Safety Risks and Risk Mitigation - Battery Energy Storage Systems

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Presented to
Energy Storage Webinar Series (organized by CEC and SNL)
Session 4: Battery Safety Codes and Standards

Electrochemical Safety Research Institute (ESRI)

Advancing the development of safer energy storage and energy generation through science

Introduction

- Energy storage in the form of batteries has grown exponentially in the past three decades.

- Batteries have been used in various consumer and unique applications for more than 70 years – consumer, space, DoD (Army, Navy, AirForce), DOE, etc.

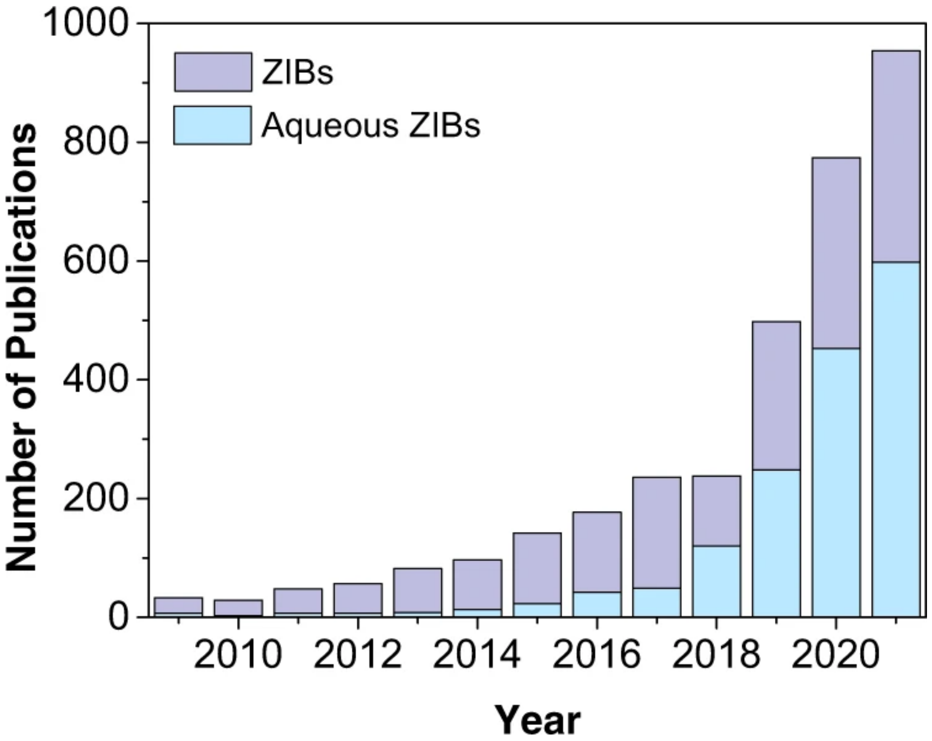
- Lithium-ion batteries are used in most applications ranging from consumer electronics to electric vehicles and grid energy storage systems as well as marine and space applications.

- Apart from Li-ion battery chemistry, there are several potential chemistries that can be used for stationary grid energy storage applications.

- A discussion on the chemistry and potential risks will be provided.

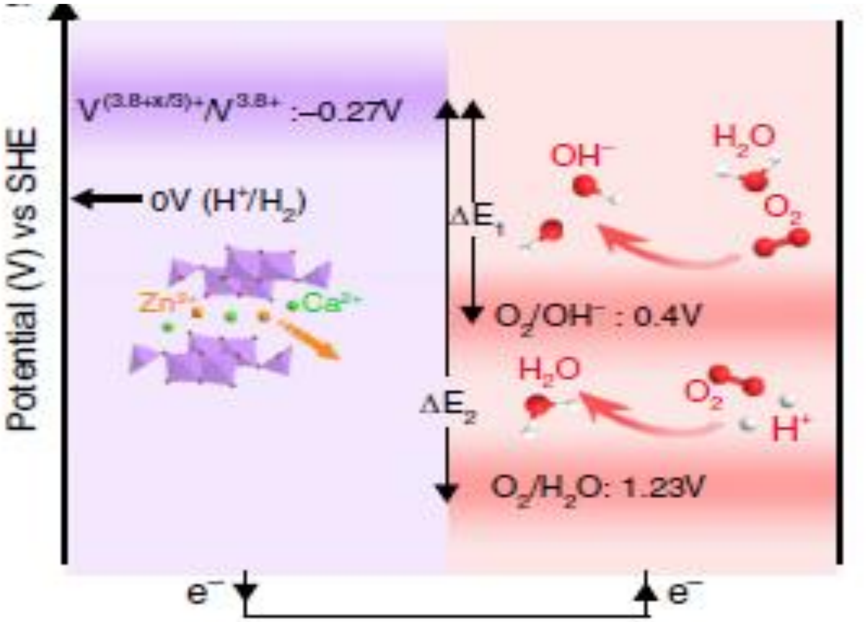
- Challenges for any large energy storage system installation, use and maintenance include training in the area of battery fire safety which includes the need to understand basic battery chemistry, safety limits, maintenance, off-nominal behavior, fire and smoke characteristics, fire fighting techniques, stranded energy, de-energizing batteries for safety, and safely disposing battery after its life or after an incident.

Aqueous Zinc-Ion Battery



https://www.nature.com/articles/s41467-022-28381-x

- Self charging (air from ambient environment)
- C/3 rate
- Theoretically capable of high discharge rates
- At 100C rate, 1/5th of C/3 rate capacity is obtained
- 10,000 cycles



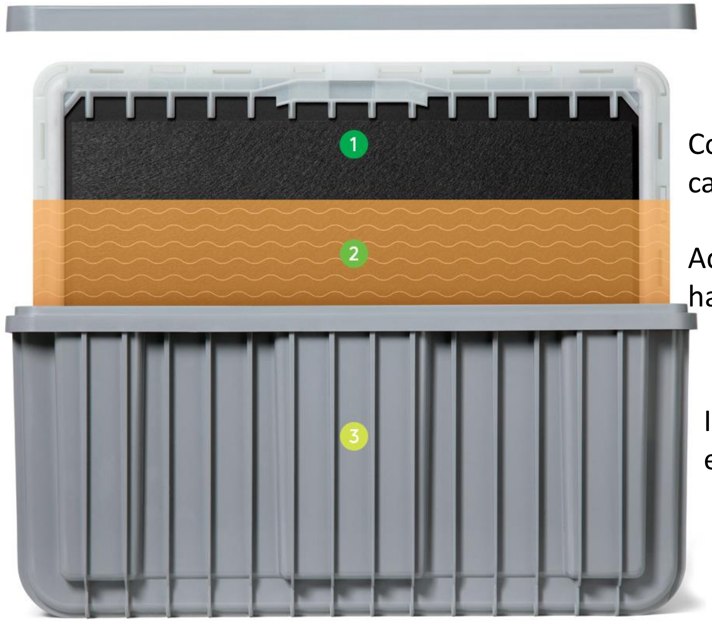
Mildly acidic

Theoretical:
volumetric capacity (5855 mAh cm^{-3})
gravimetric capacity (820 mAh g^{-1})

Practical: 40 Wh/kg or 40 mAh/g (https://doi.org/10.1038/s41467-022-28381-x)

