Overview of Potential Hazards in Electric Aircraft Charging Infrastructure

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National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5R00-83429
October 2023

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Suggested Citation
Rane, Jayaraj, Bharatkumar Solanki, Scott Cary, Prateek Joshi, and Subhankar Ganguly. 2023. *Overview of Potential Hazards in Electric Aircraft Charging Infrastructure*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5R00-83429. https://www.nrel.gov/docs/fy24osti/83429.pdf.

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Cover Image from Getty #171301443

Acknowledgments

The authors acknowledge the sponsorship of the Federal Aviation Administration (FAA) Airport Safety R&D Section (ANG-E26). We also appreciate the leadership of the FAA's Wesley Major in providing focus to this work and the review comments from FAA team members including Jonathan Torres, Jeremy Casey, and Darian Byrd were key to providing a quality outcome relevant to the FAA mission.

List of Acronyms

BESS	battery energy storage system
CCS	Combined Charging Systems
EPRI	Electric Power Research Institute
ESS	energy storage system
EV	electric vehicle
EVSE	electric vehicle supply equipment
eVTOL	electric vertical takeoff and landing
FAA	Federal Aviation Administration
Li-ion	lithium-ion
MCS	Megawatt Charging System
NFPA	National Fire Protection Association
NHTSA	National Highway Traffic Safety Administration
NYSERDA	New York State Energy Research and Development Authority
SLOSH	Sea, Lake, and Overland Surges from Hurricanes

Executive Summary

As the Federal Aviation Administration (FAA) prepares for the integration of the first generation of advanced electric aircraft, it must also prepare for significant changes to the infrastructure and related risks and hazards. Although some existing hazards related to power system configurations are already being considered, the electrification process will add a large amount of electrical load to the existing system, and infrastructure upgrades to support this change must also be considered. With these changes, it is important that site managers and operators are prepared to mitigate any potential hazards. This report aims to help the FAA identify these potential hazards and relevant standards that can help with training and mitigation planning.

The objective of this report is to document and help familiarize FAA and airport authorities with the potential hazards associated with the deployment of electric aircraft and the associated charging infrastructure. The list and examples of these hazards are nonexhaustive, and multiple hazards can occur simultaneously. This report discusses natural, human, and technological causes that can lead to fire (thermal), physical, or chemical hazards. Applicable standards and guidelines associated with electric vehicle supply equipment (EVSE) infrastructure are available for reference in the appendix. These sources, which address diverse geographic location and climate considerations, can help operators in site selection for EVSE, mitigation planning, deployment considerations, and training of staff to handle these situations.

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1 Introduction

There is increasing interest and technological development in the field of electric aviation and advanced air mobility. Advanced air mobility is defined as "an air transportation system that transports individuals and property between points in the United States using aircraft, such as remotely piloted, autonomous, or vertical takeoff and landing aircraft, including those powered by electric or hybrid driven propulsion, in both controlled and uncontrolled airspace" (U.S. Congress 2022). This has given rise to research and considerations for the deployment of electric charging infrastructure for these advanced air mobility assets. Initial evaluations indicate that the charging levels needed for uninterrupted and reliable operations will require expansion of the existing electric distribution infrastructure to provide charging capability as well as the potential deployment of large-scale battery energy storage systems (BESS) to optimize energy and infrastructure costs (Schwab et al. 2021). Aircraft-related energy storage and associated charging systems will introduce electricity as another source of energy in the existing, primarily petroleum-based fueling environment and could introduce potential risks and hazards. The new electric infrastructure will bring higher electric charge and power into the existing system, impacting the level of voltage on the local distribution system. The change in magnitude will depend on the scale of deployment and will differ from one site to another. This increased power will also increase the severity of the potential electric hazards, such as short-circuiting, chemical fire, and the release of large amounts of toxic gases. If rescue teams have limited experience with electric aircraft and their related hazards, a potential fire can take more effort and resources to extinguish, posing a threat to people, property, and the environment (MS Amlin Ltd. 2023).

According to a report on sustainable aviation fuel from the U.S. Department of Energy, jet fuel has an energy density of 43 MJ/kg, whereas the batteries used in electric vehicles (EVs) currently have an energy density of approximately 0.7 MJ/kg (Holladay, Abdullah, and Heyne 2020), making jet fuel almost 62 times more energy dense than batteries. Although the energy density of batteries is expected to increase, this discrepancy means that more energy will need to be delivered via the electrical system to power electric aircraft compared to the legacy petroleum-based fueling environment. The existing infrastructure of airports might not be equipped to deal with this significant increase in electricity demand. One study, from the National Renewable Energy Laboratory, based on preliminary modeling of electric vertical takeoff and landing (eVTOL) charging needs for one site indicates a tenfold increase in electricity demand above current levels (Solanki 2023).

