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Risk Factors and Failure Statistics of Lithium Ion BESS

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ABSTRACT

Lithium ion battery energy storage system (BESS) deployment has increased exponentially in the past few years. Failure incidents are rare, but understanding their risks is important to support continued improvements in BESS safety. This report uses real-world data from EPRI's BESS Failure Incident Database[1] to calculate the likelihood of failures and quantify failure consequences. The risk of BESS failures is compared with risk of failure of other energy infrastructure such as transformers. Several BESS design factors, including site architecture and chemistry, are analyzed to understand the impact to risk.

Keywords

Battery energy storage system
Batteries
Energy storage
Fire prevention
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Risk

[1] EPRI. *BESS Failure Incident Database*, EPRI Energy Storage Hub. https://energystorage.epri.com/hub/public/en/failure-incident-database.html

EXECUTIVE SUMMARY

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Primary Audience: Project developers, owners, operators, technology providers, insurance providers, and permitter authorities for energy storage projects

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KEY RESEARCH QUESTION

Lithium ion battery energy storage system (BESS) deployment has increased exponentially in the past few years. Failure incidents are rare, but understanding their risks is important to support continued improvements in BESS safety. This report intends to characterize and contextualize risk associated with lithium ion BESS, where risk is defined as the combination of the likelihood of an incident and the severity of its consequences.

RESEARCH OVERVIEW

This report uses real-world data from EPRI's BESS Failure Incident Database[2] to calculate the likelihood, or frequency, of failures and quantify failure consequences. The risk of BESS failures is compared with risk of failure of other energy infrastructure such as transformers. Several BESS design factors, including site architecture and chemistry, are analyzed to understand the impact to risk.

KEY FINDINGS

- The annual failure rate in terms of failures per deployed GWh has decreased by 98% between 2018 and 2025.
- The failure rate of BESS is comparable to large oil-filled transformers, a well-understood technology.
- For the vast majority of BESS incidents (93%), no injuries or fatalities have been reported, and no member of the public experienced acute injury due to a BESS arc flash, fire, or explosion.
- Detailed statistical analysis showed that failure rates decrease with system age and with more recent vintages, since newer designs have improved safety performance. Conducting

[2] EPRI. *BESS Failure Incident Database*, EPRI Energy Storage Hub. https://energystorage.epri.com/hub/public/en/failure-incident-database.html

safety reviews and retrofits of early-vintage systems can ensure they include the latest codes, designs, and practices.

WHY THIS MATTERS

This report provides evidence-based insights on factors that can reduce risk in lithium ion BESS. It also puts the risk of BESS, both likelihood and severity of failures, in context with other energy infrastructure, to support siting, permitting, emergency response planning etc.

HOW TO APPLY RESULTS

These findings can be used to refine safety specifications, conduct hazard mitigation analysis for specific projects, engage with public stakeholders and other deployment-related activities.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Fire Prevention and Mitigation Supplemental Project Phase III and Phase IV
- Program 94I: Safety, Environment, and Community Engagement for Energy Storage

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PROGRAM: Fire Prevention and Mitigation Supplemental Project Phase III

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1. INTRODUCTION

Lithium ion battery energy storage system (BESS) deployment has increased exponentially in the past few years, surpassing 300 GWh of new installations globally in 2025. Cumulative installed capacity across the world is expected to exceed 7000 GWh by 2035[3], which is more than half the electricity used across the United States on a typical day. Failure incidents are rare, but understanding their risks is important to support continued improvements in BESS safety.

All energy infrastructure carries inherent risks. This report intends to characterize and contextualize risk associated with lithium ion BESS, where risk is defined as the combination of the *likelihood* of an incident and the *severity* of its consequences. This report uses real-world data from EPRI's BESS Failure Incident Database[4] to calculate the likelihood, or frequency, of failures and quantify failure consequences. The risk of BESS failures is compared with risk of failure of other energy infrastructure such as transformers. Several BESS design factors, including site architecture and chemistry, are analyzed to understand the impact to risk.

Key Findings

- The annual failure rate in terms of failures per deployed GWh has decreased by 98% between 2018 and 2025.
- The failure rate of BESS units is comparable to that of large oil-filled transformers, another utility asset that experiences infrequent fire events. Additionally, many principles of incident command, site control, and emergency response used for transformer fires are also applicable to BESS incidents. For all recorded failure incidents involving utility-scale BESS, there was no report of fire spreading beyond the BESS facility.
- For the vast majority of BESS incidents captured in the database (93%), no injuries or fatalities have been reported. No member of the public experienced acute injury due to a BESS arc flash, fire, or explosion. Following the 2019 incident in Surprise, Arizona and dissemination of the lessons learned, there have been no reported injuries or fatalities in the U.S. related to BESS failures. Identifying data driven thresholds for implementing precautionary measures is necessary to avoid excessively burdening communities.
- Indoor BESS facilities are overrepresented in failure incidents and sustain more damage on average when an incident occurs. Propagation prevention – both within units and between units – is a critical component of BESS risk management. Fire walls or other barriers can be used to segment large indoor facilities and limit propagation.

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[3] Isshu Kikuma. Global Energy Storage Boom: Three Things to Know, BloombergNEF, October 21, 2025. https://about.bnef.com/insights/clean-energy/global-energy-storage-boom-three-things-to-know/.

[4] EPRI. *BESS Failure Incident Database*, EPRI Energy Storage Hub. https://energystorage.epri.com/hub/public/en/failure-incident-database.html

- Detailed statistical analysis showed that failure rates decrease with system age and with more recent vintages, since newer designs have improved safety performance. Safety reviews and retrofits of early-vintage systems can help ensure they include the latest codes, designs, and practices.
- Cell chemistry as a risk factor was challenging to disentangle from increased integrated unit design maturity as well as improved industry understanding of manufacturing, integration, and operation of BESS. As a result, it could not be concluded that cell-level chemistry in isolation was a risk factor for system-level BESS failures.
- Increased transparency from failures is necessary for continued improvement on BESS risk and safety.

2. DATA AND METHODOLOGY

EPRI's BESS Failure Incident Database is the main source of BESS failure data for this report. The database was initiated in 2021 following the series of lithium ion BESS fires in South Korea and the Surprise, Arizona incident in the U.S.[5]. The database gathers information on stationary BESS failure events for commercial and industrial (C&I) and utility-scale BESS. This database defines utility-scale BESS as any system that is interconnected to the grid as a front-of-the-meter asset regardless of capacity, while C&I systems could include behind-the-meter installations. The design approach and applicable codes and standards for utility-scale and C&I systems are the same, so these systems are considered together in this analysis. Residential energy storage system and electric vehicle failures are not tracked by this database and were not considered in this report. Failures in uninterruptible power supply (UPS) systems for data centers are included where known, classified as C&I systems.

The database contains incidents as far back as 2011 and continues to be updated with new incidents as they occur and are reported publicly. The focus of the database is on failures that potentially had a wider public health and safety impact. Smaller operational failures, where no additional risk to personnel was present or likely, were not considered for inclusion in the database. EPRI defines a **failure incident** as a large-scale thermal event, i.e. involving arc-flash, fire, or explosion of a BESS unit. Failures included in the database are caused by an issue internal to the BESS, rather than an exogenous cause of failure (e.g., wildfire impacting the BESS).

The database captures incidents occurring globally and cites information from publicly available sources, including media reports, government hazardous material release reporting databases, published root cause analyses (RCA), academic journals, and corporate press releases. EPRI has used academic publications, and collaborated with other organizations tracking failures[6], to attempt to ensure all publicly known stationary BESS events are captured.

However, many incidents are not reported in news media, especially before 2018-19 when the concerted industry focus on safety began. Additionally, there are incidents captured in the database for which there is no public information in news media or other sources but were confirmed by trusted BESS safety experts. These are labeled 'non-public' incidents, shown in Figure 1. Due to legal barriers and lack of public documentation, only the year and country of the incident are recorded in the database. Like other incidents included in the database, some information related to the non-public incidents was not verifiable or available. For every analysis presented, the fractions of available and missing data are noted. Non-public incidents were included in incidents counts when relevant information was able to be confirmed.

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[5] McMicken Investigation. https://www.aps.com/en/About/Our-Company/Newsroom/Articles/Equipment-failure-at-McMicken-Battery-Facility

[6] UL Solutions. *Lithium-ion Battery Incident Reporting*, UL Solutions Resources. https://www.ul.com/insights/lithium-ion-battery-incident-reporting.

Additional information on non-public incidents can be found in Appendix A. While some incidents or project-level details may be incomplete or unavailable, the EPRI Failure Incident Database provides the most comprehensive publicly available record of BESS failure events.

As of publication, the database has 150 incidents globally between 2018 and 2025 involving lithium ion BESS. Most of the analyses presented in this report use the global dataset. Some analyses use only U.S. incidents, due to information availability. Though the database includes incidents as far back as 2011, this report is concerned with the period between 2018-2025, as there is higher confidence and completeness of the dataset during those years.

Table 1. Global Incident Counts

Dataset – 2018-2025	Count
Global incidents (including public and non-public)	150
Global non-public incidents	33
Incidents in the United States (including public and non-public)	36
United States non-public incidents	7

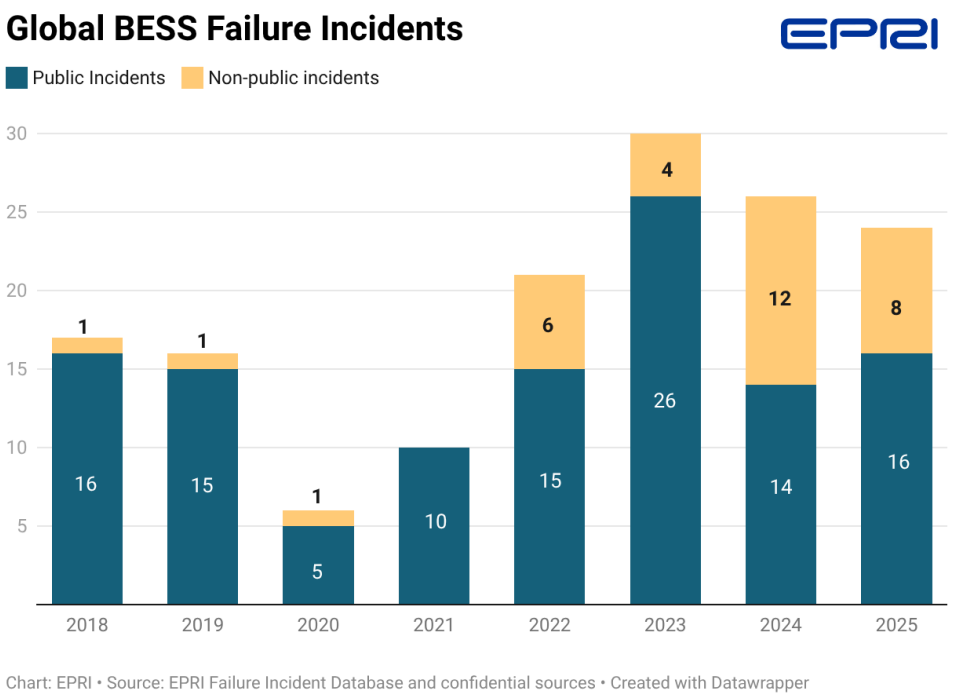


Figure 1. Public and Non-public Incidents

Data Validation and Uncertainty

Limited transparency and data gaps remain a major challenge to a complete database. Not all failure incidents are publicly disclosed, and there are 33 non-public incidents recorded as of publication. Non-public incidents account for 22% of the total incidents included in Figure 2. It

is possible that there are additional incidents that are not captured in any record. Appendix A lists the non-public incidents by year of failure and country.

Considerable effort was dedicated to validate and augment the dataset through industry outreach and collaboration. EPRI collaborated with UL Solutions to compare known BESS incidents. UL Solutions maintains a lithium ion battery incident database[7] and publishes several statistics and visualizations, though the underlying data in the database is not publicly available. The database includes consumer products; electric vehicles; micro-mobility devices such as e-bikes; and BESS, including residential, C&I, and utility-scale systems. EPRI's BESS Failure Incident Database focuses on utility-scale and C&I BESS failures only. EPRI's dataset was largely congruent with UL's database, though both databases were missing incidents captured in the other. Five incidents were added to the EPRI database based on a comparison of incidents collected by UL Solutions.

The Netherlands Institute for Public Safety (NIPV) provided information on 3 BESS failure incidents in their country, one of which was previously not captured in the database. The China Energy Storage Alliance provided information on several incidents in China that were not previously recorded in the database. The California Spill Release Reporting Database[8], which documents hazardous material releases, was used to identify additional BESS incidents. Hazardous material releases exceeding reportable thresholds are legally required to be immediately reported to the California Office of Emergency Services (Cal OES). Five BESS incidents were identified in the Spill Release Reporting Database, three of which had already been captured in EPRI's BESS Failure Incident Database. Two incidents, which had received no media coverage, were added to the database after additional confirmation. Other states and other countries do not consistently make hazardous release reports publicly available. Based on California's 17 known BESS incidents, 14% of incidents did not receive media coverage. Globally, 22% of incidents in the dataset did not receive media coverage. These figures give a sense of the potential magnitude of missed incidents.

While many additional incidents were identified through these efforts, it is not expected that all incidents are captured. The awareness of BESS failures and reporting in media and other public sources varies by country and region and additionally varies over time. There are multiple academic and news sources that catalogue failure incidents in South Korea, where there is more government oversight of BESS. In contrast there is no mandatory reporting of failure incidents in the U.S. or Europe, and media reports of incidents in China are limited – 22 out of the 25 Chinese incidents are non-public. Overall, some level of uncertainty exists in the results presented in this report. This is estimated in further detail in the subsequent section.

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[7] UL Solutions. *Lithium-ion Battery Incident Reporting*, UL Solutions Resources. https://www.ul.com/insights/lithium-ion-battery-incident-reporting.

[8] Cal OES. *Spill Release Reporting*, California Spill Release Reporting Database (current and historical databases), Accessed October, 2025 at https://www.caloes.ca.gov/office-of-the-director/operations/response-operations/fire-rescue/hazardous-materials/spill-release-reporting/.

3. LIKELIHOOD OF INCIDENTS

A key element of risk is the likelihood of a failure. This report provides different approaches to failure rate estimation, based on data within the EPRI Failure Event Database. In past work, EPRI has described a BESS failure rate based on failures per GWh deployed. This section provides background on the development and limitations of this failure rate, then discusses additional methods to calculate the failure rate.

Frequency of Failure Over Time

Previous analysis[9] of the annual failure rate of BESS has been updated to include 2025 data and non-public incidents. Figure 2 shows the number of BESS failures that occurred each year, compared against global energy capacity in terms of cumulative deployment of Lithium ion BESS in GWh. The failure rate has demonstrably improved over time. **The annual failure rate in terms of failures per deployed GWh has decreased by 98% between 2018 and 2025.** While much of the decrease comes from improvements between 2018 and 2020 in design, codes and standards, and battery management and operating practices, the failure rate continues to drop in recent years. In 2024, there were 26 incidents in a global fleet of 343 GWh. In 2025, there were 24 incidents and 634 GWh deployed globally, resulting in a 50% reduction in failure rate compared to the previous year.

[9] *Insights from EPRI's Battery Energy Storage Systems (BESS) Failure Incident Database: Analysis of Failure Root Cause.* EPRI, Palo Alto, CA: 2024. 3002030360.

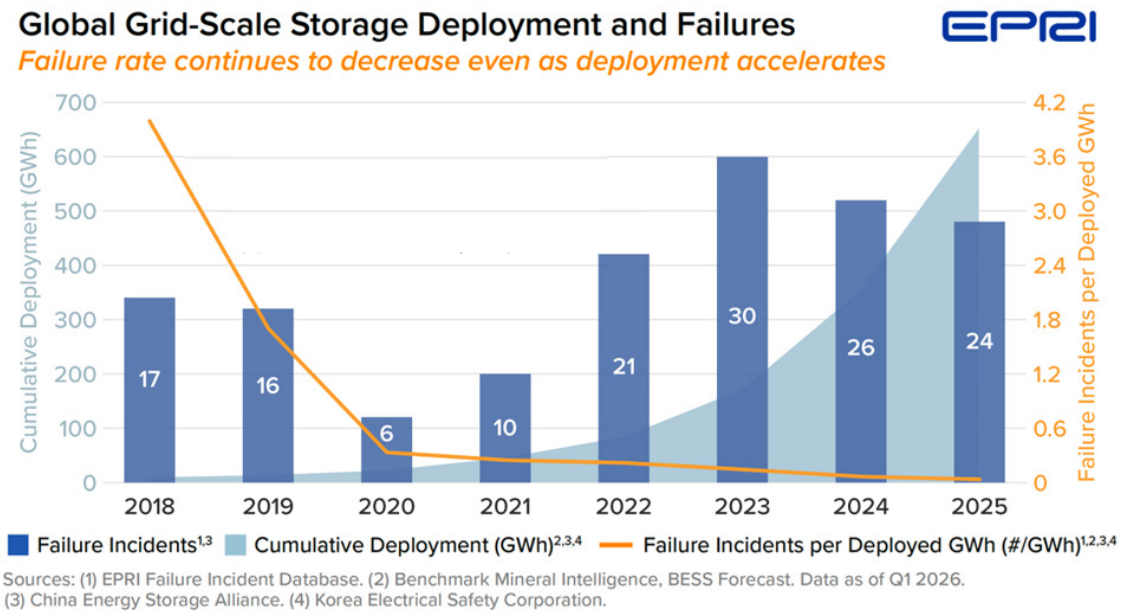


Figure 2. Global Grid-Scale Deployment and Failures

Note that the BESS failure rate described in the graph above is an annual number based on **calendar year**, using number of failure incidents and cumulative deployed energy capacity in GWh in a given year. Every failure incident in the database is counted equally in the above figure, regardless of the project capacity and extent of damage, meaning a failure in a small C&I system of 200 kWh is not differentiated from the failure of a larger facility of several hundred MWh. BESS are highly modular systems, with even a small 5 MW / 10 MWh project requiring thousands of cells that are packaged into modules, racks, and eventually self-contained 'BESS units' that can operate independently. Figure 2 normalizes failures over deployed energy capacity rather than number of projects since energy is a better proxy for BESS units, as the number of units in a system scales with energy capacity. Project sizes range widely, from ~100 kWh to GWh scale systems. The average project size has also increased over time, as show in Figure 3, making it challenging to normalize by number of projects when comparing annual failure rates. As a result, the BESS failure rate was normalized by energy capacity, instead of by project number or power capacity.

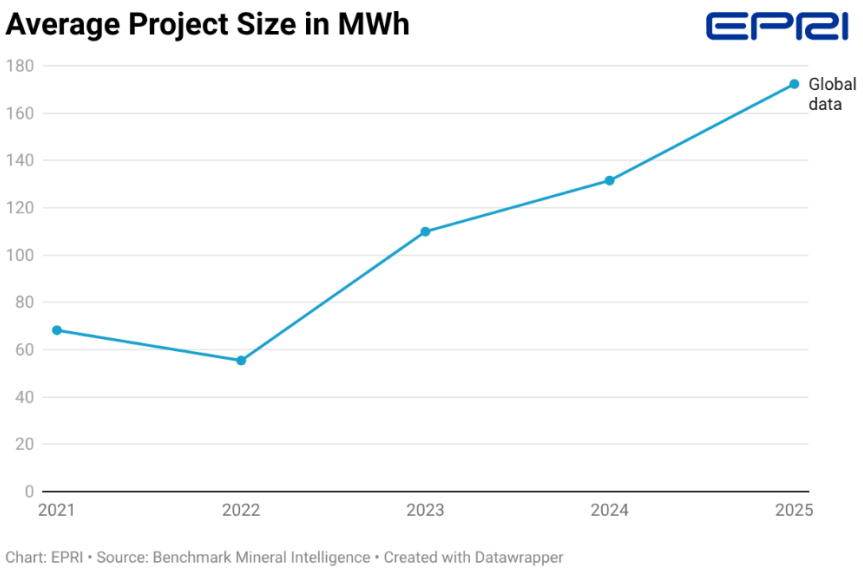


Figure 3. Project Size Over Time, Global Data

Regional Failure Rate Comparison

Figure 4 provides a comparison of storage deployment and failures between different regions of the world. South Korea's high number of incidents per GWh deployed makes this region an outlier. As an early adopter of energy storage, South Korea rapidly deployed over 1000 BESS facilities between 2017 and 2018[10] South Korea experienced a high rate of BESS incidents in early years, with 27 of the 55 recorded incidents occurring between 2018 and 2019. These early failures were investigated by a government-industry taskforce, and the broader lessons resulted in numerous measures designed to reduce failures that were incorporated or inspired similar action in other countries, including cell, battery management system (BMS) and power conversion system (PCS) safety testing; mandatory installation of electrical protection systems, emergency stops, and monitoring systems; and safety retrofits for existing BESS. Figure 5 compares the regional-specific deployment and failures between 2018-2025, while Figure 6 compares the regional failure rates over time. All regions show significant reductions in failure rate by 2025. Europe and South Korea have slight increases in failure rate between 2024 and 2025; every other region including the global trend shows reduced failure rates. Region-specific failure rates compared with deployment over time are provided in Appendix B.

[10] "ESS Incidents Cause Investigation Results and Safety Enhancement Measures Announcement" MOTIE June 11, 2019. Translated.

