Quantitative Risk Analysis for Battery Energy Storage Sites

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Objective:

The purpose of this paper is to address the risks associated with battery energy storage site facilities and the barriers and best practices in place to address those. This paper discusses the likelihoods of incidents based on statistical analysis and reliability data while considering the safeguards, industry standards, and best practices that are currently in place.

Quantitative risk assessments have shown how current safeguards and best practices can significantly reduce the likelihoods of resulting battery fires and other undesired events to levels acceptable to operator. The scope of the paper will include storage, transportation, and operation of the battery storage sites. DNV GL will consider experience from previous studies where Li-ion battery hazards and equipment failures have been assessed in depth.

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ACRONYMS

AHJ	Authorities Having Jurisdiction
AIChE	American Institute of Chemical Engineers
ARPA-E AMPED	Advanced Research Projects Agency-Energy, Advanced Management and Protection of Energy Storage Devices
BMS	Battery Management System
CAES	Compressed Air Energy Storage
CCPS	Center for Chemical Process Safety (A Division of AIChE)
ESS	Energy Storage System
EV	Electric Vehicles
FMEA	Failure Modes and Effects Analysis
HVAC	Heating Venting and Air Conditioning
IEEE	The Institute of Electrical and Electronics Engineers, Inc.
IFC	International Fire Code
LOPA	Layers of Protection Analysis
NFPA	National Fire Protection Association
OREDA	Offshore and Onshore Reliability Data
PFD	Probability of Failure on Demand
RPS	Renewable Portfolio Standard
UK HSE	United Kingdom Health and Safety Executive
UL	Underwriters Laboratories, LLC
US DOE	Unites States Department of Energy

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1 EXECUTIVE SUMMARY

Energy storage systems (ESS) are electrical (e.g., capacitors), electrochemical (e.g., lithium-ion batteries), mechanical (e.g., pumped hydro), or hybrid technologies leveraging the products of other processes (e.g., combined heat and power plants) which store energy for later use. Legacy ESS technologies, such as lead acid batteries in vehicles or Alabama's in-ground large-scale compressed air energy storage (CAES), have been used for decades. In recent years, however, energy storage has taken on new relevance as it supports increasing energy demand, a higher penetration of renewables on the grid, requirements to reduce emissions, and efforts to improve resiliency. Lithium-ion (Li-ion) batteries have emerged as front runners in this new expansion of the industry, as their high energy density and rapidly decreasing capital costs support their use in applications ranging from portable personal electronics to transportation, grid-scale capacity support, and more [1].

As with any technology, it is important to understand the technology's range of safety risks and risk mitigation measures.

While there is limited publicly available data, and few technical reports concerning Li-ion battery incidents, DNV GL has conducted destructive testing on over 150 cells from 2.4Ah to 200Ah from 15 different manufacturers, and over 50 medium and large scale tests, as well as having conducted several fire and failure investigations. These experiences have fostered at DNV GL an understanding of how Li-ion batteries fail and which designs and best practices reduce incident likelihood or severity. In addition to this confidential testing and analysis data, data from the oil and gas, nuclear power, utility, and petrochemical industries have also proven helpful in assessing scenarios. DNV GL uses these sources, in addition to statistical analysis and risk assessment tools, to estimate the risk of catastrophic battery failures, including gas release, fires, and explosion.

When comparing the risk of ESS failures in the context of common events, while the impact may be high, the likelihood of failure is low. Thus, the risk of the ESS failure is comparable to or even lower than the risks associated with activities people willingly participate in. For example, working at or living near an ESS is less risky than driving a car 10 hours per week, smoking, or working in industries such as construction, mining, or agriculture [2]. Another way of putting the risk of ESS failures into context is through guidelines set by regulatory agencies. For example, the United Kingdom Health and Safety Executive (UK HSE) has set guidelines for 'broadly acceptable risk' for both workers and members of the public as one in a million per year (10^{-6} fatalities/year) with 'tolerable risk' for workers and individuals being one in 1,000 per year (10^{-3} fatalities/year) and one in 10,000 per year (10^{-4} fatalities/year) respectively. Estimates of ESS failure risks are one in 100,000 per year (10^{-5} fatalities/year) for individuals and one in 1,000,000 per year (10^{-6} fatalities/year) for the public.

To ensure that ESS remain at an acceptable risk level, owners and operators of both permanent or portable ESS must follow design standards and best practices, regularly maintain the system's equipment (as well as safety systems and related equipment), train personnel, and communicate with local emergency responders on the storage system's hazards.

2 INTRODUCTION

With the rapid commercialization of energy storage systems (ESS)—especially in the last two years as Li-ion batteries have dropped in price and increased in prevalence—safety has become a key focus in the deployment of ESS generally and particularly for Li-ion based ESS. Though ESS code development is moving forward, the pace has been slower than industry's desire to use energy storage, resulting in large-scale deployments being handled on a case-by-case basis in many jurisdictions. Even with the development of initial permitting and large-scale testing guidelines, the requirements remain in some cases opaque, and each ESS is still evaluated for both its own safety and the safety of and risks from the surrounding environment.

Fortunately, developments are emerging in all these areas. NFPA 855, Standard for the Installation of Stationary Energy Storage Systems, is undergoing balloting now and barring considerable objection, should be published in late 2019 for the 2021 code cycle. The 2018 International Fire Code's Chapter 12 [20], with a focus on energy generation and storage, was published with much expanded reference to storage devices from the 2015 edition. The 2021 version is nearing completion as well. On the product testing side, the third edition of UL 9540A, a Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems [21], was published in 2018 and continues to be revised based on industry knowledge and experience. With these codes and standards in process or yet-to-be adopted, local jurisdictions are developing processes to handle assessments of installations. However, even with this progress, the standards still prescribe highly conservative values, relying on individual Authorities Having Jurisdiction (AHJs), such as fire departments and building departments, to interpret the developing standards and approve or deny ESS installations based on the AHJ's judgment, without clear parameters of what risks may be entailed or mitigated.

Without a definitive body of testing and risk analysis experience, standard and code development as well as the judgment of AHJs may be driven, at least in part, by potential worst-case scenarios regarding ESS failure. Such scenarios, based on limited destructive testing or non-ESS battery-powered device failure, typically involve the generation of large quantities of flammable gas that are ultimately ignited via a number of ignition sources, resulting in a catastrophic explosion with far-reaching and devastating effects. Based on continued discussion in the standards and AHJ communities about a variety of catastrophic scenarios for batteries (from cell phones to large systems), a fixation has developed around these events, creating the perception that all ESS may share this fate before reaching normal end of life. These fears are further heightened by the battery industry's lack of transparency with testing data, coupled with an abundance of marketing gimmicks, serving to create a poorly-informed and distrustful relationship between AHJs and the ESS industry.

