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Analysis, Development And Design For Early Fault Detection And Fire Safety In Lithium-Ion Battery Technology

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ANALYSIS, DEVELOPMENT AND DESIGN OF ENERGY STORAGE SYSTEM FOR EARLY FAULT DETECTION AND FIRE SAFETY FOR LITHIUM -ION BATTERY TECHNOLOGY.

by

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DEDICATION

This great achievement and milestone in my life could not be achieved without the help of God. The almighty God blessed me with the power and strength to achieve this feat and I dedicate this to God, my parents Mrs. Margaret Adoma and Mr. Stephen Boachie Danquah, my wife Abena Birago and my kids Richard Boakye Danquah and Angela Pokuaah.

The true reality of life is, no impact is too small for someone to contribute to the betterment of the universe. Sometimes, it is difficult to change ones' relativity, but when you do. boundaries become insignificant, and dreams become reality. This experience for the past years in school has taught me to change my perspective, question reality, and to not give up but always strive for the best to be on top. I therefore dedicate this research and degree earn to my wife and kids Abena Birago Angela Pokuaah, Richard Boakye Danquah, and Jessica Boakye. All to all my friends and UND institute of Energy Studies.

ABSTRACT

According to the *US Department of energy*, in 2019, about 18% of electricity were generated at utility -scale electricity generation facilities in the United States was from renewable energy and energy storage technologies play a key role in the electrical infrastructure. Electrochemical energy storage uses lithium-ion cell technology to store energy and later export to the grid for use.

At end of 2019, (*eia.gov*,2022) there were 163 large scale -energy storage system in operation in the United States. The energy storage industry is growing rapidly, and the industry is experiencing unprecedented safety concerns and issues in terms of fire and explosion. Several efforts have been made by researchers and technologies to prepare solutions to these problems , however, there is still need for a more smart, efficient fire safety containment and prevention in the energy storage industry. The failure modes for energy storage systems can be derived using different methodologies such as failure mode effects analysis (FMEA),early detection mode and other strategies in lithium-ion batteries to overcome the failure. The proposed resolution can be endothermic approach which involves modifications of anode, cathode, and electrolyte materials to improve helping in the improvement of solid-electrolyte interphase and stability. My research employs classical experimental methods to explore , review and evaluate all the five main energy technologies and narrow down to electrochemical energy storage technologies, Nickel manganese cobalt oxide NMC/G and Lithium -ion Phosphate $LiFePO_4$. My research reviewed the electrical, mechanical design of the battery module and advancements in battery chemistry, the mechanisms of potential failures, and early detection strategies to overcome these failures.

Fire safety concern was resolved by incorporating fire retardant material and honey-com and multiple temperature sensors and difficulty in transporting already fully assembled energy storage systems was resolved by using mill-grade compression ring.

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GLOSSARY OF TERMS

1. *Energy Efficiency*: is simply the process of doing more with less. The goal is to accomplish the same tasks and functions as before while using less energy. The concept of using less energy to provide the same service. (energystar.gov,2023)
2. *Greenhouse Gas*: A gas that traps the sun's heat in the atmosphere. When these gases are trapped in the atmosphere (and not reflected into space), the planet becomes warmer than it would be otherwise. This process is commonly referred to as the greenhouse effect. Greenhouse gases include water vapor, carbon dioxide, methane, ozone, chlorofluorocarbons, and nitrogen oxides; gases which are produced and sometimes released into the atmosphere when generating energy to power our homes. (energystar.gov, 2023)
3. *Renewable energy resources*: Energy resources that are naturally replenishing but flow limited. They are virtually inexhaustible in duration but limited in the amount of energy that is available per unit of time. Renewable energy resources

4. *Renewable Energy Technologies*: Technologies that produce sustainable, clean energy from sources such as the sun, the wind, plants, and water. These include biomass,

geothermal, hydrogen, hydropower, ocean, solar energy, and wind. (energystar.gov, 2023)

5. *Energy Storage*: This is a technology to store energy generated through any of the storage means such as mechanical, electrochemical, thermal , electrical and later retrieval for use.
6. *Battery Energy Storage Systems*: These are rechargeable battery systems that store energy from solar arrays or the electric grid and provide that energy to a home or business. Lithium-ion batteries are currently the dominant storage technology for large scale plants and vehicular mobility to help electricity demands.

CHAPTER ONE

1.0 BACKGROUND

This chapter will provide detailed background information of energy and storage technologies and will explain why different energy storage technologies are needed in the energy storage industry.

1.1.0 INTRODUCTION TO ENERGY STORAGE

Energy storage deployments are growing, with markets opening across the globe. These markets are recognizing the value of storing energy at one point in time and dispatching it later. This is especially true in markets where solar energy deployment is increasingly part of the grid and, due to its intermittent nature of solar, which can be disruptive. On a short time, scale, energy storage can provide frequency regulation to balance the grid (Davon, H.). But on long time scales it has a larger role, providing peaking capacity, capacity adequacy , this can defer other more expensive investments such as distribution, transmission. Energy as described is the measuring property, quantitatively that can be moved to a physical system through the performance of work in a form of heat and light (*first law of thermodynamics*). As the first law of thermodynamic states energy can neither be created nor destroyed but can change from one form to another . According to U.S. Energy information Administration (eia.gov,2019), At the end of 2019, 163 large-scale battery storage systems were operating in the United States, a 28% increase from 2018 as seen in Figure 1.1 (Lindstrom & Hoff, 2019) below. There need for energy is inevitable as society and economy rely on these resources to maintain human life. There are various types of energy, but they are categorized into two main, either Kinetic energy which has it in the form of Radiant, Thermal, Motion, Sound or Electrical energy or Potential energy which comes in the form such as Chemical, Mechanical, Nuclear or Gravitation energy.

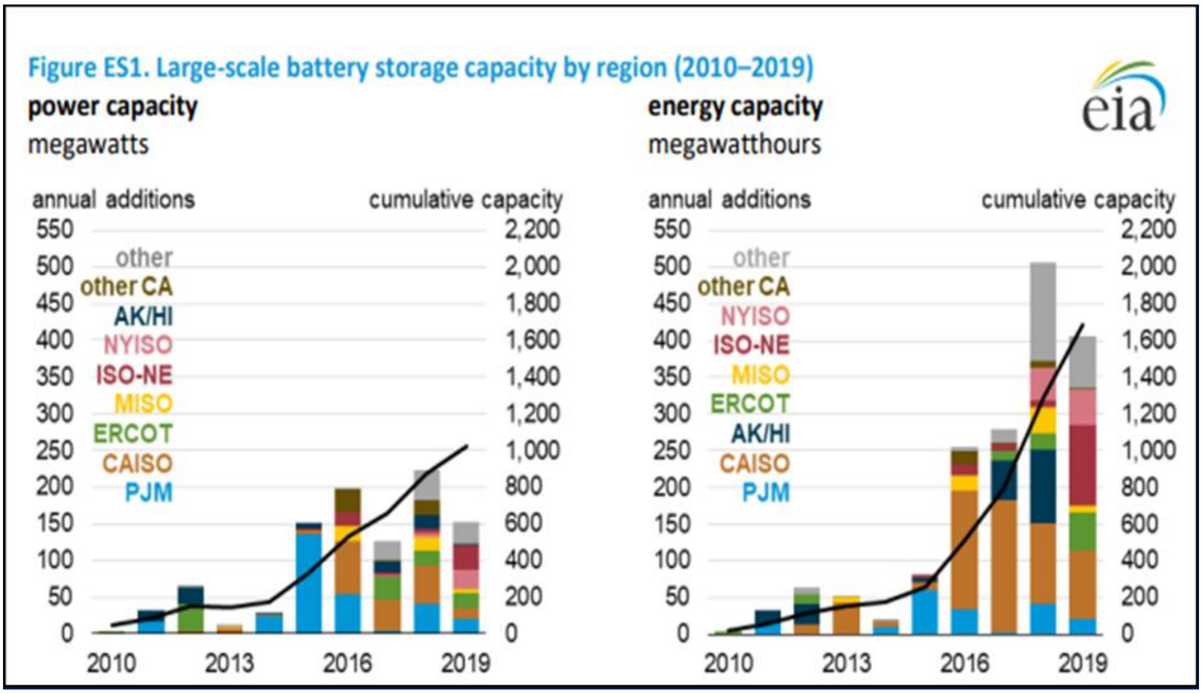


Figure 1.0*- The two graphs are based upon the USA Energy Information Administration annual electric generation report. for 2010 to 2019 which shows large scale battery storage capacity by region .*
Source: : U.S. Energy Information Administration, 2019 Form EIA-860, Annual Electric Generator Report (www.eia.gov)

Energy comes in the form of non-renewable which are petroleum, hydrocarbons gas liquids, natural gas, coal, and nuclear energy and renewable energy which are Solar energy, geothermal energy, wind energy, biomass, and hydropower energy, With the abundance source of these energies, they cannot be used in their natural form. Scientists must convert these energy resources into useable format before they can be used to power our homes, offices, and vehicles. It is out of this process is where some of the energy have some lapses, either in the renewable energy space over producing and having less demand or in the renewable space where the generation is inconsistent due to it source of generation.

Energy storage is the use of both scientific and conventional techniques actively to capture and conserve energy from various sources such as solar panels, power plants, electric generators, wind, biofuel etc. and release them to used when is required. This technology comes in many different forms, and they all work under the same principles, through energy capture, energy conversion and consumption. Energy storage technology has many forms their application differs respect to demands and use case.

According to eia.gov review, ‘‘In December 2017, there was approximately 708 MW of large-scale battery storage operational in the U.S. energy grid” (Alexandra et al.,2020). Most of this storage is operated by organizations charged with balancing the power grid, such as Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs). ISOs and RTOs are “independent, federally regulated non-profit organizations” that control regional electricity pricing and distribution. PJM, a regional transmission organization located in 13 eastern states (including Pennsylvania, West Virginia, Ohio, and Illinois), has the largest amount of large-scale battery installations, with a storage capacity of 278 MW at the end of 2017 (Alexandra et al., 2020).

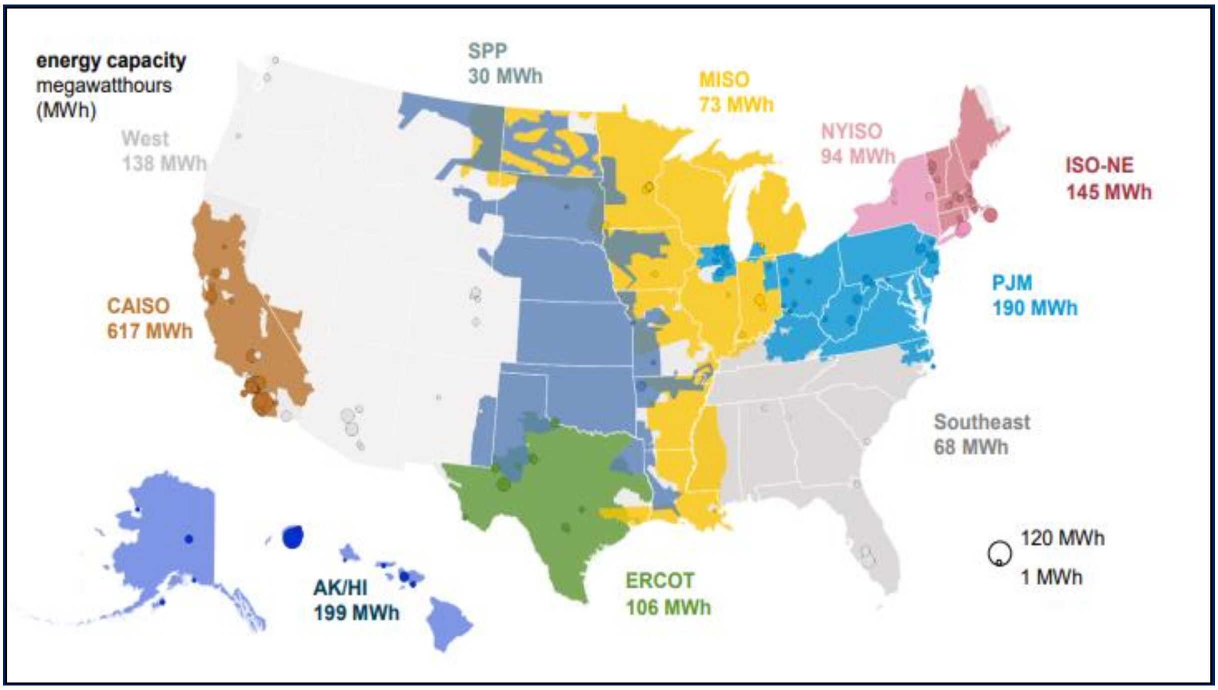


Figure 2- *Illustration of Grid scale batteries installed coast-coast, snapshot from 2019. Source: U.S. Energy information Administration, www. eia.gov, 2019)*

The second biggest owner of large-scale battery capacity is California's ISO (CAISO). By the end of 2017, CAISO operated batteries with a total storage capacity of 130MW. (Environmental and Energy Studies Institute, 2019).

Most of the battery storage projects that ISOs/RTOs develop are for short-term energy storage and are not built to replace the traditional grid. Most of these facilities use lithium-ion batteries, which provide enough energy to shore up the local grid for approximately four hours or less.

There is also a limited market for small-scale energy storage. While a minor portion of the small-scale storage capacity in the United States is for residential use, most of it is for use in the commercial sector and most of these commercial projects are in California.

With the growing demand for energy storage and price fallout, batteries prices are set to decline. 1.3, that shows a steady decline of lithium-ion battery cost.

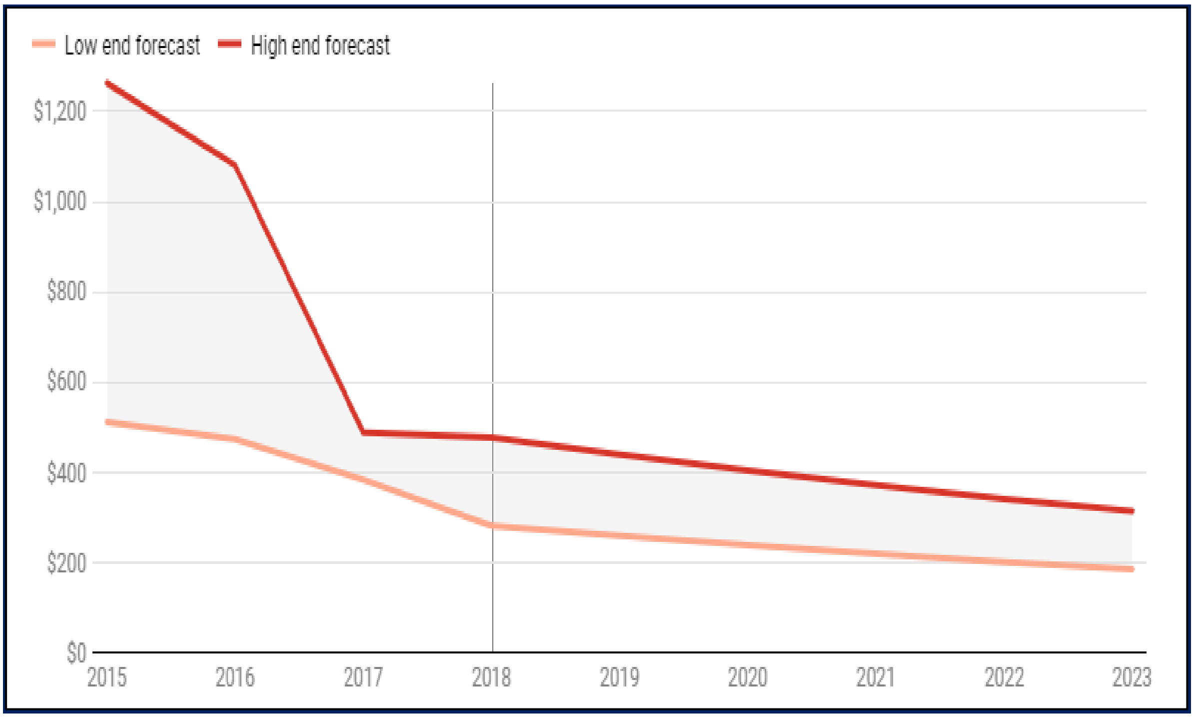


***Figure 3**- A graph of lithium-ion price over time (2015-2023)*
Source: www. green-technology.org/utilities-invest-in-big-batteries.

According to ‘‘green-technology.org, Grid-Scale battery cost per kilowatt hour in the past has plummeted in the past four years and they will probably fall further”. Inferring from Figure 1.3. Which shows a dramatic decline from $ 1,200 to $ 550.00 per $/KWh.

Notwithstanding this sharp decline and heavy push to energy storage, there have been some issues of fires and explosion associated with the lithium-ion batteries in EVs,. energy storage power stations and in air crafts and all caused by LIB failure (X. Feng et al, 2019) Most fire-related accidents of EVs are caused by the thermal runaway (TR) of LIBs, and the safety threat has become a prominent issue needing urgent address. Therefore, LIB fault diagnosis has become a global research hotspot (Z. Wang et al, 2020). Many fault diagnosis methods have been widely studied, such as state-of-health, sensor fault , connection fault and insulation fault diagnoses, internal short circuit (ISC) and external short circuit detection, and abnormal voltage (Z.H .Huang et al, 2020) , overcharge and over discharge fault diagnosis and thermal fault diagnoses. According to Federal Aviation Administration, from 2006-2022, there have been 1656 lithium-ion fire related incidences and 765 injuries with 113 deaths.

Internal short circuit -ISC is the most common and representative safety failure mode, which is one of the most important factors causing battery failure and safety problems and has been widely researched by scholars all over the world. Within safety accidents of LIBs in and energy storage EVs, Thermal runaway (TR) has become a common catastrophic safety accident, currently being the primary cause of safety accidents that have occurred (Z. wang et al,.2020). LIBs in EVs are often composed of dozens, hundreds, or thousands of cells in series and in parallel. When one of the cells presents TR, the phenomenon may spread within the battery pack, causing fire, explosion, and/or other serious consequences (Y. Zheng et al,. 2021). Due to the failure mode in lithium-ion batteries , which is often catastrophic and dangerous, this has sent a strong message to the public on the use of lithium-ion batteries. This in fact will impact the push to renewable energy in the fuel mix, as most of the renewable energy sources are intermittent in the generation.

1.1.1 TYPES AND FORMS ENERGY STORAGE TECHNOLOGIES

Energy storage comes in various forms and types. My research on how we can detect early faults in energy storage systems will review all forms of energy storage technologies and narrow focus on electrochemical energy storage. Mechanical energy storage comes in the form of Flywheels, pumped hydro storage and compressed energy storage technology. Thermal Energy Storage which comes in the form of hot water storage, thermal fluid, ceramic storage. Electrical energy storage in the form of capacitors, super capacitors, and superconductive magnets. Chemical energy storage in the form of fossil fuel, Ammonia and Finally Electromechanical energy storage which comes in as Batteries, Hydrogen, and flow batteries.

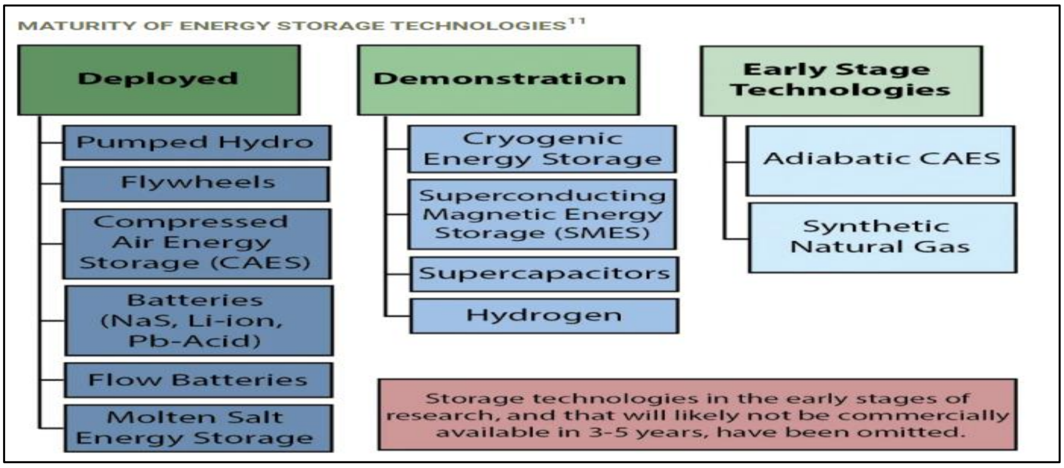


Figure 4 *- A chart of different storage technologies under various stages of maturity- Deployment, demonstration, and early-stage technologies.*
Source: Center for sustainable system, University of Michigan.2021. ‘‘ U.S. Energy Storage Factsheet. ‘‘Pub. No. CSS 15-17. www.css.umich.edu/publications

There have been large scale energy storage technologies that have been deployed over the years and others are still under demonstration and others in the early-stage technologies. According to the University of Michigan, Center for Sustainable System, pump hydro technology is the most matured and deployed technology worldwide with about 96% . It also has the longest lifetime of about 5-60 years and operational efficiency of 70 and 85%.(U.S. DOE (2013) Grid Energy Storage)

1.1. 2 MECHANICAL ENERGY STORAGE (FLYWEEL)

This is by means of drawing on the kinetic forces of rotation or gravitation to store energy. A typical example is magnetic flywheel system that employ kinetic energy stored in a rotating mass with very low frictional losses. When Electric energy input accelerates the mass to speed via an integrated motor-generator. The energy is discharged by drawing down the kinetic energy using the same motor-generator. The amount of energy that can be stored is proportional to the object’s moment of inertia times the square of its angular velocity. By conservation, Energy equation is given by:

$$\mathbf{E}_{\text{mech}} = \boldsymbol{Epot} + \boldsymbol{Ekin} = mgh + \frac{1}{2}\mathbf{m}v^2 \qquad \text{(Eq 1)}$$

Where m, g, h, and v are the mass , gravitational constant, height, and velocity of the acceleration of the motor.

Flywheel energy storage can be understood as a single mass point m rotating around a fixed axis at a distance **r** and an angular velocity **w** . The orbital speed v is then determined by the distance r and the angular velocity w :

$$\boldsymbol{V = rw} \qquad \text{(Eq 2)}$$

For a single mass point m on an orbit r, the Kinetic energy is given by.

$$\boldsymbol{Ekin = \frac{1}{2}\mathbf{m}v^2} \qquad \text{(Eq 3)}$$

1.1.3 ADVANTAGES OF FLYWHEEL ENERGY STORAGE

As a review of this storage technology, there are some advantages associated with flywheel technology. They have high energy density and substantial durability which allows them to be cycled frequently with no impact on performance. They also have very fast response and ramp rates. In fact, they can go from full discharge to full charge within a few seconds or less. A flywheel can potentially have an indefinite working lifespan. By a simple measurement of the rotation speed, it is possible to know the exact amount of energy stored.

1.1.4 DISADVANTAGES OF FLYWHEEL ENERGY STORAGE

This technology of storing energy by spinning systems has its limitations, these includes.

Flywheel storage turns to lose much of their stored energy in very short, about 20% to 50% , Much of this, is the friction responsible for the energy loss results from the flywheel changing orientation due to the rotation of the earth. This change in orientation is resisted by the gyroscopic forces exerted by the flywheel's angular momentum. Due to low tensile strength and high spinning power, they turn to be explosive and cause shattering due to wheel overloads, this creates a lot of safety concerns**.**

1.1.5 APPLICATION OF FLYWEEL ENERGY STORAGE

The global flywheel energy storage system market size was valued at USD 326.43 Million in 2021 and is expected to expand at a compound annual growth rate (CAGR) of 9.8% from 2022 to 2030. The growing energy storage market and automobile industry, globally, have supplied a boost to the market.(Fortune business insight, 2021)

Application Outlook	Regional Outlook-Countries in used of Technology
1. Uninterruptible power supply	1 North America-U.S.A
2. Data center	2. Europe-Germany, U.K
3. Distributed energy generation	3. Asia Pacific- Japan, South Korea
4. Transportation	4. Central and South America-Brazil
5. Others	5. Middle East and Africa-South Africa

Table 1*: Table of Application and regional outlook use of magnetic flywheels technology Source:. https://www.fortunebusinessinsights.com/industry-reports/flywheel-energy-storage-market-100756*

1.1.6 PUMP HYDRO ENERGY STORAGE TECHNOLOGY

Another form of mechanical energy storage technology is pumped hydro storage technology: Pumped hydro energy storage is one of the common off-grid and remote electrification applications. Nevertheless, PHES is considered the most promising system for handling large electricity networks. Pumped-storage plants operation includes an upper and lower reservoir. As shown in Figure 2, in appendix, these reservoirs are artificially constructed and stores energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation. The upper reservoir is a separate reservoir with no or negligible natural intake. The lower reservoir can either flow into a river or be self-contained. When the network requires energy, for example to cover peak loads, the generator in the machine house generates electricity that is then fed into the public network using a transformer. The generator is driven by a turbine, which is in turn driven by flowing water.

It is built with a surge tank that is used to balance rapid pressure changes during electricity generation start-up or shut down. During low-load times, surplus energy from the network is used to pump the water from the lower reservoir to the upper reservoir. The upper reservoir is generally designed to allow full load operation for at least three to five hours. Since pumped-storage facilities are high-pressure facilities and drop heights can far exceed 50m.

The energy used by hydropower plants to generate electricity is a kind of potential energy called energy of position. This is the difference in energy between a higher position and lower position. Since the upper reservoir is above the lower reservoir, it has a higher potential energy. This energy is also called work capacity. It is calculated from the storage content V ,the density of water, P, the force of gravity, the effective drop height delta h , and the total efficiency “n total” $\boldsymbol{E = V\rho . g . \triangle h . \eta total}$ (Eq 4)

Where?

E= potential energy, V=Volume, G=Gravitational acceleration (g = 9.81 m/s^2)

g= Density of water(1,000 kg/m^3)

$\triangle$H=Effective drop-height

ηtotal= total efficiency

Efficiency is the ratio between the electric energy yield or the electric power and the supplied electric energy or electric power. The losses that determine the efficiency level are illustrated in figures using a pumped-storage plant as an example. The supplied electric energy is always larger than the electric energy recuperated. With pumps and turbines, losses occur in the transformer, the generator or motor, the turbine or pump, and the pipeline (Pavlos et al, 2017). The total efficiency of a generator or pump is calculated by multiplying the partial efficiencies. Modern pumped-storage plants have efficiency levels ranging up to 83%. Pump hydro energy storage technology depends on the following key parameters, efficiency, losses, energy density, power density and full load hours.

$$\boldsymbol{W = \frac{m.g.\triangle h}{V}, p.g.\triangle h} \qquad \text{(Eq 5)}$$

Where the following

W= Energy Density

m-mass

ηtotal=ηpηT,P.ηG,M.ηTrans

ηp=Pipe efficiency

ηTp=Turbine /pump efficiency

ηG,M.=Generator /motor efficiency

ηTrans=Transformer efficiency

1.2.1.4 USE OF PUMPED HYDRO ENERGY STORAGE TECHNOLOGY

Pumped-storage plants are chiefly used to store electric energy during low-load times and generate electricity during peak-load times. They are also used to keep the power and frequency stable and to provide reactive power control, which is called synchronized condenser operation. The world's first large scale plant was constructed in 1929 and now there are over 300 PHES plants with a total installed capacity of over 120 GW, representing almost 99% of worldwide installed electrical storage capacity and about 3% of global generation (Deane et al. 2010). Due to their not-rapid response, PHES plants were initially built for energy management applications to maximize base-load generation. Assuming that most of the suitable locations with a major height difference have already been exploited, in the short-term, innovative pumped hydro should be upgraded by adding more turbines to increase flexibility and offer higher ramp rates over a shorter time (T. Undeland,. et al) . This will bypass the main drawback, which is the extremely long construction time needed. A second innovation developed in recent years and being the focus of research for PHES technology is the variable-speed pump-turbine, enabling increased flexibility, efficiency, and reliability at the expense of initial cost. Aiming to address the constraints of suitable site availability and environmental impact, alternative reservoir types such as sub-surface, instead of over-ground reservoirs, storing seawater instead of fresh water and other innovative seabasses solutions have been studied. In addition to increasing the number of suitable locations, by utilizing the open sea as the lower reservoir, concerns over freshwater use are reduced. However, additional costs related to pumping may occur in both proposed technologies due to an event of a fracture or even a collapse in the sub-surface of a PHES, or the corrosive operational environment of seawater pumped hydro (National hydropower Association, 2020). Finally, minimal environmental impact, larger energy capacities and reduced costs are also expected from other solutions proposed, such as the hydraulic lifting of masses during charging and discharge by releasing them to sink gravitationally, forcing water to pass through a turbine. Although these research proposals seem technically and economically feasible, a demonstration plant is needed for their commercialization and their contribution in sustainable development (Global market insight,. 2021).The advantages of this technology include Low lifetime cost and independence from raw materials, Provide huge amount of energy/power for longer period, relatively very large efficiency, and long asset life. It disadvantages includes. creating huge environmental discomfort to people and other living organisms, requiring huge upfront capital and expensive, not always safe and can have limited reservoir capacity, Climate Dependent, this can be severely affected by drought and high energy loss due to reverse water pump uphill.

1.1.7 PUMP HYDRO ENERGY STORAGE TECHNOLOGY MARKET

The North America pumped hydro storage market revenue is poised to reach USD 72 billion by 2028 led by ongoing adoption of renewable solutions along with an increasing demand for storage mechanisms in the region. (Global market insight, 2022)

Figure 5: Graph illustration of the global market for pumped hydro storage.
Source: [Pumped Hydro Storage Market Share / Forecast Analysis, 2028 (gminsights.com)]

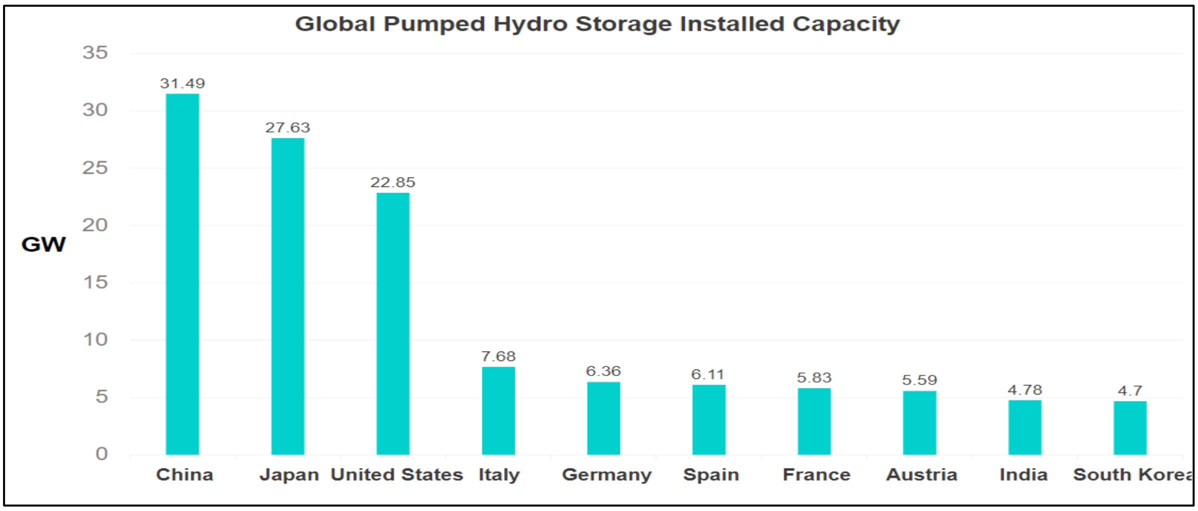


***Figure 6**: A graph of Global Pumped Hydro Storage*
Source: https://www.blackridgeresearch.com/reports/global-pumped-hydro-storage-phs-market.

1.1.8 COMPRESSED AIR ENERGY STORAGE TECHNOLOGY(CAES)

Compressed Air Energy Storage-(CAES) involves the conversion of electrical energy into high-pressure compressed air that can be released later to drive a turbine generator to produce electricity. This makes it ideally suited to work along intermittent energy sources such as solar PV and wind energy. Compressed air energy storage (CAES) plants are largely equivalent to pumped-hydro power plants in terms of their applications. But, instead of pumping water from a lower to an upper pond during periods of excess power, in a CAES plant, ambient air or another gas is compressed and stored under pressure in an underground cavern or container.

When electricity is needed, the pressurized air is heated and expanded in an expansion turbine driving a generator for power production. Compressed-air energy storage (CAES) facilities have been commercially deployed but are not nearly as widespread as PSH plants. Only two full-scale CAES systems are in operation in the world today: one in Germany and one in the United States, At the largest of these, in operation since 1978 at Huntorf in Germany, a

0.3×10^6 m^3 cavern is pressurized using 60 MW of excess nuclear generated electricity for 8 h per daily cycle and the compressed air feeds a natural gas-fired turbine to generate 320 MW for 2 h during the high-demand period (Mclarnon F et al.1989). The third commercial CAES is a 2700 MW plant that is planned for construction in the United States at Norton, Ohio developed by Haddington Ventures Inc.. This 9-unit plant will compress air to ~10 MPa in an existing limestone mine dome 670m underground. The volume of the storage cavern is about 120,000,000 m3.

Project Markham, Texas: This 540 MW project developed jointly by Ridged Energy Services and EI Paso Energy will consist of four 135 MW CAES units with separate low pressure and high-pressure motor driven compression trains. A salt dome is used as the storage vessel.

Iowa stored energy project: This project under development by Iowa Association of Municipal Utilities, promises to be exciting and innovative. The compressed air will be stored in an underground aquifer, and wind energy will be used to compress air, in addition to available off-peak power. The plant configuration is for 200MW of CAES generating capacity, with 100MW of wind energy. CAES will expand the role of wind energy in the region generation mix and will operate to follow loads and provide capacity when other generation is unavailable or non-economic. The underground aquifer near Fort Dodge has the ideal dome structure allowing large volumes of air storage at 3.6 MPa pressure.

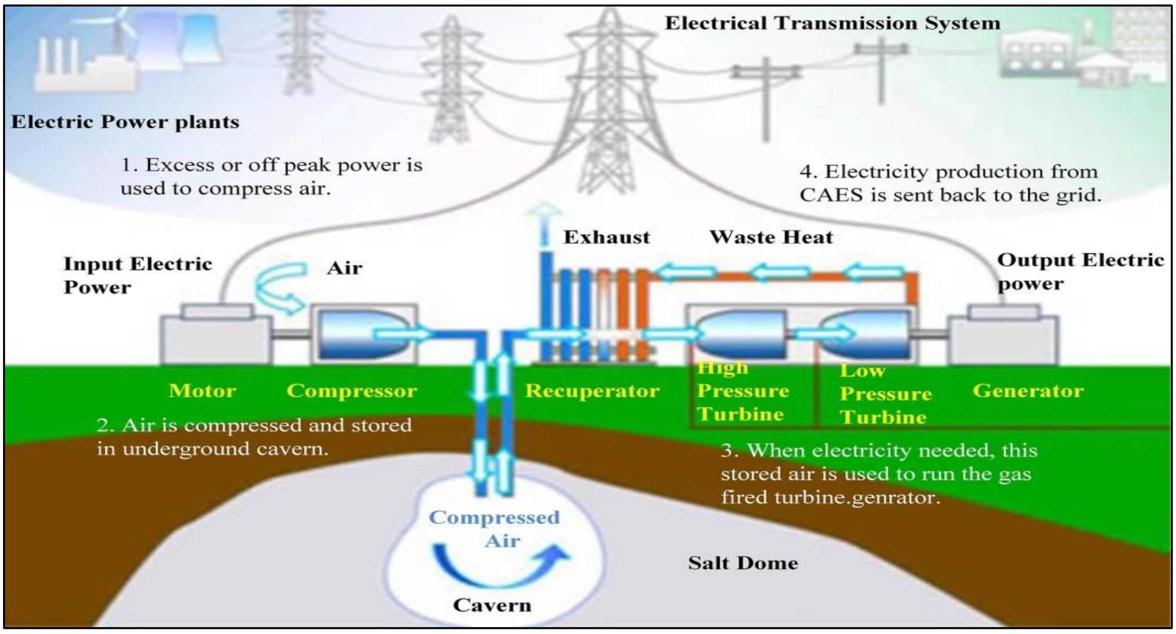


Figure 7- *Image of compressed air energy storage technology*
Source Compressed air energy storage - Energy Education

Its principle is based on conventional gas turbine generation. As shown in fig 5, CAES decouples the compression and expansion cycle of a conventional gas turbine into two separated processes and stores the energy in the form of the elastic potential energy of compressed air. In low demand periods, energy is stored by compressing air in an airtight space (typically 4.0~8.0 MPa) such as underground storage cavern. To extract the stored energy, compressed air is drawn from the storage vessel, mixed with fuel, and combusted, and then expanded through a turbine. And the turbine is connected to a generator to produce electricity as shown in figure 5. The waste heat of the exhaust can be captured through a recuperator before being released into the atmosphere.

1.1.9 PROS OF COMPRESSED AIR ENERGY STORAGE TECHNOLOGY

Due to technological advancement and high demand for energy and storage technology, there are some advantages that come with the use of compressed air energy storage technology. A CAES system stores energy by using off-peak electricity to compress air and store it in a reservoir and offer quick ramp rates like PSH facilities. Although large, steel, aboveground containers can be built to use as a reservoir for the compressed air, naturally occurring salt caverns often supply a more cost-effective alternative (Liu et al., 2016). This technology offers high reliability in combination with low environmental impact and in addition the storage volume is found underground (CAES offers operators a wide operating range of up to 90 percent with a low sustainable low (LSL) rating of 10 percent of plant output. By comparison, a combined cycle gas turbine has an LSL rating of just 50 percent of plant output.

‘‘CAES remains the most cost-effective energy storage system on a total installed cost basis for a 100MW 10-hour system’’ (U.S. Department of Energy, December 2020)

1.2.0 CONS OF COMPRESSED AIR ENERGY STORAGE TECHNOLOGY

Compressed air energy storage has lower efficiency of energy storage and conversion. As it is one of the oldest technologies many companies have been involved in this technology, it possesses some limitations and disadvantages. Some of the limitations is its low energy efficiency. During compressing air, some energy is lost due to heat generated during compression, which cannot be fully recovered. This reduces the overall efficiency of the system. Additionally, the process of compressing air requires a significant amount of electricity, which reduces the net energy generated by the system. Also, in Compressed air-based energy storage's system has low efficiency , this is because, during compressing air, some energy is lost due to heat generated during compression, which cannot be fully recovered. This reduces the overall efficiency of the system. Additionally, the process of compressing air requires a significant amount of electricity, which reduces the net energy generated by the system. Another disadvantage of CAES is the limited locations where the system can be installed. In addition, the system requires a specific geological condition, such as a salt cavern or an underground rock formation, which limits the potential locations for the system's installation. (Kendall Mongird et al.2020, Grid energy storage technology cost)

Other disadvantages include slower responding to disruptions in the grid than quick-response technologies like flywheels or batteries, which is a very big setback for its application. Specific geographic formations are typically needed for CAES installation and associated with greenhouse gas emissions and the efficiency depends on various factors, such as the size of the system, location, and method of compression. Typically, the efficiency of a CAES system is around 60-70%, which means that 30-40% of the energy is lost during the compression and generation process. (eia.gov,. 2020)

1.3.0 LIMITATIONS OF COMPRESSED AIR STORAGE TECHNOLOGY

There are various types of this technology including adiabatic systems and diabatic systems. The difference between these two configurations is that adiabatic systems capture and store the heat generated through the compression process to re-use later in the air expansion process to generate a larger amount of power output. For diabatic systems, the heat generated during compression is simply released.(Shixu et al., 2019). reserve capacity of compressed air). For peak shaving, load leveling, energy management, renewable energy integration and for standby power. However, this technology has a limitation, it highly reliance on favorable caverns is a drawback and depends on fossil fuel to run the generators. There have been two major deployments of this system worldwide, this includes the one in Huntorf in Germany and the other Mclntosh in Alabama with both size of 290 mw and 110 MWh both established in 1978 and 1991 respectively (Budt et al., 2016. pp 250-268).

1.4.0 ELECTROCHEMICAL ENERGY STORAGE AND MATERIAL CHEMISTRY.

An electrical energy storage device, which electrochemically converts chemical energy of its active components directly into electrical energy with the help of electrochemical oxidation-reduction (redox) reactions is terms as electrochemical energy storage technology. The oxidation reactions lead to loss of electrons and reduction reactions tend to gain those electrons. Continuous oxidation and reduction process within an electrochemical cell creates the flow of electrons through an external circuit to power the load connected to it. Electrochemical batteries for energy storage can be categorized into two. These are:

1. Low-temperature batteries such as lead, nickel, and lithium batteries, and high temperature batteries such as sodium-sulfur batteries.
2. Two further categories are batteries with external storage such as redox flow batteries, and those with internal storage (most batteries).

In the battery operation to release the stored energy for use, some are just one time generation and transformation of the energy use and others are repeatable forms to generate the energy. Electrochemical batteries have many technologies and chemistries which turn to give power or energy depending on the use case. Table two (2) in appendix shows batteries and their transformation of energy.

1.4.1.0 LEAD ACID BATTERY TECHNOLOGY

The lead sulfuric acid system was invented 150 years ago and is still one of the best-known electrochemical systems. In its first form, it consisted of sheets of lead rolled together. The active mass layer was produced by charging and then reversing the polarity (Gaston Planté, 1859). The first electrodes with an electrode grid and active mass paste followed (Camille Faure, 1881). Industrial production began at the end of the 19th century (Henri Tudor, 1887). Later improvements in lead batteries were intricately linked to developments in plastics. At the beginning of this century, lead-acid battery storage became increasingly important for network-connected applications in the local (10 kWh) and decentralized (1 MWh) sectors. For local applications, these facilities can be run as stand-alone systems or as network-connected systems. They are frequently used in connection with renewable energy generation. Specially designed stationary lead batteries are used for these applications.

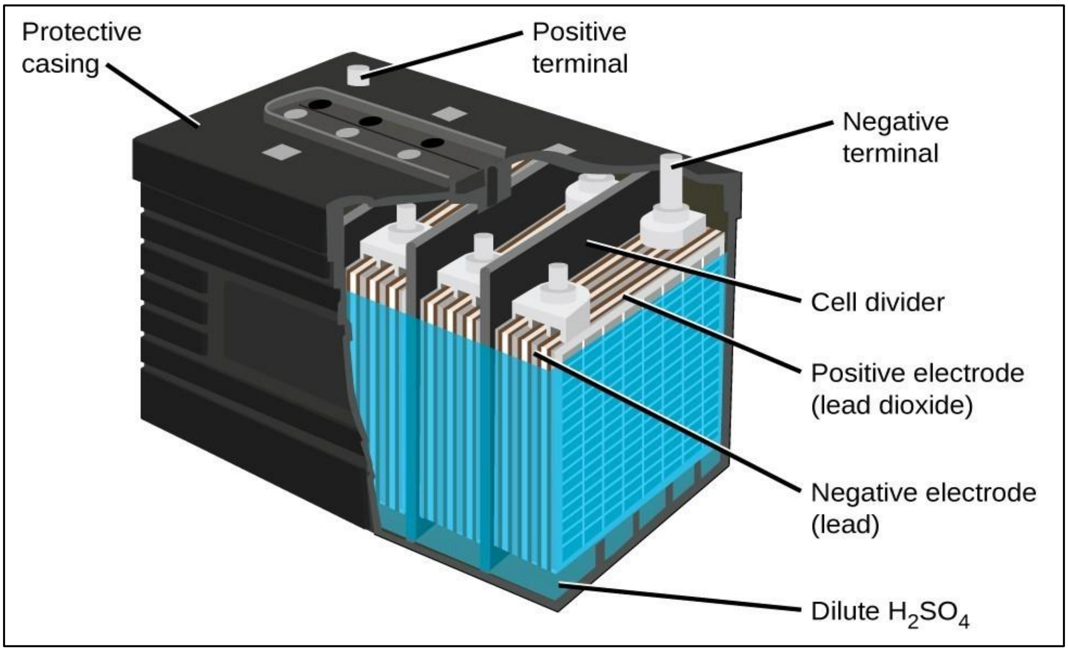


Figure 8 *. Image of a cut view of Lead acid batteries*
Source: (itielectriciantrade.com)

1.4.1.1 LEAD ACID BATTERY OPERATION

A lead acid battery consists of a negative electrode made of spongy or porous lead. The lead is porous to facilitate the formation and dissolution of lead. The positive electrode consists of lead oxide. Both electrodes are immersed in an electrolytic solution of sulfuric acid and water. In case the electrodes encounter each other through physical movement of the battery or through changes in thickness of the electrodes, an electrically insulating, but chemically permeable membrane separates the two electrodes. This membrane also prevents electrical shorting through the electrolyte. Lead acid batteries store energy by the reversible chemical reaction shown below. These constituents are all contained within a plastic container which acts to keep the electrolyte in and the battery together. The overall battery will normally consist of several cells placed in series to give the required voltage as each cell can provide an EMF of 2.1 volts. Lead acid batteries have both advantages and disadvantages as a mature technology of its kind, The charging reaction converts the lead sulfate at the negative electrode to lead. At the positive terminal the reaction converts the lead-to-lead oxide. As a by-product of this reaction, hydrogen is evolved (Wikipedia,.2023). During the first part of the charging cycle, the conversion of lead sulfate to lead and lead oxide is the dominant reaction. However, as charging proceeds and most of the lead sulfate is converted to either lead or lead dioxide, the charging current electrolyzes the water from the electrolyte and both hydrogen and oxygen gas are evolved, a process known as the "gassing" of the battery. If current is being provided to the battery faster than lead sulfate can be converted, then gassing begins before all the lead sulfate is converted, that is, before the battery is fully charged. Gassing introduces several problems into a lead acid battery (Pveducation.org , 2022). Not only does the gassing of the battery raise safety concerns, due to the explosive nature of the hydrogen produced, but gassing also reduces the water in the battery, which must be manually replaced, introducing a maintenance component into the system. In addition, gassing may cause the shedding of active material from the electrolyte, thereby permanently reducing battery capacity. For these reasons, the battery should not regularly be charged above the voltage which causes gassing. it has numerous advantages, which includes being a mature technology, relative cheap to manufacture and buy with large current capability which can be used in different applications, also tolerant to abuse and overcharging with wide range of size and specifications which are produce worldwide. Its drawbacks include shorter cycle life, typically 300-500 cycles, corrosive electrolyte and are not environmentally friendly. Also are not suitable for fast charging with lower efficiency of 70%.

