Only you can prevent lithium battery fires

The seasonal wildfires plaguing California did not emerge unexpectedly, without forewarning. For as long as we have had modern electricity, engineers have known that overgrown trees, high winds, and high-voltage transmission lines can pose a dangerous combination. We understand the risks posed by conventional grid infrastructure, and the potential for energy storage to mitigate risk by reducing the need for high-voltage transmission.

However, lithium batteries are not without risks of their own. In fact, firefighters in Arizona suffered injuries responding to a lithium battery fire in April 2019. And one of the world's largest lithium battery makers has observed safety failures from its own systems in Korea.

Storage project developers and EPCs can address the safety risks posed by lithium batteries right away. There's no need to wait for policy changes or new regulations to take effect. The small steps that we as an industry take now can help lithium batteries provide a safer alternative to conventional grid infrastructure, instead of replacing one type of risk with another. First, we need to understand why everyone is underestimating lithium battery risks, in spite of mounting evidence that they can cause fires. Next, we need to know the right questions to ask about lithium battery production, testing and performance to mitigate risk during the procurement process. Lastly, we need an example of how to manage risk during lithium battery project design and engineering.

Let's get started.

Why people underestimate battery risks

If you compare cars based on the initial purchase price, there's a good chance you, like many US consumers, will buy a gas-powered car. You might not know it, but your total cost of ownership will probably be higher than if you'd bought an electric car. Though electric cars generally cost more upfront, they have lower fuel costs and operating costs.

This isn't new information, either. We've known for years that electric cars are cheaper to own.

We also know that lithium batteries, the same kind of batteries used in electric cars, increase project risks when deployed in stationary energy storage systems. The risk factors associated with lithium batteries—degradation, thermal runaway, hazardous materials, disposal and recycling costs, ongoing development of codes and standards, and more—are also well documented. As a result, project developers put their return on investment at risk each time they opt to store energy with lithium batteries.

So why do they do it?

Unlike a car buyer, who might not know how to calculate total cost of ownership, or who might be emotionally attached to a certain kind of car, project developers are motivated chiefly by financial returns. But there are three main reasons they are most likely underestimating the risks that come with lithium batteries.

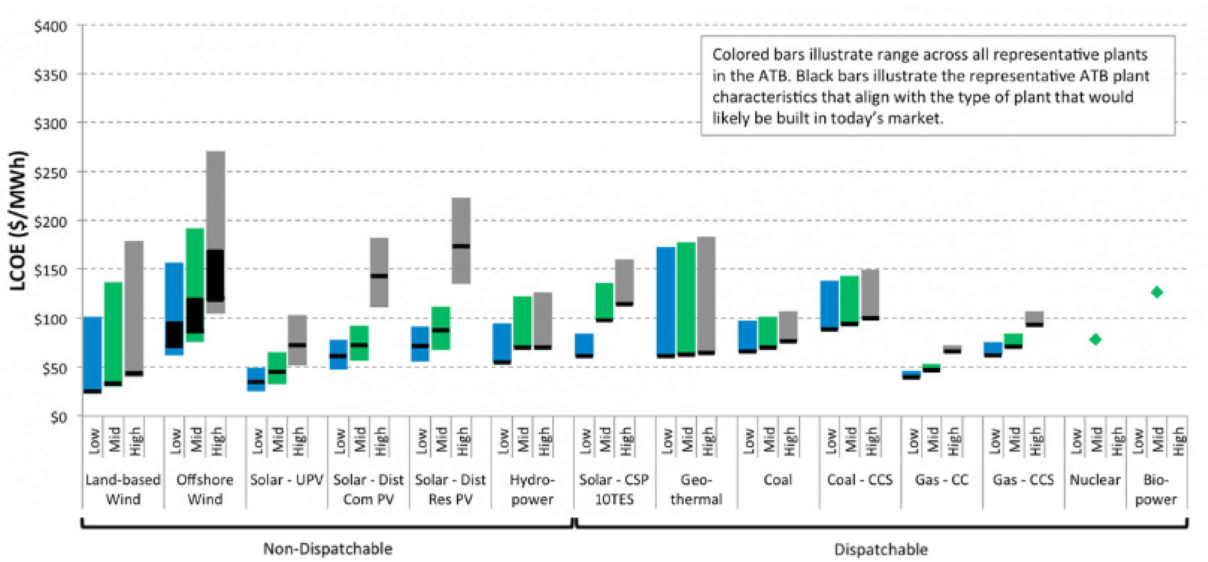
1. Energy markets tend to favor projects with the lowest capital expenditures.
2. The realities of grid insecurity have not sunk in… yet.
3. The need for more resilient energy systems is going to require a different approach to project design and engineering.

