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Safety of Grid-Scale Battery Energy Storage Systems

Information Paper

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Table of Contents

1. Foreword

Energy Storage Ireland (ESI) is a representative body for those interested and active in the development of energy storage in Ireland and Northern Ireland.

We work together to promote the benefits of energy storage to decarbonising Ireland's energy system and engage with policy makers to support and facilitate the development of energy storage on the island.

Energy storage will play a significant role in facilitating higher levels of renewable generation on the power system and in helping to achieve national renewable electricity targets.[1] Storage systems can act in the energy, capacity and system services markets to deliver a wide range of benefits such as wholesale energy price reductions, reduced CO_2 emissions and flexible system support services to help manage the grid with higher levels of renewables. Energy storage can also make a significant contribution to security of supply replacing the need for fossil fuel generation.

As energy storage systems become more common and are an increasingly important part of our global energy transition it is only natural that communities being introduced to a new technology will have questions. The first priority must be to address any concerns people may have from a health and safety perspective.

This paper has been developed to provide information on the characteristics of Grid-Scale Battery Energy Storage Systems and how safety is incorporated into their design, manufacture and operation. It is intended for use by policymakers, local communities, planning authorities, first responders and battery storage project developers.

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[1] Climate Action Plan: https://www.dccae.gov.ie/documents/Climate%20Action%20Plan%202019.pdf

2. Summary

Most grid-scale battery-based energy storage systems use rechargeable lithium-ion battery technology. This is a similar technology to that used in smartphones and electric cars but aggregated at scale to deliver much greater electricity storage capability.

They are considered one of the most promising types of grid-scale energy storage and a recent forecast from Bloomberg New Energy Finance estimated that the global energy storage market is expected to attract $620 billion in investment over the next 22 years.[2] It is also projected that global energy storage deployments will grow thirteenfold over the next six years, from a 12 GWh market in 2018 to a 158 GWh market in 2024.[3]

While there are other types of battery-based energy storage systems, these are predominantly at an early development stage. As these other technologies mature and potentially see a take-up in the Irish market, ESI will continue to monitor developments and will formulate an appropriate position on safety in relation to other types of storage system as needs arise.

The focus of this paper will be on lithium-ion based battery storage systems and how fire and thermal event risk prevention and management is currently being addressed in the storage industry.

The key takeaways from this analysis are highlighted below:

- Lithium-ion batteries have been widely used for the last 50 years, they are a proven and safe technology;
- There are over 8.7 million fully battery-based Electric and Plug-in Hybrid cars, 4.68 billion mobile phones and 12 GWh of lithium-ion grid-scale battery energy storage systems (equivalent to a further 1.2 billion iPhones) already used safely around the world;
- Grid-scale batteries typically use a slightly different type of lithium-ion chemistry to that of consumer electronics such as mobile phones or laptops (detailed further in Section 3.1).
- The main reasons why lithium-ion technology is used so widely are:
    - They are energy dense (i.e. they can hold a large amount of energy relative to their size);
    - They hold their charge relatively well compared to other battery types, for instance a lithium-ion battery pack loses only about 5 per cent of its charge per month, roughly a quarter of the rate for Nickel Metal Hydride (NiMH) batteries;
    - You do not have to completely discharge them before recharging, as with some other battery types;
    - Lithium-ion batteries can handle hundreds of charge/discharge cycles;
    - Their relative costs are lower than other battery types.

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[2] https://about.bnef.com/blog/energy-storage-620-billion-investment-opportunity-2040/
[3] https://www.greentechmedia.com/articles/read/global-energy-storage-to-hit-158-gigawatt-hours-by-2024-with-u-s-and-china

- There are numerous international standards which regulate the design, manufacture and distribution of lithium-ion batteries to ensure they are adequately tested for safety, reliability and durability (detailed further in Section 3).
- Safety is fundamental to the development and design of energy storage systems. Each energy storage unit has multiple layers of prevention, protection and mitigation systems (detailed further in Section 4). These minimise the risk of overcharge, overheating or mechanical damage that could result in an incident such as a fire. There are also international best practice guidelines for industry to aid developers in the design and operation of battery storage systems in a safe and secure manner. A global approach to hazard management in the development of energy storage projects has made the lithium-ion battery one of the safest types of energy storage system.