1.4.1.2 TYPES OF LEAD ACID BATTERIES

Sealed Lead–acid (SLA- They are used in Small UPS, emergency lighting, and wheelchairs. Because of its low price, dependable service, and low maintenance requirement, the SLA remains the preferred choice for health care in hospitals and retirement homes.

Valve-regulated lead–acid (VRLA)- Power backup for cellular repeater towers, internet hubs, banks, hospitals, airports, and others.

Absorbent glass mat (AGM)- Starter battery for motorcycles, start–stop function for micro-hybrid cars, as well as marine vehicles and RVs that need some cycling.

1.5.1 NICKEL CADMIUM BATTERIES

Nickel-Cadmium batteries are made from two electrodes (Nickel and Cadmium hydroxide) immersed in a potash solution. The positive electrode consists of Nickel hydroxide, while the negative one is made from Cadmium. The electrolyte is based on potash. The voltage varies from 1.15 to 1.45 V per cell with a nominal value of 1.2 V. Nickel batteries were developed to meet the need for electrochemical storage with a higher-energy density and greater reliability than conventional lead batteries. They can be manufactured in various technologies and the most important technologies used are Pocket-plate electrodes, sinter electrodes, Fiber structure electrodes and foam electrodes.

Nickel batteries have a low-rated voltage of only around 1.3 V. Practically no aging and corrosion processes occur in alkaline electrolytes. As a result, these cells have a long service life . Nickel batteries are suited for use at low- temperatures. The nickel -Cadmium batteries have some limitations such as losing capacity quickly and being able to store much energy and their disposal is a bit of problem since material is very toxic.

Chemical Reactions for Nickel Cadmium Batteries

Negative electrode

$$Cd + 2OH^- \underset{\text{Charge}}{\overset{\text{discharge}}{\longleftrightarrow}} Cd(OH)_2 + 2e \quad \text{(Eq 6)}$$

Positive electrode

$$2NiOOH + 2H_2O + 2e^- \overset{\text{discharge}}{\longleftrightarrow} 2Ni(OH)_2 + 2OH^- \quad \text{(Eq 7)}$$

$$Cd + 2NiOOH + 2H_2O \overset{\text{discharge}}{\longrightarrow} Cd(OH)_2 + 2Ni(OH) \text{ Charge} \quad \text{(Eq 8)}$$

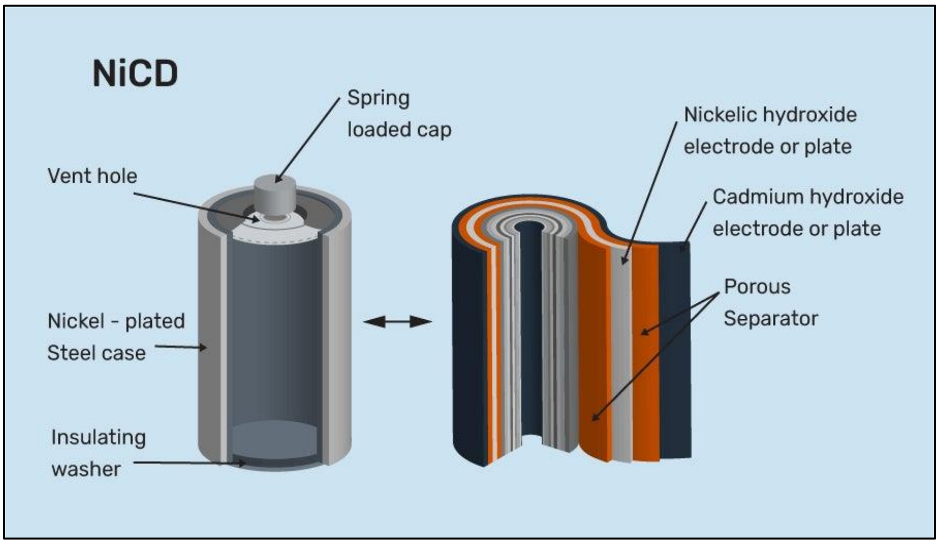


Figure 9- Internal cut view of NiCD battery
Source: https://www.solarreviews.com

1.5.2 METAL AIR BATTERIES

Metal-air batteries can be considered as special types of fuel cell which use metal instead of fuel and air as oxidants. The anodes in these batteries are commonly available metals with high energy density such as lithium (Li), aluminum (Al) or zinc (Zn), while the cathodes are made of either porous carbon or metal mesh capable of absorbing oxygen (O2) from air.

The liquid or solid electrolytes are mainly good hydroxide ion (OH^-) conductors like potassium hydroxide (KOH). Li-air has a theoretical specific energy as high as 11,140 Wh/kg, there are concerns about a probable fire hazard due to the high reactivity of Li with humid air, it possesses a much more expensive cell compared to Zn-air, which is environmentally benign and exhibits a long storage life while un-activated . Hence, Zn-air represents the only technically feasible example of metal-air batteries to date, offering a high energy density (650 Wh/kg). It supplies a cell voltage of 1.6V, temperature range from -20 to 50◦C and negligible self-discharge rate. However, it is difficult to recharge and offers a limited cycling capability of a few hundred cycles along with a quite low efficiency of 50% . However, Zn-air constitutes a developing technology that looks promising and able to contribute to future energy management applications. The chemical reactions, at the anode and cathode of a Zn-air cell shown below in the equations (10,11and 12).

Zn + 2OH− Zn(OH)2 + 2e **(Eq 9)**

H2O + 1 2 O2 + 2e − 2OH− **(Eq 10)**

3 4 O2 + 3 2 H2O + 3e − 3OH- **(Eq 11)**

1.5.3 SODIUM -SULFUR (NAS) & SODIUM METAL CHLORIDE

NaS batteries are constructed from inexpensive materials and are considered an attractive option for large-scale stationary electrical storage applications, since they offer high energy density (150-345 kWh/m3) and cycle efficiency (89-92%), long cycle life (1500-5000 cycles) and they are much smaller and lighter than NiCd, NiMH and Placid .The main disadvantages of NaS technology are the corrosive nature of the manufacturing materials and the requirement for constant heat input to maintain the electrolyte's molten state, which is ensured at 300-350◦C increasing the hazard of probable reaction between electrode materials and the associated fire risk. The two elements combine to form sodium polysulfides, the sodium ion is released back through the electrolyte. The discharge process produces roughly 2 Volts and accumulator produces temperature of around 320-degree C. The cells are placed in thermally insulated containers and require heating and cooling. Since sodium is highly reactive with water, it must be protected from contact with the environment in a metal container. During operation, current heat is adequate to maintain the optimal operating temperature. The heating system is needed in idle phases. This also figure out the efficiency :The battery itself has a low self-discharge rate . But over long idle periods ,electric heating causes the battery to discharge at an unusually high rate . Sodium Sulfur Batteries use sodium Sulfur as a composition, with negative molten sodium as cathode, positive molten sulfur as cathode and Beta Aluminum and ceramic electrolyte as a separator. It is a mature technology in the market, hermetically sealed in operation, hence very environmentally friendly with lower cost , no self-discharge, extremely quick response time make them an excellent candidate for responding to changes in demand in a grid system. The drawback of the battery includes requiring a heat source for operation and not being able to use in mobile application.

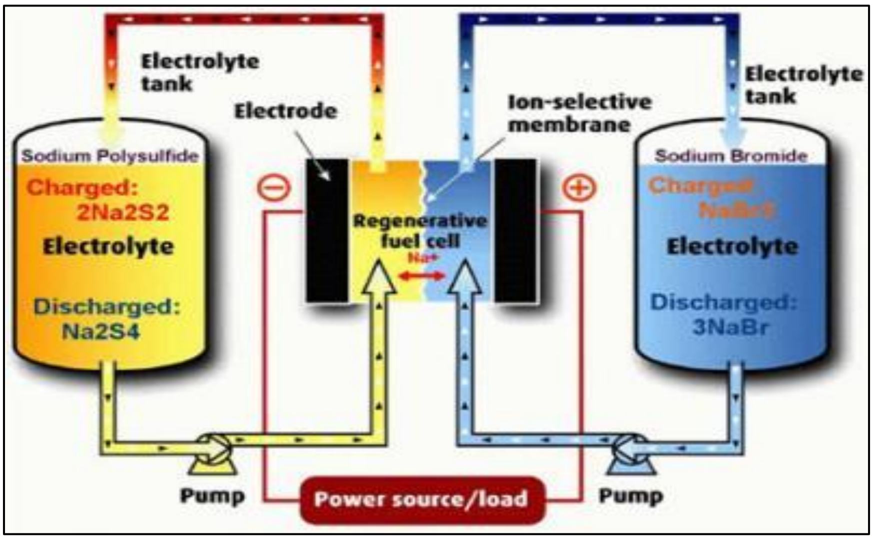


Figure 10- *Chemical operation of sodium sulfur battery system*
Source: https://electrosynthesis.com/energy-storage/

1.5.4 FLOW BATTERIES

A flow battery is a rechargeable battery in which electrolyte flows through one or more electrochemical cells from one or more tanks. With a simple flow battery, it is straight forward to increase the energy storage capacity by increasing the quantity of electrolyte stored in the tanks. The electrochemical cells can be electrically connected in series or parallel, so finding the power of the flow battery system.

The interconversion of energy between electrical and stored chemical energy takes place in the electrochemical cell. This consists of two half cells separated by a porous or an ion exchange membrane. As well as allowing ionic conduction, the separator minimizes the loss of the generated electroactive species in the half cells and so maintains high coulombic efficiency. The redox reactions during charge and discharge take place at the electrodes of the half cells. In their simplest form the electrodes themselves, usually carbon felt, are not altered by these electrochemical reactions. The cell voltage is the difference between the negative electrode reaction and that at the positive electrode. During charging electrons released at the positive electrode through oxidation of the electroactive species in that half-cell are pushed round the circuit to the negative electrode where reduction of electroactive species in that half-cell takes place. The processes are reversed on discharge.

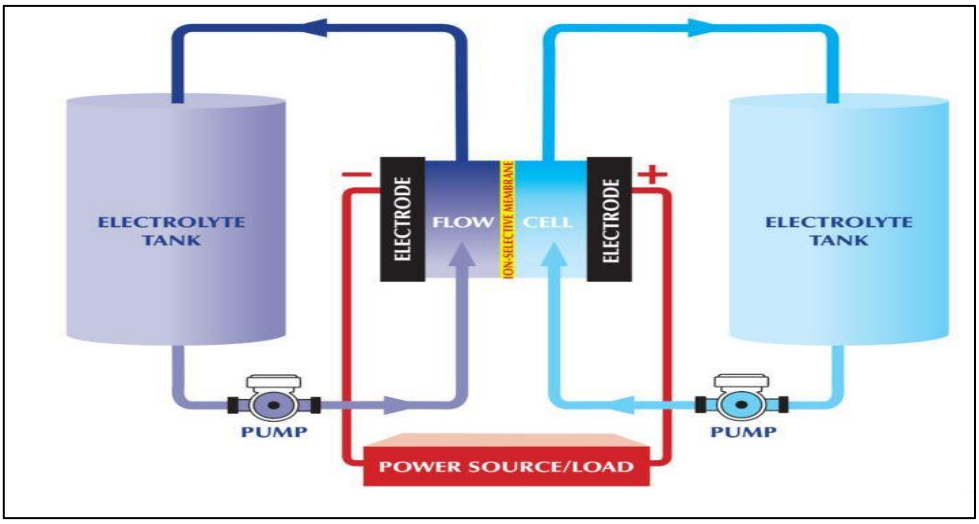


Figure 11- *An image of process of flow batteries*
source: https://flowbatteryforum.com/what-is-a-flow-battery/

1.5.6 PROS AND CONS OF FLOW BATTERIES

Flow battery technology is modular and scalable so systems can be made to suit a wide range of applications, from power ratings of watts to megawatts, and with energy durations of many hours or even days. The battery can be constructed of low cost and readily available materials, such as thermoplastics and carbon-based materials. Many parts of the battery can be recycled. Electrolytes can be recovered and reused, leading to low cost of ownership. The battery materials have low flammability and low environmental impact. The electrolytes can be used as part of the heat management strategy for the battery, reducing the need for complex heating or cooling of the battery system. This reduces costs, overcharging and fully discharged does not usually cause permanent damage to the electrodes or electrolytes. There is limited self-discharge in standby mode and, when shut down, there is no self-discharge.

The cost of an energy-storage device is a major obstacle to utility adoption. Analysis suggests that the cost of vanadium chemicals varies widely but could contribute between \$50/kWh to \$110/kWh, or from 50 -100% of the cost target of \$100 - \$200/kWh for the energy-storage system. From this standpoint, identifying low-cost redox couples with high solubility is critical to meeting market requirements. The other key cost factor is the construction of the electrochemical cell itself. The construction cost of the cell scales with the total power requirement of the application, but these costs are directly related to the specific power of the device itself - how effectively the rates of the materials are used. While flow batteries ought to be able to operate at relatively high current densities, as convection can be employed to deliver reactants to the electrode surface, flow batteries have typically been operated at ~50 mA/cm^2, a current density consistent with conventional batteries without convection.

1.5.7 SOLID STATE BATTERIES

Solid state batteries have multiple advantages over lithium-ion batteries in large-scale grid storage. Solid-state batteries have solid electrolytes which have higher energy densities and are much less prone to fires than liquid electrolytes, such as those found in lithium-ion batteries. Their smaller volumes and higher safety make solid-state batteries well suited for large-scale grid applications.

However, solid state battery technology is currently more expensive than lithium-ion battery technology because it is less developed. Fast-growing lithium-ion production has led to economies of scale, which solid-state batteries will find hard to match in the coming years.

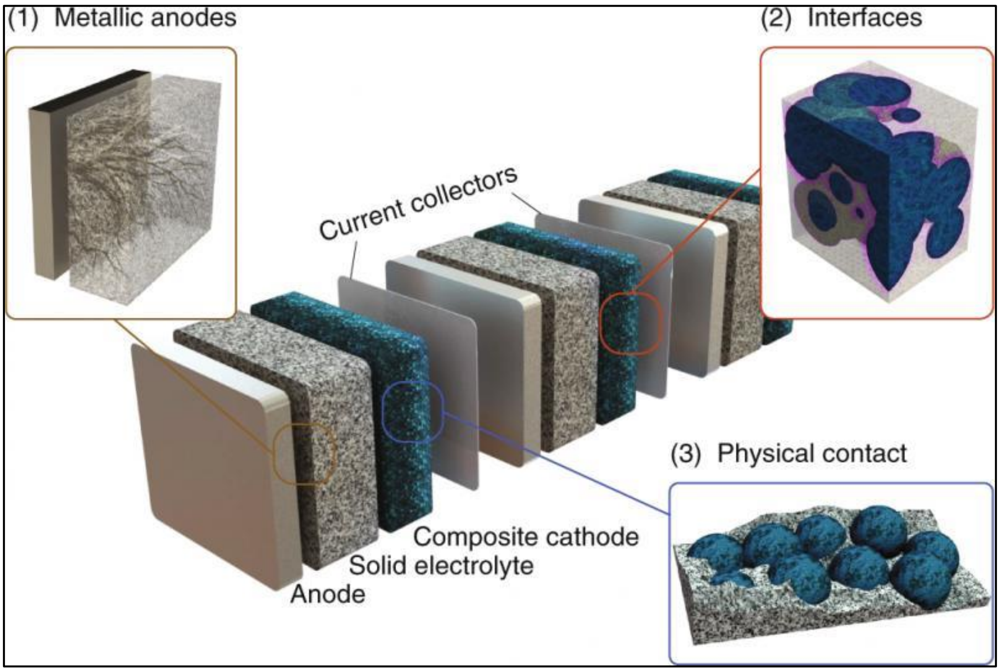


Figure 12*-A picture of Solid-state batteries*
Source: https://www.openpr.com/news

1.5.6 HYDROGEN

Hydrogen fuel cells, which generate electricity by combining hydrogen and oxygen, have appealing characteristics: they are reliable and quiet (with no moving parts), have a small footprint and high energy density, and release no emissions (when running on pure hydrogen, their only byproduct is water). The process can also be reversed, making it useful for energy storage: electrolysis of water produces oxygen and hydrogen. Fuel cell facilities can, therefore, produce hydrogen when electricity is cheap, and later use that hydrogen to generate electricity when it is needed (in most cases, the hydrogen is produced in one location, and used in another).

Hydrogen can also be produced by reforming biogas, ethanol, or hydrocarbons, a cheaper method that emits carbon pollution. Though hydrogen fuel cells remain expensive primarily because of their need for platinum, an expensive metal, they are being used as primary and backup power for many critical facilities such as telecom relays, data centers, credit card processing.

1.5.7 CHEMICAL ENERGY STORAGE

The chemical energy storage with second energy carriers is also presented with hydrogen, hydrocarbons, ammonia, and synthetic natural gas as storage and energy carriers. This energy storage system can support grid power, transportation, and a host of other large-scale energy needs including avionics and shipping. Chemical energy storage plays a vital role as an enabling technology for renewable and hybrid energy systems (*Ellen Matson, 2028)* Journal of the Royal Society of Chemistry. Chemical energy storage based on chemical reaction.is particularly appropriate for long duration energy storage applications, example , seasonal storage of solar heat, because the process involves almost no energy losses during the storing period, storage is usually done at ambient temperature. This battery technology its own strong side and drawbacks,

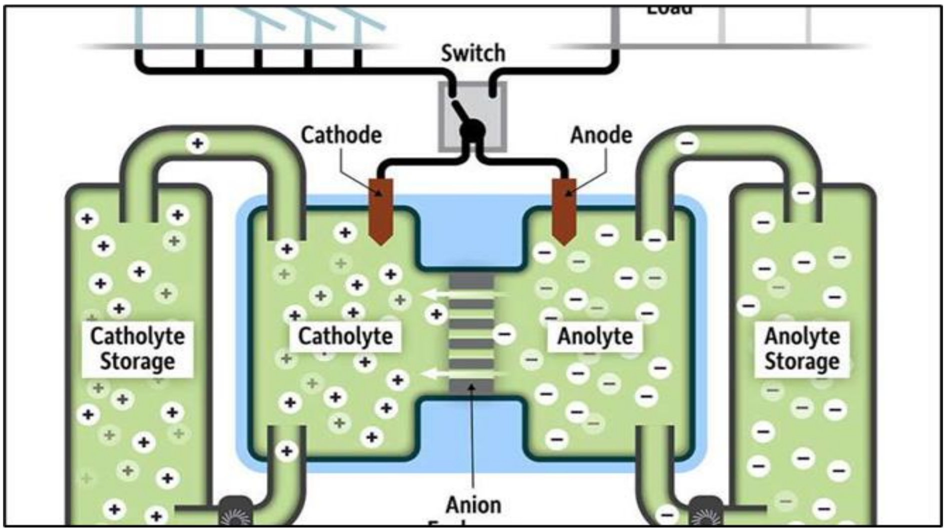


Figure 13- *Technical View of Chemical Energy Storage*
Source: *[energy storage for large grids (phys.org)]*

1.5.8 PROS AND CONS OF CHEMICAL ENERGY SSTORAGE

Can store large amounts of energy for use and it has the capacity to release large amounts of energy. The mature technology makes it useful in vehicles and airplanes. The positive sides also come with negative side , which is related to the fuel use, the hydrocarbons used in its fuel are expensive and can contribute to the greenhouse effect , which interns help to pollute the environment.

1.6.0 LITHIUM METAL AND CELL MATERIALS

Lithium was discovered from a mineral, while other common alkali metals were discovered from plant material. Lithium metal is made into alloys with aluminum and magnesium, improving their strength and making them lighter (Samar Basu et al, .1973). A magnesium-lithium alloy is used for armor plating. Aluminum-lithium alloys are used in aircraft, bicycle frames and high-speed trains. Lithium oxide is used in special glasses and glass ceramics. Lithium chloride is one of the most hygroscopic materials known and is used in air conditioning and industrial drying systems as is lithium bromide (John Bannister Goodenough , 1983). Lithium stearate is used as an all-purpose and high-temperature lubricant.

Lithium carbonate is used in drugs to treat manic depression, although its action on the brain is still not fully understood . Lithium hydride is used as a means of storing hydrogen for use as a fuel. Lithium does not occur as the metal in nature but is found combined in small amounts in nearly all igneous rocks and in the waters of many mineral springs. Spodumene, petalite, lepidolite, and amblygonite are the more important minerals containing lithium. Most lithium is currently produced in Chile, from brines that yield lithium carbonate when treated with sodium carbonate (geopolitics of Lithium, 2022). The metal is produced by the electrolysis of molten lithium chloride and potassium chloride. As lithium is an alkali metal, it is in group 2 in the periodic table and on period 3 on the table.

Figure 14. *An image of a raw lithium rock*
Source: https://mineralseducationcoalition.org/minerals-database/lithium/

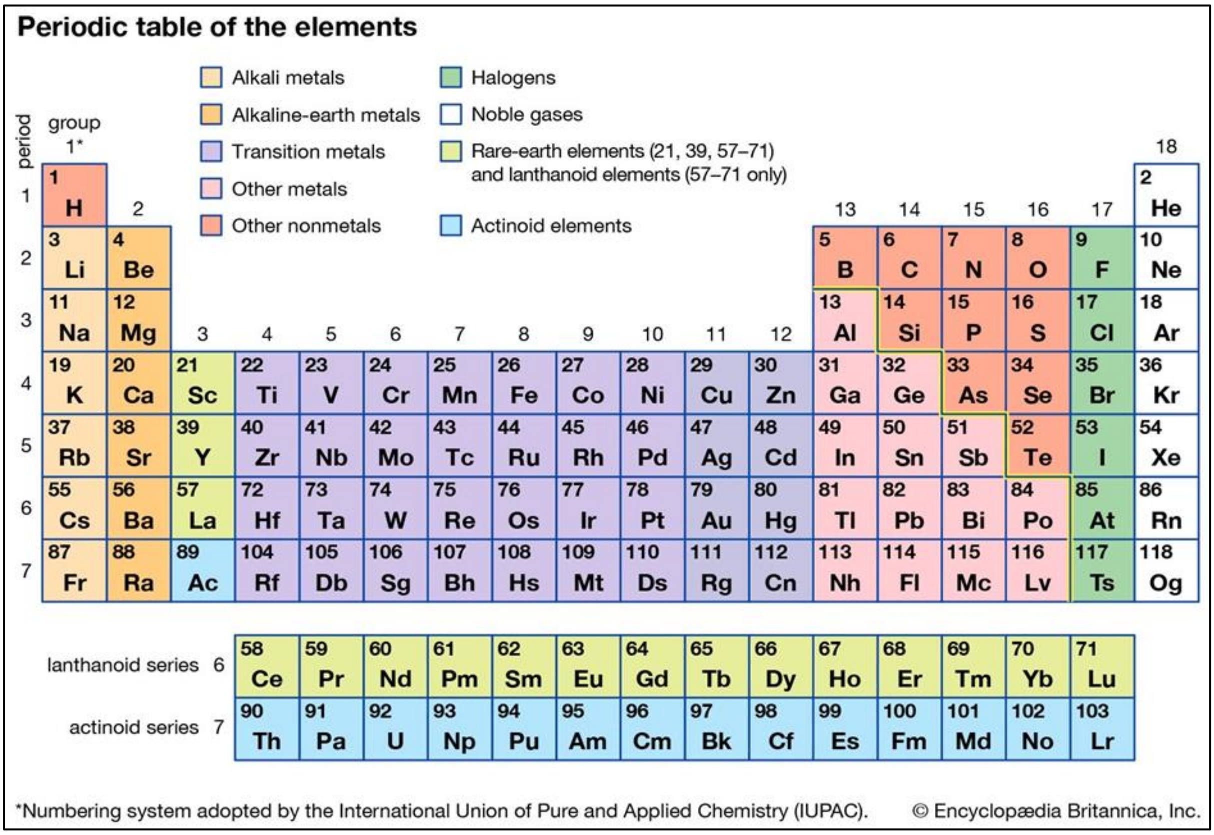


Figure 15- *The periodic table showing all elements of Global deposits of lithium minerals. Source: Global Deposit of Lithium Materials (Royal Society of Chemistry (rsc.org))*

Although it is widely distributed on earth, lithium does not naturally occur in elemental form due to its high reactivity. Actual and potential sources of lithium are from continental brines, clay mineral hectorite, pegmatites, geothermal brines, and oilfield brines.

Lithium is approximately the 25th most abundant element sharing roughly the same abundance as lead and nickel. Although it is widely distributed on earth, lithium does not naturally occur in elemental form due to its high reactivity. Seawater contains an estimated 230 billion tons of lithium, although the concentrations are comparatively low ranging from 0.1 to 0.2 ppm. There are a fairly large number of both lithium mineral and brine deposits but relatively few of them are of actual or potential commercial value. Actual and potential sources of lithium are from continental brines, clay mineral hectorite, pegmatite, geothermal brines, and oilfield brines.

Owing to continuing exploration, identified lithium resources have increased substantially worldwide and total about 89 million tons. Identified lithium resources in the United States—from continental brines, geothermal brines, hectorite, oilfield brines, pegmatites, and Searle site—are 9.1 million tons. Identified lithium resources in other countries have been revised to 80 million tons. Identified lithium resources are distributed as follows: Bolivia, 21 million tons; Argentina, 19 million tons; Chile, 9.8 million tons; Australia, 7.3 million tons; China, 5.1 million tons; Congo (Kinshasa), 3 million tons; Canada, 2.9 million tons; Germany, 2.7 million tons; Mexico, 1.7 million tons; Czechia, 1.3 million tons; Serbia, 1.2 million tons; Russia, 1 million tons; Peru, 880,000 tons; Mali, 700,000 tons; Zimbabwe, 500,000 tons; Brazil, 470,000 tons; Spain, 300,000 tons; Portugal, 270,000 tons; Ghana, 130,000 tons; Austria, 60,000 tons; and Finland, Kazakhstan, and Namibia, 50,000 tons each. (*U.S Geologicalsurvey.gov*)

1.6.1.0 SUBSITUTES OF LITHIUM COMPOUND RESOURCE

Substitution for lithium compounds is possible in batteries, ceramics, greases, and manufactured glass. Examples are *calcium, magnesium, mercury, and zinc* as anode material in primary batteries; calcium and aluminum soaps as substitutes for stearates in greases; and sodic and potassic fluxes in ceramics and glass manufacture.

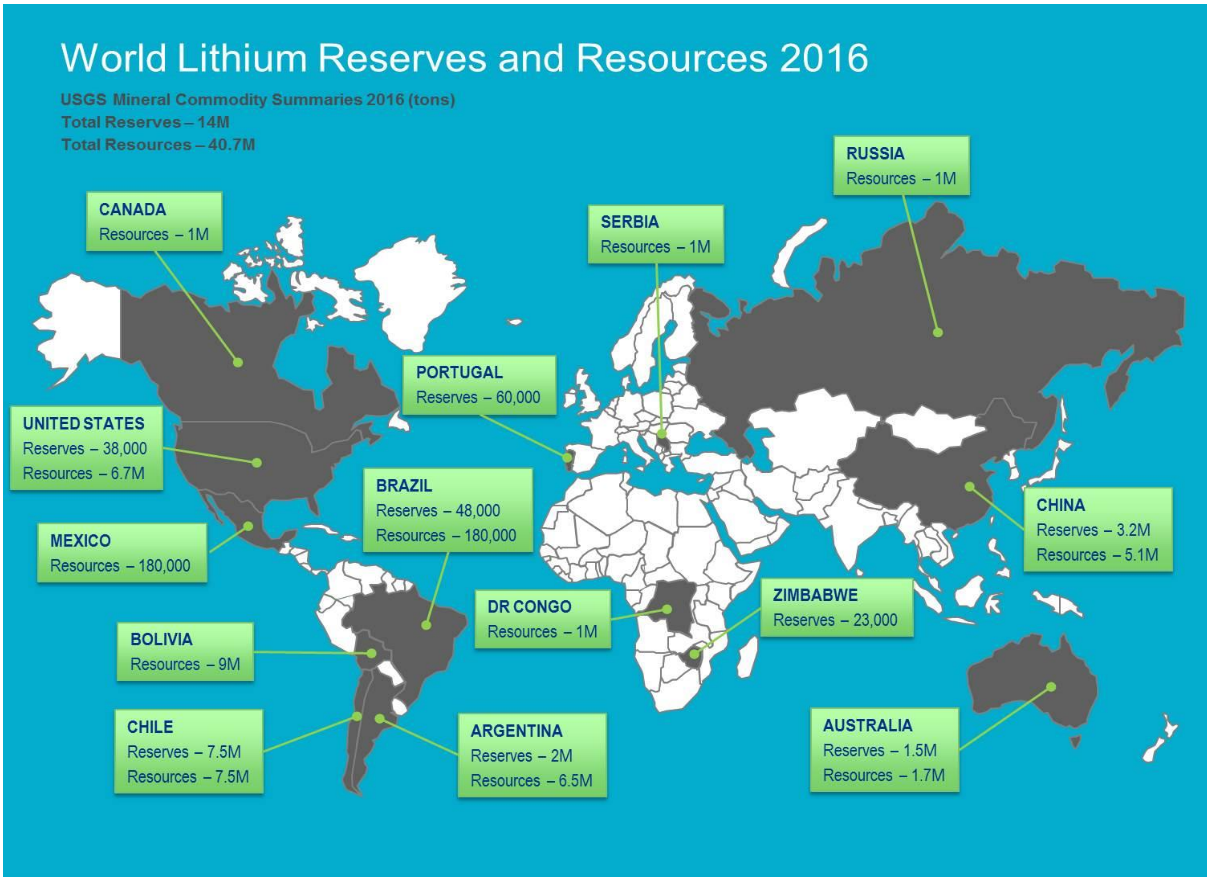


Figure 16. *Global deposit of lithium resource*
Source: [*Geopolitics of lithium - Young Diplomats (young-diplomats.com)*]

1.6.1.1 PEGMATITES

These are coarse grained igneous rocks formed by the crystallization of post magmatic fluids. Lithium containing pegmatites are relatively rare and are most frequently associated with Tin and Tantalum, with some lithium 'discoveries' resulting from the exploration for the associated minerals. ''According to geology for investors data base'', **Alaska, Northern Ontario, Quebec, Ireland, and Finland** are among many other global locations of pegmatite deposits. The principal lithium pegmatite minerals are spodumene, petalite and lepidolite. All have been used directly in the glass and ceramic industries provided the iron content is low and all have been used as the feedstock to produce lithium chemicals. A Canada-based company focused on the production of lithium from the Smackover Formation in southern Arkansas.

1.6.1.2 HECTORITE CLAYS

hectorite is a magnesium lithium smectite and the clay is most notably found in several areas in the western United States. The largest known deposit is associated with the volcanic rocks of the McDermitt caldera that straddles the Nevada/Oregon border where it occurs in a series of elongated lenses. Currently the only lithium deposit in the United States that is producing lithium is part of the McDermitt caldera and is owned by Rockwood Holdings.

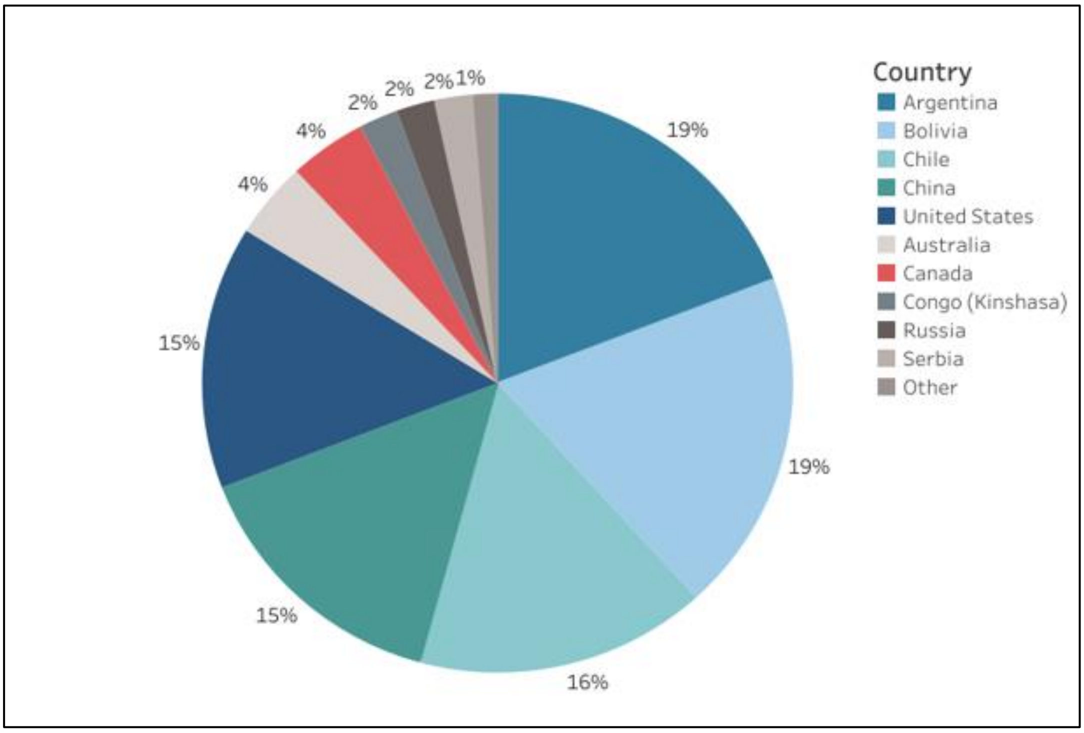


Figure 17 *. Pie chat to show a country with the highest % of lithium deposit in the world.*
Source: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets

1.6.1.3 GEOTHERMAL BRINES –

These are small quantities of lithium are contained in brines at Wairakei, New Zealand (13ppm) at the Reykjanes Field (8ppm) and other areas in Iceland and at El Tatio in Chile (47ppm). The most attractive known occurrences are in the Brawley area south of the Salton Sea in Southern California. In addition to the lithium deposits the Salton Sea Known Geothermal Resource Area (KGRA) in southern California contains some concentrations of potash lead, boron and zinc and currently sustains 10 electricity generation projects, delivering approximately 326 MW of power. A proposed project would bring the total to 511 MW of a 680 MW proven reserve.

1.6.1.4 OILFIELD BRINES

Deposits of lithium are contained in oil field brines in Alberta, North Dakota, Wyoming, Oklahoma, east Texas, and Arkansas where brines grading up to 700 ppm are known to exist. Other oilfields brine lithium deposits exist, most notably in the Paradox Basin, Utah; however,

Figure 18- *An image of oilfield brine at the Salton Sea, California*
Source: https://www.mdpi.com/minerals/minerals-09

global reviews for deposit size, potential yield and production cost estimates are not available.(Jassica Bogossia, SEG,2020)

1.6.1.5- COMPARISON CHART OF MECHANICAL ENERGY STORAGE

Mechanical Energy storage has some parameters to compare to a benchmark to select which of the technology is best for use. Technically all energy storage is selected based on the used case and time availability of the technology. There are some critical factors that we consider for comparing mechanical energy storage, this includes power rating, energy capacity, power cost, energy capital cost, O&M cost, specific power, Specific energy, Power Density, RTE, life rime, technical maturity, daily self-discharge, lifetime, cycling times, round trip efficiency and energy density (Pavlos et al,. 2017). As shown in figure 19, it shows the comparison chart of the three competing mechanical energy storage technologies, PHES, CAES and FLYWHEEL technology.

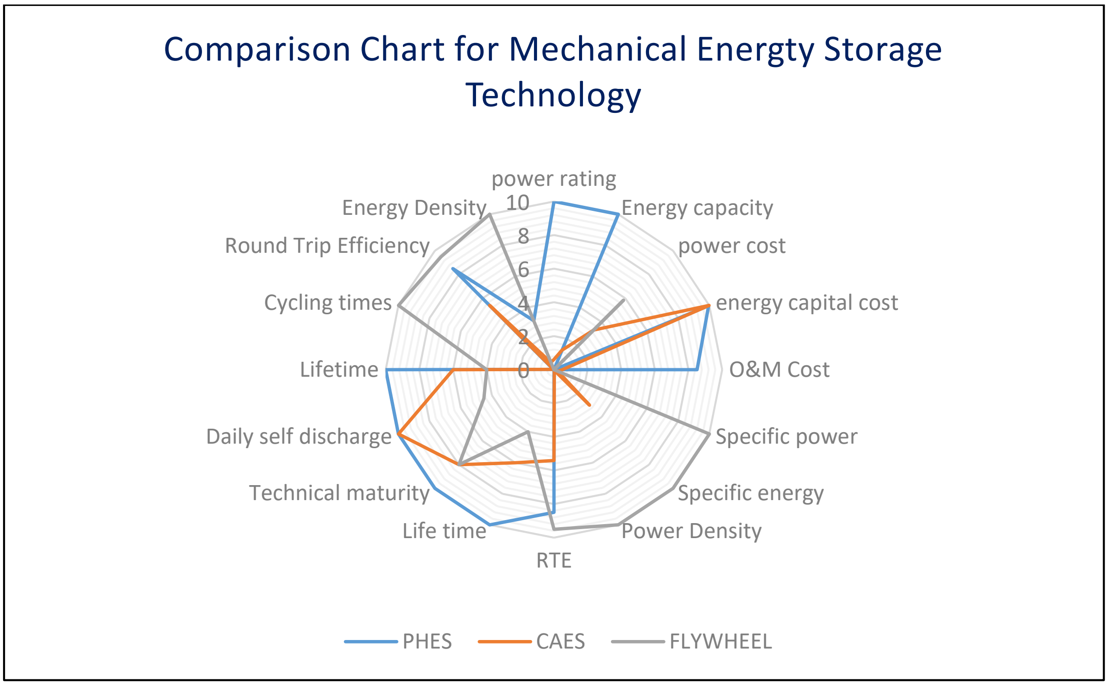


Figure 19 : *Illustration of mechanical energy storage*
Source: Graph Created by Daniel Kelly Boakye Danquah, IES-UND

Comparison table for various energy storage parameters.

PARAMETERS	PHES	CAES	FLYWHEEL
power rating	10	0.6	0
Energy capacity	10	1.25	0
power cost	0	3.33	5.83
energy capital cost	9.95	9.98	0
O&M Cost	8.5	0.5	0
Specific power	0	0.24	10
Specific energy	0.15	3	10
Power Density	0	0.05	10
RTE	8.5	5.4	9.5
Lifetime	10	6	4
Technical maturity	10	8	8
Daily self-discharge	10	10	4.5
Lifetime	10	6	4
Cycling times	0.03	0.01	10
R T E	8.5	5.4	9.5
Energy Density	3.14	0.47	10

Table 2*. A table of various mechanical energy storage parameters*
Source: www.http//researchgate.net

Table 1: Table of values for comparing various parameters for mechanical energy storage technology. This can be in the form of capacitor, super capacitors, and superconductive magnets.

1.6.1.6 EVALUATION OF ELECTRICAL ENERGY STORAGE-CAPACITORS

A capacitor is an electromagnetic device capable of storing energy in the form of an electric charge .a capacitor can store a much smaller amount of energy, around 10,000 times smaller, but useful enough for so many circuit designs. Capacitors can be used to deliver peak power, reducing depth of discharge on batteries, or supply hold-up energy for memory read/write during an unexpected shut-off. Capacitors also charge/discharge very quickly compared to battery technology and are optimal for energy harvesting and scavenging applications and depending on power requirements.

Inside the capacitor are the two electrodes connected to two metal plates separated by a dielectric. As shown in figure 20. The dielectric can be air, paper, plastic, or any other substance that does not co the capacitance of a capacitor, measured in farads, is directly proportional to the surface area of the two plates, as well as the permittivity ε of the dielectric, while the smaller distance between the plates the greater capacitance. Duct electricity and prevents the two metal poles from touching each other.

$$C=\varepsilon*(A/d) \qquad \textbf{(Equ 12)}$$

Where = the capacitance in farads ,A=the plate area in square meters, d= the diameter between the plates in meters, ε= the permittivity of the dielectric material

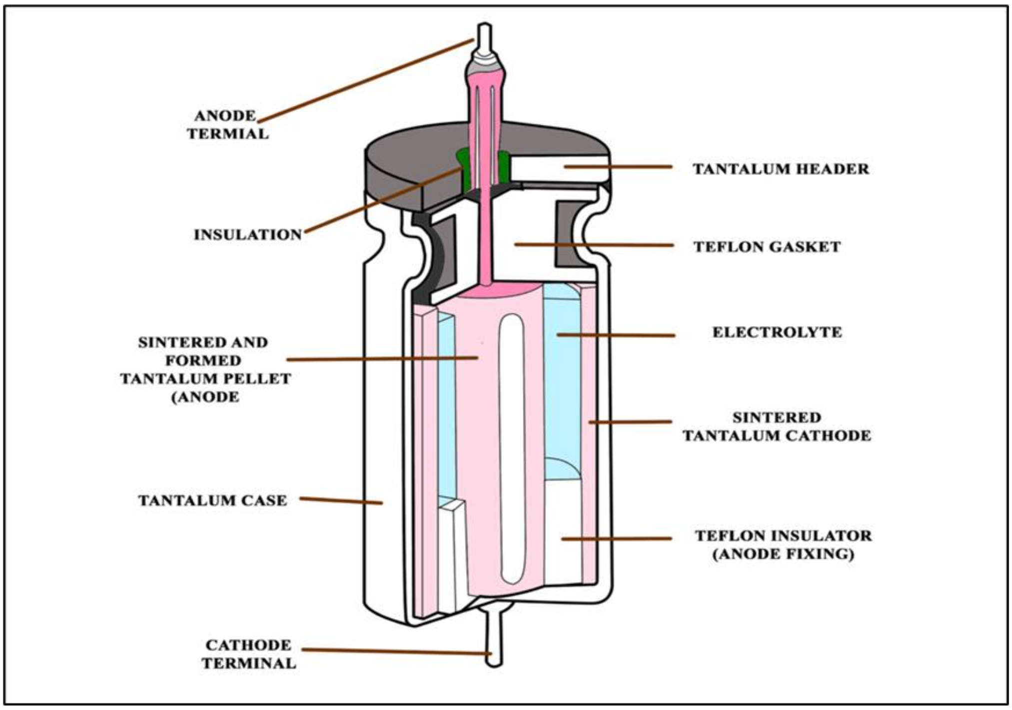


Figure 20. *An Image of cut through capacitor.*
Source: https://electricalacademia.com/basic-electrical

Parallel connection : This is where all the capacitors are attached side by side in different paths so that the same charge or current will flow through each capacitor. This increases the size of the capacitor plates without increasing the distance between the capacitors.