In addition, there is the assumption of false equivalence, that stationary lithium batteries interconnected with the utility grid have a similar risk profile as the lithium batteries in our cell phones, laptops, and electric vehicles. They do not, as we'll discuss in Section 2, "Evaluating lithium batteries for safety."

For the love of CapEx

Renewable energy industries have been hyper-focused on cost reduction to achieve parity with traditional energy sources for years.

Parity for solar energy production isn't on the horizon. It's here. Utility-scale solar costs have decreased by 13% year-over-year, putting it on par with traditional electricity sources. C&I rooftop solar has also achieved parity with coal. In fact, April 2019 was the first time that renewable energy outpaced coal in total energy generation in the US.



2017 ATB LCOE range by technology for 2030 based on current market conditions
Source: National Renewable Energy Laboratory Annual Technology Baseline (2017), http://atb.nrel.gov

However, in terms of the levelized cost of energy, energy storage still has a ways to go. While electricity from a rooftop C&I solar project may cost anywhere from 7.5 cents to about 15 cents per kilowatt-hour, according to Lazard's Levelized Cost of Energy and Levelized Cost of Storage 2019 analysis, storage increases costs considerably. Electricity from a C&I solar-plus-storage project costs 22 to 38 cents per kWh. Electricity from a stand-alone C&I storage project would cost 48.5 cents to $1 per kWh.

So projects with batteries often try to use the smallest battery possible to minimize upfront costs and reduce utility bills as much as possible. This is an economical solution to an economic problem, one that drives developers to optimize for the best return on investment.

But what good is the return on investment of a small-scale energy storage project if the grid goes down and the storage capacity isn't large enough to keep your business operating?

When the grid goes down, costs go out-of-control. The Department of Defense recorded 127 outages that lasted 8 hours or more in 2015, costing them over $179,000 per day. For many businesses, these costs can be ruinous. Instead of designing small batteries, we should be selling the biggest battery to maximize resilience and protect against grid outage risks.

This is an economic solution to a risk management problem.

Grid insecurity hasn't sunk in

The power grid isn't a monolith of energy. Natural disasters can knock it down. In 2017, for example, Hurricane Maria left 80% of Puerto Rico without power. In 2018, the Camp Fire in Northern California caused over 60,000 residents to lose power. We've seen similar grid disturbances across large parts of the Atlantic Coast after Superstorm Sandy in 2012 and along the Gulf of Mexico after Hurricane Katrina in 2007. Wildfires in California have all left their mark. No part of the country and no section of the electric grid anywhere in the US is completely safe from extreme weather events.

In some cases, communities even have had access to solar power and electric vehicles but couldn't get energy out of these assets because the grid failed. Solar by itself and solar plus storage don't necessarily prevent electricity systems from going down. Moreover, these distributed energy resources may not work when the power grid fails. There's a common misconception that solar (and storage) systems will function seamlessly during a power outage. Without microgrid capabilities, they won't.

Businesses don't always quantify and plan around the potentially crippling cost of a grid outage. By the same token, they usually don't quantify and plan around the revenue streams that batteries can create, either. In addition to qualifying for state and federal incentive programs, batteries can create long-term revenue streams from demand charge reduction, time-of-use bill management, and solar self-consumption.

One part of the problem is that incentives and policies don't encourage businesses to invest in resilience. We've come to expect that the electric grid will continue to function as a big battery without interruption. Meanwhile, as extreme winds, wildfire and flooding have become increasingly common, the evidence is mounting that we can no longer rely on the grid as we have in generations past.

The California Solar & Storage Alliance is currently working on building more resilient utility power models in the wake of national disasters rendering California's energy grid in crisis. These plans are still in motion. To see how electrical design and engineering can promote resilience, let's look at companies engaged in disaster relief and recovery.

Designing for resilience

Projects designed for disaster relief and recovery aren't judged narrowly by their ability to generate revenue but rather to supply electricity for critical loads. Think of this like subsidized insurance, but instead of insuring real property you're insuring electricity assets.

A resilient battery functions as insurance because you need it to manage risk, but like insurance, you hope to never use it. It's considered to be subsidized because when the electric grid is operating, the resilient battery can reduce energy costs, helping pay for itself. A traditional backup gas or diesel generator can't do this.

Industry research in 2016 found that power outage costs were over $27 billion annually for a group of eight market segments representing mid-size and large businesses in North America. When those businesses have data centers, the costs are much higher. A single minute of data center outage can cost $8,851.

These outages aren't uncommon with today's power grid. A survey of manufacturers showed that over 25% experienced at least one power outage a month in 2017. For 58% of these companies, outages lasted over an hour.