3. Introduction to Lithium-Ion Battery Energy Storage Systems

3.1 Types of Lithium-Ion Battery

A lithium-ion battery or li-ion battery (abbreviated as LIB) is a type of rechargeable battery. It was first pioneered by chemist Dr M. Stanley Whittingham at Exxon in the 1970s. Lithium-ion batteries have increasingly been used for portable electronics, electric vehicles and stationary energy storage systems over the last 50 years. They are an established, proven and reliable form of battery technology.[4]

All lithium-ion technologies today are based on the same principle. Lithium is stored in the anode (or negative electrode) and transported during the discharge to the cathode (or positive electrode) via an organic electrolyte.

There are a wide range of sub-categories of lithium-ion chemistry with different safety, cost, energy density and performance characteristics.

Handheld electronics like mobile phones and laptops mostly use LIBs based on lithium cobalt oxide (LiCoO2, or **LCO**). However, LCO has limited use for large power applications and has relatively limited cycling ability (i.e. the number of charge/discharge cycles) so it is typically not utilised in grid-scale energy storage systems.

Lithium iron phosphate (LiFePO4, or **LFP**), lithium ion manganese oxide (LiMn2O4, Li2MnO3, or **LMO**), and lithium nickel manganese cobalt oxide (LiNiMnCoO2 or **NMC**) battery chemistries offer lower energy density but longer battery lives and are the safest types of lithium-ion batteries.

These batteries are widely used in electric tools, medical equipment (for example defibrillators and implanted cardiac and neurostimulation devices) and other roles. NMC and LFP are leading contenders for automotive and stationary storage applications, such as grid-scale battery energy storage systems, based on their combination of density, safety and cost characteristics.

3.2 The Benefits of Battery Energy Storage Systems

As storage technologies continue to mature, and their costs continue to fall, they will be increasingly deployed as a flexible asset to support national decarbonisation goals. In June 2021, Baringa released 'Endgame – A zero-carbon electricity plan for Ireland' which projects up to 1,700 MW of large-scale battery storage will be needed on an all-island basis to meet 2030 RES-E targets and deliver a zero-carbon pwoer system.[5] The benefits these battery storage projects are as follows:

Ensuring System Stability and Reducing Power Sector Emissions

One of the main uses for battery energy storage systems is to provide system services such as fast acting frequency response and energy reserves that can replace the need to use fossil fuel generators for these services.

For example, to ensure the stability of the system in case of a sudden disruption to power generation or demand, such as a large generator failing unexpectedly, the Transmission System Operators (TSOs) must make sure that there is sufficient reserve back-up power on the system at all times. This reserve power must be available at a moment's notice and currently the TSOs meet the majority of their

[4] Scrosati, Bruno (4 May 2011). "History of lithium batteries". Journal of Solid State Electrochemistry. 15 (7–8): 1623–1630. doi:10.1007/s10008-011-1386-8
[5] https://windenergyireland.com/images/files/20210629-baringa-endgame-final-version.pdf

reserve requirement from fossil fuel generators. This means that fossil fuel generators, that would otherwise not be running, are often turned on or run inefficiently just so they are available to provide this immediate reserve back up.