Aqueous Zinc-Ion Battery

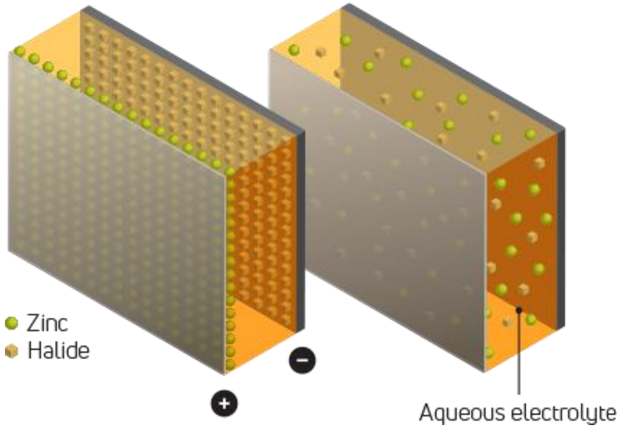
EOS



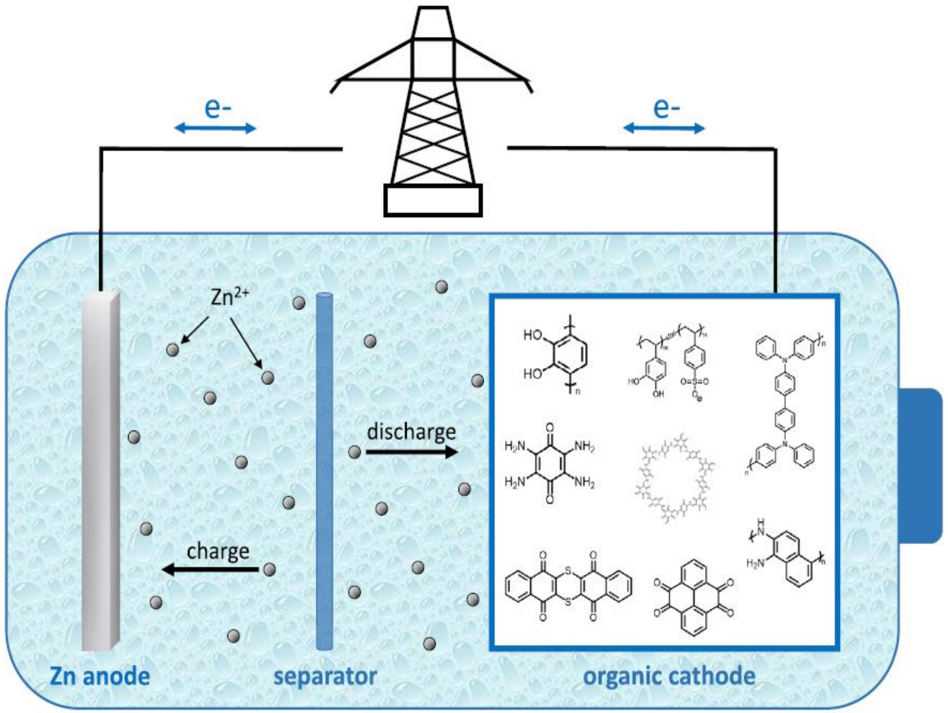
Conductive plastic anodes and carbon-felt cathodes

Aqueous electrolyte with blend of water, halides, additives, and buffering agents

Injection-molded thermoplastic polymer exterior



Organic Cathodes



Grignon, Eloi et al.
iScience, Volume 25, Issue 5, 104204

Aqueous Zinc-Ion Battery

Advantages

- Simplicity of synthesis – Zn is not sensitive to ambient environments
- Use of aqueous electrolytes – higher ionic conductivity; near neutral pH (slightly acidic)
- Long-term stability
- Low cost (less expensive due to nature of materials used such as Zn and aqueous solvents)
- Higher level of safety compared to battery chemistries that use an organic solvent electrolyte such as Li-ion – with use of aqueous electrolyte
- More sustainable alternative (expected to have a lower carbon footprint)
- Environmentally friendly

Disadvantages

- Poor cycle life and low coulombic efficiency
    - Zn dendrite growth
    - Water break down that passivates or insulates the cathode surface
    - Corrosion of electrodes
    - Byproducts that are irreversible
    - Poor structural stability
- Slow Electrode kinetics
- Small working voltage range due to narrow electrochemical stability window

Redox Flow Batteries

- ESRI research team focused on two chemistries:

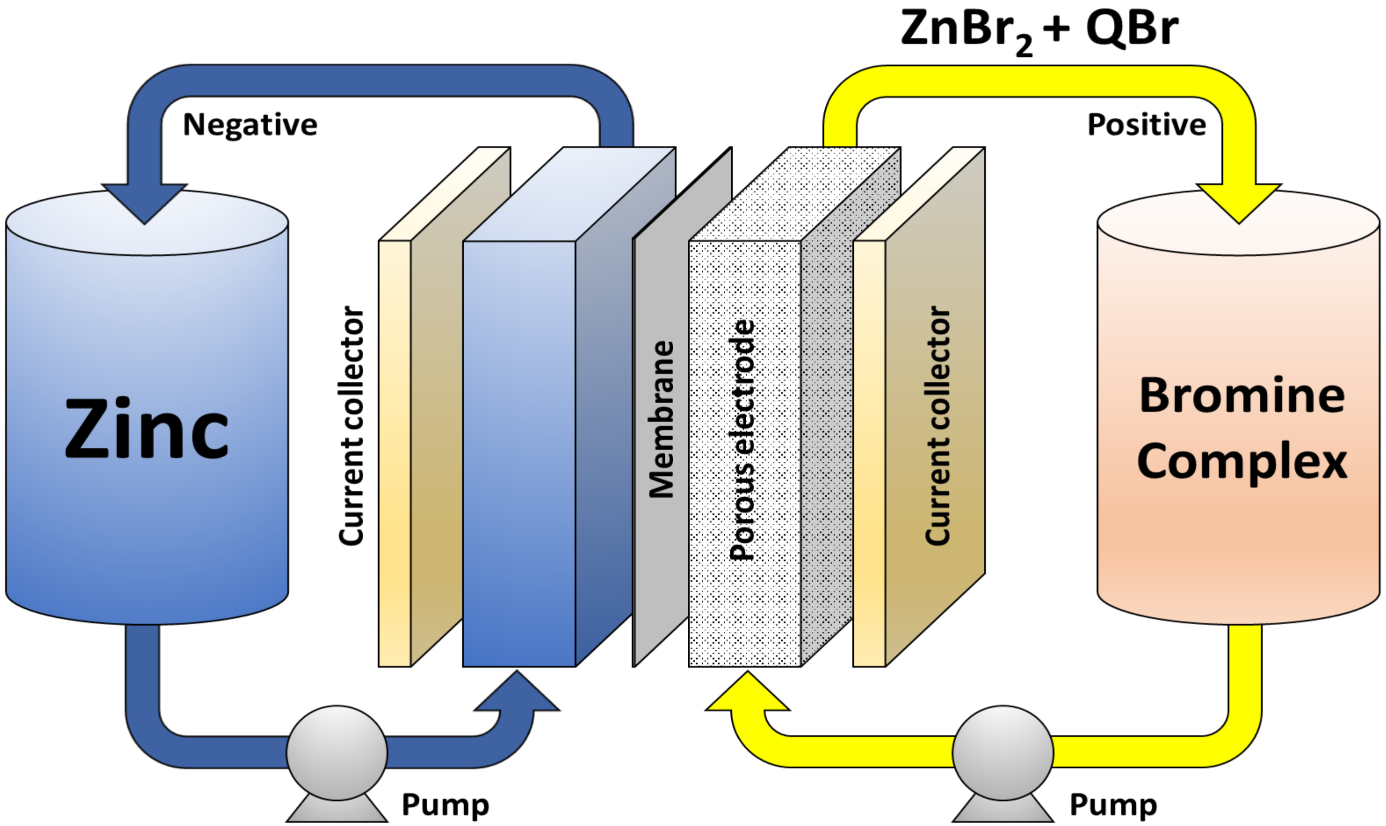
  Zinc-Bromine RFB and Vanadium RFB.

- Both types of RFBs were evaluated for the safety at the system level under off-nominal conditions, such as overcharge, over-discharge, and external short circuit. The results of the studies for both systems will be presented.

$$ZnBr_2 \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Zn + Br_2$$

$$V^{3+} + VO^{2+} + H_2O \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} VO_2^{+} + V^{2+} + 2H^{+}$$

Zinc-Bromine Redox Flow Battery



A complexing agent such as MEP (N-methyl N-ethyl pyrrolidinium bromide) is added to the electrolyte to sequester bromine and prevent it from going into the vapor phase

- Positive electrode reaction:

$$2Br^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Br_2 + 2e^-$$

- Negative electrode reaction:

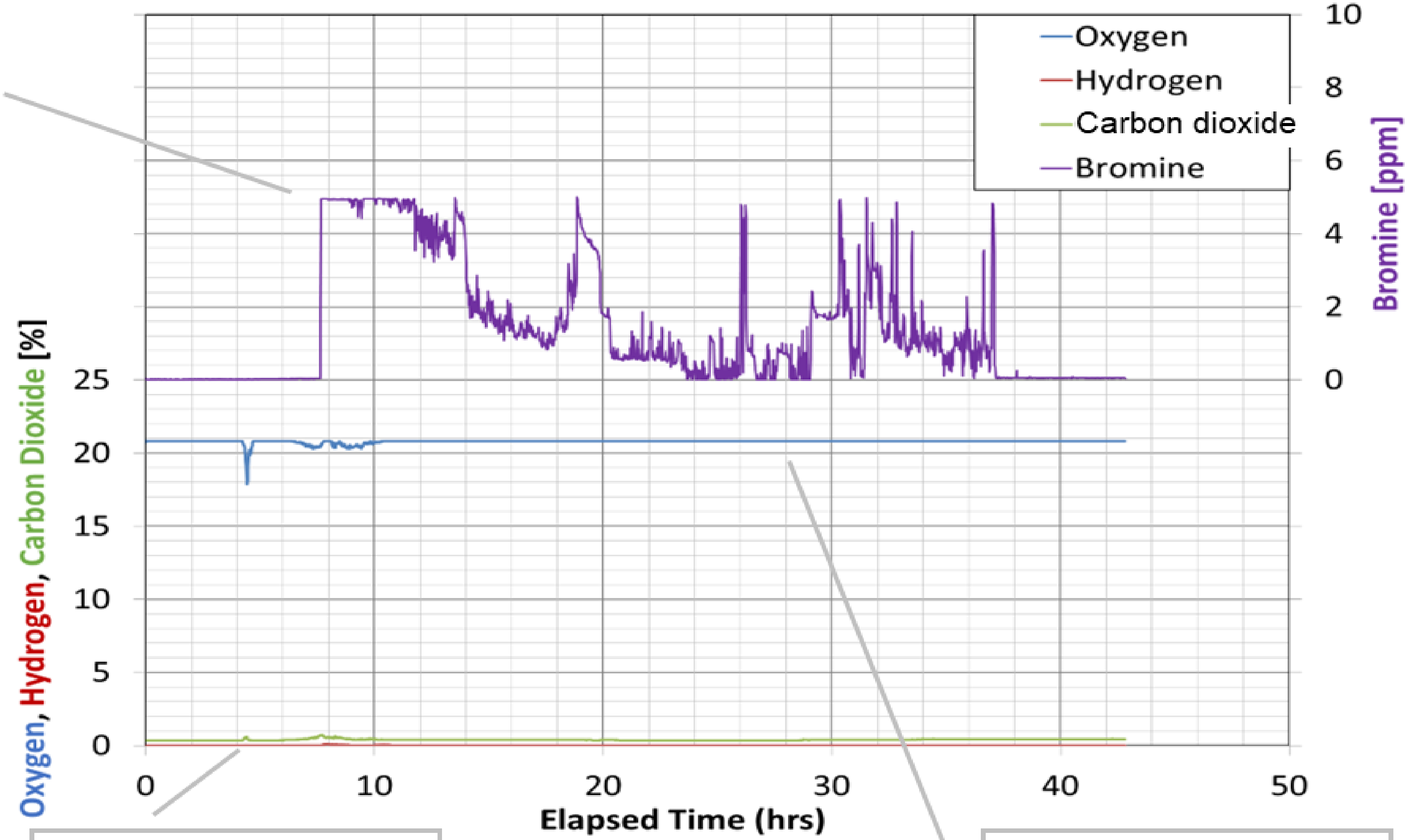
$$Zn^{2+} + 2e^- \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Zn$$

- Overall cell reaction:

$$ZnBr_2 \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} Zn + Br_2$$

Zn- Br : Overcharge Test: Gas formation

- Reddish brown Br_2 gas reached the upper sensor limit (5 ppm)



H_2 & CO_2 (~0%)

O_2 in air (21%)

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Zinc-Bromine Flow Batteries

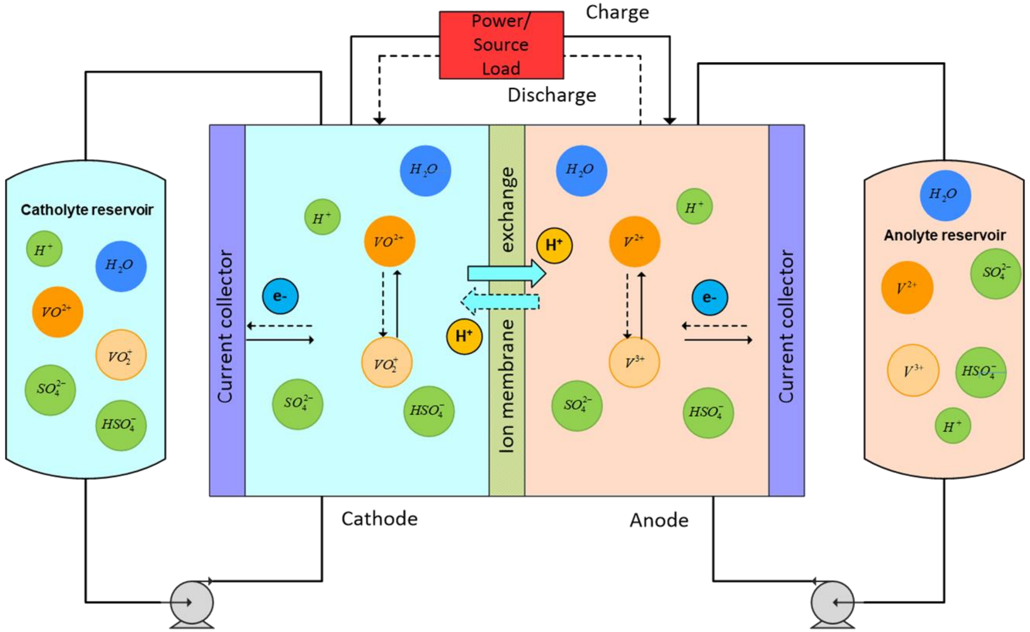
Advantages

•**Low cost**: ZBFBs are inexpensive compared to lithium-ion batteries
•**Higher energy density**- than other redox flow battery systems
•**Deep discharge capability**: ZBFBs can be deeply discharged even down to 0 V.
•**Scalable and flexible**: ZBFBs are scalable and flexible

Disadvantages

•**Low cycle efficiency**: Typically around 70-80%, compared to lithium-ion batteries, which are usually 98% or higher
•**Dendrite formation**: Dendrites can form on the zinc anode, which can decrease battery efficiency, cause short circuits, and lead to battery fires
•**Material corrosion**: Materials in ZBFBs can corrode
•**Short cycle life**: ZBFBs have a short cycle life compared to li-ion, NiMH etc.
•**Low power density**: Not capable of high-rate discharges
•**Toxicity: Presence of bromine and the release of bromine under off-nominal conditions are a toxicity concern**

Vanadium Redox Flow Battery (VRFB)



VRFBs consist of liquid electrolytes containing one or more vanadium electroactive species.

Vanadium - Oxidation States

Courtesy: Dr. Daniel Juarez-Robles (SwRI)

Positive electrode reaction:

$$VO^{2+} + H_2O \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} VO_2^{+} + 2H^{+} + e^{-}$$

Negative electrode reaction:

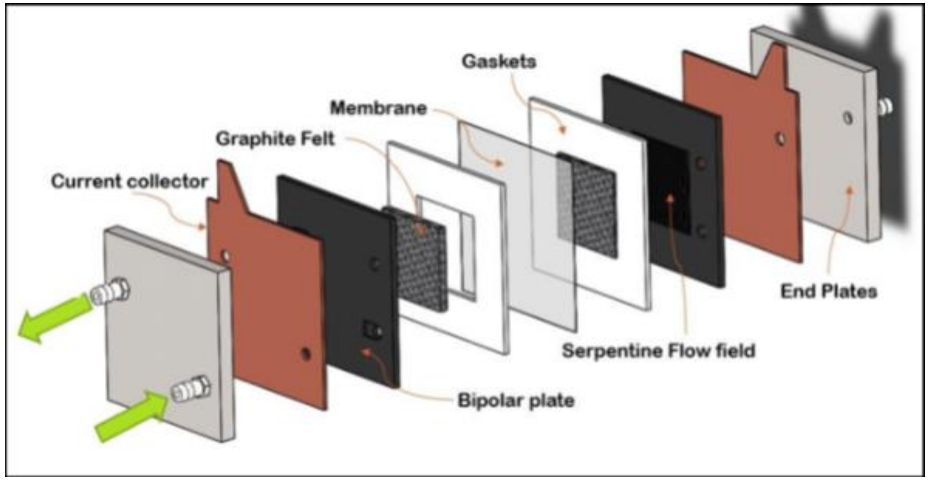
$$V^{3+} + e^{-} \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} V^{2+}$$

Overall cell reaction:

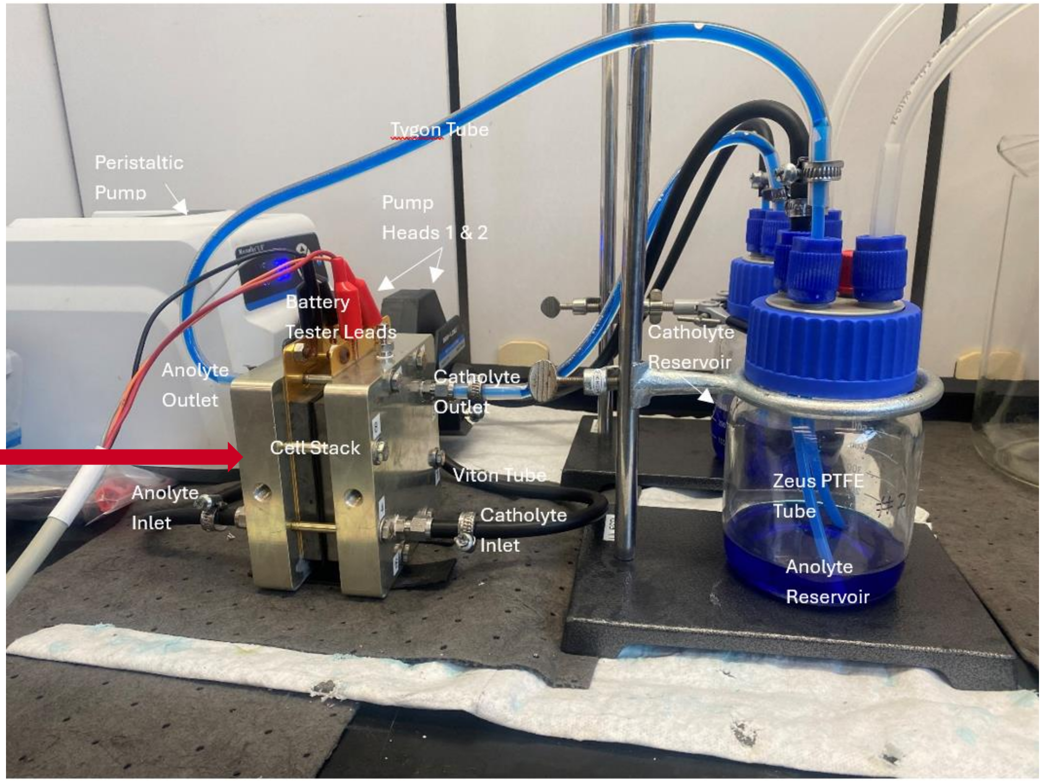
$$V^{3+} + VO^{2+} + H_2O \underset{\text{Discharge}}{\overset{\text{Charge}}{\rightleftarrows}} VO_2^{+} + V^{2+} + 2H^{+}$$

Vanadium Redox Flow Battery (VRFB) – Lab Scale

Assembly of the Flow Cell



VRFB built at ESRI



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Vanadium Redox Flow Battery (VRFB)

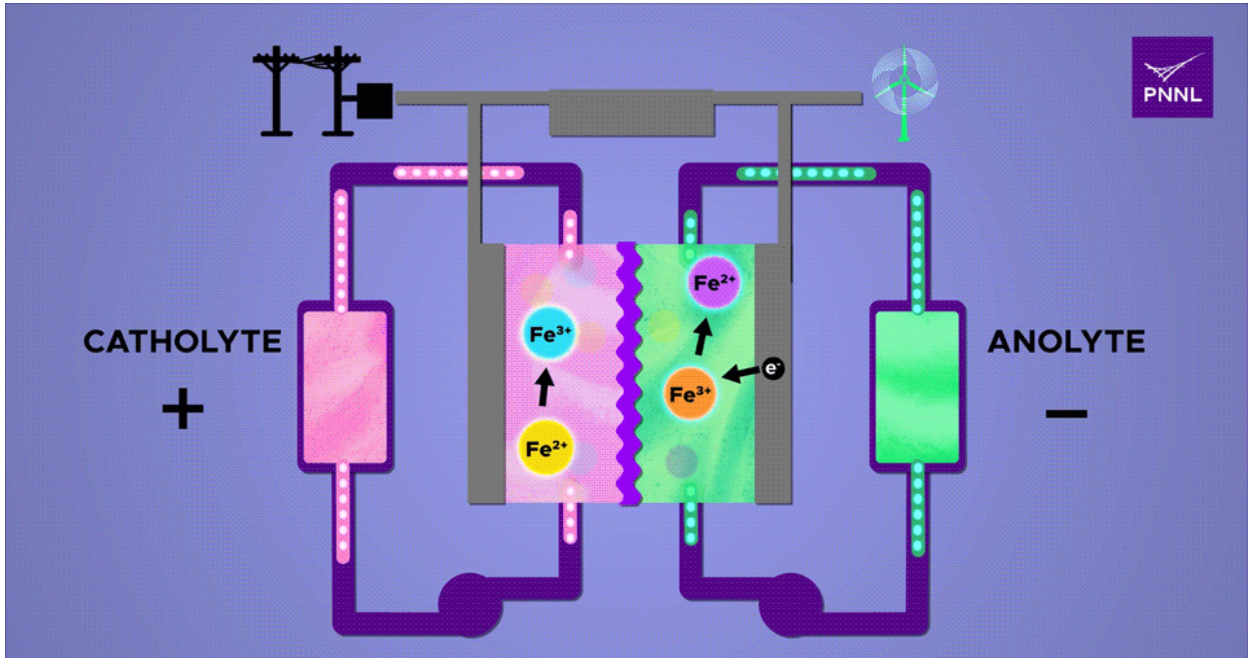
Advantages

- **Long lifespan**: VRFBs can last 50–100 years and are engineered to last 25 years even in demanding applications.
- **Safety**: VRFBs are non-flammable.
- **Limited self-discharge**: VRFBs have limited self-discharge, making them useful for long-term storage
- **Rapid response times**: VRFBs have rapid response times (0.001 to 0.02 secs), making them well-suited for UPS applications
- **Energy Efficiency**: Up to 70%

Disadvantages

- **High capital cost**: VRFBs have a high capital cost.
- **Low power density**: VRFBs have a relatively low power density (800 W/h).
- **Toxicity**: **VRFBs are relatively toxic due to the oxides of vanadium.**
- **Weight**: VRFBs are heavy due to the large electrolyte tanks and aqueous electrolyte (40 Wh/kg).
- **Energy-to-volume ratio**: VRFBs have a relatively poor energy-to-volume ratio (15-20 Wh/L).
- **System complexity**: VRFBs are more complex than standard storage batteries.

