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Ensuring Safety of Grid-Scale Energy Storage Systems

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Sandia National Labs

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Agenda

- Rise of grid-scale energy storage
- Li-ion battery safety issues, mitigations
- General hazard analysis
- Codes & standards
- Emerging practices for emergency response and predictive maintenance

Energy storage will play an increasingly important role in the grid

- Renewables integration
- Grid resiliency and reliability
- Improving power quality
- Improving the efficiency of existing generation fleet
- Demand management
- Transmission & Distribution upgrade deferral
- Off-grid applications

Balance the variability of 825 GW of new renewable generation while improving grid reliability and efficiency

Mitigate $100+ B/yr in losses from outages (2017)[1]

Enable electric vehicle integration[2]

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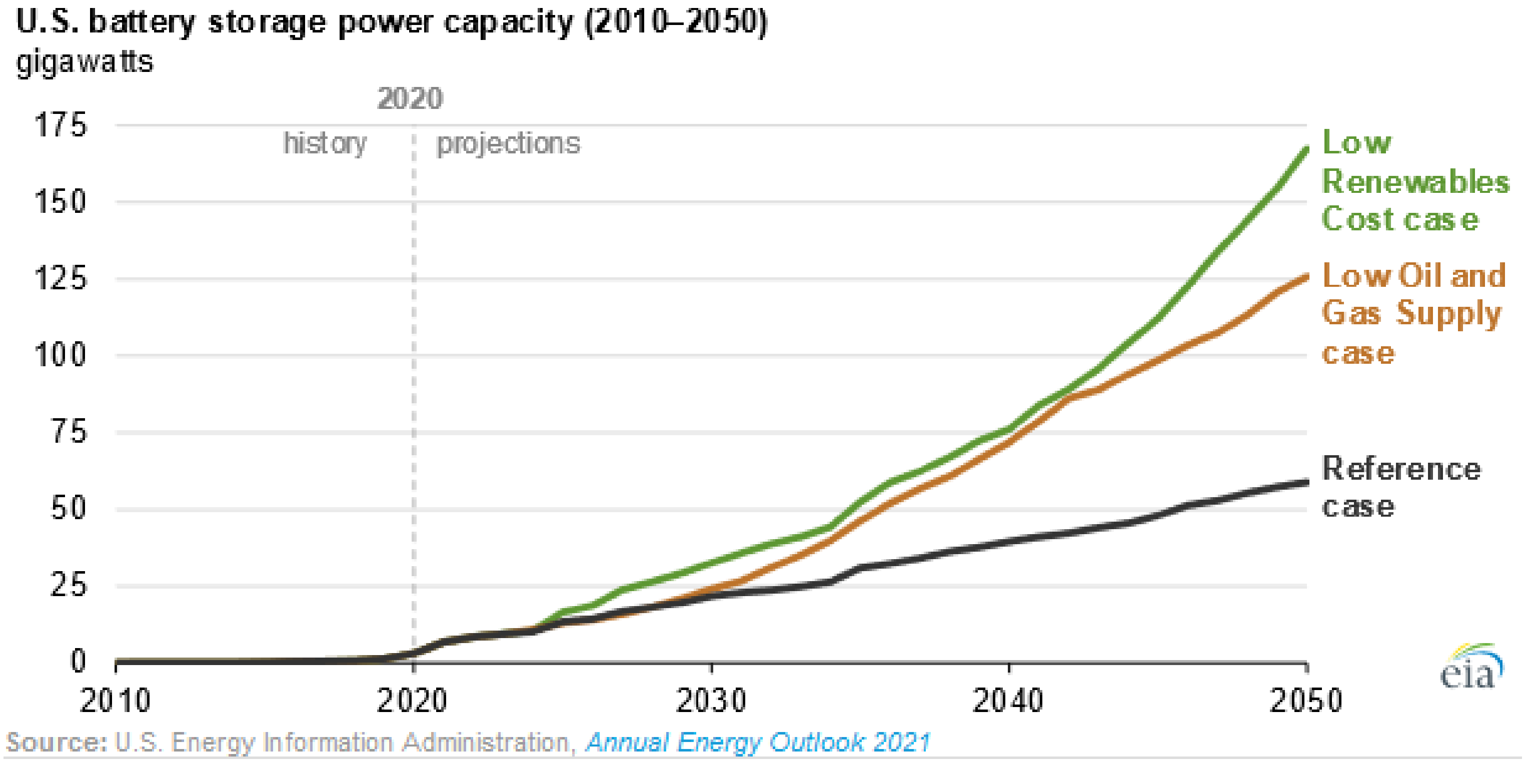
[1]https://emp.lbl.gov/news/online-tool-helps-estimate-power-outage-costs
[2] https://www.forbes.com/wheels/advice/ev-charging-levels/