It's difficult to quantify just how expensive a power outage can be. It depends on the business. Let's say that you generate $5 million a year. Therefore, revenues are $13,700 per day. If we only consider productivity — which is just one of the many buckets of cost associated with an outage — you lose $13,700 in a one-day outage. If we assume you experience only one outage per year, lost revenue is $274,000 over 20 years.[1]

Now, assume you can generate $20,000 per year in revenue from demand-charge reduction, time-of-use billing and other bill-saving measures created by the batteries you installed. Over 20 years, revenue adds up to $400,000.

Combine the insurance benefit of the battery with the subsidy benefit of battery, and you have an estimated savings of $674,000.

If turnkey installation for the battery system costs $650 per kilowatt-hour, you can finance up to about 1 megawatt-hour of energy storage based on lifetime savings only.

You can also design the system in a variety of ways. For example, you can have 1 MW of storage lasting 1 hour, 500 kW of storage lasting 2 hours, or 100 kW of storage lasting 10 hours. If you pair solar generation with the battery, the system becomes even more resilient with the ability to recharge independently from the grid.

1 This example, for illustrative purposes, does not incorporate discount rate and the time value of money.

Having all this resilience and flexibility to use as needed, in real-time, can be incredibly valuable. Asset owners can even make a profit. If a battery customer only needed 250 kWh, then the cost calculation goes like this:

20-year battery cost: $650/kWh x 250 kWh = $162,500

20-year battery revenue: $274,000 + ($400k / 5) = $354,000

Net 20-year cost to customer = cost - revenue = $162,500 - $354,000 = -$191,500

A negative cost means that the customer is making money. Even without calculating O&M, discount rates, escalators, and financing costs, the conclusion is clear: resilient batteries can deliver significant value for C&I customers.

Evaluating lithium batteries for safety

Lithium battery safety is not rocket science. Manufacturers with a robust set of production data can show customers success rates for their batteries and the conditions that cause batteries to fail. The problem is that very little safety data is accessible to most buyers or the public.

Buyers will always have to decide for themselves how much risk they are willing to tolerate. Some source batteries from a selective group of original equipment manufacturers (OEMs) and pay a premium to avert risks associated with the lowest-priced batteries. But many buyers are operating in the dark, lacking the safety data they would need to make an informed decision.

Consequently, the energy storage industry in its brief history has already witnessed dangerous and damaging lithium battery safety incidents, including the April 19 fire at Arizona Public Service's McMicken Energy Storage facility. Other notable incidents include a lithium battery fire and subsequent battery malfunction that led the Federal Aviation Administration in 2013 to ground Boeing's entire 787 Dreamliner fleet. The next lithium battery fire can happen almost anywhere, anytime.

To safeguard against fire risks, ask lithium battery makers the questions about cell production and testing in this post. Battery buyers don't have to wait for technology development or new regulations. They can bring about a new safety standard by demanding better safety data and buying lithium batteries only from OEMs that make the data available.

Questions to ask about cell production

Some online shoppers go to commerce platforms like Kickstarter for innovative products and products that may be available at a significant discount from an upstart manufacturer. When sourcing lithium batteries, you want to take the opposite approach. Instead of pursuing innovative products, look for proven products that have a long track record of consistent production. Instead of hunting for discounts from unknown suppliers, expect to pay fair value for a product that has completed a rigorous safety analysis and achieved an exceptionally low failure rate.

How many battery cells and battery packs does your supplier produce each year?

One lithium cell represents one data point. The more cells you produce, the more data you have. As such, the highest-volume producers have the most data on performance, thermal runaway, and failure.

For this reason, an OEM producing 10 million cells per year should have a better understanding of cell safety and performance. Large-volume manufacturers have probably seen every possible failure occur many times. By the same token, a small-volume manufacturer needs more time to analyze and understand cell failure. Buying cells from small-volume manufacturers may carry more risk.

What changes have been made to the battery cell and battery pack production process?

A consistent manufacturing process yields predictable safety and performance results. It's plain to see that different cell materials bring about different cells. But different production equipment can affect safety characteristics just as much. Even if the materials and equipment stay the same, a manufacturer that relocates production may alter a host of environmental conditions and other variables that affect results. Changes in relative humidity, temperature range, and impurities in the air can impact safety characteristics of lithium cells. Differences in quality control and other processes introduced by a new manufacturing technician crew can also have an effect. All these changes should be understood and quantified in a prudent lithium battery safety analysis.

How does your supplier handle material acceptance and storage?