DNV GL's goal for this white paper is to provide transparency, quantifiable data, and risk assessments relating to ESS and, specifically, Li-ion batteries. DNV GL used its own internal practices for risk assessment, leveraging its long, industry-leading history in risk assessments for maritime and oil and gas applications with its substantial history in assessments for battery technology. The discussion within this paper is based on a deep experience in battery testing, going back years to the Advanced Research Projects Agency-Energy, Advanced Management and Protection of Energy Storage Devices program (ARPA-E AMPED) and more recently through testing for public projects and confidential clients. DNV GL has previously leveraged this data to advise fire fighters on safety measures during ESS emergencies, provide feedback and review to manufacturers regarding ESS safety designs, and develop new testing programs and protocols for

stakeholders in general to gain an increasingly nuanced understanding of safe operation and failure modes. As the industry has expanded and evolved, DNV GL has observed the overall safety and stability of these systems improving in numerous ways, even to the extent that it is difficult to force systems into a catastrophic failure during destructive testing. DNV GL has assessed the ways in which these failures are mitigated through intelligent system design, or even prevented entirely, leveraging continuous monitoring and battery management systems to detect potential issues and shut down of the ESS.

These safer systems exist, improve daily, and can reduce the likelihood and severity of failures. However, approaches that drastically reduce the risk of worst-case, catastrophic failures are frequently left out of discussions about safety. The overall frequency that these systems fail and result in catastrophic impacts is low. In the last 18 months, DNV GL performed in-depth, semi-quantitative and quantitative risk analyses. These went beyond simple failure modes and effects analyses (FMEA, the basic approach for identifying all possible failures in a system) and included layers of protection analysis (LOPA), event tree analysis, and risk models. These techniques, used regularly in the oil and gas industry, analyze the risks in various scenarios, potential consequences, and the effectiveness of the barriers in place to prevent or mitigate those risks.

The scope of this paper includes:

- the analysis of the most common hazards associated with Li-ion batteries
- the frequency of events leading to these incidents based on available failure rate data and statistical analysis
- the application of quantitative risk assessment methodologies, as well as consideration of industry standards, safety barriers, and best practices, for both transportation and operation of ESS

The primary example used is a generic Li-ion ESS situated near a residential area with standard safeguards and current best practices.

The purpose of this study is not to perform an analysis of failures or to determine failure rates based on known battery failure incidents, but rather to assess the risk based on what is currently documented and used in other industries, as well as on anecdotal evidence and experience from battery tests and well-documented battery failure incidents.

DNV GL aims to return some degree of quantitative risk reality to the conversation about ESS safety. As the adage goes, “when all you’ve got is a hammer, everything looks like a nail”—thus seeing only worst-case scenarios leads to thinking that ESS are all high-risk and prone to devastating failure.

3 DEFINING RISK IN THE ESS INDUSTRY

3.1 Current energy storage industry positioning

ESS are increasingly attractive options for utility operators and energy providers to improve reliability and efficiency on the grid while reducing emissions. Various countries, including the United States (US), have established strategies to increase the use of energy storage by addressing cost competitiveness, performance and safety, market and pricing regulations, and industry acceptance [3]. Individual US states have adopted renewable portfolio standards (RPS) and zero net emissions standards. They also have developed incentive programs, which support the increased penetration of energy storage. Thirty-seven total states have an RPS or voluntary clean energy goals. California is a major leader in this space, but many states are expanding their goals. For instance, New York Governor Cuomo recently announced a target of 1500 MW of storage for the state by 2025 [4].

The energy storage market offers various options for consideration, including pumped hydro, CAES, flywheels, and batteries [5]. Currently, based on the US Department of Energy (DOE) energy storage database (which, as DOE has disclosed, is self-reported and researched and may not maintain pace with all installations), there are 180 GW of energy storage systems of all types installed and operational worldwide, with 24.5 GW installed in the US. However, of those values, both in the US and abroad, approximately 90% of the capacity is represented by large pumped hydro storage. While electrochemical batteries represent in count nearly 60% of the projects installed, they contribute just 1.6 GW to worldwide capacity and 658 MW to US capacity. Of this subsection, Li-ion chemistries account for 1.2 GW of installations worldwide and nearly 90% of US electrochemical installations (612 MW) [6]. In the two years since the database has been reliably updated, it is likely these numbers have increased considerably.

As such, Li-ion batteries are the focus of this paper. Li-ion's high-energy density and rapidly decreasing capital costs support their use in applications ranging from portable personal electronics to transportation to grid-scale capacity support and beyond [1]. But recent incidents, such as the Union Pacific train car explosion in 2017 [7] and the Boeing 787 Dreamliner fires in 2013 [8], have led to scrutiny of Li-ion batteries, though the causes of these incidents are still under investigation. Further, between Q2 and Q4 2018, the nation of South Korea and their electric utility, KEPCO, experienced over a dozen large scale ESS fires. These fires resulted in over $20 million (USD) in losses and while causes have been suggested, an official and complete explanation has yet to be provided. While these failures should be assessed for lessons learned, it is key to note that they have all occurred in a single geographic region which has yet to enact any energy storage requirements, and diligence or oversight for these locations cannot be verified. In the US, on the other hand, a recent explosion at an Arizona energy storage facility [22] severely injured several first responders. Investigations are on-going, but it is clear that a quantitative understanding of risk, both for the likelihood and the impact of failure, is critical to provide sufficient mitigation measures. While these and similar high-profile failures have received media attention, reputable manufacturers claim hundreds of thousands and even millions of hours of operation with no large failures. To this end, it is important that we learn from this sub-set of failures, to continue to reduce their likelihood and impact, rather than assume their inevitability.

The total number of ESS deployed and their failure rates currently are not tracked in incident databases. However, it is still possible to estimate the risks of ESS based on data from battery burn tests, recorded reliability data for analogous systems, and some statistical analysis. DNV GL used consequence modelling

software to determine the distance and subsequent impacts of plumes released from burning batteries. Further, cell defect data and failure rate data of electrical components was leveraged to assess the likelihood of fires at Li-ion ESS via known failure modes.

In addition to this, it is helpful to show how the risks with ESS facilities compare with those for conventional power plants, gas-powered vehicles, and other applications with which the public is more familiar. Between 1998 and 2007, oil, nuclear, natural gas, and coal plants had a combined total of 45 incidents considered major—the criteria for a "major incident" are that it must have occurred in a mine, refinery, pipeline, enrichment facility, etc.; must have resulted in at least one death or property damage above $50,000; must have been unintentional and in the civilian sector (i.e., not an effect of war); and must have been verified by a published source [9]. The study suggested that more incidents likely occurred in less developed economies but were not reported. Since 2007, incidents have continued to occur and be reported, including such highly publicized incidents as the Deepwater Horizon oil spill in 2010, the Fukushima Daiichi nuclear incident in 2011, and the Keystone Pipeline spill in 2017. Meanwhile, NFPA reports that in 2015 alone, even as vehicle fires decreased, 174,000 gasoline-powered vehicles caught on fire on highways in the US, causing $1.2B in property damage [10]. Tesla reports that there have been 5 fires in Tesla electric vehicles (EVs) for every billion miles travelled, compared to a rate of 55 fires per billion miles travelled in gasoline cars [11]. We cite these values because society as a whole has accepted significant risks for conventional technologies, while being very hesitant to accept newer technology which may have a lower risk profile.

3.2 The Concept of "Risk"

Risk is a function of two components: severity (also referred to as consequence or impact) and likelihood (also referred to as probability or frequency) of the event occurring. As illustrated in the equation below:

$$\boldsymbol{Risk = Severity \times Likelihood}$$

Each component is assessed independently and are combined to determine the risk of a situation or scenario. Risk can be defined on several levels, including health and safety (worker injuries or fatalities or impact to the surrounding community), environment, financial impact to an organization, or reputation. For health and safety, for example, the risk could be stated as "one death every 10,000 years." For financial impact the statement could be "$20,000,000 lost every 100 years."