Previous research and analysis on charging infrastructure hazards have primarily focused on ground vehicles because electric passenger cars have been deployed more widely than other forms of electric mobility. For instance, Wang et al. (2019) focus on hazards at a broader level and discuss the risks of failure for the protection systems of charging equipment, the threats of cyberattacks in smart charging arrangements, and system stability challenges when vehicle charging is not aligned with electricity generation from renewables. Hodge et al. (2019) focus on the topic of EV cybersecurity, and Markel and Sanghvi (2022) build on this by specifically assessing cybersecurity threats and mitigation approaches for the electric aviation industry. Karatzas et al. (2021) discuss hazard analysis methods such as system theoretic process analysis for decentralized EV charging, considering subsystems and processes associated with charge management, while Kivela et al. (2021) present safety requirements for charging stations and system design, including safety-related hardware and software to meet safety requirements. More studies and reports have started to cover advanced air mobility and electric aircraft, but they focus on aspects other than charging infrastructure. For example, Borges, Cardoso, and Castilho (2022) study eVTOL aircraft safety specifically for landing in urban centers, while Wasson et al. (2022) outline a broader hazard assessment of eVTOL aircraft to introduce industry stakeholders to the safety and regulatory approval process. This body of literature is relevant to but does not fully cover hazards associated with electric aircraft charging infrastructure.

The objectives of this report are to identify select potential hazards to be evaluated and potentially mitigated as new energy resources and electric charging infrastructure enter the aviation space and to present the list of existing related codes/standards associated with the charging infrastructure. The summary information provided here intends to support site managers and operators as part of a broader effort to develop an effective hazard and safety management plan for electric aviation.

1.1 Scope

This report focuses on hazards associated with aircraft charging infrastructure that can be deployed at airports, heliports, or vertiports. The term vertiport is defined by the Federal Aviation Administration (FAA) as "an area of land, or a structure, used or intended to be used, for electric, hydrogen, and hybrid VTOL aircraft landings and takeoffs and includes associated buildings and facilities" (FAA 2022a). The infrastructure includes the electric distribution system dedicated to charging, such as the distribution-level transformer, conductors, on-site BESS, protection system, and charging cables and connectors. The typically utility-owned and utility-operated transmission- and distribution-level electrical systems as well as the onboard aircraft electrical system and BESS are beyond the scope for this document. Yet it is important to highlight a finding for fire hazard occurrence on different vehicles from AutoinsuranceEZ based on compiled sales and accident data from the U.S. Bureau of Transportation Statistics and the National Transportation Safety Board: Hybrid vehicles had the most fires, 3,475 per 100,000 sales; whereas for gas-powered vehicles, there were 1,529.9 fires per 100,000 sales; and for EVs, there were only 25.1 fires per 100,000 sales (Bodine 2022). Interactions with potentially mixed-fuel environments require further research, depending on potential use cases. Other fueling infrastructure is not considered in this document.

1.2 Electric Charging Infrastructure for Aircraft

Certain components of electric aircraft charging infrastructure or electric vehicle supply equipment (EVSE) are expected to be similar to the infrastructure that exists and is expanding for electric cars. This includes the connection from the electric utility to the site, the on-site electrical protection system (e.g., relays, circuit breakers, fuses), and the on-site electrical distribution system (e.g., conductors, busbars). Components of electric aircraft charging infrastructure that might significantly differ from electric car charging infrastructure include the charging station itself, supplementary ESS, and the connector between the station and the vehicle. This is due to the different power capacities required. The maximum amount of power provided by electric car charging stations is currently around 300–350 kW (Phillips 2022); however, the larger battery capacities for electric aircraft might require megawatt-scale charging to meet recharging time requirements (Schwab et al. 2021). Thus, BESS could play a significant role in aircraft charging infrastructure.

Figure 1 outlines a typical electric aircraft charging system with its various components. Note that this typical configuration can vary from one site to another.

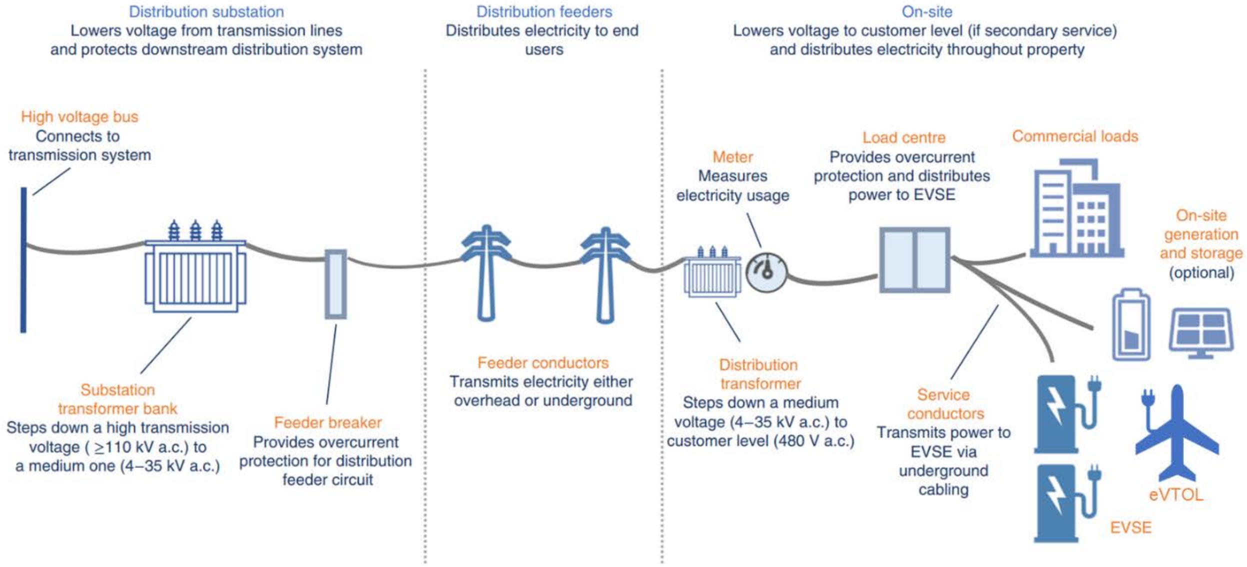

Figure 1. Typical Electric Distribution System with Electric Aircraft Charging

Image modified from Borlaug et al. (2021).

