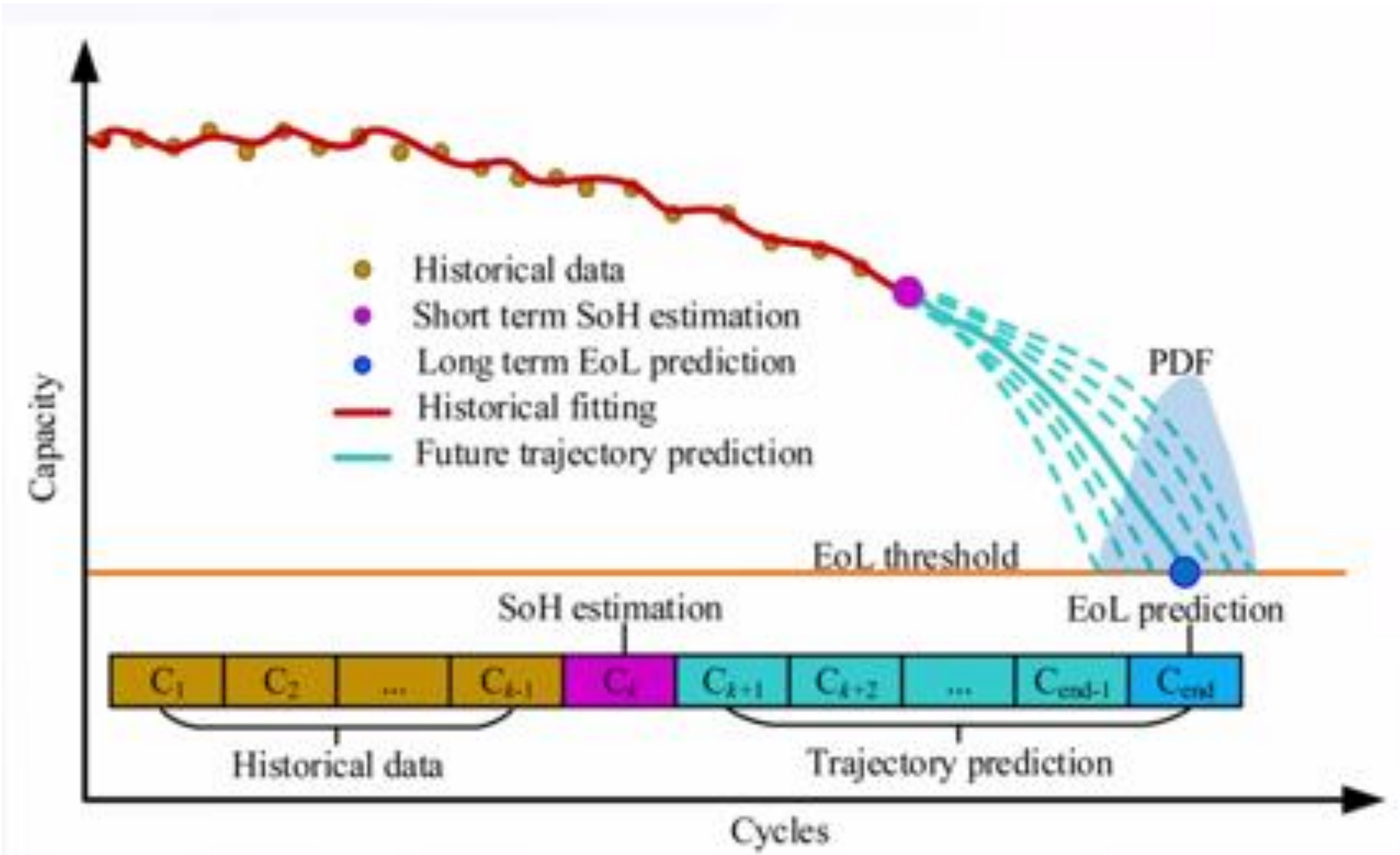