Batteries will provide substantial grid-scale energy storage

Energy Information Administration Annual Energy Outlook 2021 report projects 59 GW of battery energy storage on the grid by 2050 in the base case, 175 GW if more renewables



https://www.eia.gov/todayinenergy/detail.php?id=47276

Impact and consequence of scale on safety

Consumer Cells (0.5-5 Ah) → Large Format Cells (10-200 Ah) → Transportation Batteries (1-50 kWh) → Utility Batteries (MWh)

Safety issues and complexity increase with battery size

Safety research is heavily focused on lithium-ion as the primary application-ready technology. However, many emerging technologies identified as promising for grid-scale storage are less well studied.

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Grid-scale ESS are the new frontier of battery safety

Korea Times, 2018

IT

Frequent fire raising concerns over safety of solar energy

A fire engulfs an energy storage system at a cement plant in Jecheon, North Chungcheong Province, Monday. / Courtesy of North Chungcheong Province Fire Service Headquarters

By Nam Hyun-woo

A series of fires in energy storage systems (ESSs) has been raising safety concerns, according to industry analysts, Tuesday.

With ESSs essential for optimizing energy efficiency, further accidents may compromise the feasibility of renewable power and hamper the government's bid to expand the use of cleaner energies.

According to the Ministry of Trade, Industry and Energy, it recommended individuals, companies and other organizations to stop using 584 uninspected ESSs across the country.

Greentech Media, 2019

APS and Fluence Investigating Explosion at Arizona Energy Storage Facility

The stakes are high for the energy storage sector after an explosion with an unknown cause left several firefighters injured.

KARL-ERIK STROMSTA | APRIL 22, 2019

Earlier this year APS announced plans to build 850 megawatts of battery storage by 2025.

Fluence has dispatched a team of experts to help utility Arizona Public Service determine what caused an explosion at one of its grid-scale battery facilities. The explosion on Friday reportedly left four firefighters injured, including three who were sent to a burn center.

Firefighters responded to a call on April 19 after smoke was seen rising from APS' McMicken Energy Storage facility, one of two identical 2-megawatt/2-megawatt-hour grid-scale batteries the utility installed in 2017 in Phoenix's growing West Valley region.

According to local press reports, the firefighters were inspecting the facility's lithium-ion batteries when they were hit with an explosion. Several of the firefighters received chemical burns, the local fire department told the *Arizona Republic*.

TOP ARTICLES
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Trump Administ Lowers Import T Chinese...

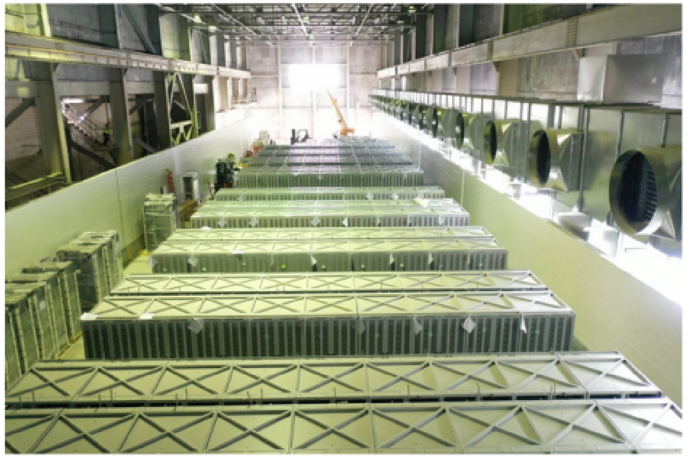
PV Magazine, 2021

Moss Landing energy storage facility knocked offline after batteries overheat

The impacted facility went online in December 2020 and features lithium-ion batteries from LG Energy Solution. Fire crews found scorched battery racks and melted wires.

SEPTEMBER 7, 2021 DAVID WAGMAN

ENERGY STORAGE | ENERGY STORAGE | CALIFORNIA



Battery placement in the Moss Landing turbine hall.