Many companies and enterprises have risk matrices based on their risk tolerance, which may also vary mildly by industry. The matrix presented in Figure 3-1 is a generic example based on DNV GL's experience with companies in various industries. Severity level is shown on the top of the chart, with five categories:

- insignificant - no injury
- minimal - first-aid injury
- moderate - lost-time injury
- severe - one potential fatality onsite
- catastrophic - multiple potential fatalities onsite, potentially reaching offsite

The likelihood level is on the matrix's left-hand side, in six categories:

- nominal - less than once in 100,000 years

- rare - between once in 10,000 years to once in 100,000 years
- unlikely - between once in 1,000 years to once in 10,000 years
- probable - between once in 100 years to once in 1,000 years
- almost certain - between once in 10 years to once in 100 years
- frequent - more than once in 10 years

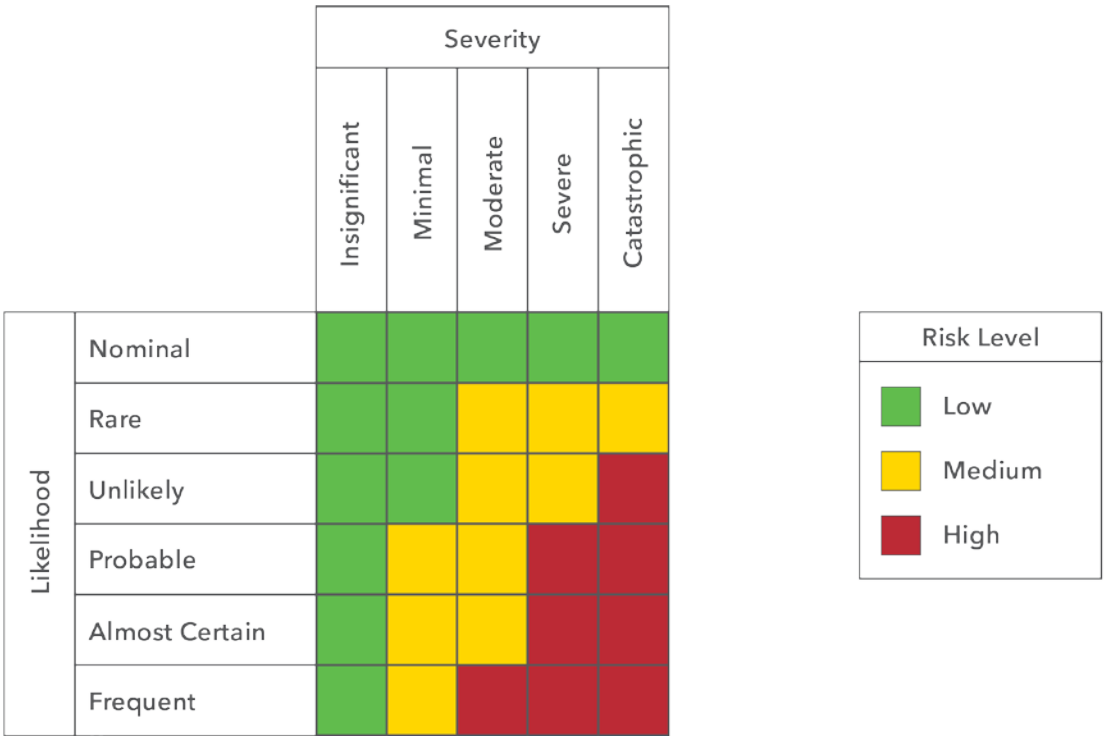

Figure 3-1 Generic risk matrix

Risk matrices illustrate the risk associated with various combinations of severity and likelihood levels. For example, if a scenario is assigned a severity of "severe" and a likelihood of "almost certain," the risk would be equivalent to "one potential fatality onsite between once in 10 years and once in 100 years.'

For an event to be considered "high risk," the combination of severity and likelihood must both be high enough to exceed an acceptable level of risk. The tolerance for an event decreases as the consequence of the event increases. Some regions have established individual risk criteria to which companies in those regions adhere so that their operations do not harm employees and the public. For example, the United Kingdom Health and Safety Executive (UK HSE) has established acceptable risk criteria of one fatality every 1,000 years for impact to employees and one fatality every 10,000 years for impact to the public [12]. The categorization by color in the generic risk matrix example shown in Figure 3-1 is based on the UK HSE tolerance level (based on the "tolerable" level), though many US-based entities, including utility companies, use similar plots.

3.3 Identifying and Managing Risk

When assessing the risk of Li-ion batteries as it affects employees and people in the community, one can use the approach shown in Figure 3-2.

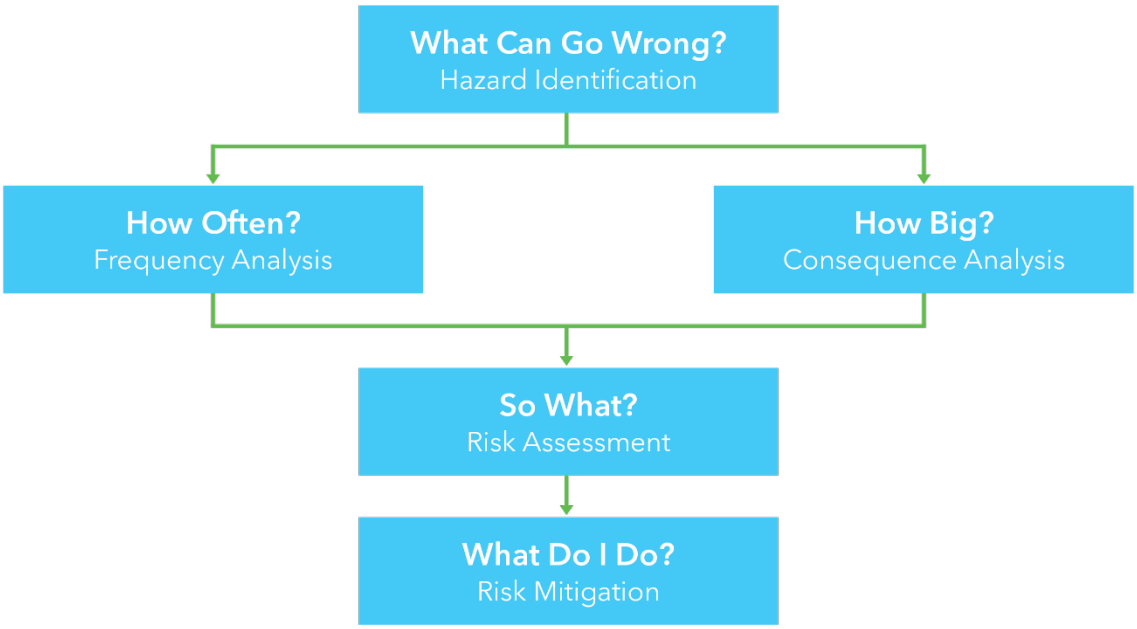

Figure 3-2 Risk Assessment methodology

3.3.1 Hazard Identification

A process hazards analysis (PHA), such as a hazard identification (HAZID) or Failure Mode Effect Analysis (FMEA) is meant to identify hazardous scenarios and specific failure modes of the batteries and equipment. In the PHA process, the consequence (severity) and the frequency (likelihood) are qualitatively assessed to determine the risks of the scenarios. Safeguards or barriers are also identified. DNV GL has used HAZIDs and FMEAs together to identify hazardous scenarios. Bowties, a form of visual hazard analysis addressed in detail in Section 4.6, have been used to further communicate the threats, consequences, and barriers or safeguards.