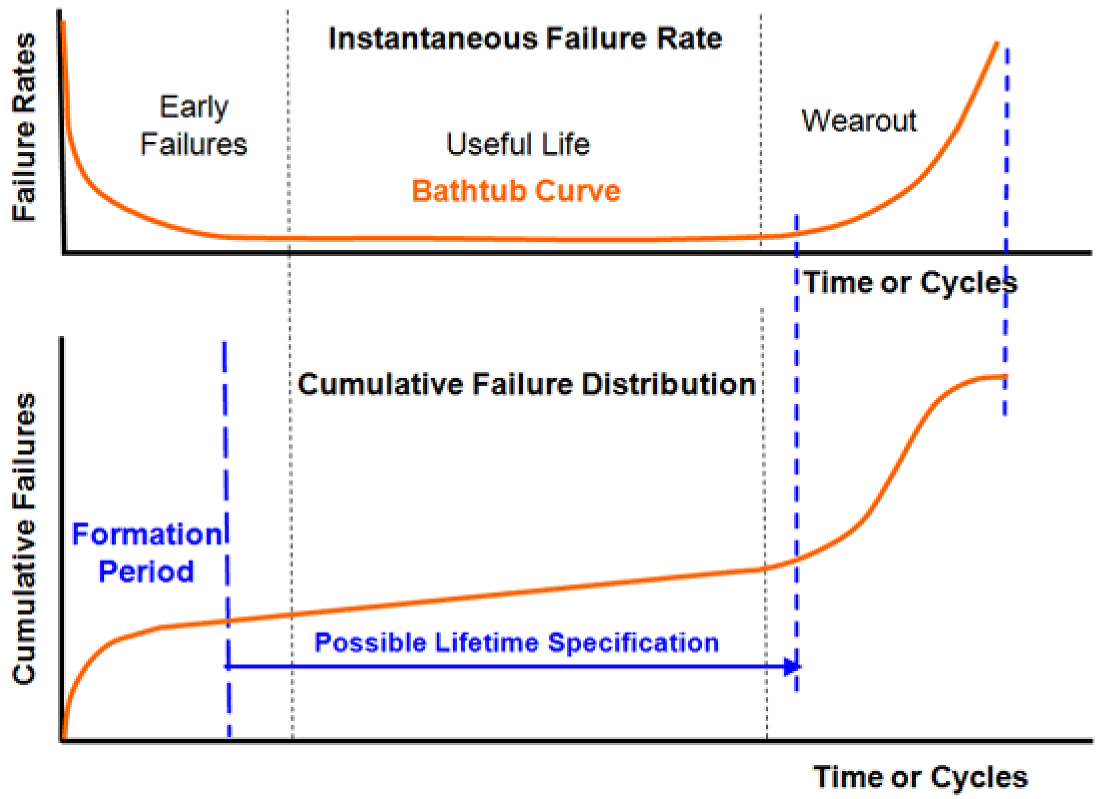
Even if everything goes right during the manufacturing process, pre-production material acceptance and storage can affect lithium battery safety. About five years ago, a global supplier of solar inverters experienced a series of product failures after electronic circuit boards had been stored in the wrong warehouse and exposed to moisture. Once product assembly was complete and the inverters were energized, a short circuit on the boards caused a fire and led to quite a bit of property damage. While moisture can also affect battery cell safety, so can other environmental conditions, such as air impurities and particulate matter.

It's not easy to perform a safety analysis that identifies failure points for battery cells. To test how moisture affects safety, you would have to take identical cells and store one of the cell materials in an environment that gets wetter in small increments until you find a statistically relevant number of failures. Then you would have to repeat the process with incremental changes in temperature, dust, and other variables. Testing would require a lot of cells, a lot of minor changes in cell processing, a lot of time, and a lot of analysis. And it would all have to be done without vastly increasing cell production costs.

What are the failure rates for your supplier's battery cells and battery packs?

In the absence of industry-wide standards, contractors seeking assurances about product safety have their work cut out for them. First, they have to request failure rates and analysis from each of their suppliers. Then the manufacturers must provide the data. Next comes the subjective test. If the contractor feels comfortable with the risk, he or she can decide if the battery quality is adequate. Different contractors have different tolerance levels for quality. A contractor who installs one small system per year may not place a great deal of emphasis on quality. The chances of failure are small. However, contractors installing many large systems must pay more attention to quality. Their businesses depend on the successful operation of a much larger population of cells.

Consider an OEM with a 99.98 percent success rate for battery cells in the first three years of operation. That translates to a 0.02 percent failure rate. If a contractor installs 1,000,000 cells per year, the contractor can expect 600 cells to fail. [Multiply failure rate (0.0002) x annual production (1,000,000) x number of years (3).] This might be an unacceptable level of risk. On the other hand, if a contractor installs 10,000 cells per year, the contractor can expect 6 cells to fail. This level of risk might be no big deal, so long as those cell failures don't propagate to the entire pack or the entire storage system.