Batteries can replace the need to use fossil fuel generators for reserve and fast frequency response, and other system services such as reactive power, as they are available nearly all the time and can respond to frequency deviations in milliseconds, thus helping to manage system stability. This has huge benefits in terms of system cost savings, emissions reductions and lower renewable curtailment as demonstrated in a study carried out by energy experts Baringa titled *Store, Respond and Save*.[6] This study estimates that procuring all system services from zero-carbon sources such as battery storage, instead of using fossil fuel generators, would avoid nearly 2 million tonnes of power sector emissions and lead to system cost savings of €117 million per year by 2030.[7]

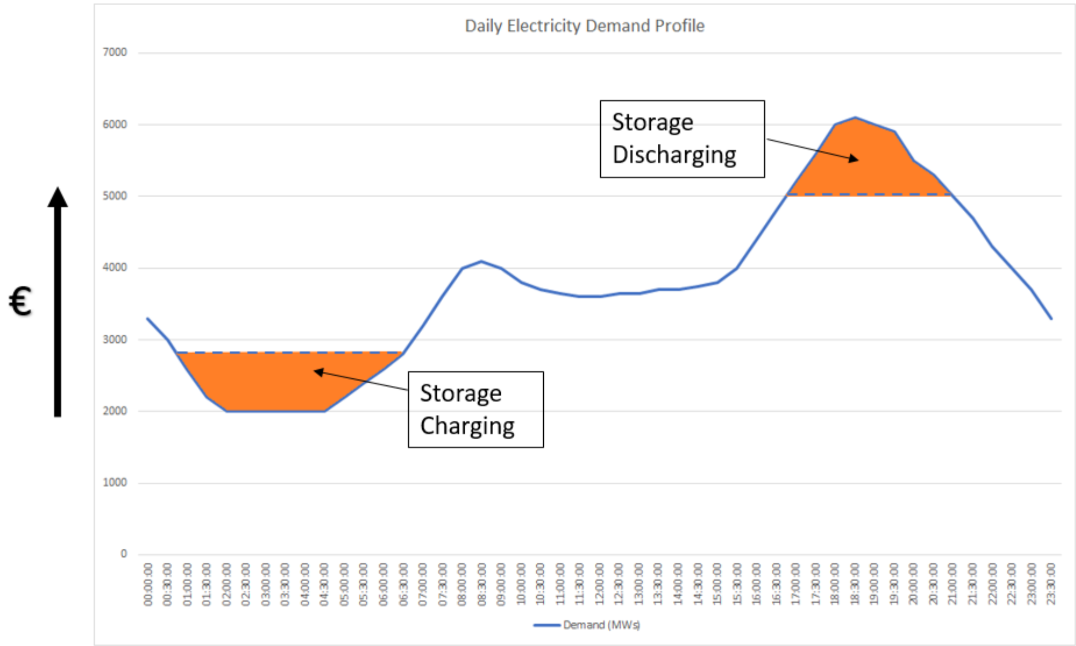
Reducing Electricity Prices

Storage technologies can reduce electricity prices through a process known as energy arbitrage by storing energy at low price periods and discharging it as a cheaper and cleaner alternative to fossil fuel generators in high price periods.

For example, the diagram below shows a typical daily electricity demand profile with generation following the blue line to meet demand. Generally, the lowest demand periods are at night with a gradual ramp up in the morning before another fairly steep demand rise in the early evening, in line with peoples' activities at home. Generation has to be scheduled to meet this demand profile, with the most generation needed to meet the evening peak. This also tends to be when the most expensive electricity prices are seen as expensive gas or diesel peaking generators are often brought on just for a couple of hours to meet this evening demand.

By charging at the low demand/price periods and discharging at the high demand/price periods, as highlighted, battery storage displaces more expensive fossil fuel generation and helps to smooth price volatility in the market. Low price periods in the market also tend to be when wind generation is high so storage can take advantage of this by storing energy at these times, helping to increase demand for renewable generation, and discharging the energy at periods of low wind as an alternative to fossil fuelled plant.