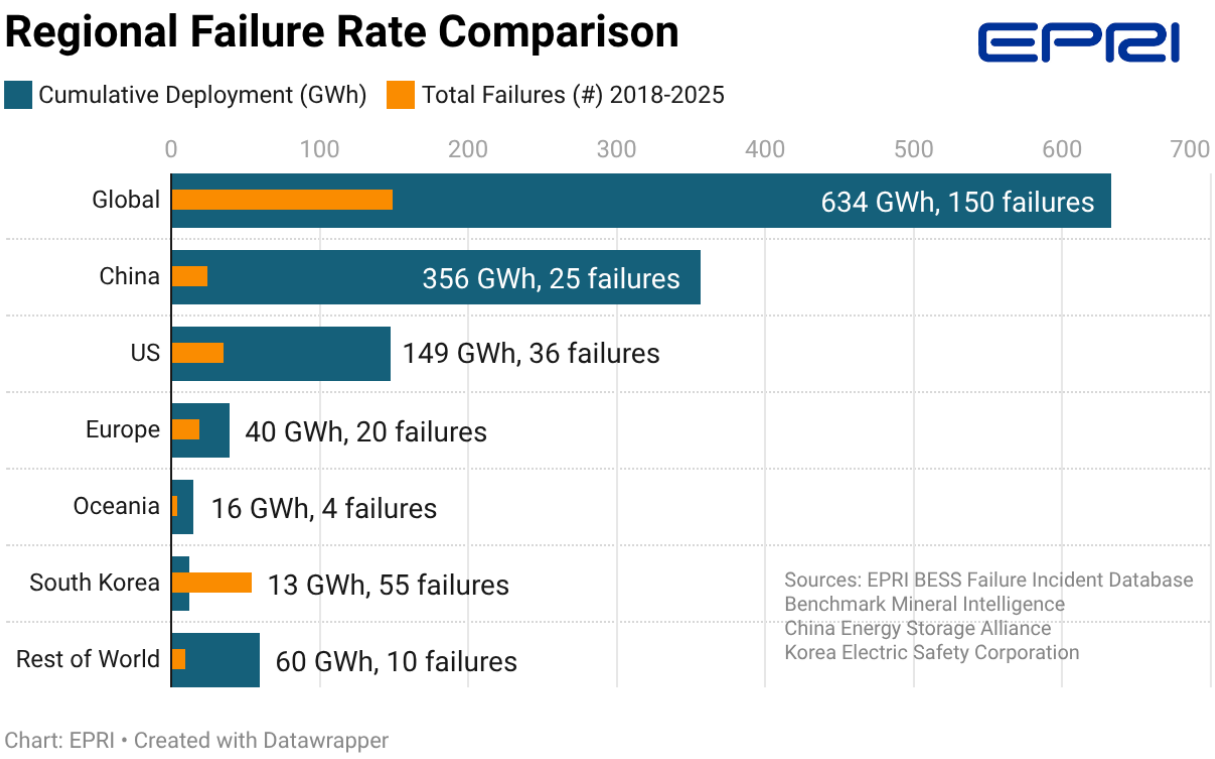


Figure 4. Comparison of Failure Rates Across Different Regionals of the World

South Korea's failure rate fell sharply between 2018 and 2020 and has since remained within the same order of magnitude as other regions. Note that the scale for total deployment between the United States, South Korea, Europe, and Oceania are consistent, while the scale for China is larger, reflecting the magnitude of deployment in that country.

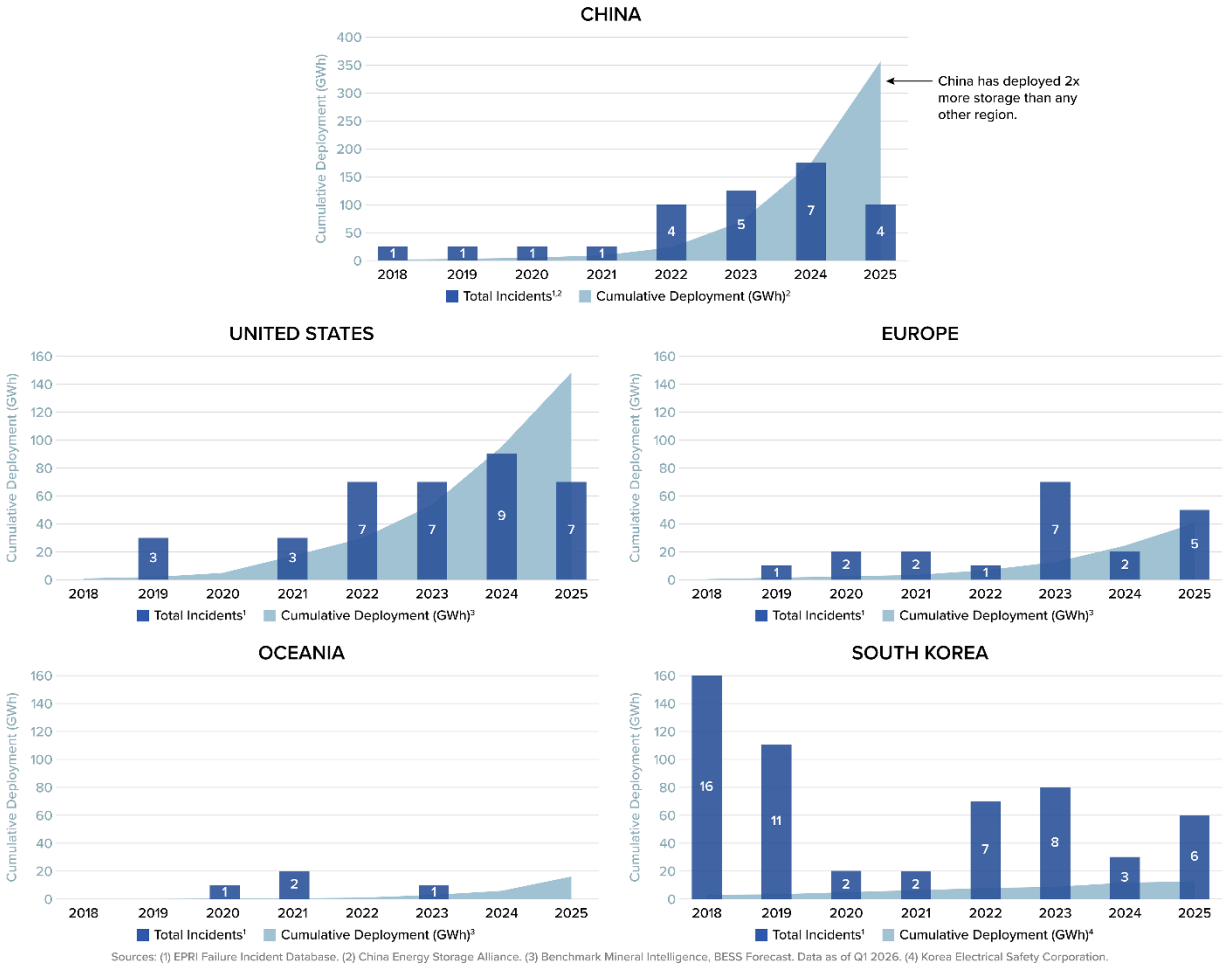


Figure 5. Comparison of Regional Deployments and Failures

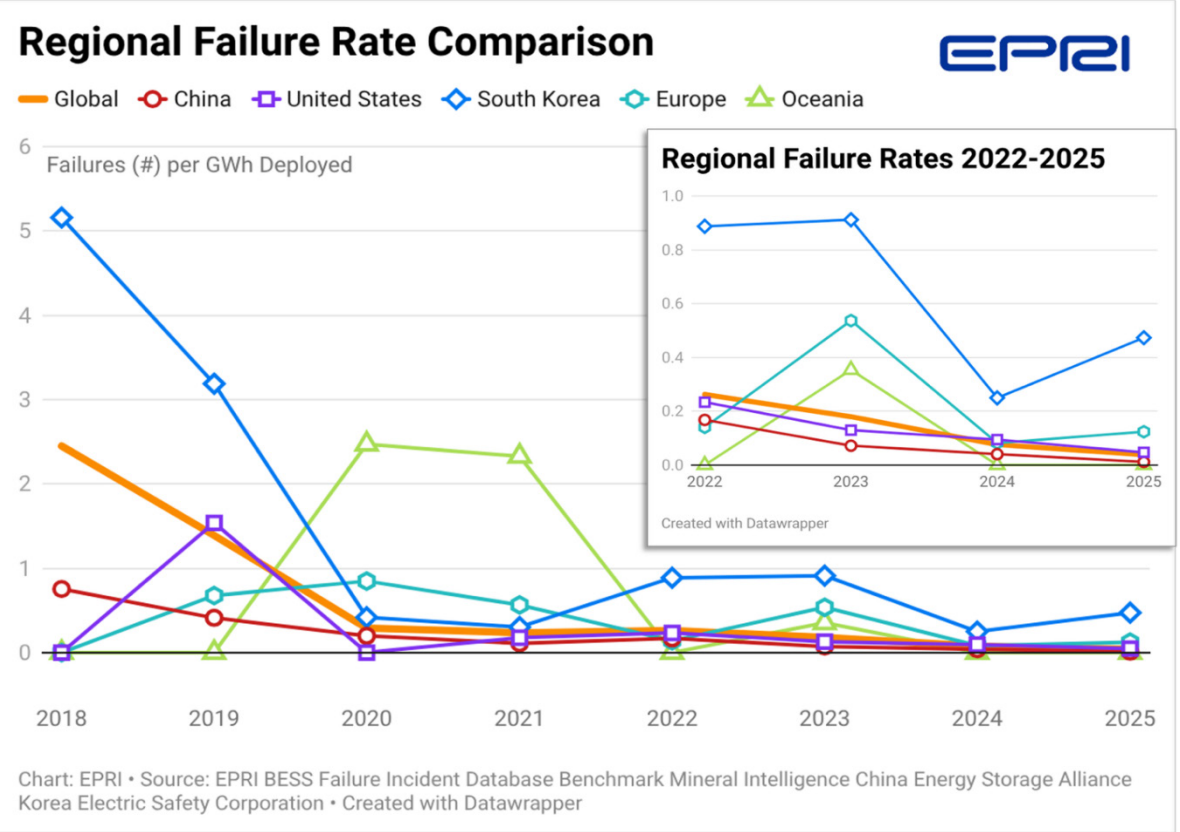


Figure 6. Regional Failure Rate Comparison

Table 2 shows the reduction in failure rate in each region. The reduction is calculated by comparing the maximum annual failure rate prior to 2021 to the failure rate in 2025. Given varied deployment and few failures in years prior to 2021 across the different regions, it was not feasible to use the same year as the starting point for calculating the failure rate reduction. That said, all regions considered in the table experienced significant reductions in failure rate over time. This is largely due to the exponential increase in deployment over time, **without** a commensurate increase in recorded failures.

Table 2. Regional Failure Rate Reduction

Region	Cumulative Deployment as of 2025 (GWh)	Total Failures (#) 2018-2025	Failure Rate Reduction as of end of 2025
Global	634	150	98%
China	356	25	99%
U.S.	149	36	97%
Europe	40	20	85%
Oceania	16	4	100%*
South Korea	13	55	91%

*Note that there were no recorded failures in this region in 2025.

Codes, standards, and regulations (CSR) have developed along with BESS products. While fire and building codes are typically updated on a three-year cycle, and can therefore lag technology and product evolution, product-level certifications can and have been updated more frequently to account for the latest learnings. Taking North American standards as an example, the overall product standard that BESS are certified to is Underwriter Laboratories (UL) 9540 Energy Storage Systems and Equipment, which references several other product standards including UL 1973 Batteries for Use in Stationary and Motive Auxiliary Power Applications and UL 1741 Inverters, Converters, Controllers, and Interconnection System Equipment for Use with Distributed Energy Resources. UL 9540 is currently going through a revision, with previous updated published in 2023 and 2025[11]. These updates have incorporated learnings from past failures, deployment, and operation of BESS projects. The applicable fire code in North America for BESS is NFPA 855 Standard for Installation of Stationary Energy Storage Systems, which is updated every 3 years. The first edition for NFPA 855 was released in 2020. The latest edition was released in 2026, and revisions and public comment are underway for the 2029 edition to incorporate the latest knowledge and leading practices.

European standards use the International Electrotechnical Commission (IEC) framework, including IEC 62933-5-2: Safety requirements for grid-integrated electrical energy storage systems, which requires demonstrating sufficient risk reduction prior to deployment. China has a robust family of component, product, and site-level standards that were recently updated and instituted in 2025-2026 timeframe[12], creating prescriptive requirements for component, system, and site design. The continued development, revision, and enforcement of CSR have helped improve BESS projects and reduce risk, as indicated by the reduction in failure rate globally and regionally.

CSR vary across the different regions shown in Table 2. While CSR are critical, the failure rate reduction across all regions also points to real improvements in design, manufacturing, and deployment practices in BESS products. Continued progress on this front requires collaborative R&D and transparency related to failures and lessons learned.

Failure Rate by Operational Year

This report also considered the annual failure rate of BESS on a unit basis, rather than normalizing by energy capacity. This annual failure rate accounts for the impact of age and time in operation on the failure rate. This calculation enables comparison with failure statistics of other energy infrastructure, namely transformers.

[11] https://www.shopulstandards.com/ProductDetail.aspx?productId=UL9540_3_S_20230628 Accessed Sep 30, 2026

[12] https://en.cnesa.org/latest-news/2026/1/27/key-energy-storage-standards-to-watch-in-2026-highly-recommended-for-industry-reference Accessed Sep 30, 2026.

Failure rate for reliability engineering (λ) is defined as the number of failures (Δn) in a given time interval (Δt).

$$\lambda = \frac{\Delta n}{\Delta t}$$

This approach is intended for **unit** failure rates based on operating year. A BESS unit, or container, consists of many battery modules, controls equipment, thermal management subsystems and other components. A single 20 ft-equivalent container was designated as the ''unit' for this analysis. Previous work on root cause has explored failures by subsystem[13], but the granularity of this exercise is maintained at the BESS container level.

The failure rate depicted in Figure 2 above is based on calendar year, rather than operational year. The latter is used in reliability engineering to develop the probability of failure over the lifetime of an asset. Such analyses typically rely on probability curves, often using a Weibull distribution[14], which can then be used in predictive models to determine the likelihood of failure for a given system over its lifetime. The dataset used in this report is limited to ~7 years of operational time, and only 2% of deployed units are over 6 years of age. Given the typical BESS lifetime for systems today is 15-20 years, any probability curve would have such extremely wide bounds as to be unusable, due to the limited data and large uncertainties. The existing failure dataset for BESS is limited and precludes projection of failure rates at this time. **This report estimates an average annual failure rate based on operational year, solely for contextualization across prior years, not prediction.** The table below provides a brief comparison between the operational and calendar failure rates:

Table 3. Comparison Between Failure Rates

	Annual Calendar Failure Rate	Annual Operational Failure Rate
Units	# of failure per GWh deployed	# of containers failure per containers deployed
Time Basis	Based on calendar year	Based on years in operation
Use	• Observe trend in failure rate *over time*. Failure rate decrease attributed to product and standard evolution, industry learnings.	• Observe trend in failure rate *over BESS lifetime*. Trend is related to system age. • Compare to failure rates of other technologies • Develop failure probability curves for prediction
Limitations	• Cannot compare to other technology failure rates due to units • Cannot predict likelihood of failure for a given project	• Current dataset is too small to predict likelihood of failure for a given project

[13] *Insights from EPRI's Battery Energy Storage Systems (BESS) Failure Incident Database: Analysis of Failure Root Cause.* EPRI, Palo Alto, CA: 2024. 3002030360.

[14] https://www.6sigma.us/six-sigma-in-focus/weibull-distribution/ Accessed Aug 24, 2026.

In order to determine the failure rate by operational year, the BESS failures were grouped by system age when the incident occurred, in one-year increments. Incidents that occurred during commissioning are included in the 0-1 year bucket. Note that for 64 incidents, the system age was not able to be determined.

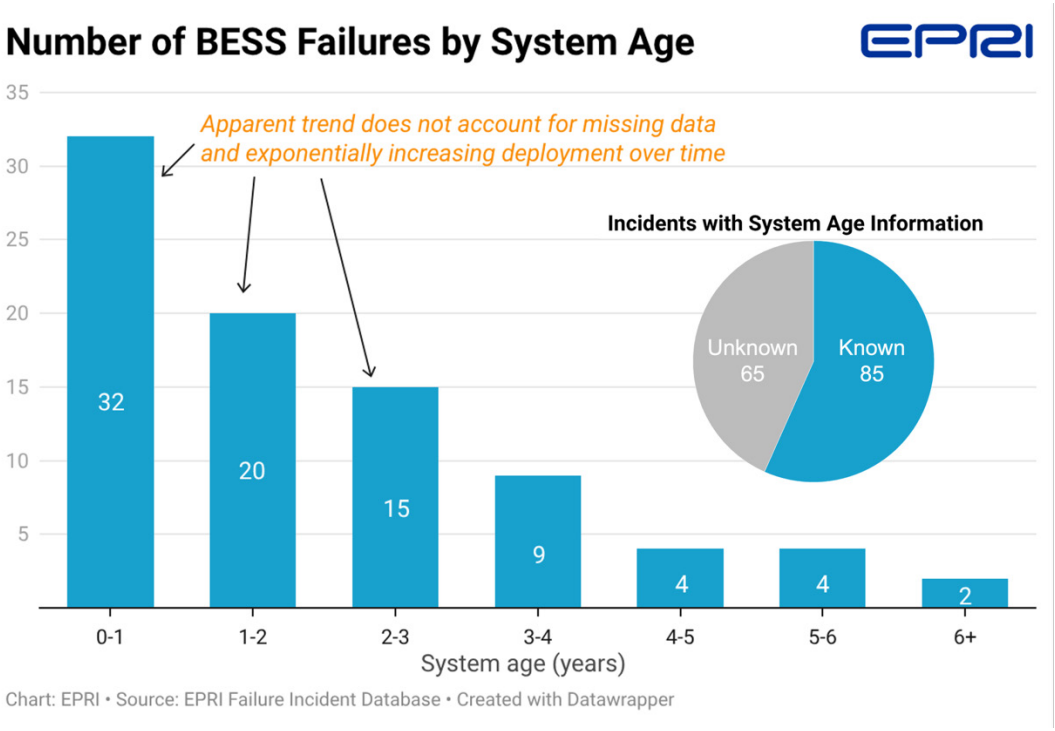


Figure 7. Failures by System Age

The analysis below calculates the failure rate based on the number of BESS units failed per BESS units deployed for each operational year, developing an annual failure rate over the life of the BESS. Data is limited past 6 years of operation, with only two incidents recorded in that age bracket.

Several assumptions were made for this calculation:

1. Deployment in GWh was converted to deployment in 20-ft ISO-equivalent containers. The energy density of BESS products has increased over time, so an average energy density was estimated for each deployment year, shown in Table 4. The energy capacity of the containerized product is normalized to the volume of a 20-ft equivalent container (TEC) shipping container to account for differently sized products. This was developed based on specification sheets of 20 BESS products from eight major BESS OEMs. See Appendix C for further details.

Table 4. Energy Density Assumptions per BESS container by Year

Year of Deployment	MWh/container
2016	2
2017	2.5
2018	3
2019	3.5
2020	3.5
2021	4
2022	4
2023	4
2024	4.5
2025	4.5
If unknown	3.5

Note that the global deployment in energy capacity is based on reported or nameplate capacity of projects. However, projects typically have some amount of overbuild to account for capacity fade and losses over time, resulting in a **conservative** estimate for number of deployed containers with this data.

2. All incidents considered for this analysis are treated as single-container failures. If other containers entered thermal runaway during the same incident, it was assumed the containers failed due to heat propagation and not due to an independent failure. A separate analysis of propagation is provided later in this report. The failure rate for containers is intended to capture the likelihood of a BESS container **independentl**y failing, and the cascading effects of one container failure upon other containers are excluded from this analysis. Therefore, it was assumed that 1 container failed in each incident. Examples of single and multiple container failures are provided below.
    a. In a 2021 incident in Moorabool, Australia[15], a BESS container failed, and fire propagated to one adjacent container and damaged two other containers. One container is considered to have failed in this case, and the other containers failed due propagation, i.e. external heat from the first failure.
    b. Though there are no confirmed examples in the database of an incident with multiple independent containers, it remains a possibility. For example, there are some incidents where the failure mode was determined to be water intrusion from storms. In such cases, it is possible that multiple containers could fail independently.

[15] EPRI. Failure Event - Australia, Victoria, Moorabool, EPRI BESS Failure Incident Database, July 30, 2021. EPRI BESS Failure Incident Database: Australia, Victoria, Moorabool Jul 31, 2021

While this assumption may underestimate the number of BESS containers that have independently failed, this is consistent with current knowledge on failure pathways and fire propagation. A sensitivity analysis below explores how an undercount would impact the calculated failure rate.

Equation 1: Formula for Annual Failure Rate Estimation for operational year *n*

$$\lambda_n = \frac{Failed\ containers_n}{Deployed\ containers_n}$$

Table 5 below shows λ_n determined for each age bracket, based on deployment and number of incidents with known ages. Note that for 65 out of 150 total incidents, the system age at failure is unknown.

Table 5. Comparison of failed containers and deployment based on system age, for incidents where age is known

System age	Number of deployed containers in each age bracket	Number of failed containers in each age bracket	Failure rate by operational year (containers failed/containers deployed)
0-1	146,304	32	2.19E-04
1-2	81,631	20	2.45E-04
2-3	42,506	15	3.53E-04
3-4	20,764	9	4.33E-04
4-5	11,372	4	3.52E-04
5-6	5,898	4	6.78E-04
>6	5,236	2	3.82E-04

Not all BESS had a known system age at failure. In order to determine the actual average annual failure rate inclusive of all known failure incidents, further calculations were performed. Of the 150 incidents, 43% had an unknown system age. These incidents were distributed proportionally across the system age groups by increasing the number of incidents at each system age by 43% before calculating the average annual failure rate. Note that the impact of system age on likelihood of failure is explored in detail in the *Analysis of Risk Factors* section of this report.

Based on the data availability limitations discussed above, there is some uncertainty in the calculated failure rate due to the potential for missing incidents as well as information missing on known incidents. Additionally, there is some uncertainty due to the assumptions made on energy density to determine the number of deployed containers globally. A sensitivity analysis was performed by creating optimistic, base, and conservative cases for both input factors to the failure rate. Table 6 and Figure 8 describe these cases in further detail.

Table 6. Cases for Sensitivity Analysis

Parameter	Case	Value	Assumptions
# of Failed Containers	Optimistic	150 total, distributed over age groups	150 is the number of known failure incidents. Assumes 1 container failed independently per incident (discussed above).
	Base	188 total, distributed over age groups	Increase number of failed containers by 25%, assuming database is missing 25% of failure incidents[16]. This also accounts for some incidents that may have had multiple containers fail independently.
	Conservative	225 total, distributed over age groups	Increase number of failed containers by 50%, assuming database is missing 50% of failure incidents[17]. This also accounts for some incidents that may have had multiple containers fail independently.
# of Deployed Containers	Optimistic	2 MWh/ 20 ft equivalent container	On the lower end of energy density for BESS, more typical for early systems. Results in higher number of deployed containers globally, meaning lower failure rate, and therefore an optimistic estimate.
	Base	Range of 2-4.5 MWh/ 20 ft equivalent container	Uses an estimate of energy density based on deployment year, using product specifications. See Table 4 and Appendix C.
	Conservative	5 MWh/ 20 ft equivalent container	On the higher end of energy density for BESS, more typical for later systems. Results in lower number of deployed containers globally, meaning higher failure rate, and therefore a conservative estimate.

[16] The 25% increase was chosen based on percentages of incidents that are non-public (22%) and incidents in California that did not receive media coverage (14%). Given limited data sources globally, it is likely this number of incidents have not been captured.

[17] The 50% increase was chosen based in industry expert interviews. Multiple experts stated that while it is possible the dataset is missing incidents, that number is on the order of 10 incidents, rather than 100. The 50% increase adds 75 incidents, making this a conservative assumption.