A variety of charging modes and standards can be considered for electric aircraft. The Combined Charging System (CCS) is an EV charging standard common throughout the world that can provide power up to 350 kW; these standard plugs are being incorporated into some smaller electric aircraft, such as those developed by Beta Technologies (Carey 2022). The Megawatt Charging System (MCS) standard has been more recently developed by an association of global industry stakeholders and is designed to support charging at greater than 1 MW for heavy-duty trucks, buses, aircraft, and other large vehicles (CharIN 2022). ABB and Lilium are partnering to deploy this standard in charging infrastructure to support Lilium's electric jet fleet (Perrins and Bell 2021). Mobile charging stations, such as one built by technology manufacturer Eaton and aircraft manufacturer Pipistrel, are also an option for portable charging that can suit the spatial constraints and needs of airports (Eaton 2022). All these electric charging technologies will need to exist within an aircraft refueling ecosystem that could involve legacy petroleum-based fuel, hydrogen, and different forms of sustainable aviation fuel. This mixed-fuel environment has the potential to introduce additional hazards.

2 Potential Hazards and Causes

Hazards and their causes are classified as natural hazards, human hazards, or technological hazards. Because most scenarios overlap and lead to some form of technological failure, the natural and human categories describe the scenarios leading to the hazards, and the technological category further defines the detailed technological impact and hazards. This list is nonexhaustive and is developed based on related industry knowledge and current operational considerations for typical general aviation operations.

2.1 Natural Hazards

Natural calamities resulting from severe climate and rapidly changing weather, as well as seismic activities, can pose operational challenges for an electrical system. These vary from one location to another, depending on the topography of the region and the geographic location. Natural events—including storms, lightning strikes, earthquakes, solar storms, and floods—can cause physical damage to the electric distribution system. In the case of high-voltage, high-power (megawatt) electric aircraft charging, specific hazards can cause damage to the conductors from the distribution transformer to the charging station and from the charging station to the aircraft, which can result in electrical hazards or physical damage to the BESS. This can lead to chemical and fire hazards or even an explosion risk in some cases (Jeevarajan et al. 2022). Chapter 4 of the National Fire Protection Association (NFPA) Standard 855 provides general guidelines for emergency planning and training as well as hazard mitigation analysis of ESS (NFPA 2023). Also, Annex G of NFPA 855 provides guidelines for fire suppression and safety for lithium-ion (Li-ion)-based BESS.

In addition to general environmental conditions relevant to all regions, specific climatic risks should be considered during siting. These include the impacts of hurricane-strength storms, floods, corrosion for coastal regions, northern climates with significant snowfall and cold temperatures, areas with high seismic activity, and sites with significant tornado risk.

2.1.1 Coastal Regions

Coastal regions have a higher likelihood of hurricane-strength storms, floods, impacts of corrosion on the equipment, and impacts of saltwater intrusion due to increases in sea level. Depending on the location of the utility equipment and EVSE components, flooding can cause damage to the equipment and potentially lead to electrical hazards (i.e., electric shock), chemical leakage, etc. Appropriate siting of assets and component protection (i.e., fuse, circuit breakers), including appropriate considerations for elevation, can be applied to minimize the impact of flooding. The design flood elevation should be considered to ensure that EVSE are properly elevated (ETEC 2010). The National Highway Traffic Safety Administration, in collaboration with the U.S. Fire Administration, has developed some guidelines for first responders (NHTSA 2014a) and second responders (NHTSA 2014b) when considering EVs; these can also be referred to for eVTOL. The location of the groundwater table should also be considered with respect to conductor and vault placement. The component protection systems should be designed to consider the ability to isolate any abnormal conditions to protect the operators and the rest of the systems (Wang et al. 2019). It is also important to understand the impacts of corrosion on typical equipment, which should be a consideration when specifying and locating components in high-saline environments. Applying precautions could also minimize the risks; these include inspecting charging cables and connectors before charging, keeping them clean in dry and warm places, inspecting the ground fault circuit interrupters, and avoiding charging during harsh weather conditions (Hyperion Chargers 2023). As an illustrative example of information that could be important for consideration in the siting of EVSE, Figure 2 depicts the coastal flood risk for Cape May County Airport in New Jersey using a Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model for a Category 3 storm.