Iron Chloride Flow Battery



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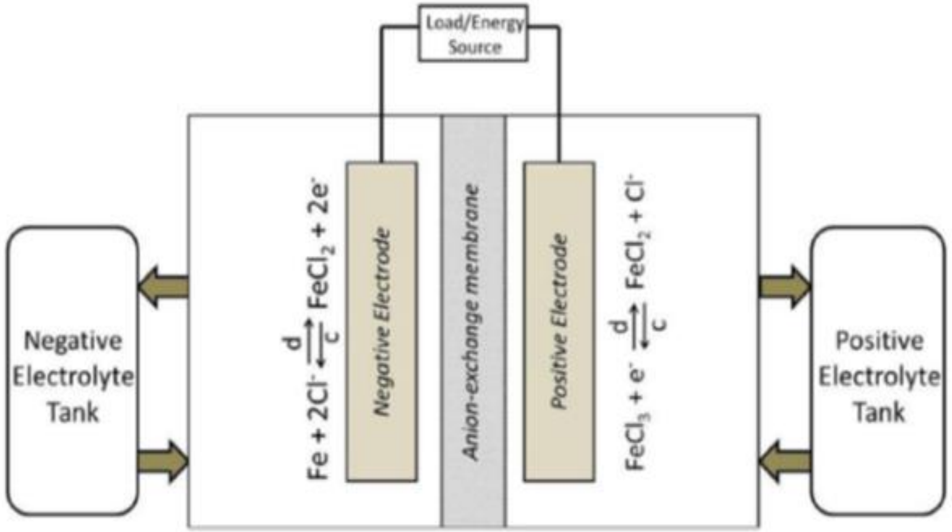
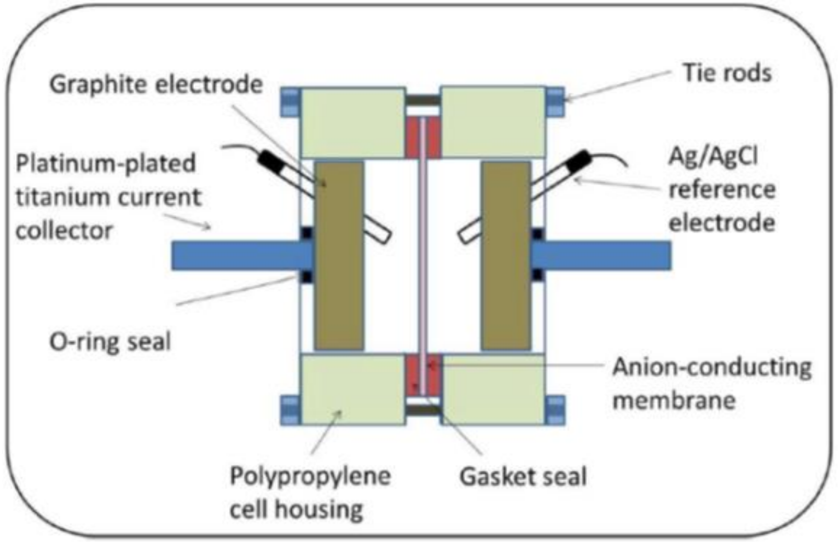
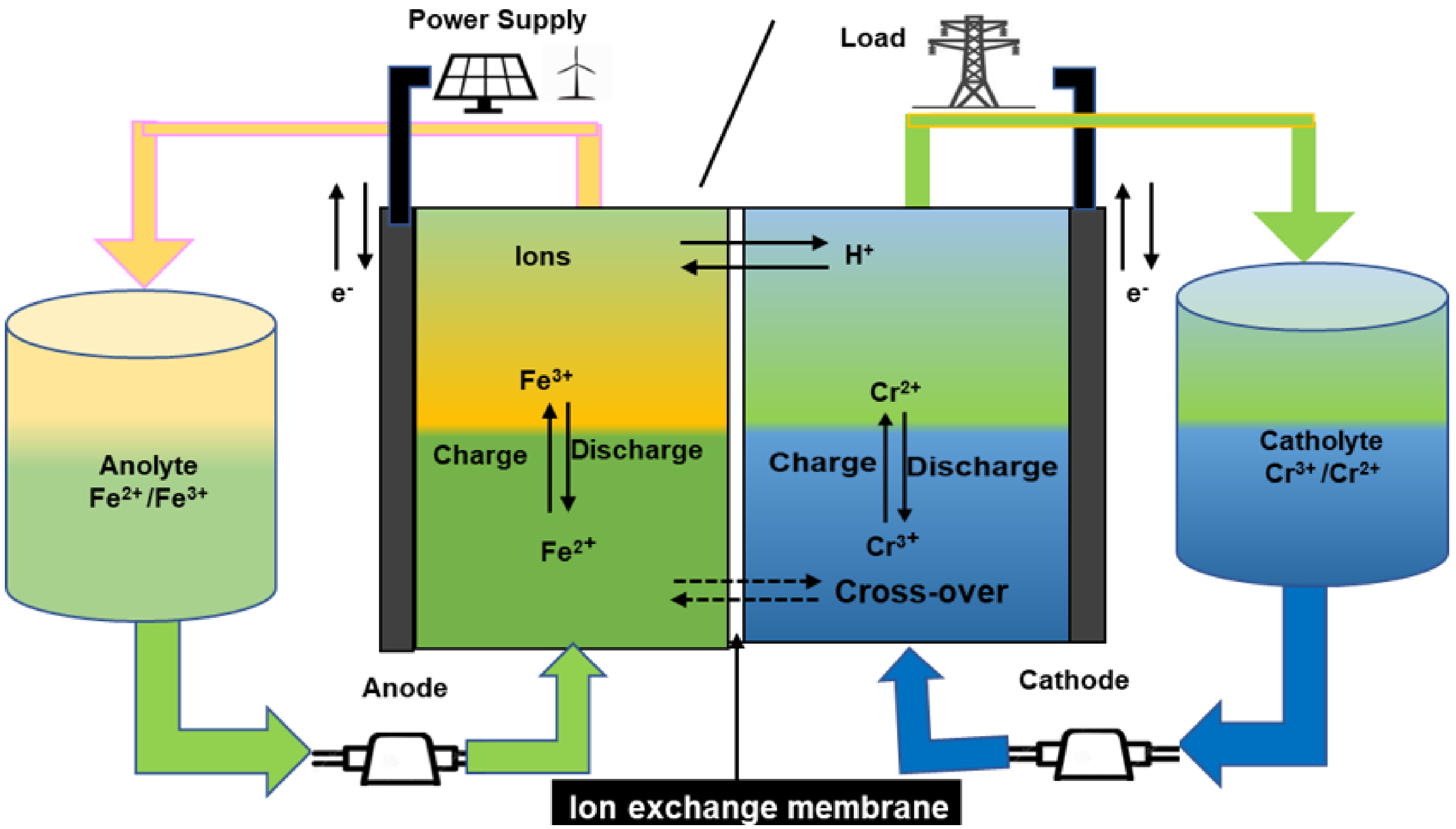




https://iopscience.iop.org/article/10.1149/2.0161601jes/pdf

Iron-Chromium Flow Batteries



https://www.battery.associates/

Iron Flow Batteries

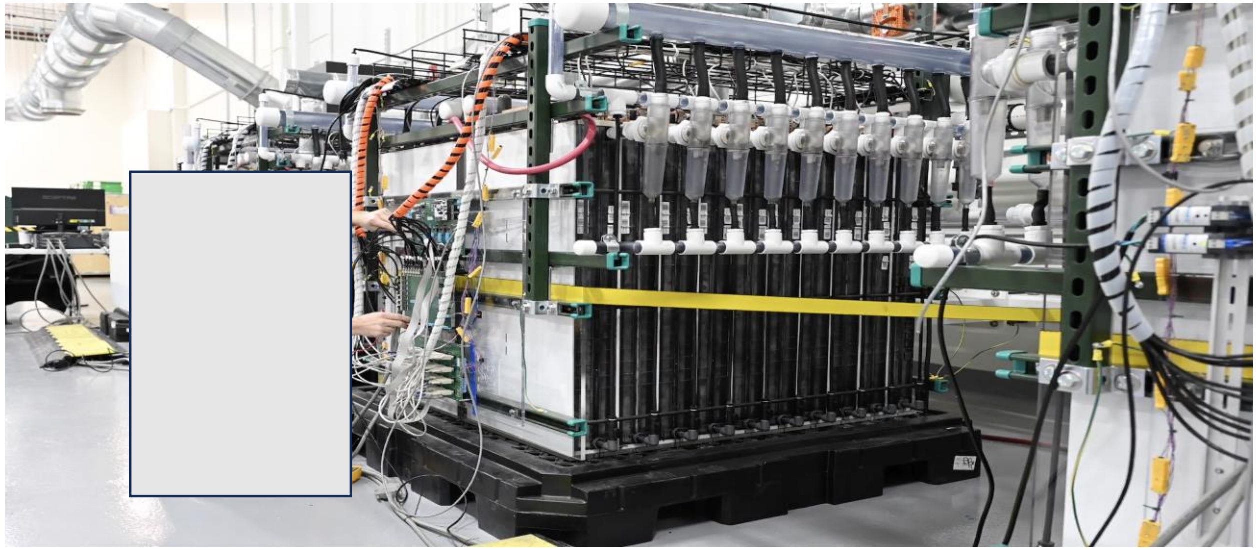
Advantages

•**Non-toxic and non-flammable**: only slightly reactive with water and air.
•**Low-cost materials**: materials are inexpensive, earth-abundant
•**Long cycle life**: Iron flow batteries have a theoretically unlimited cycle life (practical 10,000 cycles).
•**Sustainable**: Iron flow batteries have a low lifecycle carbon footprint and substantially recyclable or reusable at the end of their life.
•20 year life
•**Rapid response**: Can help with frequency control on the grid

Disadvantages

•**Low round-trip energy efficiency**: A competitive side reaction at the negative electrode during charging causes low round-trip energy efficiency.
•**Low cell voltage**: Iron flow batteries have a low cell voltage (1.2 V).
•**Hydrogen evolution**: Hydrogen evolution can occur during charging (operate below pH 3.5).
•**Low Electrochemical Performance**: Iron chloride flow batteries have low charging efficiency, self-discharge.
•**Large size:** may not be suitable for residential use