3.3.2 Consequence Analysis

Consequence analysis determines the severity level of scenarios associated with battery failures. The analysis can be conducted qualitatively, with a group of subject matter experts and experienced operations and maintenance personnel, or quantitatively, using a consequence modeling tool. Using types and quantities of toxic and flammable chemicals released during battery fires in laboratory settings, the analysis can be scaled up based on varying battery setups and modeled to determine the toxic endpoints (based on Emergency Response Planning Guidelines or National Institute for Occupational Safety and Health (NIOSH) recommended standards), lower flammability limit endpoints, thermal radiation exposure, and impact of overpressure from an explosion. The plume models can provide the PHA/LOPA teams with an estimate of the impact to people working within an ESS facility as well as those in the surrounding community.

3.3.3 Frequency Analysis

Frequency analysis assesses the likelihood or frequency of an event. It can be conducted qualitatively, based on the experience of a group of subject matter experts in a workshop, or quantitatively, using historical reliability data or incident databases to provide more exact failure rates. Since Li-ion battery failure rate data currently is not formally available, DNV GL utilizes reliability data from the nuclear, utility, oil and gas, and petrochemical industries, as these have similar applications that apply to ESS. The Offshore and Onshore Reliability Data project (OREDA), initiated by the Norwegian Petroleum Directorate (now the Petroleum Safety Authority) has collected reliability data for safety and operating equipment since 1981 [13]. The Institute of Electrical and Electronics Engineers, Inc. (IEEE) also has gathered reliability data on electrical equipment from reliability surveys and analyses for more than 35 years [14]. Since 1985, the Center for Chemical Process Safety (CCPS), a division of the American Institute of Chemical Engineers (AIChE), has compiled reliability data from various sources in the chemical process industry along with expert judgment to come up with orders of magnitude probabilities of failure for various types of scenarios. This information is used not only by the chemical processing industry, but also other industries and is available for reference in CCPS's *Guidelines for Initiating Events and Independent Protection Layers in Layers of Protection Analysis* (2015). All this information is useful in assessing the likelihood or frequency of the failure's initiating event, if associated with external equipment failures that induce battery failures. It also provides probabilities of failure on demand for electrical protections such as battery management systems, fuses, and circuit breakers.

3.3.4 Risk Assessment and Mitigation

The risk is assessed for the scenario first without safeguards or barriers and then *with* them. This is to help the PHA team identify that an adequate number of safeguards or barriers have been implemented to reduce the risk to an acceptable level, or to develop an action plan if more safeguards or barriers are needed. To reduce the overall risk (e.g., the likelihood of one fatality), the severity and/or likelihood must be reduced by installing safeguards or barriers.

Consider an event with the potential to cause one fatality in 100 years (shown as "A" in Figure 3-3), which is a "high" or "unacceptable risk". Four safeguards (with each one reducing the likelihood by once in 10 years) should be installed to reduce the likelihood of the event to less than once in 100,000 years ("B"), which would be "acceptable" or "low risk". In this example, the severity is not reduced. If another safeguard is installed to reduce the severity, the reduction might be by one level ("C"), meaning that there would be a lost-time injury once every 100,000 years.

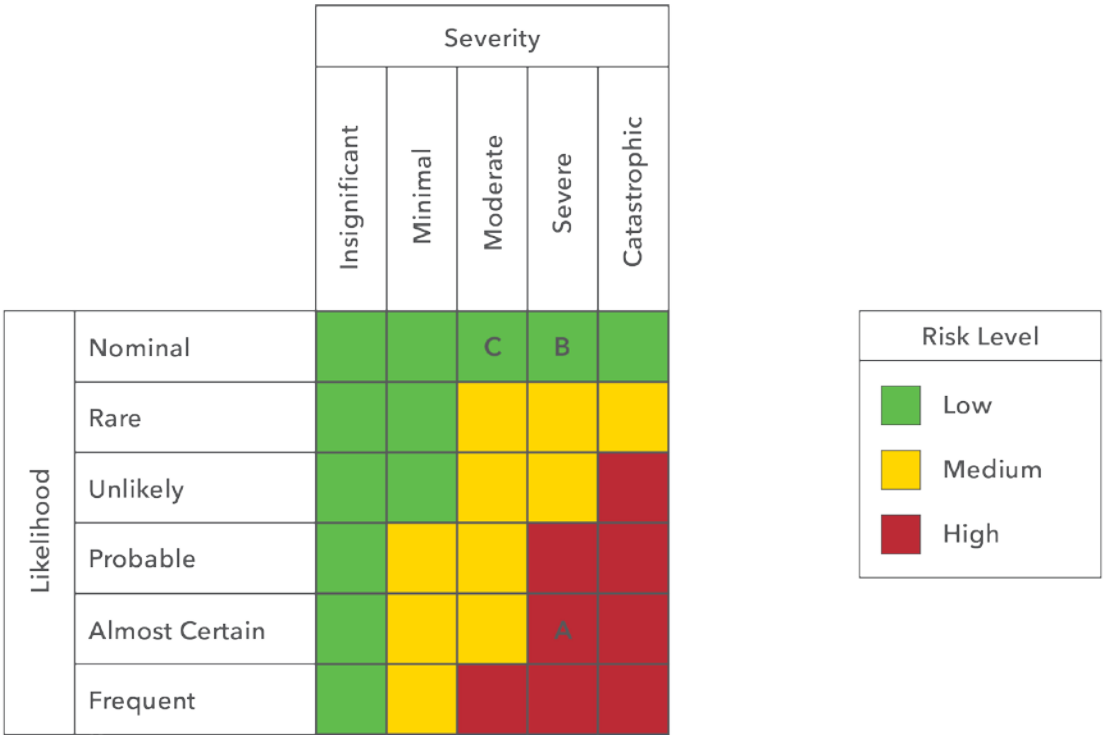

Figure 3-3 Sample risk matrix exercise

For a more quantitative assessment of hazardous scenarios that are at or above a certain severity level, one can use LOPA. LOPA can help determine if identified safeguards or barriers are sufficient independent protection layers (IPLs). For LOPA, the data used for initiating event frequencies (IEFs) and IPL probability of failure on demand (PFD), which is the probability that the safeguard or barrier will not activate or function when needed, are derived from failure rate data of equipment and instrumentation. IEFs and PFDs are based on averages of the failure rates from the different sources including recorded databases and expert judgment. The IEF and PFD are within an order of magnitude for level of accuracy. The scenarios are assigned likelihoods based on the equipment's IEF or human error rates for procedures or tasks involved. The LOPA risk analysis can incorporate other sets of factors into the IEFs:

- presence of people in the area (for example, ESS technicians may be at the facility less than 10% of their shift, nearby residents are assumed to be in the area 100% or potentially lower if the area is surrounded by other businesses that do not operate around the clock)
- Probability of ignition for flammable releases
- vulnerability of people in the surrounding community to injury or fatality based on ability to respond or escape before someone is unable to escape

For quantitative risk assessments:

- atmospheric data, e.g., based on the wind patterns can be included which shows where the frequency of impact is the highest for a fatality or injury

- presence of people in the surrounding community at different times of the day (for example, people are assumed to be at home 100% of the time in the evenings and 50% of the time in the day time)

The safeguards or barriers identified in the PHA are each further assigned a PFD. The LOPA team develops recommendations—proposing additional IPLs or strengthening existing ones—to address any gaps between the assessed risk level and the acceptable risk level. The LOPA methodology can be helpful, considering the lack of data available for battery failure scenarios leading to fires and the probabilities of failure on demand of associated safeguards or barriers.