Source: Electropaedia

Questions to ask about cell testing

We all know not to leave a fireplace unattended or a gas oven running when nobody's home. We understand that doing so introduces a serious risk of fire. But how many people know the temperature threshold that is likely to cause a lithium battery to catch fire or explode? Before procuring lithium batteries, especially those that will be sited at a building where people live or work, be sure to understand the conditions that create lithium battery safety hazards. Safety hazards that start in a single battery cell can quickly spread to the battery pack and the entire energy storage system.

What are your supplier's battery cell thermal runaway characteristics?

It's important to understand how a battery cell responds to the conditions that can initiate a fire or an explosion. There are many ways to test lithium cells for these conditions. Some examples are the top nail test, where a nail of standard size is driven with standard force into the top of the battery, and the side nail test, where the same procedure is carried out with a battery lying on its side.

Other tests include the fast heat test, where a battery inside a control chamber is exposed to a rapid temperature increase; the slow heat test, where a battery is exposed to a slow temperature increase, and the overcharge test, where a fully charged battery stays connected to a power source and is continually charged.

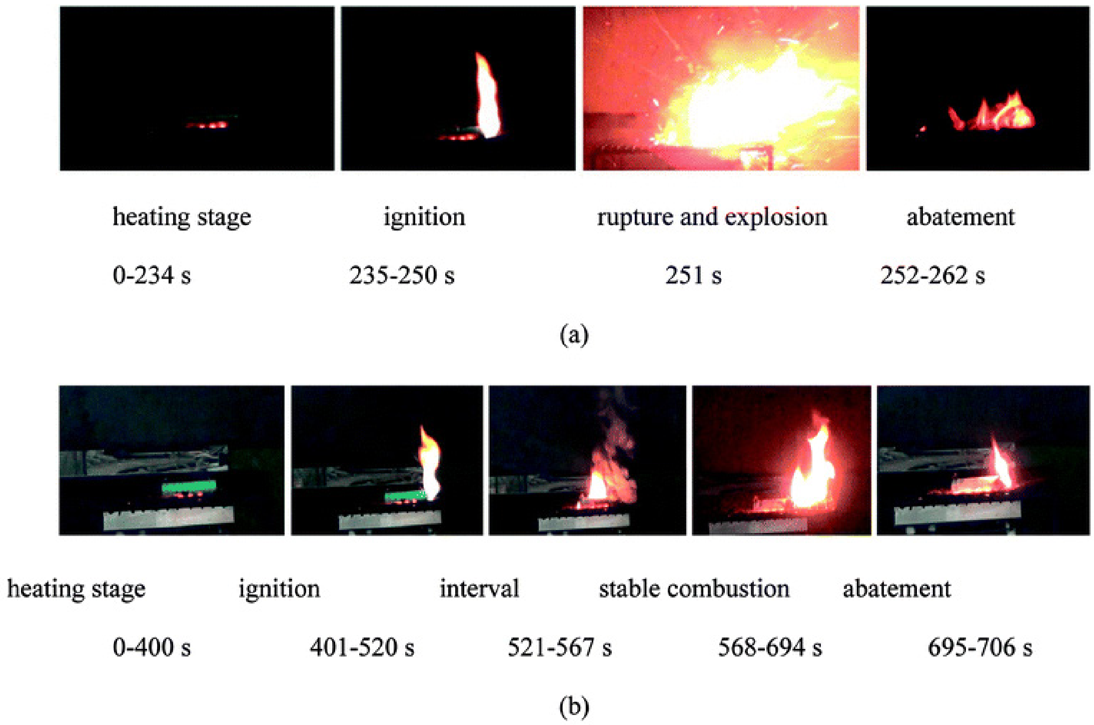
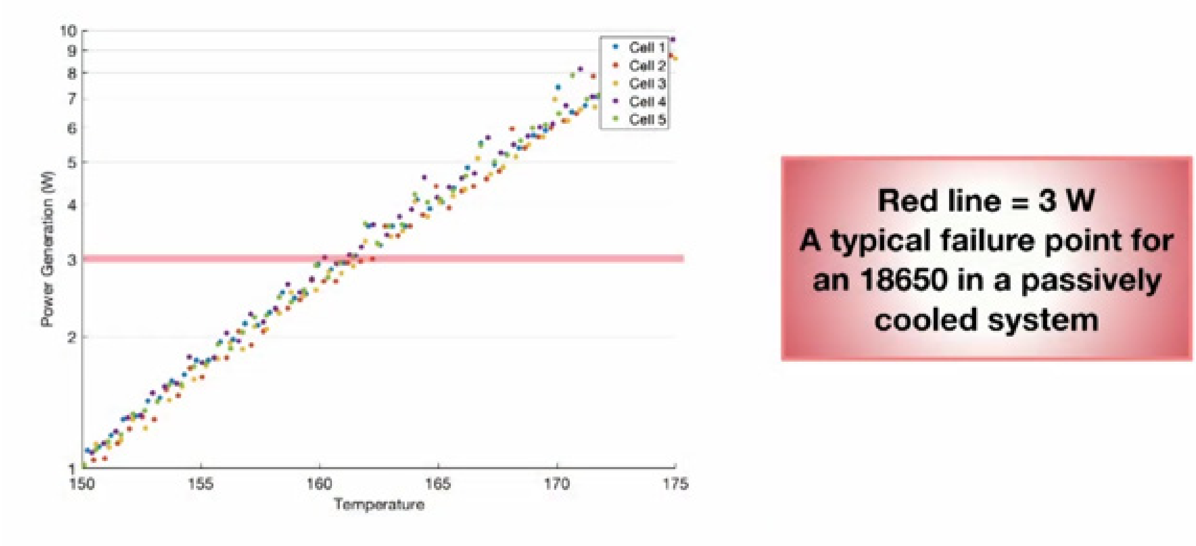