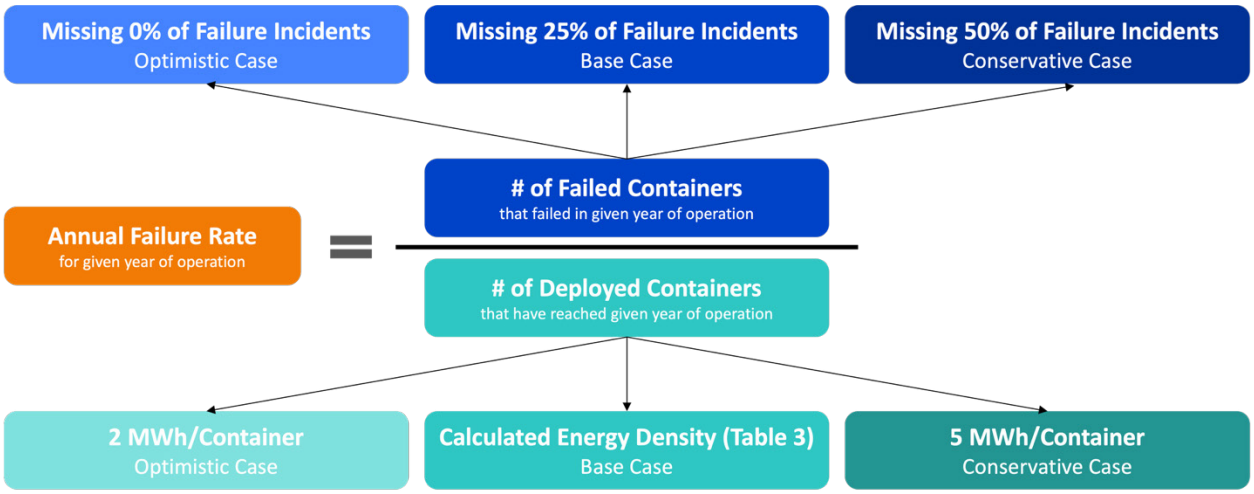


Figure 8. Sensitivity Analysis of Failure Rate

The resulting average annual failure rates are tabulated below.

Table 7. Calculated Average Operational Failure Rate

Assumption	Average Annual Failure Rate, Years 0-7 (Failed containers per deployed container per year)
Optimistic Case	3.66×10^{-4}
Base Case	8.29×10^{-4}
Conservative Case	1.37×10^{-3}

Based on this sensitivity analysis, the failure rate of BESS can be estimated as a range between 4×10^{-4} and 1.4×10^{-3}, or 0.04-0.14%. This range can be used for comparison to other infrastructure and technology failure rates. Future work in this area could include more rigorous statistical estimation of potential errors.

Aggregated Failure Rate

Another approach to determine failure rate is to aggregate both the failures and operational experience over time. This approach calculates the failure rate in units of failures per MWh-year using the equation below, where n_y is the number of failures in year y and C_y is the installed capacity in MWh in in year y.

$$\lambda = \frac{\sum_{y=2018}^{2025} n_y}{\sum_{y=2018}^{2025} C_y \times (2025 - y)}$$

This denominator in the above equation can be calculated more granularly on a per-project basis, determining the install date, installed capacity, and time in operation for each project, aggregated globally. In this report, a simpler approach was used, as shown in the equation, based on the annual installed capacity each year.

Table 8. Aggregated Failure Rate Calculation

Year	Annual deployment (MWh)	Deployed MWh-years
2018	5,895	41,264
2019	4,571	27,424
2020	9,194	45,970
2021	21,895	87,581
2022	37,571	112,713
2023	86,967	173,934
2024	176,064	176,064
2025	291,029	53,859*

*Conservative estimate since as of the end of 2025, not all systems installed in 2025 will have had 1 year of operational experience[18].

Based on the table above, the failure rate between 2018 and 2025 accounting for operational experience can be calculated as follows:

$$\lambda = \frac{150\ failures}{718{,}809\ MWh * years} = 2.087 \times 10^{-4}\ \frac{failures}{MWh * years}$$

While it is mathematically possible to use the above failure rate as a predictive metric for a given project, **this is strongly discouraged**. The calculated failure rate is historically representative but cannot be used for predicting the likelihood that a failure will occur for a given project. As discussed previously for the annual operational failure rate, **there is insufficient data to make predictions,** due to limited the dataset and operating history of BESS. These caveats hold true for this calculation as well. The aggregated failure rate obfuscates the impact of product design, codes and standards, site design, and other factors that affect the likelihood of failure for a specific project, especially as all these aspects have evolved significantly in the time period considered.

Comparison to Transformer Failure Rate

There is inherent risk in using and storing electricity, and with all technologies present in society. It is never possible to eliminate all risk, but it can be reduced to an acceptable level that can be controlled through data-driven design features, operational choices, and emergency

[18] Estimate based on data from Benchmark Mineral Intelligence as of August 2026.

response protocols. To contextualize the risk of BESS, the failure rate of BESS is compared with the failure rate of transformers. Transformers are an example of energy infrastructure with similar fire and explosion hazards. Decades of operating experience have informed effective risk management practices for transformers, resulting in societal acceptance of their widespread deployment.

The CIGRE Working Group A2.33's Guide for Transformer Fire Safety Practices[19] reviewed a variety of surveys, covering different regions and time periods between 1968-2001, and found that the likelihood of a transformer fire was on the order of 0.1% per transformer service year (i.e. 1 fire per 1000 in service transformers per year). This study was focused on large oil-filled transformers sized 10 MVA and above and rated ≥ 66 kV. Another study[20] that included 50,000 transformers rated between 5 kV and 765 kV from 40 North and South American utilities found that the annual failure rate was between 0.0032-0.0056 (0.32-0.56%) in units failed per total units in service per year over 2015-2021. This study includes failures that both did and did not result in fires. Comparatively, BESS are estimated to have a likelihood of failure on the order of 0.04-0.13% per BESS container per year. **This is comparable to the failure rate of transformers**. It is notable that the failure rate for the relatively new technology of BESS is not significantly higher than that of transformers, which have been deployed on the grid for over a century. An important caveat is that BESS do not have a long operational history and very few systems have reached end of life, in contrast with transformers which have decades of operational experience throughout the design life of systems. As shown previously, the annual calendar failure rate of BESS is decreasing as codes, standards, and product designs evolve. This trend is expected to continue as the industry gains operational experience and incorporates lessons learned, though there may be as yet unknown failure modes at end of life.

Table 9. Failure Rates Estimated for Transformers and BESS

Technology	Source	Failure rate per unit per year
Transformer	CIGRE (Global, 1968-2001)	0.1% (resulted in fire)
	Doble Engineering Company (North and South America, 2015-2021)	0.32-0.56% (operational failures)
BESS	EPRI (Global, 2018-2025)	0.04-0.14% (resulted in fire)

[19] Cigre. Guide for Transformer Fire Safety Practices, Working Group A2.33, June 2013. https://www.electricaltechnology.org/wp-content/uploads/2018/02/GUIDE-FOR-TRANSFORMER-FIRE-SAFETY-PRACTICES.pdf.

[20] R. D. Hernandez, B. Hancock and M. Salmeron, *Lessons Learned from Analysis of Power Transformer Failure Rates*, 2022 IEEE 40th Central America and Panama Convention (CONCAPAN), Panama, 2022, pp. 1-6. https://www.doble.com/wp-content/uploads/Doble_IEEE_CONCAPAN_2022_for_publication.pdf.

While one of the transformer failure studies included operational failures analyzed by failed component, the analysis of BESS failure rate in this report considers only incidents that resulted in fires or explosion hazards, and the level of detail is limited to a BESS container. This objective of this work is to characterize safety risk rather than overall system reliability. BESS reliability engineering and analysis is broader, considering failures that include reduction in capacity or loss of operation without safety risks, and provides more detailed review of subsystem and component failure rates. EPRI is engaged in this work through dedicated research programs in deployment and operation[21] as well as BESS reliability[22].

[21] EPRI. *Program 94: Energy Storage and Distributed Generation*. https://www.epri.com/research/programs/053125.

[22] *Best Reliability: Benchmarking Energy Storage Technologies for Improved Reliability.* EPRI, Palo Alto, CA: 2026. 3002031063.

4. CONSEQUENCE OF INCIDENTS

This section considers the second component of risk: the consequence. BESS are complex integrated systems with multiple components and subsystems where failures can arise. There are many failure pathways as well as layers of protection to prevent failures[23]. Incidents in the database record arc-flash, fires and explosions. All incidents involved thermal events (arc-flash or fire) and 18 incidents, or 12%, involved explosions, as show in Figure 9. A small number of C&I BESS failures resulted in fire damage to the C&I facility (e.g. datacenter, commercial building etc.) the BESS was sited at. **For all recorded incidents of utility-scale BESS, there was no report of fire spreading beyond the BESS facility.** This indicates that existing practices related to site design, vegetation control, and incident response have been sufficient to avoid fire propagation to neighboring homes, facilities, or infrastructure.

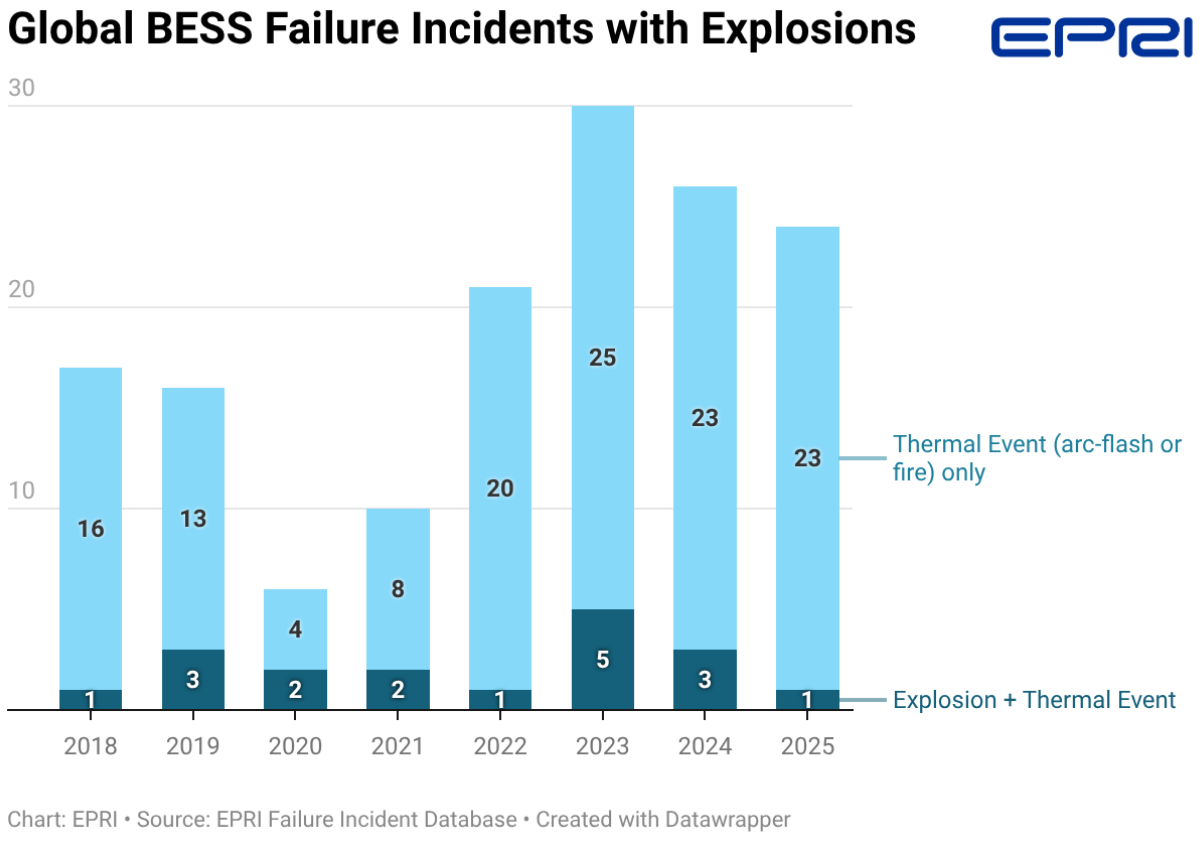


Figure 9. Global BESS Incidents Involving Explosions

[23] *ESIC Energy Storage Reference Fire Hazard Mitigation Analysis.* EPRI, Palo Alto, CA: 2021. 3002023089.

In previous work on quantitative risk assessment of BESS[24], EPRI identified several categories of consequences related to BESS fires and explosions, shown in Table 10:

Table 10. Categories of Consequences of BESS Thermal Events (Arc-flash, Fire, Explosion)

Life Safety (injuries and fatalities)
Civic impact (road closures, shelter-in-place and/or evacuation orders)
Property Protection (extent of damage and/or propagation)
Environmental and Public Health Impact
Business Continuity (loss of revenue)

The subsequent sections quantify the consequences of BESS incidents based on available data for several of the above categories. Life safety and civic impact are considered below. The extent of damage and propagation data is considered along with site architecture in the *Analysis of Risk Factors* section. Note that business continuity was not considered as this report is focused on safety risks and hazards, rather than reliability and operational impacts to BESS. Additionally, EPRI has separate work on characterization of environment and public health impact of BESS failures[25]; that aspect reviewed briefly in this report.

Life Safety – Injuries and Fatalities

For the vast majority of BESS incidents (93%), no injuries or fatalities have been reported. In a few cases, BESS incidents have led to injuries and fatalities. Eleven incidents out of the 150 recorded in the BESS Failure Database between 2018 and 2025 involve injuries or fatalities. Of those, one was a non-public incident that involved 4 injuries and 1 unconfirmed fatality. In total, there have been 24 injuries and 4 fatalities (1 unconfirmed) between 2018-2025, shown in Figure 10 and Figure 11. It was mainly first responders who were impacted in these incidents: 22 injuries and 3 fatalities involved firefighters, while 2 injuries and 1 fatality involved employees. No member of the public experienced acute injury due to a BESS fire or explosion in the incidents captured in the database.

The primary danger is from the buildup of flammable gas or arc-flash events resulting in explosions. Explosion hazards pose the greatest risk to first responders in immediate proximity to the BESS. In 6 of the 10 incidents with injuries and/or fatalities, an explosion occurred. In 1 incident, it was not possible to confirm whether or not an explosion occurred.

[24] *Battery Energy Storage Systems Failure Quantitative Risk Assessment Methodology.* EPRI, Palo Alto, CA: 2024. 3002029662.

[25] *Human Health and Environmental Considerations for Battery Energy Storage Fires.* EPRI, Palo Alto, CA: 2025. 3002033293.

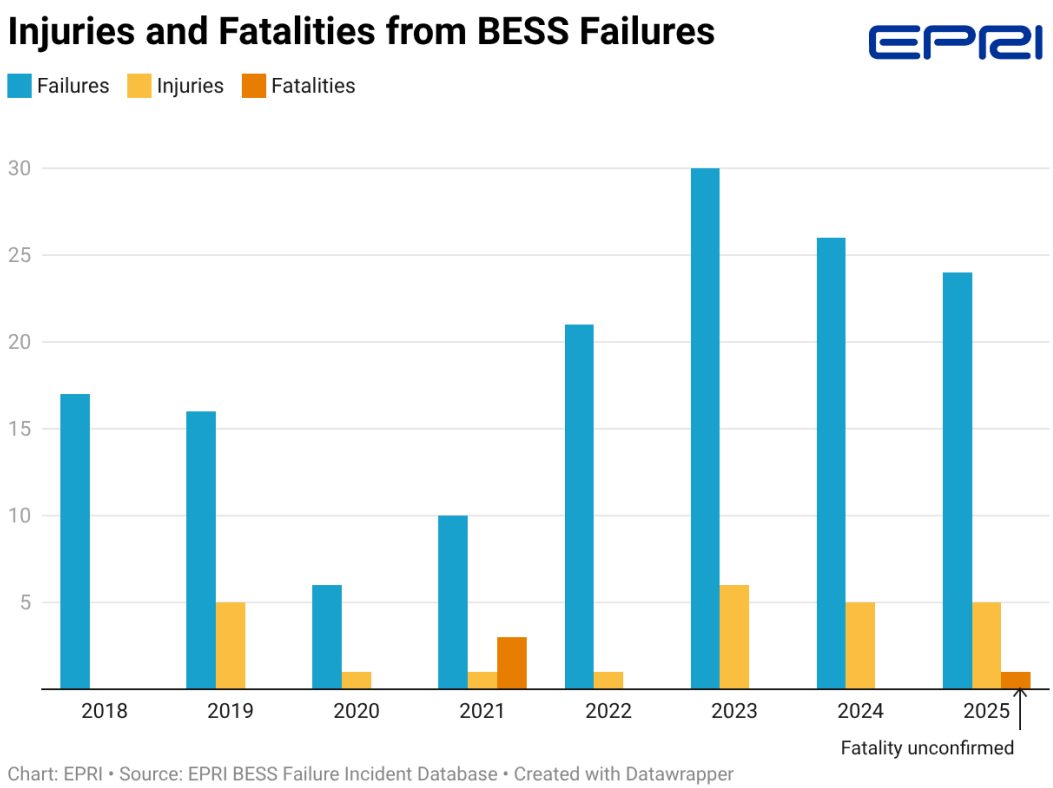


Figure 10. Injuries and Fatalities from BESS Failures

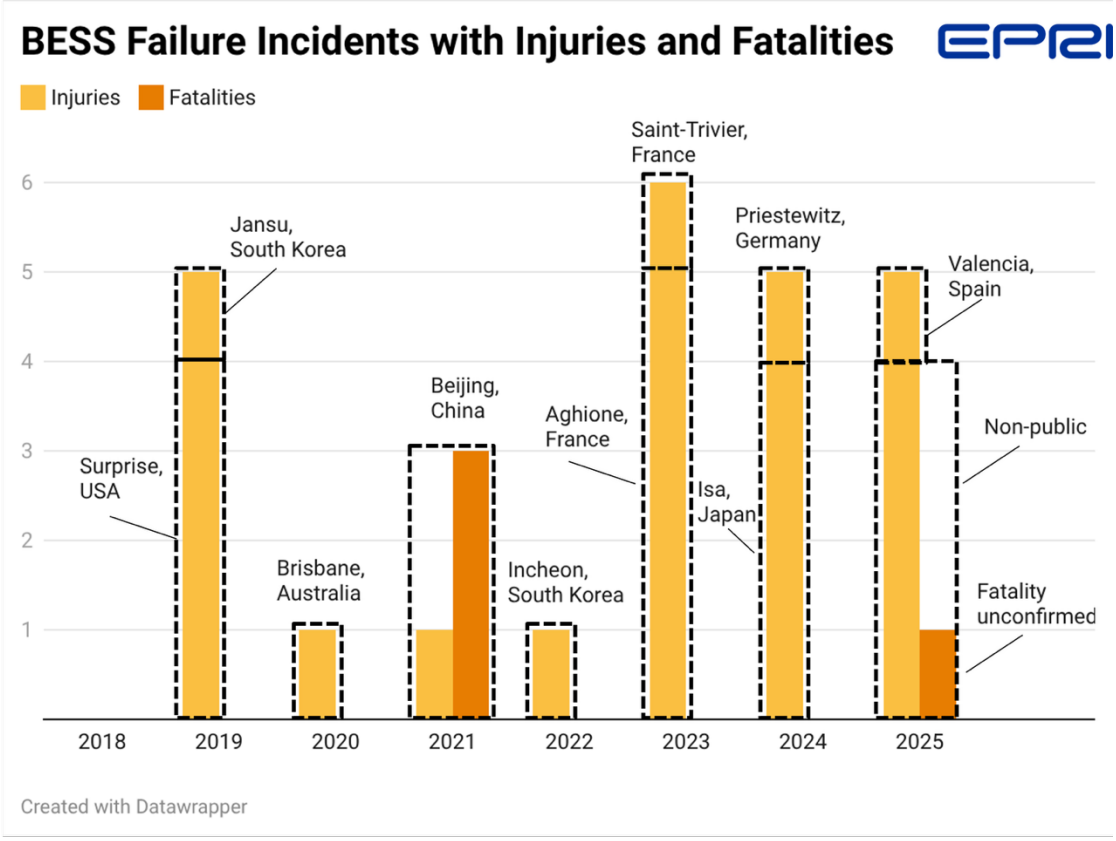


Figure 11. BESS Failures Involving Injuries and/or Fatalities

From a hazard perspective, explosions/arc-flashes are considered the worst-case threat to personnel and equipment, followed by fire. Given that, the dataset was analyzed to determine if any factors affect the likelihood of an explosion. Such a result could inform leading practices to reduce explosion risk in future systems. The vintage (year of installation), lithium ion chemistry variant, and location of systems that involved an explosion failure were analyzed; no trend or common factors were found. Note that the dataset was small and missing information especially on chemistry and vintage, preventing statistically significant conclusions from being drawn. Figure 12 and Figure 13 show the available results. Note that for incidents categorized as “Unspecified lithium ion”, it was known that the systems used lithium ion, but it was not known whether the systems used Nickel-Manganese-Cobalt (NMC), Lithium-Iron-Phosphate (LFP), or some other lithium ion chemistry variant.