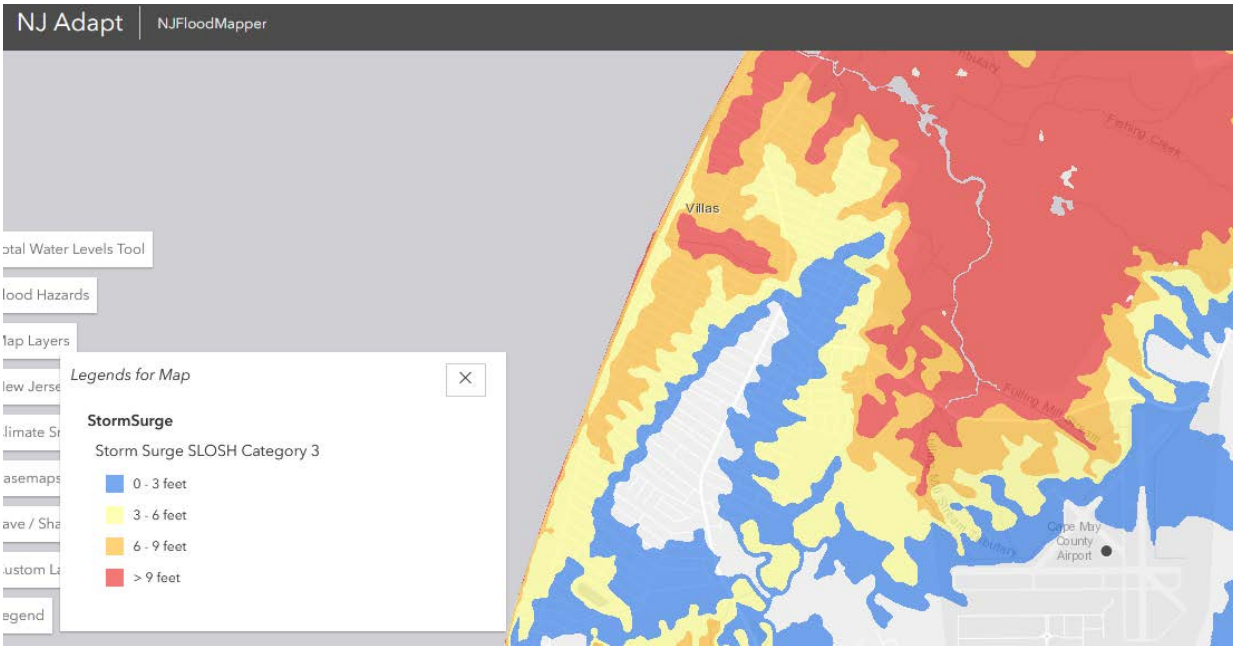

Figure 2. Illustrative Example of Coastal Flood Risk for Cape May County Airport in New Jersey

Source: NJFloodMapper

2.1.2 Cold Climates

It is essential to protect the utility equipment, EVSE components, and distributed energy resources from severe cold weather. Operating this critical equipment outside its manufacturer's recommended operating temperature range can lead to poor performance, voiding the warranty, and potentially reducing its operating life. For example, a battery used in BESS, depending on its chemistry, might not be able to discharge at the desired rate in colder temperatures.

Snow accumulation is a frequent phenomenon in cold climates; thus, precaution must also be taken in efforts to clear accumulated snow. While operating heavy equipment around EVSE components, safe distance must be maintained to avoid collision with the equipment. It is possible that heavy snow-removal equipment can slip during operation and damage the equipment and cause potential hazards of electrolyte leakage, short circuits, or electric shock. The use of deicing chemicals that might contain compounds such as MgCl can damage and corrode utility equipment and distributed energy resources. If any of the chemical-containing flammable compounds in deicing fluids come into contact with a short-circuited electric conductor or cable, it can lead to the potential risk of fire. In cold climates, frost can be an issue because the charging cables can freeze, making them brittle and causing damage. Equipping charging stations with appropriate defrosting systems can keep cables warm (Energy5 2023b).

For such a location, considerations need to be made for locating the utility equipment and EVSE components, proper drainage, and siting of in-ground systems to maintain access during freezing conditions, in addition to considering the potential impacts of snow and ice removal during recharging operations, among other localized concerns. Other solutions can also be considered, including weatherproofing the EVSE by installing weather-resistant enclosures and/or protective covers.

2.1.3 Tornados and Hurricanes

Another unique consideration is areas that have very specific and pointed threats, such as those subject to high tornadic activity. Tornados and hurricanes can cause significant physical damage to infrastructure, which can take a long time to repair and restore. In such scenarios, the risk of electrical hazards, such as short circuits and electric shock, is very high due to damaged or disconnected live distribution lines, physical damage to the EVSE components, and thermal runaway caused by damage to the BESS. These assets should be secured in robust structures and be electrically disconnected from the system during tornados or hurricanes to minimize potential damage. It is also important to consider a lightening protection system to prevent damage from lightning strikes (Energy5 2023b).

2.1.4 Seismic Activity

Vertiports close to known seismic zones also have a high threat of physical damage to the infrastructure. In the case of seismic activity, such as earthquakes or volcanic eruptions, equipment damage can vary depending on the severity and proximity of the activity. These incidents can cause severe physical damage to the infrastructure associated with the distribution system, EVSE components, and distributed energy resources. Similarly, in the case of tsunamis, there is a risk of flash floods and related hazards, as discussed further in Section 2.1.1. The physical damage caused to the infrastructure canlead to multiple electrical hazards, as discussed further in Section 2.3. The risks associated with these hazards vary, and operators should be prepared for more than one scenario of potential hazards in these cases. It is important to perform a detailed risk assessment considering historic accounts of these potential hazards and to sufficiently prepare to mitigate these risks in case such hazards strike.

2.2 Human Hazards

Human hazards can be unintentional (errors or accidents) or intentional attacks. An intentional human hazard is any activity aimed at harming or disrupting a system, causing damage to its operation or human life. In both intentional and unintentional human hazards, the system-level risks can be higher without proper mitigation planning, whether by minimizing impacts on the system or by decreasing the potential harm to personnel.