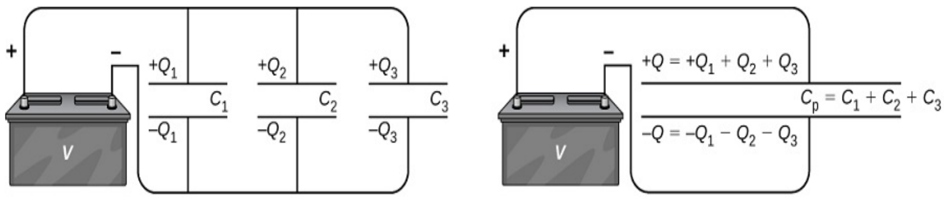


Figure 21*. A demonstration of Parallel Capacitor configuration*
Source: Designed by Daniel Kelly Danquah

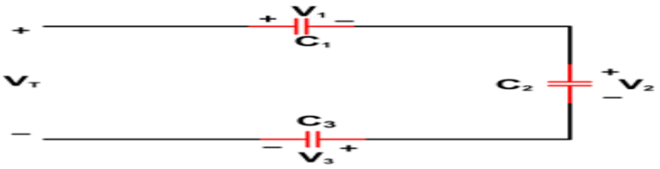
$Q=Q1+Q2+Q3$ ....(Equ 13)

$C_pV=C_1V+C_2V+C_3V$ ....(Equ 14)

Total net capacitance is given as the equation:

$C_P=C_1+C_2+C_3$..................................(Equ 15)

Series connection: This is where capacitors are linked one after another in the same track or path so that the same charge or current flows through each a capacitor. The total capacitance is achieved by adding up the reciprocal of the capacitance values of each individual capacitor.



$$V = V_1 + V_2 + V_3. \qquad \text{Equ 16}$$

$$\frac{Q}{C_S} = \frac{Q}{C_1} + \frac{Q}{C_2} + \frac{Q}{C_3}. \qquad \text{Equ 17}$$

$$\frac{1}{C_S} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}. \qquad \text{Equ 18}$$

Figure 22., *An equation illustration of series configuration of capacitors Accredited by Daniel Kelly Boakye Danquah.*

1.6.1.8 CHARGING AND DISCHARGING OF CAPACITORS

General SC charging and discharging cycle of capacitors begins with a constant current (CC) mode followed by constant voltage (CV) mode. Then SC is discharged at CC, until voltage drop is seen at the beginning of the discharge cycle. The capacitance of a capacitor , C=Q/V, where Q= the charge stored when the voltage across the capacitor is V. Capacitance is measured in farad (F).

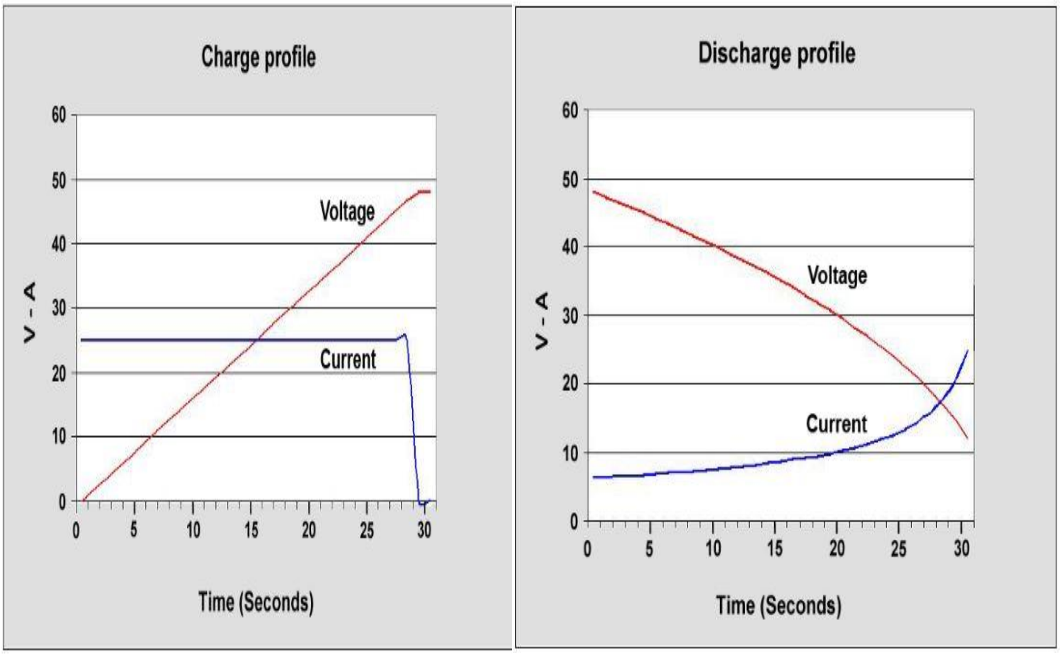


Figure 23. *Graph of charging and discharging of a capacitor.*
Source: https://batteryuniversity.com/learn/article/whats_the

1.6.1.9 PROS AND CONS OF CAPACITORS

Technically, the capacitors have various degree of pros and cons based on the use case, the capacitors have virtually unlimited cycle life can be cycling millions of times with high specific power, low resistance enables high load currents and also charges in seconds, no end of charge termination needed. Combining the superior power density of capacitors with a wide operating temperature range, high reliability, low weight, and high efficiency, it is easy to see how capacitor technology is ideal for energy storage applications. Low specific energy, hold fraction of a regular battery. Linear discharge voltage prevents using the full energy spectrum, High self-discharge and lower cell voltage require series connection with voltage balancing. High cost per watt and expensive in its usage.

1.6.2.0 LIMITATION OF CAPACITORS

Aging is induced by chemical changes in the capacitor materials (conductor, electrolyte, dielectric, separators, housing, insulation film). The following factors lead to a reduction in the capacitance: Increase in the internal resistance, increase in the electrode resistance, evaporation of the electrolytic fluid, Decomposition of the contact material (e.g., activated carbon), and change in the electrolyte due to chemical reactions, Reduction in the insulation effect of the dielectric material, which corresponds to the reduction in the parallel resistance.

The use of capacitors in the real world has increased over a time, the simple pie-chart illustrates the energy sector and the use of the component.

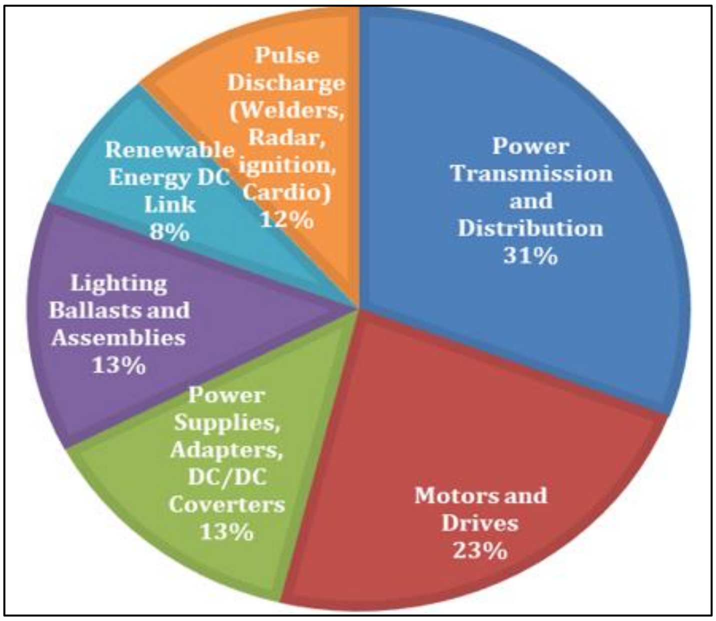


Figure 24. *Graph of total use of capacitors in the industry.*
Source: *https://www.bing.com*

1.6.2.1 IMPORTANCE OF ENERGY STORAGE

Energy sources from the sun and wind are not predictable and subject considering the continuous increase of renewable energy sources. Large-scale thermoelectric plants may reduce their operating power as a sudden change, furthermore, their integration with current thermoelectric plants is not easy. Energy Storage plays a major role in the electrical infrastructure and mobility industry in everyday life. Energy Storage can be categorized into long duration and short duration depending on their use case. Energy Storage can be applied to Residential, Commercial, Utility and Grid services and their use can be time-shift of energy delivery, capacity credit ,grid operational support, power quality and reliability, Integration of intermittent renewables generation.

All this is important for the overall improvement of the grid to support areas in the society such as information and communication technology sectors, in the penetration of electric vehicles into the society, in the effective energy distribution network, to help in the energy diverse, reducing environmental impact by lowering the burning of more fossil fuel for energy generation and improving the reliability and resilience on the grid reliability.

1.6.2.2 GENERAL APPLICATION OF ENERGY STORAGE

Energy storage by it use, has several applications, this could be use as bulk energy services, ancillary services, transmission services, distribution services and customer services. As shown in figure 25 in appendix. The taxonomy of energy storage services explains some areas of energy storage services.

1.6.2.3 ANCILLARY SERVICES-FREQUENCY REGULATION

This is the constant second-by-second adjustment of power to keep system frequency at the nominal value (50 or 60 Hz) to ensure grid stability. These variations are mitigated by a complex control system in which energy storage systems can easily run, particularly those with a quick response time such as pumped-storage hydroelectric systems or electrochemical systems. Adding energy storage helps in resolving these frequency irregularities and stabilizing the frequency of the electrical system.

Frequency regulation and black start BESS grid applications are sized according to power converter capacity. Grid applications are sized according to power storage capacity in MWh and renewable integration, peak shaving and load leveling, and micro grids Storage system size range : 1-10MVAr. Target discharge duration range: NA ,Min cycle/year: NA

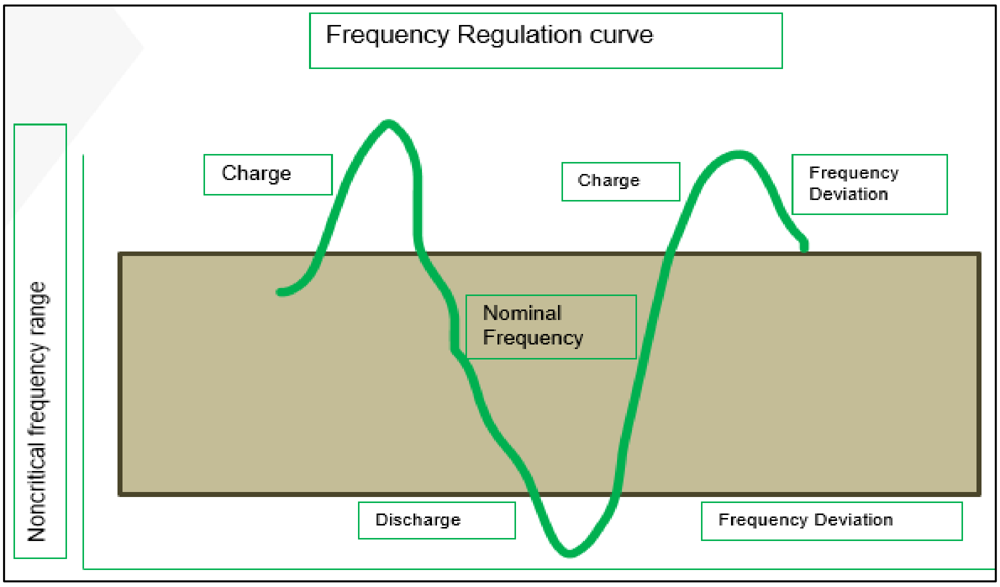


Figure 26- *A graphical representation of frequency regulation*
Source: Designed by Daniel Kelly B-Danquah

1.6.2.4 BULK ENERGY SERVICE -ENERGY ARBITRAGE

A major application of energy storage is voltage control in electrical systems, most of the time is achieved usually achieved by the reactive power regulation on each generator (U.S Energy information Administration, 2022). The voltage control performed by the energy storage system can also fall into the application category of "power quality" as it is very useful to increase the quality of the service provided by the distributor system operator.

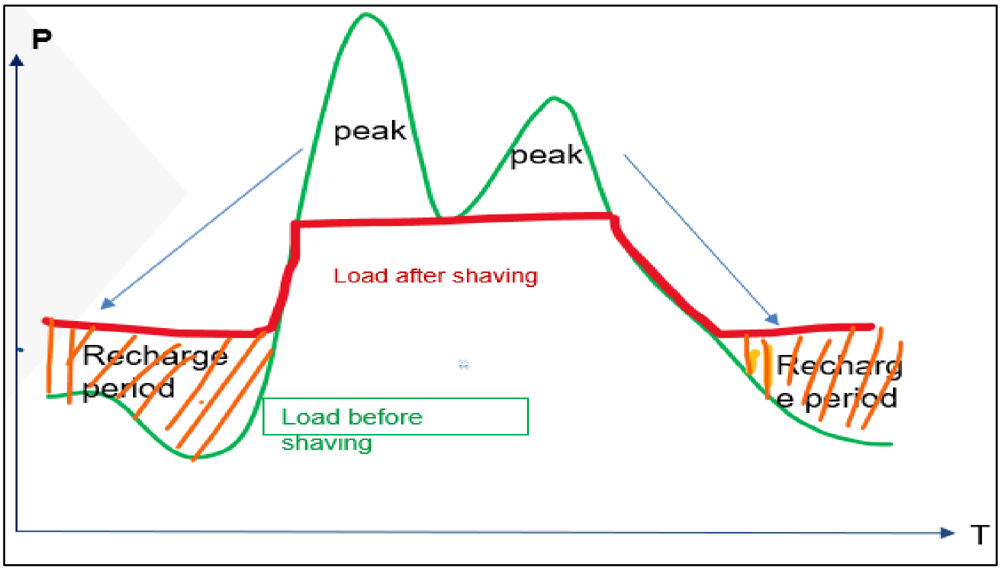


***Figure.** 27 -A graph of energy storage application of Time of use*
Source: credited by Daniel Kelly Boakye Danquah

1.6.2.5 MICRO-GRID APPLICATION

Energy storage opens the possibility of building microgrids in conjunction with renewable energy . A microgrid comprises of its own generating units, local loads, energy-storing systems, and its dedicated control and protection set up. It can be DC/AC micro grid. It operates in grid connected mode deriving the required power from the main grid fully or partially to meet its local load requirement. In cases of disturbances in the main grid, the microgrid gets disconnected from the utility and continues to run in islanded mode providing uninterrupted power supply to its intended local loads. Microgrid serves to increase the reliability and stability of a power system (Daniel et al, .2023) . It also contributes to a healthier environment through the clean and green energy sourced by the DERs. Finally, contribute to better system efficiency, reduced cost of system infrastructure, and improved power quality.

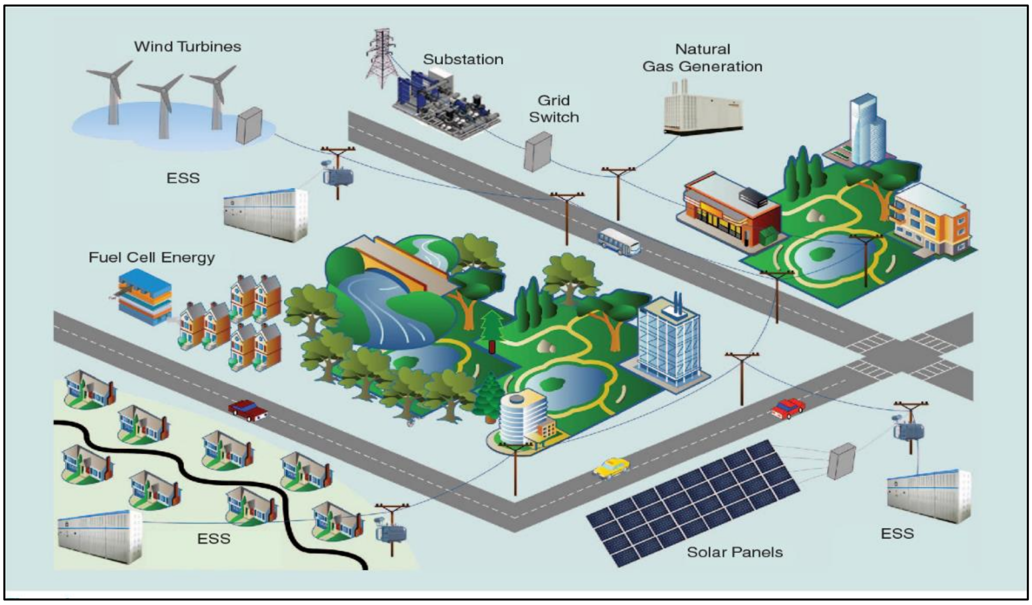


Figure 28.-*Image of Energy storage in Micro grid Applications*
Source: https://www.bing.com/images/search?view

1.6.2.6 ELECTRICITY SUPPLY CAPACITY

Depending on the circumstances in each electric supply system, energy storage could be used to defer or reduce the need to buy new central station generation capacity or buying capacity in the wholesale electricity marketplace. Storage system size range: 1–500 MW , Target discharge duration range: 2–6 hours Minimum cycles/year: 5–100

Figure 29- *An image battery to support grid infrastructure.*
Source: http// www.lge.com

1.6.2.7 SPINNING NON-SPINNING AND SUPPLEMENTAL RESERVES.

The operation of an electric grid requires reserve capacity that can be called on when some part of the normal electric supply resources unexpectedly become unavailable (iea.gov). Generally, reserves are at least as large as the single largest resource (e.g., the single largest generation unit) serving the system, and reserve capacity is equivalent to 15%–20% of the normal electric supply capacity. Storage system size range: 10–100 MW, target discharge duration range: 15 minutes to 1-hour Minimum cycles/year: 20–50

1.6.2.8 VOLTAGE SUPPORT AND REGULATION

Normally, designated power plants are used to generate reactive power (expressed in VAr) to offset reactance in the grid. These power plants could be displaced by strategically placed energy storage within the grid at central locations or by multiple VAr-support storage systems placed near large loads, following the distributed approach (Handbook of energy storage, 2017). The PCS of the storage systems used for voltage support must be capable of operating at a non-unity power factor, to source and sink reactive power.

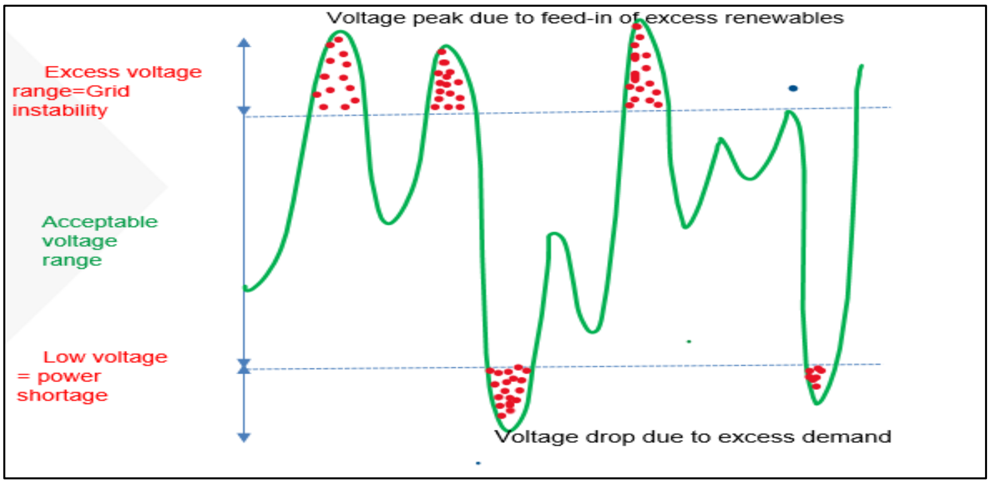


Figure 30. *A graph showing voltage support and frequency regulation.*
Source: credited by Daniel Kelly Boakye Danquah

Regulation is one of the ancillary services for which storage is especially well suited. It involves managing interchange flows with other control areas to match closely the scheduled interchange flows and momentary variations in demand within the control area (U.S Department of Energy, 2015). The primary reason for including regulation in the power system is to maintain the grid frequency. Storage system size range: 1–10 MVAr Target discharge duration range: Not applicable. Minimum cycles/year: Not applicable.

Voltage Support	**Use Parameters**
Storage system size range	1-40 MW
Target Discharge duration range	15 minutes to 1-h
Minimum Cycle/ year	250-10,000

Table 3. *Table of Application of Voltage support*
Source: Handbook of energy storage systems.

1.6.2.9 BLACK START.

Storage systems supply an active reserve of power and energy within the grid and can be used to energize transmission and distribution lines and supply station power to bring power plants online after a catastrophic failure of the grid. Storage can supply similar start-up power to larger power plants, if the storage system is suitably sited and there is a clear transmission path to the power plant from the storage system's location.

Black Start	Use Parameters
Storage system size range	5-50 MW
Target Discharge duration range	15 minutes to 1-h
Minimum Cycle/ year	10-20

***Table 4**. Table of ESS application of black start and use range.*
Source: Handbook of energy storage systems

1.6.3.0 LOAD FOLLOWING /RAMPING UP OF RENEWABLES

Load following is characterized by power output that changes as often as every several minutes. The output changes in response to the changing balance between electric supply and load within a specific region or area. Output variation is a response to changes in system frequency, timeline loading, or the relation of these to each other, and occurs as needed to keep the scheduled system frequency or established interchange with other areas within predetermined limits. Battery energy storage systems allow businesses to shift energy usage by charging batteries with solar energy or when electricity is cheapest and discharging batteries when it's more expensive. Load shifting essentially moves electricity consumption from one time period to another. The idea is that by shifting the load to another time, Load shifting can be achieved through rescheduling processes, turning on a site's embedded generation or turning off unnecessary equipment and machinery. Load shifting does not result in a reduction in the net quantity of energy used.

Energy storage can smooth the output of renewable power generation sources. Solar produces cyclically day vs. night, summer vs. winter. Energy storage allows solar energy production to mimic the consistency of fossil fuel energy sources.

Renewable Energy Integration focuses on incorporating renewable energy, distributed generation, energy storage, thermally activated technologies, and demand response into the electric distribution and transmission system. Support achievement of renewable portfolio standards for renewable energy and energy efficiency, Enhance reliability, security, and resiliency from microgrid applications in critical infrastructure protection and highly constrained areas of the electric grid.

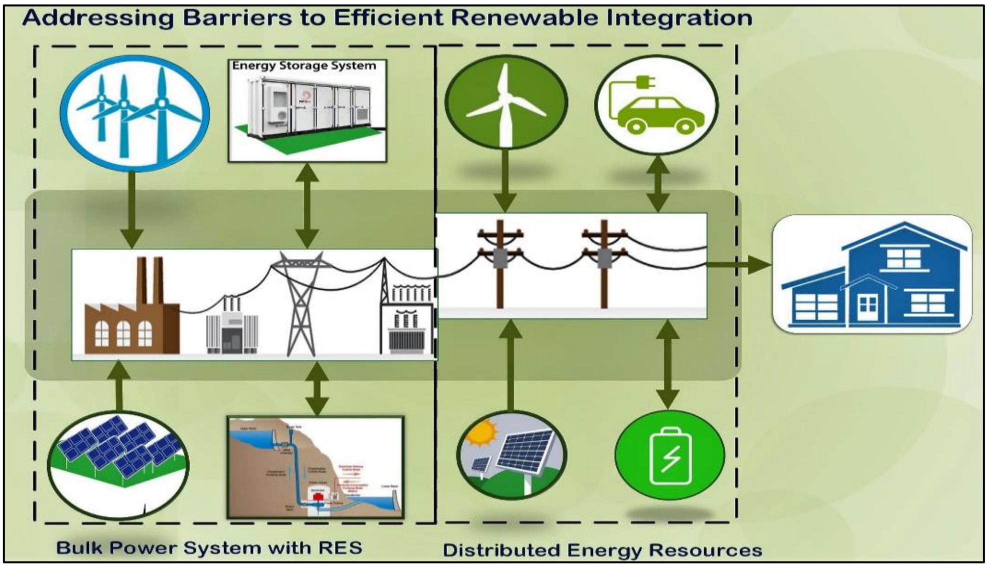


Figure 31 *- Image of Renewable integration with energy storage*
Source: Addressing Barriers to Efficient Renewable Integration | UNSW Research

- ❖ Participate in balancing services, such as frequency response.
- ❖ Trade generated electricity at times of price peaks.
- ❖ Avoid peak demand all together.

- ❖ The returns generated through energy cost savings are greater than the loss of production.

Load Following/Ramping up of Renewables	**Use Parameters**
Storage system size range	1-100 MW
Target Discharge duration range	15 mins-1hr
Minimum cycle / Year	N/A

Table 5. *Table of Application of load following.*
Source: Handbook of energy storage system

1.6.3.1 TRANSMISSION UPGRADE DEFERRAL

Transmission upgrade deferral involves delaying utility investments in transmission system upgrades, by using relatively small amounts of storage, or in some cases avoiding such investments entirely. Consider a transmission system with peak electric loading that is approaching the system's load-carrying capacity (design rating). In some cases, installing a small amount of energy storage downstream from the nearly overloaded transmission node could defer the need for the upgrade for a few years. As seen in figure 32 in appendices , it illustrates a clear picture of how transmission upgrade deferral can be done. Storage system size range: 10–100 MW, Target discharge duration range: 2–8 hours Minimum cycles/year: 10–50

1.6.3.2 TRANSMISSION CONGESTION RELIEF

Transmission congestion occurs when energy from dispatched power plants cannot be delivered to all, or some loads because of inadequate transmission facilities. When transmission capacity additions do not keep pace with the growth in peak electric demand, the transmission systems become congested. Electricity storage can be used to avoid congestion-related costs and charges, especially if the costs become onerous because of significant transmission system congestion. Up to a certain penetration rate, the integration of renewables into the power mix can be managed by existing flexibility sources. As penetration increases, it may compromise system stability against disturbances, especially in weak or isolated grids .Therefore the application of energy storage is needed to providing fast response and high ramp rates within a one-minute timeframe, to avoid system instability and consequent brownout or blackout, by absorbing and discharging energy during sudden decreases in power output over short duration variations. Storage system size range: 1–100 MW, Target discharge duration range: 1–4 hours Minimum cycles/year: 50–100

1.6.3.4 DISTRIBUTION UPGRADE DEFERRAL AND VOLTAGE SUPPORT

Distribution upgrade deferral involves using storage to delay or avoid investments that would otherwise be necessary to maintain adequate distribution capacity to serve all load requirements. The deferred upgrade could be a replacement of an aging or overstressed distribution transformer at a substation or the re-conducting of distribution lines with heavier wire. Storage system size range: 500 kW–10 MW, Target discharge duration range: 1–4 hours and Minimum cycles/year: 50–100

1.6.3.5 POWER QUALITY

Power quality means, when the provision of power is reliable and maintains nominal voltage levels, unity power factor, nominal frequency levels 50Hz or 60Hz depending on the country's standard and a purely sinusoidal waveform with zero harmonics and no transients. Power quality regulation services are the fastest acting, enabling operation within seconds to a few minutes. As the electric power quality service involves using storage to protect customer on-site loads downstream (from storage) against short duration events that affect the quality of power delivered to the customer’s loads. Some manifestations of poor power quality are the following:

- variations in voltage magnitude (e.g., short-term spikes or dips, longer-term surges, or sags)
- variations in the primary 60-hertz (Hz) frequency at which power is delivered.
- low power factor (voltage and current excessively out of phase with each other).
- harmonics (the presence of currents or voltages at frequencies other than the primary frequency); and interruptions in service, of any duration, ranging from a fraction of a second to several seconds. Storage system size range: 100 kW–10 MW Target discharge duration range: 10 seconds to 15 minutes and Minimum cycles/year: 10–200

1.6.3.5 DEMAND CHARGE MANAGEMENT

Electricity storage can be used by end users (utility customers) to reduce their overall costs for electric service by reducing their demand during peak periods specified by the utility. To avoid a demand charge, the load must be reduced during all hours of the demand charge period, usually a specified period (e.g., 11 a.m. to 5 p.m.) and on specified days (most often weekdays). Storage system size range: 50 kW–10 MW , Target discharge duration range: 1–4 hours and Minimum cycles/year: 50–500.

1.6.3.6 RESEARCH AIMS AND OBJECTIVE

The main objective of the long and deep research is to support the ongoing research by other fellow researchers in industry, academia, and public interest to help make the use of lithium-ion batteries safe.

a) Industry justification: To apply the solution to solve Industry problem of fire safety.
b) Policy Justification: To apply this to UL 9540A,NEC,NFPA and other government policy and code.

c) Academic justification: To apply the understanding in academic of how battery system fails and potential detection mechanism.

1.6.3.7 RESEARCH STATED HYPOTHESIS

As stated in the literature review, many records back the fact that current lithium-ion batteries used in simple systems like mobile phones and bigger and complex systems like commercial and utility energy storage systems poses some level of fire risk. In line of this that I will state my hypothesis as:

> ***Developing high precision sensors, module's structure and introducing high fire-retardant material to encapsulate battery modules and systems can resolve the problem of fire safety and early fault detection in lithium-Ion batteries.***

To review and evaluate this said hypothesis, my general plan is defined below in the following section of the write up.

- Determining if uncontrolled temperature is the main cause of battery failures that results in fire breakout.
- Determine if providing encapsulated fire-retardant material to cut oxygen into battery module will quench fire that comes from thermal runaway to eliminate battery fire failures.
- Determining if providing multiple sensors and using right code in the battery BMS can help determine the early fire failures.
- Employing high ruggedized structure in building the battery system can resolve system failures. When these concepts are applied to the lithium-Ion batteries in the energy storage system design, battery failures will be eliminated.

1.6.3.8 RESEARCH QUESTIONS

At this point, I will start to put forward what my research question from my topic is, dive into the real aims of the research and goals. The research methods of the following topics will build upon the information in this chapter and once that follows.

Research Question # 1

Why is safety in Lithium-Ion batteries paramount to energy storage industry and what can be done to mitigate fire in lithium batteries.?

Research Question # 1 Hypothesis

Introducing multiple sensors and writing high precision and fast acting algorithm in battery module BMS to alert and open contactors can stop further operation of batteries.

Research Question # 2

Can introducing UL 9540A and 9540 test for lithium-ion battery and making a policy to insert fire retardant in all battery module and enclosure improve lithium-ion battery safety?

Research Question # 2 Hypothesis

Introducing highly rated fire-retardant material and honey cone material to encapsulate energy storage system may prevent fire propagation in battery modules and storage enclosure.

Research Question #3

Can commercial battery systems be fully assembled and deployed on site and be able to transport via airplanes?.

Research Question #3 Hypothesis

Introducing mill graded compression ring and lug tight sealant on battery module and in rack may reduce vibration shock in assembled battery module while in transit.

1.6.3.9 RESEARCH GAP IN THE ENERGY STORAGE INDUSTRY

There have been some gaps in the energy storage industry and that need to be filled out to address the safety concerns of lithium-Ion batteries for small and large applications. These will include :

- Fire Safety: Electrical and Mechanical and chemical
- Early Fault Detection and Mitigation: Controller Development
- Module Resilience for transport: Mechanical and Structural Enhancement

1.6.4.0 RESEARCH SIGNIFICANT

This masterpiece of research has the key to unlock some of the hidden problems that are shrouded with Lithium-Ion batteries and unveil some keyways to provide a solution to batteries fires in the energy storage industry. It will also help the energy storage manufacturing sector, consumer protection and the certification bodies such as UL, CSA, and Authorities having jurisdiction and others to set a benchmark to include high level of protection in lithium-ion battery systems, from module, rack, and enclosure. Also, the research will help demystify some of the problems why lithium-ion batteries are not safe and review some of the solutions that make lithium-ion batteries a safe technology to use.

The experiment and research exercise would serve as a prove that, implementing fire protection, utilizing high precision sensors and honey cone materials in lithium-ion battery modules, racks and enclosures will stop battery fires and remove the need for lithium-ion battery manufactures to pay so much money in UL9540A certification. The final significance is to help University of North Dakota to diversify Technical Knowledge in the area of learning technology and battery pack design technique.

1.6.4.1 RESEARCH STRUCTURE

Chapter One-Introduction to energy storage and technology profiles, types of energy storage and energy storage structure.

Chapter Two- This chapter will review and dive into the electrochemical operation of lithium-ion batteries ,evaluations of various battery technology and impact of failures and review of other technical resolutions.

Chapter Three- This chapter discusses the energy storage policies and how they impact storage technology tax credits and policy implementation.

Chapter Four- This chapter reviews the methodology that is used in 4,5 and 6.

Chapter Five- The chapter contains lithium -ion faut detection strategies and mechanism of early failures in lithium-ion batteries.

Chapter Six-This review how engineering confirmation of the battery, what code, and standards the battery should fall under and the communication topology of lithium-ion.

Chapter Seven-This chapter reviews the general results of the experimental and provides a clear direction to test the research experiment.

Chapter Eight- This provides an overarching conclusion to the previous chapter's work summarizing opportunities and shortfalls of the industry to provide a reasonable assessment and contribution to the overall hypothesis. An exploratory and conceptual approach is used to identify key variables and favorable policies to the sector to help implement fire retardant as a safety requirement in Lithium-ion batteries for utility and mobility application. Also, a Limitations from each core component of the research is discussed as well as opportunities of future research. General application to industry and the probability of industry and code adoption will be assessed and analyzed across the entire sector to round out the results and conclusion of the research.

2.0 CHAPTER TWO

2.1.0 TECHNICAL BACKROUND

An electrical energy storage device which electrochemically converts chemical energy of its active components directly into electrical energy with the help of electrochemical oxidation-reduction (redox) reactions. The oxidation reactions lead to loss of electrons and reduction reactions tend to gain those electrons. Continuous oxidation and reduction process within an electrochemical cell creates the flow of electrons through an external circuit to power the load connected to it. Electrochemical batteries for energy storage can be categorized into two. These are: Low-temperature batteries such as lead, nickel, and lithium batteries, and high temperature batteries such as sodium-sulfur batteries. Two further categories are batteries with external storage such as redox flow batteries, and those with internal storage (most batteries).

In the battery operation to release the stored energy for use, some are just one time generation and transformation of the energy use and others are repeatable forms to generate the energy. Electrochemical batteries have many technologies and chemistries which turn to give power or energy depending on the use case. Table 6 below shows batteries and their transformation of energy.

Battery system	Transformation of energy	Types of technology
Primary systems	One-time transformation of chemically stored energy	Leclanché Alkaline zinc manganese dioxide and various lithium systems
Accumulators	Repeatable transformation-reversible from chemical to electrochemical energy	Lead accumulators, Nickel accumulators NiCd, NiFe, NiZn, NiMh, Lithium-ion systems, CNM, FePO4, Sodium accumulators
Double layer storage	Repeatable highly reversible storage of electrical energy through physicochemical boundary process	Aqueous and non-aqueous
Renewable systems	Transformation of chemically stored energy re-generability through external process	Zinc air
Fuel Cells	Continuous transformation of chemically stored energy	PEM,MCFC,SOFC,AFC,PAFC
Flow systems	Transformation of electrically and chemically stored energy by separation of the converter from the storage	Zinc Bromine, Vanadium flow system

Table 6 *. Table of types of chemical energy storage*
Source: Handbook of energy storage demand

2.1.2 THE CHEMICAL STRUCTURE OF LITHIUM-ION BATTERY

The principle of lithium-ion battery depends on two reactions, Oxidation Reduction reaction, this reaction occurs both at the cathode and anode of the cell material.

Reduction takes place at the cathode. Cobalt oxide combines with lithium ions to form lithium-cobalt oxide ($LiCoO_2$). The chemical equation:

$$\mathbf{CoO_2 + Li^+ + e^- \rightarrow LiCoO_2} \qquad \mathbf{(19)}$$

Oxidation takes place at the anode. The graphite intercalation compound LiC_6 forms graphite (C_6) and lithium ions. The chemical equation:

$$LiC_6 \rightarrow C_6 + Li^+ + e \quad (21)$$

Here is the full reaction (left to right = discharging, right to left = charging

$$LiC_6 + CoO_2 \rightleftarrows C_6 + LiCoO_2 \quad (22)$$

2.1.3 ELECTROCHEMICAL OPERATION OF LITHIUM -ION BATTERY

Lithium-ion batteries use carbon materials as the negative electrode and lithium-containing compounds as the positive electrode. There is no lithium metal, only lithium-ion, which is a lithium-ion battery. Lithium-ion batteries refer to batteries with lithium-ion embedded compounds as cathode materials. The charging and discharging process of lithium-ion batteries is the embedding and de-embedding process of lithium ions.

During the embedding and de-embedding of lithium ions, it is accompanied by the embedding and de-embedding of electrons equivalent to lithium ions, that is, the positive electrodes are represented by embedding or de-embedding, while the negative electrodes are represented by insertion or de-inserting. During charging and discharging, lithium ions are embedded/considered and inserted/unplugged back and forth between positive and negative electrodes, which is vividly called "rocking chair batteries".

When the battery is charged, lithium ions are generated on the positive electrode of the battery, and the generated lithium ions move to the negative electrode through the electrolyte. As an anode, the carbon is layered. It has many micropores. Lithium ions that reach the negative electrode are embedded in the micropores of the carbon layer. The more lithium ions embedded, the higher the charging capacity. Similarly, when the battery is discharged, the lithium ions embedded in the negative carbon layer are.

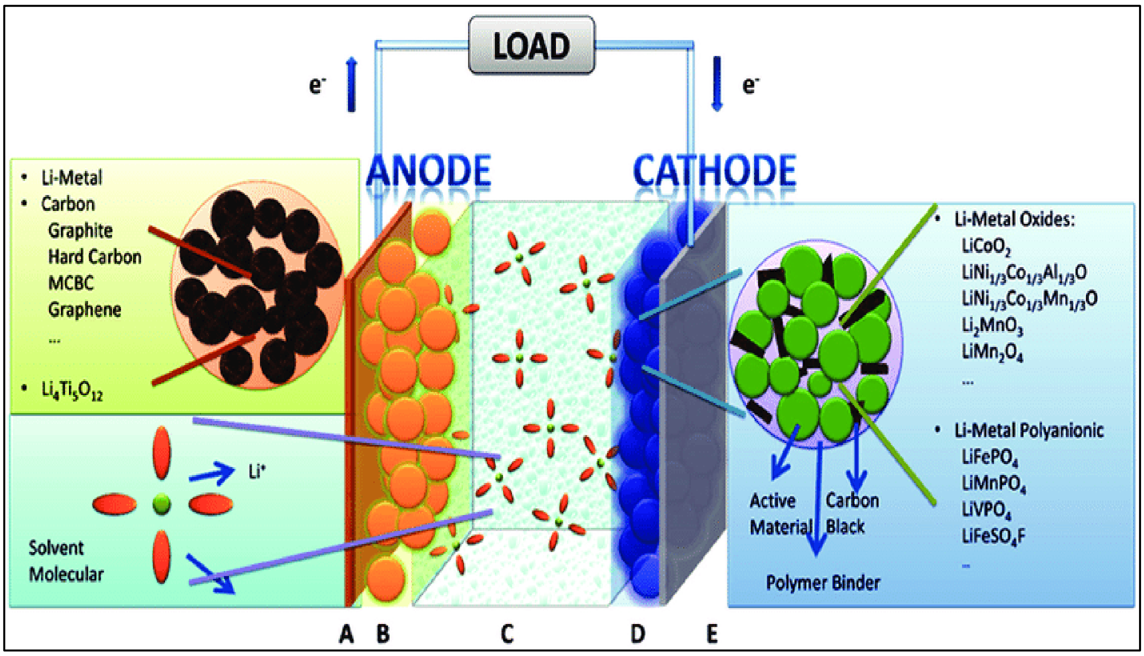


Figure 33*-Lithium-Ion Structure.*
Source. www.https://Researchgate.com

released and move back to the positive pole. In Fig 33, the image shows how lithium-ion battery cell movement and operation, The more lithium ions return to the positive electrode, the higher the discharge capacity. Charging current of lithium batteries is set between 0.2C and 2C. The greater the current, the faster the charging, and the greater the heating of the battery. Moreover, if the current is too large to charge, the capacity is not enough, because the electrochemical reaction inside the battery takes time.

2.1.4. LITHIUM-ION BATTERIES

Since 1990, when Sony first introduced the Li-ion batteries on the commercial scale much has been changed in the Li-ion battery technology and new active materials have been discovered with higher charge capacities and higher rate capabilities. Lithium-ion batteries store energy and create an electrical potential between the positive and negative terminals of the battery.

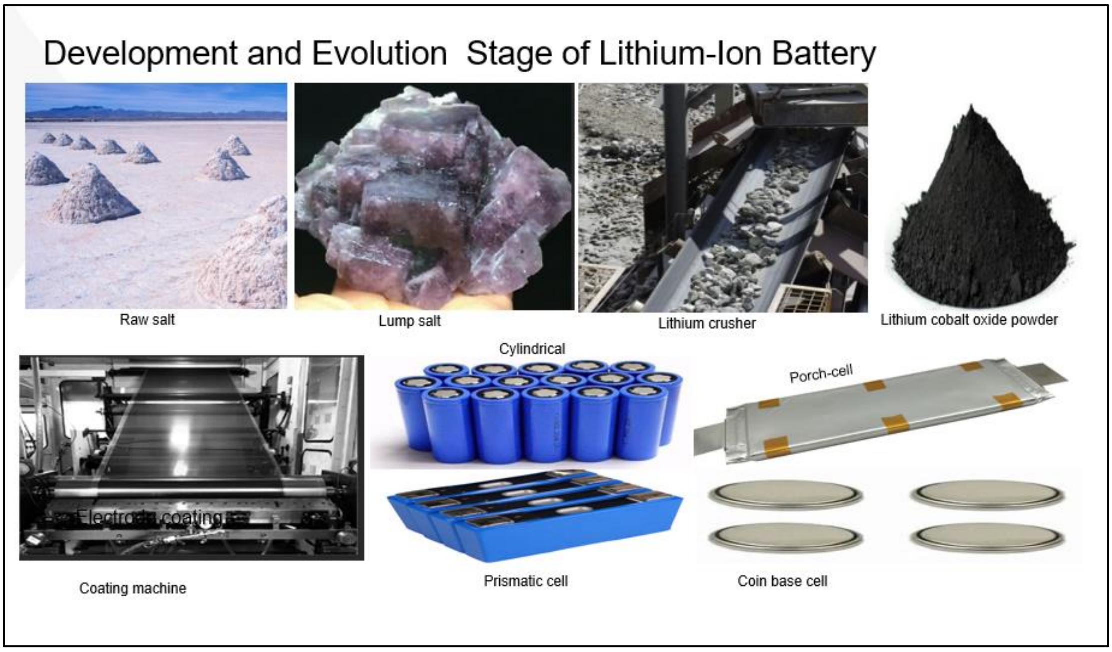


Figure 34. Alaid down of the evolution process of lithium-ion batteries
Curtesy :Daniel Kelly Boakye Danquah

cells using lithium ions. Energy storage in rechargeable lithium-ion cells is based on the reversible insertion and removal of Li ions in active materials by electrochemical redox reactions. The insertion of Li ions in the host grid is called intercalation. The active materials are also called intercalation compounds, and the electrodes are called intercalation electrodes. The positive and negative electrodes are connected by an ion-conducting electrolyte. The separator serves as an electrical insulator, preventing direct contact between the two electrodes (electrical short-circuit). The electrodes are electrically connected to the consumer by an external circuit. Li-ion batteries can use several different materials as electrodes. The most common combination is that of lithium cobalt oxide (cathode) and graphite (anode), which is most found in portable electronic devices such as cellphones and laptops. Other cathode materials include lithium manganese oxide (used in hybrid electric and electric automobiles) and lithium iron phosphate. Li-ion batteries typically use ether (a class of organic compounds) as an electrolyte. There are several configurations of Lithium-ion technology depending on the

Cobalt content and the reversible and in reversible capacity of it use, these can be NMC 622, NMC 631,NMC 640, NMC 721, NMC 802 ,NMC 820 (Jeff Dahn et al,. 2018)

2.1.5 CHARACTERISTICS OF LITHIUM-ION

Lithium-Ion has various degree of characteristic that makes it desirable for use in various capacities. This includes high working voltage of single lithium-ion pack, higher power and energy with lighter weight with small volume of Lithium-ion power pack, long cycle life and Little to no pollution of ions, no memory effect of on lithium-ion power pack and wide range of temperature-heat production during discharging/charging.

Lithium has a melting point of 180.54 C, a boiling point of 1342 C, a specific gravity of 0.534 (20 C), and a valence of 1 (Anne Marie Helmenstine, Ph.D. ThoughtCo., 2022). It is the lightest of metals, with a density approximately half that of water. Under ordinary conditions, lithium is the least dense of the solid elements. It has the highest specific heat of any solid element. Metallic lithium is silvery in appearance. It reacts with water, but not as vigorously as does sodium. Lithium imparts a crimson color to flame, although the metal itself burns a bright white. Lithium is corrosive and requires special handling. Elemental lithium is extremely flammable (ThoughCo., 2022) with all the chemical properties of lithium-Ion, it is unique in the real earth element and has many uses both as a drying agent and in medical applications as well. There are basically 6 different types of lithium-ion batteries Chemistries that have undergone testing and passed to mass production to the energy community. There is various cell chemistry still under lab test . What makes lithium ion a type is the active materials and the chemical to store energy. The types are Lithium-Ion Phosphate(LFP), Lithium Cobalt Oxide, Lithium Manganese Oxide, Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Nickel Cobalt Aluminum Oxide (NCA) and Lithium Titanate (LTO) (Ning Zhang et al., 2018)

2.1.6 Lithium -Ion Material Chemistry

2.1.7 CATHODE MATERIALS

Development of Li-ion batteries based on intercalation electrodes is touted to be one of the significant achievements of modern theoretical and applied electrochemistry. These are the emerging cathode materials categories. Some of them are already mature and deployed in batteries and some of them are in the research phase close to commercialization. Cathode materials are core components of Lithium- ion batteries, as energy density of a cell is determined through cell voltage or the capacity (ResearchGate , 2022). The choice of cathode material with different chemistry depends on parameters such as: voltage, capacity, energy and power capabilities, cycle life and temperature of operation.

