This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2020-2786C

Yuliya Preger, Ph.D.

Sandia National Laboratories

SYSTEM SAFETY AND RELIABILITY

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Safety of ESS is getting increasing media coverage

Bloomberg

Hyperdrive

Explosions Threatening Lithium-Ion's Edge in a Battery Race

By Brian Eckhouse and Mark Chediak
April 23, 2019, 4:58 PM MDT *Updated on April 24, 2019, 8:24 AM MDT*

- Battery exploded at plant in Arizona; two others were shut
- Arizona utility regulator calls for 'thorough investigation'

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4:52

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Another lithium-ion battery has exploded, this time at an energy-storage complex in the U.S.

At least 21 fires had already occurred at battery projects in South Korea, according to BloombergNEF. But this latest one, erupting on Friday at a facility owned by a Pinnacle West Capital Corp. utility in Surprise, Arizona, marked the first time it has happened in America since batteries took off globally.

Greentech Media

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

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
MOST POPULAR
MOST COMMENTS

Korea Times

Frequent fire raising concerns over safety of solar energy

By Nam Hyun-woo

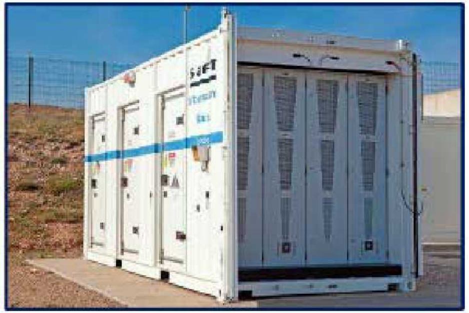
A series of fires in energy storage systems (ESSs) has been raising safety concerns, according to industry analysts, Tuesday.

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.

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

IEEE PES Power & Energy Society® IEEE

Current approaches to safety enhancement

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

Research typically siloed:

Cell Level

(MatSci, Chem, ChemE)

- New positive electrode chemistries
- Non-flammable and solid electrolytes
- Electrode coatings
- Overcharge protection
- Higher melting separators

System Level

(EE, MechE)

- Battery spacing
- Battery management system
- Advanced failure detection
- Suppressants
- Deflagration venting

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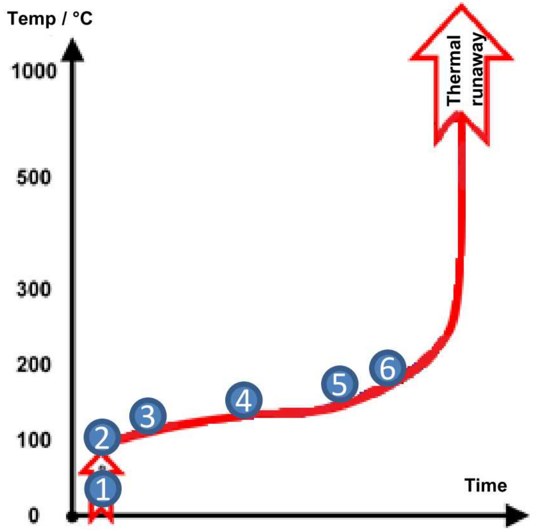
Cell-level: challenges of conventional Li-ion batteries