Iron Air Batteries



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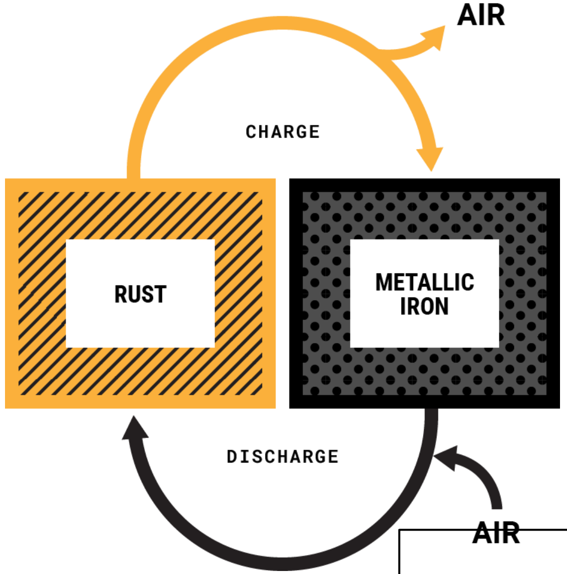
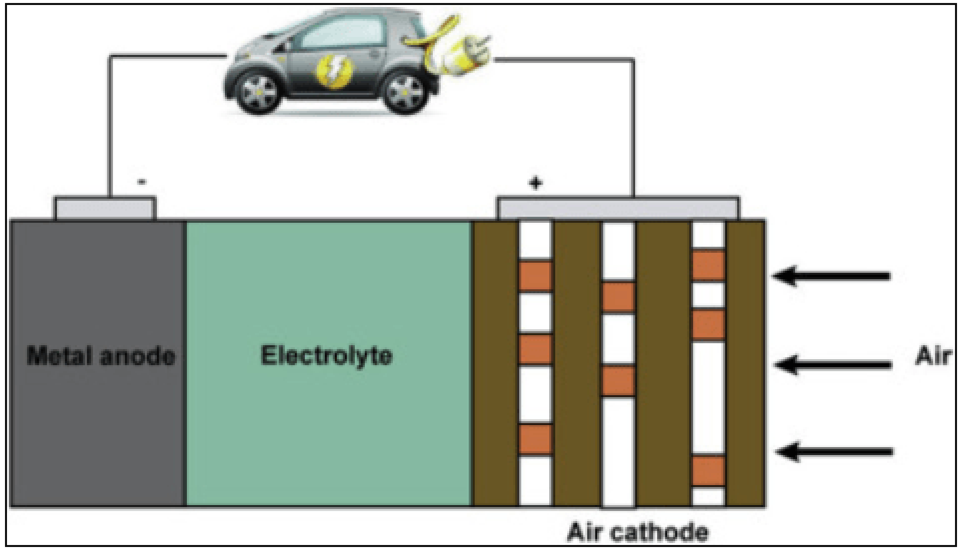




https://nanografi.com/

Iron-Air Batteries

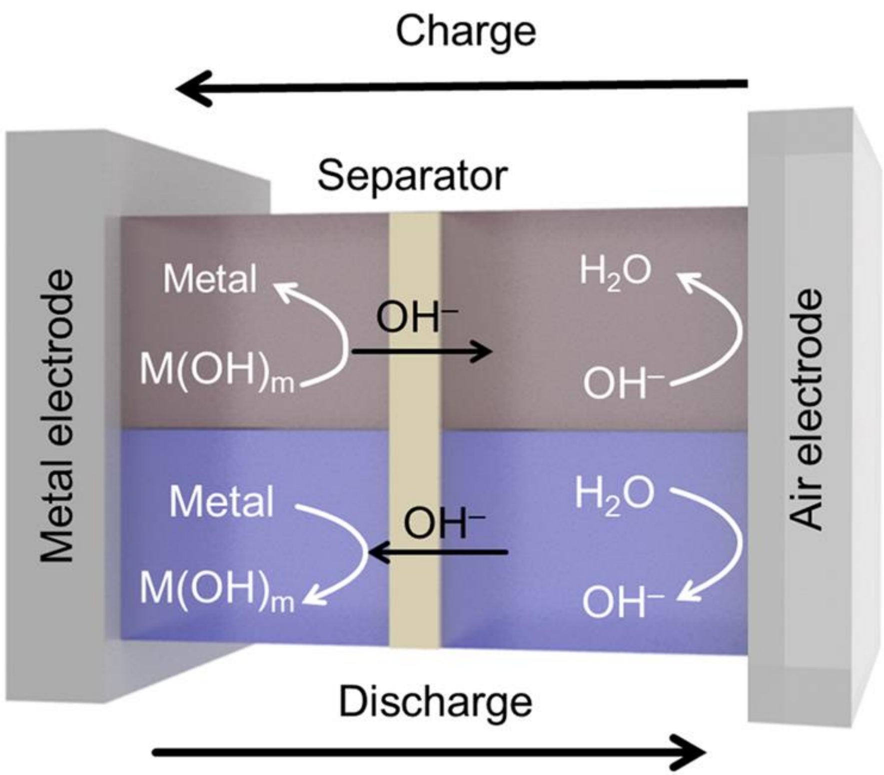
Advantages

•**Cost-effective**: Iron-air batteries are less expensive than lithium-ion batteries, especially for large-scale energy storage.
•**Environmentally friendly**: Iron-air batteries use non-toxic, abundant materials and are recyclable.
•**Long-duration storage**: Iron-air batteries can store energy for days (up to 100 hours), which is ideal for balancing renewable energy sources like wind and solar.
•**Safe**: Iron-air batteries are safer than lithium-ion batteries because they use non-flammable materials and are less likely to overheat.
•**High energy density**: Iron-air batteries have a higher energy density than many traditional flow batteries.
•**Modular and scalable**

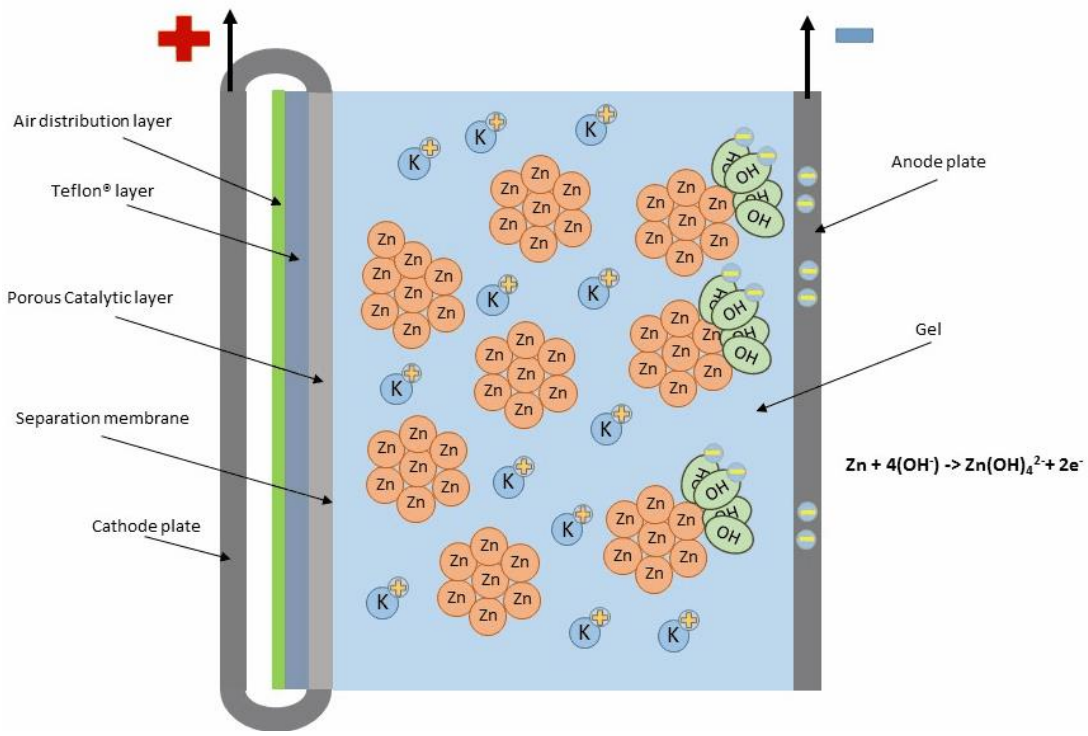
Disadvantages

•**Slow to charge and discharge**: Iron-air batteries are slower to charge and discharge than lithium-ion batteries, making them less suitable for laptops or smartphones.
•**Size and weight**: Iron-air batteries are larger and heavier than lithium-ion batteries.
•**Air electrode stability**: The stability of the air electrode is not yet sufficient for use as a stationary storage device.
•**Scale up and Cycle Life:** Scaling up production and improving the durability and cycle life of the batteries are challenges (theoretical cycle life is 10,000 cycles/ 30 years)