Image: LG Energy Solution

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EPRI database of energy storage safety incidents:
https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database

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Current approaches to Li-ion battery safety enhancement

Safety and reliability are connected to electrochemistry of materials, cell-level interactions, packaging, control architecture, and overall engineering

Development is typically siloed:

Cell Level

(MatSci, Chem, ChemE)

- New positive electrode chemistries
- Higher temperature & fracture-resistant separators
- Non-flammable and solid electrolytes

System Level

(EE, MechE)

- Battery spacing
- Battery management system
- Early thermal runaway detection
- Compact containerization
- Deflagration venting

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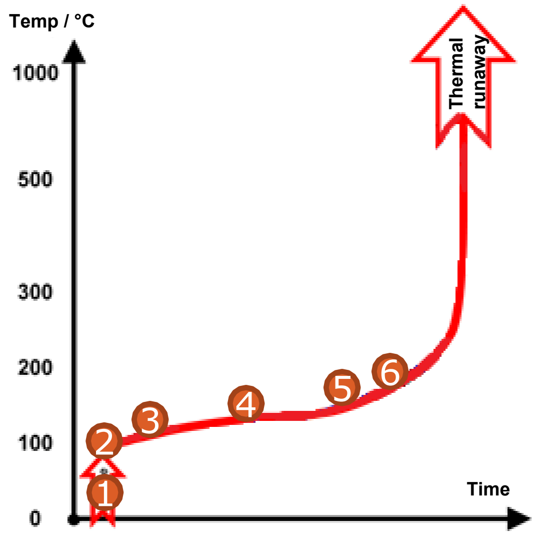
Cell-level: challenges of conventional Li-ion batteries

Li-ion batteries represent >90% of electrochemical energy storage and are expected to dominate for at least next 5 years

Thermal runaway in a Li-ion battery:

1. Heating starts
2. Negative electrode protective layer (SEI) breaks down
3. Negative electrode breaks down with electrolyte
4. Separator melts, possibly causing short circuit
5. Positive electrode breaks down, generating oxygen
6. Oxygen reacts with electrolyte



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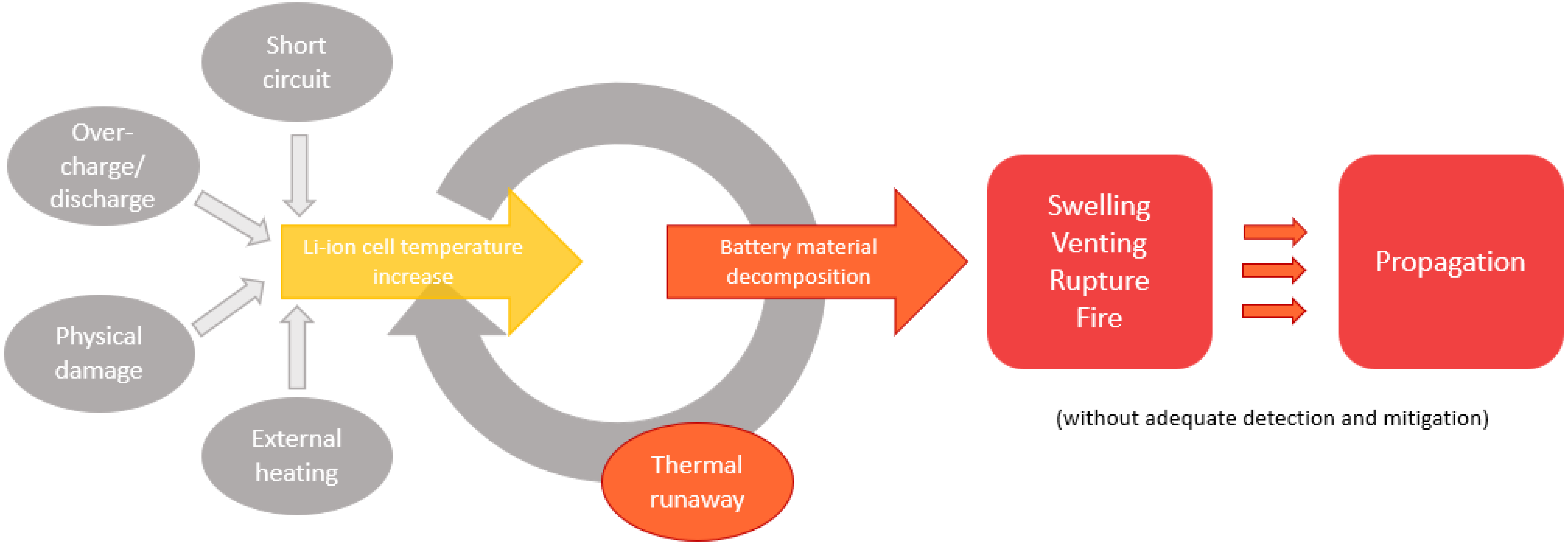
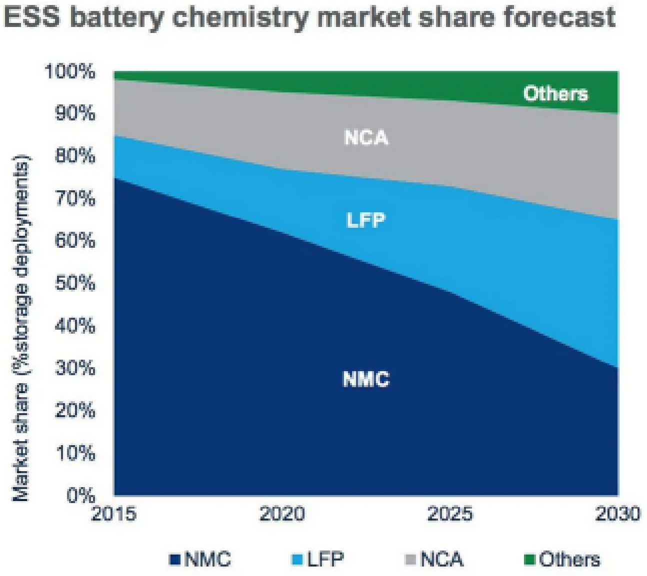
Cell-level: challenges of conventional Li-ion batteries