[6] Store, Respond and Save https://www.energystorageireland.com/wp-content/uploads/2020/02/Energy-Storage-Ireland-Baringa-Store-Respond-Save-Report.pdf
[7] Store, Respond and Save: https://www.energystorageireland.com/wp-content/uploads/2020/02/Energy-Storage-Ireland-Baringa-Store-Respond-Save-Report.pdf



Security of Supply

Transitioning to a zero-carbon electricity system in Ireland and Northern Ireland will mean reducing, and eventually removing, our reliance on conventional fossil fuel generators for our electricity needs. The majority of electricity demand will be met by variable renewable generation sources such as wind and solar which means security of supply (ensuring there is always enough electricity to meet demand) will become more and more important. Battery storage can make a significant contribution in this regard as the market is shifting towards longer-duration projects that can provide multi-hour energy to ensure electricity continues to flow during periods of low renewable output or where there is congestion on the network. Multi-hour battery storage will reduce the need to use fossil fuel generation to ensure security of supply thereby reducing power sector emissions and helping us on the path to a net-zero energy system.

Alternative Network Solutions

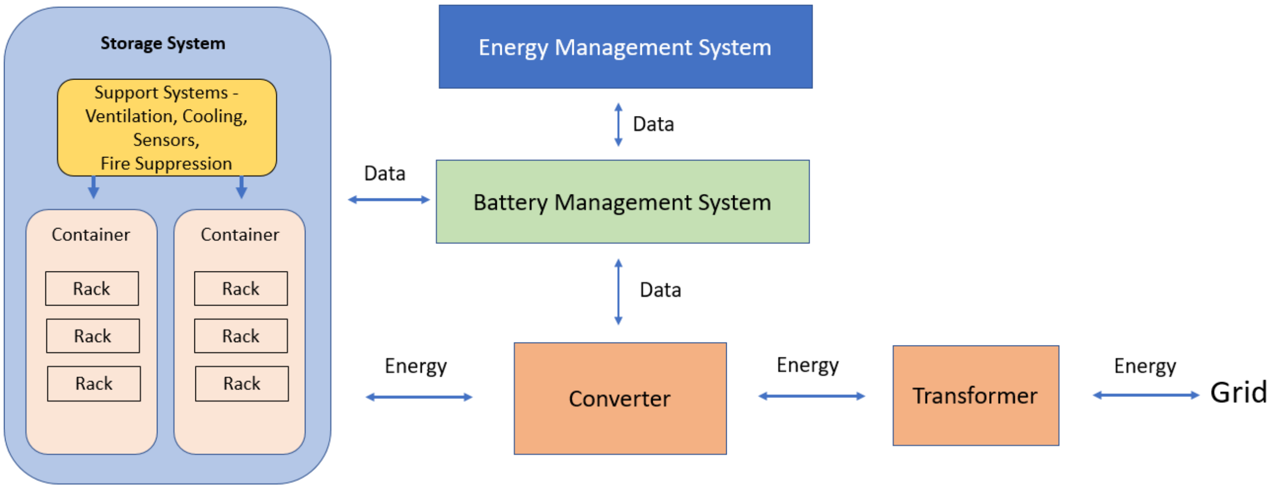
Battery storage could also be used to provide a non-wires alternative to network build out to help mitigate peak transmission or distribution network congestion. As the electrification of heat and transport adds additional demand to an already constrained grid, energy storage offers a potentially cheaper network reinforcement solution to network operators for the benefit of all users.

For instance, deployment of battery storage in large demand centres such as Dublin can help avoid network congestion during peak hours and reduce or defer the need for network reinforcement. If the batteries are charged up at times of low demand and are located close to where the power is needed, then they can supply electricity and help to reduce congestion on the network at times of high demand.

Behind-the-meter electricity storage schemes, e.g. at domestic and business premises, will also have a role to play in managing energy balancing and network congestion, increasing the overall utility of existing grid infrastructure.

4. Battery Energy Storage System Design

Below is a high-level diagram of a typical battery energy storage system:



The storage system is typically organised as follows:

- Individual battery cells are assembled into modules
- Modules are mounted within cabinet racks
- Racks are installed in a container (e.g. 40 foot container)

A storage system can be made up of one or more containers and each container typically stores about 1-5 MWh of energy. The container also contains support systems which manage ventilation, cooling, sensors and fire suppression. These will be described further in later sections.

