Transitioning to Anticipated Energy Demand Levels of Future Power Systems and Preserving Safety, Resilience, and Reliability

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***Abstract* — Variable renewable energy sources without the necessary energy storage capacity to fully replace conventional generation create an extremely unstable power system, as evidenced by the April 2025 international blackout in Spain and Portugal, and briefly in France. Safety, resilience, and reliability concerns originating from the magnitude of the utility-scale energy that would be required at such long-duration energy storage (LDES) sites could be overwhelming. In practice, safety, resilience, and reliability are closely interrelated. However, the scope of this paper is focused on the safety issues. The recent Moss Landing battery explosions and fires provide an indication of the severity of such events. The initial step of a safety assessment is presented, which is to first perform a realistic calculation of the potential threats due to explosion and fire. Lacking the operational data for a thorough assessment, an order of magnitude calculation example reveals an alarming amount of energy concentrated at a typical LDES site operating under a Net-Zero environment. An action blueprint is proposed to complete a more accurate threat assessment, which is essential in designing mitigation methods to safely manage the expected energy levels associated with LDES devices.**

***Index Terms*—Energy storage; Explosions; Fires; Safety; Resilience; Reliability.**

I. Inherent Safety Issues Of Long-duration Energy Storage (LDES)

The most prevalent renewable energy sources in operation today are solar photovoltaic panels and wind driven generators. Their production output at any time depends respectively on the amount of sun shining and wind blowing. This intermittency severely limits their operational value at utility scale applications. To provide dependable dispatchable energy, it would be necessary to have on standby a backup conventional power system rated at 100% of the peak demand plus reserves margin, which is impractical.

Renewable-based energy must first be gathered and concentrated, and an amount of energy corresponding to the peak energy and for the longest anticipated consumption time must be stored. This energy must be instantaneously available on demand and throughout the entire time that the alternative sources are not producing the required energy [1],[2]. It is this time duration of insufficient energy output, which could extend over weeks or months, that is the origin of the need for massive and potentially dangerous energy concentrated at long-duration energy storage (LDES) sites. An order of magnitude calculation of the amount of stored energy required at a regional substation is presented later as an example.

In addition to the safety issues, the potential impact to the power system of an LDES outage can result in far reaching and costly consequences [3]. Their severity depends on the type, size, and state of charge of the energy storage installation, and on the power system's existing load flows, degree of variable renewable energy penetration, and the robustness of the remaining stable and dispatchable sources and their interconnections. In a weak power system, the main effects of an LDES outage would be system voltage and frequency instability, followed by source and load disconnections. The breakup of the power system might affect neighboring systems possibly evolving into a regional blackout. [4] Presently, the most effective mitigation measure by far to avoid this spiraling collapse is for operators to immediately bring online spinning generation reserves. Such an event underscores the importance of keeping in service and even increasing conventional firm sources until proven replacement sources are commercially available [5].

II. Real world Power system conditions and resulting safety threats

A. *Renewables Plus LDES - Basic Requirements*

Unfortunately, the alternative energy systems meant to displace the power systems operating today do not exist yet. The long-duration energy storage component, which is essential for the technical and commercial viability of variable alternative energy sources, is still under development. The proposed long-duration renewables plus storage systems must, at minimum, meet the following basic requirements which conventional utility power systems have historically complied with at scale: safety, resiliency, reliability, security, and affordability.

The overall strategy to implement the 2050 Net-Zero Decarbonization energy policy[1] [6],[7], as well as to achieve various state and local energy goals, called for the elimination of existing energy sources. Some fossil-fueled and nuclear power plants have already been shut down with no alternative energy sources and delivery systems ready to fully supply the existing loads. At the completion of this energy sources transition, the renewables plus LDES systems would need to operate with no conventional energy sources as backup.

[1]https://www.google.com/search?client=firefox-b-1-d&q=The+Long-Term+Strategy+of+the+United+States%3A+Pathways+to+Net-Zero+Greenhouse+Gas+Emissions+by+2050

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Today the clear frontrunner to possibly implement a commercial utility-scale LDES system appears to be one where lithium-ion batteries would be used [8],[9]. At least six other battery technologies, including less flammable aluminum ion and flow batteries, as well as mechanical energy storage technologies, or combinations of these are being considered and researched. Caution is advised for electrochemical energy storage, due to the operating requirement of high energy density.