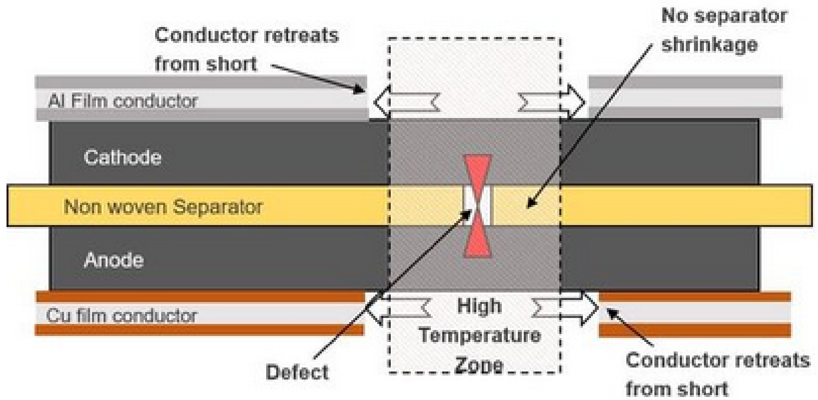
Cells can experience random "field failure" while idle/operating normally (typically short circuit due to contaminant/manufacturing issue): 1 in 1-10 million

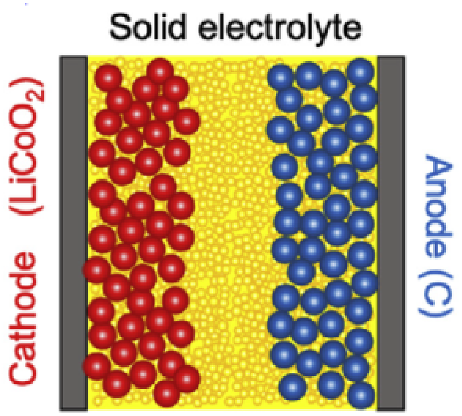
Various abusive conditions can also trigger Li-ion battery thermal runaway



New materials and designs for safer Li-ion cells







Tateyama et al. *Curr. Opin. Electrochem*. 2019, *17*, 149.

New positive electrode chemistries[1]

(Available now)

Higher temperature and fracture-resistant separators[2]

(Becoming available)

Non-flammable and solid electrolytes[3]

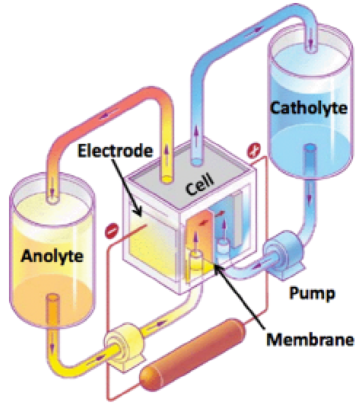
(Mostly still R&D)

1) https://www.greentechmedia.com/articles/read/lfp-will-overtake-nmc-for-stationary-storage
2) https://www.soteriabig.com/technology
3) https://www.asme.org/topics-resources/content/advancing-battery-technology-for-modern-innovations