To minimize human errors, proper training should be provided for employees, periodically recurring with updates based on the changing technology and features of the system.

Following is an example of human error: Distribution lines for charging infrastructure might be located close to the route of heavy machinery for snow removal. Due to low visibility during a snowstorm, the equipment could damage the conductors and cause an unintentional short circuit or damage the ESS, transformers, charging equipment, or power electronics equipment (inverters) installed aboveground. In these cases, there is a risk of electrocution or arc flash from the short-circuited conductors. There is also a risk of chemical leakage and thermal runaway hazards for ESS, which can lead to catastrophic fires and even explosions. In case of severe weather conditions that affect visibility, measures should be taken to address these situations. Suggestions include marking the ground to guide the operator, using reflective strips in case of low light, or installing lights on top of the equipment in regions prone to dense fog and storms. In the stage of planning and siting, the operation and route of heavy machinery should be considered and, when possible, equipment should be sited away from these routes of operation.

Similarly, using equipment or conductors outside of the manufacturer's recommended range or specifications can introduce risks of electrical failure or damage the system. An example is the overcharging or undercharging of the ESS or overloading of the charging ports. The EVSE components and distributed energy resources are generally monitored and controlled by sophisticated energy management systems. During the manual operation of such systems, any wrong operation can impact the charging of the aircraft and ultimately the consumption from the grid. This can lead to insufficient charging of the aircraft, overcharging/undercharging of the BESS, or the operation of critical equipment beyond its operational range. Because EVs are quieter, without the noise of the engine, there is also the potential risk of collisions with other vehicles or users, especially those who have impaired sight and/or hearing (MS Amlin Ltd. 2023).

Human hazards can also be intentional, as in the case of a physical attack or a cyberattack targeting the system. Additional examples of physical intentional human hazards are vandalism and theft. To avoid these hazards, it is essential that the equipment be stored in a secure location and accessible only to qualified individuals. Proper, secure siting helps enable the necessary considerations around accessibility to minimize the impact and occurrence of such hazards (Pham 2023).

Cybersecurity is another important consideration with regard to charging infrastructure for electric aircraft. Hodge et al. (2019) discuss security concerns, mitigation techniques, and considerations with respect to some cybersecurity threats to EVs, and Markel and Sanghvi (2022) discuss the considerations for electric charging infrastructure. Cybersecurity attacks can be physically or remotely triggered with an intention to upload malicious software onto the infrastructure or the electric aircraft, and they can cause failure of operation, leading to physical damage, financial losses, and/or theft of valuable data. Similarly, the aircraft itself can be targeted by a cybersecurity attack on the infrastructure's control system or the connectors at the charging station. Note that Sanghvi (2022) provides detailed cybersecurity analysis for such infrastructure.

2.3 Technological Hazards

Electric charging infrastructure can be divided into three components for ease of understanding and discussing the associated technological hazards: the EVSE distribution system, the EVSE components, and the BESS.

2.3.1 Electric Vehicle Supply Equipment Distribution System

The EVSE distribution system includes components such as the distribution transformer, electrical distribution system, conductors, and connectors at the charging stations. All these components pose potential electric hazards, such as arcing, sparking, short-circuiting, or overloading of the electric components, such as conductors or transformers. Natural hazards as well as hazards caused by humans can damage the electrical distribution system and increase the risk of these hazards. A faulty or open conductor can lead to the risk of electric shock to personnel in the vicinity who are without awareness of the hazard. Damage to the transformers can lead to the loss of power supply for the entire distribution system. If proper mitigation measures are not in place and the transformer is not repaired, this can lead to the explosion of the transformer. It is important to be able to isolate such faults in the system to prevent cascading damage to the system as well as harm to the operators. Apart from an external agent causing physical damage to the system, there can be faults in the system, such as degraded conductors (cables), resulting in high impedances that can lead to potential electric hazards. In case of overloading of the distribution system, it is important to have a proper protection system in place to isolate the fault and avoid severe hazards. Note that electrical hazards can cause fire, burnout, and projection of molten parts; thus, it is important to understand the severity of these electric hazards to prepare for mitigations against them. NFPA 70E is a standard for electric safety at workplaces (NFPA 2024). Gordon, Cartelli, and Graham (2018) discuss electric shock hazards classification, and Short (2011) addresses arc flash severity in medium-voltage systems. RC59 from the Fire Protection Association contains recommendations for fire safety when charging EVs (Fire Protection Association 2023).

2.3.2 Electric Vehicle Supply Equipment

The charging requirements of electric aircraft will vary based on each original equipment manufacturer’s design. Manufacturer-collected data for electric aircraft charging characteristics show peak DC charging power ranging from 300 to 1,000 kW and battery energy capacity ranging from 130 kWh to more than 300 kWh. The EVSE has many DC fast-charging components, including an inverter, inverter controller, and potentially a DC bus (if there are multiple charging points behind the AC-to-DC inverter). If these components are operated beyond their normal operating range or damaged, they could cause electrical hazards, such as electric shock, arcing, fire, burnout, and overloading of the charging system. As discussed in previous subsections, collisions, vandalism, and theft can damage the EVSE. Also, the wear and tear on charging equipment, cables, and plugs due to chaffing, dragging, and weather conditions can damage the equipment and increase the existing risk of electric shock. Implementing periodic maintenance and inspections of the EVSE can minimize these risks (Maddox 2015; MS Amlin Ltd. 2023).