Advanced solid state and aqueous electrolyte batteries have been proposed claiming to decrease fire and explosion hazards. Both battery types are at the research stage with the hope of breakthroughs to attain better safety, performance, and cost. Commercial aqueous batteries that exist today lack the energy density and energy duration needs to be seriously considered for LDES applications. Specifically, the drawbacks include a narrow thermodynamic electrochemical stability window and faulty operations [10].

There is another inherent factor associated with chemical energy storage that compounds the safety threat. The energy storage device must respond within milliseconds to power system changes of tens or hundreds of megawatts. This fast action requires high speed chemical reactions in the storage devices to absorb or inject energy from or into the power system. Battery chemical volatility, though desirable for dynamic performance, might increase the safety threat of an LDES system. For example, in the case of lithium-ion batteries, the heat flux generated during a battery failure event can be higher than that from an oil-filled power transformer fire. Battery chemical instability can also cause deflagration and erratic fire behavior, making it exceptionally difficult to suppress these fires [11].

B. LDES Threat Assessment

There has been a concerted effort in both government and industry laboratories to better understand the failure mechanisms of batteries. Progress has been reported in basic research from the battery cell level through demonstration field projects. On the other hand, explosions and fire incidents are consistently publicized in the media. The energy ratings of these installations have generally been orders of magnitude smaller and considerably less intricate than those of LDES systems that would be deployed in a truly decarbonized future power system. The many thousands of components and their complex relationships in a bulk energy storage system exponentially increase the probability of catastrophic failures.

Although the challenge is formidable, the premise is that safety, at a scale to be determined, could be feasible if the potential threats or hazards can be characterized accurately in order to develop effective mitigation measures. This task requires an engineering driven systems approach and a commonsense vision of what can be achieved in a practical manner. A threat assessment is due diligence that allows investors, regulators, ratepayers, and operators to adjust early in a project and proceed with less risk and higher efficiency. Generally, a threat assessment should include other elements such as weather, terrorism, sabotage, human error, proximity to first responders, etc. To accurately assess the threat of an LDES site not only should true values of energy demand be accounted for, but also the frequency of occurrence of the events and their impact. The level of risk can then be calculated. These considerations are beyond the scope of this paper. The threats to be discussed here are only those associated with explosions and fires at LDES systems. Today there is minimum field experience and laboratory data on utility-scale LDES devices. Hence, this assessment is restricted to the process of estimating a realistic energy rating value at an LDES site and its potential threat. Also, because key physical parameters have yet to be characterized, <u>a highly conservative analysis must be followed</u>. Worst case scenario conditions are assumed in this safety threat assessment.

The requisite <u>operational</u> conditions under which a threat assessment of an LDES site should be performed are two:

1) In the incident being considered, both the prevention and the suppression systems have failed, resulting in a literally full-blown event.
2) The second condition comes into play by default. When prevention, as well as suppression measures fail, containment is the last line of defense. Containment consists of providing a primarily passive thermally and structurally rated enclosure, which might be a building or multiple buildings, with some active functions such as pressure relief and cooling in certain applications**.** Effective containment protects life and assets, resulting in reduced recovery times.

C. Basis for the Magnitude of "energy at scale" of LDES

The driver of "energy at scale" is the duty cycle of the major components of the power system. Conventional generators are scheduled for maintenance at about six-to-twelve-month intervals. Transmission lines have even longer maintenance periods. For practical purposes, these operational requirements represent a quasi-continuous duty cycle and would correspond to energy storage duration requirements of not just days or weeks, but actually months. All loads must be served at all times, in addition to having on demand the energy reserves margin to assure safety, resiliency, reliability, and security continuously. To power system planners and operators, reliability with "load shedding and rolling brownouts" is contradictory and unacceptable.