There have been studies by various schoolers to improve cathode material performance through the following.

1. *Dimension Reduction of the particles- This helps in faster ion and electron transport, higher surface reactivity and relief stress and improved mechanical stability.*
2. *Improve Composite formation -This helps to improve the structural support of the cell.*
3. *Doping & Functionalization- This helps to create faster ion and electron transport and improve chemical and thermal stability.*
4. *Morphology Control-This helps to improve structural stability, faster ion, and modified reactivity.*
5. *Coating and Encapsulation- This protects the electrolyte and prevents the electrolyte from decomposition and stabilizes the surface for reaction.*
6. *Electrolyte Modification-This helps in formation of passive layer(s) on the surface of the electrode which helps to control the solubility of active material and decomposition of the battery material.*

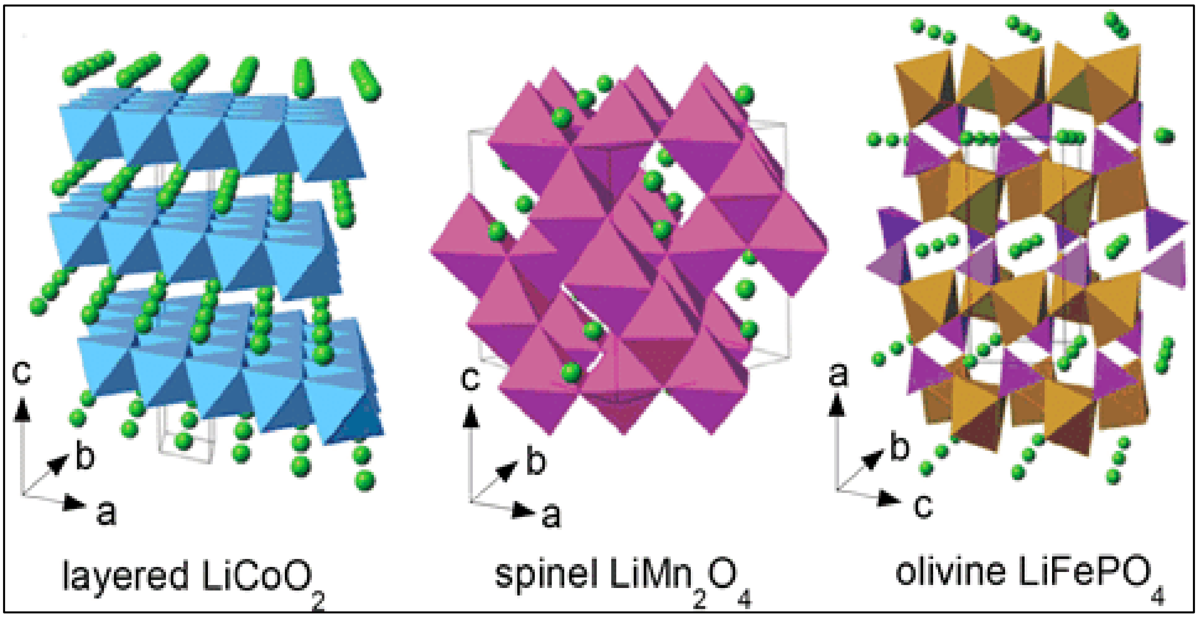


Figure 35*-Chemical Structural view of Cathode materials*
Source: https://www.researchgate.net/publication/318648747

2.1.8 ANODE MATERIALS

Carbon is a prime anode material in lithium-ion batteries due to its affordable cost, easy availability, and favorable electrochemical properties. One of the main challenges with the usage of carbon as an anode material is the poor theoretical Lithium-intercalation capacity of graphitic carbon compared to the very high charge density of the Lithium (Aaron et al. 2018). The other key problem with most anode materials is volume changes that go with during charge-discharge process limiting the life cycle of the battery. The following are widely used anode materials in Li-ion batteries. Carbonaceous anodes , Lithium titanium oxide (Li4Ti5O12/LTO) ,Alloy anodes , Silicon Currently, the two most used anode materials are those based on carbon (graphite) and lithium alloyed metals. One of the commercialized lithium alloyed metals is the oxide spinel Li4Ti5O12.

2.1.9 LIST OF KNOWN CATHODE MATERIALS

- Lithium–manganese spinel's ($LiMn_2O_4$)- this allows for higher discharge.
- Layered lithium-metal oxides. ($LiCoO_2$)
- Vanadium oxides ($LiFeSO_4F$)
- Olivine's ($LiFePO_4$)

Parameters	Graphite	Si	SiO
Capacity	372 mAh/g	Approx. 4200 mAh/g	Approx. 2400 mAh/g
Cycle Life (80% Retention)	>1000	<100	> 300
Mechanism	$Li + 6C = LiC_6$	$15Li + 4Si = Li_{15}Si_4$	$Li+5Sio=Li_{15}Si_4+ Li_2O+Li_xSiO_4$
Cost	$10-15/kg	$65/kg	Approx $20-30/kg
Other Key Issues	Poor low-Temperature Performance and rate capability	Low conductivity	Low conductivity

Table 7. *Table of Anode materials and characteristic*
Source: https://newenergyandfuel.com/wp-content/uploads/2010/02/Lithium-Ion-Battery-New-Material-Flow-Chart.jpg

2.2.0 REVIEW OF LITHIUM -ION CELL TECHNOLOGY

Lithium cobalt oxide ($LiCoO_2$**,** Lithium Manganese Oxide ($LiMn_2O_4$), Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$, or NMC, Lithium iron phosphate ($LiFePO_4$), Lithium titanate ($Li_4Ti_5O_{12}$)Thes battery technologies are the industry known ones that have been into mass production and cut into use (Dahn et al,. 2018).

Lithium-ion Technology	**Uses**	**Advantages**	**Drawbacks**	**Voltage Range**
Lithium-ion phosphate (LFP)	In energy storage, in cars and computers	Cheaper, longer life, durable and higher tolerance to temperature	Relatively low specific energy, it can suffer low temperature in operation	(2.0-3.6)V
Lithium Cobalt Oxide (LCO)	Cell phones, tablets, laptops, cameras	High specific energy	Short lifespan, low thermal stability, and expensive	(2.5-4.3)V
Lithium Manganese Oxide(LMO)	Medical instruments and power tools and other hybrid cars	Fast charge, handle high load application,	Lower cycle life	(3.0-4.2)V
Lithium Nickel Cobalt Aluminum oxide(NCA)	Electric vehicle application	Higher energy density, longer lifespan	Not very safe, very expensive	(3.0-4.2)V
Lithium Titanate (LTO)	Used in electric vehicle, energy storage telecommunication, and aerospace and military application	Very safe, long-life span. Very safe and wide temperature range	Low energy density, expensive and very heavy	(2.4-3.0)V
Lithium Nickel cobalt oxide (NMC)	Energy storage, vehicle application and military application	Higher energy density, smaller footprint, lighter weight	Expensive, weakness to higher temperature	(2.8-4.2)V

Table 9*-Analysis of various known lithium-ion technologies*
Source: Daniel Kelly Boakye Danquah, UND 2023

2.2.1 LITHIUM-ION MATERIAL CONTENT FOR CELL TECHNOLOGY

Lithium in its raw form does not make battery cell, but rather it must mix with other composite materials, metals and substances before a useful product is formed. The battery is made up of cathode and anode materials, these two together constitute about 42% of the total slurry for the battery cell. The rest of the battery electrode components make-up 58% of the battery cell. As can be seen in table 10 in appendices, it illustrates all mechanical compositions of lithium-ion battery cells.

2.2.2 EVALUATION OF VARIOUS LITHIUM BATTERY TECHNOLOGY

Lithium Cobalt Oxide ($LiCoO_2$). This technology is the most used cathode material. $LiCoO_2$ batteries have very stable capacities. Their capacities are lower than those based on nickel-cobalt-aluminum (NCA) oxides. Cobalt is relatively expensive compared to other transition metals, such as manganese and iron, despite the attractive electrical properties of LiCoO2 cathodes, it has a property of a highly insoluble thermally stable source suitable for glass, optic, and ceramic applications. It has various parameters that make it suitable for various applications, as shown in figure 36 below

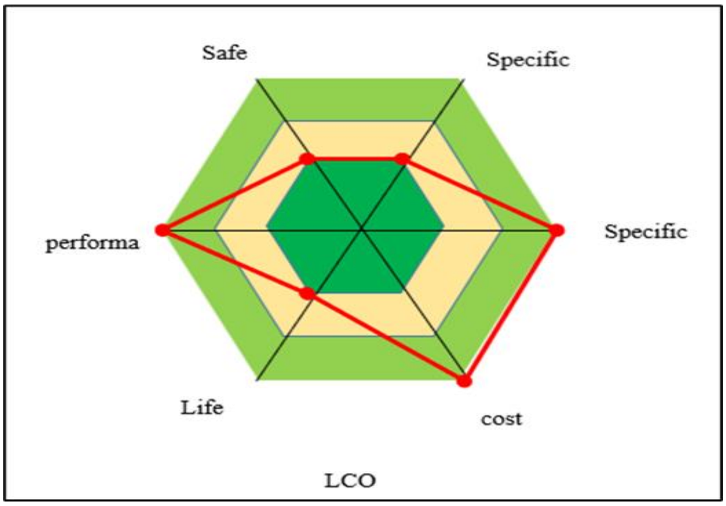


***Figure 36** – Diamond matrix evaluation of* $LiCoO_2$ *Battery*
Source: Figure designed by Daniel Kelly Boakye Danquah.

Oxide compounds are not conductive to electricity; however, certain perovskite structure oxides are electronically conductive finding application in the cathode of solid oxide fuel cells and oxygen generation systems. They are compounds containing at least one oxygen anion and one metallic cation.

They are typically insoluble in aqueous solution (water) and extremely stable making them useful in ceramic structures as simple as producing clay bowls to advanced electronics and in light weight structural components in aerospace and electrochemical applications.

Metal oxide compounds are basic anhydrides and can therefore react with acids and with strong reducing agents in redox reactions. Cobalt Lithium Oxide is also available in forms such as pellets, pieces, powders, sputtering targets, and nanoparticles (American elements, 2019).

Parameters	Properties
Compound formular	$LiCoO_2$
Molecular Weight	97.87
Appearance	Blue-black, blue, or gray powder
Exact Mass	97.93
Monoisotopic Mass	97.93
Signal Word	Danger
Use and Application	Phones, laptops, computers, and tablets
Thermal runaway	High charging @ 150 ºC
Life span	500 – 1000 Cycles

***Table 11**. Lithium Cobalt Oxide Technical Properties.*
Source: American elements, Table design: Daniel Kelly Boakye Danquah

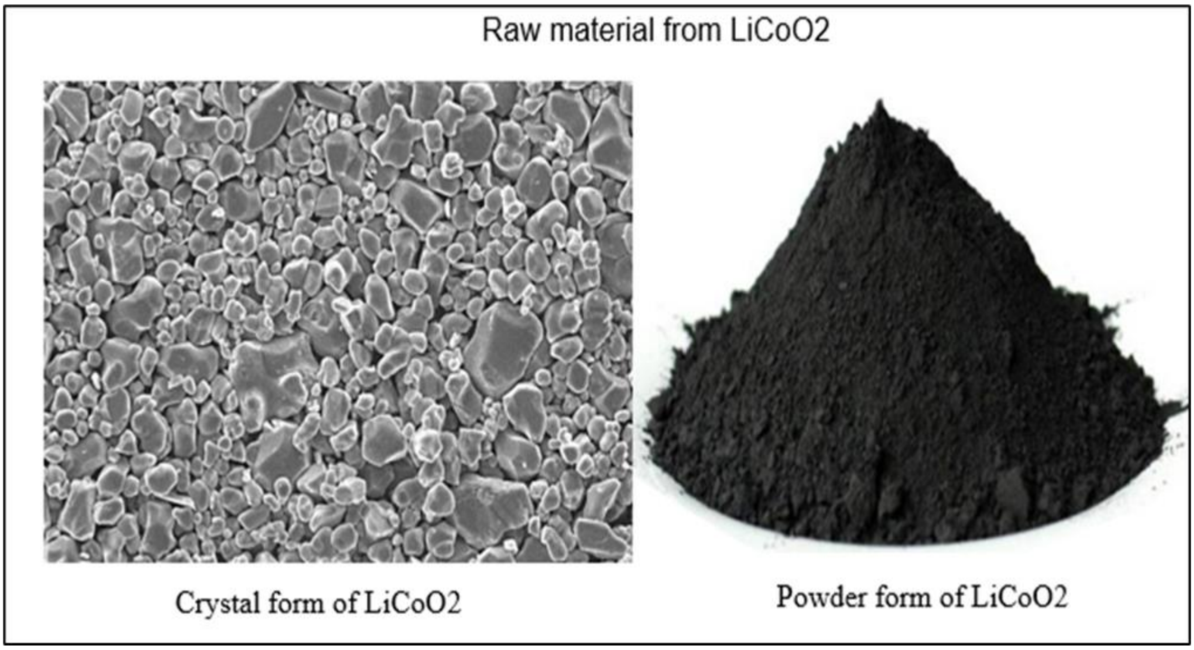


Figure 37. *Image of Cathode Material Powder of lithium cobalt oxide*
Data Source: American elements, Table design: Daniel Kelly Boakye Danquah

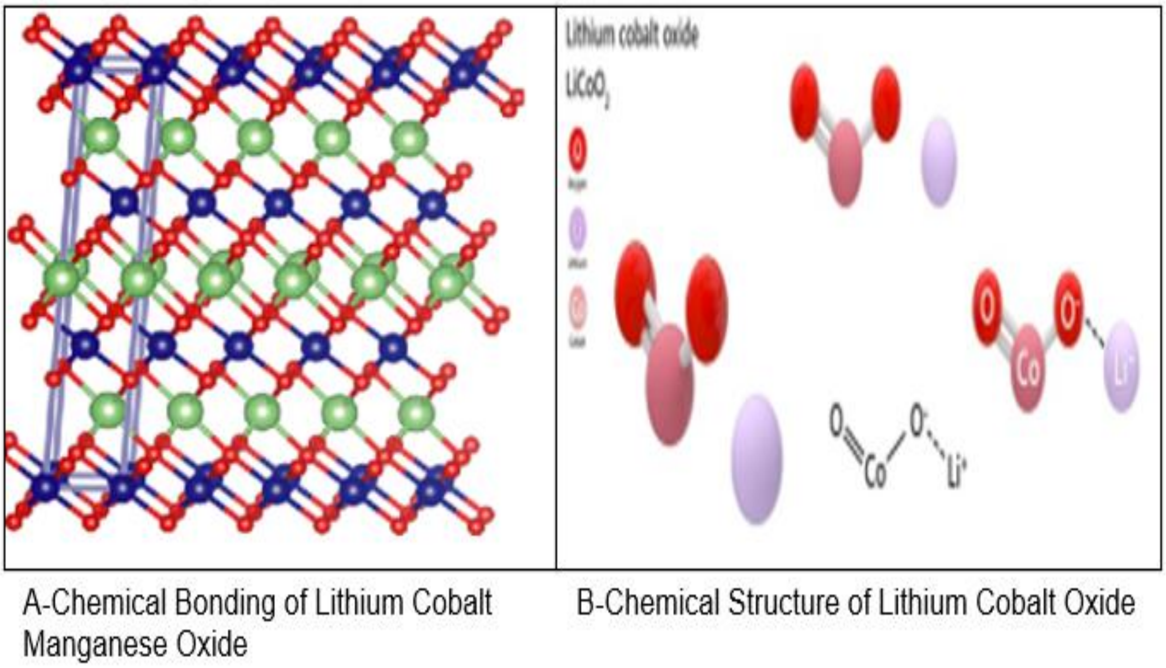


Figure 38 *- The bonding and chemical structure of Lithium Manganese Oxide*
Source: https://www.semanticscholar.org/paper/

Lithium Manganese Oxide ($LiMn_2O_4$): $LiMn_2O_4$ is a promising cathode material with a cubic spinel structure. $LiMn_2O_4$ is one of the most studied manganese oxide-based cathodes because it holds inexpensive materials. A further advantage of this battery is enhanced safety and high thermal stability, low cost . The drawbacks are 0the cycle and calendar life is limited and lower performance. Its applications are in medical devices, power trains. Extracting lithium from Li_2MnO_3 at such a high potential can also be compensated by loss of oxygen from the electrode surface which leads to poor cycling stability. New allotropes of Li_2MnO_3 have been discovered which have better structural stability against oxygen release (longer cycle-life).

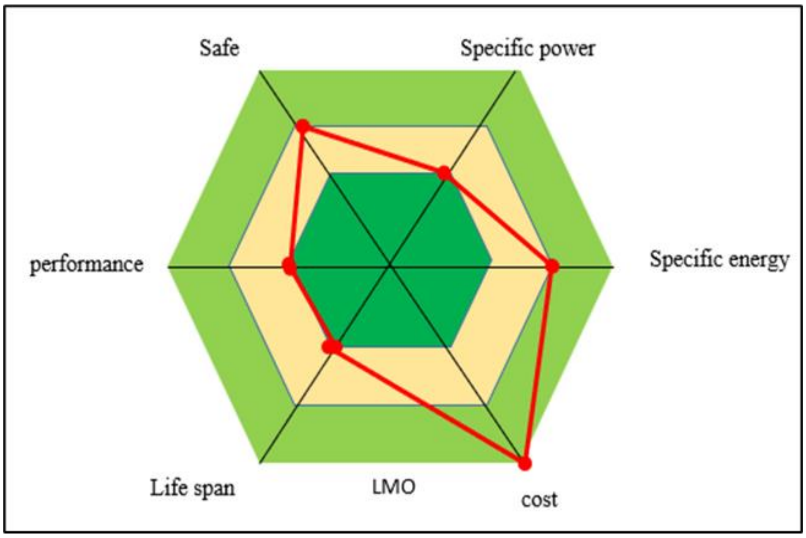


***Figure 39** – Diamond matrix evaluation of* $LiMn_2O_4$ *Battery*
Source: Designed by Daniel Kelly Boakye Danquah

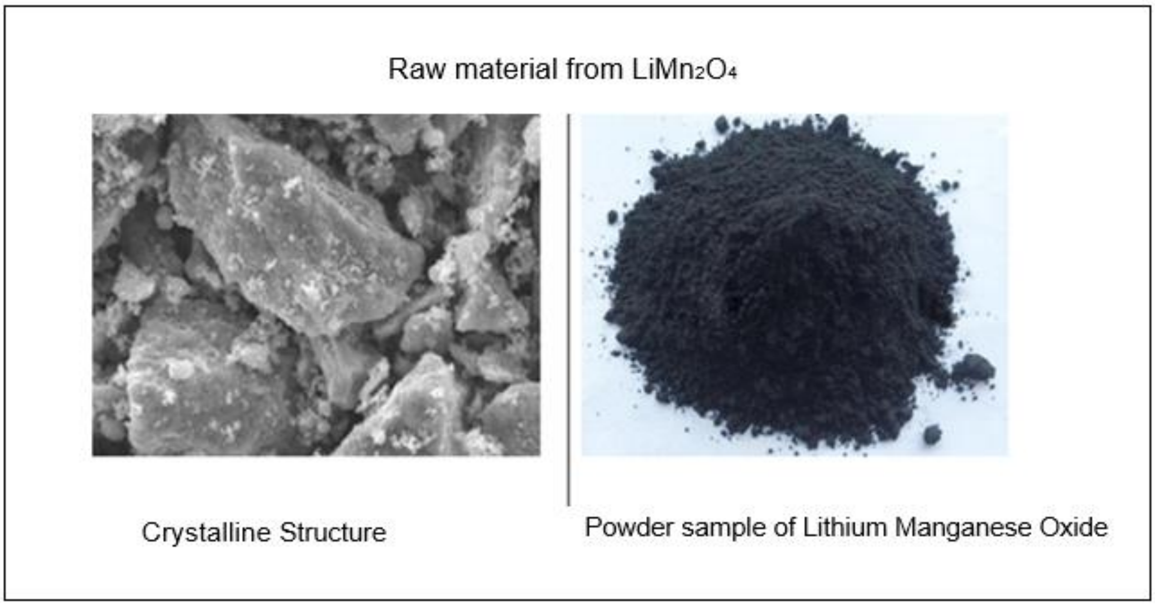


***Figure 40** – An Image of Cathode Material Powder of lithium Manganese Oxide*
Data Source: American elements, design: Daniel Kelly Boakye Danquah.

Parameters	Properties
Compound formular	$LiMn_2O_4$ ---LMO
Molecular Weight	180.81
Appearance	Dark blue to black powder
Exact Mass	180.871
Monoisotopic Mass	180.871
Melting point	>400 °C
Signal Word	Danger
Use and Application	Medical devices and power tools
Thermal runaway	High charging @ 250 ºC
Life span	300 – 700Cycles

***Table 12** - Characteristics of Lithium Manganese Oxide*
Data Source: American elements, Table design: Daniel Kelly Boakye Danquah

Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) – NMC: Nickel manganese cobalt (NMC) batteries contain a cathode made of a combination of nickel, manganese, and cobalt. Lithium nickel manganese cobalt oxides (abbreviated Li-NMC, LNMC, or NMC) are mixed metal oxides of lithium, nickel, manganese, and cobalt [27] They have the general formula $LiNi_xMn_yCo_zO_2$. NMC is one of the most successful cathode combinations in Li-ion systems. Lithium Nickel Manganese Cobalt Oxide (NMC, or LiNiMnCo) is a highly thermally stable electrode material used in the newest generation of rechargeable lithium-ion batteries. Lithium Nickel Manganese Cobalt Oxide (NMC) is generally at once available in most volumes . It can be tailored to serve as energy cells or power cells like Li-manganese. has two major advantages as compared to the other batteries. As figure 41 shows, is its high specific energy, which makes it desirable in electric powertrains, electric vehicles, and electric bikes, energy storage. (Dahn et al,.2018) The other is its low cost. It is moderate in terms of specific power, safety, lifespan, and performance when compared to the other lithium-ion batteries. It can be optimized to either have high specific power or high specific energy. NMC batteries are used for power tools, e-bikes, energy storage and other electric powertrains.

To lower the Co content while maintaining good electrochemical performance three series of materials with different transition metal ratios: The materials were synthesized via a co-precipitation/solid state sintering method. Powder X-ray diffraction (XRD) and electrochemical measurements using coin-type cells were made to characterize the materials. Accelerating rate calorimetry (ARC) was used to study the reactivity of charged NMC positive electrode materials in the presence of electrolyte at elevated temperatures. NMC721, NMC631 and NMC6.5:2.5:1 which have 50% less Co content than current commercialized NMC622, exhibited excellent specific capacity and thermal stability, and therefore deserve careful consideration as next generation materials.(Huang et al,. 2018)

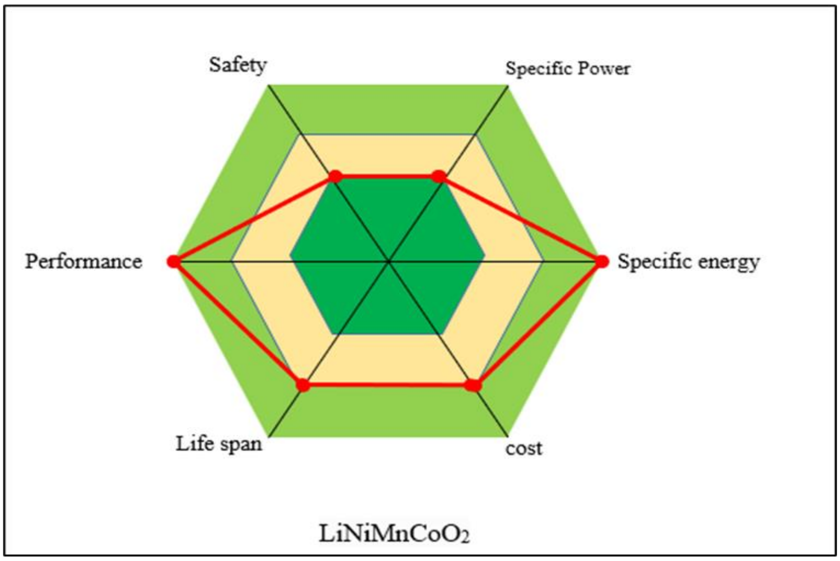


Figure 41 *– Diamond matrix evaluation of LiNiMnCoO₂ Battery*
Source: Figure designed by Daniel Kelly Boakye Danquah.

PARAMETERS	PROPERTIES
Compound formular	$LiNiMnCoO_2$
Molecular Weight	Varies by composition
Appearance	Black powder
Firefighting Measures	Use water spray, alcohol resistant form or carbon dioxide
Varieties	NMC333, NMC 532,NMC 622, NMC 811
Melting point	>290 °C
Signal Word	warning
Use and Application	Energy storage, vehicle application, e-bike
Thermal runaway	High charge over 200
Life span	3000-7000 °C

Table 13 *- Nickel Manganese Cobalt Oxide Technical Properties.*
Data Source: www. http// Americanelements.com

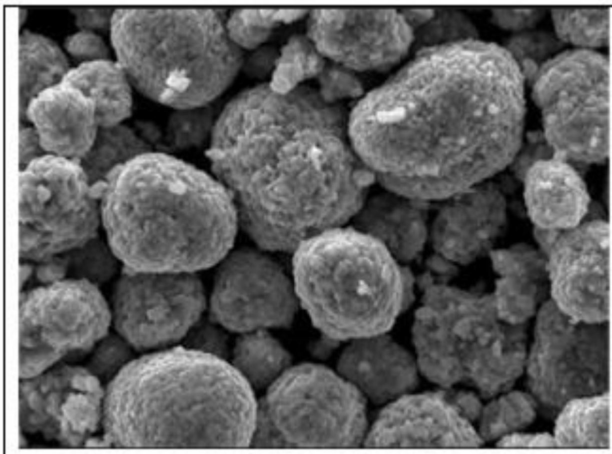
	
Crystal structure LiNiMnCoO2	Powder Form of LiNiMnCoO2

Figure 42 *- Image of Cathode Material Powder of lithium iron Phosphate*
Data Source: American elements, Table design: Daniel Kelly Boakye Danquah

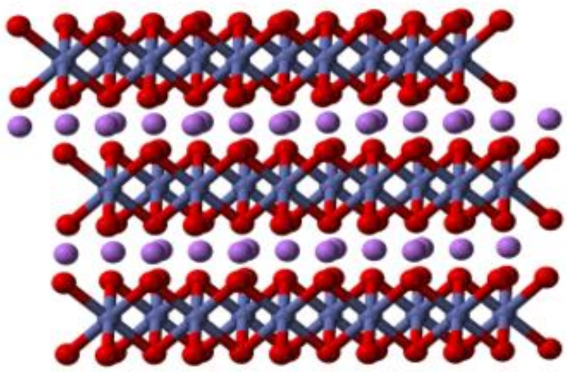
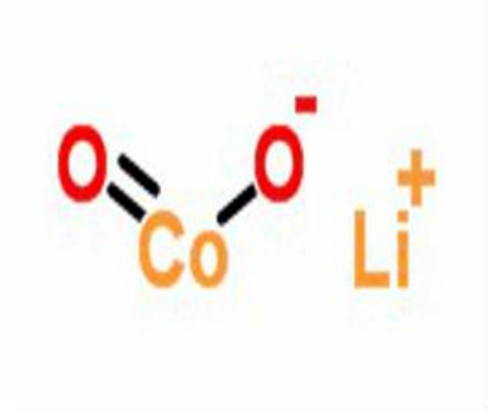
	
Chemical Bonding of Lithium Nickel Manganese Oxide	Chemical Structure of Lithium Manganese oxide

Figure 43 *- The bonding and chemical structure of Lithium Nickel Manganese cobalt oxide*
Source: https://www.semanticscholar.org/paper/

LITHIUM-IRON PHOSPHATE ($LiFePO_4$); This battery technology is one of the most recent cathode materials to be introduced as of 2017. Lithium Iron Phosphate (LFP) is a cathode material for use in next-generation, environmentally friendly lithium-ion batteries with high energy density and thermal stability. Lithium iron phosphate is generally at once available in most volumes. High purity, submicron and nano powder forms may be considered [15]. The energy density of an LFP battery is lower, because of their lower cost, high safety, low toxicity, long cycle life, and other factors, LFP batteries are finding several roles in vehicle use, utility-scale stationary applications, and backup power. The working voltage is around 3.0 ~ 3.3 V. has cycle life ranges from 2,700 to more than 10,000 cycles depending on conditions. Lithium Iron Phosphate only has one major disadvantage when compared to other types of lithium-ion batteries, and that is its low specific energy. Other than that, it has moderate to high ratings in all the other characteristics. It has high specific power, offers a high level of safety, has a high lifespan, and comes at a low cost.

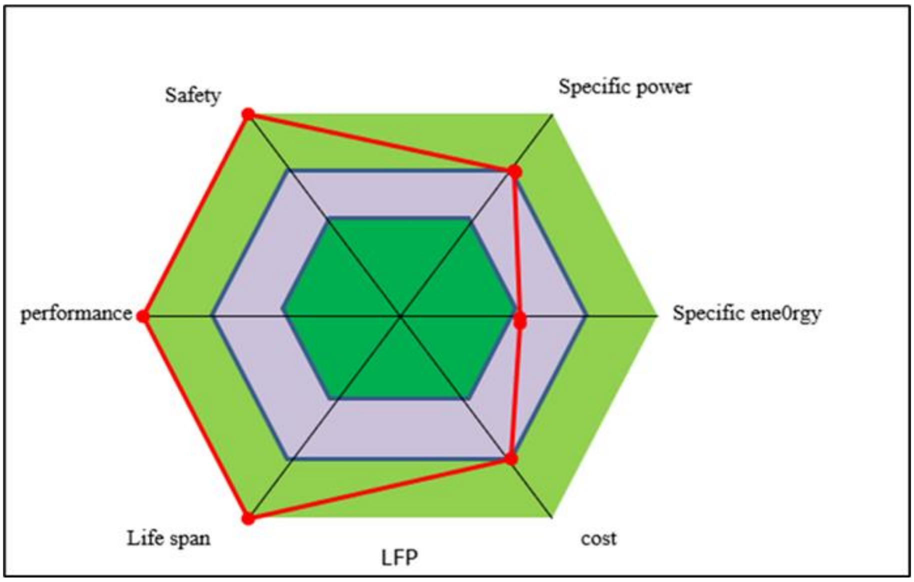


Figure 44 *– Diamond matrix evaluation of LFP Battery*
Source: Figure designed by Daniel Kelly Boakye Danquah.

Parameters	**Properties**
Compound formular	$FeLiPO_4$
Molecular Weight	157.76
Appearance	Gray to black Powder
Firefighting Measures	Use water spray, alcohol-resistance foam, dry chemical
Volumetric energy	220 Wh/L
Gravimetric energy density	90 Wh/kg
Cycle life	2,700 to 10, cycles depending on condition
Application	Energy storage, vehicle, motorcycles
Safety	High
Thermal runaway	>300 °C
Cost	$ 450/kwh

Table 14. *Image of Cathode Material Powder of lithium iron Phosphate*
Data Source: http//.ww. Americanelements.com.

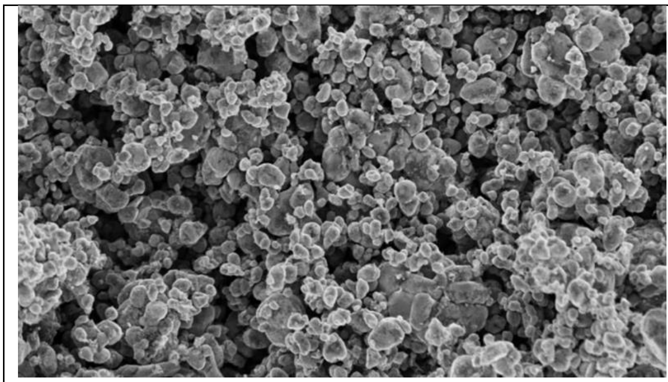
	
Crystal Structure of **LiFePo4**	Powder form of **LiFePo4**

Figure 45. *Image of Cathode Material Powder of lithium iron Phosphate*
Data Source: American elements, Table design: Daniel Kelly Boakye Danquah

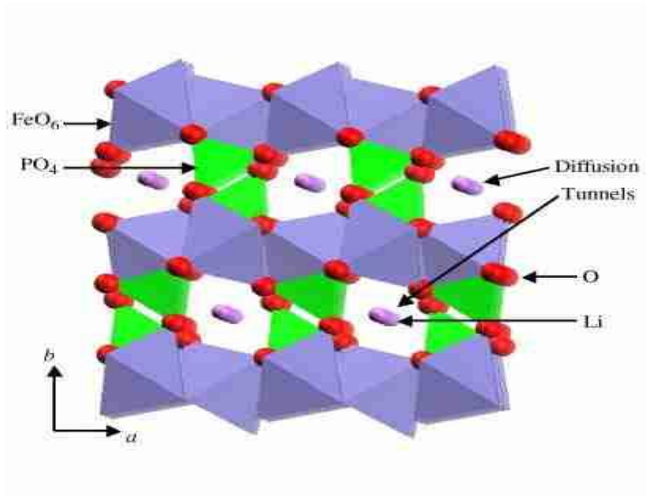
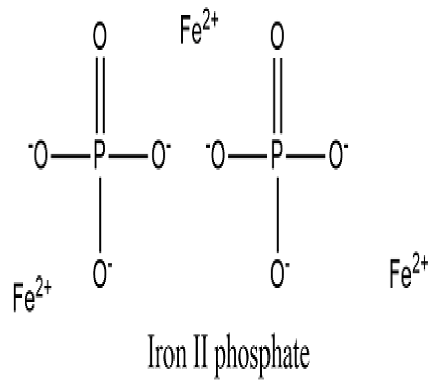
	
Chemical Bond structure LiFePo4	**Chemical Equation LiFePO4**

Figure 46*- Chemical bond and structure of Lithium-ion phosphate*
Source: Society of chemical engineers, 2020.

LITHIUM NICKEL COBALT ALUMINUM OXIDE (LINICOALO$_2$) – NCA: Lithium nickel cobalt aluminum oxide batteries (NCA) were first used in 1999 and were used in some special applications. It has some characteristics like NMC. It offers high specific energy, a long-life span, and reasonably good specific power. NCA's usable charge storage capacity is about 180 to 200 mAh/g. The capacity of NCA is significantly higher than that of alternative materials such as $LiCoO_2$ with 148 mAh/g, $LiFePO_4$ with 165 mAh/g, and NMC 333 ($LiNi_{0,33}Mn_{0,33}Co_{0,33}O_2$)with 170 mAh/g. The voltage of these batteries is between 3.6 V and 4.0 V, at a nominal voltage of 3.6 V or 3.7 V. Another advantage of NCA is its excellent fast charging capability. Nevertheless, its weak points are the limited resources of cobalt and nickel and the high cost**.** Lithium Nickel Cobalt Aluminum Oxide offers one strong advantage compared to the five other batteries: high specific energy and high thermal stability. It is moderate in the rest of the characteristics like performance, cost, specific power, and lifespan.

The only downside to this battery type is its low level of safety. Its high specific energy and moderate lifespan make it a good candidate for energy applications.

The two materials NCA and NMC have related structures, quite similar electrochemical behavior and show similar performance, relatively high energy densities and relatively high performance. It is estimated that the NCA battery of Model 3 holds between 4.5 and 9.5 kg of cobalt and 11.6 kg of lithium.

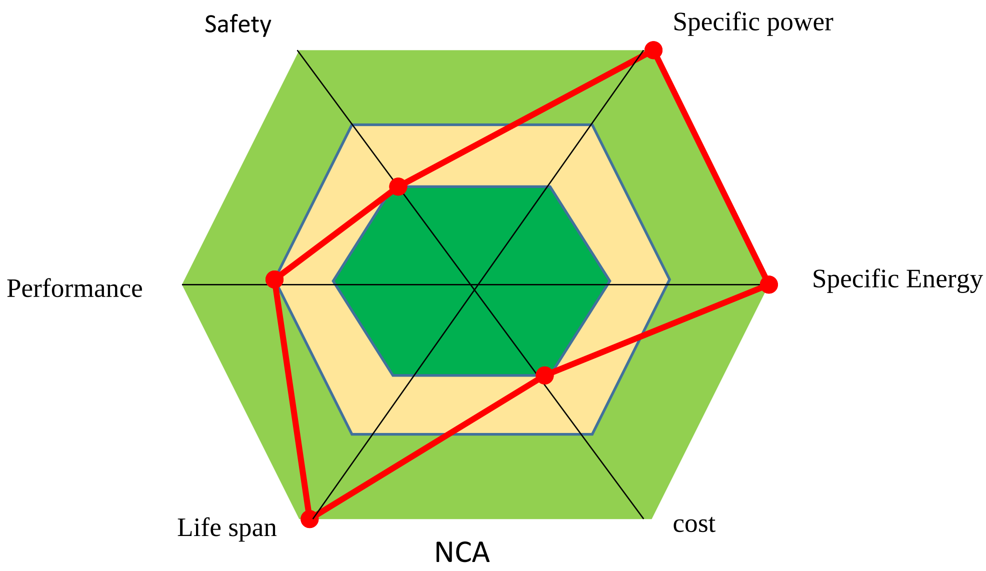


Figure 47. *Diamond matrix evaluation of NCA Battery*
Source: Figure designed by Daniel Kelly Boakye Danquah

Parameters	Properties
Compound formular	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$
Molecular Weight	183.54 (LiNiCoAlO2); varies by composition
Appearance	Black Powder
Firefighting Measures	Water spray form and alcohol resistance foam
Specific energy	200-260Wh/kg
Volumetric capacity	190 mAh/g
Gravimetric Density	4.45 g/cm^3 **(Crystal Density)**
Cycle life	1,000—2000, Related to DOD, temperature
Application	E-Bike, Medical Device,
Safety	Medium to High
Thermal runaway	>180 °C
Commercially available	1999
Cost	$ 350/kwh

Table 15 *- Characteristics of Lithium Nickel Manganese Cobalt Oxide (NMC)*
Source: Americanelements.com

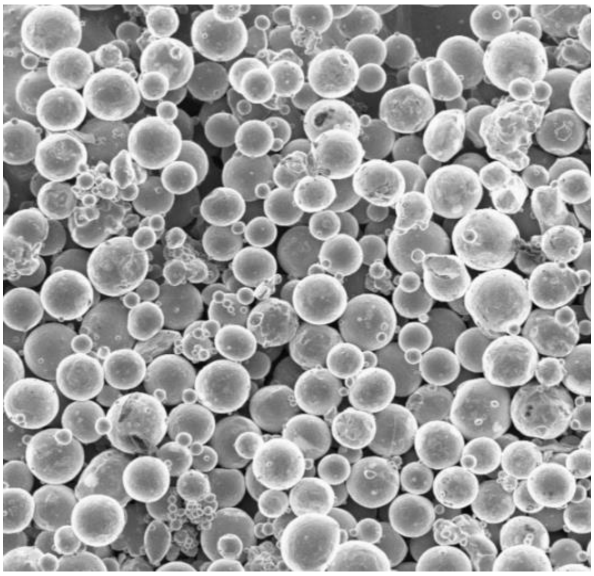
	
A-Crystal form of $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	**B-Powder form of** $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$

Figure 48. *Characteristics of Lithium Nickel Manganese Cobalt Oxide (NMC)*
Source: Americanelements.com, Table design: Daniel Kelly Boakye Danquah

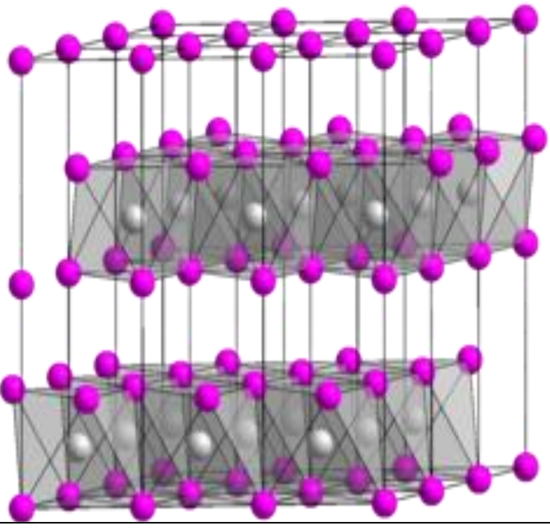
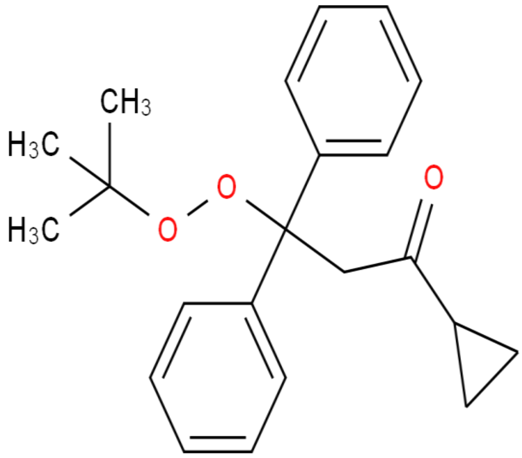
	
Chemical bond of Lithium Nickel Aluminum cobalt oxide	Chemical structure of Lithium Nickel Aluminum cobalt oxide

Figure 49- *Chemical bond and structure of Lithium Nickel Aluminum cobalt oxide*
Source: Society of chemical engineers, 2020.

LITHIUM TITANATE [Li_2TiO_3]-LTO: This battery chemistry offers high safety, high performance, and a high lifespan which are very important features every battery should have. Its specific energy is low compared to the five other lithium-ion batteries, but it compensates for this with moderate specific power. The only major disadvantage of lithium titanate as compared to the other lithium-ion batteries is its extremely high cost. Another important feature of this battery worthy of mention is its remarkably fast recharge time. It can be used for storing solar energy and creating smart grids. Electric powertrains. Unlike other lithium-ion batteries — LFP, NMC, LCO, LMO, and NCA batteries — LTO batteries don't use graphite as the anode. Instead, their anode is made of lithium titanate oxide nanocrystals. This unique feature significantly impacts this battery's properties. In a lithium-ion battery, ions move from one electrode to another.

The direction in which these ions move depends on whether you're charging or discharging the battery. During charging, the lithium ions move from the cathode to the anode. Lithium ions can enter and exit the anode's structure. The speed/rate at which this happens depends on the anode's ability to "accommodate" these lithium-ions. In chemistry, the term for this "accommodation" is intercalation. Graphite is the prime anode material for most lithium-ion batteries. This is due to its low cost, availability, and convenient electrochemical properties. However, its lithium intercalation capacity is relatively poor.

The LTO anode's structure eases lithium ions entering and exiting, allowing electrons to enter and exit the anode faster. This makes fast charging/discharging (higher current) much safer for LTO batteries than graphite as the anode since lithium dendrites are less likely to form, avoiding degradation and possible short-circuit. Moreover, the anode's properties minimize the risk of SEI film formation and lithium plating .This helps avoid capacity loss.

Finally, LTO batteries charge well under low temperatures and support thermal stability under high temperatures. Another advantage of LTO batteries is their high resistance to extreme temperatures. For instance, an LTO battery's performance is resistant to being left in a warm place/under sunlight — though it's best to avoid doing this. Lithium titanate batteries offer many advantages over other lithium-ion chemistries, including longer cycle life, Increased safety, Wider working temperature range, Faster charge/discharge rates. However, energy density is relatively low among these batteries. In addition, high C-rates inevitably impact the battery's capacity over time. LTO suffers from severe gassing due to a reaction between the organic electrolyte and the LTO active material (Jeff. Dahn et al,. 2019) This reaction can be suppressed by carbon coating, but carbon can also catalyze and accelerate electrolyte decomposition in the formation of an SEI, especially at high temperatures.