4 LI-ION BATTERY FAILURE RISK AND MITIGATION

Li-ion battery fires can have very impactful consequences. However, a high-consequence level is often falsely interpreted to mean that the overall risk level is also high. To understand the full picture of risk, one must consider the likelihood or the frequency of the event occurring in addition to the associated consequences or severity. Standard safeguards and best practices used in Li-ion battery ESS have been included in risk assessments discussed in this paper, helping to both reduce the likelihood and severity of failure events.

4.1 Common Failure Scenarios of Li-ion batteries

There are three categories of common Li-ion battery failures: electrical, mechanical, and thermal [15]. The potential hazards associated with them are gas release, fire, and explosion. Battery fires share similar characteristics with plastics fires, including thermal radiation, convective gas flow impact, and release of toxic chemicals. Overpressure during flashover and backdraft events, due to fully involved battery fires' significant emission of flammable gases into often small, containerized spaces, also represent a potential consequence of Li-ion battery fires. As such, the potential for explosions in battery containers or buildings must be accounted for.

4.2 Consequence Analysis

DNV GL's battery test data provides a list of toxic and flammable chemicals released during battery fires in laboratory settings. This data is scaled up based on varying battery setups and modeled in DNV GL's Process Hazards Analysis Software Tool (Phast) to determine the toxic endpoints based on Emergency Response Planning Guidelines, lower flammability limit endpoints, thermal radiation exposure and impact of overpressure from an explosion. The plume models can provide estimates of the impact to people (potential number of fatalities or injuries) within an ESS as well as the surrounding community.

4.3 Frequency Analysis

When DNV GL has performed risk assessments, it has used the following of the most common Li-ion battery failures, shown in Table 4-1. Publications from CCPS [16], as well as IEEE [17], were used as references for assessing frequency of failures for various scenarios. For manufacturing defects, DNV GL assumes that the six-sigma or lean manufacturing principle is applied [18] .

Failure Category	Failure	Probability of Failure (per year)
Electrical Failure	Overcharge or undercharge based on catastrophic inverter failure	0.01 Inverter vendor literature along with DNV GL Experience
Mechanical Failure	Physical damage onsite due to heavy impact during maintenance (internal short circuit)	0.01 (Human error initiating events, CCPS)
	Physical damage due to impact during transport (internal short circuit)	0.01 (Human error initiating events, CCPS)
	Manufacturing defect (internal short circuit) that affects multiple cells	0.01 (Six Sigma assumption and DNV GL experience with battery designs)
Thermal Failure	Overheating (due to HVAC failure)	0.1 (Process control failure, CCPS)
	Overheating from electrical or mechanical failures referenced in this table (Table 4-1)	
Human Error	Human error during commissioning, installation, repair, or operations activities	0.01 (Human error initiating events, CCPS)

Table 4-1 Common Failure Mechanisms and Frequency of Failure

As shown in Table 4-1, the orders of magnitude of these failures is once in 10 years to once in 100 years, depending on the number of batteries and the electrical equipment (inverters or transformers) that could have an impact on battery performance. It should be noted that these are failure rates of the equipment and not fatality rates associated with the failures.

4.4 Risk Assessment

As with any fire or explosion, a potential consequence of Li-ion battery fires is the endangerment of life and property. In the risk analysis, these consequences are assessed based on their severity and likelihood. First, the severity of this consequence changes based on the quantity of cells in a system, as well as the system's proximity to people and property. Therefore, the size and location of the installation should be taken into consideration—an ESS unit with 10 racks in an isolated location will have a lower level consequence and a lower level risk than a building containing hundreds of racks in a more populated area. Though no known fatalities from Li-ion ESS fires or subsequent releases have occurred to date, property loss, as well as significant brand reputation destruction, have occurred. The potential for a fatality is present in the absence of safeguards and must be considered when assessing risk.

An example based on DNV GL's experience is illustrated in this paper with aspects of the LOPA methodology. The LOPA methodology is a simple way to estimate the order of magnitude risk associated with ESS. Consider a building containing several hundred racks that can store/discharge 40,000kWh power. DNV GL has performed consequence modeling of the various types of chemicals (including carbon monoxide,

hydrogen fluoride, hydrogen cyanide, benzene and others) released during battery fires and has estimated zones of impact for toxic chemicals, flammability and overpressure from explosions. For an ESS of this size, a potential worst-case scenario could mean a release of CO that could go ~30' downwind of the facility. This could potentially impact several members of the public (based on distance between the facility and neighboring businesses or homes and population density surrounding the ESS). Additional assumptions based on our experience include:

- Technician (worker) presence at one hour of their shift per day for 5 days out of the week during a 5-day work week would be approximately 3% of their time. Based on our experience, technicians are not at the facility full-time. The facilities are monitored from remote control rooms offsite. For LOPA, 10% would be used for presence.
- Public is assumed to be present 100% of the time (this is a conservative estimate as not everyone is home during the day)
- Probability of fatality is assumed to be 100% (unless additional information is known) within the radius of the plume where lower exposure levels of the chemicals is at a maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects (ERPG-3) per American Industrial Hygiene Association (Emergency Response Planning Guidelines).

When considering a potential fatality for the severity level in addition to the most conservative probability of failure or likelihood estimate (once in 10 years for an HVAC failure leading to failure, based on Table 4-1), *without* safeguards in place, this would equate to the following risk or likelihood of an incident leading to one fatality to both a technician and someone in the public *without* safeguards:

$$\boldsymbol{Initial\ likelihood\ of\ one\ fatality\ (technician)} = \boldsymbol{IEF\ \times\ Technician\ Presence\ Factor\ \times\ Probability\ of\ Fatality}$$

$$= \frac{\boldsymbol{One}}{\boldsymbol{10\ years}} \times \boldsymbol{0.1\ \times 1}$$

$$\boldsymbol{Initial\ Likelihood\ of\ one\ fatality\ per\ year\ (technician)} = \frac{\boldsymbol{0.01}}{\boldsymbol{year}}$$

$$\boldsymbol{Initial\ Likelihood\ of\ one\ fatality\ (public)} = \boldsymbol{IEF\ \times\ Societal\ Presence\ Factor\ \times\ Probability\ of\ Fatality}$$

$$= \frac{\boldsymbol{One}}{\boldsymbol{10\ years}} \times \boldsymbol{1\ \times 1}$$

$$\boldsymbol{Likelihood\ of\ one\ fatality\ per\ year\ (public)} = \frac{\boldsymbol{0.1}}{\boldsymbol{year}}$$

These are high-risk scenarios and they are unacceptable.