The image below shows what the inside of a storage container can look like. It is possible to see the separate racks and modules of battery cells.

Batteries are controlled using a Battery Management Systems (BMS). The BMS also manages the support systems. The role of the BMS is detailed further in section 5.4.

At a high-level, there is the Energy Management System (EMS) which takes care of overall power flow and operation of the battery in terms of when to charge, discharge and operate in the market. As the diagram shows, information continually flows to and from the EMS, the BMS and the storage system itself.

Finally, there is the power conversion equipment which changes the energy to a state where it can be transported to and from the electricity grid. The image below shows a typical storage system container with support systems and power conversion equipment.

5. Safety Management

Safety management is a fundamental feature of all lithium-ion energy storage systems. Safety incidents are, on the whole, extremely rare due to the incorporation of prevention, protection and mitigation measures in the design and operation of storage systems.

5.1 Fire risk

A common concern raised by some communities living close to sites identified for battery energy storage systems is around the risk of fire.

In this section we will outline how this threat is guarded against but first it is important to understand where the risk of a fire comes from.

In the absence of the proper prevention and protection measures outlined below a battery cell can become overheated. This can happen for reasons that could be mechanical (such as impact or vibration), thermal (such as exposure to high heat or inadequate ventilation) and electrical (where the battery cell is overcharged due to improper management).

Any of these could lead to what is known as a ‘cell failure’. If temperature increases at a faster rate than it can be dissipated then this can cause the cell to start to break down, which causes a reaction due to the chemical components of the batteries, that leads to self-heating. This is known as **thermal runaway** and, if no action is taken to prevent this, it can lead to a fire and the release of toxic or flammable gases such as carbon dioxide or hydrogen fluoride inside the container.

When multiple cells are present there is a risk that an individual overheating cell or cell fire can start to impact its neighbours leading to a cascade effect as more and more cells overheat.

The design of battery storage systems is extremely important in this regard as the goal is to prevent a single cell failure from spreading to others and to contain and reduce the chances of thermal runaway occurring in multiple cells.

The following sections will explain how this is achieved.

5.2 Safety Standards & Testing

There are numerous international standards that ensure that safety is incorporated in the design, manufacture and transportation of batteries in order to minimise the occurrence of defects which could result in a potential hazard.

The International Electrotechnical Commission (IEC), which develops international standards for all electrical, electronics and related technologies, including batteries, has a range of safety standards for testing and certification of lithium ion batteries and storage systems:

- Battery cells certified to UL1642 and IEC62619 (Safety requirements for secondary lithium cells and batteries, for use in industrial applications);
- IEC 62620 (Secondary cells and batteries containing alkaline or other non-acid electrolytes - Secondary lithium cells and batteries for use in industrial applications);

- IEC 63056 (Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems);
- IEC 62933-5-2 (Safety requirements for secondary batteries and battery installations - Part 5: Safe operation of stationary lithium ion batteries)
- IEC 62485-5 (Safety requirements for secondary batteries and battery installations - Part - 5: Lithium-ion batteries for stationary applications).

Testing to these standards is conducted by the battery manufacturer. International codes and standards are regularly updated using real-world experience and new testing to ensure safety standards are continuously evolving.

Lithium based batteries are also subject to the United Nations Regulations on the Transport of Dangerous Goods (UN/DOT 38.3). These provide for the safe packaging and shipment of lithium-ion batteries and require a variety of testing under different altitude, vibration, impact and thermal conditions before transportation. Manufacturers of lithium batteries and products using lithium batteries must account for these testing requirements in the design, manufacture and distribution of their products.

These standards and codes mean that developers can be sure that the batteries they are sourcing for their systems are certified to high safety standards with extremely minimal chance of defects occurring.