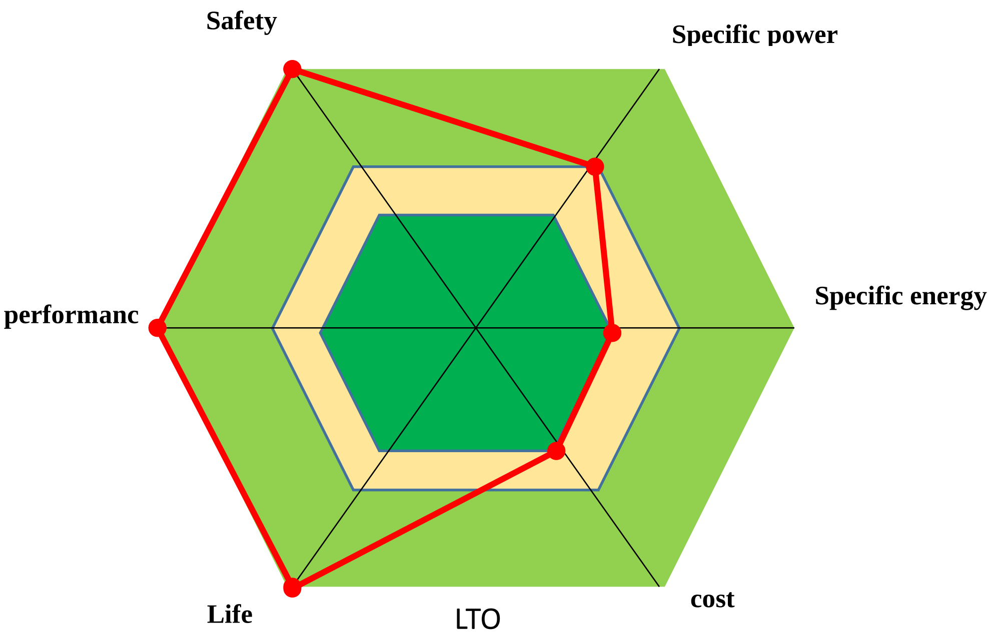


Figure 50 *- Diamond matrix evaluation of NCA Battery*
Source: Figure designed by Daniel Kelly Boakye Danquah

Parameters	Properties
Compound formular	Li_2TiO_3
Molecular Weight	109.75
Appearance	White powder
Firefighting Measures	Novec
Specific energy	50-80wh/kg
Volumetric capacity	0.4217 nm^3
Gravimetric Density	3.43 g/cm^3
Cycle life	3,000-7000
Application	Electric vehicle, solar power streetlight
Safety	Highest safety
Thermal runaway	1,533 °C
Cost	$1,005 per kwh (source: RWTH, Aachen)
Charge(C-Rate)	1C typical, 5C max, max voltage 2.85V
Commercially available date	2008

Table 16 Characteristics of Lithium Titanate
Source: Wikipedia.com,2021.

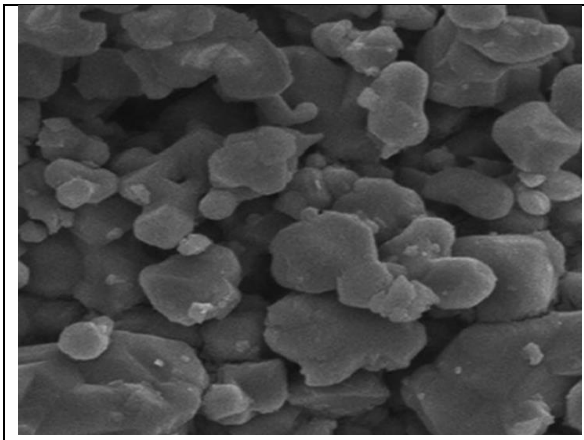
	
A-Crystal form of $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	**B-Powder form of** $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$

Figure 51*- Image of raw processed Lithium titanate*
Source: Americanelements.com

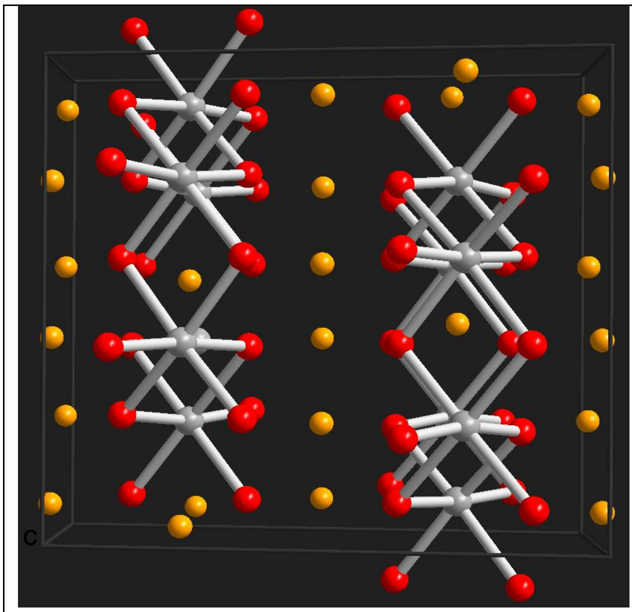
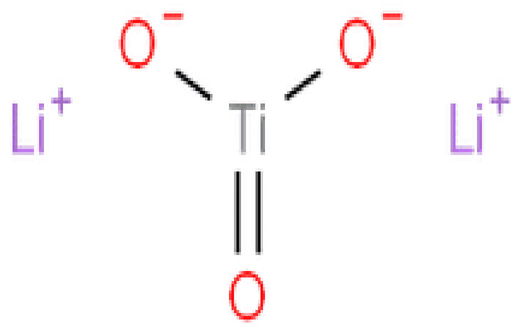
	
A-Crystal form of $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	**B-Powder form of** $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$

Figure 50.*- Illustration of chemical bond and characteristics of LiNi0.8Co0.15Al0.05O2*
Source: Americanelements.com,2022

LITHIUM POLYMER BATTERIES: A lithium-ion polymer (LiPo) battery (also known as Li-pol, lithium-poly, and other names) is a type of Li-ion battery with a polymer electrolyte instead of a liquid electrolyte. All LiPo batteries use a high-conductivity gel polymer as electrolyte. Lithium polymer cells have evolved from lithium-ion and lithium-metal batteries. The primary difference between lithium-ion and Li-pol is that instead of using a liquid lithium-salt electrolyte (such as LiPF6) held in an organic solvent, the battery uses a solid polymer electrolyte (SPE) such as polyethylene oxide (PEO), polyacrylonitrile (PAN), polymethyl methacrylate (PMMA) or polyvinylidene fluoride (PVdF). LiPos supplies higher specific energies than other lithium batteries, often used in systems where weight is an important factor, such as mobile devices, drones, and some electric vehicles. All Li-ion cells expand at high levels of (SOC) or over-charge, due to slight vaporization of the electrolyte. This may result in delamination and thus bad contact of the internal layers of the cell, which in turn brings diminished reliability and overall cycle life of the cell. This is very noticeable for LiPos, which can visibly inflate due to lack of a hard case to contain their expansion. Unlike lithium-ion cylindrical and prismatic cells, which have a rigid metal case, LiPo cells have a flexible, foil-type case, so they are relatively unconstrained. Moderate pressure on the stack of layers that compose the cell results in increased capacity retention because the contact between the components is maximized and delimitation and deformation is prevented, which is associated with increase of cell impedance and degradation. LiPo cells provide manufacturers with compelling advantages. They can easily produce batteries of almost any desired shape. They also have a low self-discharge rate, which is about 5% per month. Use case , they are used in electric vehicles, uninterruptible power supply, cars, and watches. Cells with solid polymer electrolytes have not reached full commercialization. After a comprehensive overview of the most important energy storage technologies with their technological progress, performance, and economic aspects. Also, the requirements and preferences relating to the potential applications across the power chain and potential sustainability have been reviewed comparative assessment to help in decarbonizing the atmosphere and help grid resilience. All energy storage technologies are essential and useful based on the application and environmental condition. Pump hydro technology is currently the most suited in large-scale energy management applications, mainly due to its technical maturity. With high power and energy per unit mass and volume. Lithium-ion technology monopolizes portable electronic devices and electric mobility and short duration energy, but current have price constrains, hence more difficult to be applied in larger scale, stationary EES applications. As the cheapest battery option, Pb acid enjoys exclusivity in automotive starting, lighting and ignition applications and is considered the best choice for small-to-medium scale stationary applications of UPS and back-up power. Most of these technologies need more time to become mature and economical, and without storage opportunities their future contribution will go ahead more slowly. My research is to focus on finding how fault could be detected at the earlier stage in lithium-Ion battery storage technology and prevent fire and make lithium-ion battery a safe technology to use both in automotives, energy storage and any aspect of our lives. Lithium ion as energy storage technology comes in different forms and factors, Li-aluminum (NCA), LTO, LFP, LCO, LMO ,Solid states, lithium sulfur and lithium are few examples of the technologies known in the industry which has mature and can be mass produce without disruption in supply chain.

After review of the technology ,Lithium cobalt aluminum (NCA) is the clear winner by storing more ability than other systems, this only applies to specific energy. In terms of specific power and thermal stability, Li-manganese (LMO) and Li-phosphate (LFP) are superior. Li-titanate (LTO) may have low ability, but this chemistry outlives most other batteries in terms of life span and has the best cold temperature performance. Moving towards the electric powertrain, safety and cycle life will gain dominance over capacity. Future Batteries, such as Solid-state

Li-ion, has High specific energy but poor loading and safety. Lithium-sulfur also has high specific energy, but poor cycle life and poor loading and Lithium-air has high specific energy but poor loading, needs clean air to breath and has short life. The Li-ion battery has clear fundamental advantages and decades of research have developed it into the high energy density, high cycle life, high efficiency battery that it is today. Research continues new electrode materials to push the boundaries of cost, energy density, power density, cycle life, and safety. Various promising anode and cathode materials exist, but many suffer from limited electrical conductivity, slow Li transport, dissolution or other unfavorable interactions with electrolyte, low thermal stability, high volume expansion, and mechanical brittleness. Various methods have been pursued to overcome these challenges to help improve the batteries from catching on fire as safety has been the biggest roadblock to advancement of energy transition and dependencies on oil.

2.2.3 LITHIUM-ION BATTERY INCIDENCE IN THE INDUSTRY

The start of lithium-Ion battery industry is characterized by many fires of late, some are huge, medium, and big fires. Each of these fires causes a threat in the industry, this makes the advances in lithium-ion technology difficult, since society is shrouded in the myth of lithium-ion batteries that may catch fire when being used. This instance might be true in some cases when we can support these claims with real incidence of lithium-ion batteries catching on fire. Geographically, all countries that have lithium-ion battery in one form to another has experience a safety issue since lithium-ion batteries account for more than 90% of the installed power and energy capacity of large-scale battery storage in operation in the United States and around the globe at the end of 2018. In addition, Lithium-Ion high energy density (stored energy per unit of weight) makes them the current battery of choice for most portable electronic and electric vehicle applications.

Despite the safety of these batteries, they can become hazardous in certain situations. If they've been damaged or have some kind of defect, they can cause devastating fires. The U.S. Consumer Product Safety Commission reported that there were more than 25,000 issues involving fires or overheating stemming from lithium-ion batteries in a five-year period. Under this number, here are some incidents that makes, Royal waste services in Jamaica, New York, Superior Battery in Morris, Illinois, Felicity Ace burns in the Atlantic Ocean, one of the biggest battery fires in the Atlantic Ocean, which brought down a ship loaded of over 4,000 vehicles from Volkswagen.

Also, Shoreway Environmental Center in San Carlos, California A four-alarm fire broke out at South Bayside Waste Management Authority's Shoreway Environmental Center back in 2016. It took 79 firefighters several hours to put the fire out. Others included Vistara energy facility in Moss Landing , California, Vistara Energy is the world's largest battery storage facility for storing solar and wind energy (Wood Mackenzie,2022).

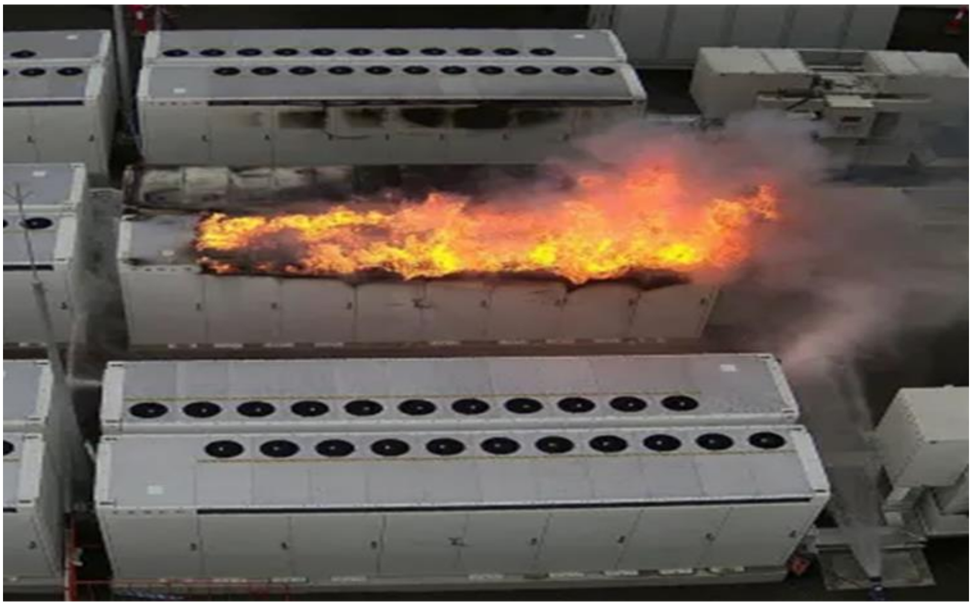


Figure 52. Image of Tesla megapack catches on fire in Australia.
Source: https://www.teslarati.com/tesla-megapack-fire-victoria

The risk of combustion from overheating is higher, especially if the batteries are damaged in some way. Back in September, the 300-megawatt facility shut down when several overheating battery packs melted and triggered the fire suppression system to kick in. About 7,000 batteries were soaked by the system and damaged in the process . The company shut down the 300-megawatt facility, but a smaller 100-megawatt facility was still in operation at the site. February 13th, that smaller facility experienced a second incident. Again, it's believed that water hoses leaked and damaged some of the facility's battery packs. It was especially concerning as the company was about to reopen the 300-megawatt facility. Those plans have since been scrapped until the facility can figure out how to prevent added meltdowns if there are hose leaks. While the fire suppression system worked effectively both times, there are fears about what could happen if the systems failed and hundreds of these batteries exploded.

2.2.4 TOTAL CAPACITY OF INSTALLED ENERGY STORAGE

Across all segments of the industry, the U.S. energy storage market installed 4.8 gigawatts of capacity in 2022, nearly equal to the combined 2020 and 2021 installed capacity of 5 GW, becoming a record year for battery storage, according to a new report from the American (Clean Power Association and Wood Mackenzie, 2021)

According to the lates US energy storage monitor report",(eia.gov, 2022) the market added 1,067 megawatts across all segments in the fourth quarter of 2022, making the quarter only the fifth highest for installations – 33% lower than Q4 of 2021, which is the highest on record.

The new report's findings show that the U.S. grid-scale segment installed a total of 848 MW in Q4 2022, which was a decline from more than 1 GW of installations in both Q2 and Q3 of this year (eia.gov, 2022). Decreased installed capacity was largely caused by supply chain and interconnection constraints. These headwinds continued to affect the project pipeline, with over 3 GW of projects scheduled to come online in Q4 delayed or cancelled.

However, the residential storage segment increased by 11% over Q3 and broke another record with 171 MW installed, ousting Q3 2022 by 17 MW. Capacity installations increased for this segment every quarter in 2022, confirming sustained demand for residential back-up power and resiliency. Deployment in the community, commercial, and industrial storage segment recovered from a significant drop in Q3 2022 with 48 MW installed in Q4, an increase of 78%. States traditionally strong in the CCI segment, such as New York, bounced back to higher deployment levels which boosted Q4 numbers.

“Despite a slow fourth quarter, total 2022 installations were still 44% over 2021. Grid-scale installations increased by 7% year-over-year, CCI by 3%, and residential experienced the strongest growth with installations up 36%. Looking ahead, we expect the U.S. storage market to install almost 75 GW between 2023 and 2027. Grid-scale installations account for approximately 60 GW, 81% of the new capacity.

Forecasted capacity for the grid-scale and CCI segments will more than double in 2023, partly due to robust storage demand and to projects that were delayed from 2022 coming online. Wood Mackenzie also expects residential capacity to increase by approximately 88% in 2023 – with four times more residential storage to be installed in 2027 compared to 2022 volumes.

“California continues to hold the largest market share of residential installations through 2027 at 47%, which dwarfs any other state by far. Puerto Rico is still the second largest through 2027 with an 11% share,” Witte said.

Project volume in the interconnection queue from 2023 to 2028 declined by approximately 10% from the last quarter; a result of independent system operators filtering through applications and developers withdrawing applications now that the rush to secure queue positions has somewhat subsided.

According to the report, 7 GW of projects with an original 2022 Commercial Operation Date have been pushed into later years or cancelled outright, likely due to increased costs or developers' inability to procure equipment within the timeframe needed. [67]

Price relief for batteries is on the horizon, as commodity prices have begun to decline after prices for battery precursors, such as lithium carbonate, peaked in Q4. System cost declines are expected in 2023 though other issues remain, such as supply delays and an increasingly tight labor market.

	China	**United States**	**Europe**	**South Korea**	**Japan**	**Rest of the world**
2015	**0**	**0.2**	**0.1**	**0**	**0**	**0**
2016	**0.1**	**0.2**	**0.1**	**0.2**	**0.1**	**0**
2017	**0.1**	**0.2**	**0.3**	**0.2**	**0**	**0.2**
2018	**0.3**	**0.3**	**0.6**	**0.3**	**0**	**0.1**
2019	**0.4**	**0.3**	**0.5**	**0.2**	**0**	**0.2**
2020	**0.9**	**1.1**	**0.5**	**0.7**	**0.1**	**0.1**
2021	**1.9**	**2.9**	**1**	**0.1**	**0**	**0.5**

Table 17. *Annual grid- Scale battery storage additions from 2016-2021*
Source: IEA (2022), Grid-Scale Storage, IEA, Paris https://www.iea.org/reports/grid-scale-storage, License: CC BY 4.0

2.2.5 LITHIUM-ION BATTERY SAFETY AND INCIDENT RECORDS

With the growing number of battery deployment in the world and around the globe, you cannot read the news without hearing a story about a lithium-ion battery fire incidence that occurred in a high rise building, electronic shop, electric vehicles, vape in some one pocket, a fulfilment warehouse or in a waste cycle facility.it is obvious that, the technology will suffer some issues which are related to fires and other.

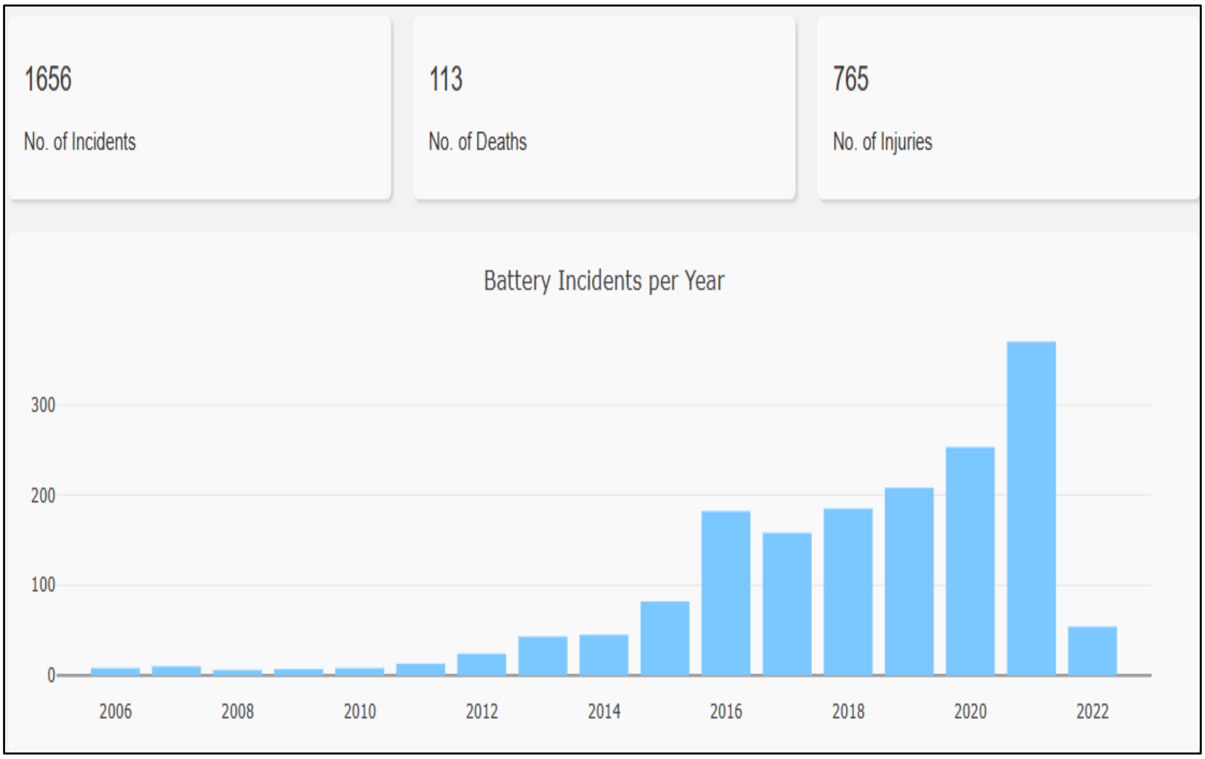


Figure 53: *A graph of recorded battery incidence per year*
Source: Source: Federal Aviation Administration, security and Hazardous Materials safety, Last updated February 2023

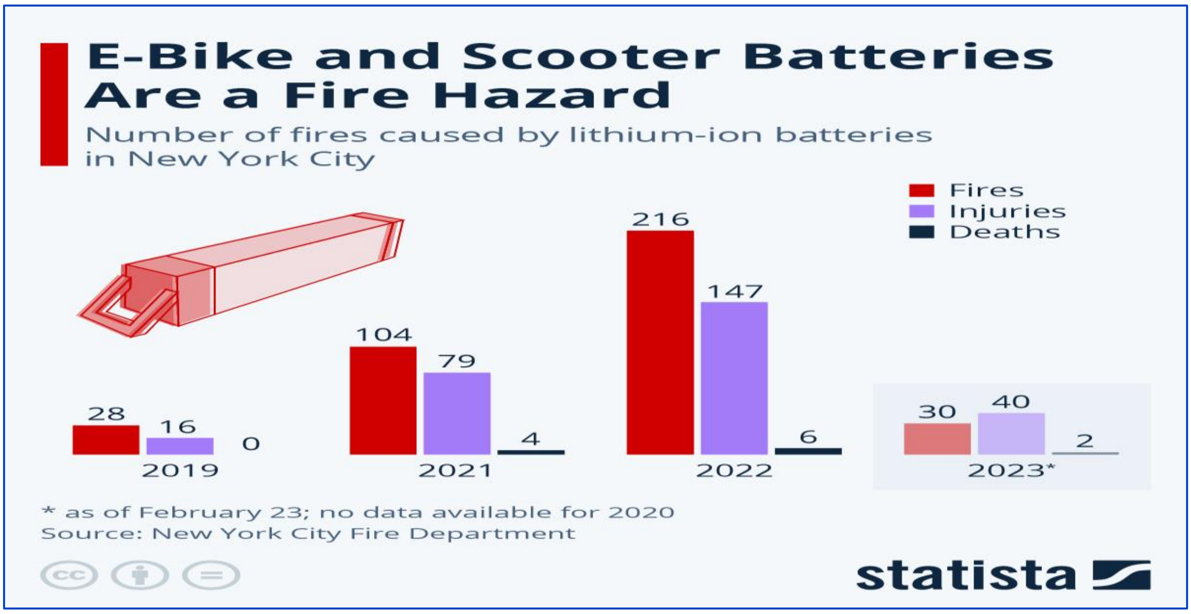


Figure 56*- A graph of number of fires caused by lithium -ion batteries in New York City*
Source: https://www.statista.com/chart/29472/fires-caused-by-lithium-ion-batteries/

Fires aboard large yachts are not new, but what is changing is the types of fires and struggles to put them out. The latest year for which reliable data exists is 2018. During that year there were 39 fires on board large yachts, with 32 of those on-board vessels under 500 gross tons; of the 39 fires, 37 were on motor yachts. There is a growing concern within the industry about the number of lithium-ion battery devices on board and the fire danger those devices present.

The high occurrence of the laid down fire incidence totaling about 1656 recorded and traceable incidence, with 113 death, billions of properties destroyed and huge business at stake calls for action to remedy this situation [56]. It is against this backdrop that I propose the following research questions, goals, hypothesis, and method to address the bigger issue at stake.

2.2.6 RESEARCH PROBLEM IDENTIFICATION AND STATEMENT

With the supported evidence of fire safety hazards with lithium-ion batteries and associated problems in the energy storage industry. I will dive into some of the causes of lithium-Ion battery issues that lead to fires.

2.2.7 CAUSES AND IMPACT OF FAILURES IN LITHIUM-ON BATTERIES

In recent years, there have been many fires and explosions of mobile phones, laptops, EVs, energy storage systems, power stations, and planes, yacht and etc., are all caused by LIB failure. Most fire-related accidents of EVs are caused by the thermal runaway (TR) of LIBs, and other secondary causes and the safety threat have become major issues needing urgent address. Therefore, lithium-ion. fault diagnosis has become a global research hotspot [54]. Majority of the fault diagnosis methods have been widely studied, such as state-of-health, sensor fault, connection fault, and insulation fault, diagnoses, internal short circuit (ISC) external short circuit detection, and abnormal voltage, overcharge and over discharge fault diagnosis, and thermal, fault diagnoses. In the battery cell and module, itself, Internal short circuit (ISC) is the most common and representative safety failure mode, which is one of the most important factors causing battery failure . These safety problems have been widely reviewed and researched by known researchers and scholars around the globe. battery failures are not only limited to batteries alone, but also in the system, where components such as miniature circuit breaker, SMPS and main DC/AC breaker can fail due to high inrush current and cause fire. Thermal runaway in batteries is caused by positive feedback loop between on-resistors, temperature, and power, also because of the interaction between leakage power and temperature.

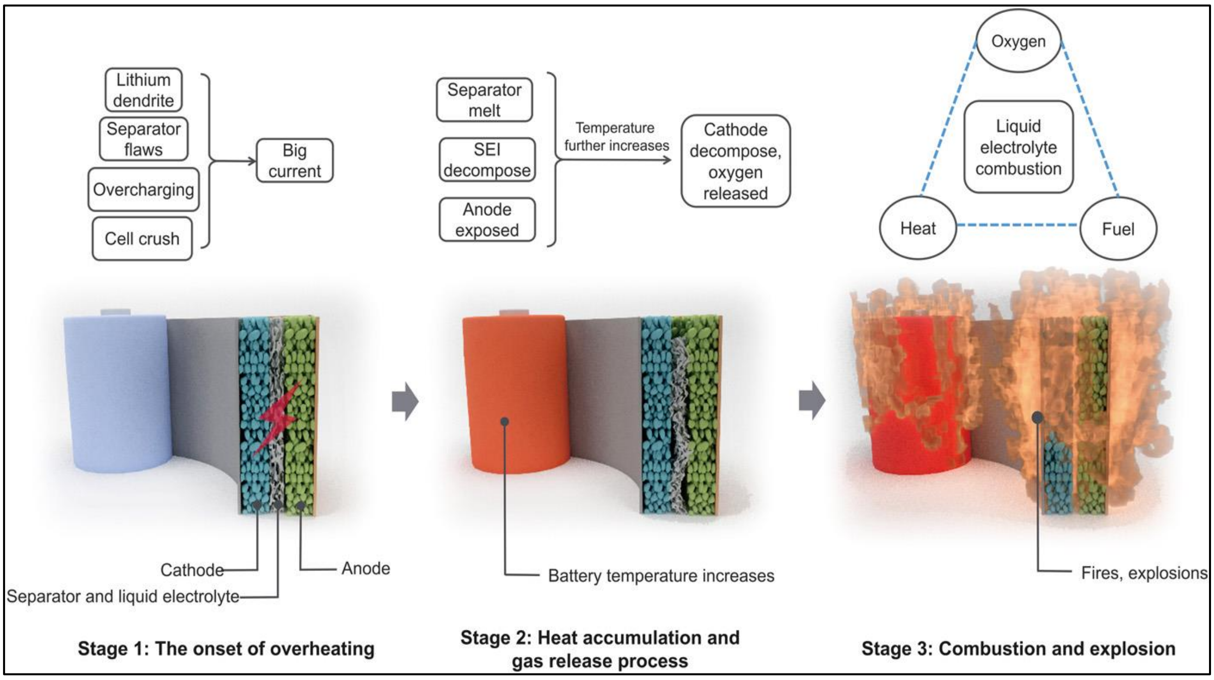


Figure 59 - *The three step process of thermal runaway of lithium-Ion batteries*
Source: https://www.science.org/doi/10.1126/sciadv.

In the evolution of internal short circuit (ISC), the temperature inside the battery rises, which leads to complex chemical reactions among the electrode materials, electrolyte, and separator. Most of these chemical reactions are exothermic, which will further aggravate the severity of internal short circuit current (ISC) like as shown in figure 40. When the temperature rises to a certain degree, a series of incidents will occur, such as the decomposition of the Solid-Electrolyte Interphase (SEI) layer, anode-electrolyte reaction, electrolyte decomposition, separator meltdown, and cathode breakdown. Eventually, these incidents increase battery's internal temperature that later triggers the Thermal runaway.

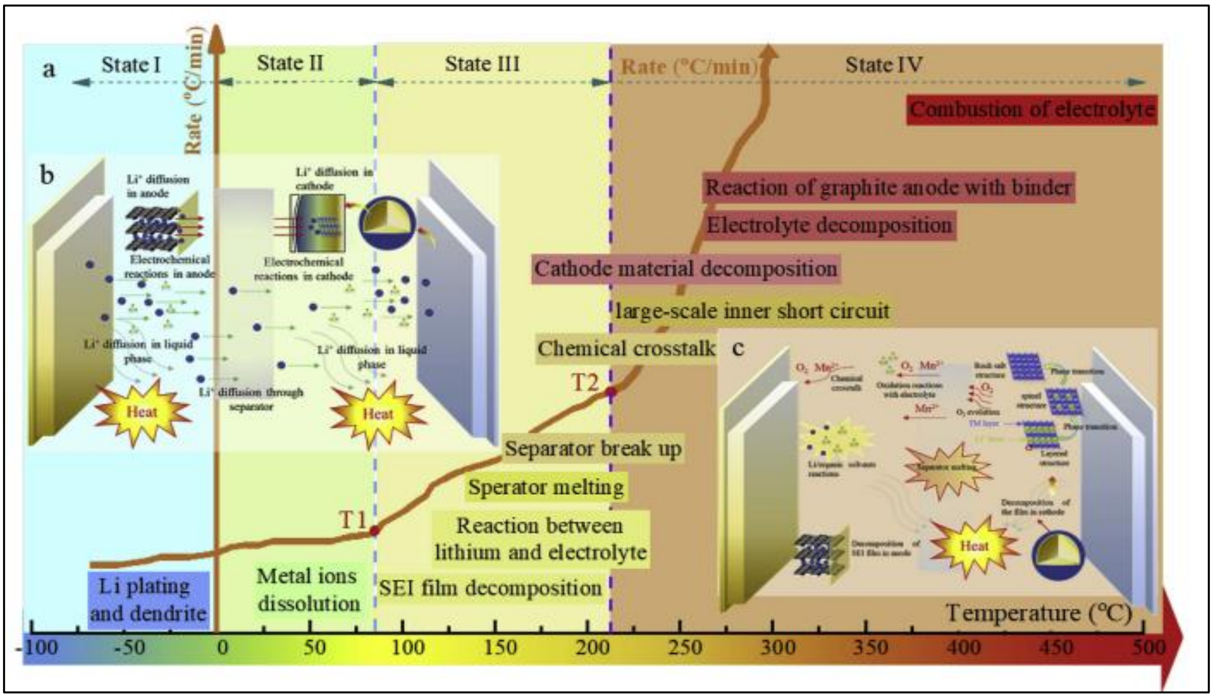


Figure 59*- An image of full lithium-ion failure process-thermally runaway.*
Source:[*www.elservier.com/locate/ensm*](www.elservier.com/locate/ensm)

2.2.8 EXISTING TECHNICAL SOLUTION TO RESEARCH PROBLEMS

Lithium-ion battery cell does not work alone by itself, it needs to be connected into a system to make it functional. The system is made up of multiple components which include the cells, modules, racks , DC combiner box, AC combiner box, inverter, air-condition system, power suppliers and EMS-BMS controller, each of these present some level of failures in the battery system. but will review some of the works that others have done to prevent fire from spreading and detecting these failures at the early stages. Heat and flammable and toxic gas production are the two basic factors to determine the hazard of battery failure. [67]. As others in the industry and academic institutions have proposed numerous methods to resolve these. Safety of a battery system can be improved by first avoiding the condition leading to heat and gas generation, and secondly by managing the heat and gas generation to alleviate the effects of failure. The design of safer lithium-ion battery cells can be achieved either through improving stability through modification of chemistry, through fabrication structure or through internal safety device. Others proposed safety trials that academics and industry expect have done is through introducing a complete robust thermal management system to maintain lower temperature , that either using fire suppression system or water injection system.

2.2.9 MECHANICAL APPROCH TO METIGATING FIRE SYSTEM

In Figure 45, is an example of **Mechanical** approach executed by one of the big giant in the energy storage industry (LG Energy solution) to mitigate early fire, by introducing water injection system with multiple smoke detectors to sense early warning, this will trigger a valve to open in the stored water tank and pump water to the nozzle pf the rack pipe, if the temperature continue and hit the highest threshold, a passive valve will open and eject water to the affected battery module. This technology is to mitigate potential fire spread during thermal runaway. This module has been put to commercial use and able pass the UL 9540A fire test, but it has Drawback in the industry, the major setback of this technology is that, when a module fails on the top of the battery rack, water injected will drip down and damage all battery module downstream, also, since it has it water source normally connected to the building main water source and building sprinkler controller, if the building controller detects or malfunction and sends signal to open sprinkler water, it will also flood all connected battery racks and finally destroy all the batteries.

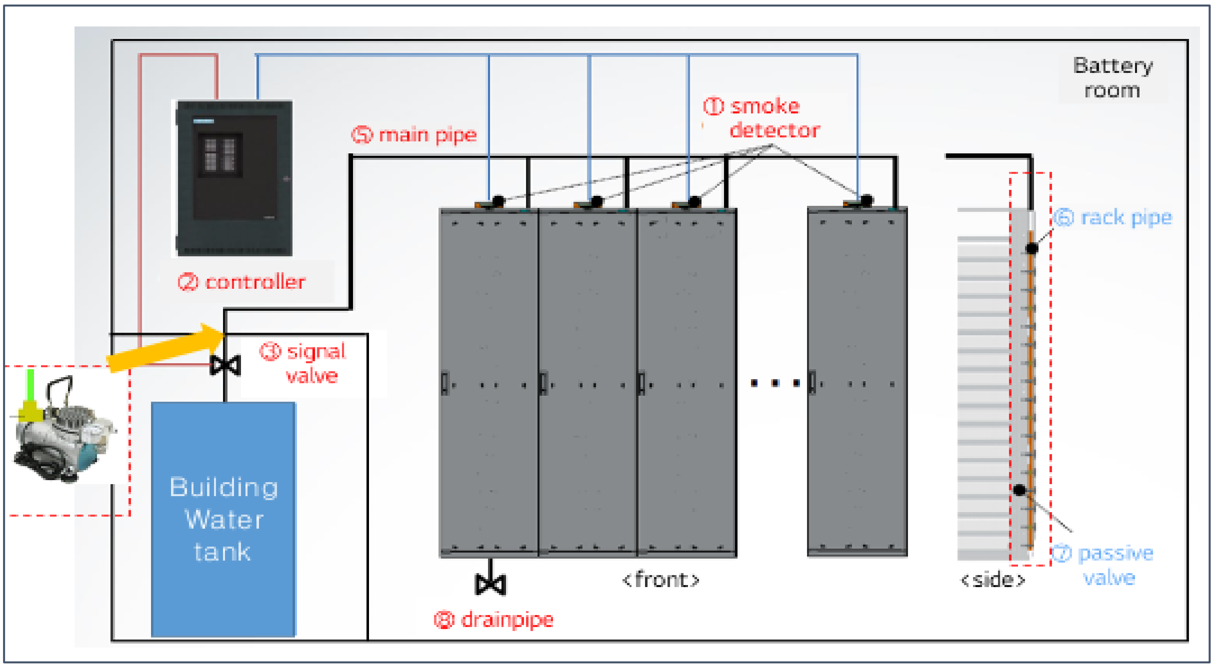


Figure 60 *- Water injection system by LG energy solution for cell to module fire control Source: LG Energy solution*

2.3.0 INHERENT SAFETY METHODS-CELL LEVEL

Ther has been other significant efforts made to modify lithium-ion battery components to improve safety. The modifications can be divided into the following categories: modifications of the cathode, anode, or electrolyte.

Cathode modification as for the cathode modification, coating a common form to improve the thermal stability of cathode. coated the $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ with TiO_2, and the coating did not affect the lattice of $Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ but did improve the discharge capacity and cycling stability. The battery prepared by the obtained cathode material has high specific capacity, high temperature stability, excellent safety and cycling performance at high temperature.

2.3.1 ANODE MODIFICATION

Anode modification includes surface modifications and electrolyte additives (SS. Zhang et al,.2013) could improve the thermal stability of SEI layer (Drews et al) introduced a reserve material into the graphite which could help inhibit lithium plating on the anode when the primary graphite material has been fully intercalated so as to improve battery safety, and the reserve material could be SrO, Mn_4N, K_2SO_4, $CaCl_2$, CaF_2, SrF_2, Ag, Mg, or Zn.

In addition to graphite, several new materials were used for LIB anode. Silicon has a low discharge potential but highest known theoretical charge capacity (4200 mAh g^{-1} (Qingsong Wang et al 2019). However, the volume of the silicon changes 400% upon insertion and extraction of lithium, which may cause structural damage and capacity fading.

2.3.2 SAFE ELECTROLYTE

Organic solvents are the main fuel (Qingsong. W et al,. 2019) for the flaming combustion process initiated as a result of LIB thermal runaway. If the carbonate content is reduced, the electrolyte out-gassing can be minimized when the cell is exposed to temperatures above 100 °C (Qingsong. wang et al,.2019) . Lithium salts found in the electrolyte, for example, the $LiPF_6$, can react with solvents. This reaction has a negative impact on the thermal stability of lithiated graphite as well as charged cathode . Here we discuss the most common approaches to the improvement of electrolyte safety: electrolyte additives, ionic liquids, and solid polymer electrolytes.

2.3.3 ELECTROLYTE ADDITIVES

Several electrolyte additives have been tested for their ability to improve the thermal stability or overcharge protection efficiency of the electrolyte and LIB cells. (Zeng et al, 2020). indicated that safer LIBs can be obtained by combining nonflammable phosphonate electrolyte, LFP cathode and alloy anodes. The phosphonate electrolyte has electrochemical compatibility and strong fire-retardancy, and the LFP and anode materials in this electrolyte show similar charge-discharge performances with those in the conventional electrolyte. (Xu et al,. 2019) (Stanislav. L,.2019) synthesized a novel fluorinated alkyl phosphate, tris(2,2,2-trifluoroethyl) phosphate (TFP), as a flame-retardant cosolvent for Li-ion cell electrolytes, and the nonflammable electrolyte formulated with less than 20% TFP performed.

The low vapor pressure makes ionic liquids hard to ignite, but their high viscosity relatively low electric conductivity, and incompatibility with other battery materials makes them less than an ideal choice for electrolyte replacement.

The solid polymer electrolyte is regarded as one of the feasible solutions for the fire risk of high-power lithium or sodium ion batteries. Solid polymer electrolytes do have some advantages compared with liquid electrolytes including non-volatility, low flammability, easy processability and electrochemical and chemical stability. Moreover, solid polymer electrolytes can eliminate the need for extensive sealing in batteries production and reduce final cost [85]. Youcef et al. (Binbin et al,. 2019) introduced a method to prepare a solid polymer electrolyte based on modified cellulose. In other studies, aluminate ester (Al-PEG) and dimethoxy ethylene glycol were added into the all-solid polymer electrolyte (SPE) as plasticizer in order to increasing the ionic conductivity of polymer electrolyte .

Even though there has been research in adding additives to electrolyte to resolve the thermal runaway, there have been some Limitation and Challenges in adding electrolyte additives. The introduction of additives may lead to the capacity fade or worse cycle performance for lithium-ion batteries (LIBs). Finding electrolyte additives that improve safety without causing degradation of the battery electrochemical performance remains a challenge. It should also be pointed out that the design and characterization of the new electrolytes has been mainly based on the laboratory-scale coin cells (wang et al,.2019)

A considerable additional development effort will be required to scale up these safe electrolyte technologies to commercial lithium-ion batteries (LIBs).

discharge, but it does not eliminate the possibility of ISC, which may be caused by a range of factors including a manufacturing defect.

2.3.4 FIRE EXTINGUISHING AGENTS -WATER AND POWDER FORM

There are four basic approaches to suppression of a typical fire, fire isolation method, smothering method, cooling method and chemical suppression method. Lithium-Ion Batteries (LIB) fire is not a typical fire because at least a portion of it consists of direct reactions between battery components. These reactions do not require external oxygen. Water is the cheapest and most widely used extinguishing agent in a wide range of fire extinguishing systems.

2.3.5 CONS OF WATER AS A SUPPRESSANT IN LITHIUM-ION BATTERIES.

At the same time, the salt in the electrolyte, $LiPF_6$, can react with water to release a large amount of HF which is toxic and harmful to people (J. Feng et al,. 2008) Besides, lithium can reduce water to form highly flammable hydrogen. Lastly, water is conductive and may create external short circuits in a battery system, which, in turn, may induce LIB thermal runaway.

2.3.6 PROS OF WATER AS SUPPRESANT FOR FIRE IN LITHIUM-ION

On the other hand, water is a perfect cooling agent because of its high heat of vaporization and heat capacity. It may not only help suppress flaming combustion but also may be able to slow down or stop propagation of the thermal runaway. To summarize, water remains a good candidate for LIB fire suppression due to its strong cooling effect and despite its potential impact on integrity of electrical circuits.

2.3.7 WATER BASE ILLUSTRATION FOR FIRE SUPPRESANT LITHIUM -ION

Figure -55 above, its agents with a heat capacity such as water and foam can provide rapid cooling and fire extinguishment. On the other hand, agents with lower heat capacity such as powder and inner gases will provide less cooling. Besides, the agents with a high viscosity may not be able to penetrate inside the module to the burning cells, thus the suppression is limited (Binbin.Wang et al,.2019). Currently, the conventional fire-extinguishing agents are unable to stop the thermal runaway reactions inside the Lithium-ion batteries (LIB), but the application of agents can extinguish the open flame and decrease the surface temperature of Lithium-ion batteries (LIB), and thus reduce the heat transfer to the adjacent virgin cells and, potentially, prevent the propagation of thermal runaway. The application of fire-extinguishing agent can help win sufficient time for people to escape and evacuate (Binbin.wang et al,.2019). The work on lithium-ion batteries (LIB) fire suppressants is far from complete. Environmentally friendly and more effective suppressants for Lithium-ion batteries (LIB) fire still need to be identified.

Figure 61.-*An image of Novec fire suppression system as secondary fire control in energy storage system.*
Curtesy: Daniel Kelly Boakye Danquah

Faster and more accurate detection designed specifically for this type of fire will also be required. The future automatic fire suppression systems must be capable of putting out a large-size battery pack fire and be able to cool down the pack quickly; preferably, with minimum damage to the battery pack.

2.3.8 SUMMARY OF EXISTING FIRE FIGHTING TECHNOLOGIES

Safety issues and fire evolution are still the main obstacle to the usage lithium-ion batteries (LIB) of LIBs in large scale applications, such as EVs and energy storage systems. Thermal energy released because of internal short circuits and chemical reactions between battery components are the main heat sources inducing thermal runaway. The chemical reactions and their onset temperatures are summarized in this review. The decomposition of electrolyte, and reactions between the active materials, especially the intercalated lithium with solvents, can release various flammable gases including H_2, CO and hydrocarbons. The flammable gases and solvent vapors mixed with oxygen can be ignited and lead to a fire. Multiple jet flames can be observed during the LIB fire. However, batteries with different geometries, different electrodes and electrolytes may show different failure features. The occurrence and progression of thermal runaway also depends on SOC and abuse conditions. Details of the chemistry and physics of the thermal runaway are the subject of ongoing investigations.

At point I will focus my research on how I can improve on safety techniques that will make lithium lithium-ion batteries the safest technology that will be used in the energy transition and decarbonization.