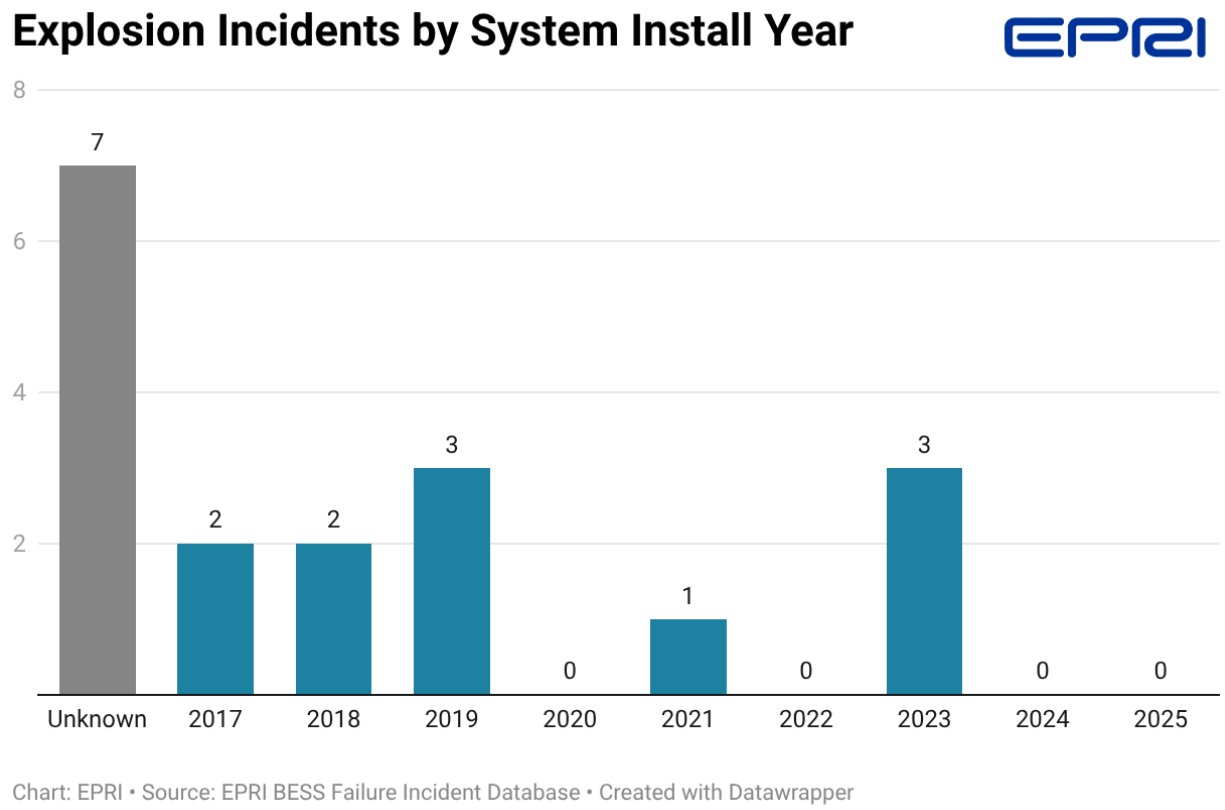


Figure 12. Analysis of Explosion Incidents by System Vintage

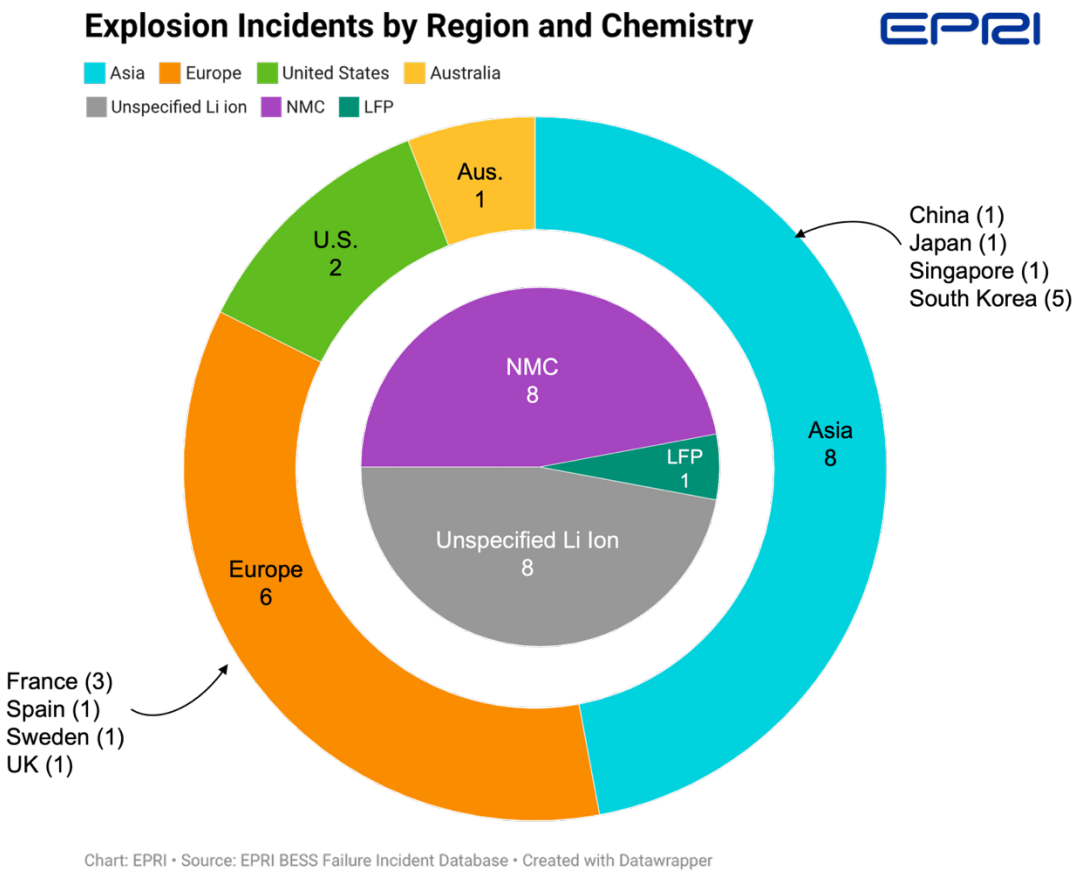


Figure 13. Explosion Incidents by Region and Chemistry

Since the explosion in the 2019 incident in Surprise, AZ[26], codes, standards, and designs have been updated to include explosion prevention and explosion mitigation features. Additionally, increased focus was placed on emergency response planning and first responder training. EPRI developed an Explosion Hazard Calculator[27] to characterize explosion hazards and support high-level design of explosion mitigation. Note that the public release of root cause information from the Surprise, Arizona incident enabled the lessons learned to be implemented to prevent future failures. **Increased transparency from failures is necessary for continued BESS safety improvement.**

[26] EPRI. *Failure Event - US, AZ, Surprise*, EPRI BESS Failure Incident Database, April 19, 2019.

[27] *Battery Storage Explosion Hazard Calculator v2.0*. EPRI, Palo Alto, CA: 2023. 3002028116.

The leading practice in BESS incident response involves a 'monitor and contain' approach that limits interaction with and proximity to BESS units. Several incidents involving explosions have highlighted the importance of this strategy. In both the 2019 Surprise, Arizona incident[28] and the 2024 Germany incident[29], explosions were triggered after enclosures were opened during response operations[30]. These events underscore the importance of safety-oriented site design and detailed emergency response planning in coordination with local fire departments. Along with regular training, these actions can reduce risks of explosion and life safety consequences[31]. These preventative measures are now common leading practices and are also being mandated by the latest fire codes in some jurisdictions such as New York[32] and California[33]. **Following the 2019 incident in Arizona and dissemination of the lessons learned, there have been zero reported injuries or fatalities in the U.S. related to BESS failures recorded in the database.**

Civic Impact

BESS incidents can result in temporary civic impacts such as road closures, shelter-in-place orders, or evacuation of the surrounding community. These measures are typically implemented by incident commanders and local officials out of an abundance of caution. Other less common civic impacts recorded are building evacuations, school closures, interruption to train service, park closure, and damaged EV infrastructure. Conservative precautionary approaches are common and appropriate in situations with limited data but also risk causing disruption and unnecessary alarm among those impacted. Better tools, more transparency on failure characteristics, and improved guidance for emergency responders could help ensure protective actions are more targeted and appropriate to the situation. EPRI's research portfolio is actively addressing these gaps.

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[28] Note that some media reports indicate eight injuries from the 2019 incident in Surprise, Arizona. Four firefighters were critically injured, while an additional four were observed overnight for possible hydrogen cyanide exposure. Based on available information and OSHA regulatory definitions for record-keeping, these latter four cases would not be considered reportable injuries. Therefore, EPRI has identified the injury count for the incident as four. Further information can be found in Appendix D.

[29] EPRI. *Failure Event - Germany, Priestewitz*, EPRI BESS Failure Incident Database, April 18, 2024.

[30] *Explosion Prevention and Control Guidance for ESS Installations*. FPRF Webinar dated Feb 3, 2026. Presented by Nick Warner of ESRG. https://www.nfpa.org/videos/ess-installations-explosion-prevention-and-control-guidance-fprf-webinar

[31] *Proactive First Responder Engagement for Battery Energy Storage System Owners and Operators.* EPRI, Palo Alto, CA: 2021. 3002021774.

[32] New York Inter-Agency Fire Safety Working Group https://www.nyserda.ny.gov/All-Programs/Energy-Storage-Program/New-York-Inter-Agency-Fire-Safety-Working-Group

[33] Public Utilities Commission of the State of California, May 20, 2025. https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M566/K891/566891631.pdf

Figure 14 shows the fraction of incidents in the U.S. that involved civic impacts. This analysis is limited to the U.S., as civic impacts are more often documented in media reporting in the U.S. and as a result, there is higher confidence in data completeness for U.S. incidents. In 18 out of the 36 incidents in the U.S., precautionary emergency response measures such as road closures or shelter-in-place orders were implemented. The remaining incidents either had no civic impacts or did not have sufficient information to classify the incident. Of the five incidents with unknown impacts, 3 were non-public incidents, and the two others were identified through non-media sources such as the California spill database or other public documentation. Information on road closures and other temporary emergency responses were not provided in these sources.

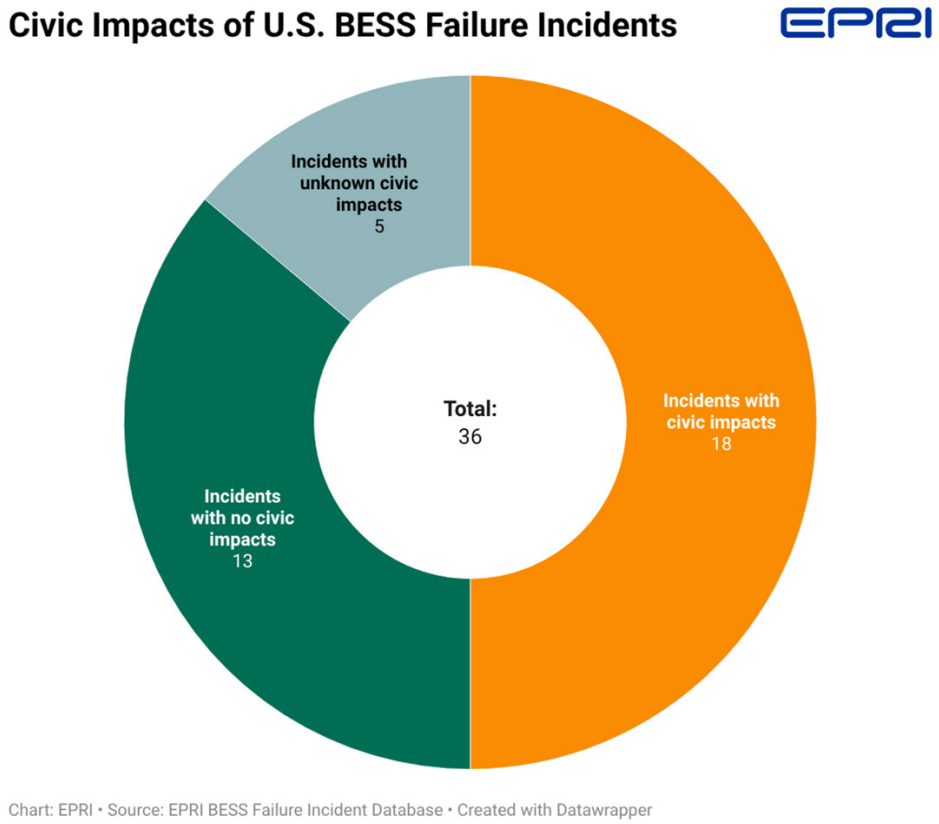


Figure 14. Civic Impacts from U.S. BESS Failures

Table 11. Civic Impact Details for U.S. BESS Failure Incidents

#	Evacuation (Distance shown in miles where known)	Shelter-in-place (Distance shown in miles where known)	Road closure	Other Civic Impact
1	Yes			
2		0.5		
3	0.25		Yes	
4				Park closure
5		3	Yes	
6			Yes	Train service interrupted
7	Yes	0.25		Schools closed
8	Yes	0.25		Schools closed
9		1		
10	0.25	0.5	Yes	
11			Yes	
12	1	1.5	Yes	Schools closed
13	0.15			
14	0.25			
15	0.25	Yes	Yes	Schools closed
16				Building evacuated
17	2			
18				Charging station closed
Count	**10**	**8**	**7**	**8**

Table 11 provides a breakdown of the exact impact for each of the 18 U.S. incidents with civic impact. The table shows the distance in miles, where known, for evacuation and shelter-in-place orders. Blank cells indicate that the event did not have that particular impact. There were no significant patterns in the emergency response for the incidents considered. Some of the variation in civic impact is expected due to differences in site location, proximity and vulnerability of nearby populations, terrain, wind patterns, etc. Additionally, data-driven decision-making practices are still being developed for BESS failures, and leading emergency response approaches may not be uniformly disseminated to all jurisdictions and first responders.

In many of the incidents with civic impact, it was noted by first responders and in media reports that evacuations and shelter-in-place decisions were made out of an abundance of caution, rather than by real-time monitoring or modeling of potential pollutant spread. Some fire departments may not have all the equipment or resources to conduct real-time environmental

monitoring. **Identifying data driven thresholds for implementing precautionary measures is necessary to avoid excessively burdening communities.** EPRI is engaged in research on common practices and gaps in incident response to address this need.

Environmental and Public Health Impacts

Any fire, whether a wildfire or combustion of manmade structures, will emit toxic pollution that could impact nearby populations and environment if they are exposed at sufficiently high amounts. Most chemical pollutants emitted from BESS fires are also emitted from other structure fires, but each may have different proportions of the pollutants. Some studies have found that the emissions are very similar overall (in the type of chemicals emitted and their amounts) to other structure fires[34]. Other studies have found bigger differences in the amount of chemicals emitted from experimental testing.

Monitoring of real-world fires is **very limited to date**; most incidents did not involve air quality monitoring. When air quality monitoring has been done during and after BESS fires, the data suggest it was **uncommon** to detect airborne pollutants in nearby communities, and that **detectable concentrations were almost always below threshold levels** used by public health agencies to determine the potential for human harm.

The January 2025 event at Vistra's Moss Landing Phase 1 BESS[35] had the most extensive set of environmental monitoring and modeling performed for a BESS fire to date, given the scale of the failure. Numerous detailed reports, maps, and detailed analytical results can be found at the Monterey County emergency website[36]. Some residents nearby reported symptoms of respiratory distress, eye/throat irritation and headaches[37] after the fire. There were also observations of deposition of battery metals on the soil near the BESS site[38] post-incident. The EPA conducted air monitoring during and after the incident and did not detect any readings of PM or HF above the "Moderate" Air Quality Index[39] classification throughout the incident. It was determined there was no risk to public health. Additional monitoring from Vistra's

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[34] DNV-GL (2017) Considerations for ESS Fire Safety. Final Report submitted to Consolidated Edison and NYSERDA. February 9, 2017. https://www.nyserda.ny.gov/-/ media/Project/Nyserda/Files/Publications/Research/ Energy-Storage/20170118-ConEd-NYSERDA-Battery- Testing-Report.pdf

[35] EPRI. *Failure Event - US, CA, Moss Landing*, EPRI BESS Failure Incident Database, January 16, 2025.

[36] 2025 Moss Landing Vistra Power Plant Fire. County of Monterey: Emergency, Readiness, Response, and Recovery. (2025). https://www.readymontereycounty.org/Home/Components/News/News/11637/13527?widgetId=10358

[37] https://www.montereycountynow.com/news/local_news/one-year-later-the-moss-landing-battery-fire-leaves-more-questions-than-answers/article_996d6185-1fce-4131-90b1-292dbe96a291.html

[38] Aiello, A.W., Endris, C., Cunningham, S., Fountain, M., Grand, M.M., Heim, W., Kahn, A.S., and Wasson, K. (2025) Coastal wetland deposition of cathode metals from the world's largest lithium-ion battery fire. *Nature Sci. Reports*. 15:42113, doi:10/1038/s41598-025- 25972-8

[39] Air Quality Index (AQI) Basics. Air Now. https://www. airnow.gov/aqi/aqi-basics/

contractor and the Monterey Bay Air Resources District support this conclusion. A recently released report from Monterey County's Environmental Health Bureau concluded that there are no long-term risks to public health based on soil, sediment, and water samples taken after the incident[40]. It is important to note that the 2025 Moss Landing incident is an **outlier** in terms of the scale and duration of the fire. As shown in Figure 19 and Figure 20 in the subsequent *Analysis of Risk Factors* section, the quantity of batteries damaged – and therefore the volume of pollutants released – is six times any other known incident. The Moss Landing system is of an atypical design (building-based) and is an older vintage, without the design features that may have prevented the propagation of the fire and limited the scale of the incident. Containerized, outdoor systems that are common today limit the scale of failure incidents significantly, as shown in Table 13.

Further information on environmental monitoring of other BESS fires, available data on impacts, and ongoing research in this space can be found in other EPRI reports[41]. This is a significant focus area for modeling, testing, and analysis.

Failure Consequence Comparison

It is informative to evaluate BESS risk in the broader context of other energy infrastructure. Comparing BESS to long-established and widely accepted technologies can help contextualize the frequency and consequence of failure events. The failure rate of BESS was compared to transformers earlier in this paper. The following section compares the consequence of failure events in BESS and transformers. This comparison can inform siting, public perception of safety, and failure incident response.

Transformers are a crucial component of the electric grid and are a well-understood technology with decades of operational experience. However, impactful transformer failures can and do still occur. In the absence of a transformer failure database documenting the impact of failures, the following section discusses two transformer failure examples to illustrate the extent of the impact that can result from a major transformer failure. Note that these examples are not necessarily representative for all transformer failures.

In March 2025, one of three supergrid transformers at the UK's North Hyde 275kV substation caught fire and tripped[42]. The adjacent supergrid transformer also subsequently tripped due to the fire, which also disconnected the third transformer. A total of nine fire appliances from the London Fire Brigade responded to the fire. This resulted in an outage affecting over 70,000 customers and led to the temporary closure of Heathrow Airport due to loss of power to

[40] Agencies complete study of battery fire. July 29, 2026. https://www.montereycountynow.com/blogs/opinion_blog/a-report-concludes-there-s-no-long-term-health-risk-from-the-moss-landing-battery/article_c7713cdc-3c5d-4ef5-9984-cbed443813f7.html

[41] *Human Health and Environmental Considerations for Battery Energy Storage Fires.* EPRI, Palo Alto, CA: 2025. 3002033293.

[42] NESO. *North Hyde Review Final Report*. June 30, 2025. https://www.neso.energy/document/363891/download.

operationally critical systems. Note that the loss of power to Heathrow Airport was not only due to the transformer fire but involved other complicating factors. 179 people were evacuated. While there was evidence that oil from the oil-filled equipment leaked into watercourses, emergency spill response techniques were rapidly deployed to contain the impact. Water sampling of the local watercourses found no impact from the incident. Runoff that carried firefighting foam was contained to the site and disposed of as hazardous waste. The substation was re-energized approximately 24 hours later.

In June 2022, one of four transformers at Australia's Yallah substation failed, causing multiple explosions and starting an oil fire[43]. Approximately a dozen fire crews (over 60 firefighters) responded to the incident to contain the fire and the spilled oil. There was no impact on the electricity supply for residents, and the three remaining transformers continued operation after the incident. Nearby residents were urged to shelter-in-place with windows and doors closed due to poor air quality[44].Transformers can also cause a fire or explosion risk when they fail. Transformers are an integral part of the grid. Depending on the location of the transformer, the loss of a transformer can have significant impacts on the electric power supply. For example, if the transformer is on the output of a generator, the loss of the transformer results in the immediate loss of the power generated, which may affect supply of electricity to the consumer. Downstream from generation on the transmission system, there is built-in redundancy, so the failure of a transformer has a much lower probability of resulting in loss of electricity supply. Transformer failure rates remain low[45], and the fire and explosion risks are well understood.

BESS also play an important role on the grid by improving grid resilience and providing community benefits[46]. While civic impacts such as road closures and shelter-in-place have occurred during major BESS failures, no power outages have been reported in media coverage related to these events. BESS are a newer technology, and as deployment increases and leading practices evolve, it will be important to continue to reduce frequency of failures and resulting grid and civic impacts. The types of consequences and impacts from transformer fires and BESS fires are similar. Risk mitigation and incident response approaches developed for transformers can be applied to BESS.

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[43] ABC News. *Yallah substation fire leaves Transgrid with rebuild cost of up to $10m*, June 18, 2022. https://www.abc.net.au/news/2022-06-19/wollongong-transformer-destroyed-by-catastrophic-fire/101165640.

[44] ABC News. *Fire engulfs major substation south of Sydney, with one transformer fully alight,* June 18, 2022. https://www.abc.net.au/news/2022-06-18/fire-engulfs-part-of-power-sub-station-in-yallah-south-of-sydney/101165042.

[45] Cigre. *Guide for Transformer Fire Safety Practices*, Working Group A2.33, June 2013. https://www.electricaltechnology.org/wp-content/uploads/2018/02/GUIDE-FOR-TRANSFORMER-FIRE-SAFETY-PRACTICES.pdf.

[46] *Tangible Benefits of Energy Storage.* EPRI, Palo Alto, CA: 2025. 3002034078.

Standard incident response for transformer fires[47] has many similarities with BESS incident response. For BESS fires, the defensive "monitor and contain" approach to managing incidents is well established[48] and consistent with typical fire service training and electric power company emergency response plans for transformer fires. The following table compares incident response considerations for BESS fires and transformer fires. Green check marks indicate that the consideration applies to the specific scenario, while red crosses indicate that the consideration does not apply. Additional information is provided in text where appropriate.

Table 12. Incident Response Comparison for BESS and Transformer Fires

Incident response consideration	BESS fire[49,50]	Transformer fire[51]
Defensive approach and focus on life safety.	✓	✓
Requires a utility escort due to high voltage hazards at the site	**Depends.** Required for utility-scale BESS. Not required for smaller commercial or industrial BESS.	✓
Self-contained breathing apparatus (SCBA) for first responders.	✓	✓
Exposure protection of adjacent structures/facilities with water when necessary. Runoff should be contained where possible.	✓	✓
Avoid the application of water directly to fire. Burning equipment generally cannot be saved.	**Depends.** Recommended leading practice is to monitor and contain rather than active water-based suppression.	✓ Never apply water directly. This can cause boilover: the water sinks below hot oil, which boils and rapidly expands as steam, leading

[47] National Grid. *Module 3: Fires involving electrical facilities*. 2016. https://firstresponder.ngridsafety.com/ngrid-panel-review/electric/module3/story_html5.html.

[48] *Emergency Response Planning for Battery Energy Storage System (BESS): Review and Guidance.* EPRI, Palo Alto, CA: 2024. 3002030488.

[49] ibid

[50] *Safety Considerations for Lithium Ion Energy Storage Specifications and Requests for Proposal.* EPRI, Palo Alto, CA: 2024. 3002030558.

[51] Substation Fires: Working with First Responders. July 19,2029. https://www.nerc.com/globalassets/our-work/webinars/substation_fires_working_with_first_responders_20190619.pdf

Incident response consideration	BESS fire[49,50]	Transformer fire[51]
		to a sudden and violent eruption
Use of aerosol, dry agent, or foam fire suppression	**Depends.** Aerosol or dry agents may be used for electrical (non-battery) fire suppression within BESS.	
Managing re-ignition risk with post-fire thermal monitoring	 Thermal runaway can continue in damaged cells.	 While fire suppression agents can suppress flames, residual heat can maintain the oil above its ignition point.
Managing stranded energy hazard.	 Cells can contain stranded energy when damaged, posing an electrical hazard.	 No stranded energy hazard.
Managing explosion risk.	 Gases vented during thermal runaway pose an explosion hazard. Deflagration panels and ventilation can reduce risk.	 Electrical faults causing arcing can vaporize insulation oil and produce an explosion. Relief valves and proper maintenance can reduce risk.

