The Codes and Standards Facilitating the Design and Adoption of Energy Storage for Power System Applications

Keeping pace with evolving safety codes and standards.

Energy storage, primarily in the form of lithium-ion (Li-ion) battery systems, is growing by leaps and bounds. Analyst Wood Mackenzie forecasts nearly 12 GWh of deployments in 2021 in the United States alone. Installations of more than 100 MW and hundreds of megawatt-hours are becoming commonplace.

How we arrived here was not so easy. The early systems were designed and installed largely in the absence of safety standards and codes, with manufacturers and system integrators taking their individual approaches to safety. Missteps have been made, as indicated by the Electrical Power Research Institute’s Battery Energy Storage System Failure Event Database (storagewiki.epri.com),...
which includes 41 events in systems totaling at least 228 MWh, since 2017.

Codes and standards have been playing catch-up, in some cases with multiple iterations, since 2017. The result is the imposition of a certain discipline—albeit a rather costly one—on the integrators of energy storage systems (ESSs) in their designs and deployments. Although the development of these codes and standards is by no means complete, the power industry can proceed with new ESS deployments with a greater sense of confidence in their safety.

This article describes the development of ESS-related codes and safety standards, with a focus on North America, and their impact on the industry. It will also detail standards that go beyond the realm of safety, making it easier to evaluate new storage technologies and interconnect to the electric power system.

**ESS Deployments**

Throughout the 1990s and most of the 2000s, nearly all large-scale, grid-connected energy storage was in the form of pumped-hydro installations, and the systems using battery storage were mostly limited to funded demonstrations. That started to change in 2009 with the first shipments of containerized Li-ion batteries, and by the late-2010s, the deployment of battery-based ESSs had entered a period of exponential growth, as depicted in Figure 1. Although the figures for the first quarter of 2021 showed a significant drop from the previous quarter, Wood Mackenzie described this period as the “quiet before the storm,” forecasting a total of nearly 12 GWh to be deployed for the full year.

The share of those deployments, by technology, is presented in Figure 2. Recent installations are made almost exclusively with Li-ion chemistries, and indeed, Li-ion has constituted the majority of deployments since the early 2010s.
Li-ion Safety Issues
All those early installations of Li-ion ESSs were made in the absence of safety standards relevant to the scale of these systems. At that time, the standards applicable to portable batteries typically covered safety at the level of individual cells and small packs, while the issues facing larger systems were more concerned with the propagation of thermal runaway (TR) between modules and racks, effectiveness of fire suppression, and management of explosive gas buildup. It is not the purpose of this article to describe the details of these safety issues but to show how current codes and standards are influencing Li-ion system design and providing both the operators and authorities having jurisdiction (AHJ) with a greater sense of confidence in the deployment of these systems.

Safety Standards

Development Timeline
In those earlier ESS deployments, it was left to the battery manufacturers and system integrators to ensure an adequate level of safety. Inevitably, there have been missteps along the way, with system designers not always considering all the ways in which cell failure can influence system-level safety. While the industry understanding of holistic safety has been advancing, codes and standards have been playing catch-up. The standards from Underwriters Laboratories started to move beyond the portable battery world in 2013, but it was not until the last few years that they comprehensively addressed complete battery-based ESSs, with the second edition of UL 1973, Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power and Light Electric Rail (LER) Applications (2018); the second edition of UL 9540, Energy Storage Systems and Equipment (2020); and the fourth edition of UL 9540 A, Standard Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems (2019). Fire codes have similarly been evolving, introducing stringent spacing and energy limitations for indoor systems beginning in 2018. The code requirements for ESSs have been further developed in NFPA 855, Standard for the Installation of Stationary Energy Storage Systems (2020), which is already in the process of being updated, supported by more data from the field.

One of the challenges for manufacturers is product development in the midst of an evolving landscape of installation and product safety standards. The key model fire codes in the United States, the International Fire Code and NFPA1 Fire Code, are amended on a three-year cycle. The technology is evolving more rapidly than the codes cannot keep up with evolution of the technology, which may unintendedly create barriers to solutions not addressed or impose restrictions with limited justification. The changes in product safety standards can require recertification, which may impose significant time delays and cost. It is imperative to have broad stakeholder input into the development of these consensus codes and standards to ensure that the best possible language is achieved with the most current data available.