CHAPTER THREE

3.0 ENERGY STORAGE POLICY

Energy storage is one of the fastest growing technologies that is helping us transition into decarbonization and mobility for the future. This transition is fast growing as the world hydrocarbons diminish and other countries start to weaponizes the resources. As the technology of clean energy turns to mature, like solar and wind, they also have some limitation by not providing constant power during the nighttime when there is no sun. For the industry to thrive and achieve this transition from hydrocarbon to clean energy, there should be an energy policy to back the adoption and transition to clean energy . The two major trends that have enabled increased deployment of energy storage are declining costs and technological advances. State policy can help maximize these benefits through a combination of establishing a framework for easy integration, adoption of energy storage into the grid and establishing a marketplace that monetizes the benefits of energy storage for cost-effective investments. Energy storage standards can cover a variety of different policies that enable states to use renewable energy more effectively. Policies will reduce barriers to the implementation of advanced batteries, push to the revolution of electric mobilities, while others attempt to incentivize their adoption and modernize entire energy grids. Because energy storage standards are a suite of different policies, Energy regulators at various levels of judicial and institutional level such as local, state, regional, and national will be tasked with keeping the lights on (energy.gov).

But as states around the country clean up their electricity grids with renewable power, there are concerns that renewables will not be sufficiently reliable. For example, rooftop solar panels can help power homes and businesses, but without the capabilities to store the energy they're left in the dark if the sun isn't shining. Energy storage presents a solution for those concerns. Energy storage system-ESSs can help balance power demand and supply, help in grid resilience, and ensure a stable power supply. There have been numerous demonstrated projects and businesses that centered on ESSs have been carried out globally for purposes such as reducing greenhouse-gas emissions and supporting aging power facilities. Expert says the energy storage market-ESS market is still in its infancy stages, but it has been growing steadily fast, mainly in Australia, Europe, Japan, and the United States (US). Key factors behind this growth are the fall in battery prices, improved stability of power systems, integration of alternative and renewable energy sources, and Energy storage policies. These elements are also expected to influence the increase in demand for ESSs for assisting power networks as power transmission and distribution costs rise with the aging of power networks (energy.gov)

Distributed Energy Resources - DER is a complex machine interconnected to a complex system, and like the entire energy industry must comply with policies and regulations set in place. In many ways, policy is what drives the development of energy resources. This has been recognized in recent decades with a higher adoption of customer owned generation rather than primarily large, centralized generators owned and/or operated by electric utility providers (Farrell, 2018) (Peak Substation Services, n.d.). This is largely driven by the technological developments in renewable energy, energy storage technologies, and the financial feasibility for customers to own their own source of power generation (Farrell, 2018). This change in electricity delivery has created new challenges that the regulatory authorities such as the U.S. Department of Energy, Federal Energy Regulatory Commission, North American Electric Reliability Corporation, State Public Utility Commissions, Regional Transmission Operators, Independent System Operators, and electric utilities will have to adapt to (Farrell, 2018). The primary reason that distributed energy resources (DERs) such as energy storage, lithium-ion batteries and solar technology are a challenge for policy regulators and electric utilities is due to the change in the *movement of electricity (Farrell, 2018)*, cost of batteries, fire safety and standardization in the industry.

Traditionally, electric energy was operated and managed by electric utilities and strategized in a way that electric energy is generated at a large power station, transmitted at high voltages over longer distances, transformed to lower voltages and distributed to local homes and business at their required service levels (Surendra, n.d.). In this sense, electricity flowed in "one direction" from the generator to the ultimate end user (Aczel, n.d.). The energy transition began to pick up speed in the 1990's when homeowners and businesses found it to become common place to install a backup generator on their building ran from either side of the grid, presumptively energy storage.

3.1.0 DEFINING ENERGY STORAGE AND RENEWABLE TO POLICY

Energy storage, by itself and in combination with distributed generation (termed ESSDER), is a new and emerging technology that has been identified by FERC as a key functionality of the smart grid, and standards related to storage should be treated as a key priority by the Institute and industry in the interoperability standards development process, subject to certain reservations. Coupled with inverter-based technology, these systems can be used to improve EPS performance. Due to the infancy of the use of storage and inverter technologies as a grid-integrated operational asset there are few standards that exist to capture how it could or should be utilized on the legacy grid and Smart Grid. For example, to date there exists no guidance or standards to address grid specific aspects of aggregating large or small mobile storage, such as Plug-in Hybrid Electric Vehicles (PHEVs) or mobile power systems. ES-DER is treated as a distributed energy resource in some standards, but there may be distinctions between electric storage and connected generation. Storage-based systems may function as a load more than 50% of the time. At the same time, we are moving towards large penetration of renewables into the Grid, which could be destabilizing, but should, in the context of the Smart Grid, allow these renewables to be true utility assets. The potential for instability is twofold; first, due to the intermittent nature of renewables and therefore their unsuitability to be dispatchable resources, and second, due to the interconnection regulations themselves that can lead the electronic interconnection interface (the inverter) to trip off in response to minor variations in grid voltage or frequency. As low frequency is the result of insufficient generation, tripping a high level of inverter-based systems would contribute to the problem and cause possible stability issues in response to a relatively minor disturbance. Appropriate interconnection standards, smart grid devices, and storage are all key elements of the solution. In addition, ES-DER systems based on photovoltaic, wind, and other renewable, intermittent sources of energy are also exploring the use of storage to help smooth their intermittency, augment their ability to respond to distribution power grid management requirements, such as avoiding back-flow on networked power grids, and enhance commercial output by shifting when the energy is delivered. [90]. Eventually electric storage will play a larger role in islanded systems by helping to stabilize generation and load variations. Island system applications do provide some early examples of the stabilizing support needed when renewable is added to islanded (weak electrical) systems. Various types of ES-DER systems are emerging. Each type will have different ranges of abilities to respond to power grid management requests and will use different systems.

Currently, IEEE 1547 defines the interconnection of distributed energy resources (DER) rated 10 MVA and less with the electric power system. This standard defines distributed energy resources DER as a small-scale electric generator located in and connected to the local electric power system (e.g., the customer facility), near the loads being served with an electric grid interconnection. The standard does not specify a distinction between energy storage devices and generators within the distributed energy resources (DER) portfolio. However, there is no standardization for functioning during islanding (P1547.4 is still a draft), there are no ramp rate specifications that would enable hybrid generation-storage to mitigate intermittency of renewables, the trip point specifications do not enable renewables or storage to avoid tripling under moderate grid transients, there are no voltage support specifications, and there are inconsistencies between the anti-islanding requirements of IEEE 1547 and the ride through requirements defined by FERC’s Large Generator Interconnection Procedure (LGIP), depending on interpretation and application.

In particular, the standards that cover the period between event onset and when a resource must stay on or must disconnect from the grid can have conflicting time requirements, and the FERC LGIP ride through requirements extend beyond the 1547 default values for DER ceasing to energize the point of common coupling with the grid. Regulatory issues also need coordination. FERC Order 719 currently prohibits generation of power within Islanding Distribution systems are beyond the purview of FERC and regulation does not exist for authorizing the application and dispatch of storage. ISOs and regulatory bodies today tend to treat storage as a generation device and struggle with seeing transmission or distribution entities owning storage. Revision or augmentation of IEEE 1547 will need to be closely coordinated with FERC. FERC has requested that the individual specification of IEEE 1547 be itemized (e.g., 1547.8.1) so that they can be adopted individually as FERC requirements. IEEE 1547 was developed for interconnected systems of limited DER and renewable energy system penetration levels. The proposed new IEEE SCC21 P1547.8.x Standards are needed to enable the grid to accommodate increased renewable penetration levels, systems greater than 10 MVA, and to get value from inverter-based systems to improve EPS performance, and further address end-use operational support, applications, and regulatory technical needs. There have been many policies that have been laid down to help in the renewable and energy section statewide. policies will address issues with utilities, ISO/RTO, Vendors,, researchers, regulators.

3.1.2 POLICIES AND INTERCONNECTIONS REFORM TO ENERGY STORAGE

Outdated interconnection policies remain a significant barrier to unlocking the full value of energy storage on the distribution grid. Here's how to fix it. It is widely recognized that one of the greatest challenges in transitioning from an electric grid powered predominantly by fossil fuels to one powered by clean energy sources like solar and wind is the intermittent of many renewables. Unfortunately, despite the increase in changes and demonstrated consumer demand, outdated interconnection policies remain a significant barrier to unlocking the full value of energy storage on the distribution grid. With no pragmatic interconnection policies to address these shortcomings of these policies which control which storage capabilities are recognized and how efficiently they are evaluated–that clean grid of the future may be out of reach, at least within the timeframe needed to mitigate the worst impacts of climate change.

Many states' interconnection rules do not explicitly address energy storage, creating uncertainty that slows and complicates the interconnection process and that can negatively impact financing prospects. Additionally, many interconnection policies use unrealistic assumptions when assessing the impacts of potential storage projects on the grid. These policy flaws present significant barriers to unlocking the broad energy storage deployment that will be needed to achieve high-renewable scenarios.

One of the major benefits of energy storage, particularly when co-located with solar or other intermittent distributed energy resources (DERs), is that storage offers the flexibility to control when power is exported to (or drawn from) the grid, mitigating the grid management challenges presented by these sources. Software including power conversion systems or PCS) that manages energy storage exports makes this possible. For example, instead of exporting during the middle of the day when there is an excess of solar energy, ESS can store that energy and send it to the grid in the evening when solar is offline and home energy demand increases. Likewise, project developers could also propose "operating schedules" for their ESS projects, exporting more or less power to the grid during periods when the grid can accommodate more generation (such as when consumers are using more power to run air conditioners) and limit export when the grid is more constrained. Storage systems could also be designed to change their export levels in response to dynamic signals, such as demand response programs that disincentivize exports. Neither of these functions is in widespread use today, however, and current interconnection rules are a key reason why. Power conversion system PCS also allows DER projects with energy storage to be designed as “non-export” projects that do not export power to the grid, or “limited export” projects that do not export over a certain threshold. This option can be particularly valuable in allowing DER projects to proceed in areas of the grid that are capacity constrained.

Most interconnection policies currently require individual project owners to pay the full cost of any distribution grid upgrades that are needed to accommodate their project. Because upgrade costs are high, this factor may prevent new projects in areas of the grid with high penetrations of DERs. Interconnection customers can avoid hefty grid upgrade fees by designing their projects to operate as non- or limited-export systems, which can reduce grid impacts. However, few interconnection procedures provide a clear pathway for such systems. Atypical interconnection system process in the current state has five processes, this includes Preliminary application process, feasibility studies, system impact studies, facility studies and approval /cancelation stage. In the below figure 62, Each of the stages has an impact on weather a project can proceed to the next stage or not.

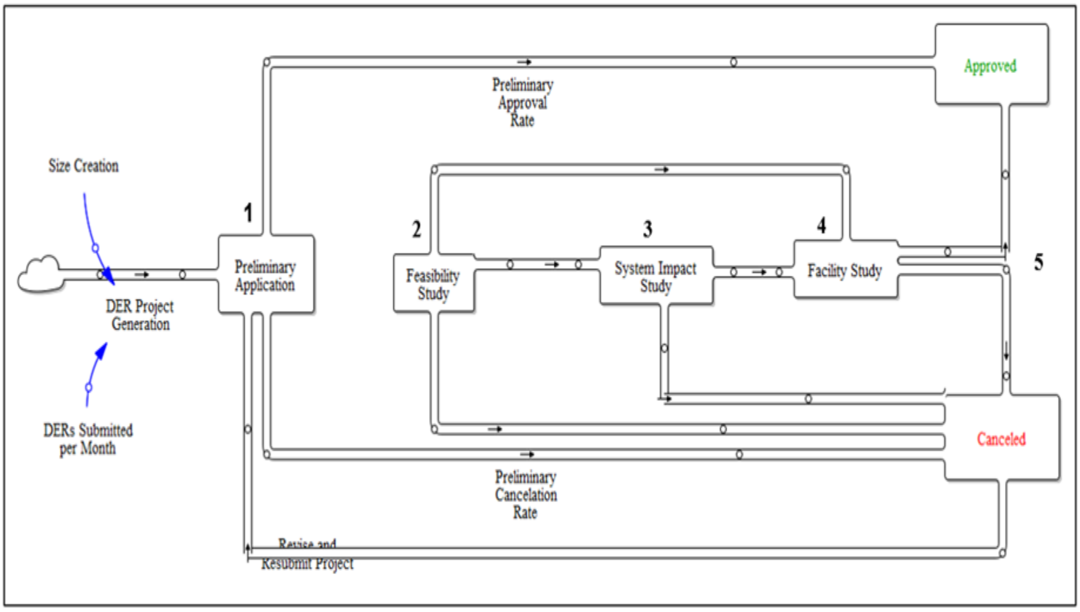


Figure 62. *A typical interconnection process for DER which is used to allow systems to be approved and installed online.*
Source*: Daniel Kelly Boakye Danquah.*

3.1.3 PRELIMINARY APPLICATION PROCESS

Most interconnection policies hinder the use of all these beneficial energy storage functions. That's because the screening or study process in which utilities evaluate the potential impacts of a proposed distributed generation facility seeking to connect to the grid, generally fails to recognize the controllable nature of energy storage. To get to the point where an interconnection request can be submitted, several things need to happen. The developer usually has a contract executed for a potential project and has a plan or strategy for getting it complete including the following items: preliminary design of the project, operational characteristics, and siting a location with an appropriate interconnection method. At a minimum, these steps allow a developer or customer to submit a preliminary interconnection request to the respective distribution utility they seek to interconnect to. The default method is to study projects with the assumption that the project may export or import its full capacity at any time, as opposed to being able to reduce capacity during specific times or to limit it altogether. This assumption may lead to unnecessary and time-consuming studies that slow the interconnection process, or to costly upgrades that may make projects infeasible. This makes it harder for project developers to deploy projects that are specifically designed to provide beneficial services on the grid. Interconnection rules need to include revised screening and study processes for these types of systems if we want to unlock the unique value of ESS in enabling a high-DER future. Processes for evaluating non- or limited export projects will need to be developed. Additional processes will need to be defined for evaluating systems that export varying amounts of power at different times, such as based on an operating profile.

3.1.4 FEASIBILITY STUDIES STAGE

In the current process, a project proceeds into the Feasibility Study phase once a potential adverse impact to the system has been found and needs further evaluation to determine if or to what extent the risk is present. The Feasibility Study is the first official engineering studies stage and seeks to serve as a filter to separate smaller projects with less impact from those generally larger projects that need more extensive evaluations (Federal Energy Regulatory Commission, 2018). This evaluation has a maximum cost of $1,000 and a mandated timeframe of 30 business days as seen in the below characteristics of the Feasibility Study listed below from section 3.3 of FERC's Small Generator Interconnection Procedures (Federal Energy Regulatory Commission. The overarching aim of this stage of the process is to keep an efficient process moving for all parties, and to only continue in-depth evaluations for projects that present risks for other equipment or customers. FERC has developed a standardized agreement for utilities to formalize this procedural step published as the Feasibility Study Agreement in their Small Generator Interconnection Procedures (Federal Energy Regulatory Commission, 2018). The Federal Energy Regulatory commission has some steps which details as initial identification of any breaker short circuit capability limits that exceeds as a results of the interconnection, thermal overload and voltage limits violations, initial review of grounding requirements and electric system protection and Description and non-binding estimated cost of facilities required to interconnect the proposed Small Generating Facility and to address the identified short circuit and power flow issues.

3.1.5 SYSTEM IMPACT STUDIES

System Impact Studies are conducted when reliability to the bulk power system could have adverse effects due to the DER project that needs further evaluation. Typically, impact to the bulk power occurs when energy is exported from the distribution or secondary side of the substation onto the primary side or the transmission lines, which could impact the movement of bulk power along those lines. These studies are divided into two categories given the level of anticipated system disruption as being classified as distribution or transmission respectively. In general, the System Impact Study is performed based on the anticipated implications of the proposed in the distributed energy resources -DER. This step, like the Feasibility Study, can be skipped if no adverse impact was noted as needing additional evaluation then, can proceed on to an interconnection agreement (Federal Energy Regulatory Commission, 2018). During a System Impact Study, the respective electric utility is responsible for evaluating any impact to the distribution or transmission systems. The concerns being evaluated by this step are issues that pose a risk of adverse effects on the distribution circuit in question, other distribution circuits, the substation itself, or greater transmission impacts depending on the level of concern (Federal Energy Regulatory Commission, 2018).

3.1.6 FACILITY STUDY

The Facility Study is an in-depth design and pricing exercise to be performed upon receiving the results of the System Impact Study and to mitigate the concerns stated in their findings. Like the System Impact Study, there are no maximum associated costs or timeframes associated with the Facility Study (Federal Energy Regulatory Commission, 2018). This is because when these studies are needed there needs to be adequate time to evaluate concerns, design solutions appropriately, and ensure a reliable electric grid. The purpose of the Facilities Study is to specify and estimate the cost of the equipment, engineering, and construction work needed to interconnect the proposed facility. The study will also identify electrical configurations of the transformer(s), switchgear, meters, and other station equipment. Finally, the study will also identify the nature and estimated cost of any transmission network upgrades needed because of the interconnection. The purpose of the Facilities Study is to specify and estimate the cost of the equipment, engineering, and construction work needed to interconnect the proposed facility. The study will also identify electrical configurations of the transformer(s), switchgear, meters, and other station equipment. Finally, the study will also identify the nature and estimated cost of any transmission network upgrades needed because of the interconnection. The interconnection customer is provided with two options regarding the accuracy of the cost estimates to be provided in the Facilities Study. The options are:

- ❖ Ninety (90) calendar days with no more than a ± 20 percent cost estimate in the report,
- ❖ One hundred eighty (180) calendar days with no more than a ± 10 percent cost estimate.

Before the execution of the Facilities Study Agreement, modifications to the interconnection request are permitted under certain instances without affecting the queue position.

3.1.7 INTERCONNECTION AGGREMENT

The last step in the process is having all parties reach a conclusion on how to move forward, which has become known as an interconnection agreement. The project is approved for construction from the utility perspective once this agreement has been reached (Peterson et a., 2018). From the developer or customer perspective, cost is the largest factor as to whether a project continues or gets cancelled (Peterson et al., 2018). The customers or developers typically do not install these infrastructure improvements as they are commonly owned and operated by the electric utility (Sivaraman et al., 2021). In most scenarios, the line of demarcation between customers and utilities is the point of common coupling where the energy metering is taking place (Sivaraman et al., 2021). Assuming an agreement is reached, both entities can begin working on completing their scope with regards to the project (Peterson et al., 2018). If a project doesn't proceed forward with construction, rather than canceling the entire project, a customer can either potentially relocate the project elsewhere or descope the project to avoid costly upgrades (Peterson et al., 2018).

The Interconnection Agreement - also termed mutual services, operations and maintenance, control area, or consolidated agreement in some regions - provides for the long-term operation and maintenance of the interconnected facilities. It generally includes sections on licensing, maintenance, operations, special instructions, and funding. When to the benefit of the interconnecting entity, the Interconnection Agreement may be tendered at the same time as the earlier Construction Agreement. The interconnected facilities may be energized following execution of the Interconnection Agreement. Several states, including California, Hawaii, Arizona, and Nevada, have updated their interconnection rules with these challenges in mind. Illinois, Massachusetts, and New York are actively working on this, while related proposals have been introduced in Colorado. As part of a toolkit of solutions that the team will develop to address key barriers to energy storage interconnection, the energy storage project will produce resources to inform the development of updated study processes that can be incorporated into interconnection rules. The project aims to reach regulators and utilities in most states with resources to reform energy storage interconnection.

3.1.8 DEFINING POLICY STRUCTURE ENERGY STORAGE

Discussion of the Policy of energy storage, Energy storage offers a unique opportunity to dynamically manage supply and demand while maximizing the value of grid resources. By deploying storage in strategic locations, utilities can more effectively manage their energy portfolios. First, storage provides management of intermittent demand ,helping to flatten peak demand requirements for the utility. Second, the responsiveness of energy storage can allow the utility to implement voltage regulation and other ancillary services [98] which are useful for improving system efficiency. Third, storage can dispatch power to better integrate intermittent resources like renewable energy. The flexibility of battery storage, combined with advanced metering infrastructure, allows customers to control, for instance, how and when they use energy from the grid or from solar panels installed on their home or business. In most cases, this can provide greater cost savings than standalone solar systems. Combined with time-varying rates or real-time pricing programs, state policy can further support customer choice and open a new market for energy services

Energy storage can be described in two ways: power capacity and duration. Power capacity is expressed in kilowatts (kW), or megawatts (MW) and duration is expressed in hours. Different energy storage technologies provide different benefits and services to the system because they vary in terms of capacity and duration. This is important when looking at potential applications of energy storage technologies. Storage has distinct roles when providing services on the utility's side of the meter or on the customer side (behind the meter).Two major trends have enabled increased deployment of energy storage: declining costs and technological advances. State policy can help maximize these benefits through a combination of establishing a framework for easy integration of energy storage into the grid and establishing a marketplace that monetizes the benefits of energy storage for cost-effective investment. Prices that better reflect the time-varying and location-dependent costs of producing and delivering electricity can lead to several economic and environmental gains. Energy storage can also help the commercial sector avoid demand charges . Demand charges establish an incremental cost above energy usage based on the highest period (highest 15 minutes, for example) of demand during the month. Eliminating spikes in demand with storage can reduce these costly charges for businesses . In 2018, Massachusetts approved demand charges for net metering customers. As utilities around the country consider extending demand charges to the residential sector, energy storage will become more relevant as a

Different policy options have been employed to improve the economic feasibility of distributed solar PV, with feed-in tariffs (FiTs) being the main incentive adopted in many countries in the last decade . However, until recently, there has been little or no policy support for distributed EES, such as small-scale batteries, which is shown to be a key.

barrier in deploying storage under current policy regimes . Supporting distributed renewable generation without adequate incentives for onsite flexibility and distributed EES might not fully realize the private and system-level benefits of distributed energy generation.

systems. Introducing such policy supports can contribute to a significant adoption of distributed EES, such as the subsidy mechanism for PV paired with EES by the California Public Utilities Commission. The economic feasibility of distributed EES has been subject to a wide number of studies with different modelling approaches. (Uddin et al,.) examines the feasibility of residential EES by applying a battery degradation model, showing no financial benefits and even possible economic losses.(Zakeri et al,.) apply a holistic life cycle.

cost analysis of different EES systems, concluding that the levelized cost of storage (LCOS) for most batteries is way too high to be competitive.

3.1.9 TYPES OF POLICIES FOR ENERGY STORAGE

There are multiples of policies that has been in place to boost renewable energy and energy storage, this includes, interconnection, net metering, Renewable Portfolio Standard, Shared Renewables ,Renewable Standard Offer, Aggregate Net Metering, Distributed Generation /

Solar Carve-out. Commercial Building Energy Codes, Modified Energy Efficiency Cost/Benefit Tests, Decoupling and DSM Performance Incentives, Low-Income Energy Efficiency, Solar Incentives, Non-Solar Distributed Generation Incentives, Advance vehicle incentives, commercial natural gas fueling incentives, vehicle charging rates, grid modernization , new utility business model proceeding and energy storage standards, Self-generation incentive program -SGIP.

3.2.0 INTRODUCTION OF STORAGE TARIFFS

The introduction of a storage tariff for rewarding owners of EES for each kWh of electricity discharged at the peak time could improve the financial case for EES. The storage tariff is calculated in a way that reflects the value created by the EES device relative to an investment in solar PV alone, which makes this tariff a function of the type of electricity tariff.

3.2.1 PRICE -GAP WIDENING POLICY

We introduce a new electricity pricing policy called “Price-gap widening” tariff. In this policy, the system operator purposely increases retail electricity prices at peak hours while decreasing off-peak prices for consumers. This tariff resembles “critical peak pricing” policies in Japan, the US, or similar tariffs in France, where the system operators is interested in load levelling due to abundant, low-cost, nuclear baseload generation. This tariff not only encourages consumers to shift their peak consumption to off-peak hours, but also widens the gap between off-peak and peak prices, which contributes to the profitability of EES from price arbitrage. The optimal operation of residential EES for price arbitrage is not dependent on the absolute price of electricity but rather on the gap between prices at charging and discharging times. However, the increase in peak prices should be done smartly to not negatively affect the yearly electricity bills of consumers without EES.

3.2.2 SOLAR PV CONSUMPTION POLICIES

Initial incentives for residential solar PV were mainly rewarding solar PV generation, or the export of excess solar PV generation to the grid, or a combination of both. A review of such policies by the International Energy Agency (IEA) shows that the self-consumption of solar PV has been poorly rewarded in many countries, leading to an indirect incentive for householders to export their PV overproduction to the grid. In some cases, this has led to inefficient public expenditure, e.g., by rewiring of the PV system to the distribution grid instead of onsite usage in Spain. In a few countries, like China, the self-consumption is directly incentivized, which can encourage consumers to reduce their dependency on the grid. As the share of decentralized solar PV increases in the grid and PV subsidies phasing out in many countries, it is a crucial policy concern to encourage prosumers to increase their self-consumption rather than exporting to the grid. The EU Renewable Energy Directive (2018/2001) has explicitly asked Member States to look for policies to increase “renewable energy self-consumption” in buildings through storage and other options .

3.2.3 INTRODUCING STORAGE TARIFFS AND CASH SUBSIDY

The introduction of a storage tariff for rewarding owners of EES for each kWh of electricity discharged at the peak time could improve the financial case for EES. The storage tariff is calculated in a way that reflects the value created by the EES device relative to an investment in solar PV alone, which makes this tariff a function of the type of electricity tariff.

3.2.4 ENERGY STORAGE INCENTIVE TAX CREDITS

The Energy Storage Tax Incentive and Deployment Act Without clear statutory guidance and market certainty, businesses and investors will continue to face hurdles to expand and innovate. The U.S. tax code should grant full ITC eligibility for investment in the business and home use of energy storage, with the same ramp-down assigned to the ITC for solar technology through

2021. Under that extension enacted in 2015, the ITC is at a rate of 30% for 2017-2019, 26%% in 2020, 22% in 2021 and 10% thereafter for commercial and utility-scale projects. The Energy Storage Tax Incentive and Deployment Act would result in the acceleration of the energy storage deployment and would encourage continued innovation and reconfiguration of existing storage technologies to realize other benefits. Under this bill, all energy storage technologies would qualify for the ITC regardless of energy source. The congressional Joint Committee on Taxation (JCT) estimates this legislation would only cost an estimated $300 million over 10 years.

3.2.5 INFLATION REDUCTION ACT

On August.16, 2022, President Joe, Biden signed into law the inflation reduction act of 2022 (IRA**)**), which includes new and revised tax incentives for clean energy projects This alert provides a summary of the IRA’s impact on tax credits for energy storage technologies, which were extended and significantly expanded. The Inflation Reduction Act’s incentives for energy storage projects in the US came into effect on 1 January 2023.(eia.gov)

Standout among those measures is the availability of an investment tax credit (ITC) for investment in renewable energy projects being extended to include standalone energy storage facilities. Alongside the rest of the act’s US$369 billion package of climate spending, the change has been forecast to transform the US clean energy industry, bringing certainty for investment into deployment as well as manufacturing.

Previously, storage projects were only eligible for an ITC if paired directly with solar PV and the storage system charged directly from the solar. The standalone option now decouples developers from this need, opening the possibility of charging directly from the grid, and reducing the development timeline of storage projects, which require far less land than solar-plus-storage. Energy storage projects of 5kWh or more will be eligible.

3.2.6 POLICY IMPACT OF ENERGY STORAGE ON THE GRID

The impact on electric vehicle technology and the advancement of Lithium-Ion batteries, and its impact on the grid will be analyzed for use in the United States at a large scale for grid readiness. Three key areas will be examined to bridge the gap between the current state of Li-ion battery EV technology and grid infrastructure and where this technology needs to meet future demand. These areas include understanding the driving factors for the need to change to e-mobility. The second is to identify and examine the roadmap linking Li-ion technology to grid design and recommendation for resolving the negative impact on grid infrastructure. The third is to evaluate the pathway forward in emerging Li-ion battery storage and technology to meet consumer needs. Results of this study show the benefits of transitioning the transportation market from ICEV to EV are considered favorable. Limitations to a quick deployment include policy structure and grid reliability. Further research should be considered in areas of local and regional utility upgrades, grid distribution systems and meshing with appropriate policies to seamlessly integrate EVs into the market.

3.2.7 ELECTRIC VEHICLE EFFECTS ON EXISTING GRID INFRASTRUCTURE

The electric grid must undergo significant improvements to meet the needs of future energy use. This includes increased capacity for growing populations, bi-directional power flows, stability measures, and end-of-life replacement of thousands of aging electrical components and conductors. With the transition to electric mobility, a large portion of the energy sector must transition from direct fossil fuel power to electric power. This exacerbates both the need for capacity and the importance of ensuring the electric grid can handle the added demand. As such, we must examine the effect adding sufficient electric vehicle charging infrastructure has on the existing grid infrastructure.

3.2.8 RESIDENTIAL SECTOR

As the penetration of EVs continues to grow, the refueling paradigm will shift from almost exclusively shared infrastructure to include private charging stations as well. As such, utility planners must begin to include private EV charging stations in their demand projections. While commercial chargers are more likely to be in industrial areas with robust grid infrastructure, residential are**as** will likely require upgrades to accommodate typical EV charging patterns .Residential utility planners currently consider factors such as square footage, electric appliances, and the presence of HVAC systems in their demand assessments. For example, San Diego Gas and Electric Company (SDGE) estimates between 1.5 kW and 8.0 kW for homes . This covers a range from 0-3000 ft^2 and apartment units to detached, single family homes. Homes greater than 3000 ft^2 require more in-depth analysis to estimate the higher demand. Assuming homes are typically outfitted with Level 1 or 2 chargers, this means an added electrical demand of between 1.9 to 19.2 kW [33]. When aggregated, residential EV charging has the potential to more than double peak demand. Many studies have been performed to simulate, model, and predict the effects of EV charging on residential grid infrastructure, and each author predicted a moderate increase in demand capacity (Cooper et al, 2023) However, most studies predict an increase in demand requiring significant upgrades to residential electric distribution systems. The major element that appears to influence each of these studies is simultaneous vehicle charging and peak power demand, as shown in Figure 5. The studies agree that, to minimize the grid impact, charging times should be controlled so they occur during off-peak hours to minimize the electric system impact.

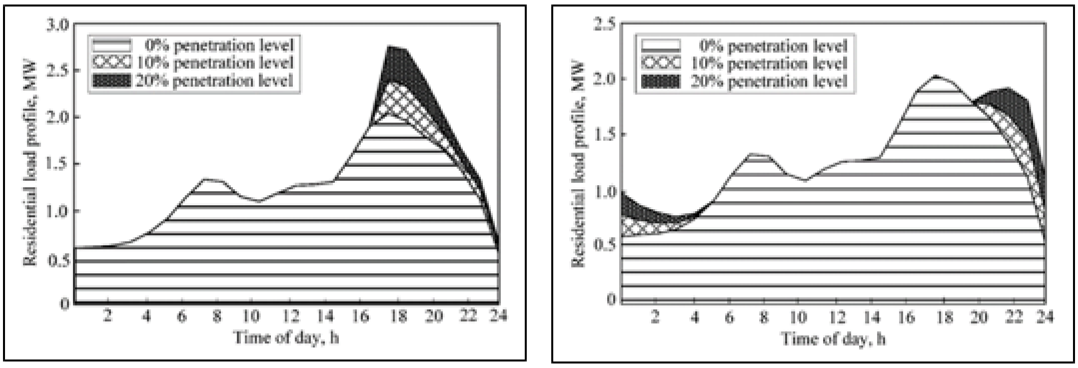


Figure 63: Difference between On-peak vs. Off-peak charging (Residential) [39]

According to U.S. Department of Transportation data, on average, each U.S. driver travels 13,476 miles annually – or 36.9 miles per day. Assuming 0.35 kWh/mile, this equates to an energy usage of 12.9 kWh/day. If a Level 2 residential charging station rated at 7.2 kW (AFDC, 2022) is used, this requires approximately 1.8 hours/day of charging per driver . Since most residential demand profiles peak between 5pm and 8pm, if EVs begin charging when drivers return home in the evening, the peak is exacerbated. However, if charging is set to occur between 9pm and 6am, the grid is much better prepared to meet this demand.

3.2.9 COMMERCIAL SECTOR

Commercial EV charging can be broken down into two categories based on their usage patterns – return-to-base models and models relying on public charging infrastructure . Return-to-base models are those in which commercial EV fleets have dedicated, private charging infrastructure at their facilities. Public charging models are those in which commercial EVs would need to have access to publicly available charging stations along their routes. These public charging scenarios could include lengthy local delivery routes as well as long-haul trucking. Each category of commercial EV charging has unique obstacles to overcome.

Return-to-base charging models face the following challenging issues:

1. Upgrading of electric power infrastructure
2. Peak demand electricity charges
3. Operational conditions of the business and facilities
4. Deterioration of battery health

The relatively large size of commercial EV batteries and potential large number of vehicles in a commercial fleet would likely necessitate capacity upgrades to electrical infrastructure, potentially at multiple distribution levels, to deliver the required capacity to a single, private facility (Daniel et al, 2023). Since some utilities have peak demand charges for the highest demand for any given period during a billing cycle, uncontrolled charging of large loads could coincide with peak facility base load. This could result in significant excess costs via both utility bills and capacity upgrades for facilities using the same commercial rate for both the building and charging infrastructure (Cooper .w et al,. 2023).

As facilities control operational conditions, this could have impacts on the demand profile for vehicles as well as the infrastructure required to sufficiently charge all vehicles regularly . To meet demanding driving schedules, vehicles could be required to charge at higher power, maintain a higher state of charge, and be subject to deep discharges – each of which could lead to the deterioration of battery health . Addressing these challenges for the return-to-base model, commercial facilities should analyze proposed systems and work with utilities to ensure any EV additions have adequate electrical capacity. Operations management should also optimize the charging patterns of the on-site vehicle fleet.

Public charging models for commercial EVs face their own challenging issues – 1. Daily operational schedules; 2. Charging costs at public charging stations; 3. Utilization rates of public charging stations; and 4. Stability limits of the grid system . Commercial EVs often must adhere to strict daily operational schedules. As such, public charging infrastructure should be accessible at times and locations conducive to keeping such a schedule – e.g., located at or around destinations, daily parking places, or fast chargers along major transportation corridors (Alec. E et al, 2023). Time of use tariffs are often tools to incentivize EV drivers to charge at off-peak times. However, commercial EVs do not have the same operational flexibility, leading to paying much higher costs at public charging stations and potentially adding large electrical demand during peak hours.

Utilization rate, or the kWh per unit time, that public charging infrastructure achieves directly relates to the economic feasibility of such a charger existing. Therefore, in areas where utilization rates may be low, access to public charging infrastructure could be severely limited Like residential charging infrastructure, stability limits on the grid must be considered, and upgrades made, to support large commercial EV electrical loading at available charging stations . Tackling these challenges for the public charging model, chargers should be located along commercial EV routes with sufficient capacity to handle planned stops from multiple commercial entities simultaneously. This will likely require significant electrical infrastructure upgrades, especially along high-traffic corridors where Level 3 chargers must be more prevalent to serve the larger commercial EV volume and operational schedule needs.

3.3.0 ELECTRIC VEHICLE POLICY

Decarbonization of any industry is a topic of growing concern and therefore interest. This effort has been largely influenced and driven through consumer interest, and soon followed by governmental entities around the world. This pressure from regulatory bodies and consumers has forced corporations around the globe to respond by adapting their supply chains, operating procedures, and overall consumer behavior. This effort has been largely motivated through industry research and government supported projects conducted to assist in realizing the public health and policy benefits that a cleaner atmosphere brings for both current and future generations. (eia.gov, 2023) Therefore, the turn of the 20th Century has yielded vast amounts of policy proposals regarding environmentally friendly technologies across all sectors. The United States has been among a small group of pioneering nations to recognize the need to decarbonize the transportation sector. During the past two decades, the globe has seen rapid deployment of wind and solar renewable resources to assist in the decarbonization of the electric grid. With these developments, energy storage in the form of electric energy batteries has seen equally as rapid developments with more progress anticipated to come, some experts estimating growth by 15 times from 2022 to 2030. These developments in energy storage for grid applications have yielded traversed benefits into the electric vehicle industry that have assisted in lowering EV production costs, increased battery efficiencies, and improved safety features on energy storage components . All these variables combined have contributed to the economic feasibility of purchasing EVs for the average vehicle purchaser.

Policy surrounding electric vehicles in the United States consists of largely three categories which are public policy, incentivized policy, and integration policy. Each policy category has their own unique set of goals that they seek to achieve based upon the jurisdictional authority and local goals. In the United States, the structure of energy policy consists of a complex structure of federal, regional, state, and local entities that adapt policy based on their respective jurisdictions. Each policy category mentioned previously has a slightly different regulatory and policy structure revolving around EVs that changes based upon who is impacted. Each independent policy structure will be evaluated independently in the following sections. Bearing in mind, the policy issues explored surrounding EVs in the U.S. can also be seen ongoing similarly in countries around the globe as countries assess the growing need to adapt.

3.3.1 PUBLIC POLICY

Public policy has long been the driver for renewable energy and has likewise transitioned the same motivation and interest towards EVs. Public policy is a set of regulations or laws that are designed to benefit public interest [53]. EVs have gained notoriety due to their acclaimed contribution towards public policy benefits. The U.S. Department of Transportation attributes EVs with the contribution of decarbonization via the mitigated burning of fossil fuels, which therefore do not contribute to climate change, global warming, and air pollution [54]. These mitigated effects of EVs as compared to traditional internal combustion engine vehicles directly contribute to improved public health benefits [54]. This alone is a large supporter of EVs from the perspective of lawmakers and representatives tasked with maintaining their constituents' best interests when making laws and regulations.

With public interest as the major contributor towards EV development and adoption, the U.S. among other nations have begun to set ambitious public policies surrounding the technology. As of 2021, the U.S. consumed 37% of all available energy (not including losses during conversion) for use by the transportation sector [56]. As shown in Figure 64, 94% of the transportation sector is fueled from petroleum-based resources, 4% is fueled through renewable or alternative green fuels, and less than 1% is fueled by electric energy [56]. Realizing this, the federal government has decided to begin determining methods to decarbonize the transportation sector. The most likely contender for this presents an opportunity for EVs to position for rapid growth in coming years.

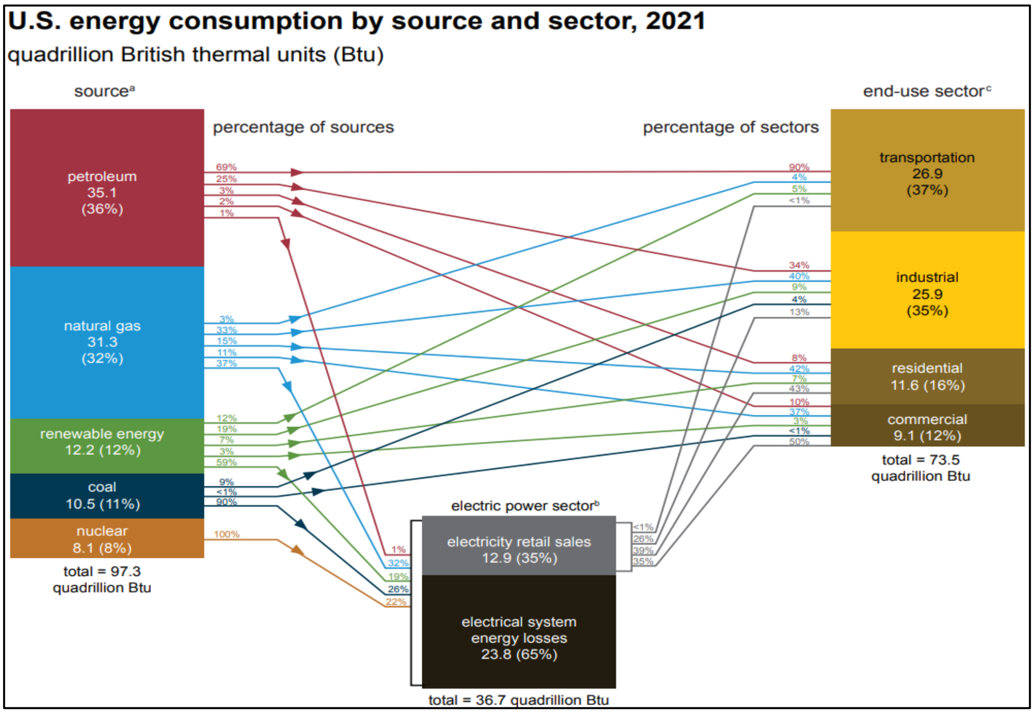


Figure 64: *Consumption of energy in the U.S.*
Source: www.DoE.gov

Through the recognition of the need to decarbonize the transportation sector, the U.S. has set some ambitious goals as a part of their public policy initiatives. Regarding policy structure, public policy consists of state and federal policies depending upon what the constituent bodies support for the respective jurisdictions. In 2022, the Biden Administration announced their aggressive transportation electrification plan, which targets achieving half of all new vehicle sales to be EVs by 2030 as well as implementing 500,000 EV chargers to support this goal [56]. Individual states have also begun setting goals for EV adoption such as California and New York leading the most ambitious efforts. In 2021, the state of New York set a goal for 20% of all vehicles to be EVs by 2030 subsequently vowing to support this through implementing over 10,000 EV chargers to support growth as well as setting the goal for all new vehicles to be zero-emission vehicles by 2035. Similarly in 2022, the state of California approved a policy led by the California Air Resources Board to set a goal of having all new car sales be 100% zero-emission vehicles by 2030, which is primarily supported through EV adoption . From public benefit alone, it can be recognized that EVs are being relied on as a primary method to decarbonize the transportation sector, and now that goals are being set subsequent policy needs to be implemented that encourages the achievement of those goals.

3.3.2 INCENTIVIZED POLICY

Private industry has utilized incentives to manipulate consumer behavior since the 1920's and the U.S. government, whether it be state or federal levels, have begun providing incentives to drive consumer behavior . Some legal researchers have traced energy subsidies from the U.S. government back to the earliest accounts in 1789 shortly after the country's Independence in 1776 . Nevertheless, this strategy has long been prevalent in the energy industry and can be popularly recognized since the beginning of the 21st Century through renewable energy incentives. In 2017, an evaluation was performed that found that the U.S. has provided energy incentives of over $1 trillion from 1950-2016, thus indicating the level of importance of the industry with regards to national security and public prosperity. These revolutionary incentive models began as Investment Tax Credits, Production Tax Credits, Bonus Depreciation, Rebates, etc. and have evolved rapidly to begin influencing the EV market. These forms of incentives are intended to financially motivate early adopters to purchase these new technologies such as EVs. In early cases, EVs weren't cost competitive when compared to traditional combustion engine vehicles, and therefore the government stepped in to assist new vehicle owners through easing the costs of purchasing an EV.

Currently, EV incentive policy consists of state and federal programs that provide benefits for manufacturing, purchasing, and EV chargers. In 2022, the largest infrastructure funding plan in the U.S. was enacted through approval of the Inflation Reduction Act . This federal law package provided mutual manufacturing and consumer incentives for zero-emission vehicles. This act established the Clean Vehicle Credit, which modifies the previous IRC 30D: Qualified Plug-in Electric Drive Motor Vehicle Credit, to provide consumers with a tax credit of up to $7,500 per zero-emission vehicle purchased in 2023 and after . Subsequently, to qualify for this credit the vehicle must have final assembly performed in the U.S., which also supports the U.S. economy through manufacturing .

From a state level perspective, every state currently has incentives for either incentives applied towards purchasing a zero-emission vehicle or funding for installing chargers at homes, businesses, and public places. Colorado currently has the most valuable incentives for purchasing a new zero-emission vehicle by providing up to $10,000 in the form of rebates . Regarding EV chargers, in 2021 the state of New York passed the Infrastructure Investment and Jobs Act which provided $175 million in funding for long distance EV charging infrastructure . It is evident from these examples that when combining state and federal incentives for EV charging as well as EV purchasing, the endeavor could be potentially more rewarding than driving an internal combustion engine vehicle when it comes to the decision to purchase.

3.3.3 INTEGRATING POLICY

The United States' energy industry is managed through a complex hierarchy led by the Department of Energy and then flowing down the local distribution electric utilities as shown in Figure 7 [68]. The Department of Energy utilizes the Federal Energy Regulatory Commission alongside the North American Electric Reliability Corporation to develop standards that the industry must follow.