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

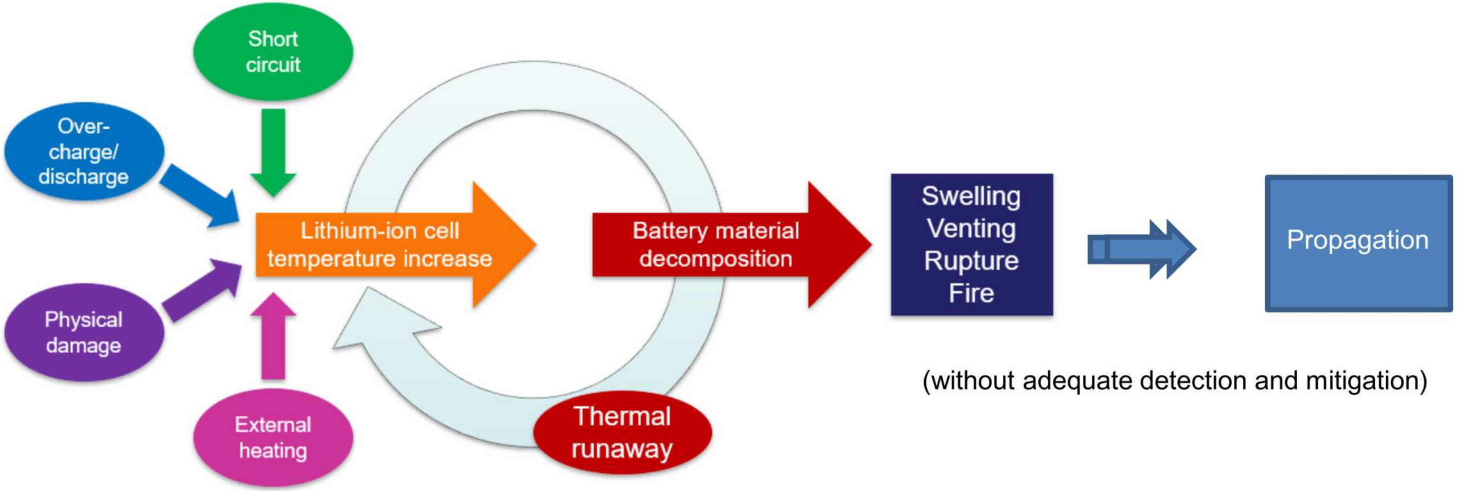
Thermal runaway in a Li-ion battery:

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

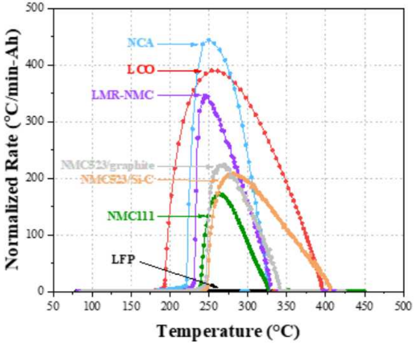


Cell-level: challenges of conventional Li-ion batteries

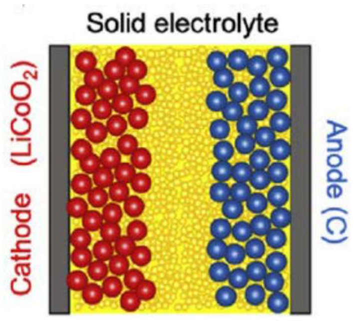
Various abusive conditions can trigger Li-ion battery thermal runaway



New materials for safer Li-ion cells

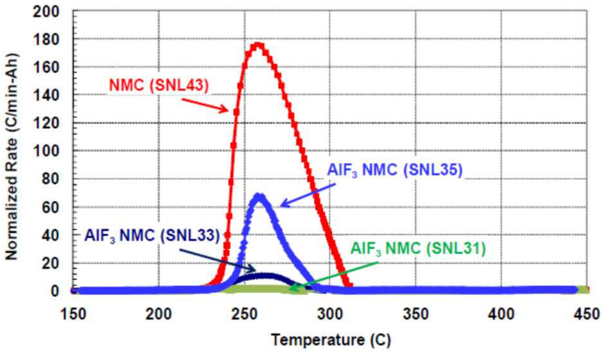


New positive electrode chemistries

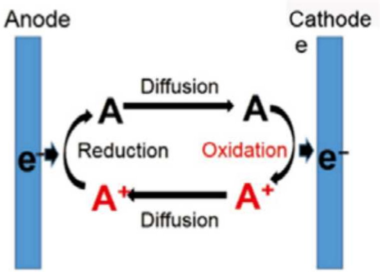


Tateyama et al. *Curr. Opin. Electrochem.* **2019**, *17*, 149.

Non-flammable and solid electrolytes

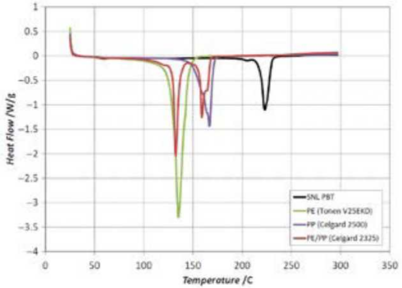


Electrode coatings



Liu et al. *Sci. Adv.* **2018**, *4*.