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Mind the (Safety) Gap
An example of just one of the challenges fire codes attempt to address is in the area of fire suppression and explosion control. The current requirements call for fire sprinklers for many systems installed indoors (which includes walk-in enclosures) and outdoors near exposures. Historically, sensitive electronics have been well protected by clean-agent suppression systems, such as Novoc 1230, FM200, or carbon dioxide. As these agents are designed to either displace oxygen or rapidly cool the environment, they are quite effective for visible flames, but for certain Li-ion chemistries are ineffective in suppressing deep-seated fires in modules due to exothermic and oxide-releasing reactions during TR.

When a clean-agent system is designed, one requirement is to maintain a certain concentration and duration in the space. This requires that the area be sealed from exterior air, and as a result may allow continued TR and the release of highly flammable gas constituents, such as hydrogen, carbon monoxide, and hydrocarbons. So, in essence, the attempt to suppress a fire will often create an explosion hazard. Continued research is needed in effective suppression systems designed to address fires at the module level. Manufacturers must consider the explosion hazard and respond with mitigation designs.

Similarly, it is possible for water-based fire-suppression systems (FSSs) to cause more problems than they solve. Water has much greater cooling efficiency than clean agents, but it must be supplied in sufficient volume within and around battery modules to arrest the propagation of TR, thus limiting cell venting and the release of flammable gases. Ceiling-level sprinklers may not be effective at delivering sufficient water if modules are tightly packed, and this may favor designs with more directed water flow across the tops of modules. Another potential issue is with water-mist systems, which, depending on the ingress protection rating of the battery modules, may deliver enough water flow to create short circuits between cells but not enough to remove the heat generated by those shorts. The need for, and effectiveness, of FSSs with Li-ion batteries can be demonstrated most effectively by large-scale testing according to UL 9540 A, as discussed later in this article.
**System Certification**

Since 2017, the National Electrical Code has required batteries other than lead acid to be listed, that is, tested by a nationally recognized testing laboratory to comply with an applicable safety standard. For stationary batteries, that standard is UL 1973, first published in 2013 and extensively revised in 2018. Additionally, batteries such as Li-ion, which incorporate a battery management system with safety functions, must demonstrate compliance with UL 991, UL Standard for Safety Tests for Safety-Related Controls Employing Solid-State Devices [Third Edition, (2010)] and UL 1998, UL Standard for Safety Software in Programmable Components [Third Edition (2013)].

Certification is not limited to the battery, however, as the complete ESS must be certified to UL 9540, first published in 2016 and revised in 2020. Certification to UL 9540 requires that a UL 1973-listed battery be paired with a UL 1741-listed power-conversion system, with additional testing to verify the adequacy of system integration. The hierarchy of codes and standards applicable to ESSs is depicted in Figure 3.

**Large-Scale Fire Testing**

Arguably the most impactful, safety-related document for batteries is UL 9540 A, which is not a qualification standard but rather a standardized test method with no pass/fail criteria. This testing assesses the extent of TR propagation within the battery and the effectiveness of fire suppression, if needed. UL 9540 A testing is referenced by fire codes and NFPA 855 and is required whenever it is proposed to exceed mandatory energy limits or to reduce mandatory spacing between battery segments, or between batteries and exposures. Results of the testing, including video recordings, are submitted to the AHJ to inform their decision making on code variances.

The evolution of UL 9540 A is an example of the response of the standards-writing community to unfolding ESS safety events around the world and the lessons learned from those events. Originally published in 2017, the standard was revised twice in 2018, and most recently, the fourth edition was published in November 2019.

The test method in UL 9540 A takes a stepwise approach, with testing starting at the level of individual cells and continuing to modules, units (racks), and finally, complete installations. The document is applicable to all battery technologies that are subject to installed-energy standards-writing community to unfold the world and the lessons learned from those events. Originally published in 2017, the standard was revised twice in 2018, and most recently, the fourth edition was published in November 2019.