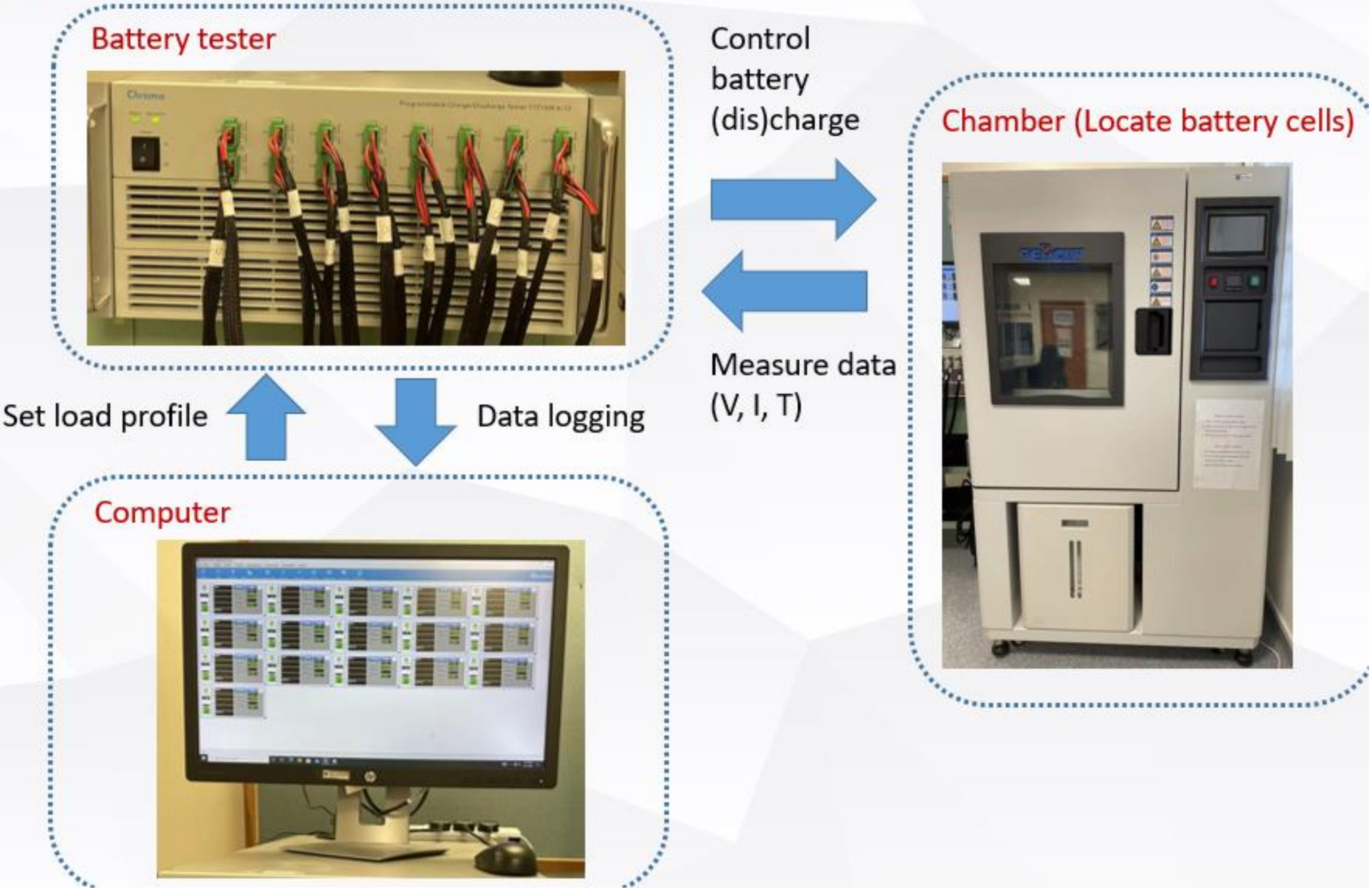