Fig. 10 The burning process of the batteries during the tests: (a) battery failure due to overcharge; (b) battery failure due to over-discharge.

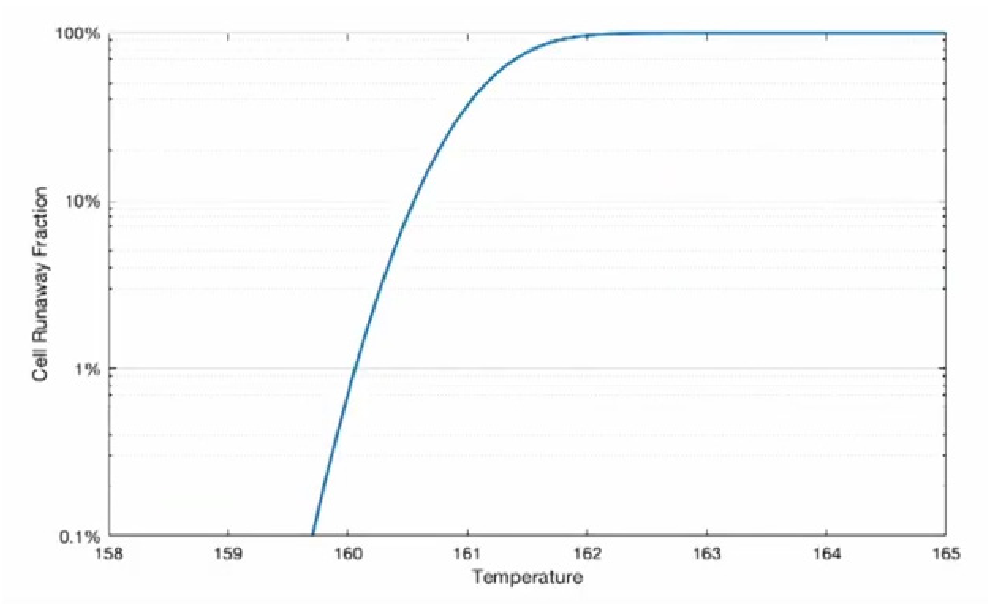
What is the probability of thermal runaway for your battery cells?

With test results in hand, you can make reasonable predictions about how a battery will perform according to design specifications. Graph 1 shows how increased temperature leads to thermal runaway. While all five cells exhibit similar power generation as temperature increases, there is a notable difference in how close each cell comes to the failure point represented by the horizontal red line at 160°.