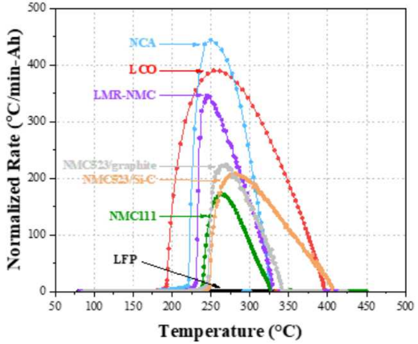
Overcharge protection



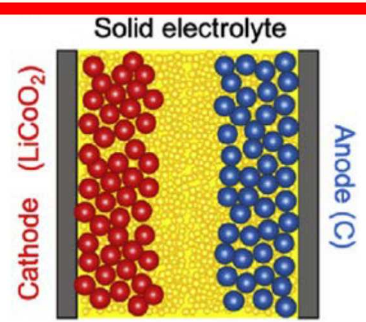
Orendorff et al. *Adv. Energy Mater. 2013, 3, 314.*

Higher melting separators

New materials for safer Li-ion cells



New positive electrode chemistries



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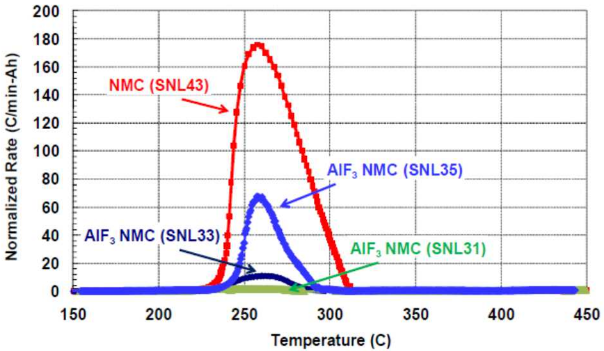
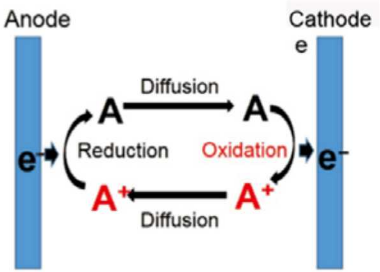
Non-flammable and solid electrolytes



Electrode coatings



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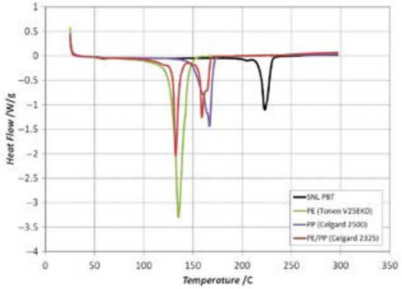

Orendorff et al. *Adv. Energy Mater. 2013, 3, 314.*

Higher melting separators

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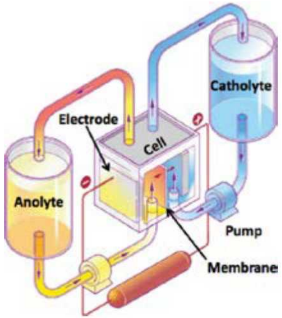
Development of non Li-ion battery chemistries

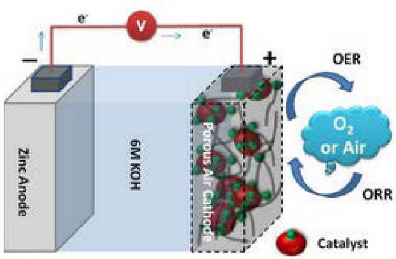
Increasing push toward 'safe' aqueous batteries

- Aqueous redox flow batteries (mostly vanadium so far)
- Zn-based batteries



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

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



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

https://www.greentechmedia.com/articles/read/eos-inks-deal-with-holtec-to-scale-up-battery-manufacturing

‘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 gases is possible depending on chemistry
- Thermal runaway is possible in some non-flow batteries

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

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System Level

(EE, MechE)

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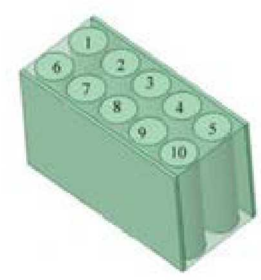
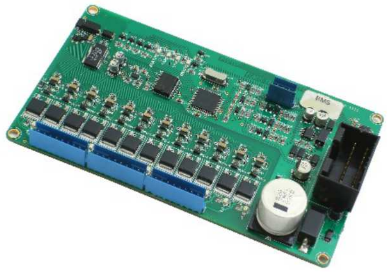
- Deflagration venting

Safety developments beyond cell materials



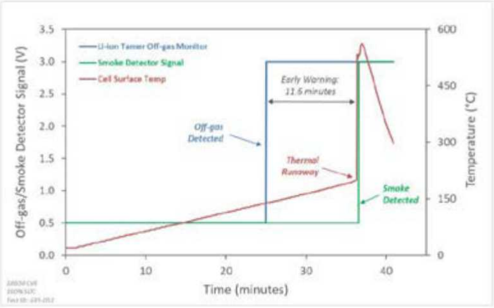
Kshetrimayum et al. *Appl. Therm. Eng.* **2019**, *159*, 113797.