4.5 Safeguards and Best Practices

Safeguards incorporated into ESSs (both portable and permanent) reduce the likelihood and severity of events before a battery fire escalates. Table 4-2 lists some of the most commonly used ESS safeguards

along with their respective PFDs. Publications from CCPS [16] and IEEE [17] were used as references when determining PFD per year.

Safeguard Type	Safeguards	PFD (per year)	Source
Inherent design	UL 1973 Criteria Heating Ventilation and Air Conditioning (Redundant Units)	0.1 (CCPS) (Once in 10 years)	CCPS
Basic Controls	Active Cooling/Thermal Management Controls HVAC with failure alarm	0.1 (CCPS) (Once in 10 years)	CCPS
Safety Systems	Battery Management Systems which can isolate battery racks Master Controllers which can isolate battery systems and medium voltage equipment external to the ESS	0.1 – 0.01 (Once in 10 years to once in 100 years) (depending on Safety Integrity Level rating or reliability) (CCPS)	CCPS
Electrical protection	Fuses and Circuit Breakers	0.1 (IEEE) (Once in 10 years)	IEEE
Fire Suppression	Active fire suppression Emergency HVAC	0.1 (CCPS) (Once in 10 years)	CCPS
Procedures	Remote monitoring 24/7 and isolation	0.1 (CCPS) (Once in 10 years)	CCPS

Table 4-2 Common Safeguards and Probability of Failure on Demand

In the previous scenario, the following safeguards can be implemented:

- Battery Management Systems (PFD_1) - 0.1 (assume lower PFD)
- Heating Ventilation and Air Conditioning (Redundant Units) (PFD_2) - 0.1
- HVAC failure alarm with procedure for control room personnel to address (PFD_3) - 0.1
- Active fire suppression that meets NFPA 2001 and 17 and is part of the maintenance and inspection program (PFD_4) - 0.1

The likelihood of failure leading to a fatality of technician or someone in the neighboring area (which accounts for all factors mentioned in the introduction of Section 4.1 and the PFDs of safeguards in place) could occur once in 100,000 years (1×10^{-5} per year) to once in 1,000,000 years (1×10^{-6} per year). Considering the same example used in Section 4.4., the final likelihood of failure leading to a fatality of a technician or someone in the surrounding community are illustrated in the calculations below:

$$\boldsymbol{Final\ likelihood\ of\ one\ fatality\ (technician) = \frac{0.01}{year} \times (PFD_1 \times PFD_2 \times PFD_3 \times PFD_4)}$$

$$\boldsymbol{Final\ likelihood\ of\ one\ fatality\ (technician) = \frac{0.01}{year} \times (0.1 \times 0.1 \times 0.1 \times 0.1)}$$

$$\boldsymbol{Final\ likelihood\ of\ one\ fatality\ (technician) = \frac{1 \times 10^{-6}}{year}}$$

Societal risk is as follows:

$$\boldsymbol{Final\ likelihood\ of\ one\ fatality\ (public) = \frac{0.1}{year} \times (PFD_1 \times PFD_2 \times PFD_3 \times PFD_4)}$$

$$\boldsymbol{Final\ likelihood\ of\ one\ fatality\ (public) = \frac{0.1}{year} \times (0.1 \times 0.1 \times 0.1 \times 0.1)}$$

$$\boldsymbol{Final\ likelihood\ of\ one\ fatality\ (technician) = \frac{1 \times 10^{-5}}{year}}$$

Table 4-3 shows the comparison of likelihood of the example scenario with UK HSE Tolerable Risk Criteria. Impact to workers and society are lower than UK HSE Tolerable Risk Criteria.

Population	Example Scenario Likelihood	UK HSE Criteria (Tolerable Risk Criteria)	Comparison
Individual (worker)	$\frac{1 \times 10^{-6}}{year}$	$\frac{1 \times 10^{-3}}{year}$	Individual (worker) risk is *lower* than UK HSE tolerable risk criteria
Society	$\frac{1 \times 10^{-5}}{year}$	$\frac{1 \times 10^{-4}}{year}$	Societal risk is *lower* than UK HSE tolerable risk criteria

Table 4-3 Comparison of Example Scenario Likelihood of Fatality with UK HSE Tolerable Risk Criteria

Table 4-4 shows the comparison of the likelihood of the example scenario with UK HSE Broadly Acceptable Risk Criteria. Impact to workers is comparable to UK HSE Broadly Acceptable Risk Criteria, while impact to society is higher. This is also based on the assumption that people are always present in the surrounding areas, which is a conservative assumption.

Population	Example Scenario Likelihood	UK HSE Criteria (Broadly Acceptable Risk Criteria)	Comparison
Individual (worker)	$\frac{1 \times 10^{-6}}{year}$	$\frac{1 \times 10^{-6}}{year}$	Individual (worker) risk is *lower* than UK HSE broadly acceptable risk criteria
Society	$\frac{1 \times 10^{-5}}{year}$		Societal risk is *higher* than UK HSE broadly acceptable risk criteria

Table 4-4 Comparison of Example Scenario Likelihood of Fatality with UK HSE Broadly Acceptable Risk Criteria

While the risks to society are higher in this case than broadly acceptable risk criteria, these numbers should be further compared to risks with activities that people live with daily. When comparing the risk of ESS failures within the context of events that society is already comfortable with, the risks are low, as is illustrated in Figure 4-1. The figure shows the likelihood of fatality when engaging in these activities. Working at or living near an ESS is less risky than driving a car 10 hours per week, smoking, or working in other industries such as construction, mining or agriculture [2].

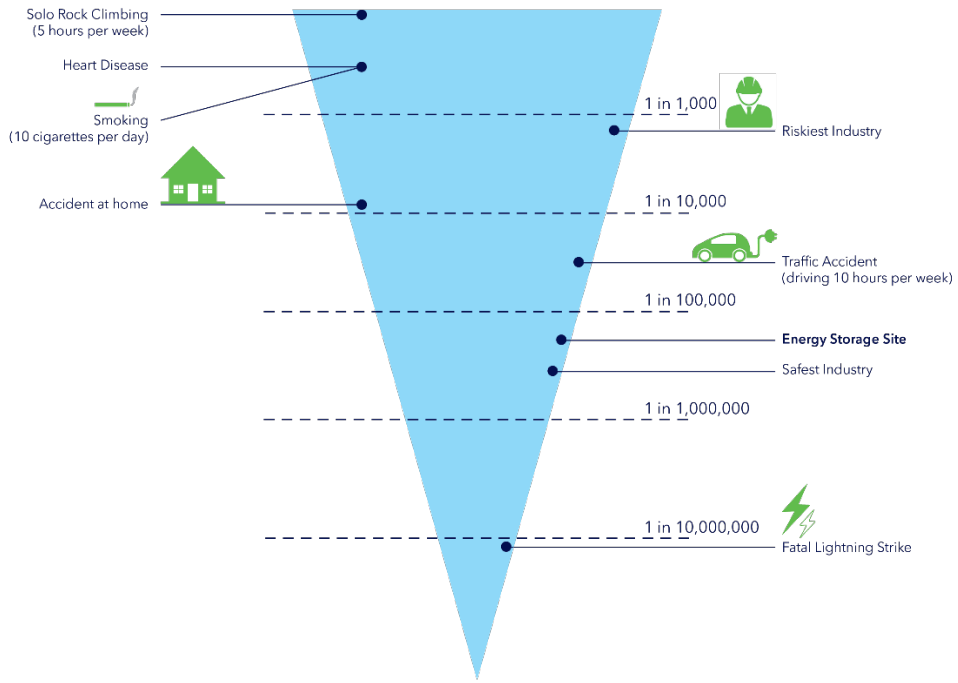

Figure 4-1 Framework of Risk Perspective

It should also be noted that it is simplistic to compare the likelihood of fatality in one scenario with the risk criteria. Normally the final likelihood of all scenarios at a facility that potentially lead to a fatality are added together before comparison with risk criteria. This is more accurately accomplished with a quantitative risk model and an F-N Curve (Frequency of incidents leading to fatalities vs. number of people impacted). For this specific example, the mitigated likelihoods for all identified scenarios that could potentially lead to a fatality were added together.