A communication system is very important for energy management and successful charging operation of the aircraft. A communication loss due to equipment damage, loose connection of wires, or other reasons could lead to the discontinuation of the aircraft charging. This could lead to insufficient charging and could affect the operational schedule of the aircraft. Similarly, overall charging system behavior should be analyzed for such failure modes, including the loss of power and the loss of communications. The following SAE International standards provide guidelines for the design of the charging equipment and their components:

- SAE J1772 is the standard for EV conductive charge couplers; it describes the charging of EVs and plug-in hybrid EVs and defines a common method for the supply equipment, including functional requirements.
- SAE J2847 provides specifics on the digital communications of the charging infrastructure and establishes specifications for plug-in EVs and DC chargers.

- SAE J2847/1 is the standard for smart charging.

UL provides the following relevant certificate-of-compliance standards for charging equipment.:

- UL 2202 is the standard for EV charging system equipment; it consists of requirements for conductive DC charging equipment, with input voltages ranging from 1,000–1,500 V and output voltages up to 1,500 V.
- UL 2231-1 presents general requirements for personal protection systems for EV supply circuits.
- UL 2251 provides guidance for plugs, receptacles, and couplers for EVs.

More codes and standards associated with safety considerations of EVSE are listed in the appendix.

2.3.3 Battery Energy Storage Systems

Large-scale energy storage solutions can be deployed to facilitate the added charging demand, which could optimize both energy and infrastructure costs. BESS are widely used for such use cases due to their availability and ability to scale and control features. BESS have many associated electrical, chemical, and thermal hazards. It is important to have a battery management system in place to monitor the use and health of the battery and to periodically conduct operational maintenance. Constant use of batteries can lead to imbalances in the cells/cell modules of the battery and can lead to catastrophic failures (Jeevarajan et al. 2022).

Physical impact on the batteries caused by human hazards or natural hazards can destabilize the electrodes or damage the separating layers within the battery. This damage can lead to internal short circuits, causing thermal runaway or leakage of electrolytes, eventually causing toxic gas releases, fires, or even explosions (Jeevarajan et al. 2022).

Li-ion batteries are one of the most widely used energy storage solutions in EV charging operations. These batteries can overheat or become destabilized if they are operated outside of their manufacturer's recommended specifications. Operating batteries beyond the recommended specifications for limits of charging and discharging can lead to overcharging, or over-discharging, or growth of dendrites. This can lead to the destabilization of electrodes, swelling of the battery, overheating of the electrolyte, etc. These issues can cause short-circuiting within the battery and can damage the conductors connecting the battery, which can cause thermal runaway, leading to fires. Li-ion batteries use lithium metal oxides as cathodes. The electrolyte is made from carbonate-based organic solvents, which are highly flammable, although there is ongoing research to develop nonflammable solvents. In case of physical damage, short circuits, or improper use, the internal exothermic reaction can lead to fires in a battery. In case the battery catches fire, there should be a mitigation plan in place to extinguish it.

Some effective fire suppressants for lithium battery fires are water, CO_2, foam, sand, nitrogen, or chemical-based dry powders (Ghiji et al. 2020). An alternative is water mist applied using the droplet-size distribution method (Mawhinney, Dlugogorski, and Kim 1994). NFPA has also conducted research on the effective use of sprinklers for battery fire suppression (Long Jr. and Blum 2016). Annex G of NFPA 855 provides guidelines for suppressing fires associated with Li-ion batteries, and Chapter 4 provides general guidance for emergency planning, training, and hazard mitigation analysis of ESS (NFPA 2023). UL 9540A provides information on the installation of test procedures to determine the necessary protection in case of battery fires caused by thermal runaways (Hopper 2019). Additional resources to consider for BESS possible failures include the BESS Failure Event Database developed by the Electric Power Research Institute (EPRI 2023), and TUV SUD provided insights about the myth versus reality in the risk of Li-ion battery fires (TUV SUD 2023).

BESS are also associated with chemical hazards. Batteries are made of various chemical compounds that form the electrodes, electrolyte, and separation layers. These compounds are potentially flammable when exposed to high heat, leading to fire, and in some cases release toxic pollutants when exposed to air or when burning. NFPA 400 provides guidelines for chemical hazards for the mitigation and disposal of batteries in case of accidents (NFPA 2022). Fire from a Li-ion battery canreignite after suppression because toxic and flammable gases are being formed by and released from a damaged battery. It is essential to immediately disconnect and isolate the damaged battery during the process of suppressing the fire. Batteries can be located in a facility with a mixed-fuel environment for nonelectric aircraft. UL 2202 guidelines mention that a BESS should be at least 20 feet away from an outdoor fuel dispensing device and should not have any arcing or sparking components, such as a switch or relay, within 18 inches (UL Solutions 2022). A first-response action plan should identify the necessary steps to minimize the potential damage if this happens.

There are increasing research and opportunities for other longer-duration storage methods that could complement EVSE equipment, including hydrogen fuel cells and other more traditional methods. These opportunities are evolving and might be necessary to consider in deployments, depending on the technology advancement. Significant safety and code efforts have been developed for fixed storage systems surrounding hydrogen technology; however, this is beyond the current scope.