Battery spacing



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

Battery management system



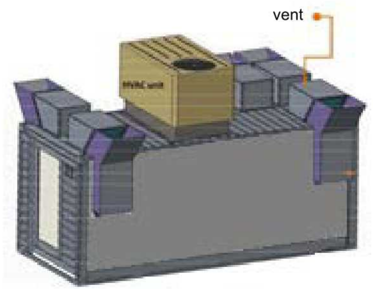
Frank, N. Li-ion Tamer. ESS Safety and Reliability Forum, 2019.

Advanced failure detection

https://www.solarpowerworldonline.com/2017/04/trinabess-introduces-trinamega-large-scale-storage-solution-u-s-market/

Suppressants

(clean agent vs. water)



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

Deflagration venting

Understanding component interdependency is key to safety

No one material or device is the silver bullet

The key is understanding how they interact with one another

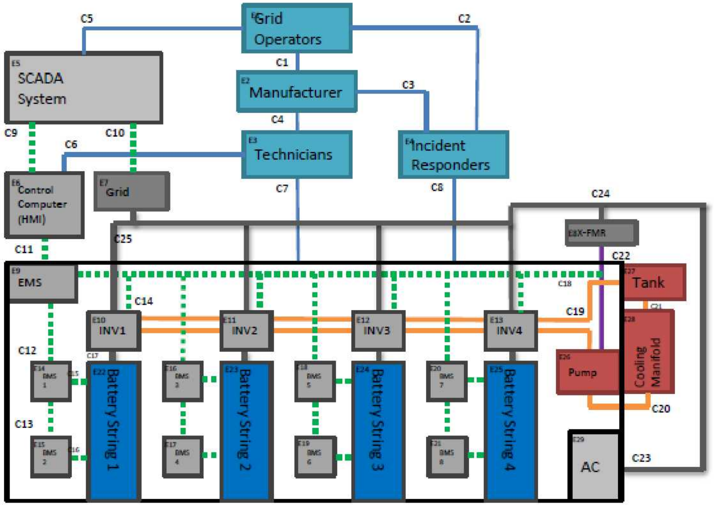


Image Credit: David Rosewater

Safety considerations incorporate diverse issues

- Siting (location, protection, egress/access, separation)
- Ventilation, thermal management, exhaust
- Interconnection with other systems (electrical, non-electrical sources)
- Fire protection (detection, suppression)
- Containment of fluids (from ESS and incident response)
- Signage

Analysis methodologies to enhance safety

Approaches involve qualitative/quantitative risk assessment or hazard mitigation analysis

- Each has pros and cons
- Applicable to any ESS (e.g. Li-ion or flywheel)

Probabilistic Risk Assessment

Accidents happen because the components of a system fail

Systems Theoretic Process Analysis

Accidents happen when component interactions violate safety constraints

Probabilistic risk assessment

Accidents happen because the **components** of a system fail

Analysis answers three questions:

1. **What** can go wrong?
2. How **likely** is that?
3. How **bad** would that be?

Techniques: Fault tree, FMEA, etc.