Development of non Li-ion battery chemistries

There is an increasing push toward 'safe' aqueous batteries

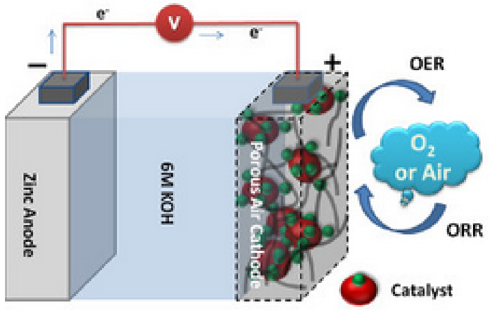
- Aqueous redox flow batteries (mostly vanadium so far)



Chalamala et al. *P. IEEE*, **2014**, *102*, 976.

http://energystoragereport.info/redox-flow-batteries-for-energy-storage/

- Zn-based batteries



https://www.advancedsciencenews.com/new-air-electrodes-zinc-air-batteries/

https://urbanelectricpower.com/commercial-energy-storage-system/

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‘Safer than Li-ion’ does not mean safe

Aqueous electrolyte does not mitigate all hazards

- H_2 generation is possible in aqueous systems
- Generation of other, toxic gases is possible depending on chemistry
- Thermal runaway is possible in some non-flow batteries

Fire damage from VRLA thermal runaway

Due diligence is necessary for any system to understand degradation and failure modes

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Further reading: Wittman et al. “Perspective – On the need for reliability and safety studies in grid-scale aqueous batteries” *J. Electrochem. Soc*. 2020, 167, 090545.

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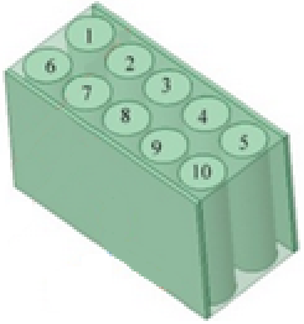
Safety developments beyond the cell

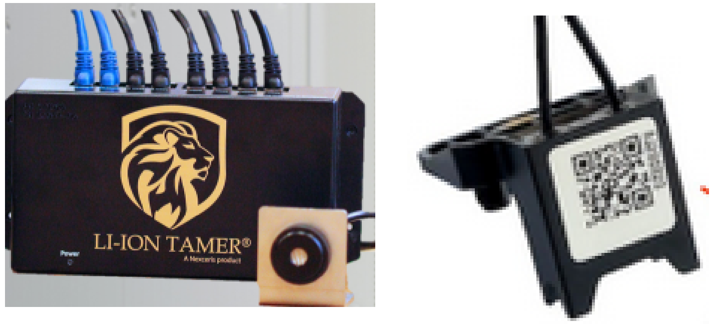


Kshetrimayum et al. *Appl. Therm. Eng.* **2019**, *159*, 113797.

Battery spacing

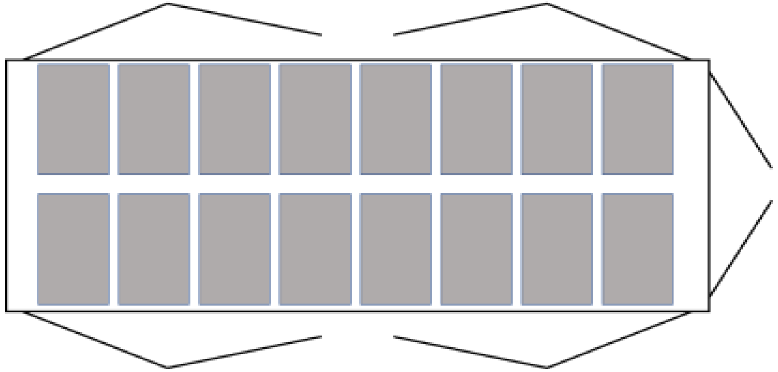
https://avidtp.com/battery-management-systems-bms/

Battery management system



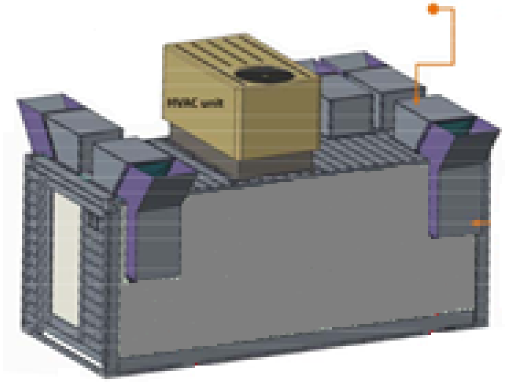
Frank, N. Li-ion Tamer. ESS Safety and Reliability Forum, 2019.
https://www.greencarcongress.com/2020/04/20200422-amphenol.html

Early thermal runaway detection



Torres-Castro et al. "Lithium-ion Batteries" in Elements in Grid Energy Storage, Cambridge Press.