Graph 1

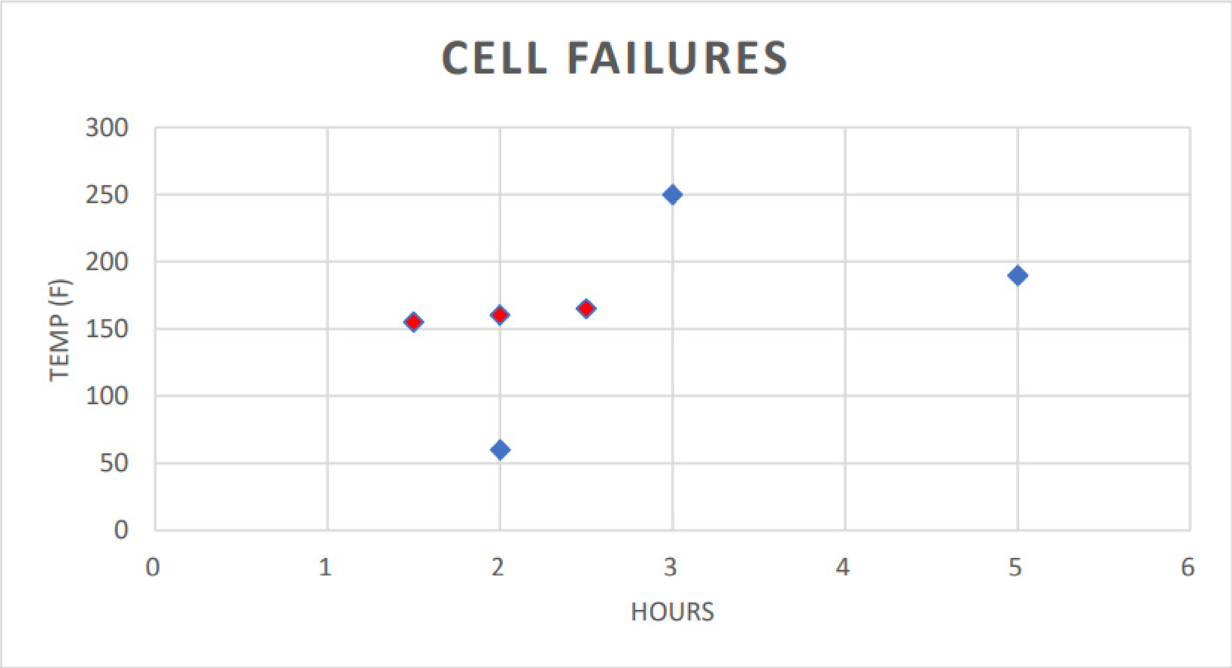
Graph 2 shows how constant temperature over time leads to thermal runaway. The battery cell depicted by this graph remains at very low risk of thermal runaway when temperature is held constant at 159°. But a 1° increase in constant temperature vastly increases the probability of thermal runaway. A 2° increase makes thermal runaway a near certainty.



Graph 2

One of the challenges when characterizing lithium cell failure is calculating at what temperature and over what duration a cell fails. Because the answer is different for each cell, we need to see how different the answers are. What if one cell failed after two hours at 60°, another cell failed after 5 hours at 190°, and a third cell failed after 3 hours at 250°? This data would be difficult to characterize. It seems like almost every temperature is dangerous and could lead to cell failure.

Now what if the data looked more like this? Cell 1 fails after two hours at 160°, Cell 2 fails after 2.5 hours at 165°, and Cell 3 fails after 1.5 hours at 155°. This data suggests that thermal runaway is consistent and predictable. If we can find consistent results, we know when failures occur and how to prevent failure by designing systems for lithium battery safety.



How does thermal runaway spread from cell to cell?

This is really a two-part question. For starters, let's look at how thermal energy from a failed lithium cell gets distributed across neighboring cells. Do all neighboring cells get the same amount of energy from the failed cell? Does one cell get all the energy while the others get none? Do two cells get 90 percent of the energy? Next, let's look at how much stress an initiator cell applies on neighboring cells. If a failed cell exposes neighboring cells to temperatures up to 120°, the risk of cell-to-cell propagation is low. The risk is much higher if a cell failure has a magnitude of 180°. If energy is distributed unevenly, we would want to know the magnitude of stress for each of the neighboring cells.

What are the conditions that lead an entire battery pack to catch fire?

If cell-to-cell propagation extends to one or two neighboring cells and stops, failure of the whole battery pack or battery module is unlikely. If cell-to-cell propagation extends to hundreds of neighboring cells, it's far more likely that the entire pack will burn. By understanding when battery packs catch on fire and start heating up the neighboring packs, the system designer can plan for fire detection and suppression systems as required by NFPA 855 and UL 9540A to kick in as a last line of defense.

What are the conditions that lead an entire energy storage system to catch fire?

If a fire containment system fails to contain a fire within the energy storage system enclosure, the charging infrastructure for the batteries may also catch on fire. (Think of a car catching on fire while being pumped with fuel at the gas station. Fire can spread to the gas pump, then the entire gas station.) Once the charging infrastructure is on fire, the entire property, including its occupants, are at risk. In sum, one battery cell failure can lead to the destruction of an entire building and the loss of life.

Demand lithium battery safety data

A safe battery is a well-documented battery. Test data helps engineers, system integrators, system owners, and regulators make smart, effective system (or "project") design, procurement, and business decisions. While data doesn't eliminate risk, it does inform us of the risk, thereby empowering us to make decisions on how to manage, contain, suppress, mitigate, or ignore it. By putting appropriate measures in place, we can reduce risk to an industry-acceptable level. Without test data, a battery might operate safely today, but we don't know why. Then if conditions change and the battery is no longer safe, we won't know how to mitigate the risk.

The industry can expect a steady supply of safe lithium batteries as soon as buyers make purchasing decisions conditional on access to safety data. There are many safe batteries on the market. But there are many more cheap, risky batteries on the market. The simple solution is to buy safe batteries—which might mean accepting a higher price.