Where it works

- Lots of historical knowledge on failure modes

Problems

- Hard to apply in early products
- Probability assessment can be subjective

Example Fault Tree: If…

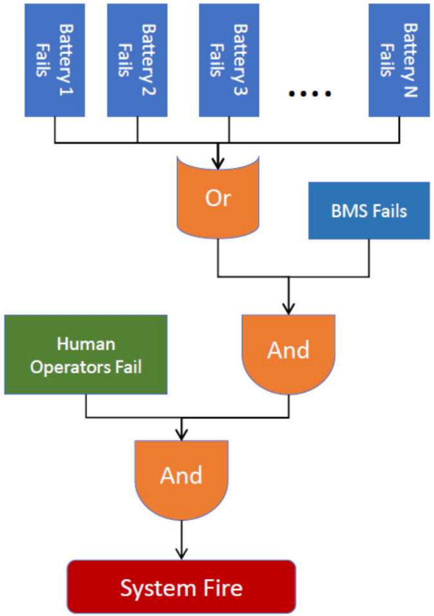


Image Credit: David Rosewater

Example: failure modes and effects analysis

Component	Failure Mode	Hazard Effect	Consequence	Prevent	Detect	Probability, Severity	Expected Value for Risk
BMS	System doesn't operate safely through normally expected temperature operating range	Fire	Safety incident	BMS testing	Independent temperature sensor	3, 10	30
Battery Cell	Group of failures	Fire	Safety incident	Abuse testing	Fire alarm	3, 9	27
Inverter	Inverter fails to detect/react to over temperature IGBTs	Loss of function	Power output de-rating	Rely on supplier		3, 4	12

Table Credit: David Rosewater

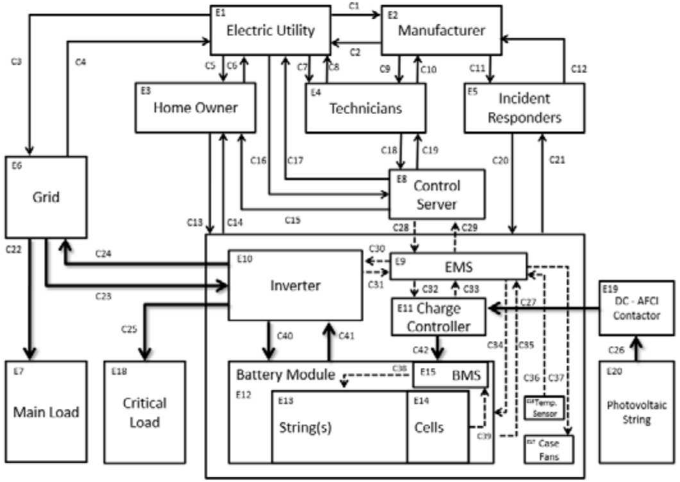
Systems theoretic process analysis

System = collection of interacting control loops

Accidents happen when component interactions violate **safety constraints**

Analysis answers three questions:
1. What are hazardous **control actions**?
2. What are the **causal factors**?
3. Unsafe interactions between **multiple controllers**?

Example Control Structure



Rosewater et al. *J. Power Sources*, **2015**, *300*, 460.

Where it works
- New development of complex systems

Problems
- Complexity and volume of results can make it unmanageable

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Regardless of the analysis approach…

Not a box checking exercise for code compliance

- All relevant codes/standards are applicable regardless of assessment conclusion
- Codes and standards are a starting point

Not about manipulating the numbers to pass requirements

- Does not serve anyone in the end

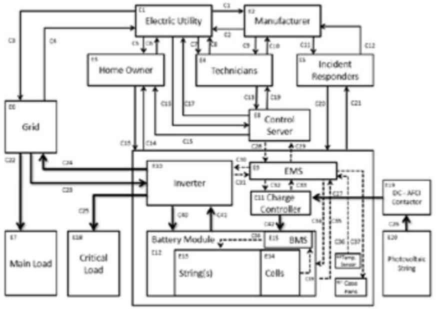
Limitations of codes and standards

Standards 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

Insufficient to prevent accidents, but still critical

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



Hundreds of pages of analysis…

vs.

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

Accidents are still happening – what's missing?

23 ESS fires in South Korea since 2017 → ~500 ESS units shut down in Jan. 2019

Gaps identified in what may best be described as "**Random errors in design, installation**"

- Faults developed in installation (e.g. wiring)
- Limited protection against electrical shocks (e.g. ground faults)
- Poor integration between battery/energy/power management systems
- Inadequate environmental control (e.g. humidity/temperature swings degrade electronics)

Outcome was Li-ion battery fires, but causes are not battery-specific

Accidents are still happening – what's missing?

"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)

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

Limited emphasis in standards (so far)

Possible approach:

- Create list of faults linked to leading indicators
- Determine if indicators are tracked in current systems
- Finalize check-list of indicators

Conclusions

- Many research efforts to enhance safety at both battery and system level
  - No silver bullets; everything needs to be properly integrated
- Need to analyze degradation/failure modes of any battery, even if not Li-ion
- Adherence to codes and standards is the minimum
  - Need risk assessment/hazard mitigation analysis for integrated system
- Moving beyond Day 1: what does maintenance look like after the project is completed?