5. ANALYSIS OF RISK FACTORS

BESS designs are complex, involving many integrated components of hardware and software. In this section, two aspects of BESS design – site architecture and battery chemistry are analyzed to determine correlations between the design choices and likelihood of failure. The impacts of system age and vintage on failure rates are also analyzed.

Site Architecture

Site architecture varies across BESS sites and governs spacing, layout, enclosure design, and building-based or outdoor approaches. Site design has significant implications for heat and fire propagation in the case of a thermal runaway failure. This analysis focuses specifically on building-based versus outdoor site designs. Note that building-based here refers mainly to dedicated-use buildings as differentiated from human-occupied or multi-use buildings.

Containerized, outdoor solutions are able to take advantage of the modular BESS design to mitigate the risk of fire propagation and limit equipment damage, mainly through spacing. Damage to the whole system can be avoided by minimizing the size of a "unit" and preventing the spread of fire. As shown in Figure 15, the smallest "unit" in containerized BESS is one container, but the smallest "unit" in a building-based BESS is one building, assuming no fire barriers or propagation mitigation exists.

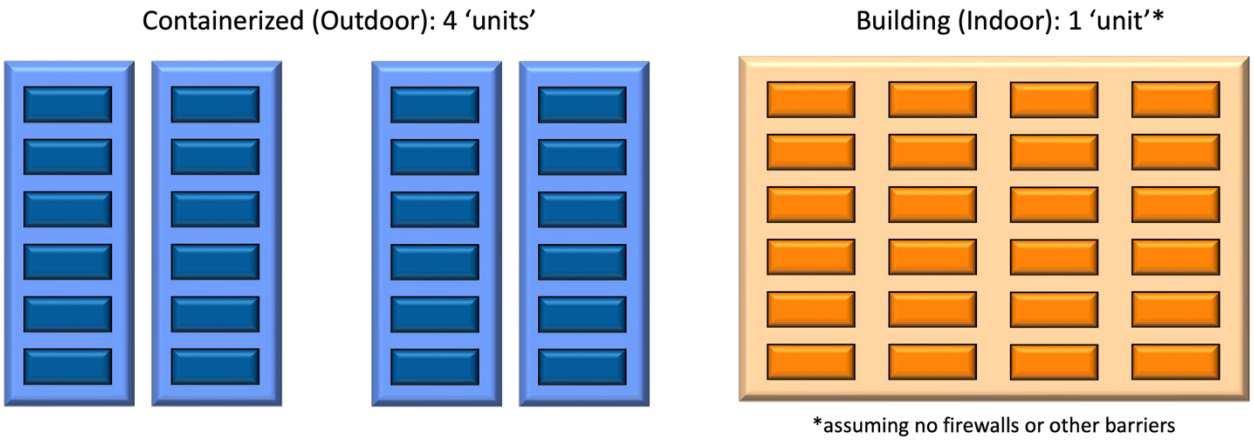


Figure 15. Depiction of Different Unit Sizes for Containerized and Building-based BESS

To understand the risk implications of BESS site architecture, BESS facilities were categorized between **indoor** building-based systems and **outdoor** containerized systems, where possible. Two different analyses were conducted:

1. Comparison of the proportion of failed indoor vs. outdoor systems to deployments of indoor and outdoor systems. This analysis was **limited to U.S. incidents** due to the availability of architecture-specific deployment data for the U.S. This deployment data was not available for other countries.

2. Analysis of the extent of damage for **global** incidents, comparing indoor vs. outdoor. architectures.

For the first analysis, the proportion of indoor and outdoor BESS incidents as recorded in the BESS Failure Database were compared against the proportion of indoor and outdoor BESS present in the overall fleet. Fleet data was obtained from the Energy Information Agency (EIA)[52], which is limited to U.S. systems that are at least 1 MW in size.

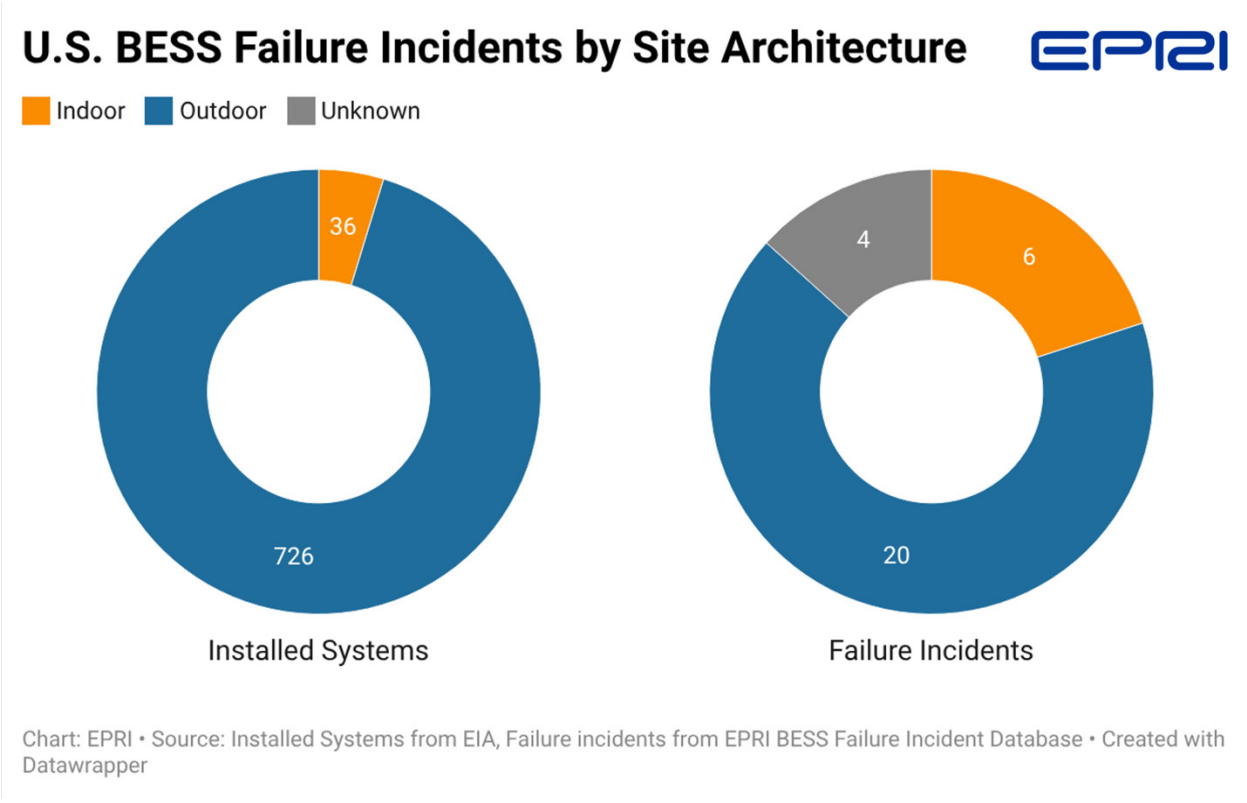


Figure 16. Comparison of Failure Incident Count by Architecture, U.S. Only

Comparing the sizes of the orange segments, Figure 16 shows that indoor BESS facilities are overrepresented in failure incidents. Note that of the 36 incidents in the U.S., 30 are shown in the figure, including 4 incidents where the site architecture was unknown. Of the 6 remaining incidents, one incident was excluded because the power capacity was below 1 MW and therefore would not merit inclusion in the EIA fleet data. An additional 5 incidents were excluded because the power capacity was unknown and it was unclear whether those systems would have been captured in the EIA data. Note that if these last 5 incidents are included in the comparison regardless of their installed power capacity, the proportion of indoor failure incidents would increase.

[52] U.S. Energy Information Administration. *2024 Energy Storage Data,* Accessed February 2026 at https://www.eia.gov/electricity/data/eia860/.

It should be noted that the EIA dataset represents a snapshot of operating BESS in 2024, while BESS failures occurred between 2018-2025. EIA data for the full year of 2025 was not available at the time of analysis. Of the seven U.S. incidents that occurred in 2025, five involved systems installed in 2022 or earlier and would therefore be represented in the EIA fleet data. Of the remaining two incidents, one involved a system installed in 2025 (outdoor architecture). The installation year of the last system (indoor architecture) was unknown. The U.S. industry has converged on outdoor containerized solutions as the typical architectural approach for BESS facilities, and dedicated-used buildings have become increasingly uncommon, as per Figure 17. While there may be more BESS installed within substation buildings or data centers in the future, these would not be captured in the EIA dataset if they are below the 1 MW threshold. Given the shift in architecture over time, it could be instructive to analyze correlations between deployment year, site architecture and likelihood of failure. Future work could expand this analysis to understand which risk factors are most significant in failure likelihood.

Seventeen BESS facilities out of 762 total BESS in the EIA dataset retired over this time period, resulting in an overall error in the fleet data of ~2%. Note that the number of indoor systems is much smaller than outdoor, so the potential error in deployment count for indoor systems specifically is higher, up to 8%. These potential errors are unidirectional, meaning that the counts of installed indoor and outdoor systems in Figure 16 can only be too high, rather than too low. This means that the figure shows a conservative assessment of the disproportionately high number of indoor incidents, accounting for potential error. Even with the data limitations described, indoor BESS facilities are overrepresented in failures compared to outdoor systems.

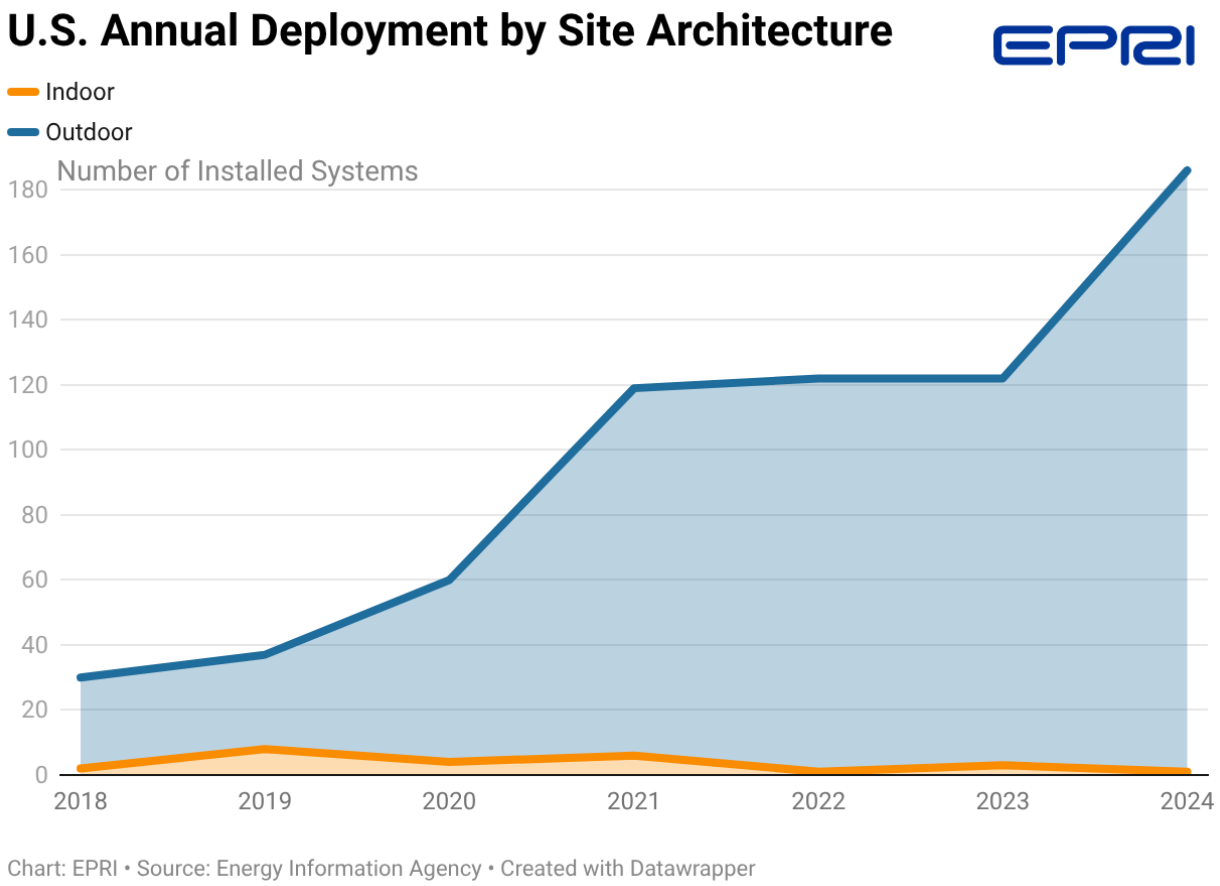


Figure 17. U.S. BESS Deployment by Architecture

For the second analysis related to site architecture, relationship between site architecture and the extent of damage in a given incident was considered. For each incident, the site architecture (indoor or outdoor), the percentage of the system that was damaged, and the equivalent energy capacity (in MWh) that was damaged were determined. This information was then plotted according to the date of each event. For this analysis, both dedicated-use buildings and other building-based systems were included in the 'indoor' count. There were several incidents where information was missing or unable to be confirmed with available information, and these incidents were not included in this analysis. For a handful of incidents, the system vintage and design information were used to determine energy density and estimate the damaged capacity or damaged percentage when only one of those numbers was reported publicly. The energy density assumptions are provided in Appendix C. The breakdown of incident classification is provided in Figure 18 and the results of the system damage analysis in Figure 19. A total of 68 incidents out of 150 (45%) were used in this analysis.

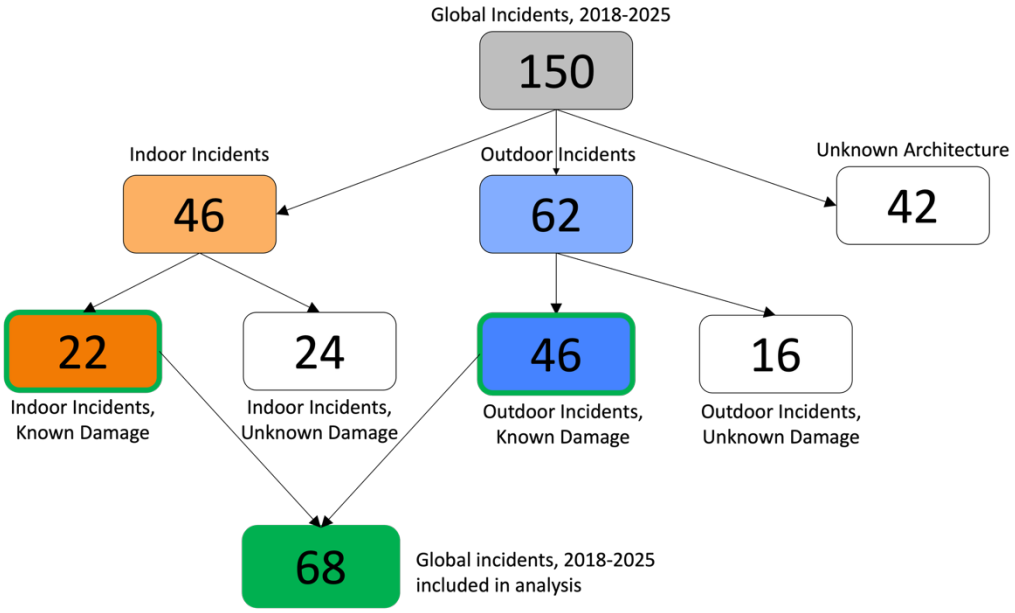


Figure 18. Incident Classification for System Damage Analysis

Figure 19 below shows how much damage a BESS sustained in an incident, with the size of the bubble indicating the MWhs of system capacity damaged. Orange bubbles represent indoor BESS, while blue bubbles represent outdoor BESS.

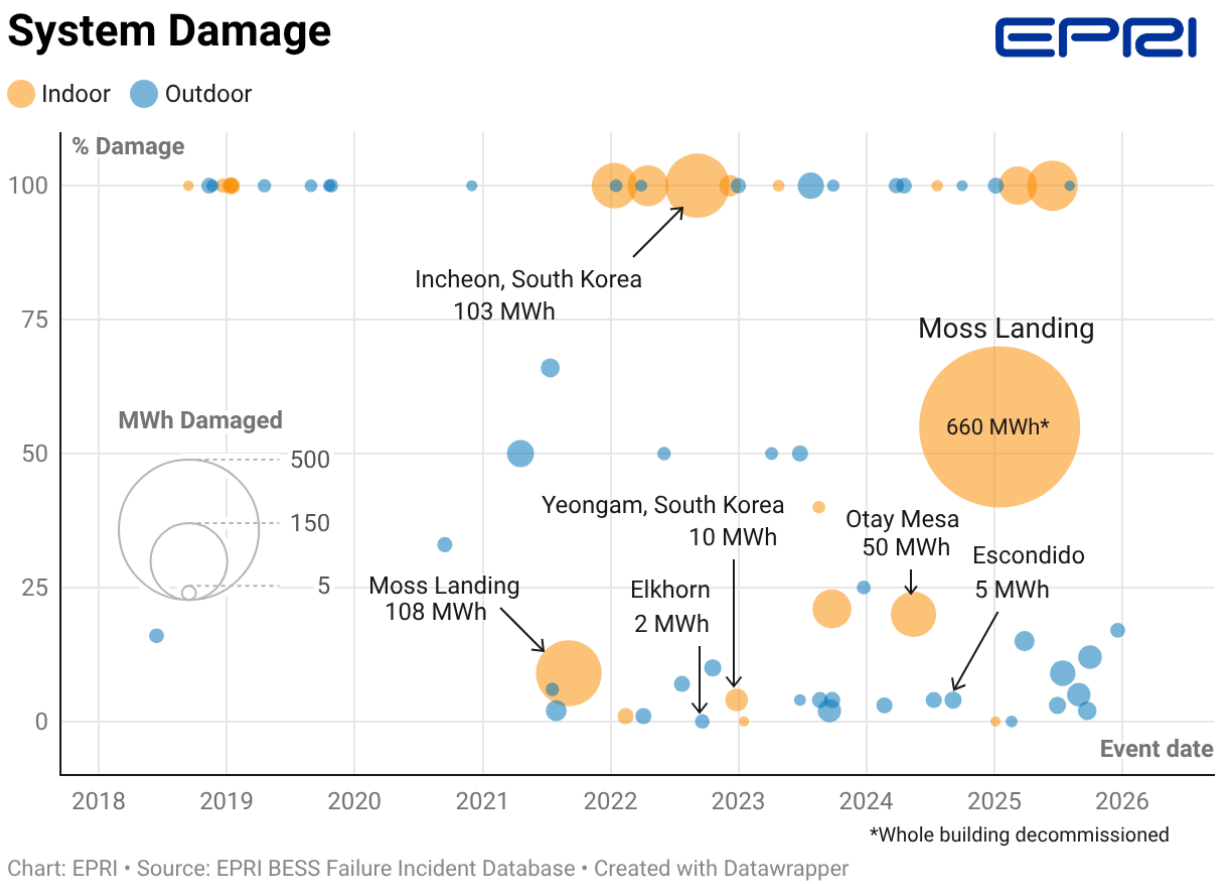
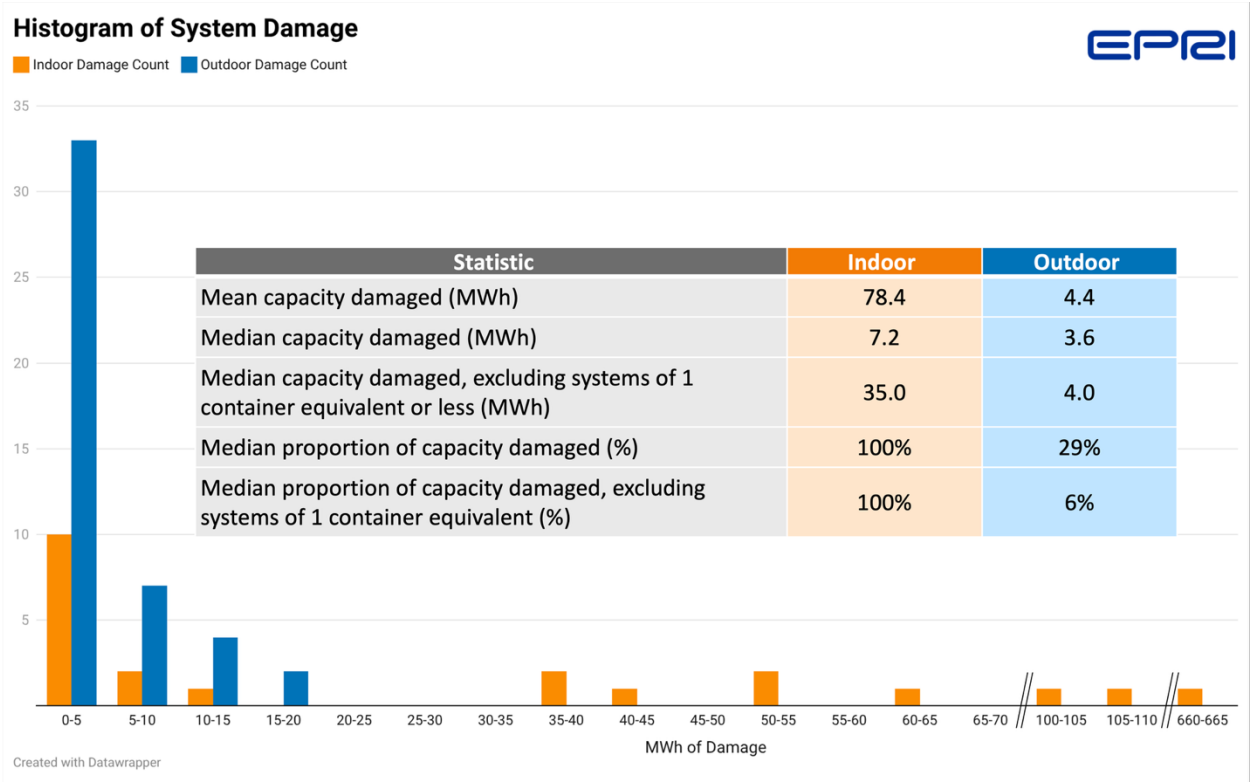


Figure 19. System Capacity Damaged in Global BESS Incidents

Indoor systems sustain more damage on average when an incident occurs. The largest incident to date by damaged system capacity was the Janauary 2025 incident at Vistra's Moss Landing system, resulting in approximately 660 MWh damaged, or 55% of the installed capacity[53]. The magnitude of this incident was anomalous due to the system's size as one of the largest lithium ion BESS as well as the large proportion of damage due to the indoor architecture of the system, with over 1 GWh of capacity installed within a single building.