3 Relevant Considerations and Standards for Safety and Mitigation of Hazards

Aircraft charging infrastructure can be deployed at airports, heliports, and vertiports. Ideally, a site-specific hazard analysis should be completed before the deployment of the charging infrastructure, identifying potential hazard scenarios, their likelihood, and their mitigation strategies. FAA processes such as a risk matrix (FAA 2017), the safety management system framework (Oatman, Van Buskirk, and Adair 2010), and the *Risk Management Handbook* (FAA 2022b) can be followed to perform the site-specific safety management review. Also, the U.S. Department of Energy has provided a handbook for the integration of hazard analyses that highlights the hazard analysis process (DOE 2020) as well as a safety management framework (DOE 2014).

3.1 Risk Matrix

Risks and hazards vary for each facility and application, depending on the quality of training, geographic conditions, and certain unexpected conditions that vary by location; thus, conducting an individualized risk assessment for each location is necessary. A risk matrix can help identify the potential hazards and risks in a particular system or facility, which can help in designing a mitigation plan or hazard management plan, as well as in training the employees for a particular facility. Table 1 is an example of a risk matrix (Vector Solutions 2018; FAA 2017).

Table 1. Example Risk Matrix—General Aviation Operations/Small Aircraft and Rotorcraft (FAA 2017)

Severity Likelihood	Minimal 5	Minor 4	Major 3	Hazardous 2	Catastrophic 1
Frequent A	[Green]	[Yellow]	[Red]	[Red]	[Red]
Probable B	[Green]	[Yellow]	[Yellow]	[Red]	[Red]
Remote C	[Green]	[Green]	[Yellow]	[Yellow]	[Red]
Extremely Remote D	[Green]	[Green]	[Green]	[Yellow]	[Red] * [Yellow]
Extremely Improbable E	[Green]	[Green]	[Green]	[Green]	[Yellow]

High Risk [Red]

Medium Risk [Yellow]

Low Risk [Green]

* High Risk with Single Point and/or Common Cause Failures

3.2 Federal Aviation Administration Orders and Guidance

FAA Order 8000.369C: Safety Management System can be considered a starting point for developing a hazard management or mitigation plan (FAA 2020). By conducting site-specific risk assessments, prioritizing the risks, and taking guidance from the relevant standards, a robust plan can be designed. FAA's safety management system framework and *Risk Management Handbook* can be followed to develop the plan.

3.3 General Safety Considerations

An important safety consideration mentioned earlier in the report is that the isolation of a fault is critical to hazard mitigation. Electrical systems should have proper protection systems in place and must be periodically updated as the facility grows. Electric protection equipment—such as relays, fuses, circuit breakers, and reclosers—must be inspected and replaced by trained professionals to avoid faults propagating throughout the system.

In the case of hazards related to BESS, it is essential for a trained professional to isolate and move the affected module to a safer location. If a BESS is not deployed or operated as recommended by the manufacturer, fires, toxic gases, toxic smoke, and explosions might occur, and thus a high degree of precaution must be taken while isolating and suppressing the fault. While dealing with any hazard, proper personal protective equipment must be used, and only trained and qualified personnel must take the necessary actions. To avoid human errors that can lead to fatal injuries, it is essential to have a training program designed for the operators of this equipment and ensure that only the trained individuals operate the equipment. There are existing standards and considerations within the industry to mitigate some of these hazards—these consider electrical, chemical, and thermal hazards, and they provide training and guidance for safety in case of accidents, considerations for the mitigation of some known hazards, and considerations for deployment and operation. These standards are listed in the appendix.

Currently, guidelines exist for EVSE infrastructure for vehicles, but specific guidance for developing EVSE for electric aviation have not yet been developed; however, some guidelines related to electric distribution infrastructure and equipment can be adopted as a base for developing new guidelines for electric aviation. The Electric Transportation Engineering Corporation (ETEC 2010) and the New York State Energy Research and Development Authority (NYSERDA 2015; NYSERDA 2023) provide considerations and deployment guidelines that can be adopted as a reference while designing EV charging infrastructure.

A risk and hazards assessment or analysis can prepare site operators for potential hazards and help them develop safe operation and mitigation plans. Developing a risk matrix for a particular site and conducting assessments—such as a fault tree analysis, root cause analysis, and a failure modes and effects analysis—can help aid in the understanding of the causes, impacts, and severity of the hazards. Previously identified or known hazards can impact systems in different manners in new environments. Similarly, as discussed in Section 2, identical hazards can have multiple sources. For example, natural hazards (such as tornados or floods) or human errors (such as in operating heavy equipment) can all lead to physical damage to the infrastructure, causing short circuits, shock, or both. A functional hazard analysis, as described by Wasson et al. (2022), can be adopted to assess these scenarios. For a functional hazard analysis,SAE ARP4761 should be referred to conduct the fault tree analysis and failure modes and effects analysis and to identify possible ways a hazard can impact the system. SAE ARP4754A addresses a system development process to support the safety certification of the system. A bigger system can be divided into smaller subsystems for the assessments, and a system-specific mitigation strategy can be developed.

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Appendix: Standards for Consideration

This is a nonexhaustive list of standards and guidelines that can be referred to for safety considerations, deployment considerations, and mitigations of the hazards mentioned in this report. These standards are periodically updated, and operational guidelines derived from these standards must also be updated by the operators. Note that some of these standards and guidelines cater to electric vehicles (EVs) and not specifically electric aircraft. The power dissipation, energy storage sizing, and receptacle sizing can differ from road-based EVs. These standards can be referred to as potential guidelines to develop standards and procedures for electric aircraft.