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the final installation-level test is performed with fire suppression and other safety measures in the design to assess the effectiveness of preventing unit-to-unit propagation and preventing or reducing deflagration risks.

Conducting tests according to UL 9540 A can be time-consuming and expensive, particularly if installation-level testing is required. However, the wealth of information provided, including video recordings, is invaluable in allowing the AHJ to make informed decisions on proposed installations and for fire protection engineers to design fire-suppression and/or deflagration systems.

**Influence of Safety Standards on Battery Design**

As ESS deployments have shifted to multihour applications such as the replacement of peaking generation, a system’s footprint has become progressively more important, causing containerized Li-ion battery systems to be designed with increasing energy density. Figure 4 shows the rise in energy density over time for containerized Li-ion battery systems offered by one company: Saft. All of its systems use Li-ion chemistry based on nickel oxides, including Li nickel cobalt aluminum oxide and lithium nickel cobalt manganese oxide (NMC).

The earlier container designs included relatively small modules that incorporated thermal barriers between large cylindrical cells, and those barriers were effective at preventing cell-to-cell propagation of TR. A standard FSS using a clean agent, Novec 1230, is installed to handle any electrical fires that may occur, and its cooling effect provides an additional safety margin against propagation. For the 2020 container design, the installed energy is maximized using close-packed pouch cells in large modules. This arrangement makes it difficult to avoid propagation of TR. A clean-agent FSS extinguishes any visible flame but is unable to eliminate ongoing propagation deep within the modules. In this case, the primary FSS is supplemented by a water FSS.

The easiest way to implement a water FSS is to have a dry-pipe system with a connection for the fire department and to provide firefighters with status information and a decision tree for when to use the system. Ideally, the connection point would be located a safe distance away, although that may create issues for service access to the containers. Moreover, a manually actuated system may be problematic from an effectiveness standpoint as it requires human intervention within the period between actuation of the clean-agent FSS and reignition because of ongoing propagation. Testing on the 2020 container design indicated a maximum interval of 90 min for the fire department to arrive on site, assess the situation, consult documentation, and activate the water FSS. A manual system would also present problems with certification. An automatic system would meet certification needs but would require a high-volume source of water to be available at each container, which can present problems at remote sites.

Considering such issues, the newer codes and standards are having a significant influence on battery system design for ESSs. The cells that use Li-iron phosphate (LFP) chemistry, which is more resistant to TR, are becoming the standard, despite their lower energy density. (The adoption of LFP is also helped by lower cost.) Module manufacturers are taking extra steps to limit cell-to-cell propagation of TR within their units. Beyond limiting propagation, battery enclosures must be designed to avoid or mitigate the buildup of potentially explosive gases released during a TR event.

One of the challenges in UL9540A fire testing is the interpretation of the performance requirements of the module-, unit-, and installation-level tests. The intention is to understand the performance under propagating TR conditions, yet different chemistries respond differently when in TR, and the test itself may introduce some variability in battery response compared to field conditions, depending on the way in which TR is initiated.

For example, most NMC chemistries produce sparking and often flames when TR is initiated using an external heater, as in the UL 9450 A test. These flames can

**Figure 4.** The evolving energy density in 20-ft containerized systems. (Source: Saft America Inc.; used with permission.) (a) 2012: 0.6 MWh, (b) 2017: 1.2 MWh, and (c) 2020: 2.5 MWh.
Managing vented gases has become one of the thorniest issues in Li-ion battery-enclosure design.

consuming vented flammable gases, thus reducing a buildup of these gases within the enclosure. In the field, however, TR is more likely to be initiated by an internal cell short, where the cell’s energy rapidly reduces as the temperature rises and venting occurs. This difference in cell status at the point of venting raises the question of whether there will still be sparking and flames, and if not, the resulting gas buildup will be quite different. Furthermore, if flames are suppressed by the discharge of a clean agent but TR is allowed to propagate, there could be a considerable increase in flammable gas concentration before a water FSS is actuated. This situation should be seen in the UL 9540 A testing, but all possible conditions leading up to such an event should be considered in a failure-modes-and-effects analysis.