Contractors should request data from OEMs or look for third-party evaluations from independent engineering (IE) reports or independent test laboratories. The data is not publicly available, or hard to find, which is a serious problem. UL, the "gold standard" in product safety, even has trouble gaining access to this sort of data. So one requirement in the UL 9540 standard is to capture thermal runaway data, even for batteries that pass all the tests. In other words, when a lithium battery goes for the UL 9540 test, the test lab will force the battery into thermal runaway and then document the results to help characterize lithium cell failure.

Use Case: Managing battery risks during project design and engineering

In 2012, SepiSolar was designing a commercial-scale solar-plus-storage and electric vehicle charging project for the car rental company Avis at LaGuardia Airport in New York City.

To prepare for permitting and interconnection with the electric service provider Con Edison, the design team needed detailed plans for the energy storage system. We received specification sheets for the lithium battery modules and battery packs. But we did not get detailed designs showing all components: the system enclosure, the HVAC system, critical loads, foundation, inverters or transformers, and all the wiring that connects everything together.

The energy storage system integrator had separate drawings and specs for each component. It did not have a system-level plan set. So it hired SepiSolar to produce one. That's how we discovered there were no fuses between the battery packs and their respective battery management modules, which are components of the battery management system.

To be clear, the modules themselves had overcurrent protection built in. SepiSolar believed additional breakers were needed for wiring between the battery packs and their modules. This high-amperage wiring ran very close to some thermal exhaust vents built into the enclosure. The thermal exhaust outlets get hot. The conductors were large and made of fine-stranded cables that were not UL listed. These conductors are known for experiencing failures from time to time. In fact, they're designed for failure. Welders like this type of cable because they can "cut off" the ends over time until the entire conductor has to be replaced.

SepiSolar made the following recommendations.

1. **Replace the non-UL listed fine-stranded cable with UL-listed fine-stranded cable.**

   This was very hard to find. The only conductor that met the requirements for 600V, UL listed, wet-rated cable was something called "W cable." The insulation was almost twice the thickness of the original. It made a significant difference.

2. **Install fast-acting fuses right at the battery modules.**

   Though redundant to the battery module breakers, in a high-amperage fault scenario, it's better than relying on a breaker that might be 20 feet away and running close to thermal exhaust vents. Placing a fast-acting fuse right next to the battery modules mitigates risk.

3. **Double-check conductor sizing.**

If one of the fast-acting fuses tripped, the conductors need to be large enough such that parallel-connected battery modules, packs, and W cables would not get overloaded and also trip. System design had to ensure that if one fuse tripped, it would not cause a chain reaction that would blow all parallel-connected fuses. Subsequently, SepiSolar performed arc flash and coordination studies to evaluate whether the system design was effective.

Code generally discourages systems from tripping fuses by design. Fuses should only trip for safety purposes, not because of design issues.

As a result, SepiSolar up-sized all the W cable conductors so they could handle the full load of the batteries, even if other parallel circuit fuses tripped. This increased the cost of wiring. But the added cost had less than a 1% material price impact on the battery overall. SepiSolar and the lithium battery integrator valued the benefit of improved safety as greater than the added cost.

Later, we learned that SuperStorm Sandy had flooded our battery and taken out much of Avis' New York City operations. After the storm subsided, we drained the battery and re-commissioned it. And it worked great!

Some of the breakers and fuses had blown and needed replacement. That's all. We like to think that the safety precautions in design and engineering helped make the system more resilient. Hardware engineering, enclosure design, and software design should get most of the credit. The system automatically shut down once it detected water inside the enclosure. Hopefully SepiSolar played a small, albeit meaningful, part, too.

A different value proposition

In this paper, we have explained that people underestimate lithium battery risk for three reasons: because we often evaluate projects based on capital expenditures instead of total cost of ownership, we like to believe the grid is more reliable than it is, and we don't include the value of resilience in financial modeling for storage projects. We discussed four key questions about battery cell production and five questions about cell testing that contractors should expect battery suppliers to answer during the procurement process. Lastly, we described how SepiSolar contributed to a safer solar-plus-storage project in the ConEdison service territory in New York.

The great thing about resilience is that a little bit can go a long way. In addition, the value of resilience is tied to company revenues or profits, rather than electricity prices and operations costs. As a result, the value of resilience in a battery based on revenue will always be higher than the battery's economic value based on avoided cost of energy or demand. For profitable companies, revenue is always greater than costs.

If you're trying to reduce electricity costs, you measure progress in terms of cents per kilowatt-hour. When optimizing company revenues, you're likely measuring progress in hundred-thousand- or million-dollar increments. It's a totally different value proposition.

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