National Electric Code, NFPA 70E

The National Electrical Code describes safety practices related to electrical hazards. It consists of guidelines and considerations regarding electric shock and arc flashes, among other electrical hazards. It was established by the National Fire Protection Association (NFPA) and is commonly referred to as NFPA 70E. Article 625, “Electric Vehicle Charging and Supply Equipment Systems,” covers the electrical conductors and equipment external to an EV that connect it to a supply of electricity by conductive or inductive means as well as the installation of equipment and devices related to EV charging.

NFPA 855: Standard for the Installation of Stationary Energy Storage Systems

This standard contains information regarding chemical and fire hazards that can occur due to a fault in an energy storage system (ESS) leading to the emissions of toxic chemical gases. Chapter 4 of this standard provides guidelines for emergency planning and training, hazard mitigation, and analysis of ESS. Annex G provides guidelines for fire suppression and safety regarding lithium-ion-based battery energy storage systems (BESS).

NFPA 400: Hazardous Materials Code

This code consolidates safeguards for the storage, use, and handling of hazardous materials in a facility and provides guidance for chemical hazards related to BESS. These guidelines are useful when isolating and mitigating a battery-system-related hazard.

NFPA 418: Standard for Heliports

This standard provides minimum requirements for fire protection for heliports and rooftop hangars and also potentially for vertiports and vertistops in future editions.

NFPA 68: Standard on Explosion Protection by Deflagration Venting

This standard applies to the design, location, installation, maintenance, and use of devices and systems that vent the combustion gases and pressures resulting from a deflagration within an enclosure so that structural and mechanical damage is minimized.

NFPA 1561: Standard on Emergency Services Incident Management System and Command Safety

This standard contains requirements and best practices for emergency services to structure and implement the operations of an incident management system during emergencies. It is intended to ensure the safety of emergency responders and others on the scene of an incident.

NFPA 1600: Standard on Continuity, Emergency, and Crisis Management

This standard is recognized by the National Commission on Terrorist Attacks as the National Preparedness Standard and is adopted by the U.S. Department of Homeland Security for the same. It establishes a common set of criteria for all hazards, disasters, and emergency management and business continuity programs.

NFPA 69: Standard on Explosion Prevention Systems

This standard provides requirements for the design, installation, operation, maintenance, and testing of systems for the prevention and control of explosions in enclosures that contain flammable materials. Some of the methods for explosion prevention include the control of oxidant and combustible concentration.

NFPA 424: Guide for Airport/Community Emergency Planning

This standard lays out the structure for the command, communication, and coordination of elements of an airport/community emergency plan that require consideration before, during, and after an emergency to provide effective emergency services.

NFPA 75: Standard for the Fire Protection of Information Technology Equipment

This document includes requirements for construction to help mitigate damage from fires.

Occupational Safety and Health Act of 1970

This act provides guidelines for the workplace safety of employees and enforces standards to maintain a safe and healthy environment.

SAE Standards for Electric Charging Infrastructure

SAE has certain standards that provide guidelines for the design of charging equipment, architecture of the modules used, communication and power quality standards, and compatibility of the instruments used:

- **SAE J1772:** Maintains general physical, electrical, functional, and performance requirements for conductive charging. It also defines the charging method considering the operational, functional, and dimensional requirements for the vehicle and charging connector.
- **SAE J2293:** Describes performance requirements for EV and electric vehicle supply equipment (EVSE) used to transfer electrical energy to an EV from a utility power system. The standard ensures the functional interoperability of EV and EVSE physical systems.
- **SAE J2847:** Establishes a specification for communications between plug-in EVs and EVSE. Interactions between the vehicle and vehicle operator are also noted in this standard, though no formal specifications on the interactions are given.
- **SAE J2894:** Provides guidelines for onboard charger power quality, identifying key control parameters of EVSE impacting the power quality, AC service characteristics impacting EVSE performance, and values for power quality, susceptibility, and control parameters.

- **SAE J2929:** Sets minimum acceptable safety criteria for electric and hybrid vehicle propulsion in lithium-based rechargeable cells. The primary focus of this standard is on conditions that can be evaluated using the battery system alone.

UL Standards

UL provides certifications for compliance with relevant standards. Some UL standards for safety with EVs and BESS are as follows:

- **UL 2202:** Standard for EV charging system equipment covering the chargers that convert AC to DC and feed the power to batteries. This standard applies to both off-board and onboard chargers and specifies the indoor/outdoor use classification for each.
- **UL 2231-1:** Covers general requirements for personal protection systems for EV supply circuits to reduce the risk of electric shock to the user from accessible parts.
- **UL 2251:** Provides guidance for plugs, receptacles, and couplers for EVs. The standard is intended for conductive connection systems for either indoor or outdoor nonhazardous locations.
- **UL 9540A:** Covers information about test requirements for BESS for battery fires and thermal runaways. The standard provides details on the installation of required necessary protection.

FEMA 426: Reference Manual to Mitigate Potential Terrorist Attacks Against Buildings

This manual provides risk assessment techniques, protective measures, and design guidance for buildings to reduce the physical damage and causality from terrorist attacks using chemical, geological, and radiological agents.

FEMA 427: Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks

This document addresses design strategies to mitigate the effects of explosive, chemical, biological, and radiological attacks, with a focus on mitigating the effects of explosions.