If a renewables-plus-storage combination is to replace existing generation and its delivery system on a one-for-one energy basis, the "energy at scale" of the new power system arrangement must equal the total of the energy ratings of all the existing energy sources, including all interconnections and the energy reserves margin. The new long-duration energy storage system's energy rating should match the sum total of all energy sources and reserves in the power system's region under study.

D. Quantification of "energy at scale" – Example

Below is a hypothetical and simplified example, but it is based on a large utility's typical configuration and use of energy sources, load demand duration, and interconnections to adjacent regions. The replacement to displace conventional generation at present appears to be a renewables plus LDES scheme. To address the LDES's safety concerns, the amount of energy concentrated at a site must first be established

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applying the above definition of "energy at scale". Following are the key steps a transmission planner might take to assess the threat from an LDES system interconnected to the transmission system of a region of the utility's power system. In this example, the major power components operating in this region and their power ratings (MW) are:

- 3 conventional generation plants (350; 350; 150)
- 3 inter-region tie lines (250, 200, 150)
- Reserves margin, 20% of region's sources (290)

Per the energy at scale definition and conservatively assuming a 6-month duty cycle for the sources, the sum of the region's energy sources plus the reserves (1-month duty cycle) is:

[(850 + 600)MW * (Duty Cycle: 4,320)hours] +
[(290)MW * (Duty Cycle: 720)hours] = 6,472,800 MWh

The potential safety threat at full state of charge that this amount of energy represents can be physically appreciated by using the customary industry practice of converting megawatt hours of energy to equivalent tons of TNT (2,4,6-Trinitrotoluene) [12],[13]:

1 MWh = 0.86 metric tons of TNT

This conversion factor considers energy release efficiencies.

Note that, although it is not likely that all the energy an LDES site would be released at once as most of the energy would be released at a lower rate during the fire, explosions at battery energy sites have been reported over the years at large and small chemical energy storage applications. The probability of explosions is definitely nonzero, and under the worst-case scenario assessment, explosions should be considered until testing at utility scale fully characterizes energy release magnitudes and rates at an LDES site. Contingent on the availability of such data, Sections II. A. and II.F. of this paper outline a proposed test strategy to verify the corresponding fire containment protection corresponding to the electrochemical technologies of interest.

In order to compare the effect of duty cycle on the magnitude of the resulting safety threat, the load demand duration hours were drastically decreased from 6 months to 10 days, and then to just 3 days as shown in Table I.

Table I. LDES Safety Threat as Load Demand Duration Varies for the Regional Calculation Example

Load Duration (hours)	**Required LDES Energy (MWh)**	**Equivalent Tons (metric) TNT**
4,320	6,472,800	5,566,608
240	417,600	359,136
72	125,280	107,741

The magnitude of the threat is not acceptable even at the lowest duration of just 72 hours, which would fall considerably short of meeting realistic energy replacement requirements of the regional transmission region. For illustration purposes, if the duration was reduced even further to just 7.2 hours per energy storage site, there would need to be about 600 sites with energy ratings of 10,788 MWh each.

This elementary exercise can also help to understand other energy-versus-safety relationships, such as how the possibility of importing variable renewable resources' energy via the three interconnection lines could reduce the safety threat. However, the practice of sharing energy presupposes: the rare existence of close cooperation between utilities; the availability of spare energy; and ready access to transmission line capacity.

The 2025 Iberian Peninsula 10-hour outage of a 30 GW load equal to 300 GWh is relatively small compared to the regional energy requirements example, and yet the disruption was international in extent and at a cost to be determined. Clearly the 'renewables plus storage' scheme at these energy levels appears to be non-scalable and requires fundamental adjustments.

Retaining and significantly increasing existing clean and dependable generation, such as nuclear, hydro, and natural gas with advanced carbon scrubbers, would make the energy transition viable. The required LDES magnitudes could also be reduced to safe and manageable levels by increasing the number of energy storage sites and distancing them in a power system.