Figure 10: SOH estimation results and errors

Remaining Useful Life (RUL) Prediction



Battery Aging Test Facilities



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2. G. Dong, **Y. Xu**, and Z. Wei, "A Hierarchical Approach for Finite-time H-∞ State Observer and Probabilistic Lifetime Prediction of Lithium-Ion Batteries," ***IEEE Trans. Energy Conversion, 2022.***
3. W. Liu and **Y. Xu**, "Data-Driven Online Health Estimation of Li-Ion Batteries Using A Novel Energy-Based Health Indicator," ***IEEE Trans. Energy Conversion, 2020.***
4. B. Gou**, Y. Xu**, et al, "State-of-Health Estimation and Remaining-Useful-Life Prediction for Lithium-ion Battery Using A Hybrid Data-driven Method," ***IEEE Trans. Vehicular Technology, 2020. -*** **Web of Science highly cited paper**
5. B. Gou, **Y. Xu**, et al, "An Ensemble Learning-based Data-Driven Method for Online State-of-Health Estimation of Lithium-ion Batteries," ***IEEE Trans. Transportation Electrification, 2020*****.**
6. W. Liu, **Y. Xu** et al, "A Hierarchical and Flexible Data-Driven Method for Online State-Of-Health Estimation of Li-ion Battery", ***IEEE Trans. Vehicular Technology*****, *2020*****.
7. W. Q. T. Poh, Y. Xu, and R. T. P. Tan, "Data-driven estimation of li-ion battery health using a truncated time-based indicator and LSTM," ***Proc. IEEE PES General Meeting, Orlando, FL, USA, Jul. 2023.***
8. B. Gou, **Y. Xu**, et al "Remaining Useful Life Prediction for Lithium-ion Battery Using Ensemble Learning Method," ***Proc. IEEE PES General Meeting, Atlanta, US, Aug. 2019.*** – **Best Paper Award**
9. W. Liu and **Y. Xu**, "A Comprehensive Review of Health Indicators of Li-ion Battery for Online State of Health Estimation," ***IEEE EI2 Conference*****, 2019**.

Health Management of ESS

- How to prolong the life of Li-ion batteries?