Compact containerization



Hoff, M. GSS Design for Safety. ESS Safety and Reliability Forum, 2019.

Deflagration venting

Understanding component interdependency and developing multiple layers of protection is key to safety

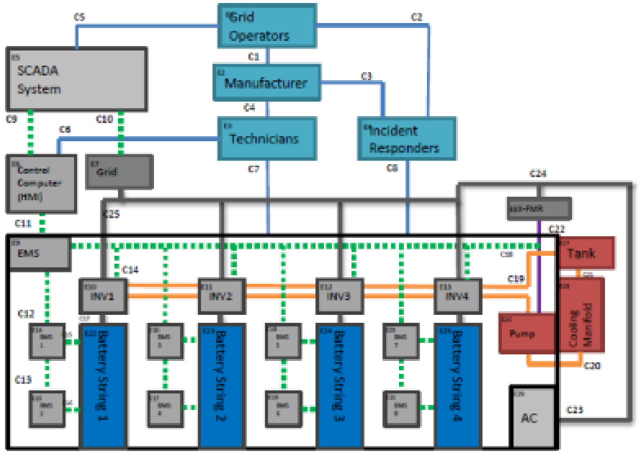


Image Credit: David Rosewater

No one material or device is the silver bullet

The key is understanding how they interact with one another

https://www.yourvalley.net/stories/aps-explosion-in-surprise-goes-viral-world-watching-investigation-of-battery-mishap,12493

All possible hazards must be considered during design stage to ensure measures intended to prevent one hazard don't enhance one another

Ex. If batteries in a closed ESS are in thermal runaway, active fire suppression may be deployed. But, this may cause combustive gas build-up, which will lead to an explosion risk once the container is opened.

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https://www.sandia.gov/ess-ssl/wp-content/uploads/2020/09/Rosewater-APS.pdf

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Even well-established technologies like PSH require thoughtful hazard analysis

December 2005; Taum Sauk Pumped Storage Plant, Missouri, USA

https://www.marshall.edu/cegas/geohazards/2009pdf/7_Water_Brewster_pdf/4_TaumSauk_Reservoir_Schmitt.pdf

Upper reservoir overtopped and damaged due to faulty gauging system and lack of spillway. Over a billion gallons of water drained in less than half an hour, injuring five people and halting power generation for five years.

October 2007; Cabin Creek Generating Station, Georgetown, Colorado, USA

https://www.denverpost.com/why-subscribe-to-the-denver-post/

Highly volatile solvent (methyl ethyle ketone) used during maintenance of epoxy on pipe interiors. Flash fire trapped and led to deaths of five workers.

August 2020; Srisailam Left Bank, Telangana, India

https://www.thehindu.com/news/national/telangana/officials-baffled-at-srisailam-hydroelectric-power-station-fire/article32416687.ece

Fire started in control panel in powerhouse during maintenance. Nine workers died.

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B.R. Chalamala, D.M. Rosewater, Y. Preger, J. Lamb, R. Wittman, A. Kashiwakura “Ensuring Safety of Grid-scale Energy Storage Systems” *IEEE Electrification*, Vol. 9, No. 4, Dec. 2021.

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Guidance from codes and standards

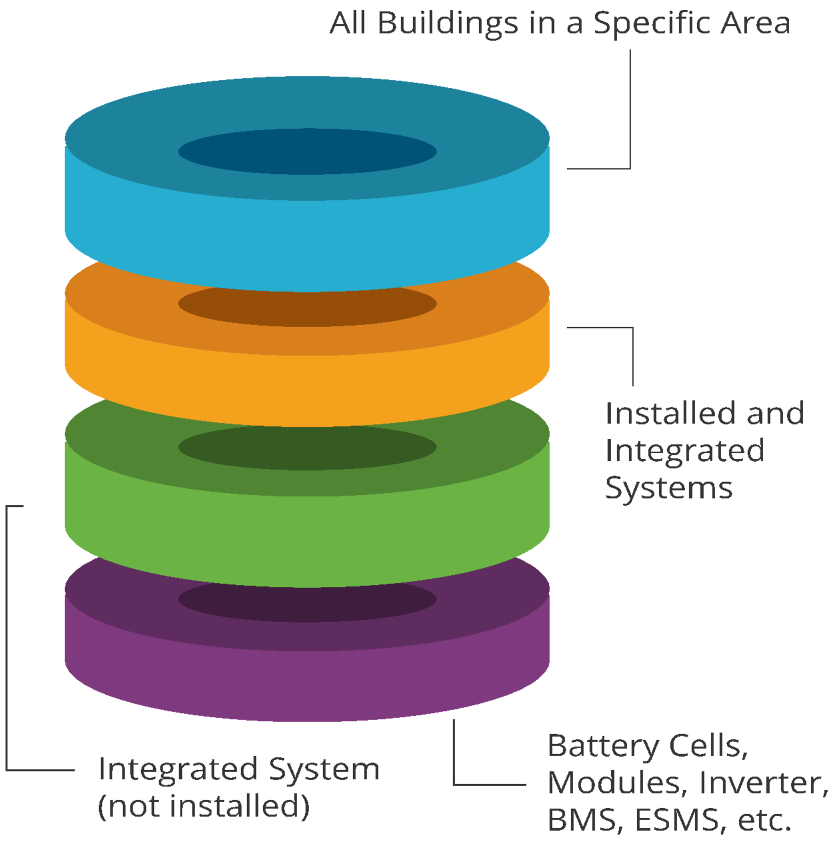
There is a clear trend to increase requirements/regulations on all ESSs, driven by Li-ion concerns