On the other hand, LFP cells are more stable at higher temperatures and less likely to exhibit propagating TR. When venting, they may not produce the sparking and flaming normally seen in NMC products, and individual cells can produce very high amounts of hydrogen and other flammable gases per cell. This is particularly the case as LFP cells are often manufactured with higher ampere-hour capacities because of their lower risk. The designs of enclosures to address this explosion hazard must base their solutions on accurate gas generation data from testing to the most current edition of UL 9540 A. The resulting enclosure designs will incorporate systems to either address any explosion pressure waves, or ideally, prevent an explosion in the first place.

Managing vented gases has become one of the thorniest issues in Li-ion battery-enclosure design. The two National Fire Protection Association documents that apply here are NFPA 68, Standard on Explosion Protection by Deflagration Venting and NFPA 69, Standard on Explosion Prevention Systems. These documents are called out in NFPA 855 addressed this issue, including correcting a gap for ESS cabinets (where all the components are accessed from exterior doors). The amendment provides for explosion-control solutions in lieu of NFPA 68 or 69, in ESS cabinets where fire testing demonstrates an absence of shrapnel, projectiles, or pressure waves.

Beyond Li-ion

Battery technologies for ESS are not limited to Li-ion, particularly considering the future need for technologies capable of providing low-cost storage for discharges of longer than 4 h. Many new technologies have been proposed, each promising lower cost at scale than Li-ion, often with better cycle life or some other advantage. Although there may indeed be a “Li-ion killer” out there, it can be extremely difficult to determine which claims are real and which are projected from early test results. It is not unusual for a new technology to show very promising results with small button cells in a lab, only to find that the technology cannot be made to work in larger formats, that manufacturing cannot be scaled up as expected, or that unexpected failure modes show up, causing the new batteries to fail prematurely.

Li-based batteries are far from immune from this sort of hype. New Li-ion active materials are proposed with some frequency, promising to be safer, cheaper, more energy dense, or able to be recharged in scant minutes—and often with all four features at the same time. Furthermore, there is a new class of batteries using solid-state electrolyte and metallic Li negatives, which promises all of these improvements. Technologies of this type have been around since the 1990s, although not in a form acceptable for mass-produced electric vehicles, and now enormous sums are being spent by auto companies and venture capitalists to accelerate their development and industrialization. Although it
is difficult to go more than a few days without reading about a new breakthrough in this field, the consensus of industry experts is that these new solid-state Li batteries will not enter full-scale production for electric vehicles until approximately 2025.

For these emerging technologies, there is a need for a common framework for manufacturers to characterize their systems and for prospective users to evaluate them. That framework is provided by IEEE Std 1679, IEEE Recommended Practice for the Characterization and Evaluation of Energy Storage Technologies in Stationary Applications. Even though the primary focus is on battery technologies, the standard is applicable to other storage media that provide a means for the reversible storage of electrical energy; that is, the systems that receive electrical energy and are able to release electrical energy at a later time. The standard forms a foundation for the objective evaluation of an energy storage technology by providing a common basis for the expression of performance characteristics, treatment of life-testing data, analysis of failure modes, and assessment of safety attributes.

Revised in 2020, IEEE Std 1679 is supported by a growing series of subsidiary guides to its application for different classes of batteries. The published guides include IEEE Std 1679.1 for Li-based batteries and IEEE Std 1679.2 for sodium-beta batteries. Other guides are in preparation for flow batteries and alkaline batteries. The following paragraphs provide additional detail on each guide.

The initial release of IEEE Std 1679.1 was in 2017, and there is a move underway to revise the document to reflect the changing qualification environment and emergence of newer technologies, especially solid-state Li batteries.

The sodium-beta batteries covered by IEEE Std 1679.2-2018 include high-temperature sodium-sulfur and sodium-nickel chloride technologies, typically operating at around 270 °C. This group of technologies may soon be expanded with the potential development of new material capable of conducting sodium ions at just above the melting point of sodium metal.

Flow batteries are the subject of the standards project that is likely to be published next year as IEEE 1679.3. This document will cover a broad range of redox and hybrid flow chemistries. There is much interest in this class of batteries, especially when required discharge times start to exceed 4 h. It is thought that these longer discharge times will favor these technologies and that they will finally emerge from the shadow of Li-ion.