4.6 Layers of Protection

While Table 4-2 broadly covers the barriers that minimize these risks and includes expected failure rates, it is more often helpful to visualize the barriers as they exist along the failure pathway, to see the order in which they stand and their strength in mitigating a failure. DNV GL uses the bowtie analysis, a technique used in the maritime, oil and gas, and energy sectors to communicate risk and consequences. This approach shows the threat pathways on the left side of a potential event, with each barrier in place to mitigate the threat before it escalates to critical incident. In Figure 4-2, the right side of the chart examines the barriers in place to manage the consequences if the event has occurred.

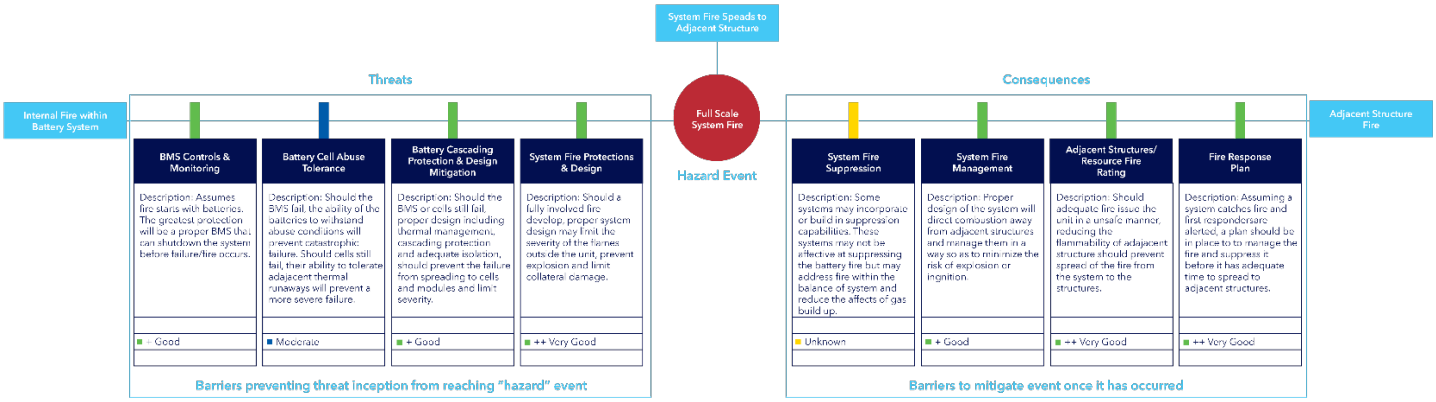

Figure 4-2: Bowtie Overview

First, details of the left side of the bow tie analysis is shown in Figure 4-3, demonstrating the individual barriers in place to mitigate these failure pathways.

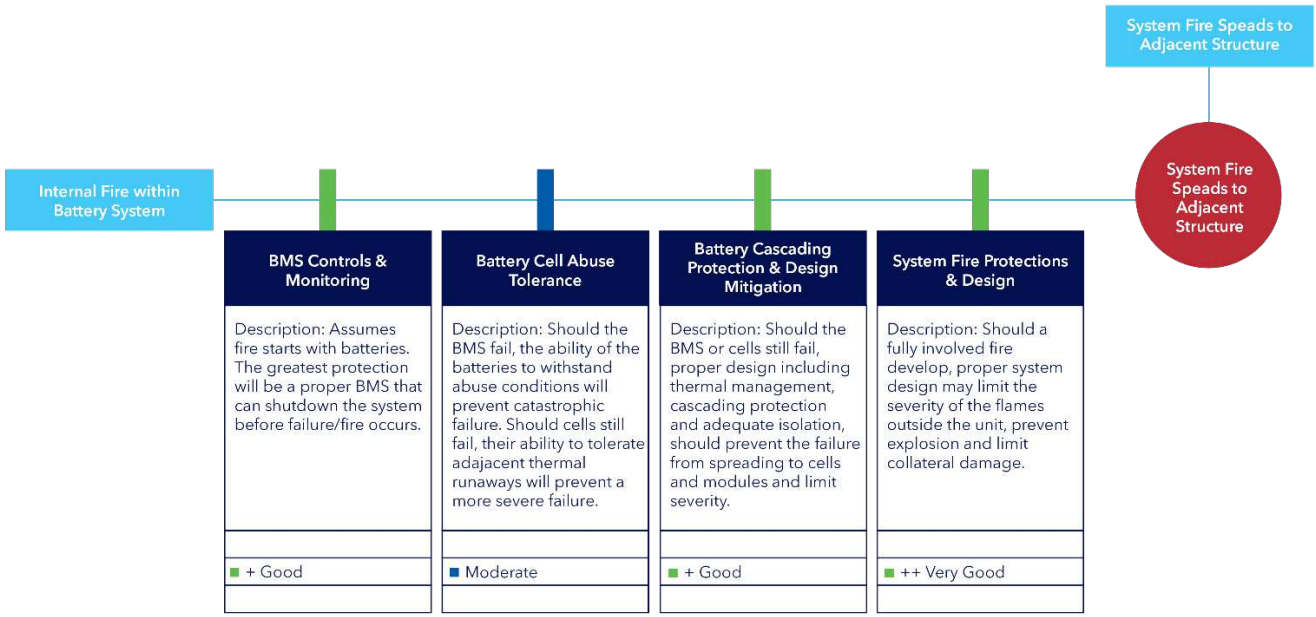

Figure 4-3: Simplified Threat Pathway

Figure 4-3 shows a simplified view of this analysis. Even simplified, multiple strong barriers may exist that slow the spread of an internal failure through a system. In a detailed analysis, these failure pathways are even more specific and the barriers may be greater. An average bowtie model covers 20 or more failure modes on the threat side, of which three or more—usually many more—barriers form the realistic layers of protection. These barriers include thermal management of the systems, active monitoring of cell and ambient conditions by the battery management system (BMS), ability of the BMS, when failure is detected, to properly isolate the system, resilience of the cells to electrical and thermal abuse, design considerations within the system to limit or manage propagation among cells, modules, and racks, and fire protection schemes within the system or container. Thus, a barrier with a 10% rate of failure (once in 10 years) is one

of many that must fail sequentially for an event to become truly catastrophic. This requirement for sequential failure in many cases is how a non-negligible event or failure rate results in probability of failure several orders of magnitude lower. Even two or three barriers with 1% -10% failure rates (one failure in 100 years to one failure in 10 years) can quickly result in a once-in-10,000-year event or once-in-100,000-year event.