4 **Built Environment**
International Codes – IFC, IRC, IBC
IEEE – C2, SCC 18, SCC 21
NFPA 5000, NFPA 1, ISA

3 **Installation / Application**
NFPA 855, NFPA 70, IEEE C2, IEEE 1635/ASHRAE 21, IEEE P1578,
FM Global 5-33, UL 9540A, NECA 416

2 **Energy Storage Systems**
UL 9540, MESA
ASME TES-1, NECA
NFPA 791

1 **System Components**
UL 1973, UL 1974, UL 810A, UL 1741,
CSA 22.2 No. 340-201, IEEE 1547, IEEE 1679



B.R. Chalamala, D.M. Rosewater, Y. Preger, J. Lamb, R. Wittman, A. Kashiwakura "Ensuring Safety of Grid-scale Energy Storage Systems" *IEEE Electrification*, Vol. 9, No. 4, Dec. 2021.

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ESS safety codes & standards that are making waves

Subscribe to the DOE Energy Storage Safety Collaborative Quarterly Codes & Standards Update: https://www.sandia.gov/energystoragesafety-ssl/

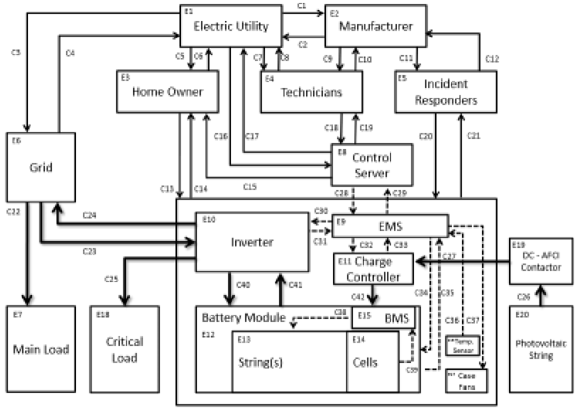
Limitations of codes and standards

Standards are developed in working groups using accident data + operational experience

- Useful for specific guidance for most common accidents
- Slower to respond to new technologies, applications, and hazards
  - E.g. NFPA 855 development began in 2016; 1st edition published: 09/2019
- **Adhering to standards is not enough; still need to do a thorough hazard mitigation analysis**

Standards are insufficient to prevent all accidents, but still serve an important role

- Difficult to judge quality of full system safety analysis, but easy to check if system complied with standard



Hundreds of pages of analysis…

Compliance to standards	
Cell safety	UL 1642, IEC 62619
Module safety	EN 50178 / IEC 60950
Container safety	IEC 61508 (SIL1)
EMC	IEC 62 040-2 Cat C1 and C3
Container protection class (operation)	IP 33
Container dimension and transport	ISO668
Container corrosion protection	ISO 12944 Level C5I
Seismic	Eurocode zone 5 / IEEE 693 high level
Environment	IEC 60721 (dust, chemical / biological pollution, wind, precipitation, fire exposure)
Transport classification	UN 3480 - Class 9
Transport regulation compliance	UN 3480 - ST/SG/AC.10/11 Rev 5 § 38.3
Marking	CE
Directives	ROHS, REACH, WEEE
Manufacturing plants	ISO 9001, QS 9000, ISO 14000
Noise	56 dB at 2 m