In addition to showing that the energy magnitudes required for the application of LDES as planned would exceed safe operational practice, the above numbers also imply that the LDES solutions under development could already be close to their practical and economic limits. The Moss Landing 3,000 MWh lithium-ion battery, one of the largest in the world until its explosion, fire, and environmental impact incidents starting on January 16, 2025, provides an actual indication of what could be the safe upper bound of energy rating values for LDES [14]. At full state of charge this energy storage site had a potential equivalent energy value of 2,580 tons of TNT.

As population and electrification grow, the trend is for energy consumption to increase, thus stressing further power system reliability, and adding pressure to safety, resilience, and costs. To help avert this oncoming crisis, it is important that research on promising energy sources, including fission and fusion, be continued [15],[16]. To meet the mid and long-term energy needs, new research on yet-to-be-discovered clean energy sources should also be pursued.

E. Tools and Information Needed for an Accurate Threat Assessment of a Long-duration Energy Storage Facility

At this time there exists no industry-wide norm with which to perform a complete and accurate threat assessment of an LDES system at scale. Specific and clear information in the form of a threat assessment protocol is needed, and the necessary testing infrastructure to verify safe mitigation of threats at utility scale needs further development. Existing codes and standards, such as NFPA 855 in combination with

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UL 9540 and UL 9540A, provide energy storage safety guidance and a starting point to develop the needed tools. [17],[18],[19]. However, long duration energy storage at true scale as indicated in Table 1 is an application with no precedent, requiring new information to be generated and included in existing or new codes and standards.

To augment safety at LDES sites it is recommended that certain gaps in the standards listed above be addressed. UL 9540A is a test method calling for testing of one or more "energy storage system" (ESS) assemblies as defined in those standards and housed in an enclosure having a maximum energy capacity of 600 kWh. The test results are then used to establish the capability of fire propagation due to thermal runaway at an actual field installation configured with the same type of ESS's as the test sample. The standard classifies these tests as "large-scale". However, this extrapolation from the 600 kWh test sample maximum capacity to the several hundred or even thousands of MWh of an actual LDES site could be a high-risk prediction due to the large nonlinear data range between these two points, which extends over three orders of magnitude with no verified data points in between [20],[21]. The expectation that compartmentalizing and spacing the "energy storage systems" (ESS) would be sufficient to limit the spread of fire and explosion damage must be validated under a worst-case scenario at utility energy levels.

Fire resistance rating was adopted by these standards, and ratings of one or two hours are specified in the standards for fire containment walls. Yet Appendix G of NFPA 855 cautions that lithium ion fires can burn for days, which is inconsistent with the specified ratings. This discrepancy can be rectified by performing fire resistance rating tests applying for the desired rating period, the heat flux time-temperature curve corresponding to the specific electrochemical technology being investigated. Related to fire resistance rating is the use in the standards of the term 'noncombustible materials', when technically the proper term should be 'fire resistant materials', as noncombustibles such as regular concrete and steel can fail thermally and mechanically under fire, whereas a 'fire resistant material' will maintain its integrity throughout a fire.

Other items to review are that these standards can be considered either mandatory or voluntary depending on the location where they are being applied. Also, these standards allow several exemptions in meeting some of the requirements in the standards. For example, UL 9540A, Section A1.3 states that testing can be performed "in lieu of meeting the specific criteria provided in the codes". NFPA 855 provides a blanket exemption for facilities where utilities have direct control. This approach can lead to confusion, misuse, and reduced safety.

The following specific tasks are proposed:

1.- Update the codes to methodically categorize and provide thermal resistance ratings for long-duration energy storage containment. Revise the relevant codes, to categorize a utility-scale energy storage application according to the type and volume of "fuel" (specific chemical energy storage technology being used), risk factors, use, and site conditions.

Define and include a thermal resistance rating for the containment construction and create research facilities focused on this aim. That type of research facility to fully characterize the various types of energy storage devices does not currently exist. An example would be a facility to measure the energy release rates and efficiencies, and the Temperature versus Time curves. Note that such a laboratory will not be the same as the product certification test labs that would also be needed later during commercialization.

2.- With input from all stakeholders, develop the criteria needed to assure effective safety. Aligned expectations help remove potential conflicts.

3.- Write the standards that specify energy storage safety at scale and disseminate them widely.