Of the indoor incidents with a less than 25% of system capacity damaged, two occurred in systems that consisted of multiple buildings, and building separation prevented propagation to the entire facility at Otay Mesa (2024) and Yeongam (2022). The many small bubbles at the top of the graph represent systems with only 1 unit, where the entire unit was damaged, i.e. no propagation was possible. These include incidents where the unit was a small building and outdoor containerized systems with a single container.

[53] Moss Landing Vistra Battery Fire Response. EPA in California. January 2025. https://www.epa.gov/ca/moss-landing-vistra-battery-fire



Statistic	Indoor	Outdoor
Mean capacity damaged (MWh)	78.4	4.4
Median capacity damaged (MWh)	7.2	3.6
Median capacity damaged, excluding systems of 1 container equivalent or less (MWh)	35.0	4.0
Median proportion of capacity damaged (%)	100%	29%
Median proportion of capacity damaged, excluding systems of 1 container equivalent (%)	100%	6%

Figure 20. Histogram and Statistics of System Damage for Global BESS Failures

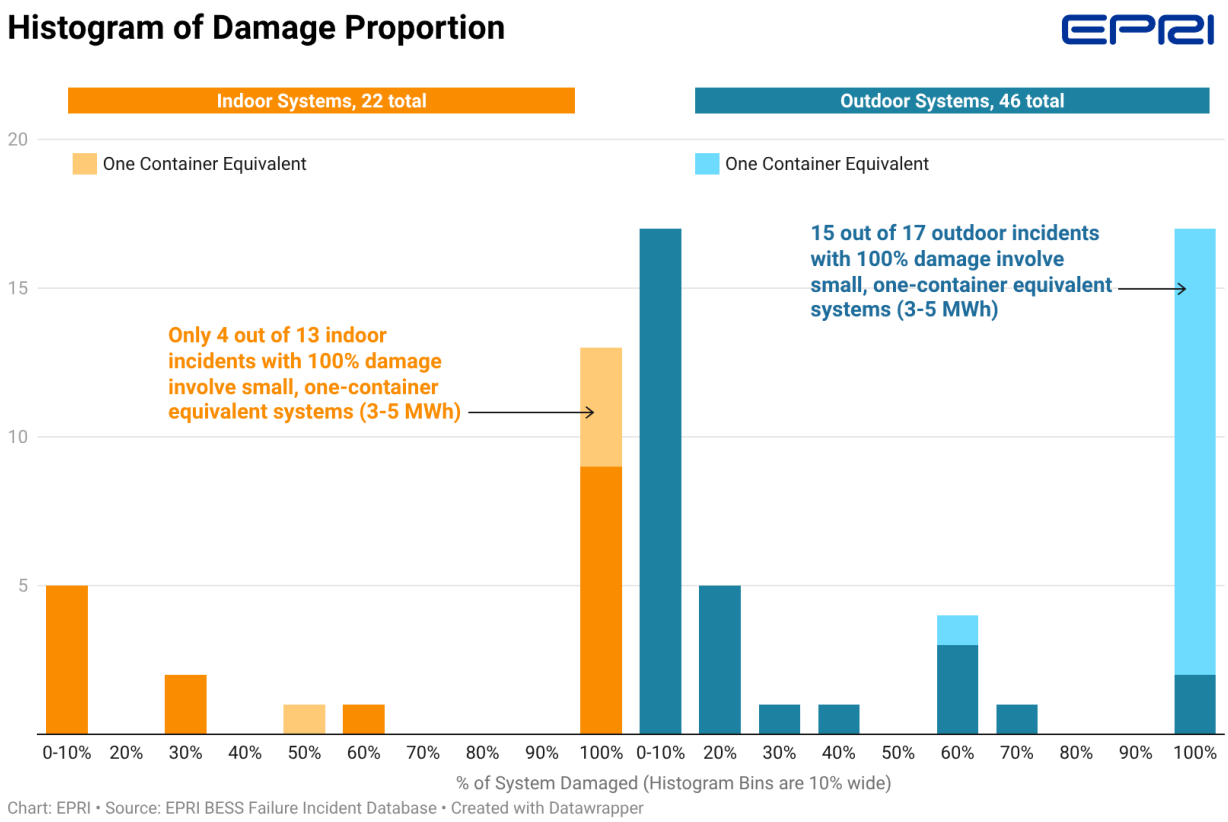


Figure 21. Histogram of System Damage Percentage

Figure 20 and Figure 21 show the histograms and statistics of system damage depicted in Figure 19. It is notable that the outdoor systems typically have <10 MWh of damage, regardless of system size. In contrast, indoor systems see a wide distribution of MWh damaged, reflecting the fact that the 'unit' size described earlier is a strong determinant of capacity damaged. This is further demonstrated by the statistics – when systems of 1 container equivalent or less are excluded (i.e. no propagation is possible), the median proportion of capacity damaged for indoor systems remains 100%, whereas the median drops significantly for outdoor systems, to 6%. Figure 21 provides the histogram of percentage of system damaged and depicts this visually. The indoor architecture usually leads to full propagation within a unit. For both indoor and outdoor systems, incidents generally damaged at least an entire unit. But for indoor systems, that unit size is large, often the entire system. Outdoor, containerized systems have inherent propagation prevention through spacing and layout. Their modular design helps limit the impact of a single unit failure on the whole system.

It is also necessary to consider **unit-to-unit propagation**. Indoor systems are more likely to be single-unit, however some notable exceptions mentioned above (Otay Mesa, Yeongam) demonstrated the impact of building separation on limiting damage. Outdoor systems typically have more separation, though that is no guarantee of avoiding propagation. Figure 21 shows the unit-to-unit propagation for incidents where this data was available. Only 11 out of 68 incidents (16%) had unit-to-unit propagation, where the 'unit' may be an outdoor container or

a building, depending on the incident. Of those 11 incidents, 10 involved outdoor systems. Nine of those outdoor systems were installed prior to 2024; half were installed prior to 2022, when propagation mitigation designs and testing were more limited. Site design elements such as unit wall thickness, spacing, and fire barriers play an important role in mitigating unit-to-unit propagation; this analysis was not able to distinguish between these detailed design choices. Figure 23 provides additional context on site architectures for systems that were single unit or did not have propagation. It is notable that the proportion of indoor and outdoor systems stays relatively constant across the three different categories.

In the following categories:

1. Incidents where propapagation was possible (second donut chart in Figure 23)
2. Incident where propagation occurred (second donut chargt in Figure 22)
3. Incidents where propgation did not occur (third donut chart in Figure 23)

indoor systems represented ~9% of the total in each case. Propensity for unit-to-unit propagation does not seem to correlate with site architecture. Note that it was not possible to normalize these results by fleet deployment, as global data on site architecture is not available.

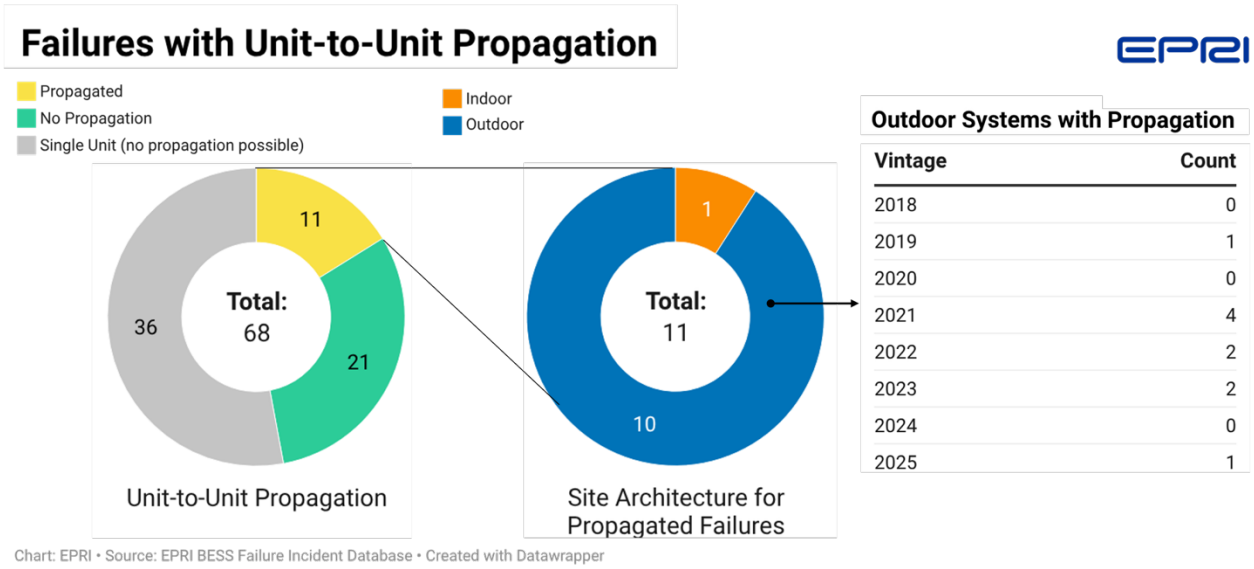


Figure 22. Failures with Unit-to-Unit Propagation

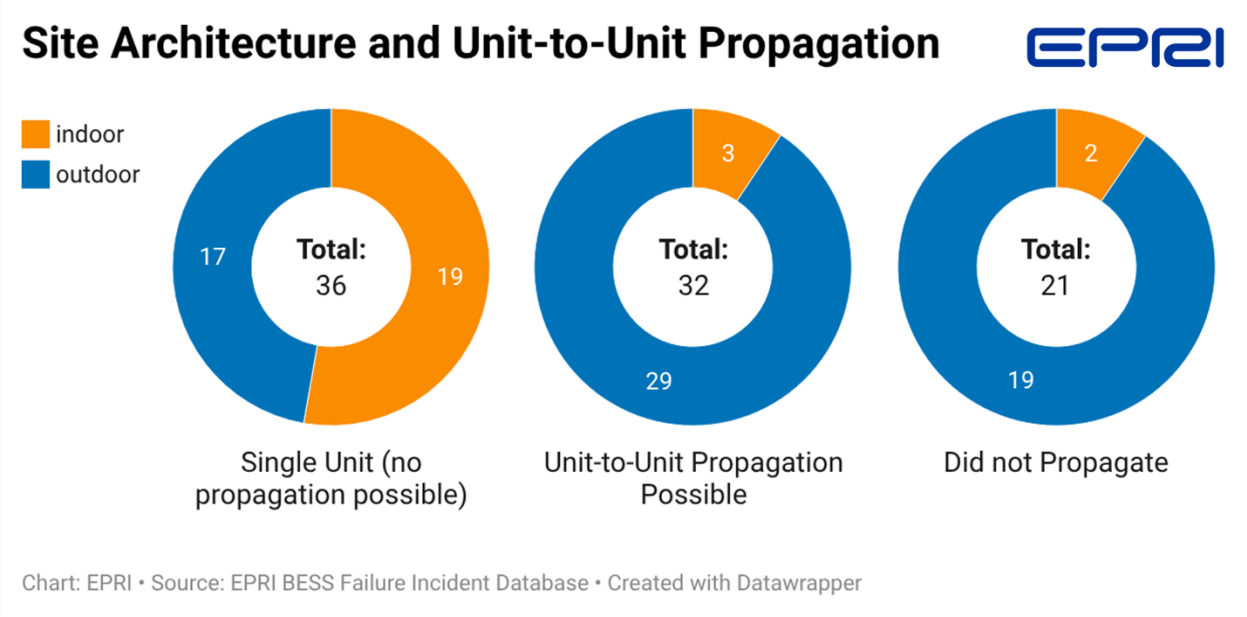


Figure 23. Site Architecture and Unit to Unit Propagation for BESS Failure Incidents

Table 13. Comparison of Moss Landing and Elkhorn incidents

Moss Landing	Elkhorn
Indoor	Outdoor
1200 MWh total capacity	730 MWh total capacity
660 MWh damaged	3 MWh damaged
55% damaged	0.4% damaged
Entire building sustained damage	1 container sustained damage

A comparison of the impact of architecture is shown in a case study in Table 13. The table compares the Moss Landing incident from January of 2025 to the incident at the Elkhorn system nearby in September of 2022. At Elkhorn, the failure was limited to a single container, which caught fire and was allowed to burn itself out. The fire department monitored the container and cooled adjacent containers and exposures with water. The incident lasted ~24 hours. As described above, the Moss Landing incident lasted several days, with significantly more damage in terms of energy capacity and percentage. While the Elkhorn system was similarly sized to the Vistra Moss Landing system, the architecture limited the damage to less than 1% of the system's energy capacity.

Minimizing the amount of damage from a failure has multiple benefits from a risk perspective:

- Limiting duration and severity of fire and consequent life safety risks
- Reduction in emergency response needs and potential civic impacts
- Reduction in quantity of pollutants that could impact surrounding air, water, soil
- Reduction in property damage, downtime, decomissioning, and recovery costs

Propagation prevention – both within units and between units - is a critical component of BESS risk management. Indoor systems without firewalls or barriers allow propagation within the entire unit, which can be many MWhs in size. For this type of site architecture, propagation prevention within the unit is paramount. The installation of barriers and segmentation of indoor systems can prevent propagation within the structure. Note that risks and emergency response considerations change significantly for batteries installed in human-occupied buildings; preventative and mitigative measures should go beyond fire barriers and consider life-safety impacts. Outdoor systems, especialy of older design, may have unit-to-unit propagation in a failure. For this site architecture, unit-to-unit propagation prevention is key. The latest UL9540A and NFPA 855 codes mandate large-scale fire testing, which specifically considers unit-to-unit propagation. These updates were instituted in the 2025-2026 cycle, so older systems may not have been evaluated against this criterion.

System Age and Vintage

The age of a BESS is a potential risk factor affecting the probability of failure. Electrochemically, certain degradation mechanisms within the cell could increase the risk of the failure. As an example, the formation of dendrites within a cell over many cycles could lead to an internal cell short, thermal runaway, and subsequently a fire. It is necessary to monitor BESS over time, adjusting operation to account for the state of health and other parameters in real time. That said, most BESS deployed today have relatively short operating histories and it was necessary consider both system age and vintage (install year) together to understand failure trends.

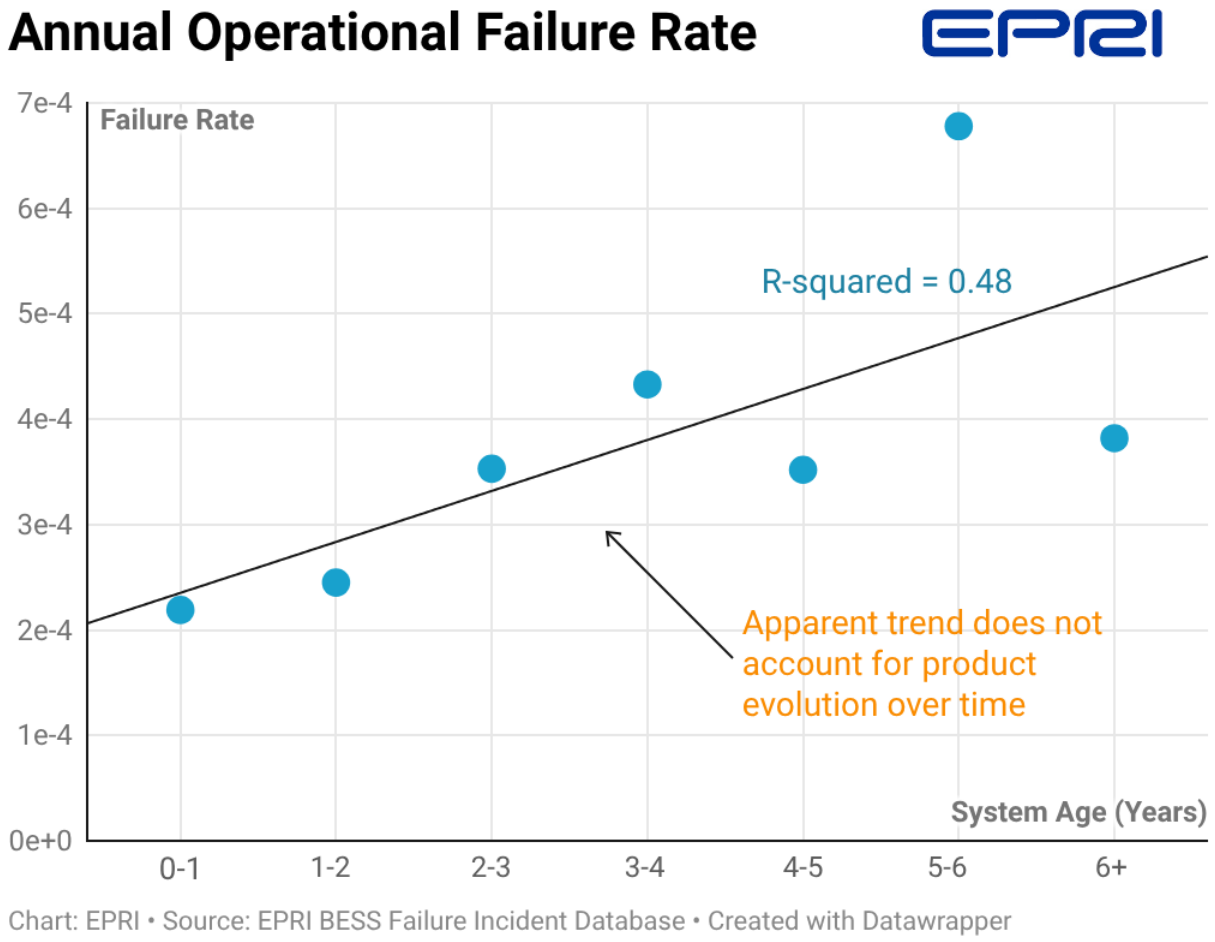


Figure 24. Annual Operational Failure Rate, Where System Age is Known

In reliability engineering, a bathtub curve represents the expected failure rate over product lifetime. The curve is characterized by high rate of failures initially at beginning of life followed by a period of low failure rate during the majority of operating life and finally and increasing failure rate at the end of product lifetime, resembling the shape of a bathtub. Figure 24 shows the trend in annual operational failure rate over time, determined using the method described in the frequency analysis section previously. There appears to be a general trend of increasing failure rate as systems age, though the R^2 value of 0.48 indicates only a weak linear relationship between age and failure. Additionally, this apparent trend does not conform with the expectation of a bathtub curve. Further analysis was performed to better understand the factors driving the increase in failure rate over system age. Importantly, a bathtub curve usually represents the failure rate of a product with a fixed design. BESS product design has undergone rapid evolution over the last decade, so it is necessary to distinguish between different install years, or vintages, when considering the impact of system age.

Figure 25 shows the failure rate for each vintage between 2018 and 2023, in terms of units failed per units deployed. Note that deployment data was unavailable prior to 2018 and given the limited operating history for systems installed in 2024 and 2025, they were excluded from the figure. The orange line showing the average failure rate is same trend shown in Figure 24. One notable observation is the high failure rate at the beginning of life for the 2018 vintage. All of these incidents occurred in South Korea. There have been several detailed investigations of these incidents and potential root causes include integration quality issues[54] and BMS controls issues[55], manufacturing defects[56]. These systems were deployed before significant development of safety standards and BESS product development.

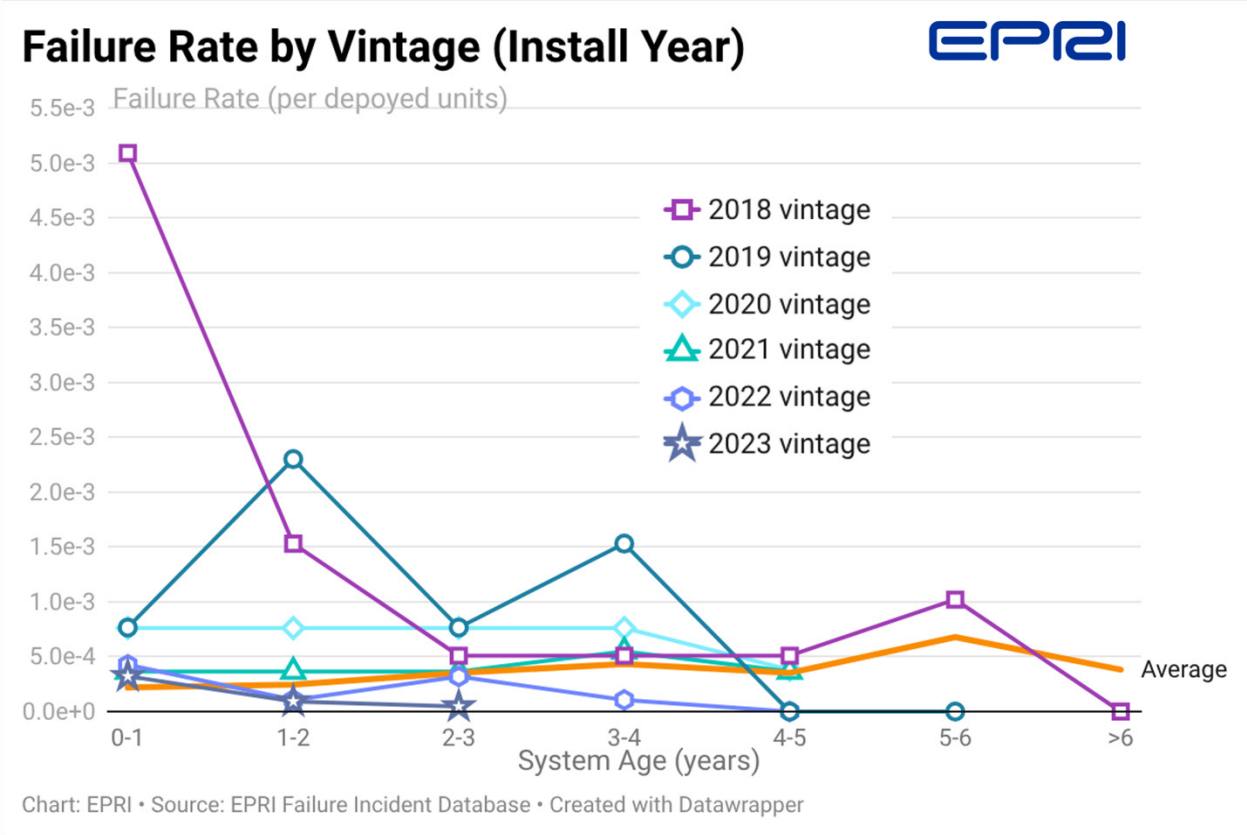


Figure 25. Failures per Deployed Unit For Each Vintage

[54] DongA Science. *Faulty Installation, Construction, and Management Blamed for String of ESS Fires,* June 11, 2019. https://m.dongascience.com/en/news/29281.