Source: Saft, Seanergy Battery System Datasheet

Single page summary of standards compliance

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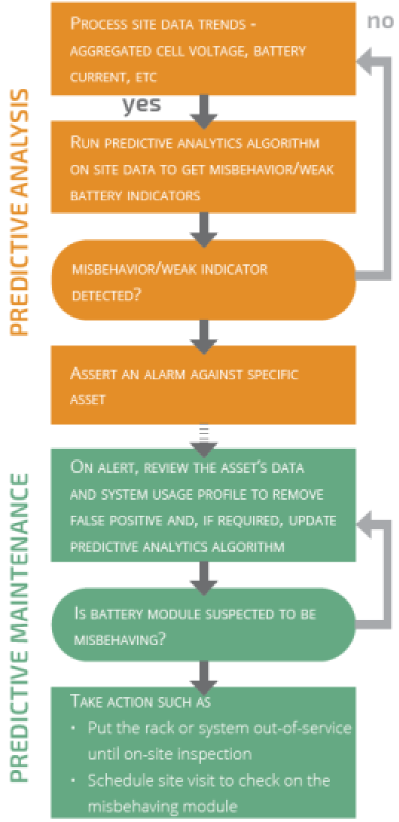
Emerging areas of emphasis for energy storage safety

Training first responders

Predictive maintenance



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See Alarm Response Management section in "Electrical Energy Storage Data Submission Guidelines, v 2" Electric Power Research Institute & SNL, 2021. 3002022119.
Fioravanti et al. "Predictive-Maintenance Practices: For Operational Safety of Battery Energy Storage Systems" *IEEE Power and Energy Magazine*, Vol. 18, No. 6, pp. 86-97, Nov.-Dec. 2020.

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Training first responders – best practices

Pre-fire

- Consult with them during the ESS installation process
- Develop an emergency response plan
- Clarify all of the points of contact: system operator, SMEs, etc.

At the scene

- Provide ready access to system data (e.g. what are the alarms, gas levels, etc.)
- Develop guidance for when to put the fire out vs. let it burn

Post-fire

- Decide on how to deal with damaged batteries
- Identify appropriate monitoring procedure in case of reignition

Adapted from: Paul Rogers, retired FDNY, presentation at Resilience Week 2020
For further info: energyresponsegroup.com

Training first responders – new US national programs

Lead Organization	Target Audience	Description
NFPA[a]	Firefighter	Self-paced online Energy Storage and Solar Systems Safety Training, Fire Service Edition. 3-hour module uses engaging videos, animations, simulations, and review exercises to inform firefighters about basic electrical theory, types of PV installations, battery chemistries, and response strategies.
NFPA[b]	Firefighter	Develop a suite of training tools, including a multiplayer serious gaming platform with several energy-related incidents at each scene.
IAFF[b]	Firefighter	Develop training programs by testing installed residential energy storage systems to understand what happens when batteries fail and pose risks to emergency responders.
IREC[b]	Building Officials	Introduce educational materials and resources on clean energy codes, standards, permitting and inspection for those interacting with solar energy and storage systems
Southface Energy Institute[b]	Building Officials	Create educational programming and resources that can be tailored to different markets and jurisdictions
New Buildings Institute[b]	Building Officials	Develop guides and education modules to streamline the design, permitting, inspections, and maintenance of solar, storage and electric-vehicle charging stations for single- and multifamily homes and offices.

[a]Existing training.
[b]Training under development (as of December 2020).

Predictive maintenance

“One of the major lessons learned from [that] project and others was the idea of "Day two" management and anticipation, in other words, how will maintenance look once the project itself is completed?”

- National Grid (Utility Dive, Feb. 2020)

Predictive maintenance may help identify reliability issues that crop up after initiating operation

- Standards emphasize factory testing, commissioning, and emergency response rather than O&M
- Current maintenance guides focus on routine inspection
- Important to identify recoverable faults; typical steps taken to contain ESS failure result in total loss of unit

“Electrical Energy Storage Data Submission Guidelines, v 2” Electric Power Research Institute & SNL, 2021. 3002022119.
Fioravanti et al. “Predictive-Maintenance Practices: For Operational Safety of Battery Energy Storage Systems” *IEEE Power and Energy Magazine*, Vol. 18, No. 6, pp. 86-97, Nov.-Dec. 2020.

Conclusions

- There are many avenues to enhance safety at both the battery and system level, but no silver bullets
  - Everything needs to be properly integrated
- Need to analyze degradation/failure modes of any battery and energy storage technology, even if not Li-ion
- Adherence to codes and standards is the minimum
  - Need risk assessment/hazard mitigation analysis for integrated system
- Need to work with first responders during ESS installation process
- Moving beyond Day 1: what does maintenance look like after the project is completed?

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