The installation of the battery storage system at the site is finalised via site acceptance testing.

The purpose of this testing is to ensure that the system is installed properly, that no defects have occurred in transport and that the battery management and protection systems are working properly. This testing is carried out in cooperation between the battery system operator and the supplier.

At a system level, UL9540A[8] is a test method for evaluating thermal runaway in battery storage systems that reduces the risk of a single cell event spreading to the rest of the system. This is a global standard that storage system suppliers test their products under to demonstrate compliance.

The international energy consultancy, DNV, has created global best practice guidelines for the safety, operation and performance of grid-connected energy storage systems (RP43)[9]. These guidelines are intended to help battery storage system developers and were created by drawing on international expertise from numerous industry bodies, associations, universities and technical experts. They contain a wide ranging set of recommendations in areas such as storage system design and safety, risk management, testing and coordination with local authorities.

In July 2020, DNV also published a detailed technical report titled 'McMicken Battery Energy Storage System Event Technical Analysis and Recommendations' which contains important information and recommendations on system design and incident prevention using the latest industry experience.[10]

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[8] https://www.ul.com/offerings/ul-9540a-test-method

[9] DNV GL best practice guidelines for energy storage systems: https://rules.dnvgl.com/docs/pdf/DNVGL/RP/2017-09/DNVGL-RP-0043.pdf

[10] https://www.aps.com/-/media/APS/APSCOM-PDFs/About/Our-Company/Newsroom/McMickenFinalTechnicalReport.ashx?la=en&hash=50335FB5098D9858BFD276C40FA54FCE

5.3 System Design

Battery energy storage systems are designed to prevent a problem in one battery cell from spreading to others in the system. Cells can be separated from each other using air gaps or thermal barriers between cells composed of heat resistant materials. These techniques help to dissipate heat in the event of a cell failure, and subsequent overheating, and prevent adjacent cells or modules from being affected. This is one of the most important design considerations in a storage system that greatly reduces the risk of a thermal runaway event occurring. As shown in Section 4, the battery cells are housed in separate modules and the modules are in turn separated from each other in individual racks. This design spacing helps to improve ventilation between the cells and reduces the risk that overheating in one cell, module or rack can spread to others in the system. This also makes it easier to contain problems if they do arise in one part of the system.

To provide an additional layer of protection, batteries for energy storage systems are also generally housed in separate containers. This reduces the risk of a problem in one container spreading to the rest of the facility.

This design layout ensures the batteries are held securely within the containers which provides protection from external elements that might cause mechanical damage such as impacts or vibration.

It is important that batteries are kept at a stable operating temperature to ensure they are operating within their design limits. This also improves the performance and operating life of the battery.

Energy storage systems contain cooling and ventilation systems. These maintain the batteries at a stable operating temperature and remove excess heat if there is a risk of overheating. For example, these systems may use ventilation, air conditioning or liquid cooling to help keep batteries at the right temperature.

5.4 System Control

The safety systems for a battery storage project operate on multiple layers from the individual battery cell right up to the whole storage system and this is managed by the BMS.

The role of the BMS is to continually monitor and manage:

- The charge level of each cell; it prevents voltage from going too high or too low. It also manages the charge levels among different cells and can redistribute flows ensuring the system is managed stably.
- State of health; it also works to identify problems before they occur. It allows the operators to know the state of health of the individual battery cells so that any deterioration or fault can be detected, and appropriate maintenance carried out.
- Temperature of the battery system components and can control supporting systems to regulate this.
- Providing real-time information at a cell, module, rack and system level to the EMS and storage system operators.

In this way, the BMS ensures that the batteries are continually monitored and protected to prevent problems and to ensure the batteries are ready to deliver power to the grid when needed.[11]

As soon as the BMS detects that a specific battery cell, or group of cells, is acting in a way that it should not it can instantly reduce the flow of electricity through the cell, switch it off or disconnect it completely from the power supply depending on the seriousness of the problem. This minimises the risk of a problem escalating in a cell or group of cells and spreading to others.