[55] Na, Y.-U.; Jeon, J.-W. Unraveling the Characteristics of ESS Fires in South Korea: An In-Depth Analysis of ESS Fire Investigation Outcomes. *Fire* 2023, *6*, 389. https://doi.org/10.3390/fire6100389.

[56] Batteries News. *Korea to Tighten Measures for Energy Storage Systems Safety as Batteries Catch Fire*, May 9, 2022. https://batteriesnews.com/korea-measures-energy-storage-systems-safety-batteries-fire/.

Figure 25 shows that, for a given vintage, failure rates generally decline as systems accumulate operating experience. The figure also shows that, at a given system age, more recent vintages tend to exhibit lower failure rates than older vintages. To quantify these relationships, a regression analysis was performed to evaluate the independent effects of system age and vintage on failure rate. Holding vintage constant, each additional year of operation was associated with a 31% reduction in the failure rate. Similarly, holding system age constant, each one-year increase in vintage (that is, a more recently installed system) was associated with 44% reduction in the failure rate. See Appendix E for further details.

These results provide important context for interpreting the age-based trend shown in Figure 24. While Figure 24 suggests a slight increase in failure rate with system age, the regression analysis indicates that this apparent trend is driven by vintage effects and the limited deployment of older systems. Only approximately 3% of deployed BESS capacity has reached more than five years of operation, and these systems represent earlier generation products. As a result, older age groups are disproportionately composed of older vintages that exhibit higher incident rates overall. Overall, the data shows that the failure rate decreases with system age and with more recent vintages.

Table 14 shows incident count by system vintage, where known. Note that this dataset includes only 85 of the 150 incidents used for this report. While global deployment data was unavailable for 2017, it is likely the failure rate is of similar magnitude as 2018. The failure rate decreases for new vintages. Note that the failure rate for the latest vintages (2024 and later) should not be taken at face value. These systems have had very little operating history.

Table 14. Incidents Count by System Vintage, Where Known

Vintage (Install Year)	Number of failures	Annual Deployment in containers	Failure Rate by Vintage
2016	5	Data unavailable	N/A
2017	13	Data unavailable	N/A
2018	18	1,965	0.92%
2019	7	1,306	0.54%
2020	9	2,627	0.34%
2021	11	5,474	0.20%
2022	9	9,393	0.10%
2023	10	21,742	0.05%
2024	1	39,125	0.0026%*
2025	3	64,673	0.0046%*

*Limited operational history

In the past few years, there has been a rapid evolution of BESS safety codes and standards[57], covering safety design elements such as explosion mitigation, test methods to characterize thermal runaway failures, site-level emergency response measures, and more. Additionally, there have been concurrent improvements in BESS product maturity and design, which have incorporated lessons learned from past deployments and failures. **Conducting safety reviews and evaluating retrofits of early-vintage systems can help to ensure they include the latest codes, designs, and practices.** The expected lifetime of BESS can range from 10-20 years; older vintages have shorter design lives compared to newer systems, which are expected to last 15-20 years. Few BESS today have operated to their end of life. As systems age, it will be essential to continue monitoring failures and degradation to understand how failure rates change over the lifetime of a system.

Battery Chemistry

The vast majority of BESS deployed in recent years use lithium ion chemistry – 88% of global deployment between 2018 and 2025 are lithium ion, by energy capacity[58]. Most of the remaining 12% use lead-acid chemistry, with deployment concentrated in early years. EPRI's BESS Failure Incident Database has 2 incidents involving lead-acid systems and 1 incident involving a sodium-sulfur system; these are not included in this report focused on lithium ion BESS.

Currently, the two most commonly deployed lithium ion chemistries are NMC and LFP, together accounting for 96% of annual deployments by 2022[59]. These two sub-chemistries have different performance, cost, and safety characteristics at the cell level; however, such characteristics may not translate directly into differences at the system-level, where module-, enclosure-, and site-level design and engineering decisions play a critical role in shaping overall system characteristics. Chemistry-driven safety differences between LFP and NMC include higher peak thermal runaway temperature for NMC, higher thermal runaway onset temperature for LFP (meaning less likely to go into thermal runaway), and a lower ratio of flammable to non-flammable gas concentration for LFP[60].

[57] *The Evolution of Battery Energy Storage Safety Codes and Standards*. EPRI, Palo Alto, CA: 2023. 3002028521.

[58] BESS Forecast Q12026 - Benchmark Mineral Intelligence. Accessed March 2026. https://data.benchmarkminerals.com/bess/data-reports

[59] ibid

[60] *Safety Implications of Lithium Ion Chemistries*. EPRI, Palo Alto, CA: 2023. 3002028522.

It should be noted that product evolution in LFP cells is trending towards larger prismatic cells. Recent announcements include cells up to 2710 Ah[61], which is several orders of magnitude larger than typical NMC cells, which range from single-digit Ah (cylindrical 18650 format) to 94 Ah (prismatic format)[62]. At the cell-level the format (cylindrical, prismatic, pouch) can impact operational and safety-related factors such as temperature uniformity and energy density. Prismatic cells can be packed more densely due to their shape, but are also susceptible to temperature gradients and swelling[63]. Fire and explosion mitigation may be more challenging with increasing cell capacity, which increases the total amount of heat and gas released from a single-cell failure[64].

Over the last five years, the industry has rapidly transitioned away from NMC to LFP due to cost and safety considerations. While there is broad messaging that LFP is "safer", multiple LFP BESS incidents have occurred, and there are 34 recorded incidents involving LFP BESS between 2018-2025. Figure 26 shows the BESS failures by chemistry. Nearly half of all incidents were not able to be classified as LFP or NMC chemistry. It is expected that the vast majority of those incidents categorized as 'Unspecified Li ion' are either NMC or LFP chemistry, though there was some limited deployment of NCA and other sub-chemistries prior to 2023.

[61] Energy Storage News. *BYD launches 14.5MWh BESS as energy density race continues,* September 23, 2025. https://www.energy-storage.news/byd-launches-14-5mwh-bess-as-energy-density-race-continues/.

[62] Samsung SDI. *ESS Batteries by Samsung SDI: Top Safety & Reliability Solutions*, March, 2018. http://samsungsdi.com/upload/ess_brochure/201803_SamsungSDI%20ESS_EN.pdf.

[63] Volta Foundation. *2025 Annual Battery Report*. https://volta.foundation/battery-report-2025/.

[64] *Battery Energy Storage Systems Explosion Hazards.* EPRI, Palo Alto, CA: 2021. 3002022706.

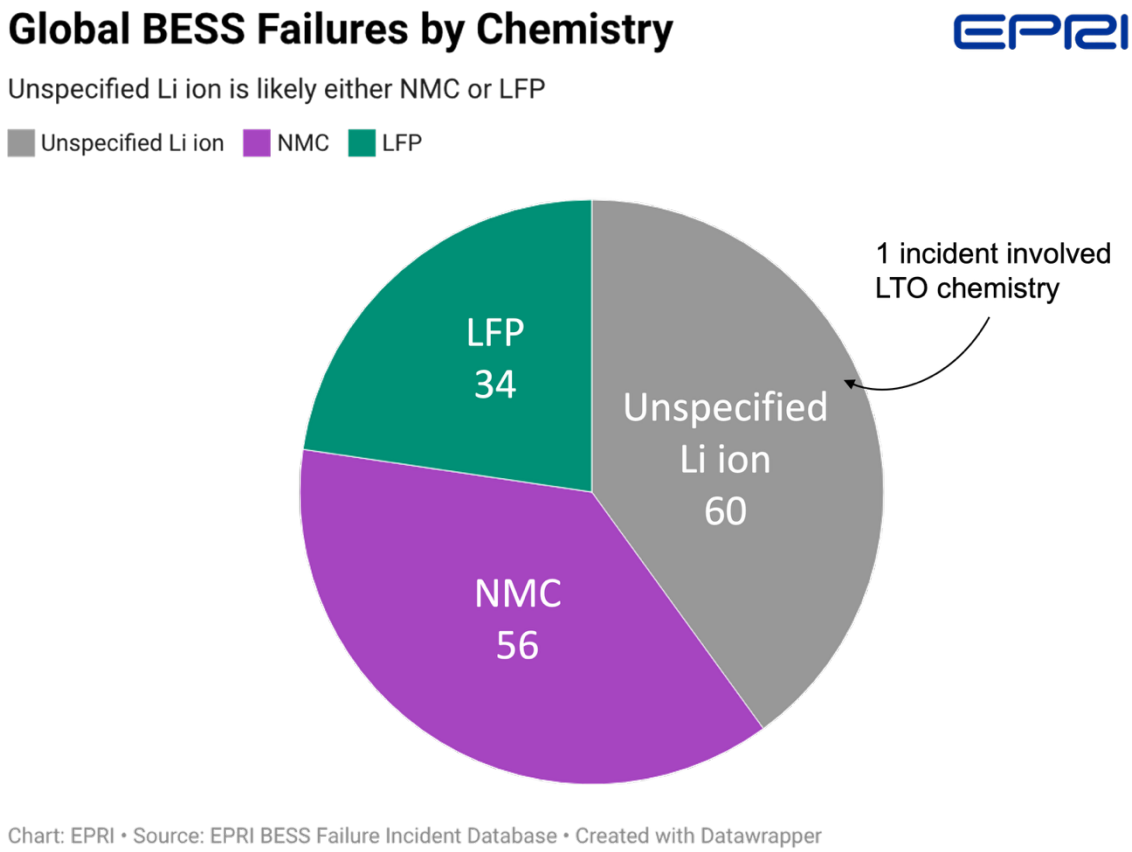


Figure 26. Global BESS Failures by Chemistry

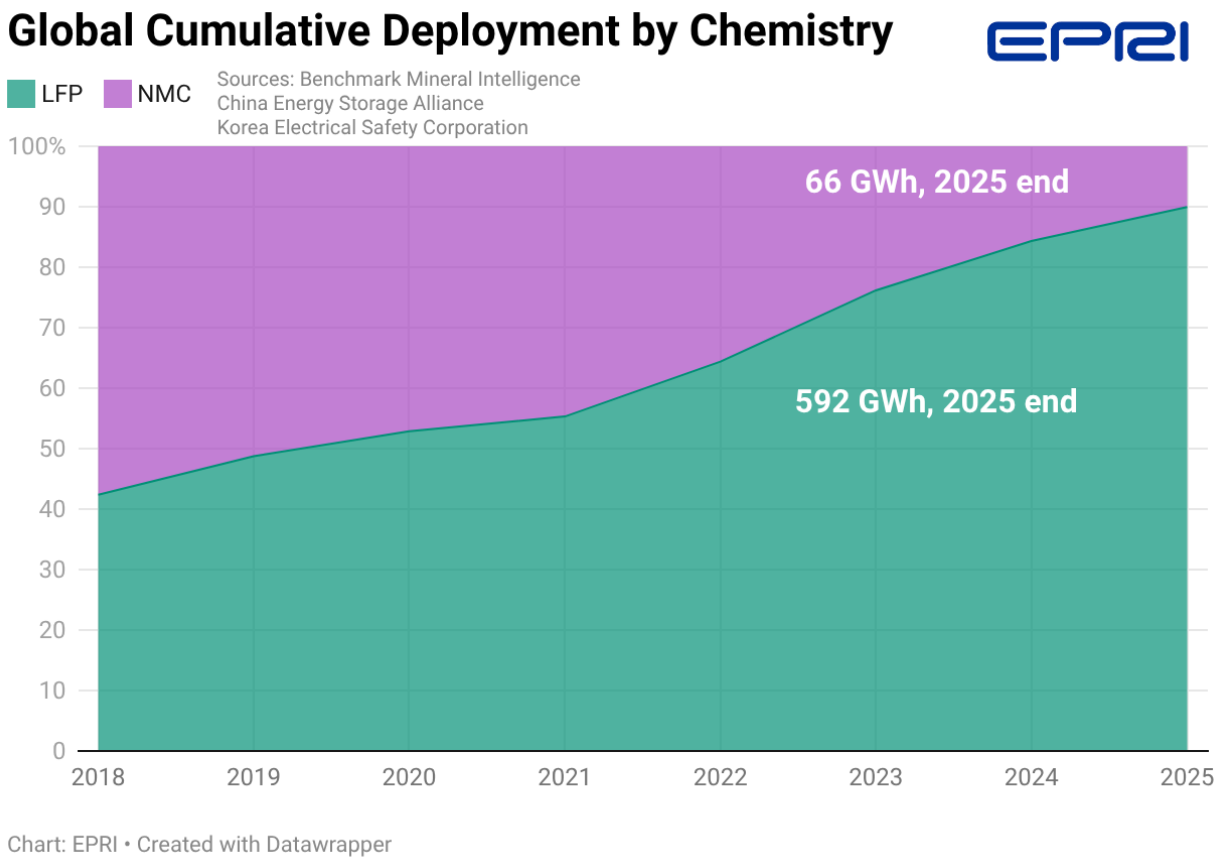


Figure 27. A Look at Deployment of Lithium ion by Sub-chemistry

Figure 27 shows the deployment of LFP and NMC globally. Other data sources[65] show similar trends, though exact magnitudes do not always match. There is a 4% error in global capacity summed by chemistry compared to cumulative deployment data used elsewhere in this report. Estimates of deployment by chemistry varied between sources. EPRI opted to use in-country sources where available for deployment data. Despite the data challenges, all sources agree that grid-scale storage deployment has shifted predominantly towards LFP in the last few years.

It is important to note that at the same time as deployment shifted towards LFP, BESS products were also evolving, especially in terms of improved safety design. EPRI examined the relationship between vintage, or system install year, and chemistry. This data was limited to incidents where the system vintage was known.

[65] https://about.bnef.com/insights/clean-energy/global-energy-storage-growth-upheld-by-new-markets/

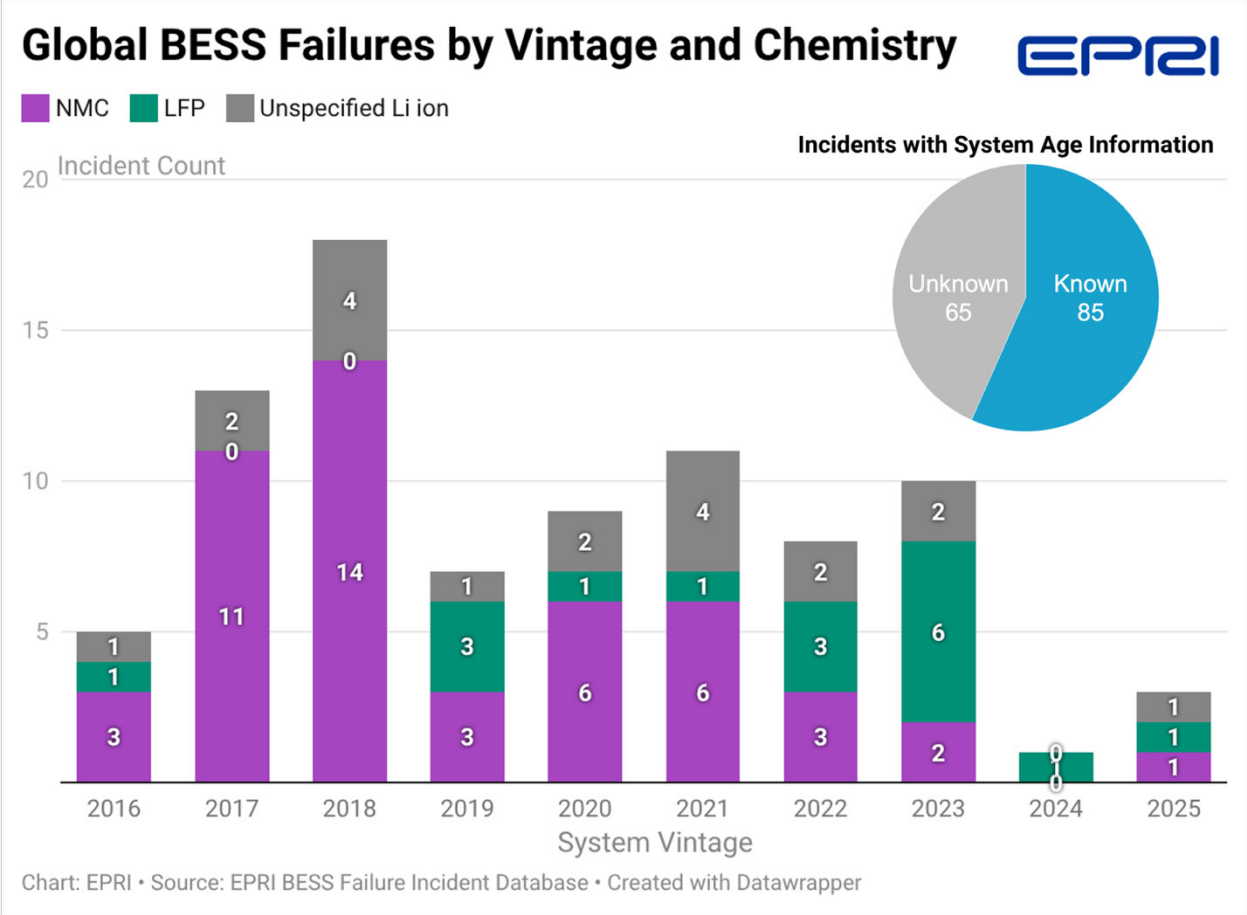


Figure 28. Global Failures by System Vintage and Chemistry

Figure 28 shows more failures occurring for BESS that were deployed in 2017-2018, as described in the previous section. Though the majority of these have been identified as NMC-based systems, there was no definitive conclusion from investigations that cell-level defects or issues were the root cause[66]. While it could be hypothesized from Figure 26 and Figure 28 that NMC failures are more prevalent than LFP failures, the data does not support definitive conclusions. In many incidents, it was known that the chemistry was lithium ion, but it was unknown whether it was LFP or NMC. Figure 26 shows that it was not possible to determine the lithium ion sub-chemistry for 40% of incidents. Additionally, the trends in the deployment of LFP and NMC show that LFP increased in market share at the same time as BESS products matured. Vintage was identified as a significant factor affecting likelihood of failure in the previous analysis. **This makes it difficult to disentangle the effects of cell chemistry from integrated unit design maturity as well as improved industry understanding of manufacturing, integration, and operation of BESS.**

[66] Na, Y.-U.; Jeon, J.-W. Unraveling the Characteristics of ESS Fires in South Korea: An In-Depth Analysis of ESS Fire Investigation Outcomes. *Fire* 2023, *6*, 389. https://doi.org/10.3390/fire6100389.

Other simultaneous industry trends also complicate the relationship between chemistry and risk of failure. The focus on increasing energy density has led to larger format LFP cells and tighter cell packing, and in turn, this has increased cooling requirements. The industry's shift to liquid cooling allows for more effective thermal management, which is an important operational and safety component in BESS. However, liquid cooling also creates new failure mechanisms; incidents have occurred due to coolant leaks[67].

In an aggregate root cause analysis that EPRI published in 2024[68], the most common failed components that were identified were the balance of plant and controls. The cell was rarely identified as the root cause of the failure, although it is important to note that this determination is difficult to make after the loss of physical evidence during a fire. While NMC and LFP have differing safety characteristics, chemistry is only one aspect of safety. For example, in incidents where the cause of failure was water intrusion into the container or coolant leak, it is likely that the chemistry would not have influenced whether or not the BESS failed.

When examining system-level failures, module- and system-level design choices impact failure progress. Authorities having jurisdiction (AHJs) rely upon module, rack, and installation level UL9540A testing to understand the system-level risk during BESS siting and permitting processes, because module- and system-level design choices affect how thermal runaway events progress and how failure hazards are mitigated. **As a result, it could not be concluded at this time that cell-level chemistry in isolation was a risk factor for system-level BESS failures**. Future work in this space could include conducting a regression analysis for chemistry, vintage, and age together, similar to the work done for vintage and age.

[67] Energy Storage News. Investigation confirms cause of fire at Tesla's Victorian big Battery in Australia. May 11, 2022. https://www.energy-storage.news/investigation-confirms-cause-of-fire-at-teslas-victorian-big-battery-in-australia/

[68] *Insights from EPRI's Battery Energy Storage Systems (BESS) Failure Incident Database: Analysis of Failure Root Cause.* EPRI, Palo Alto, CA: 202. 3002030360.

6. CONCLUSION

BESS can be commissioned, operated, and decommissioned safely, and have been for years. Risk continues to decline through efforts to reduce both the frequency as well as the consequence of incidents. This report provides quantitative and qualitative risk assessments of BESS, focusing on the likelihood of failure, severity of consequences, and the impact of various risk factors. This work and the conclusions presented in this report were only possible because of the public nature of EPRI's Failure Incident Database, which enabled some level of transparency and information-sharing to collect the necessary data. However, as noted in the report, the conclusions and analysis were limited by missing information and possibility of missing incidents altogether. **Without increased transparency and collaboration, it is not possible to fully identify gaps or trends that could lead to improved design, deployment practices, and increased BESS safety.**

The first section of the report focused on likelihood of BESS failures. The global BESS failure rate continues to decrease over time, dropping 50% between 2024 and 2025. An average annual failure rate was also determined for BESS, based on operational year and deployed units. This frequency of BESS incidents is comparable to widely used oil-filled transformers. As more operating experience with BESS occurs, the failure rate is expected to keep falling. Incident consequences can be minimized by designing BESS with current leading safety insights in mind, mitigating or eliminating explosions, limiting fire propagation within the BESS site, and thorough up-to-date first responder training. In comparison to other common energy infrastructure, such as large oil-filled transformers, BESS failure consequences are not uniquely severe. Similar incident response approaches are used for BESS fires and transformers fires. No BESS incident recorded in the database had fire spread beyond the facility. In the U.S., no incident since the 2019 incident in Arizona resulted in acute injuries or fatalities.

The impact of several design and system factors including vintage, age, site architecture, and chemistry on failure likelihood were examined. Indoor, or building-based systems are over-represented in the failure data set compared to deployment, for U.S.-specific data. Indoor systems also experience greater proportion of damage in an incident compared to outdoor containerized systems. Isolating impacts of chemistry type, age, and vintage was complicated by how trends in BESS deployment shifted and evolved over time. It was determined that for a given vintage, increasing age reduced the likelihood of failure, pointing to higher failures at beginning of life. Additionally, the analysis showed that likelihood of failure at a given age decreased for newer vintage. Newer systems with improvements in design, codes, and standards show material improvement in risk. BESS owners may consider safety reviews, retrofits, and potential retirement of older vintage systems if they cannot be updated to meet latest safety design and practices. **In conclusion, the risk associated with BESS can be effectively managed to limit impacts on storage facilities, the grid, and the public, enabling BESS to continue serving as a key segment of the global energy infrastructure.**

EPRI continues to track global BESS failures and provide insights based on new findings. Future work in this space could include more rigorous statistical analysis on error and frequency and potentially developing predictive models for failure rates. Additionally, an analysis of variance could be conducted, to determine which of the various design factors examined in this report have the most impact in reducing risk. A quantitative risk assessment framework is being developed in parallel, which could be used in conjunction with this report to provide practical guidance and quantified cost-risk tradeoffs for various safety mitigations. More broadly, EPRI's BESS safety research portfolio aims to address gaps related to incident response, siting, operations & maintenance, new technologies and more.