4.- Design and build the certification test facilities capable of verifying the safe design, construction, and operation of energy storage facilities.

5.- Perform full-scale demonstration projects in utility commercial settings.

F. *Essential Elements for Containment Testing*

Test criteria for LDES containment units need to be developed with input from all participants. The following specific test requirements should be included:

- The test specimen must be representative of the commercially produced unit and not a "special" sample fabricated just for testing. The test specimen size should preferably be full-scale; or of a reduced scale only if all scaling laws have been verified. All connections, joints, interfaces, etc., must be included in the test specimen.
- Each "fuel" has a characteristic Temperature versus Time curve. The conditions under which these curves are generated must be the same as those of the type of energy storage device in service.
- It is critical that the correct value of the "energy at scale" be applied, as described before. In addition, the steady state conditions must be maintained for the period equal to the thermal resistance rating period required for the containment system.
- Heat flux and thermal radiation, which are key parameters to evaluate the potential hazard of a fire, are to be measured directly.
- Fire suppression might cause as much damage as the fire itself; hence, the energy storage system must be tested under the stresses created during fire suppression. The containment structure must maintain its integrity in order to confine the fire to its location of origin and continue to protect neighboring equipment.
- The fire test facilities capable of testing energy storage devices at scale will need to be huge, customized, and costly. Explosion testing also requires very large and specialized facilities, which will likely need to be located in remote areas. Separate test facilities for fire and for explosion would be ideal.

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III. Safety at Scale: Blueprint for Action

A. *Main Attributes of the Action Blueprint*

1. BIG and BOLD

Among existing energy storage technologies, only pumped hydro energy storage gives a hint of the magnitude of the storage needed to replace the energy provided to an average-size regional power system. But even at the largest pumped hydro storage facility in the US, Raccoon Mountain, the stored energy is considered as a supplement to the power system for only 22 hours. It is rated at 36,344 MWh, which is only about 0.5% of the stored energy required by the regional power system in the example. To realize the energy transition as planned (with zero reliance on conventional sources), renewable sources coupled with energy storage unique in capacity and duty cycle ratings would be needed.

These massive LDES facilities present potential tera-threats requiring correspondingly big and bold at-scale mitigation. As illustrated in the calculation example, the resulting safety threats are unacceptable and unmanageable without first reducing the energy ratings of these LDES sites and providing dependable and economic backup energy sources of some type. It will only be practical to apply measures such as containment of explosions and fires after reducing the energy levels at LDES sites.

2. IMMEDIATE and FAST

To meet the net-zero decarbonization goals by 2050, safe energy storage at scale must be in widespread commercial operation within the next 15 to 20 years. The correct action is needed now and at a fast pace. It is essential that regulators: recognize the higher costs of renewable sources with LDES that present a higher potential safety threat to the public, utility personnel, fire fighters, and assets; issue clear technical and market rules; and expedite the approval process.

3. COLLECTIVE

Decarbonization is a global undertaking of never-before-seen proportions in terms of cost and effort, involving many interests and disciplines. By comparison the Manhattan Project cost $33 billion in a 3-year project; Project Apollo cost $207 billion over 12 years; and according to the McKinsey Global Institute, Earth's decarbonization by 2050 is estimated to cost $275 trillion (all in 2022 US dollars) [22]. Again, government aid will be crucial to develop LDES in synchronism with the market. To succeed in achieving long-duration energy storage safety within that framework, a shared effort and sustained collaboration among all participants will be necessary over several decades.

B. *In Summary*

As a first step, the following two-part joint-action must be taken immediately by industry and government leaders:

1. Develop codes and standards specifically applicable to "at utility-scale" energy storage.
2. Perform a complete and accurate explosion and fire threat assessment at full-scale on a planned typical "renewables plus storage" project replacing regional conventional generation and its delivery system and verify the resulting safety level achieved at multiple commercial LDES installations.

By bringing to the forefront basic questions that need to be resolved now, this first step will reveal the facts, redirect the course of action, and put into perspective the state of readiness necessary to safely and reliably meet energy demand.

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