5.5 Mitigation

In the unlikely event that a problem occurs such as thermal runaway that could lead to a fire, energy storage systems have additional design measures such as smoke sensors and alarms to detect the issue and measures such as deflagration venting and fire suppression systems to contain and reduce it.

These suppression systems use techniques such as inert gas, foam suppression, fire sprinklers or water mist etc. to control fires. In the first instance an inert gas or clean agent suppression system that either targets oxygen or cooling may be used to extinguish a single cell fire, or an electrical fire not related to the battery, to prevent it spreading to other modules. In the second instance a water-based suppression system may be used to cool the system completely and prevent escalation.

These measures, or combination of measures, help ensure that the risk of fire or accumulation of toxic or flammable gases within the container is minimised.

Before constructing the project battery energy storage project developers should work with the Local Authority, first responders and fire services to ensure they understand the kinds of batteries and fire suppression technologies used in the storage facility and how best to work together to deal with any problem that might arise. This should involve incident pre-planning and the arranging of a site visit before the facility is operational.

As battery fires can release flammable gases, it is important that first responders and fire services are aware of these risks and have plans in place on how to deal with any potential hazards. Two resources to assist in this regard are as follows:

- The Energy Institute, which is a chartered professional membership body for the global energy industry, has produced a guidance note for battery energy storage system fire planning and response.[12] This document is intended to help developers to understand and plan for potential risks and provides guidance to first responders on how to respond to BESS fires.
- The European Advanced Rechargeable and Lithium Batteries Association (RECHARGE)[13] provides technical and legislative expertise on lithium batteries and works to ensure best practices and standards for the use of this technology. They carry out work on lithium-ion battery safety and have published a rescue and training manual for first responders and fire services regarding lithium batteries in storage facilities.[14]

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[11] https://www.mpoweruk.com/bms.htm
[12] https://publishing.energyinst.org/__data/assets/pdf_file/0005/702095/Battery-Storage-Guidance-Note-2jk.pdf
[13] https://www.rechargebatteries.org/
[14] https://www.rechargebatteries.org/wp-content/uploads/2015/01/RESCUE-AND-TRAINING-MANUAL-LITHIUM-BATTERY-IN-STORAGE-2014-12-05.pdf

It must also be noted that grid-scale energy storage systems must apply for planning permission and meet the relevant Local Authority or An Bord Pleanála planning requirements, including any appropriate fire safety assessments.

6. Conclusion

The use of lithium-ion in rechargeable batteries is well established globally. Over the last 50 years it has reached widespread adoption in consumer electronics and in the last decade with electric vehicles and grid-scale energy storage systems.

However, the sector is far from static, continually applying new best practices and learning from experience to design energy storage systems that operate as safely as possible.

There are over 8.7 million fully Electric and Plug-in Hybrid cars in use around the world, and over 12 GWh of stationary battery storage in operation (equivalent to approximately 1.2 billion iPhones), yet battery fires are an extremely rare occurrence due to the multiple levels of prevention, protection and mitigation measures that go into their design, manufacture, distribution and operation.

Safety is fundamental to the development and design of energy storage systems. Each energy storage unit has multiple layers of prevention, protection and mitigation systems that minimise the risk of overcharge, overheating or mechanical damage that could result in an incident such as a fire. There are also international best practice guidelines for industry to aid developers in the design and operation of battery storage systems in a safe and secure manner. A global approach to hazard management in the development of energy storage projects has made the lithium-ion battery one of the safest types of energy storage system.

ESI will continue to engage with its members to ensure that safety is at the forefront of grid-scale battery energy storage developments in Ireland.

We are also eager to work with Local Authorities, first responders, fire services and others to ensure battery storage projects in Ireland are developed to the highest standard and that key stakeholders understand how this technology operates.