The project for alkaline batteries is P1679.4, where “P” denotes a not-yet-published standards project, and has just commenced. This document will cover a broad range of chemistries with non-flowing alkaline electrolytes, many of them zinc-based. The current list includes zinc-air, nickel-zinc, nickel-metal hydride, nickel-iron, and rechargeable zinc-manganese dioxide. Although nickel-cadmium chemistry technically fits in this grouping, these batteries are excluded because they are already well characterized and covered by other IEEE standards.

The IEEE Power & Energy Society Energy Storage and Stationary Battery Committee remains on the lookout for other classes of energy storage technologies that could be covered by a guide in the 1679 series. The base standard covers emerging and alternative technologies, where emerging technologies are those recently, or soon to be, made available for sale under customary commercial terms (e.g., defined scope of supply and warranted performance). The alternative technologies are those that are currently mature but less well known or frequently deployed as traditional technologies. These definitions keep the committee focused on technologies where prospective users are genuinely in need of guidance in their evaluation, rather than on those that have yet to emerge from the laboratory.

(Inter)Connecting the Dots

It is one thing to develop safer and well-characterized ESSs, but interconnection can remain a barrier to large-scale deployment. The potential concerns with ESSs depend on the level at which the interconnection is made. In the distribution network, distributed energy resources (DERs), including ESSs, are often set up to export power to the grid, and there is a concern that if this export continues when the grid has failed, numerous problems could occur, including a potential safety issue for line workers, who may be unaware that a feeder is still energized. An additional concern relates to the performance of grid services by aggregations of distributed systems, where the dispatch signal can shift rapidly between charge and discharge, potentially creating disturbances on a feeder. On the plus side, a grid-forming ESS can be the lynchpin of a microgrid, providing resilience to a facility that is normally grid-connected but can disconnect as needed and function independently, provided that the microgrid has sufficient control and protection systems to meet the requirements of both on- and off-grid operation. Having such a “sheddable load” can be a benefit for the network operator, but the transition to and from islanded mode must be achieved without disruption.

At the transmission and subtransmission levels, the concern is more over the loss of inertia in the bulk electric
system as spinning generators are replaced by renewable energy resources and energy storage, all of which connect to the network through power electronics. The fast, bidirectional response of energy storage can contribute to the mitigation of any stability issues, but such responses by multiple resources must be properly coordinated.

Standards are essential in addressing these issues. Interconnection standards provide widely accepted, consensus-based requirements and best practices for connecting resources to power systems, and they help to create consistency in policy across multiple jurisdictions. IEEE has been writing interconnection standards for decades, starting with IEEE 929-1988, which dealt exclusively with distribution-connected, residential photovoltaic systems, focused mainly on potential power quality issues, and was only seven-pages long, including an annex. Since then, the number, scope, and length of standards have increased considerably and now cover energy storage connected at the distribution or transmission levels.

Large-scale energy storage will often be implemented in the form of inverter-based resources (IBRs) interconnected with transmission or subtransmission systems, and there is a group of standards under development for these interconnections. The first of these, IEEE P2800, Draft Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting With Associated Transmission Electric Power Systems, is expected to be published later this year. (Note that the document is subject to change as it goes through the balloting process, so statements in this article may not accurately reflect the content of the final document.) IEEE P2800 defines a set of minimum capabilities and performance requirements for all IBRs connected to transmission or subtransmission systems. This new standard was crafted with energy storage in mind and includes multiple examples, explanatory footnotes, and other materials illustrating the application of P2800 to transmission-connected energy storage. This standard also addresses several common applications of large-scale grid energy storage, such as hybrid plants (e.g., plants that include both photovoltaics and energy storage) and fast frequency response.