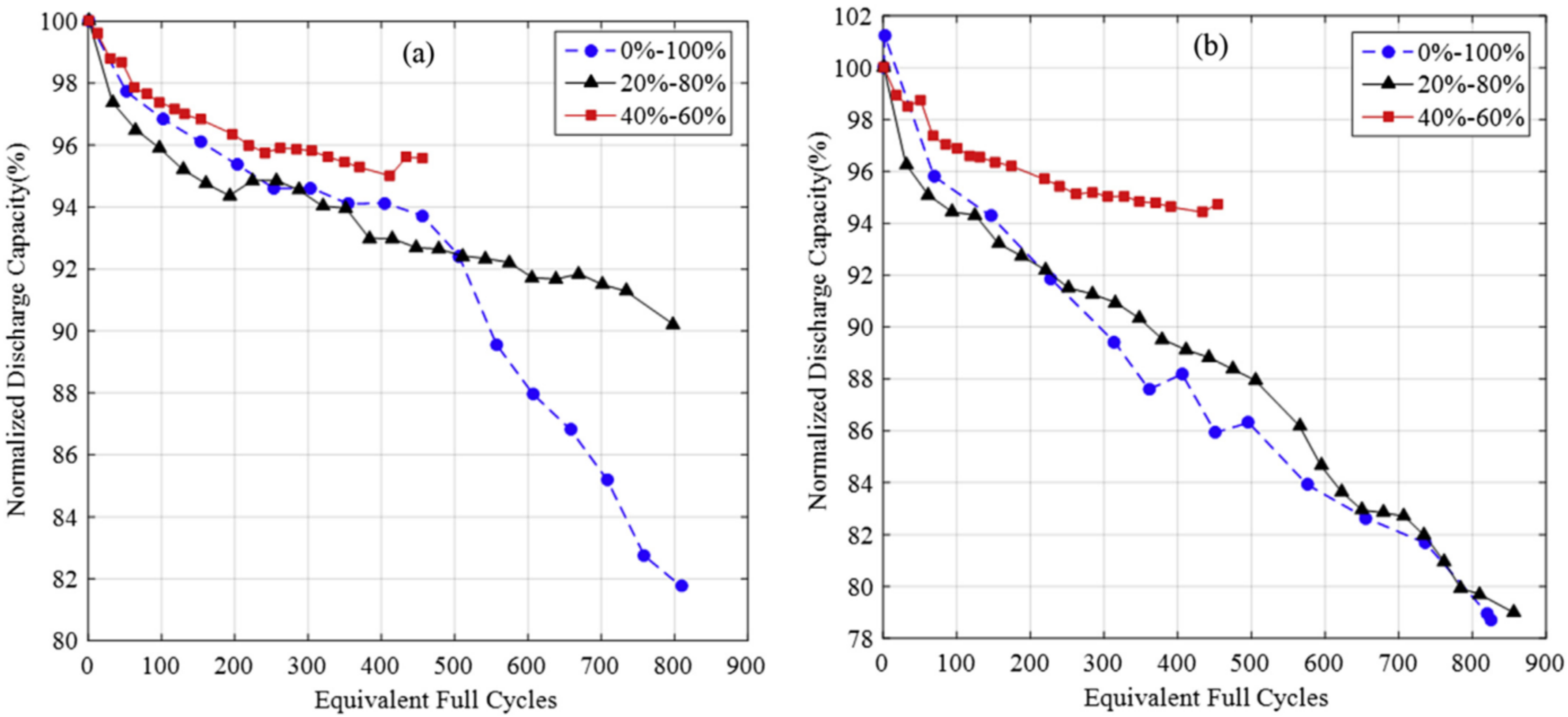

Figure 15: Capacity fade results for Mean SOC = 50%, ΔSOC = 100%, 60%, 20%, (a) C/2 rate, (b) 2C rate.

Health Management of ESS

- In Figure 15, the mean SOC during cycling is fixed at 50% for the three cycling ranges (0% - 100%, 20% - 80%, and 40% - 60%). ΔSOC is the varying parameter with values 100%, 60%, 20% respectively. Also two discharge rates of C/2 and 2C are used.
- It is evident from Figure 15 (a) that cells cycled at 40% - 60% range outperform the cells cycled at the other two ranges up to 450 equivalent cycles. The performance of 20% - 80% range cycled cells either falls below by a small percentage or overlaps with the 0% - 100% range cycled cells up to around 500 equivalent cycles.
- However, if we look at the long term cycling operation at C/2 rate, the 20% - 80% cells outperform the 0% - 100% cells in terms of retaining their capacity by an 8% margin after approximately 800 equivalent full cycles. Also beyond 500 equivalent cycles, the capacity loss curve for 0% - 100% range is steeper than that for 20% - 80% range suggesting a faster degradation rate in the 0% - 100% range.

Health Management of ESS

- For cells discharged at 2C, the cells cycled in the 40% - 60% range perform far better than the cells under the other two ranges up to 450 equivalent cycles. However, the capacity loss (%) difference between cells under 20% - 80% and 0% - 100% ranges is almost negligible at the end of 800 equivalent cycles.
- At high discharge rates such as 2C, cells see a significant temperature rise due to ohmic heating. For cells at a 2C rate and under 20% - 80% or 0% - 100% ranges, the temperature rise is significantly high and exceeds the ambient temperature by more than 15 ℃.
- The high temperature may be playing a larger role than ΔSOC, and hence diminishes the performance gap between the cells cycled in the 20% - 80% and 0% - 100% ranges.