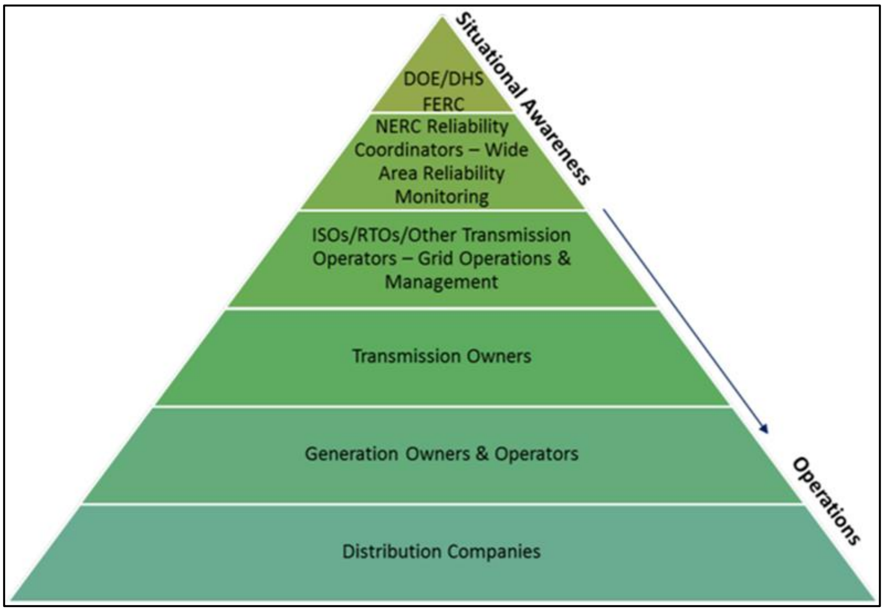


Figure 65: The hierarchy of Jurisdictional Authority of the U.S. energy industry.

The hierarchy displayed in Figure 65 flows down to the regional authority consisting of regional transmission operators and independent system operators that are more tuned to the needs of their regional transmission and distribution utilities. At the local level, 35 states have public utility commissions that regulate distribution utilities and the method for integrating resources into the grid. This structure is what develops, adapts, and enforces technology integration that operates in tandem with the grid.

At this point, electric vehicles are primarily viewed as consumers of energy, however there are discussions ongoing that are exploring grid interactive functionality. Electric vehicles have a significant amount of energy storage currently available within them, and automakers as well as utilities are evaluating the feasibility of utilizing these mobile batteries to relieve the grid in times of need. On average, an EV contains an energy storage capacity of about 60 kWh which is enough to power the average American home for two days . During the past 10 years annual car sales have been between 14.4 million and 17.4 million vehicles, if the Biden Administration’s goals of having half of all new car sales by 2030 being EVs then that results in an additional amount of energy storage ranging from 432,000,000 kWh – 522,000,000 kWh each year .

This thought exercise helps everyone to realize the resources being deployed around the country that could be utilized to benefit the American electric grid. The challenge here is figuring out a standard for providing the electric utilities access to stored energy within EVs at the time of need, ensuring grid reliability and user safety, providing vehicle owner's compensation, and ensuring that vehicles still maintain a state of charge for their owners. These resources as they grow in saturation are currently being looked at as to how to implement the technology needed for EVs to back feed to the grid when needed. Changes needed to accommodate this operational ability are potential changes to the National Electric Code regarding EVs since they currently do not fall under this code. This could also result in UL listings developed specifically for EVs designed to back feed to the grid. From a strictly policy perspective rather than standards, the federal government will be the first to set a standard defining this process and the necessary tolerances. As discussed previously and shown in Figure 3, the process will continue downward to the local jurisdictional levels to adapt the solution to the localized need.

There is no question that EVs present the potential to be a vital resource to support grid reliability as needed, but they also present challenges due to the increase in demand that they introduce to the electric grid. This transition is not to be taken lightly, because an entire transportation industry becoming electrified to any substantial degree is going to present a significant burden on the electric grid that needs to be mitigated. This is a significant amount of load that wasn't present on the grid before that is now rapidly increasing its presence. The challenge this presents is the need for improved transmission and distribution infrastructure to handle this amount of load that based on behavioral patterns is likely to occur during two short timeframes during each day.

To address the ongoing transmission capacity challenges anticipated, the Inflation Reduction Act of 2022 included approximately $2.9 billion in funding for transmission improvements to support EVs and renewable energy implementation . From a distribution standpoint, this responsibility largely is delegated to electric utilities and state Public Utility Commissions to determine. Typically, distribution improvements such as upsizing conductors, breakers, transformers, or adding additional circuits and the associated costs therein are borne by the rate payers of the respective utilities.

To mitigate the amount of improvements and subsequent costs imposed, state regulators and utilities are proposing alternatives to help ease the financial burden of the infrastructure improvements. The most progressive methods currently considered throughout the U.S. involve time-of-use rates that financially motivate consumers to charge and potentially discharge during certain periods to maintain lower costs. Other methods include load controls that allow the utility to adjust consumer demand to benefit the network. In either manner, integration standards are still being developed and considered as we are still in the early stages, but nevertheless this is how regulators and utilities should be thinking as this develops further.

Energy policy is complex and requires constant adjustment as technology changes and the need to adapt over time. The U.S. is currently pursuing ambitious public policy and incentive policy regarding zero-emission vehicles. The areas that need further development are the integration policies surrounding the potential to back feed the grid or buildings such as a home or business. The three categories that need to be coordinated for this to occur are:

1) Grid-EV interconnection via chargers
2) Charge-discharge compensation

3) Vehicle safety operational standards

4) Controls allowing utilities to access stored energy.

If solutions can be found that coordinate between different makes **a**nd models of vehicles to safely allow grid integration, then the demand response capability of EVs could be significant and help ease grid stress due to charging and discharging.

3.3.4 RECOMMENDATIONS

Based upon current trends in technology, policy, and pricing, EVs are anticipated to increase in saturation in the coming years around the globe. Some issues that are expected to occur due to the rapid saturation of EVs are the increased loading during specific time frames, power quality fluctuations, and capacity constraints. Policy and regulation will have to address these operational issues and in turn recognize these EVs as grid assets rather than as end users. In this manner, utilities and consumers can benefit each other through fair and equitable policies set in place for mutual benefit. Recommendations based upon the review of current technology, integration methods, and policies are listed as the following:

- Utilities should include EV charging demand into capacity planning for both residential and commercial areas of the grid.
- Utilities should account for increased charging capacity needs along high traffic corridors.
- Utilities should investigate the opportunities arising from EVs as energy storage assets in the larger electric grid.
- Local and regional policy makers should create mutually beneficial rate schedules or compensation methods between EVs owners and utilities.

- Regional grid operators should develop transmission expansion plans to stay ahead of capacity from consumer demand anticipated.
- Regional grid operators develop operational standards for EV charging and back feeding methods.

From the list of recommendations above, it is evident that the areas needing the most development are the integration and operational aspects of EVs. This requires attention and collaboration from policy makers, grid operators, utilities, and EV manufacturers to develop operational standards to better benefit all stakeholders. At this point goals have been set and funding has been allocated for the development of the EV industry, but the integration standards need further development. Progress in this area needs to occur in a timely fashion, because it takes a significant amount of time to expand grid capacities and EVs are increasing in adoption at an increasing rate.

3.3.5 SUMMARY

It is no doubt that policies and good energy incentive programs will not help in the adoption and penetration of renewable and energy storage. Storage deployment provides opportunities for job creation, fair transition, economic recovery, and the creation of new business models across the value chain. These technologies are in place in sectors such as electric mobility, building or industry, and promote the development of new business models such as independent aggregators .

CHAPTER FOUR

4.0 RESEARCH METHODOLOGY

4.1 INTRODUCTION

The rapid growth of the energy economy is still dependent on refined fossil fuel reserves. Advanced and Modern power systems could not exist without the many forms of electricity storage that can be integrated at different levels of the power chain. This work holds a review of the most important applications in which storage provides electricity-market opportunities along with other benefits such as arbitrage, balancing and reserve power sources, voltage and frequency control, investment deferral, cost management and load shaping and levelling.

The landscape of energy generation is characterized by both renewable energy and storage technologies. The idea of storage technology comes into play when there is excess generation and consumers need to consume the needed generation. Hence the technology of batteries and other technologies are considered, Lithium-Ion batteries are by far the most energy dense and power pack with smaller footprint which many industries have clinched on to support the energy transition and mobility.

The industry is growing with some pain points, such as battery safety, catastrophic fire concerns which have been brought to the attention of industry leaders. As stated in the literature review, many records back the fact that current lithium-ion batteries used in simple systems like mobile phones and bigger and complex systems like commercial and utility energy storage systems poses some level of fire risk.

4.1.1 METHODOLOGY

This research is motivated by the safety concern in the energy storage industry, there have been wide spread of fire issues that have engulf the commercial and utility scale energy storage, Hence, I decide to conduct this research and come out with a solution to demystify the fear in the use of Lithium-Ion batteries. Also, to provide alternative way to design and test the battery to meet UL9540A and resolve fire propagation in battery modules and transfer to system level. Again , the research will help battery manufacturers and system integrators to build and test battery systems that can be transported from one to another without disassembling the battery module and reduce cost.

4.1.2 RESEARCH PROBLEM

As discussed, the problem this research seeks to resolve is big devastating cost and damages associated with fire in lithium-ion as it pertains to the use in automobiles, commercial and utility scale energy storage and in all our electronic appliances such as computers, drones etc. The problem of fire safety has been discussed by underwrite laboratory (UL) principal engineer Laurie Florence, February 2017 and published by Sandia lab (www. sandia.gov, 2017) in the Energy Storage Safety forum in 2017. UL has been struggling with the problem of lithium-ion battery fire from propagating from a single cell to cell, module to module and at full system level. In line with the underline problem of fire safety, it is realistic to design battery modules to prevent a single cell failure from cascading or propagating to the outside of the enclosure through the use of well designed and manufactured cells that are not susceptible to failures during anticipated worse case use scenario. Also use afire resistance or retardant materials to inhibit the spread of fire in the event of fire outbreak in the battery module .The overall problem in the energy storage industry with lithium-ion battery is simplified and stated as follows:

Fire propagation in lithium-ion battery, cell to cell, module to module and system level is getting out of hands and there is the need to have a solution to curb that.

UL and other relevant organizations are with the view that strengthening the UL9540A testing will curb the problem, but there is much more to be done that to limit ourselves to the testing above.

4.1.2 RESEARCH MAIN HYPOTHESIS

Many have been talked about the resolution of the fire safety issues in the energy storage industry , because of that, I write to propose this hypothesis to by research:

Developing high precision sensors, module's structure and introducing high fire-retardant material to encapsulate battery modules and systems can resolve the problem of fire safety and early fault detection in lithium-Ion batteries.

4.1.3 RESEARCH STATED QUESTIONS

The problem presented by UL and public on fire safety and propagation has three sides to the equation. This includes how lithium-ion can safely be applied without fear, how operation of these batteries can work without fire outbreak and how commercial batteries can be assembled in factory and transported to site without disassembly. The research questions are as follows as a scientific and economic question.

Q#1. Why is safety in Lithium-Ion batteries paramount to energy storage industry and what can be done to mitigate fire in lithium batteries.?

Q#2. Why is UL introducing UL 9540A and 9540 test for lithium-ion battery and will making a policy to insert fire retardant in all battery module and enclosure improve lithium-ion battery safety?

Q#3. Why can't commercial battery systems be fully assembled and deployed on site and be able to send in airplanes?

The presumptions result of the above questions can be answered with this hypothesis to question 1,2 and 3.

4.1.4 Research Question # 1 Hypothesis.

Can introducing multiple sensors and writing high precision and fast acting algorithm in battery module BMS alert and open contactors to stop further operation of batteries.

4.1.5 Hypothesis #1 Explanation

Thermal challenges exist in the applications of LIBs due to the temperature-dependent performance.(K.J Laidler, Chem. Educ., 61(1984), PP.494-498). For that reason, it will be important to insert multiple sensors and write algorithms that will pick up these elevated temperatures and use to determine when to open a contactor to stop charging to protect the battery from overcharging to cause fire outbreak.

4.1.6 Research Question # 2 Hypothesis

Introducing highly rated fire-retardant material and honey cone material to encapsulate energy storage system resolve fire propagation in battery modules and storage enclosure.

4.1.7 Hypothesis #2 Explanation

Fire mitigation at the cell and module level requires a technique to inhibit and contain the spread of fire , a material that can suppress fire and cut oxygen . Deep research was conducted to select the type of required fire-retardant material. The weight of the material, standing temperature, material make, coating technology , surface treatment, application, and feature and thickness play a vital role in the fire extinguishing. It is against this backdrop that

I proposed to introduce a fire-retardant material made of silicone coated that will suppress the spread of fire in the battery module should there be fire outbreak.

4.1.8 RESEARCH DESIGN AND APPROACH

The main methods used in this research was a pure classical quantitative and qualitative approach, since this involves data collections to review the behavior of different lithium-ion battery technology, and the use of experimental and simulation ways to arrive at a defined result. Battery failures happen in different forms.

The goal is to develop is to develop a lithium-ion battery module that will employ the highest safety system such as fire-retardant material, honeycomb material and high precision sensors to detect battery failures at the early stage to avoid catastrophic battery fires. Also, to help battery manufactures , EPC to build and test transportable batteries without disassembling the battery module. The methodology deployed within this study is in direct alignment with the research questions presented. Understanding the different battery technology and make up, what causes a battery to fail, what other researchers have done to mitigate the failures, the outcomes of what they did and policies they derived to support the implementations of their findings .The research outline will be considered as follows.

4.1.9 RESEARCH PHILOSOPHY

The research paradigm that will be employed within this study is primarily from a positivist standpoint utilizing real world data collected on-site, both in China, DFD advanced laboratory from 2020, battery innovation center 2021 and LG laboratory in Georgia, USA. This experimental and quantitative approach will utilize testing and experiments as primary methods of collection. Examination of grounded theories will govern feasibility when outreaching capability or scope is established.

4.1.9 RESEARCH TYPE

The research type that is that of an inductive nature. Baseline data will be collected, and the approach will be exploratory regarding solutions. Theory will mix in to determine what is capable and what makes the most sense or what is confirmed. The quantitative mixed method approach will allow for alignment to future policy, Codes and business optimization that will allow for strict key process indicators to judge effectiveness.

4.2.0 RESESRCH STRATEGY

The research strategy is to utilize primary an experimental approach. Collecting baseline data, developing key consumption and production of emissions metrics. From this point an analysis into the impact of each and how they affect both the environment and the company's bottom line. Current renewable and mitigation techniques will be explored through case studies and feasibility studies previously explored by the author. These technologies will be analyzed and deployed in a manner to model scenarios that affect cost and reduction across growth and time. This will ultimately give a vessel or scenario guideline.

4.2.1 TIME HORIZON FOR RESEARCH

The data for this study will be longitudinal, as it will be collected in a period, data will be extracted from the years 2019 through 2023 and real-time data will be collected in the year 2022.

4.2.2 SAMPLING STRATEGY

Practicalities and resource constraints will be considered. Non-probability will ultimately be considered as the ideal approach to sampling strategy as the data will be collected on-site. Consideration will be given when developing a model usable for all manufacturing plants.

4.2.3 PROF OF CONCEPT

To authenticate the research, and to reasonably answer the hypothesis a proof of concept is used through designing a battery module with fire retardant material, honeycomb, and multiple thermocouples to detect elevated temperature and shut down the battery module when there is potential fire in chapter 6. Also, a comprehensive test method has been designed to test the design when an actual buildable product is built. These will act as the governing methods to qualify the results of the research questions presented in the subsequent chapters.

4.2.4 DATA COLLECTION AND ANALYSIS

Data collection method: Quantitative collection methods will be limited to available tools on location at the site. Calibration will be documented and deployed by certified individuals as much as possible.

4.2.5 RESERCH DATA ANALYSIS METHOD AND TECHNIQUES

In this quantitative approach the data will be analyzed using a developed model that will project impact as well as overall impact to the bottom line of emissions reduction and plant profit.

4.2.6 LIMITATIONS

The limitations of the study are as follows. The limitation was cash constrained to physically built the first prototype to test all the material behavior, even though the fire retardant was tested with fire touch at a temperature of 200 degrees Celsius and passed the test, the honeycomb material also melted and passed the test as design, but getting other battery module to build and operate the module was not achieved. This can create a sense of skewness and uncertainties.

4.2.7 ASSUMPTIONS.

It is assumed that all responses, interpretations, and subjective thoughts when expressed are of the author's own opinion and are truthful and honest. When possible these opinions have been quantified through data collection and design with simulations.

4.2.8 SUMMARY OF EXPETED RESULTS AND OBJECTIVE

The overall arching goal and expected results is to have justification in the industry to apply the solution to solve Industry problem of fire safety and enforce policy to introduce fire retardant as part of battery module design and built so that UL can have the certification of UL9540A easy and cost effective and resolve fire propagation in battery module . Finally, academic justification to apply the understanding in academic of how battery system fails and potential detection mechanism.

CHAPTER FIVE

5.0 LITHIUM-ION BATTERY FAULT DETECTION MODE

Lithium-ion batteries contain both oxidizers (negative) and fuel (positive) within the enclosed battery space and therefore also carry the risk of fire and explosion in case the user overcharges, overcharges, excess current, or short circuits . For battery safety, safety design is essential at the cell, module, pack, and final product level. If safety fails at one level, catastrophic accidents at the higher levels can quickly follow. There is no single standard and parameter for assessing battery safety. A battery protection circuit will improve safety by making such accidents less likely or by minimizing their severity when they do occur. There have been many incidents that have occurred involving lithium-ion batteries worldwide either in utility scale lithium-ion energy storage, commercial energy storage, e-mobility or even in the ocean fleet. Most of this system when they fail, engineers, scientists, fire fighters and experts come out to perform fire forensic to ascertain the root cause of the problems. Many a times, these forensics proves otherwise and do not pinpoint the exact cause of the cause of the problem. Example of battery fire that left the expert wondering the full cause of fire was ,Arizona APS ESS fire.

Figure 66 - *An image of the Arizona Public Service(APS) electric utility fire in Lithium-ion battery enclosure, April 2019.*
Source :Images.search.yahoo.com/image of Arizona lithium fire

This incident changes a lot of view in the energy storage industry, it drove the industry to where safety should be a key to success in the energy storage and on lithium-ion. Many institutions such as DNV-GL, Exponent and UL had a contradictory statement on what might be the real root cause of the failure in the battery system. UL was pointing to temperature and humidity sensors that were not properly placed to measure extremes improperly placed sensor locations to measure extreme temperature and humidity. Large temperature differences between available sensing points were observed. The dew point temperature gradually increasing over time, indicating changing environmental conditions and not a truly closed loop system. Relative humidity regularly exceeded 80%,The role of high relative humidity and/or condensation on electronics in the BESS cannot be ruled out as a contributor to the root cause of the initial failure.

The UL report does not address this issue and focuses on the fire responders' procedure, including discussions around the fire detection and suppression scheme and the information available to the first responders. Contributing factors, as discussed by UL in their report, are detailed here: Improperly trained HAZMAT team, No flammable gas detection in ESS, Lack of information delivery to HAZMAT team because of ESS communication system failure, No emergency response plan available prior to the incident, No NFPA 68/69 compliance.

The lesson learned here was that there was an ineffectiveness of fire suppression in the ESS, there were not early fire system detection at the cell level and ventilation and deflagration solution were not present in the design of the system.

5.1.1 LITHIUM-ION BATTERY EARLY FAILURE

Within safety accidents of Lithium-ion batteries, thermal runaway has become a common catastrophic safety accident, currently being the primary cause of safety accidents that have occurred. Lithium-ion batteries in electric vehicles are often composed of dozens, hundreds, or thousands of cells in series and in parallel. either a porch cell or cylindrical cells, when one of the cells presents thermal runaway, the phenomenon may spread within the battery pack, causing fire, explosion, and/or other serious consequences . Globally, scientists and engineers have carried out extensive research on thermal runaway. The mechanism, inducement, and suppression methods of thermal runaway have gradually become clearer . Generally, the main causes of thermal runaway are mechanical, electrical, and thermal abuses. As shown in Fig 67,

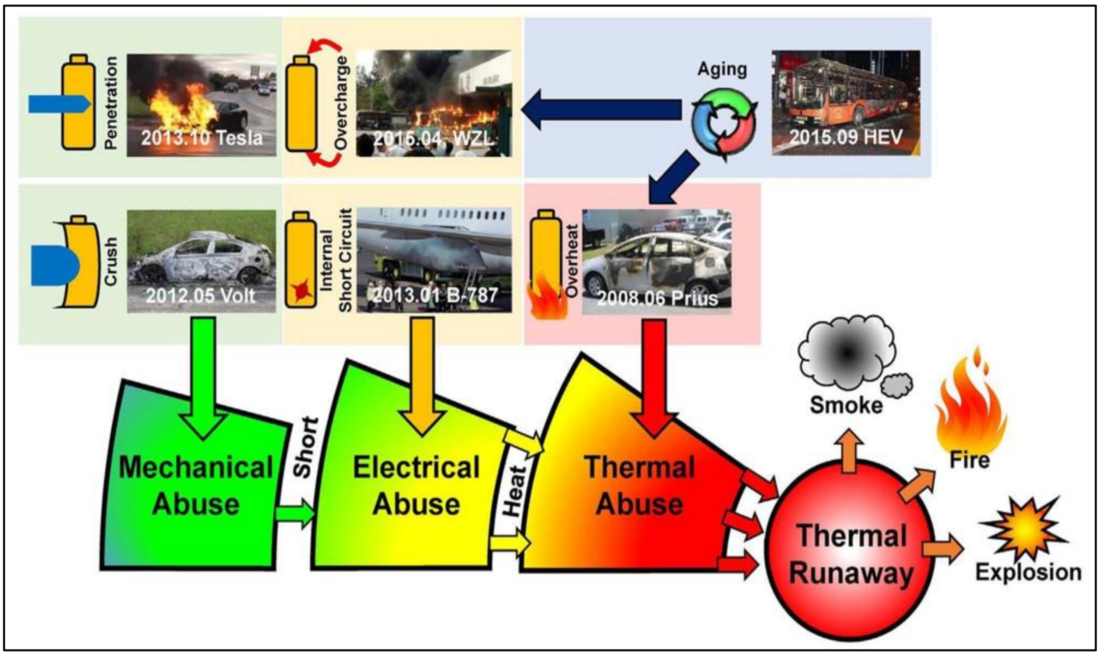


Figure 67*-The mechanism of thermal runaway process and cause of fire*
Source: https://www.ifpenergiesnouvelles.com/article/modeling-improve-safety-lithium-ion-batteries

Internal short circuit-ISC in the lithium-ion batteries –(LIB) is a common link of the mechanical, thermal, and electrical abuses leading to thermal runaway. After internal short circuit- ISC occurs, the energy heat generated by the short-circuit current in the battery will cause a temperature increase of the battery. Then, if the local heat accumulation triggers the chain reaction of the TR, catastrophic accidents such as fire and explosion will eventually occur .With the increase of the specific energy of the battery system, the electrode material of LIB becomes thicker, and the diaphragm becomes thinner, and the probability of ISC increases.

According to the statistics in Ref. (eia.gov),(DoE) 52% of battery fire accidents are caused by ISC, and 26% of battery fire accidents are caused by external SC. It can be concluded that ISC is one of the main failure forms of batteries, threatening the overall safety of batteries. Notably, as a common cause of TR, ISC has a long incubation period in the early stage, which provides a sufficient time window for the detection and early warning of ISC and provides the possibility of early prevention of thermal runaway- TR. Therefore, it is of great significance to study the mechanism, process, and detection methods of ISC to improve our understanding of overall battery safety. In both energy storage electric mobility technology , the environment of the power battery is severe, inevitably leading to corrupted working environment conditions such as high current charge and discharge, high and low temperature charge and discharge, rainwater immersion, vibration, and even overcharge and over discharge, which lead easily to ISC. Notably, ISC occurs over the whole life cycle of the battery, which has a long latency and concealment, and it is not a visible indicator. Moreover, the internal short circuit- ISC process of lithium-ion batteries LIBs is a complex physical and chemical process, involving electrochemistry, thermodynamics, heat transfer, and other disciplines. For these reasons the inducement, process, detection, and prediction of the ISC are relatively diverse and complex. At present, the key content and core technology of ISC can be summarized as follows:

- ❖ Mechanism of ISC: What are the causes of ISC to thermal runaway under inducement.
- ❖ Evolution process of ISC: What are the evolution stages of ISC in the whole life cycle of LIBs?
- ❖ Detection methods of ISC: What are the available ISC detection methods?
- ❖ Prevention methods of ISC: What are the methods of ISC prevention,?.

5.1.2 MECHNISM OF CELL FAILURE-INTERNAL SHORT CIRCUIT

Structurally, the positive part of the battery includes a positive current collector (aluminum) with a positive material coating, and the negative electrode of the battery includes a negative current collector (copper) with a negative material coating. The positive and negative of the battery are separated by an insulating separator. The cathode material, anode material, and separator as seen in Figure 68, have porous structure, and the pores are filled by electrolyte.

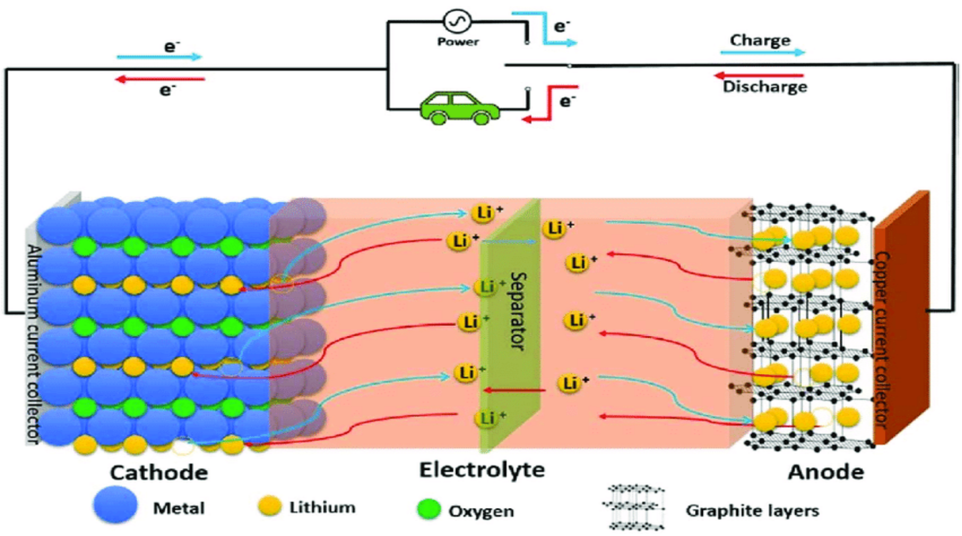


Figure 68 *- An image of lithium-ion operation process.*
Source: www.researchgate.net

Because the electrolyte can only conduct ionic current and not electronic current, the separator can only conduct ionic current. Therefore, inside the battery, the positive and negative parts serve as ionic conduction and electronic insulation; outside the battery, the positive and negative parts are. connected by external circuits to establish electronic conduction.

Figure 69 - *Internal view of the lithium-ion battery with electronic board and sensors. Source: Produced by Daniel Kelly Danquah @LGEUS lab.2023.*

Under normal battery operation, the internal ion conduction and external electronic conduction are closed together to form a current loop. However, if electronic conduction occurs between the positive and negative parts in the battery, this conduction will be directly closed with the ion conduction inside the battery, forming the internal current loop of the battery and resulting in ISC. In this broad sense, ISC refers to the phenomenon of continuous discharge and heat generation due to potential difference when the positive and negative electrode materials of the battery are connected.

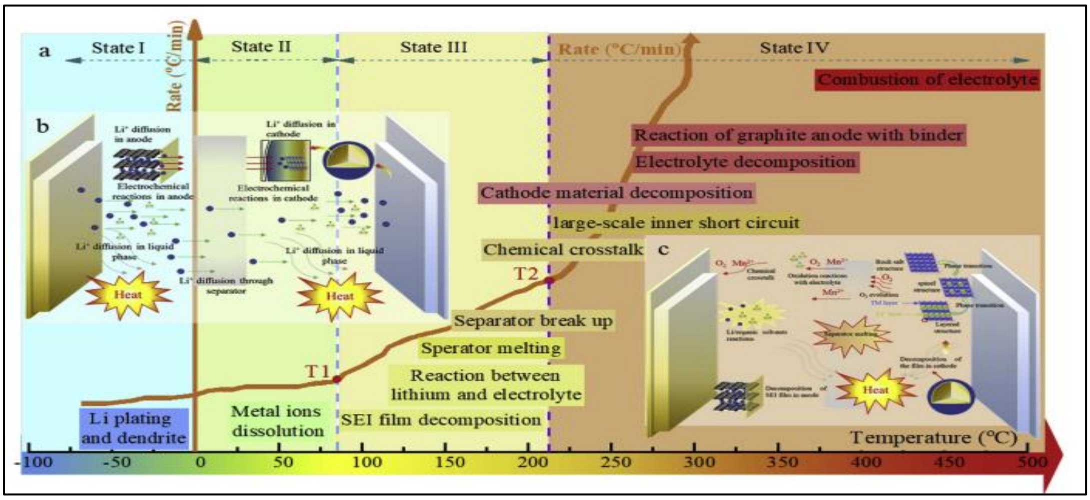


Figure 70*- An evolution of battery fire from the cell level during internal short circuit. Source:* [*www.elservier.com/locate/ensm*](www.elservier.com/locate/ensm)

When ISC occurs, the short-circuit resistance is small, which produces a large current and high Joule heat. Simultaneously, the poor heat dissipation performance of the negative material leads to the continuous accumulation of heat in the local area, which easily triggers thermal runaway-TR and propagates rapidly.

5.1.3 EVOLUTION OF INTERNAL SHORT CIRCUIT TO BATTERY FAILURE

Lithium-Ion batteries system have configuration from cells, sub-module, modules/packs, racks and finally to system. The configuration of the battery system depends on the number of cells to be used, the expansion materials that form in the middle, and the temperature measuring materials that are used. In this way, when a there is an issue with a cell from inducing factors such as manufacturing deficiencies like metal impurities, electrode dislocation, physical abuse, improper operation such as overcharge and high temperature environments caused by improper design of battery management system -BMS, a short circuit can occur.

5.1.4 OVER DISCHARGE CONDITION TO INTERNAL SHORT CIRCUIT

Over-discharge will lead to the decrease of battery capacity and the abnormal heating of the battery. The possible oxidation/reduction reactions of Cu/Cu^+ and Cu^+/Cu^{2+} in the electrolyte system during over discharge and charging are as follows:

1 Oxidation : $Cu \rightarrow Cu^+ + e^-$ Equ 22

2 Reduction : $Cu^+ + e^- \rightarrow Cu$ Equ 23

3 Oxidation : $Cu^+ \rightarrow Cu^{2+} + e^-$ Equ 24

4 Reduction : $Cu^{2+} + e^- \rightarrow Cu^+$ Equ 25

The above chemical reactions will not occur during the normal charging and discharging of the battery. When the battery is over discharged, the anode chemical reactions○1 and○3 occur successively, that is, copper (anode current collector) is oxidized to Cu+, and then Cu+ is further oxidized to Cu2+. Finally, these Cu2+ ions are transferred to the cathode side by diffusion through the separator [85]. At the cathode side, the reduction reactions ○2 and ○4 take place successively, that is, Cu2+ is reduced to Cu+, and Cu+ is further reduced to Cu. In the process of repeated over-discharge, the copper collector is continuously dissolved into Cu2+ at the anode side and is continuously reduced to metal Cu at the cathode side, finally forming copper dendrite that is connecting the positive and negative electrodes, resulting in a large area of ISC [85, 86]. Fig. 4 shows the evolution of ISC caused by overcharge.

5.1.5 LITHIUM PLATING

Lithium plating Improper charging methods (e.g., low-temperature charging, high-rate charging, and overcharging lead to internal side reactions, among which the most important side reaction is lithium plating , that is, the lithium dendrite grows at the surface of the oxide due to excess lithium intercalation. The generation of heat and gas is an external feature of these side effects [90-92]. Lithium dendrites grow continuously with the cycle of LIBs, and eventually penetrate the separator, causing an ISC between the positive and negative electrodes [93]. Ref. [94] confirmed that the kinetic conditions of lithium insertion in the negative electrode become worse at low temperature, such that the electrochemical polarization of the negative electrode is clearly intensified during the charging process, easily leading to the plating of lithium metal on the surface of the negative electrode. If the plated metal lithium develops further, it will become lithium dendrite, leading to ISC. Ref. [95] confirmed that the initiation and growth of lithium dendrites are affected by the texture, structure, and surface roughness of graphite electrode. In addition, because of the expansion and contraction of the positive and negative electrode materials in the process of charging and discharging, ISC is caused by stress fatigue rupture of the separator. Fig. 5(a) shows the lithium plating during high-rate charging. Notably, when the cell is overcharged at high-rate charging, a relatively large amount of lithium plating will occur on the negative electrode, which may develop into lithium dendrites. The resulting sharp lithium dendrites can easily penetrate the separator and cause ISC, as shown in Fig. 5(b). The growth morphology of lithium dendrite is affected by many factors (YS Jung et al., 2010) , such as electrode roughness, current density, temperature, and electrolyte infiltration degree. For example, lithium dendrite easily grows in the convex place of the electrode surface with poor roughness. In addition, the growth shape of the dendrite is related to its original morphology, and thus dendrites easily grow within the sharp parts. Temperature is also a key factor affecting the morphology of lithium dendrites. Fig. 5(c) shows the morphology of lithium dendrites at different ambient temperatures (SS. Zhang, 2006) pp.1379 -1394. illustrating that for lower temperatures, the lithium dendrites are thicker and longer.(Chen et al, 2008) revealed the enhanced lithophilic and lithium-ion migration ability at elevated temperature were proved to facilitate the formation of large nuclei size with small nucleation density. In this case, dendrite-free lithium deposition layer can be obtained, as shown in Fig. 5(d). Therefore, temperature control can control the growth of lithium dendrite, which can be used to inhibit ISC in theory.

5.1.5 REACTION DURING INTERNAL SHORT CIRCUIT

During the evolution of ISC, the temperature inside the battery rises, which leads to complex chemical reactions among the electrode materials, electrolyte, and separator. Most of these chemical reactions are exothermic, which will further aggravate the severity of ISC. When the temperature rises to a certain degree, a series of incidents will occur, such as the decomposition of the solid-electrolyte interphase (SEI) layer, anode-electrolyte reaction, electrolyte decomposition, separator meltdown, and cathode breakdown. Eventually, these incidents increase battery's internal temperature that later triggers the TR. The main chemical reactions during ISC are summarized as follows.

5.1.6 REACTION AT THE ANODEDURING SHORT CIRCUIT

When ISC occurs, the internal temperature of the battery increases, which promotes the internal chemical reaction. The first exothermic reaction is the decomposition of the SEI layer, which is generally considered to occur at 80-120 °C. The SEI layer is assumed to consist of stable (such as Li_2CO_3), and metastable components (such as $(CH_2OC_2Li)_2$). The metastable components might exothermically react as follows :

$$(CH_2OCO_2Li)_2 \rightarrow Li_2CO_3+C_2H_4+CO_2+0.5O_2 \qquad \text{Equ 26}$$

$$2Li+(CH_2OCO_2Li)_2 \rightarrow 2Li_2CO_3+C_2H_4 \qquad \text{Equ 27}$$

When the SEI layer on the surface of the anode decomposes at high temperature, the intercalated lithium metal in the graphite anode has a chance to react with the electrolyte. The commonly used electrolytes for commercial LIBs are composed of lithium hexafluorophosphate ($LiPF_6$) salt, ethylene carbonate (EC), and linear carbonate solvents such as dimethyl carbonate (DMC), diethyl carbonate (DEC), or polycarbonate (PC), and/or ethyl methyl carbonate (EMC) [101]. The decomposition of graphite anode with electrolyte can be described as follows [91, 102]:

$$2Li + C_3H_4O_3(EC) \rightarrow Li_2CO_3+C_2H_4 \qquad \text{Equ 28}$$

$$2Li + C_5H_{10}O_3(DEC) \rightarrow Li_2CO_3+C_2H_4+C_2H_6 \qquad \text{Equ 29}$$

$$2Li + C_3H_6O_3(DMC) \rightarrow Li_2CO_3+C_2H_6 \qquad \text{Equ 30}$$

$$2Li + C_4H_6O_3(PC) \rightarrow Li_2CO_3+C_3H_6 \qquad \text{Equ 31}$$

Obviously, the reaction products between the anode and the electrolyte are the main component of the SEI layer. This phenomenon is called the regeneration of SEI layer . However, the regenerated SEI layer is very irregular, which cannot protect the lithium metal inside the anode. Therefore, the reactions between the anode and the electrolyte will continue, leading to the continuous temperature rise of the battery and further development of ISC.(Q .Wang et al, 2016).

5.1.7 REACTION DURING SEPERATOR MELTDOWN

As the reaction between the anode and the electrolyte continues, the temperature inside the battery continues to rise. The common separator materials are polyethylene (PE) and polypropylene (PP), whose melting points are 130 °C and 170 °C (Jinhua Su et al, 2019) , respectively. When the temperature reaches the melting point of the separator, the separator will melt, and heat shrink. In the process, the holes in the separator will be closed, making it difficult for the lithium ion to transfer inside the battery. The melting of separator is an endothermic process; thus, the temperature rise rate of the battery will slow down. However, when the separator melts and the hole on the separator closes, the internal resistance of the battery will increase significantly, and the temperature will rise further, which may cause the anode and cathode materials to contact locally and aggravate the ISC. With the development of ISC, massive heat will be generated inside the battery, which will lead to the collapse of the separator. In this case, ISC may develop into TR and cause serious safety accidents. It should be noted that the development of ISC can be effectively inhibited by improving the thermal shrinkage resistance of the separator.

5.1.8 REACTION OF CATHODE WITH ELECTROLYTE

The melting of separator causes the internal temperature of the battery to rise rapidly to 300 °C or even higher, resulting in the decomposition of the cathode material. At present, the most used cathode materials for LIBs are LiCoO2 (LCO), LiMn2O4 (LMO), LiFePO4(LFP), LiNixCoyMnzO2 (NCM). The decomposition of cathode materials with electrolyte can be summarized as follows.

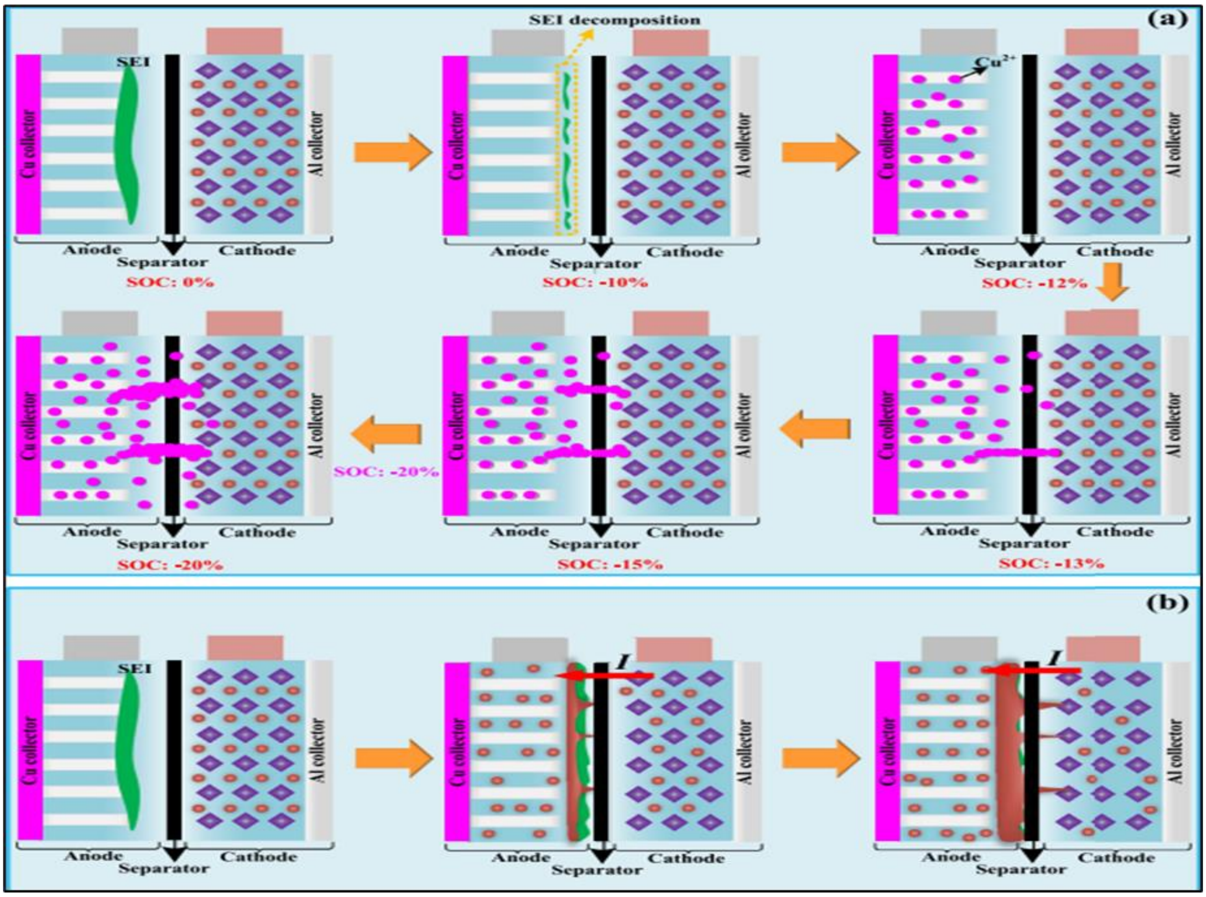


Figure 71. *The evolution of dendrite induced by over-discharged.*
Source: www.energystoragematerials.com

The decomposition of the electrolyte will produce a large amount of gas, which will increase the internal pressure of the battery. If the pressure inside the battery exceeds the threshold value of the battery safety valve, the safety valve will open and the gas inside the battery will be ejected. Lithium-ion short circuit can be detected by several means. This includes:

1. Voltage inconsistency: In this method, the ISC is detected by comparing the voltage difference of each series cell in a battery pack. When the voltage of one or more cells is significantly lower than that of other cells at a certain time, it is considered that the

ISC has occurred . In this method, the voltage of the cell is directly used as the criterion to judge the ISC, thereby reducing the storage and calculation burden of the BMS.

2. State of Charge Inconsistency: The battery voltage changes significantly under dynamic conditions, resulting in fluctuations in the voltage difference, which leads to inaccurate ISC judgment. However, the SOC fluctuation with the load current is not evident, and ISC causes the SOC to decrease abnormally. Therefore, the inconsistency of SOC is an excellent criterion.

3. Remaining Charge capacity: Because each cell in a module is connected in series, each cell has the same charge and discharge electricity quantity during the charging and discharging process. Due to the inconsistency of cells, only some of the cells are fully charged at the end of each charging. At this time, if the unfilled cell is taken out and recharged separately, the amount of electricity charged in this process is called the remaining charge capacity (RCC), which is equal to the difference between the capacity of the cell and the charging electricity quantity when the module is fully charged [94]. For a normal cell, the RCC of each cell is constant. However, when ISC occurs in a cell, the cell will leak electricity. The greater the degree of ISC, the greater the leak in electricity
4. Dormancy period: Statistics show that among the fire accidents of EVs in 2019, 41% were caused by the spontaneous combustion of the battery when the vehicle was parking, accounting for a relatively high proportion. The spontaneous combustion during vehicle parking overturns people's conventional understanding of battery safety and puts forward higher requirements for battery safety management; not only in the process of operation, but also in parking, the battery failure should be effectively

detected. Generally, there are long and frequent dormancy periods in EVs, which brings a long-time window for ISC detection. At present, many EVs are equipped with automatic battery inspection systems, that is, after the EV stops, the BMS is opened periodically (such as 20 h) to detect the voltage and temperature of the cell. Each time the inspection system is turned on, the duration is merely tens of seconds, and thus, it will not increase the storage burden of the BMS. This automatic inspection system could allow for the convenience of ISC detection of the EV during the dormancy period. Therefore, we propose an ISC routing inspection method for dormant EVs.

5. ISC detection method considering balanced electric quantity: At present, the BMS of EVs is often equipped with a battery equalization system. When the inconsistency of the cells increases to a certain extent, this equalization system is turned on, causing the cells to maintain high consistency. Generally, there are two forms of equalization system: active or passive equalization. The active equalization achieves the consistency requirement by transferring the power in each cell, whereas the passive equalization achieves the consistency of each cell by consuming excess power. This equalization system of the BMS can eliminate or reduce existing inconsistencies to improve battery safety. However, the enhancement of consistency can also weaken key electrical characteristics of the ISC judgment and mask the ISC occurrence, possibly leading to the misjudgment of the early ISC or a long detection time. Notably, the electrical characteristics may be the only significant feature available in the early stage of ISC, and the equalization has a great influence on the ISC detection. For the later ISC detection, on one hand, the difference in electrical characteristics (e.g., voltage and SOC) caused by ISC is significant, whereas the equilibrium electric quantity (EEQ) is relatively limited, which leads to the minimal influence of equalization on ISC.