A. NON-PUBLIC BESS FAILURE INCIDENTS

There were 33 incidents not captured in public sources. These incidents are listed in the EPRI BESS Failure Database by region and year. These incidents were confirmed by trusted energy storage industry experts. The incidents have been included in calculations of the failure rate and other analyses as noted, where pertinent information was available and verified.

Table 15. List of Non-public Incidents

Region	Year
Asia	2025
China	2018
China	2019
China	2020
China	2022
China	2022
China	2022
China	2022
China	2023
China	2023
China	2023
China	2023
China	2024
China	2024
China	2024
China	2024
China	2024
China	2024
China	2024
China	2024
China	2024
China	2025
China	2025
China	2025
North America	2024
South America	2025
United Kingdom	2025

Region	Year
United States	2022
United States	2022
United States	2024
United States	2024
United States	2024
United States	2024
United States	2025

B. REGIONAL FAILURE RATES

The following figures show region and country-specific failure rates over time. Note that these are annual calendar failure rates, rather than annual operational failure rates.

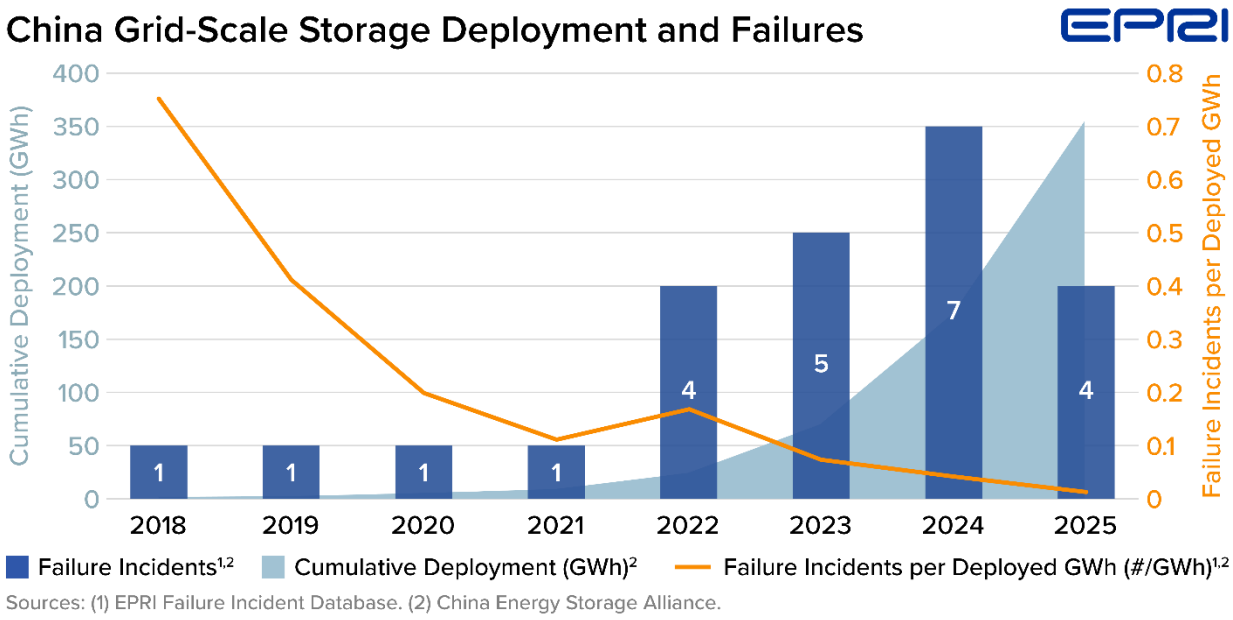


Figure 29. Grid-Scale Deployment and Failures, China

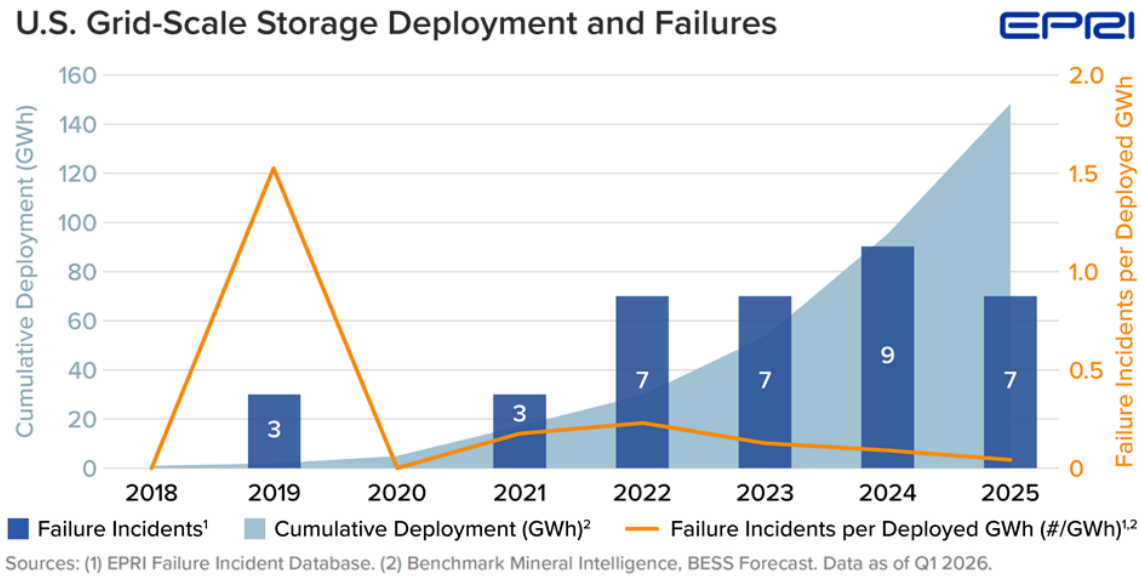


Figure 30. United States Failure Rate

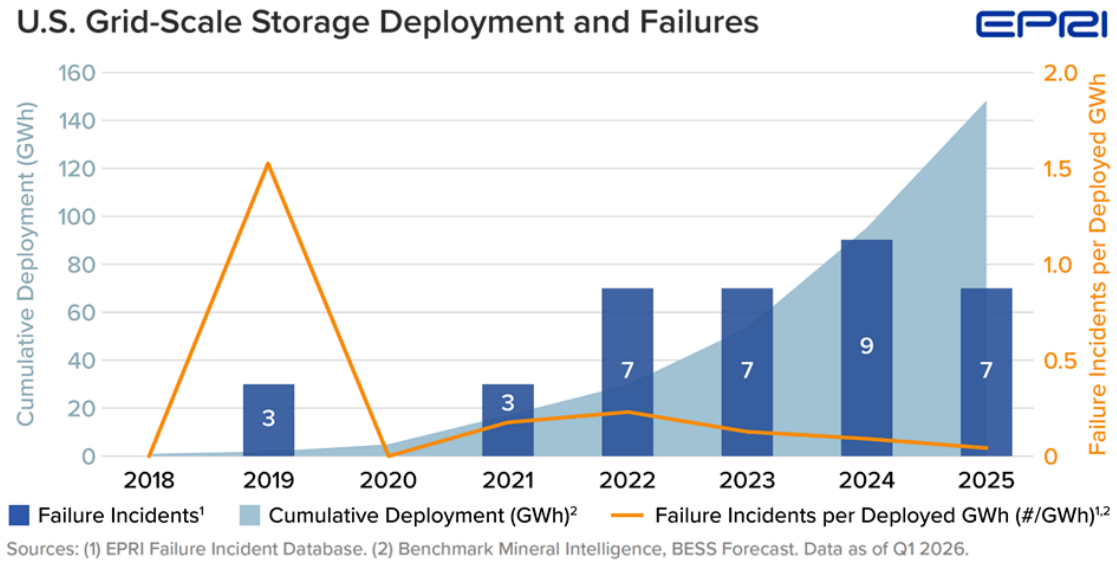


Figure 30. United States Failure Rate

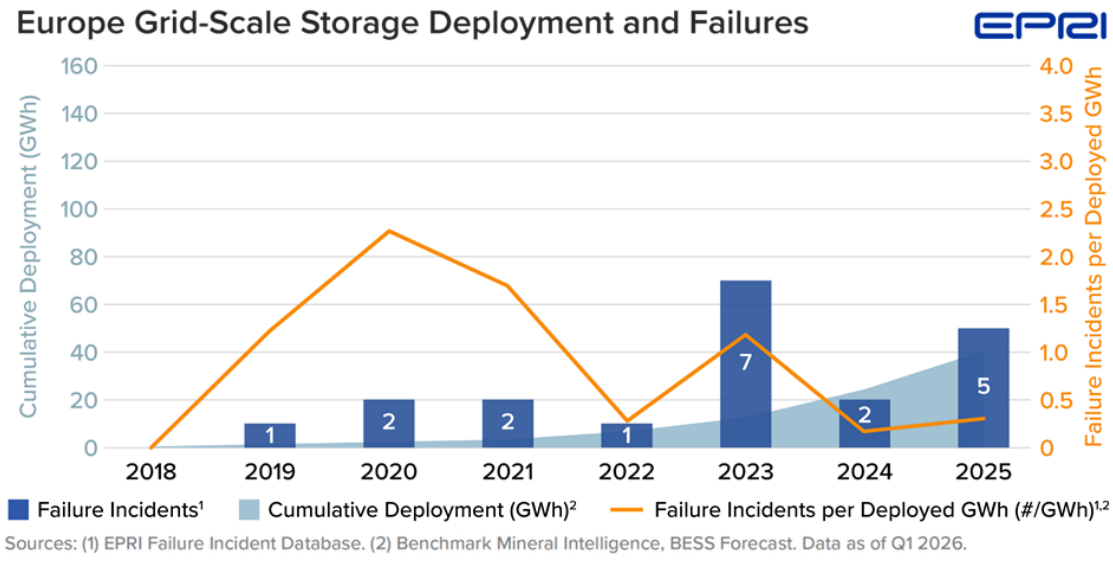


Figure 31: Europe Failure Rate

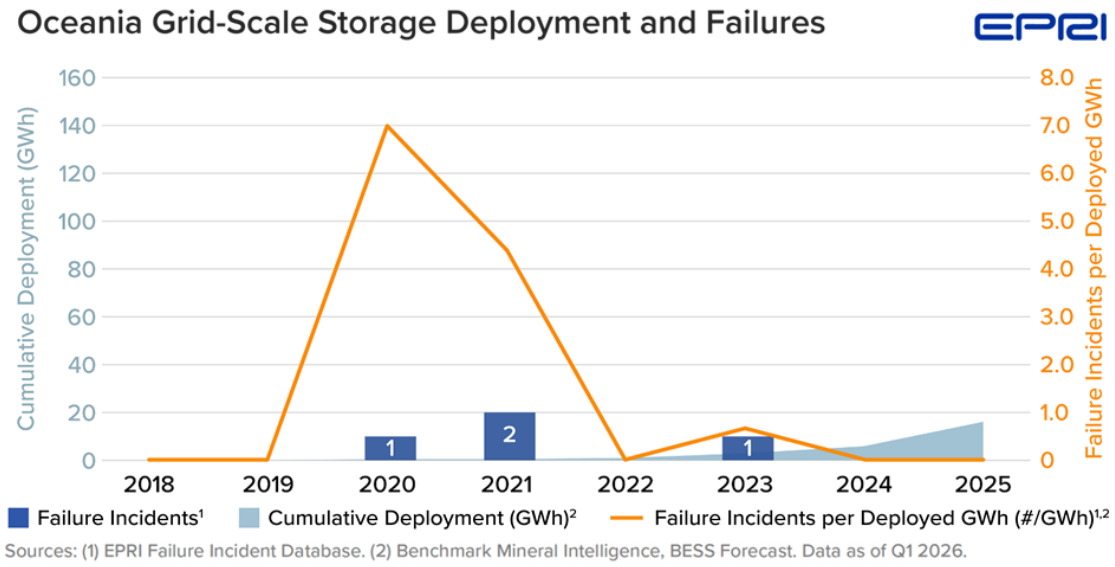


Figure 32: Oceania Failure Rate

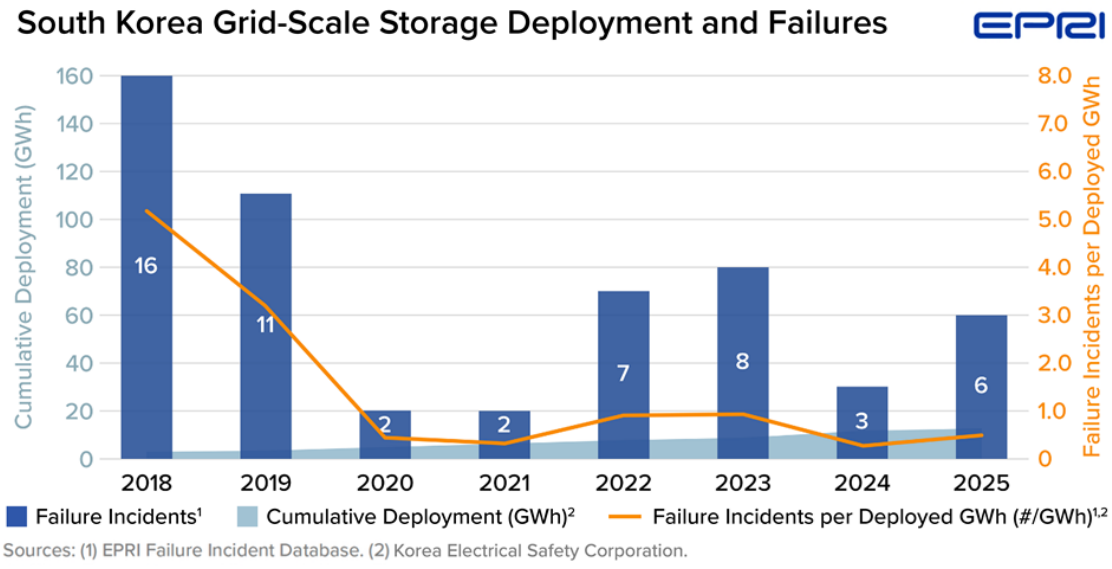


Figure 33: South Korea Failure Rate

C. BESS PRODUCT ENERGY DENSITY OVER TIME

BESS deployment data as well as the size of specific BESS facilities is often provided in MWh instead of number of units. To calculate failure rate on the basis of units failed per units deployed, it was necessary to estimate the number of container units per MWh. The energy density of BESS products has increased over time, so an average energy density was estimated for each year based on the specification sheets of 20 BESS products from eight major BESS OEMs. Note that this is not an exhaustive list of available products. The size of BESS enclosures has also varied over time, so a container unit was normalized to the volume of a standard twenty-foot shipping container, or TEU (twenty-foot equivalent unit). Table 16 shows the list of specifications and product launch years used for this estimate. Table 17 shows the assumed average energy density for each year used for calculations in this report, based on the specifications in Table 16.

Table 16. BESS Product Specifications

BESS Product Specifications	Launch year (delivery)
Tesla PowerPack 2h	2016
Samsung SDI Container Variants	2016
LG High Energy Container	2018
LG Energy Container	2018
Samsung SDI	2018
Tesla MP1 2h	2019
Tesla MP1 4h	2019
Tesla MP2 2h	2021
Tesla MP2 4h	2021
Tesla MP2XL 2h	2022
Tesla MP2XL 4h	2022
Sungrow PowerTitan 1 (ST2752UX-US)	2022 announced
Powin Centipede 2h	2023
Powin Centipede 4h	2023
Sungrow PowerTitan 2 2h	2023 announced (2024 est. delivery)
Sungrow PowerTitan 2 4h	2023 announced (2024 est. delivery)
CATL Tener	2024 announced
Fluence Gridstack Pro 2000	launch 2023, delivered 2025
Sungrow PowerTitan 3	2025 announced
BYD Haohan	2025 announced

Table 17. Average Energy Density of BESS By Vintage

System Vintage (Install Year)	Average MWh/TEU
2016	2
2017	2.5
2018	3
2019	3.5
2020	3.5
2021	4
2022	4
2023	4
2024	4.5
2025	4.5
If Unknown	3.5

D. INJURY COUNT METHODOLOGY

In the 2019 Surprise, Arizona incident, four firefighters were critically injured, and an additional four were observed overnight for possible HCN exposure.

OSHA 1904.7(a) defines the criteria for a recordable injury or illness: *"You must consider an injury or illness to meet the general recording criteria, and therefore to be recordable, if it results in any of the following: death, days away from work, restricted work or transfer to another job, medical treatment beyond first aid, or loss of consciousness. You must also consider a case to meet the general recording criteria if it involves a significant injury or illness diagnosed by a physician or other licensed health care professional, even if it does not result in death, days away from work, restricted work or job transfer, medical treatment beyond first aid, or loss of consciousness."*[69]

Based on the available information, it does not appear that the latter four firefighters received medical treatment beyond first aid. According to OSHA, "*An overnight stay does not determine whether the case is reportable or not.*"[70] As a result, EPRI has identified the injury count for the incident as four.

[69] U.S. Department of Labor: Occupational Safety and Health Administration. *OSHA 1904.7(a)*. https://www.osha.gov/laws-regs/regulations/standardnumber/1904/1904.7#:~:text=Basic%20requirement.,aid,%20or%20loss%20of%20consciousness.

[70] U.S. Department of Labor: Occupational Safety and Health Administration. *Frequently Asked Questions,* Reference 39-10. https://www.osha.gov/faq/39-10.

E. STATISTICAL ANALYSIS OF SYSTEM AGE AND VINTAGE EFFECTS ON FAILURE RATE

Method

To quantify the independent effects of system age and vintage on failure rates, a regression-based analysis was performed. Regression models estimate the relationship between explanatory variables (age and vintage) and a response variable (incident count or failure rate). A Poisson regression model was selected because the response variable represents counts, the dataset is relatively small, and the approach supports inclusion of exposure (deployment) as an offset, allowing estimation of failure rates rather than raw incident counts. An additional advantage is that the model does not require detailed age or vintage information for systems that did not experience failures. The model takes the form $\log(E[\text{incidents}]) = \beta_0 + \beta_1 \cdot \text{age} + \beta_2 \cdot \text{vintage} + \log(\text{deployment})$, where annual deployment is included as an offset.

Data

The data included deployed and failed systems installed between 2018 and 2023. Systems installed after 2023 were not considered due to their short operational life. Failures that occurred between 0-1 years of operation, including pre-commissioning, were grouped in the "0" bucket. Failures that occurred between 1-2 years of operation were grouped in the "1" bucket, and so on. The annual deployment was included as an offset to account for different population sizes over the years.

Vintage / System Age	0	1	2	3	4	5	6	Annual Deployment (GWh)
2018	10	3	1	1	1	2	0	5.89
2019	1	3	1	2	0	0	0	4.57
2020	2	2	2	2	1	0		9.19
2021	1	2	2	3	2			21.90
2022	3	1	3	0				37.57
2023	7	2	1					86.97

For the analysis, incidents were aggregated by vintage year and system age at failure, with each row representing a combination of these two variables (e.g. 2018 vintage, 2 years of operation at failure) and the corresponding number of observed incidents.

Vintage	Deployment (GWh)	Age	# of Incidents
2018	5.89	0	10
2019	4.57	0	1
2020	9.19	0	2
2021	21.90	0	1
2022	37.57	0	3
2023	86.97	0	7
2018	5.89	1	3
2019	4.57	1	3
...	...	...	...

Results:

Dependent Variable	Incidents	No. Observations	32
Model	GLM	Df Residuals	29
Model Family	Poisson	Df Model	2
Link Function	Log	Scale	1.0000
Method	IRLS	Log-Likelihood	-46.815
No. Iterations	5	Deviance	23.681
Covariance Type	nonrobust	Pearson chi2	22.7
		Pseudo R-squ. (CS)	0.8750

Variable	Coefficient	Standard error	*z-Statistic*	*p*-value	95% CI
Intercept	1183.1533	141.198	8.379	<0.001	[906.410, 1459.897]
Age	-0.3738	0.088	-4.239	<0.001	[-0.547, -0.201]
Vintage	-0.5863	0.070	-8.390	<0.001	[-0.732, -0.449]

Both age and vintage coefficients are negative, indicating that the incident rate decreases with increasing system age and with more recent vintages. The estimated coefficients are on the log scale; exponentiating them yields incidence rate ratios (IRRs) of approximately 0.69 for age and 0.56 for vintage. This means that, holding vintage constant, each one-year increase in system age is associated with a 31% reduction in the incident rate. Similarly, holding age constant, each one-year increase in vintage (i.e., a more recent system) is associated with a 44% reduction in the incident rate. The 95% confidence intervals for both variables exclude zero, indicating statistical significance. Model diagnostics suggest that the Poisson specification is appropriate: the pseudo-R^2 is high, indicating strong explanatory power, and both the deviance and Pearson

χ2 statistics are close to the residual degrees of freedom, suggesting no strong evidence of overdispersion.

This analysis was followed up with a Bayesian approach with the same Poisson regression model, again including deployment as an offset. In the Bayesian framework, parameters are calculated as probability distributions rather than point estimates, which is advantageous for small datasets where estimates may be noisy. Weakly informative priors were assigned to the intercept and to the coefficients for age and vintage, providing regularization while allowing the observed data to primarily determine the posterior estimates.

Priors:

Variable	Prior
α (intercept)	Normal(0,2)
β_{age}	Normal(0,0.5)
$\beta_{vintage}$	Normal(0,0.5)

Results:

Parameter	α	β age	β vintage
mean	-1.192	-0.369	-0.577
Standard deviation	0.175	0.088	0.069
95% Equal-Tailed Interval Lower Bound	-1.50	-0.54	-0.72
95% Equal-Tailed Interval Upper Bound	-0.86	-0.20	-0.44
Effective Sample Size (Bulk)	2491	2593	2286
Effective Sample Size (Tail)	2608	2492	2220
Potential Scale Reduction Factor ($\hat{R}$)	1.00	1.00	1.00
Monte Carlo Standard Error of the Mean	0.0035	0.0017	0.0014
Monte Carlo Standard Error of the Standard Deviation	0.0026	0.0012	0.0011

Posterior estimates from the Bayesian Poisson model are consistent with the previous results. The mean coefficients for age and vintage are nearly the same, with IRRs of 0.69 and 0.56 respectively. The model's convergence diagnostics are satisfactory: R^=1.0 for all parameters, and effective sample sizes are high for both bulk and tail, suggesting stable and well-mixed chains.

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