Health Management of ESS

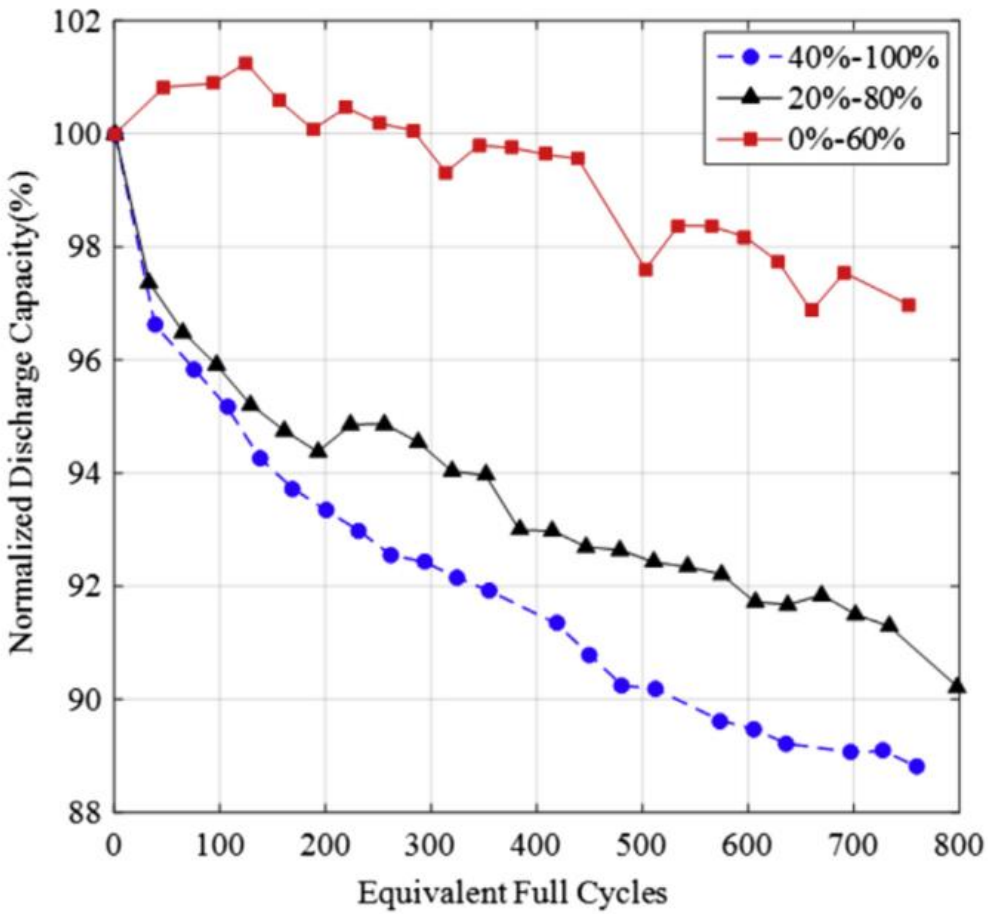

Figure 16: Capacity fade results for Mean SOC = 30%, 50%, 70%, ∆SOC = 60%, C/2 rate.

- Figure 16 shows average results for three cycling ranges (0% - 60%, 20% - 80% and 40% - 100%) with a fixed ∆SOC value of 60% and varying mean SOC values of respectively 30%, 50% and 70% at a C/2 discharge rate.
- It can be observed that lowering the mean SOC reduces the rate of degradation.

Health Management of ESS

- Capacity fade data for individual cells for different lower and upper SOC limits at C/2 cycling rate.