Zinc- Air Rechargeable Batteries



Nano-Micro Lett. (2024) 16:138



Specific energy	470 (practical),1370 (theoretical) Wh/kg
Energy density	1480-9780 Wh/L
Specific power	100 W/kg
Nominal cell voltage	1.45 V

Zinc- Air Rechargeable Batteries

Advantages

- **Cost-effective**: Zinc is abundant, making zinc-air batteries inexpensive.
- **Environmental**: Zinc-air batteries have a low environmental impact.
- **Energy density**: Zinc-air batteries have a high volumetric energy density, meaning they provide more energy for their size than conventional batteries.
- **Safety**: Zinc-air batteries are safer than lithium-ion batteries because they have chemically inert components and minimize fire risk.
- **Shelf life**: Zinc-air batteries have a long shelf life if sealed to keep air out.

Disadvantages

- **Limited output**: Zinc-air batteries have a limited power output and short lifespan.
- **Water loss**: Zinc-air batteries lose water over time because they rely on atmospheric oxygen.
- **Dendrite formation**: Zinc dendrites can form on the anode, causing the cell to short and fail.
- **Oxygen reduction reaction**: The oxygen reduction reaction (ORR) and oxygen evolution reaction (OER) kinetics are sluggish, which hinders commercialization.
- **Air electrode corrosion**: The air electrode can corrode.

Factors to Consider in Installation of Chargers / Charging Infrastructure Inside Buildings

- Ventilation
- Toxic gas sensors
- Oxygen sensors

Currently available commercial sensors installed inside ESS containers are overwhelmed; first responders are recommended to carry their own gas sensors when entering such enclosed areas that can trap toxic and combustible gases

- Access to charging station main power
- Access to charging station / battery data (Battery Management System) – to determine stranded energy and reignition concerns)
- Physical access for first responders and fire fighters
- Proper PPE/ respirators (acid gas for Li-ion battery fires)
- Relevant fire extinguishers

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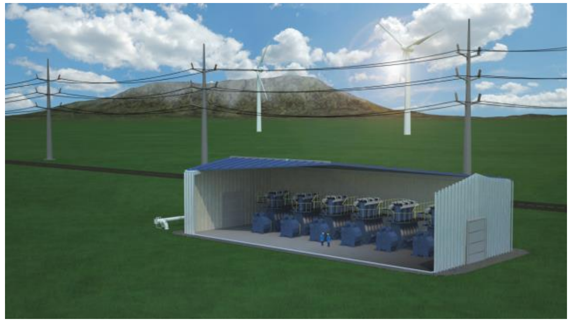
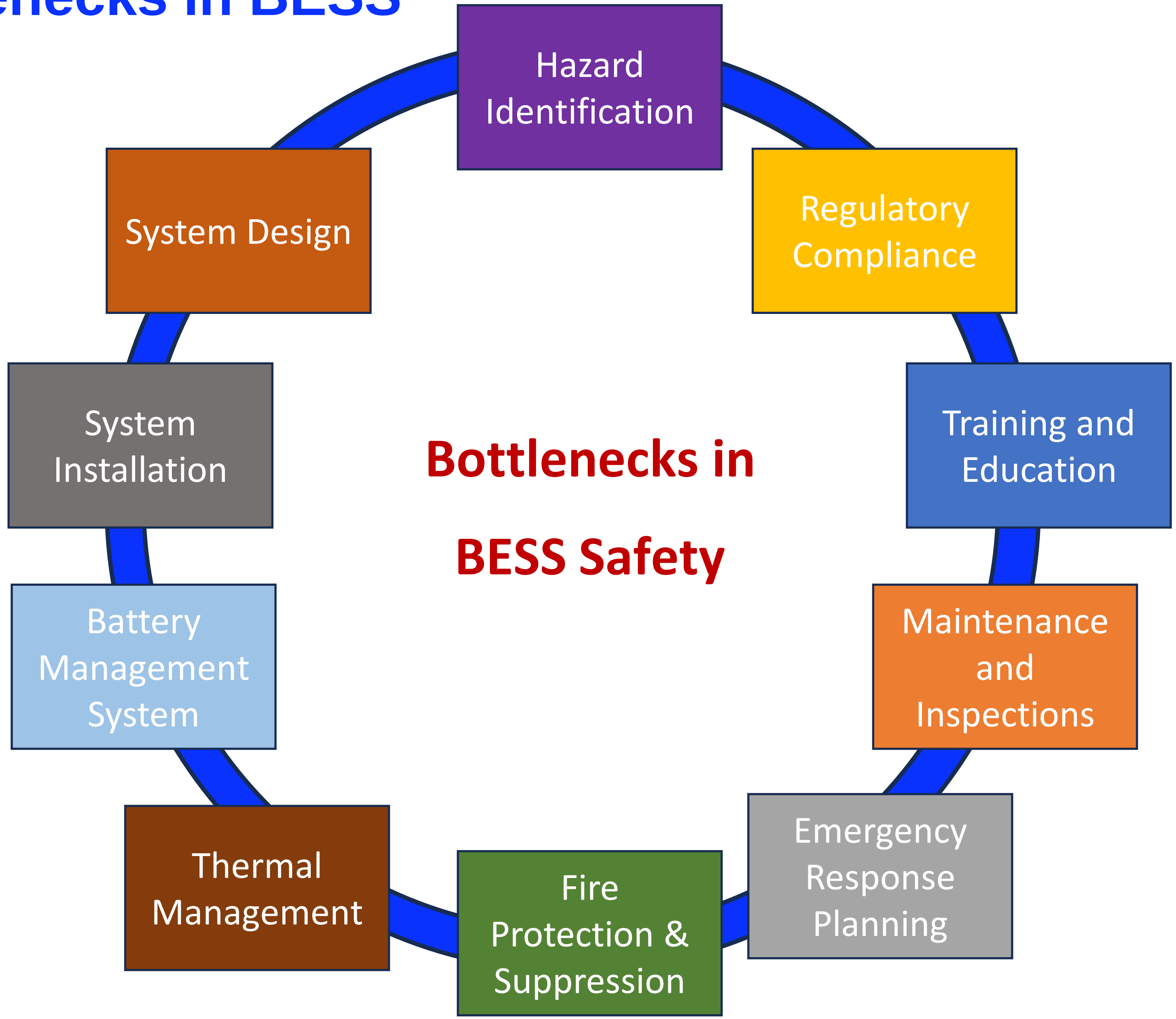
Challenges for Energy Storage Systems

- Toxicity (of vented liquids and gases)
- Flammability and Off-gassing
- Environmental Pollution
- High Voltage Safety
- Vent products - particulates
- Fire Extinguishing methods
- Transportation Safety