IEEE Std 1547-2018, IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources With Associated Electric Power Systems Interfaces, is the standard that applies at the distribution level, whether to individual systems or aggregations that act as virtual power plants. This document is a revision of IEEE 1547-2003. The 2003 version of the standard was written in an environment in which the aggregate power level of DERs on the system was very low, such that they did not have a discernable impact on transmission system behavior, and thus, the 2003 standard took the approach of tripping DERs offline for many abnormal system conditions, leaving the system to handle the condition. By the time the 2018 revision was completed, the number of DERs on the system had become sufficiently large that transmission impacts were already evident, and thus, the 2018 revision contains extensive requirements for capabilities that support the bulk system, including ride-through requirements for DERs to stay online over a much broader range of conditions than before. Further addressing the unique characteristics of distributed ESSs—with bidirectional flow of both real and reactive power in the context of IEEE Std 1547—is the focus of a new standard, IEEE P1547.9, Draft Guide to Using IEEE Std 1547 for Interconnection of Energy Storage Distributed Energy Resources With Electric Power Systems, expected to be published in 2022. An ESS connected at the distribution level is referred to in this document as an energy storage DER (ES DER).

The respective scopes of these interconnection standards and their subsidiary “dot-standards” are shown graphically in Figure 5. The transmission-level requirements set by IEEE P2800 and the distribution-level requirements set by IEEE 1547-2018 do have some significant differences. One key example of importance to energy storage is the requirement for fast frequency response. At the distribution level, IEEE 1547-2018 does not explicitly require fast frequency response but does require the capability to provide frequency-droop response (a frequency response proportional to $\Delta f$). However, the shortest response time allowed for this droop

![Figure 5](image_url)
This new standard was crafted with energy storage in mind.

function is 1 s, meaning that DERs can react only during the recovery phase of a system-level frequency event, not the arresting phase. Hence, this droop function is not specifically referred to as fast frequency response in IEEE Std P2800 and is typically within the arresting period of a system-level frequency event. As a result, this droop function could play a fast-frequency-response role if the ES DER response time is parameterized appropriately. The frequency-droop equation is given, along with default parameter values and ranges over which the parameter values may be adjusted. The frequency droop applies for both high- and low-frequency excursions. The utilization of frequency-droop capability is by mutual agreement between the ES DER operator and system operator.

IEEE 1547-2018 also allows ES DERs to perform “inertial response” (a frequency response proportional to dP/dt), but it does not require this capability and it makes no recommendations regarding its formulation or parameters. IEEE P1547.9 provides more useful information in this regard, but as a guide it cannot impose mandatory requirements. Those requirements will have to wait for the next revision of IEEE 1547.

At the transmission level, IEEE P2800 requires that IBRs provide frequency droop for both positive and negative frequency deviations within the limitations of the primary energy sources available to the IBR. To facilitate this response, the draft standard defines two nameplate ratings: continuous and short-term (surge) ratings. The IBR plant can exceed the continuous rating, but not the short-term rating, to provide frequency support. P2800 does allow the two ratings to be the same for those IBRs that have no surge capability. This droop response is referred to as a primary frequency response, and its speed of response is limited only by the active-power ramp rate of the IBR. In addition to that primary-response droop requirement, IEEE P2800 also requires that all IBR plants have fast-frequency-response capability for negative frequency excursions. This fast frequency response is also formulated as a frequency droop, but as mentioned previously, the response time is required to be no greater than 1 s. The standard gives the droop equation for this fast-frequency-response function and provides default parameter values and allowable ranges of parameter adjustment. IEEE P2800 also allows inertial response and provides details for its implementation in an annex.

Looking to the Future
The ESS battery industry has come a long way from the early “Wild West” days when each manufacturer made its own decisions about safety. The rapid development of codes and standards has imposed a level of rigor in system design, where safety is a critical component at every step, rather than being treated as an “add-on” after other requirements are met. The video record of large-scale testing to UL 9540 A is an important element that can provide a strong sense of assurance to prospective users and the AHJ alike.

That said, this is by no means the end of the story. New lessons are being learned, and safety standards and codes are being revised, even as this article is being written. New requirements will be imposed on manufacturers, who will have to be nimble in responding with necessary design changes. This is a process that has no end.

The evolution of interconnection standards at both the transmission and distribution levels will also provide a pathway for increasing ESS deployments at all levels within the grid. IEEE 1547 and the future IEEE 2800 will be pivotal in adapting the electricity system to one with more widespread DERs, two-way power flows in the distribution system, and lower inertia as rotating generators are supplanted by IBRs.

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For Further Reading


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