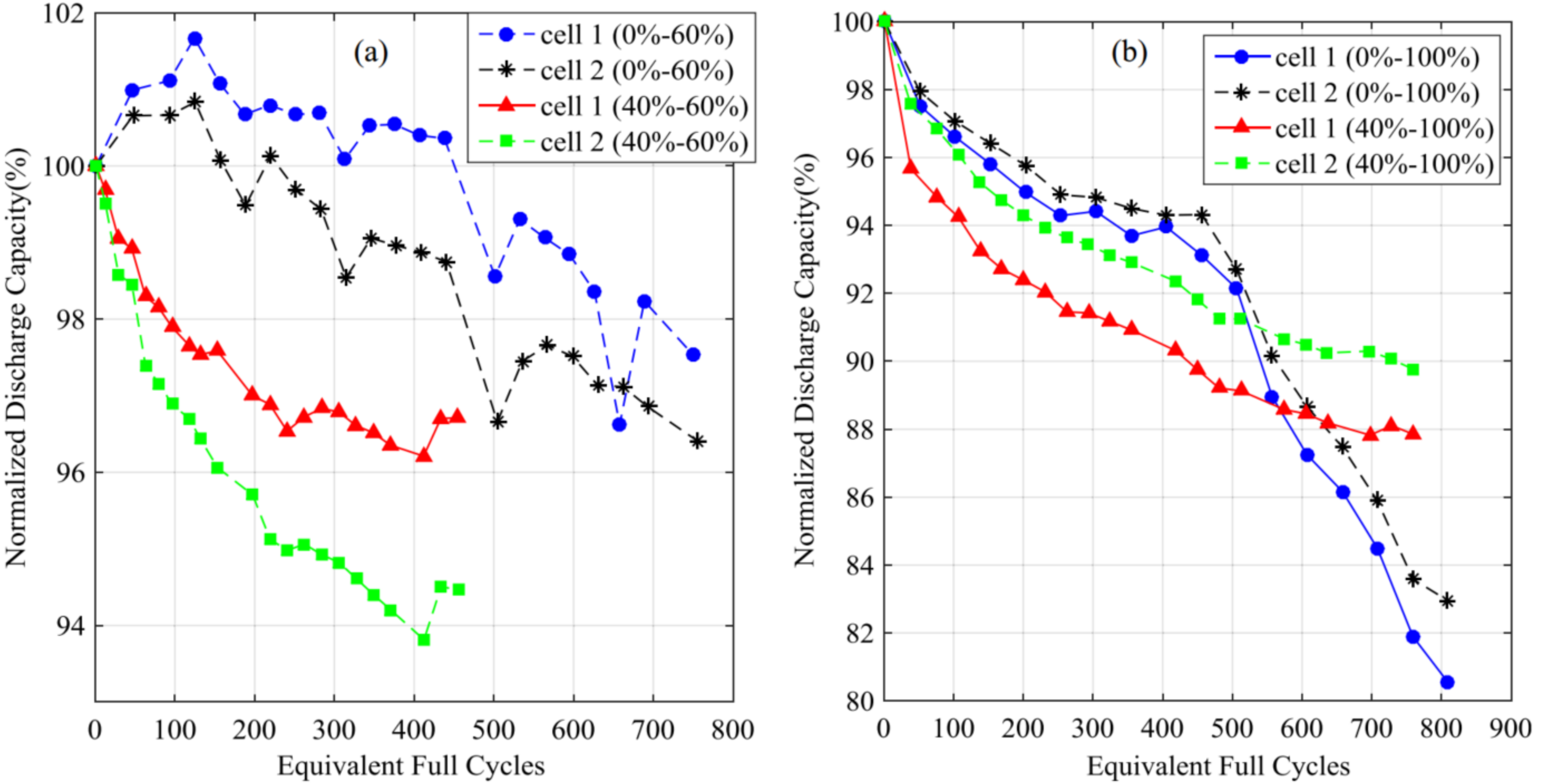

Figure17: Capacity fade results for (a) Lower SOC = 0%, 40%, Upper SOC = 60%, (b) Lower SOC = 0%, 40%, Upper SOC = 100%, all at C/2 rate.

Health Management of ESS

- Figure 17 shows the effects of changing the lower SOC limits while keeping the upper SOC limits constant at 60% and 100% respectively.
- For a fixed upper SOC limit of 60% increasing the lower limit from 0% to 40% results in higher capacity loss (%) for cells. Similar results are found for fixed upper SOC limit of 100% as well up to 500 equivalent cycles.
- These observations seem counterintuitive as increasing the lower SOC limit from 0% to 40% will result in reduction of ΔSOC and hence the capacity fade (%) should be lower for cells with 40% lower SOC limit.
- However, a closer look at the data shows that increasing the lower limit from 0% to 40% for fixed upper SOC limits of 60% and 100% results in an increase in the mean SOC values from 30% to 50% and 50% to 70% respectively.
- The results **up to 500 equivalent cycles suggest that the mean SOC has a major effect** on capacity fade as compared to ΔSOC during cycling.
- However, **after 500 equivalent cycles, ΔSOC seems to be playing a major role** and hence resulting in decreased capacity loss (%) in cells cycled in a 40% - 100% range as compared to those cycled in the 0% - 100% range.

Health Management of ESS

- The results for fixed lower SOC limits of 0% and 40% are shown in Figure 18 a) and b) respectively. The upper SOC limit has two different values of 60% and 100%. It is clear from Figure 18 that increasing the upper SOC limit increases the capacity fade (%). Increasing the upper SOC limit increases both mean SOC and ∆SOC, thus resulting in higher capacity loss rate.