BESS Procurement Certification

Areas of Bottlenecks in BESS Safety



Areas of Bottlenecks in BESS for Authorities and Operators

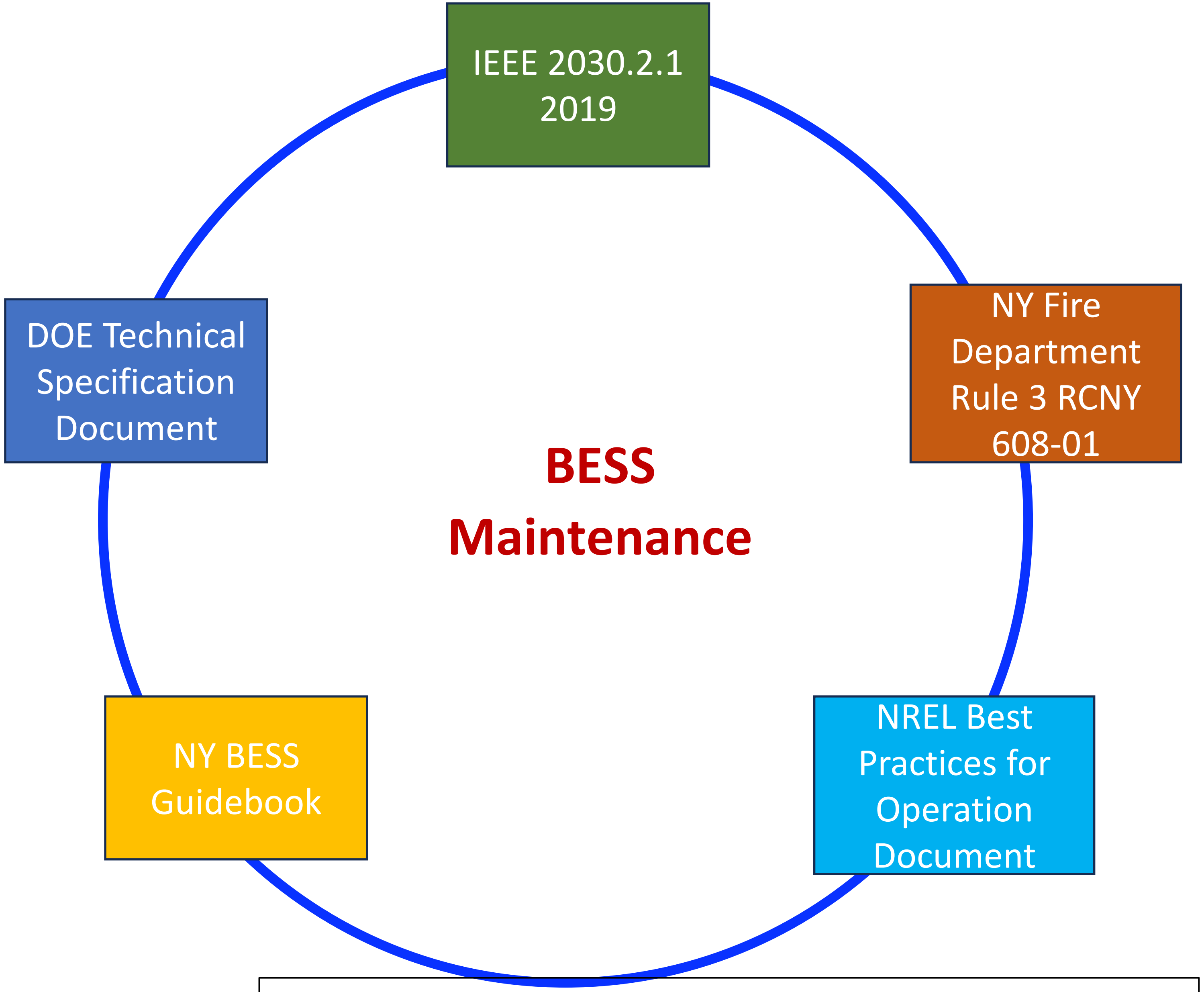
Authorities

- Regulatory Compliance
- Permitting & Approval Process
- Inspection & Audit Programs
- Incident Investigation & Reporting

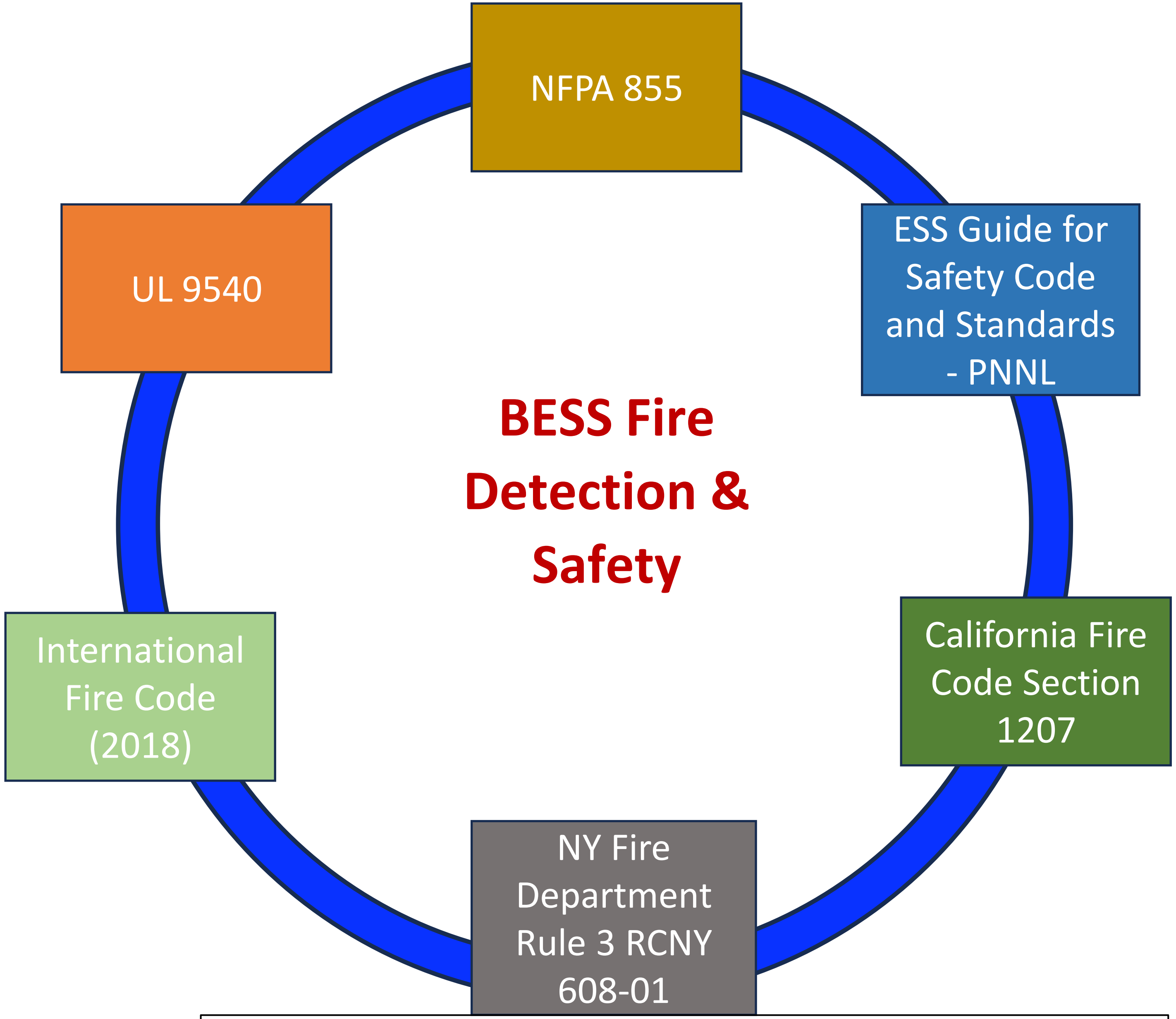
Operators

- Safety Management System
- Maintenance and Inspection Programs
- Training and Competency
- Documentation & Record keeping

Standards and Regulations Relevant to the BESS Maintenance



Codes, Standards Relevant to the BESS Fire Detection and Safety



Standards and Regulations Relevant to the BESS Operation

Standards and Regulations for BESS Operation

- **Safety and Operation Standards**
  - IEC 62619
  - NFPA 855
  - UL 9540A
- **Performance and Reliability**
  - IEC 62933
  - IEEE 1547
- **Interconnection and grid integration**
  - IEC 61850
  - IEEE 1547
- **Emergency response and shutdown**
  - IEEE C-2
  - NFPA 1
  - NFPA 101
  - Other codes listed also provide guidelines on emergency
- **Operation management and control**
  - IEC 62897
- **Cybersecurity**
  - NIST 800-82
  - NIST 800-53
  - NERC CIP-007-6
  - IEEE 2030-2011
  - IEEE 2030.2-2015
  - IEEE 1547-2018
  - IEEE 1547.3-2007
  - NIST IR 7628
- **Environmental and operational impact**
  - Follow local and regional regulations
  - No international code specific to this for BESS
- **Maintenance and inspection**
  - Protocols are governed by manufacturers guidelines and industry practices

Summary

- Few non-Lithium-ion battery chemistries are either in existence and several in research or small scale.
- Vanadium redox flow batteries are the oldest with some dating back to the 1860s (Schmid Group, Germany)
- A full characterization (from cell to battery to entire system) to understand the limitations with respect to safety should be carried out.
- Certifications based on standards should be completed at the battery as well as entire system level.
- Attention should be paid to limitations of the systems that are related to fire, smoke, toxicity, and environmental pollution.
- Maintenance and periodic audits are imperative for safe functioning of long-term energy storage installations.

Back-up Slides

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