Once a critical event is reached, such as full involvement of more than one battery rack, multiple barriers exist on the bowtie's consequence side (as shown in Figure 4-4) to help control and mitigate the failure and potential consumption of the entire system. In many cases, these systems will no longer stop the fire that has occurred but will work to minimize its spread and prevent explosion, thus affecting the severity of the risk. These include the ability of the system to isolate the fire further, gas management (such as ventilation and exhaust), clean agents or initial fire suppression systems, water-based fire suppression systems, and response of the fire service or local first responders. Such barriers help prevent a single or even a multi-cell event from spreading to an unmanageable level.

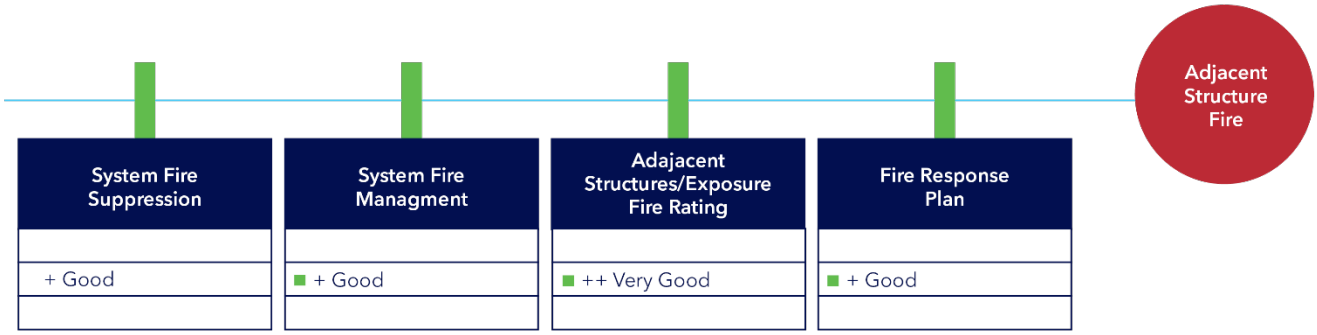

Figure 4-4: Simplified Consequence Pathway

Each consequence pathway within the bowtie has its own risk matrix. In this case, four barriers exist under the event block and show the customizable results. Because of the nuanced detail at this level, the risk matrices are broken down into categories, with individual risk matrices for "damage to the system itself," "damage to the environment and risk to property," "risk to life," and "risk to reputation and industry." The example case shown above was an intentionally extreme case for a hypothetical system placed in a high-risk area near a neighborhood and, as a result, the potential risk from each evaluation, except in one case, was simply unacceptable. This is not the normal case though and exists only to show the multiple facets at play within the model.

5 CONCLUSIONS

Li-ion batteries are becoming increasingly more attractive given their advantages relating to energy density, falling equipment costs, and applications which are supportive of a grid increasingly supplied by intermittent renewable resources. As the number of ESS facilities increases, the need to understand and assess the risks associated with those facilities increases—especially in light of previous negative incidents that have made the headlines. While there is no database of failure rate data available for Li-ion batteries and their associated barriers, it is possible to estimate the risks of ESS based on data for analogous systems. There is also data available on process control loops and systems failures from other industries to estimate what the probability of failure upon demand might be for a battery management system.

The findings of DNV GL's assessments showed that the initial event frequencies (potentially leading to fires) could occur between once in 10 years and once in 100 years *without* safeguards in place and *without* considering the additional on-site mitigating factors. Assuming that the worst credible severity is a fatality from a fire, the level of severity and likelihood would place the scenarios in the "high risk" area of a risk matrix (illustrated as "1" in Figure 5-1). However, in most of the scenarios, multiple safeguards are in place. Event trees and quantitative risk assessments have shown that the final probability of failure or likelihood of the event (which accounts for all safeguards) is between once in 100,000 years (1×10^{-5} per year) to once in 1,000,000 years (1×10^{-6} per year). When considering the higher probability of failure (once in 100,000 years) and the same severity level, this would place the events in the low-risk zone of a risk matrix (illustrated as "2" in Figure 5-1).

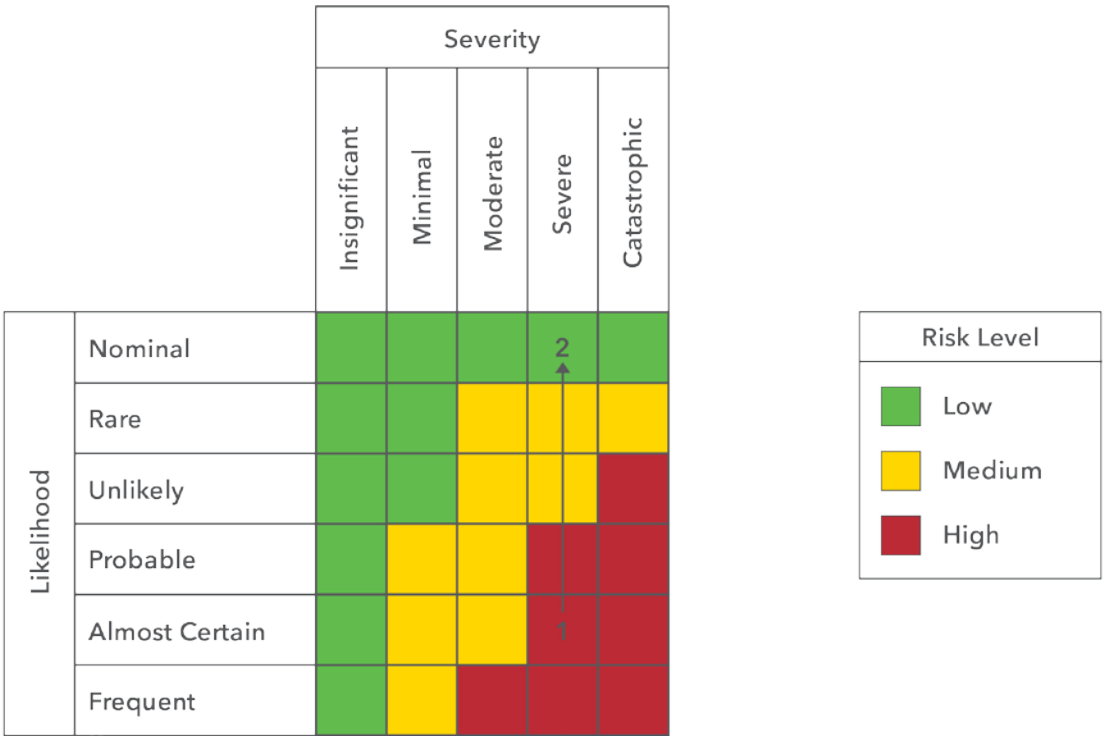

Figure 5-1 Comparison of Risk of ESS *Without* safeguards in Place (1) and *With* Safeguards in Place (2)

To ensure this assessment's accuracy, ESS designers, manufacturers, and installers must move forward transparently to verify that they have developed safe systems with multiple barriers to failure, including

quality assurance, testing, training (both for operators and AHJs), routine operations and maintenance, and sharing of lessons learned.

As requirements are standardized, codified, and adopted, risks posed by this equipment will likely continue to reduce. In the interim, this paper strives to serve to support internalization of the relatively low risk levels associated with ESS.

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