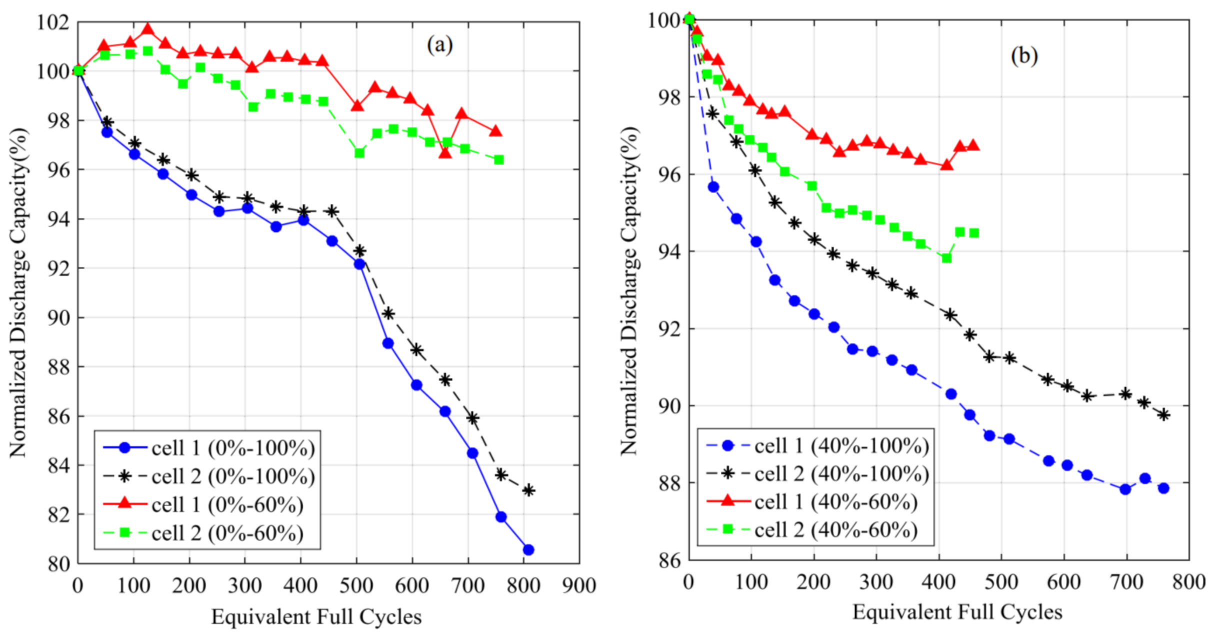

Figure 18: Capacity fade results for (a) Lower SOC = 0%, Upper SOC = 60%, 100%, (b) Lower SOC = 40%, Upper SOC = 60%, 100%, all at C/2 rate.

Health Management of ESS

- For safety reasons, many lithium-ions cannot exceed 4.20V/cell. (Some NMC are the exception.) While a higher voltage boosts capacity, exceeding the voltage shortens service life and compromises safety. Figure 19 demonstrates cycle count as a function of charge voltage. At 4.35V, the cycle count of a regular Li-ion is cut in half.

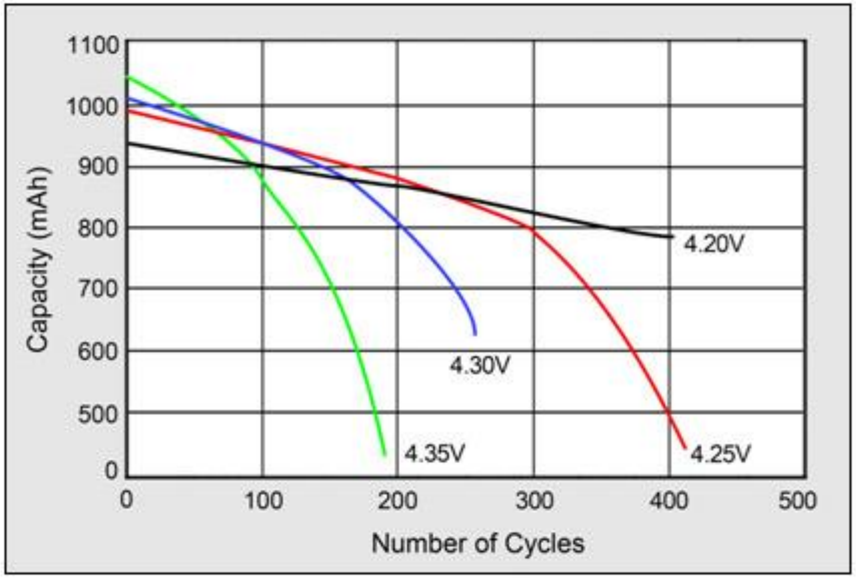

Figure 19: Effects on cycle life at elevated charge voltages. Higher charge voltages boost capacity but lowers cycle life and compromises safety.

Health Management of ESS

☐ Conclusion

- For the first 500 equivalent full cycles mean SOC is found to have major effect on the capacity fade of cells as compared to ΔSOC.
- However, towards the end of the testing (600 - 800 equivalent cycles) ΔSOC becomes the major factor affecting the capacity loss rate of the cells.
- The mean SOC as well as the ΔSOC during cycling should be minimized to reduce the long-term capacity fade rate and achieve higher number of equivalent full cycles or higher amount of cumulative discharge capacity over the battery's useful life.
- Higher charge voltages boost capacity but lowers cycle life and compromises safety.