5.1.9 MECHANISM OF SYSTEM FAULT

Energy storage system is a complex system that has many components that are put together to form one complete system. This complex system is made up of both hardware and software. The system is made up of cell, modules, racks, DC-panel, AC panel, water injection system, fire suppression system, air-conditioning system, inverter-power conversion system, transformer, disconnect and energy management system. Each of these systems has about 50-subcomponents that make up the energy storage piece of the system. Since all these components are interconnected together, when a fault occurs in the system, it is very complex to point out where exactly the issue happens. The figure below illustrates the hierarchy of energy storage systems.

Figure 72*-Energy storage system architecture from cells, module, rack, and System*
Source: Daniel kelly Boakye Danquah

Energy storage systems are always made up of subsystems of cells, submodules, modules racks and other secondary components such as AC panel, DC panel, inverter, HVAC, water injection system, fire suppressing system. Any of these complex components when triggered in the storage system can cause catastrophic failure. The cell, either prismatic, coin, cylindrical or porch has its structure deficiencies and can contribute to system failure in a different mechanism.

5.2.0 CELL MECHANISM TO SYSTEM FAILURE

The cell of energy storage system is the core of the technology. It contains 60% of the total system cost and is the most delicate part of an energy storage system. This part is mostly made of chemical materials mixed with electrical, mechanical, and plastic. The battery system operation is based on the electron and ion movement from cathode to the anode through a separator. During the operation of the battery system, the movement of the electrons creates heat. This can lead to high internal resistance; this can lead to internal short circuits. The internal short circuit of the cell can happen through multiple ways, this includes manufacturing defects, through physical abuse and improper operation. When this scenario happens, it has a cascading effect on the energy storage system. Example, when the battery system is being improperly operated at low temperature charging, higher current charging, over charge or over discharge, high temperature environment. The mechanism of failure is laid down : Reaction at the anode, separator breakdown, reaction of the cathode with the electrolyte, Decomposition reaction of electrolyte and finally there is the decomposition reaction of fluorinated binder. All these are internal cell failure mechanisms which are caused by operation of the battery system at the cell level.

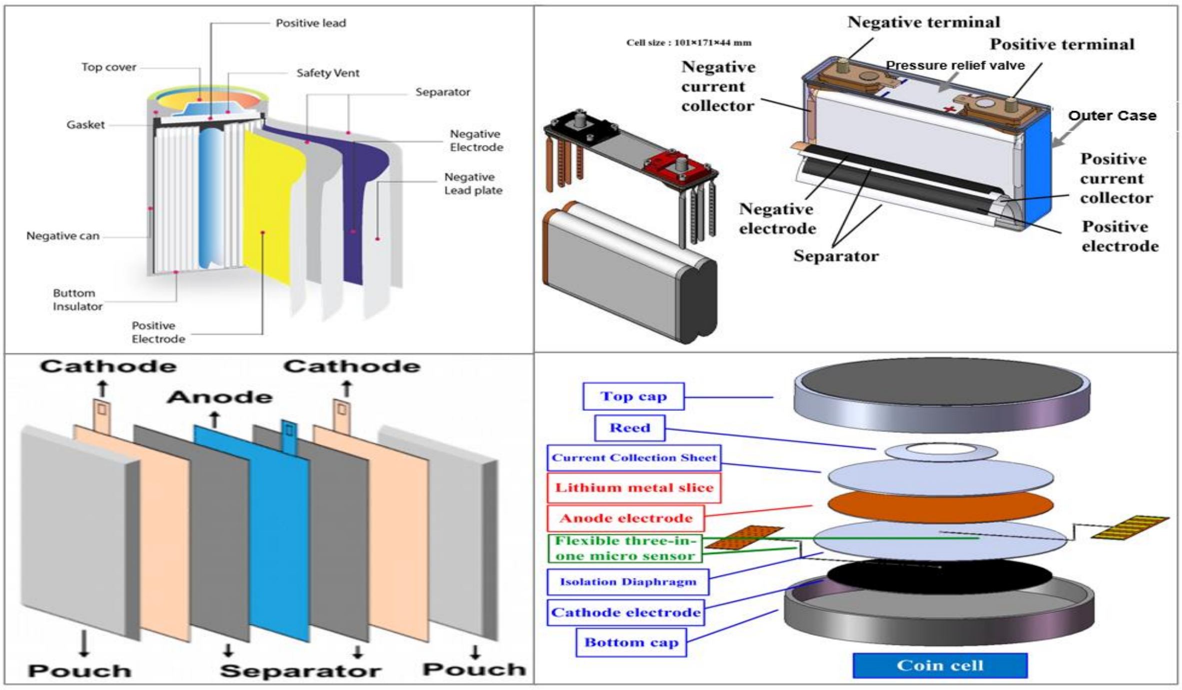


Figure 73*-An internal view of various lithium-Ion battery cells.*
Source: Curtesy of Daniel Kelly Boakye Danquah

There is also another process that contributes to cell failure, which is external mechanism, this includes physical abuse such as drop the cell, crushing, and fatigue. The final mechanism is manufacturing defects which includes material impurities during coating and mixing process conductive dust on the surface of separator, dislocation of positive and negative electrodes, burs of electrode pieces and uneven distribution of electrolyte.

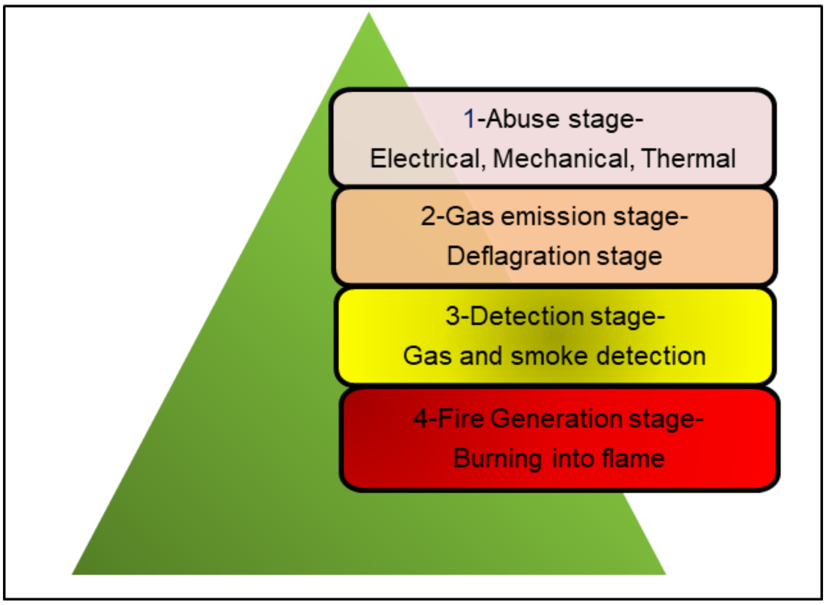


Figure 74- *Hierarchy of lithium-ion failure stages*
Curtesy: Daniel Kelly Boakye Danquah-(University of North Dakota)

This mechanism of cell failure creates a dominant effect in the energy storage system which can create fires. Example of case studies of two known Lithium-ion battery technologies, NMC and LIF, the burning process of lithium-ion is divided into five stages, which are (a) heating stage; (b) rupture and ignition; (c) violent ejection; (d) stable combustion; and (e) flame abatement. During the heating stage, the battery remained stable and only part of the packing melted. With the continuous rise of temperature, the safety vent cracked, accompanied by a clear sound. Hereafter, smoke was released and then the smoke ignited. The flame lasted until a large quantity of smoke was liberated, resulting in violent ejection, and then stable combustion could be observed. With the depletion of the combustibles, the fire began to abate and extinguished. These phenomena were consistent with those observed in previous works [18]. Comparing the fire behaviors of 4.2 V LIB and 5.0 V lithium-ion batteries (LIB), the overcharged Lithium-ion (LIB) exhibits earlier ignition, ejection, and stable combustion than the normal Lithium-ion battery (LIB).

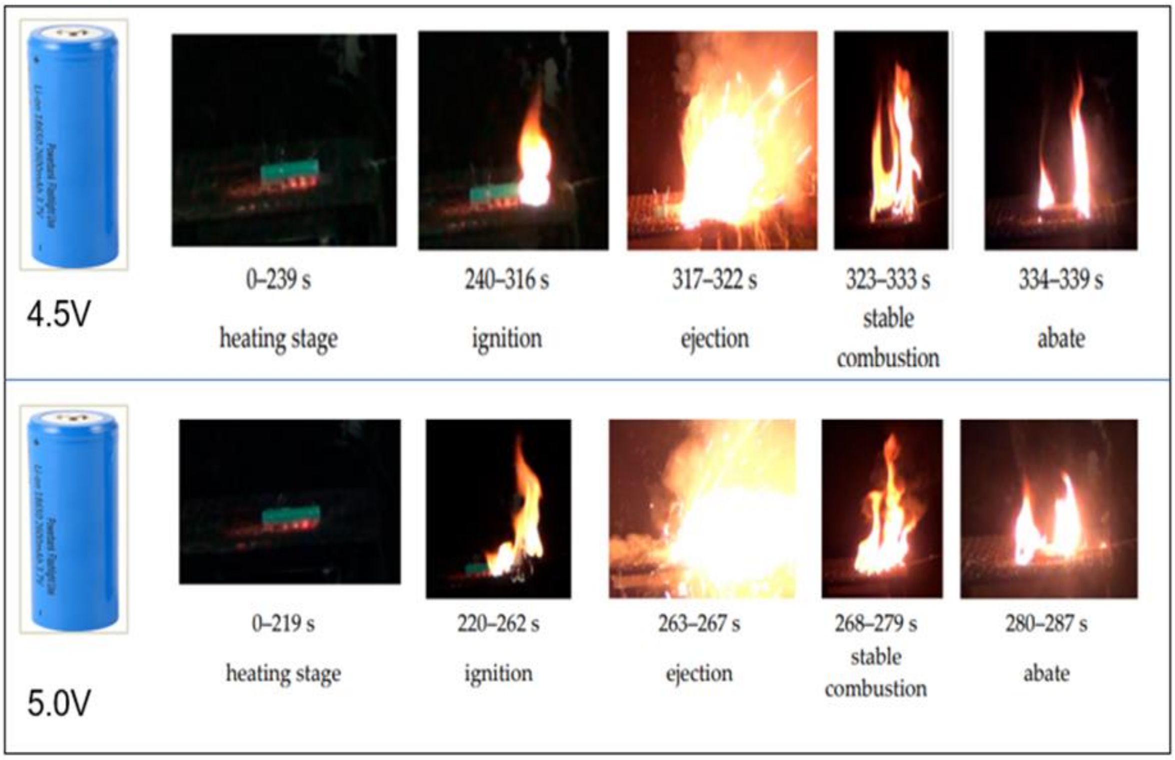


Figure 75 *- Experiment to show time stages of lithium-ion battery failure to burning.*
Source: Applsci-07-01314.pdf

Moreover, its ejection and combustion are much more violent. This reveals that the overcharged LIB possesses a more serious combustion process and a lower stability than the normal LIB. It is the result of unstable electroactive materials, where highly delithiated electroactive materials become more reactive in the overcharged LIB.

The separator in the cell is gradually damaged owing to the temperature increase. The cathode and anode of the cell are in contact with each other, resulting in an ISC. According to Joule's law, part of the electric energy stored in the cell is converted into heat energy.

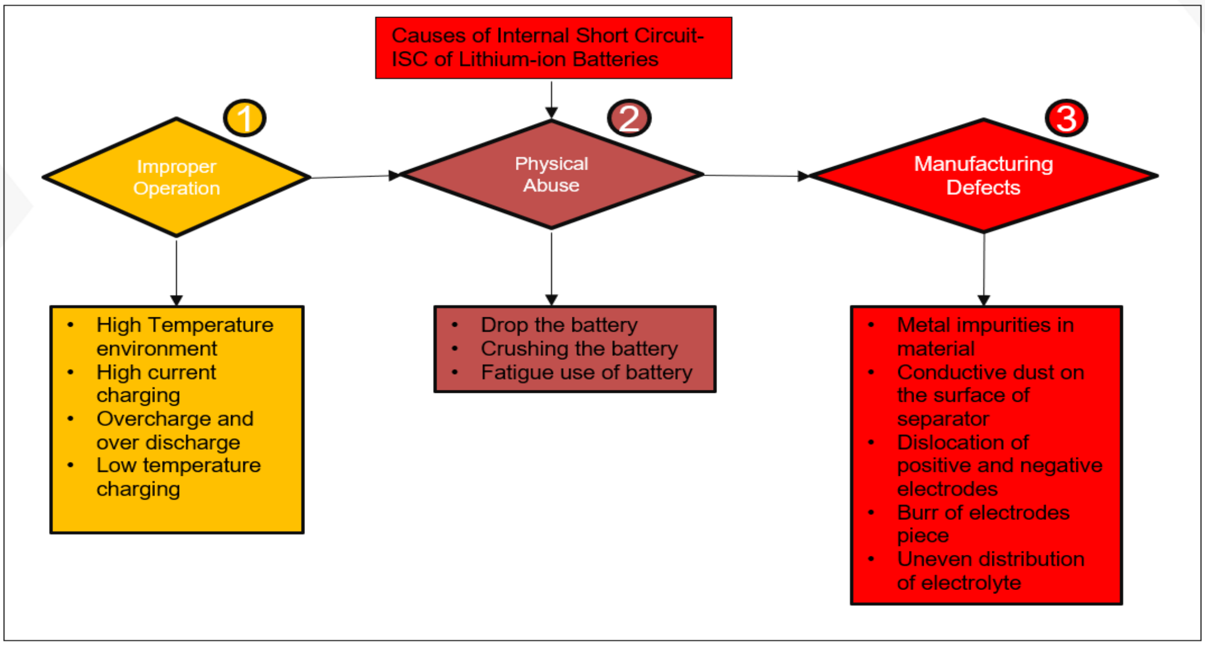


Figure 76. *An illustration of short circuit in lithium-ion battery*
Source: Designed by Daniel Kelly Boakye Danquah.

Internal short circuit ISC has self-limitation in the initial stage, and the voltage characteristic is weak; however, the time of this stage is relatively long. Therefore, how to accurately detect ISC in the early stage is the key. The characteristics of ISC in the middle stage are evident. However, the time window is short, and thus, it is necessary to pay attention to the timeliness of detection. Overall, the identification and response of ISC should be realized in the early and middle stages due to their long-term characteristics, as well as the higher risk and likely mutation of ISC at the later ISC stage.

5.2.1 FAILURE MECHANISM AT MODULE LEVEL

Battery cell is the smallest unit of the battery and is also the fundamental energy storage unit. When these cells are interconnected together either in parallel or series form, then a module is built.

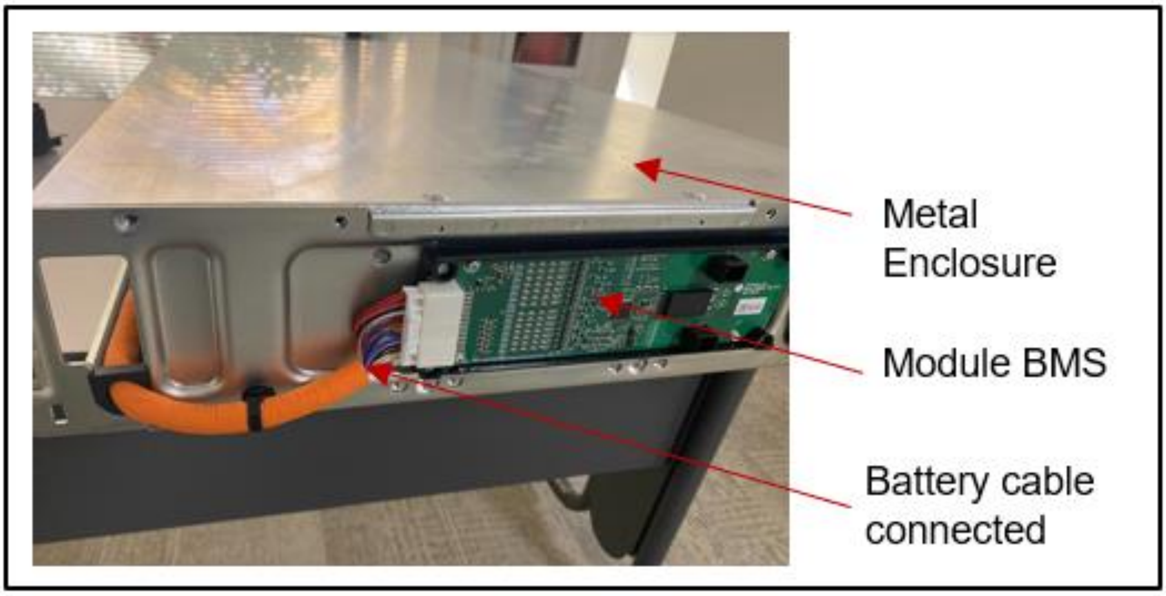


Figure 77*-Internal view of battery module*
Cutesy: Daniel kelly Boakye Danquah @ LGEUS

Increasing the configuration in series will increase the voltage and increasing the configuration in parallel will increase the current carrying capacity of the module configured. When the module is formed, it has multiple components units that comes to make it. The components are the battery cell itself, fans, cables, battery management system (BMS), metal enclosure, fuse, sensors, electronic board. These components are interconnected to make the battery module complete.

Failure in the battery module can either occur during operation of the system, during the installation of the system or during the transportation of the system. Each of the failures can result into catastrophic and devastating fires (Dongsheng Ren et al,.). During battery system operation, there are set bound conditions for the battery to stay in to operate as optimal, these conditions include module to cell voltage too high, cell voltage too low, voltage difference, SoC threshold change high to low, cell temperature high. Once any of these set parameters are exceeded in the operation of the energy storage system, a failure can occur, when this failure occurs, it not only limited to the cell alone, but it tries to cascade into the other adjacent battery module and causes fire if the other secondary fire suppressing mechanism are not able to stop the fire. This secondary fire mechanism includes the battery management system, controller BMS and the EMS, others have the water injection system, Novec as a secondary fire protection system.

Other failure mechanism to the lithium-ion battery is external cause, these are mainly electrical components inside the battery module, this includes fuse, fan, temperature sensors or cable break. The final mechanism is installation and transportation failures, since this happens during transition of the battery from one point to another or during assembling them into the rack, it is mostly mechanical, and their failures are not as devastating as the cell-to-cell failure. Since this is mechanical and mostly caught during the initial start-up, but if it did happen during operation it can be very fatal and devastating. Most of the lithium-ion battery faults occur in the module level and cascade to the other parts of the energy storage system. Since the energy storage system is a built up of cells to module, racks, and system, it is important to control.

5.2.2 SYSTEM LEVEL FAILURE MECHANISM IN LITHIUM ION BATTERY

Energy storage system is a complex integration of components to offer energy stored in batteries/accumulators for later use. These systems are the battery module ,which are configured in racks based on the energy needed by the customer, DC junction box made up of electrical breaker/DC disconnect, AC panel made up of all the electrical circuitry, the inverter which is the power conversion stage, the air conditioner which helps to keep ambient temperature of the lithium ion battery at required temperature, the enclosure that is made up of the system, the Energy management system-which has unit controller as part of it and helps to manage the overall charging and discharging of the energy storage system. The complex web of components present failure point at any point, this could be cell level failures which would make the system stand not to produce energy as design, this could be AC panel which lead to fire break out, this could be faulty air condition which could lead to rise in cell/module temperature and cause battery system to fail, All together, system failure is very difficult to point and control since multitude of factors come together to form energy storage system.

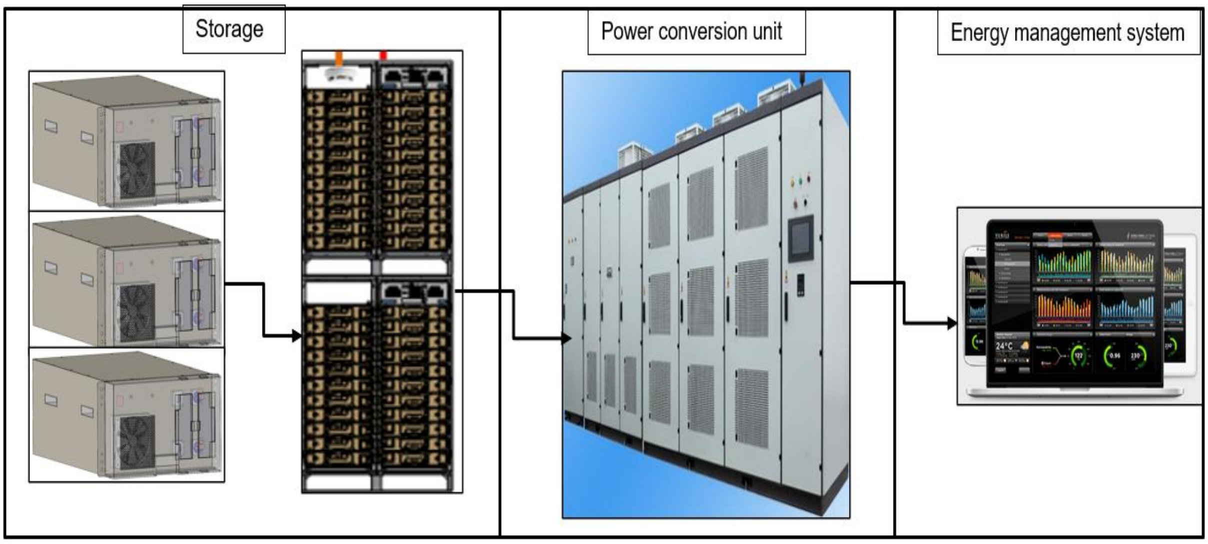


Figure 78*-An overview of real energy storage system structure.*
Curtesy : Daniel kelly Boakye Danquah, University of North Dakota

The main critical pieces of the energy storage system that need to be protected all the time are the battery modules which contain enormous amount energy and can create fire when not taken care of. Protection devices are integrated into the cell, module, and battery systems to prevent abnormalities and cut down on accidents. Current interrupt devices (CIDs), positive temperature coefficient (PTC) thermistors, current-limiting fuses, diodes, battery management systems (BMSs), etc., control the occurrence and intensity of heat and gas.

Moreover, the need for fire suppression systems is getting increasing attention as plans are made to reduce the severity of accidents.   It is against this research; many possible detection methods would be examined and provide one that could adopt to be introduce as a standard to mitigate lithium-ion battery fires.

5.2.3 IMPACT OF LITHIUM-ION BATTERY FAILURE.

Energy storage is emerging as an integral component to a resilient and efficient electrical.

grid in recent years, there has been an increase in the deployment of lithium-ion (Li-ion) batteries in Energy Storage Systems (ESSs). Local authorities having jurisdiction (AHJs) along with ESS integrators and installers are challenged by the lack of clear direction regarding the hazards of these installations. With all new technology comes new risks. What will we need to think about as this battery technology grows? The risk of fire becomes barer and clearer. Technically, when the right technology and safety is employed, batteries will not catch on fire, but they can, through faults inside the battery, or from external damage. And when they do catch fire, the consequences can be serious. There have been many concerns raised by various people on the impact of lithium-ion batteries when they fail, the concern includes: How are Li-ion ESSs different from other battery systems? Do Li-ion ESSs pose a greater fire hazard than traditional batterie e.g., lead acid, VRLA, etc.)? How can Li-ion fires be suppressed? Is water, dry chemical, and clean agent? What are the best practices for firefighters to suppress Lion-ion ESS fires? Do we need additional equipment necessary for putting out these fires? Do we need different tactics/strategies required? Do Li-ion battery ESSs pose additional hazards, such as respiratory or electric shock to first responders compared to traditional fires? What is the cleanup/overhaul hazards? What are the best practices for fire fighters to suppress Lithium-ion ESS fires?

With all these listed concerns, there are many impacts both economic, environmental, and social that the fire risk in failure of lithium-ion battery brings to the society.

The economic impact includes energy storage companies going out of business, since society feels lithium-ion batteries are not safe and will not adopt and invest in them. It will also limit the decarbonization effort, since solar plus storage is the absolute way to harness renewable energy to be free from the use of hydrocarbons. Also, there will be a huge lost in human life, equipment, and other valuable infrastructure, since lithium-ion is found in consumable life phones and computers, so when this fire happens, the tendency to kill human is high. Finally, Lithium-ion fir will impact the reliance on the battery for grid applications. With at said, there are some recommendations that we can do to mitigate fire safety. Lithium-ion batteries are here to stay. The solution is not to throw away anything with a rechargeable battery, but there are steps to take that will minimize the chances of a fire.:

- Don't keep devices plugged in longer than it takes to reach full charge.
- Keep devices at room temperature and do not store devices in windows or in hot vehicles.
- Only use batteries designed and tested for the device in use and approved by UL.
- Do not throw batteries in the trash; instead, take them to a battery recycling center.

5.2.4 INTERNAL SHORT CIRCUIT PREVENTION, LITHIUM-ION BATTERIES

The passive prevention of ISC refers to preventing the ISC, which has already occurred, from further developing into TR and causing more disastrous consequences. At present, the main methods are the suppression of TR propagation and utilizing thermal cut-off batteries and self-destruction batteries. They can be described as follows: Suppression of TR propagation. The main measures of this method include reducing the heat production of cells, optimizing the insulation between cells, and strengthening the heat dissipation (Dongsheng. Ren et al,. 2020). The reduction of heat production of cells is mainly realized by active prevention. For the aspect of optimizing the heat insulation between the cells, the flame-retardant insulation layer can be set between the cells to delay the heat transfer process (Andrew A. et al,. 2015) . The methods of enhancing heat dissipation include air cooling, liquid cooling, and phase change cooling (Zhao. W et al, 2020) . In addition, when the TR propagation becomes unavoidable, spray cooling may be used as a last resort to prevent battery fire or explosion. However, the cost of an active sprinkler is high, and its effect needs further evaluation. Thermal cut-off battery, a layer of positive temperature coefficient (PTC) material can be added between the positive active material layer and the collector. When the temperature exceeds 100°C, the PTC expansion will be triggered, resulting in the separation between the positive active material and the collector, thereby blocking ISC. When the temperature was less than 70°C, the battery would return to normal. Self-destruction battery. Three main technical routes include: (1) The thermally triggered coating is coated on the electrode to block the lithium-ion transport pathway and inhibit TR propagation. Polydopamine (PDA)-coated polyethylene (PE) microspheres were coated on the negative electrode of the battery to realize the function of automatic shutdown of LIBs when the set temperature was reached.

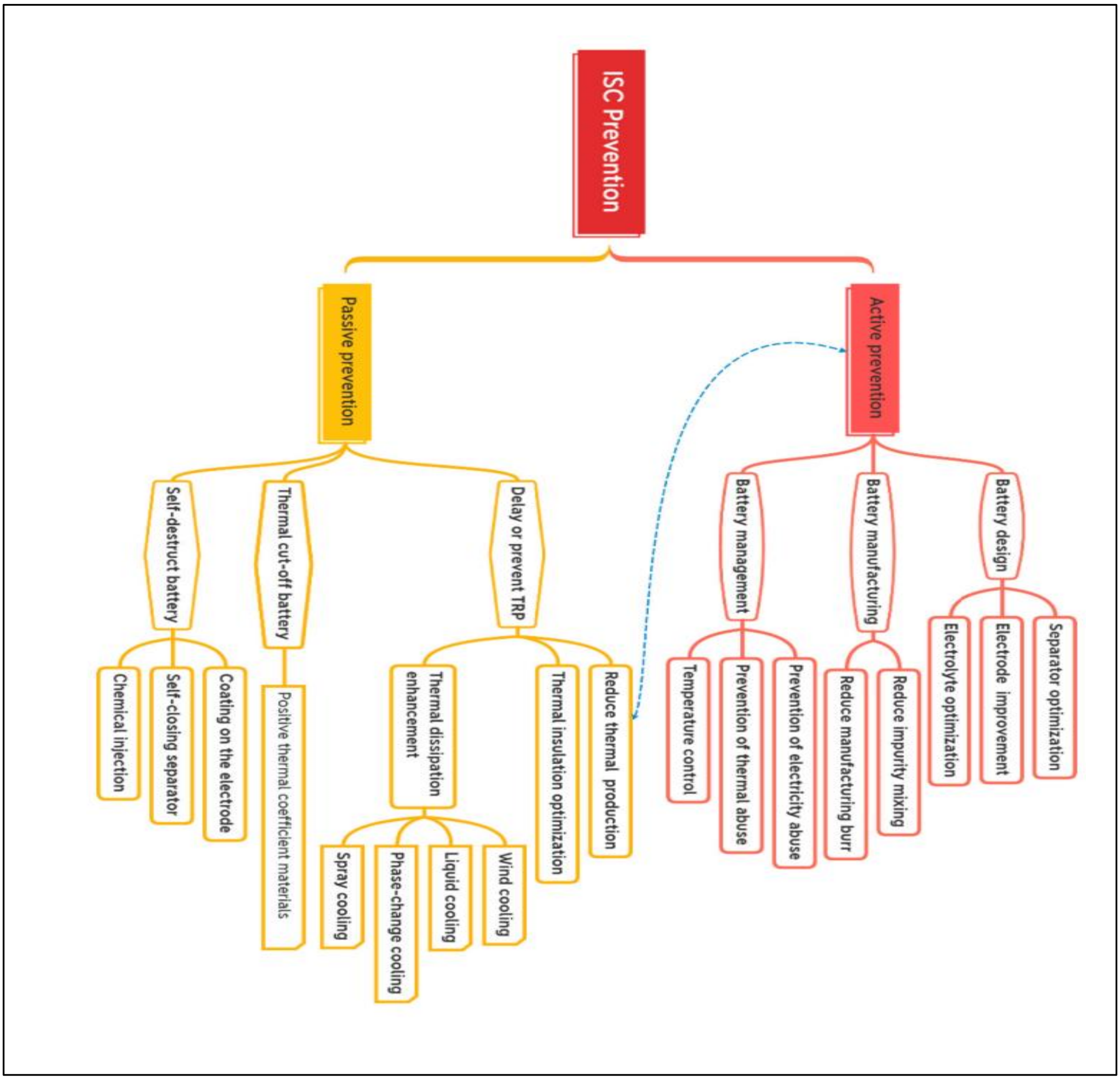


Figure 79 *- Schematic diagram of ISC prevention method.*
Source: Energy storage material ,(W.Yi et al,.2020)

5.2.5 SUMMARY

Several large-scale lithium-ion energy storage battery fire incidents have involved explosions. The large explosion incidents, in which battery system enclosures are damaged, are due to the deflagration of accumulated flammable gases generated during cell thermal runaways. within one or more modules. Smaller explosions are often due to energetic arc flashes within modules or rack electrical protection enclosures. These smaller explosions can either initiate or exacerbate energy storage system fires. Safety is one of the most prominent and concerned problems in the large-scale application of LIBs, and TR is the most common and catastrophic form of battery safety accidents.

The internal short circuit -ISC of LIBs is the common characteristic of TR and is caused by mechanical abuse, thermal abuse, and electric abuse. The detection and identification of ISC in its early and middle stages can prevent ISC from developing into TR, which is of great significance to improve the safety of batteries. Therefore, standards and regulations for lithium-ion storage battery systems should explicitly require protection to prevent and/or control thermal runaways leading to possible deflagrations. Also, there should be imposed measures to limit electrical fault lithium- ion batteries by standardizing battery control unit and limiting the arc flash energy, these new measures may allow modules and other electrical enclosures to withstand otherwise excessive arc explosion pressure.

CHAPTER SIX

6.0 ENGINEERING DESIGN FOR FAILURE DETECTION

6.1.0 DETECTING INTERNAL SHORT CIRCUIT

In terms of ISC detection and identification, I employed multiple temperature sensors in my design. Temperature data acquisition will greatly improve the accuracy of ISC and shorten the detection time. This is because the application of multiple temperature sensors makes it possible to capture more temperature data points and send it to the controller BMS to analyze and control the battery operation. In the ISC early detection method, not only the characteristic parameters of each cell in the battery pack can be compared horizontally, but also the changing trend of the historical characteristic parameters of each cell can be extracted from the rich historical data that I have accumulated for longitudinal comparison, to improve the detection accuracy and robustness and reduce ISC misjudgment.

Figure.80 *- A sub view image of the multiple temperature sensors for detecting temperature change in the lithium module structure.*
Source: Image capture by (Daniel kelly Boakye, UND 2023)

6.1.1- LITHIUM-ION BATTERY MODULE STRUCTURE

After extensive research into the energy storage technologies, identifying a major problem in the industry, indiscriminate fires in the lithium-ion batteries for both residential, commercial, and utility scale battery system, I decide to design this battery module which I have incorporate a safety material, fire retardant material, a honeycomb material, sensors to report various temperature to trigger early detection and protect the battery module from fire propagation., the concept formulation, during the design of the proposed battery module, included various factors which I considered, This includes putting together a design product requirement document, assembly procedure, testing protocol and also how the design of the module can mitigate the fire hazards, I took into consideration the electrical, mechanical, Software consideration, thermal management consideration and testing to validate the energy storage system module.

6.1.2 ENGINEERING DESIGN AND CALCULATION OF BATTERY MODULE

The design of the battery was hinged on multiple calculations, weight of the battery module, heat dissipation, thickness of the fire-retardant material, spacing required for air flow, energy density required by battery module, electrical configuration, overall size of the battery module, space tolerance during operation expansion, temperature at which honeycomb material will melt, and time it will take for full encapsulation of honeycomb material. Also, the type of cable that is used, Battery management system controller, and overall metal material will be required.

6.1.3 BATTERY MODULE CALCULATION

The technology of choice for this research experiment was Lithium-Ion Phosphate, which is a technology that many applications are resulting to use in the energy storage industry right now. The prismatic cell satisfies the demand for thinner sizes and lower manufacturing costs. Prismatic cells make optimal use of space by using the layered approach. There is no universal format for this battery, each manufacturer designs depending on its requirements. In Figure 1, the specification of a prismatic cell is presented. To design a battery module 36 pieces of prismatic cells were used, where 18 cells were in series and two banks in parallel. The schematic of the proposed system is shown in Figure 63.The minimum and maximum cell voltage of a single module are 45 and 65.7 V, respectively.

The cell that I chose for the research design and experiment was 72 Ah, 21.6 A,3.2V, Grade A lithium-ion (LiFePO4). As shown in Table 22. Cell technical datasheet, the configuration for the for the design was as follows to achieve the energy density per the module.

EQUATION:

Total Energy of Module =(Total Cell * configuration *cell V *Max Cell Current)/1 (equ 32)

[16S2P]---Configuration

[16*2*3.2*72]=7.37W.

The energy density of the module is 7.4KW

(i) Technical Specification of the proposed battery cell

.

Cell			
	Parameters	**Value**	**Units**
Size	Weight	1.78	Kg
	Length (max.)	3.1	cm
	Width (max.)	13.6	cm
	Height (max.)	22.18	cm
Voltage	Voltage (charge max.)	3.65	V
	Voltage (nominal)	3.2	V
	Voltage (discharge end)	2.5	V
Current	Constant charge current (max.)	72	A
	Continuous discharge current (max.)	144	A
	C-rate (charge, max)	1 C	-
	C-rate (discharge, max)	2C	-
	Maximum capacity	72	Ah

Table 18 *- Technical Specification of Lithium-Ion cell*
Source: Table and calculation by Daniel Kelly Boakye Danquah

6.1.4 MODULE VOLTAGE CALCULATION

Since the battery module would be used to build a rack for the overall energy application. I considered using the module under 1000V, when module is connected in series, a voltage rise is generated and when connected in parallel, current increases, by Ohms Law.

Rack			
	Parameters	**Value**	**Units**
Size	Weight	961.2	Kg
Voltage	Voltage (charge max)	985.5	V
	Voltage (nominal)	864	V
	Voltage (discharge end)	675	V
Current	Constant charge current (max)	144	A
	Continuous discharge current (max)	288	A
	C-rate (charge, max)	1 C	-
	C-rate (discharge, max)	2C	-
	Maximum capacity	144	Ah

Table 19 *- Technical specification of Lithium-ion battery rack*
Source: Table by Daniel Kelly Boakye Danquah

Engineering Calculation:

Total modules per individual 2U- rack =17 module,

Cell voltage =3.2

Cell totals current=72A

Configuration=16S 2p

Total energy of full module= 7.4 KW

Total Rack Energy density =(Product of all modules parameter/1)

=(7.4*15)=105 KWh.

=Module voltage was =(18S2P)= 18*3.2=57.6V.

Since the system was using 15-modules for 2-U cabinet. overall rack for my system was.

Voltage=Current(I) * Resistance(R)

=(17*57.6) = 979.2

(ii) BATTERY MODULE ENGINEEING CONFIGURATION

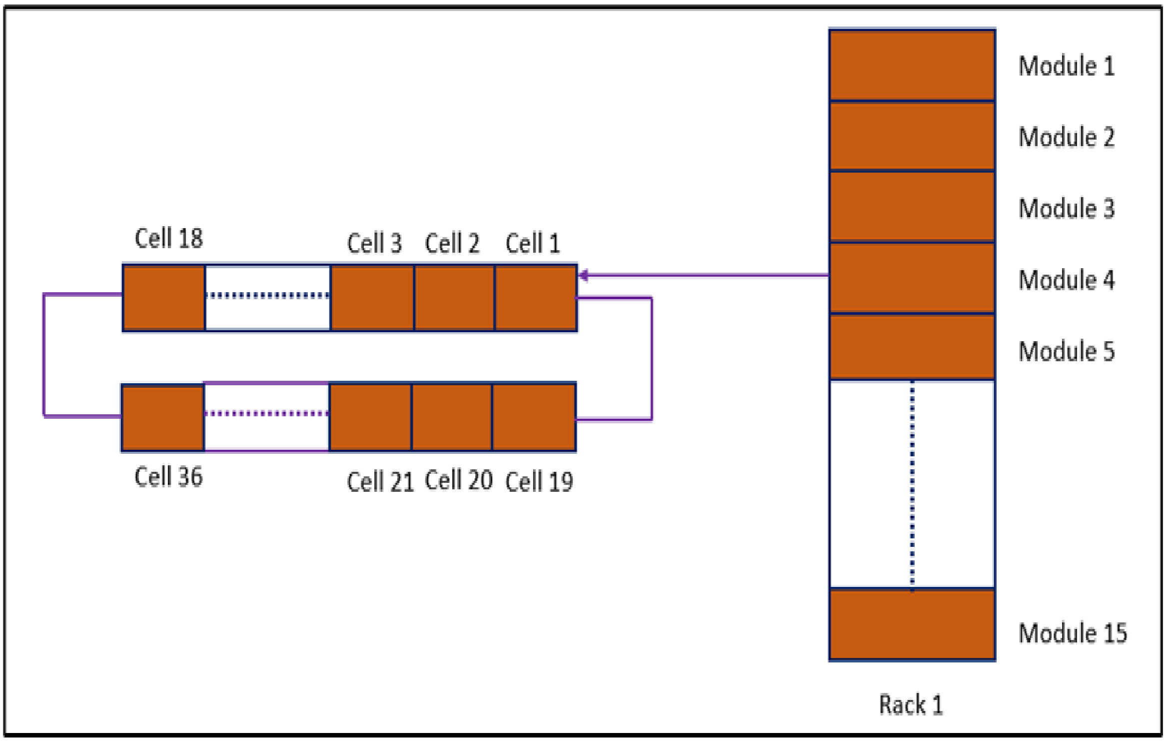


Figure.81*-Electrical configuration of my design for early detection of battery failures*
Source: Table and configuration by Daniel Kelly Boakye Danquah

After all the engineering, voltage and current calculations were completed, the next was to evaluate the mechanical design and how fire retardant and sensors can be implemented to achieve full system results.

6.1.5 - FIRE RETARDANT MATERIAL CONSIDERATION

There are several considerations required when designing energy storage systems to withstand fire propagation at the module level. The power and duration of the battery are determined by its purpose in the project. The purpose in the project is determined by the economic value. The economic value is determined by the market in which it will participate, and that market ultimately determines how the battery will export, what power, charge, or discharge and for how long. The power and duration not only determine the capital cost, but also the lifetime. Fire mitigation at the cell and module level requires a technique to inhibit and contain the spread of fire , a material that can suppress fire and cut oxygen . Deep research was conducted to select the type of required fire-retardant material. The following data points were considered. The weight of the material, standing temperature, material make, coating technology , surface treatment, application, and feature and thickness. These factors play a major role in the material selection since the surface temperature of lithium-ion reaches (180-300)ºC before combustion. The silicone coated fiberglass fabric uses satin weaved fiberglass fabric, coated with special formulated silicone double sides, the silicone coating provides better abrasion resistance, stronger strength to basic fiberglass cloth. It is a multi-purpose fireproof and heat insulation cloth. (Silicone coated fiberglass fabric, 2020) can withstand max temperature to 550°C. It has many good advantages, such as resistance to high temperatures, fire resistance, water resistance, oil resistant, ozone resistant, oxygen aging resistant, good chemical resistance to acids and lye, easy for fabrication and sewing, etc..

The table below shows a technical overview of the fire-retardant material and the application.

TECHNICAL DETAIL OF FIRE-RETARDANT MATERIAL

Brand Name: Suntex
Model Number: SI123-1008
Application: Wall/Roof covering Cloth
Weight: 510gsm
Surface Treatment: Silicon Coated
Width: 0.8m to 2m
Yarn Type: E-glass
Alkali Content: Alkali Free
Standing Temperature: -50°C to +550°C
Processing Service: Cutting
Product name: Heat Insulation Glass Fiber Fabric Fireproof Fiberglass Cloth
Weave: 4H Satin
Coating: One Side Silicone Coated
Thickness: 0.44mm
Colors: Grey
Feature: heat resistant, fire retardant,weatherproof,waterproof
Application 1: Removable Insulation Jacket, Cover, Blanket, Pad, Mattress
Application 2: Fire Blanket, Welding Blanket, Fireproof Curtain, Fire Barrier
Supply Ability

Figure.82 *- An image of fire-retardant material to maintain stop fire propagation.*
Material test conducted by Daniel Kelly Boakye Danquah,2021.
Source: www.suntexfiberglassfabric.com

6.1.6 -METAL HONEYCOMB MATERIAL

The material for the honeycomb was selected based on the following features: The temperature range, thermal conductivity, moisture & corrosion resistance, fungi resistance and light weight. The technology operation of introducing the honeycomb into my design was to expand at an elevated temperature to fill up all the pore of the battery module inlet and outlet air vent to encapsulate the entire module to cut away oxygen from fueling the battery to burn. Per the design of the honeycomb material, (PAMG-XR1 5052 Aluminum Honeycomb) which is a lightweight core material which offers superior strength and corrosion resistance over commercial grade aluminum honeycomb. PAMG-XR1 5052 honeycomb is made from 5052 aluminum alloy foil and meets all the requirements of AMS C7438 Rev A.[91] .

5052 aluminum honeycomb uses include aircraft floors, aircraft leading and trailing edges, missile wings, fan casings, fuel cells, fuselage components, helicopter rotor blades and navy bulkhead joiner panels, energy absorption, air/light directional and EMI/RFI shielding. 5052 honeycomb is suitable for applications where materials conforming to AMS C7438 Rev A are required. The PAMG-XR1 5052 aerospace grade aluminum honeycomb is a lightweight core material which offers superior strength and corrosion resistance over commercial grade aluminum honeycomb. PAMG-XR1 5052 honeycomb is made from 5052 aluminum alloy foil and meets all the requirements of AMS C7438. The PAMG-XR1 5052 honeycomb uses include aircraft floors, aircraft leading and trailing edges, missile wings, fan casings, fuel cells, fuselage components, helicopter rotor blades and navy bulkhead joiner panels, energy absorption, air/light directionalization and EMI/RFI shielding. PAMG-XR1 5052 honeycomb is suitable for applications where materials conforming to AMS C7438 are required. The honeycomb material has remarkable features, this includes elevated use temperatures, high thermal conductivity, flame resistant, excellent moisture and corrosion resistance, fungi resistant, low weight / high strength, long shelf life. The mechanical properties referenced are maintained for 15 years minimum if not exposed to moisture, weather, or any normal hazard.

The material, PAMG-XR1 5052 honeycomb is available in four forms: unexpanded blocks, unexpanded slices, untrimmed expanded sheets and cut to size expanded sheets. It is also available with or without cell perforations to facilitate cell venting for certain applications. The honeycomb material, by design, is to be used to allow circulating cold air into the battery module and act as a passage for hot air to exit the battery module.

A common strategy to improve the flame-retardant performance of the honeycomb material involves the modification of the structure by the addition of micro-sized flame-retardant agents. Several studies in many scholarly literatures have successfully demonstrated improvement in fire reaction properties of composites inclusion of flame-retardant additives (Fanhao Ji et al,.2019) (Chenkai Zhu et al,. 2019) However, the flame-retardant performance of composites is achieved at elevated fire-retardant loading concentrations, while high fire-retardant loadings lead to the degradation in mechanical properties of flame retarded polymer composites(Kandare. E eta al,. 2010). To prevent the issue of fire spread, flame retardant strategies should preclude the inclusion of flame-retardant additives into the honeycomb material.

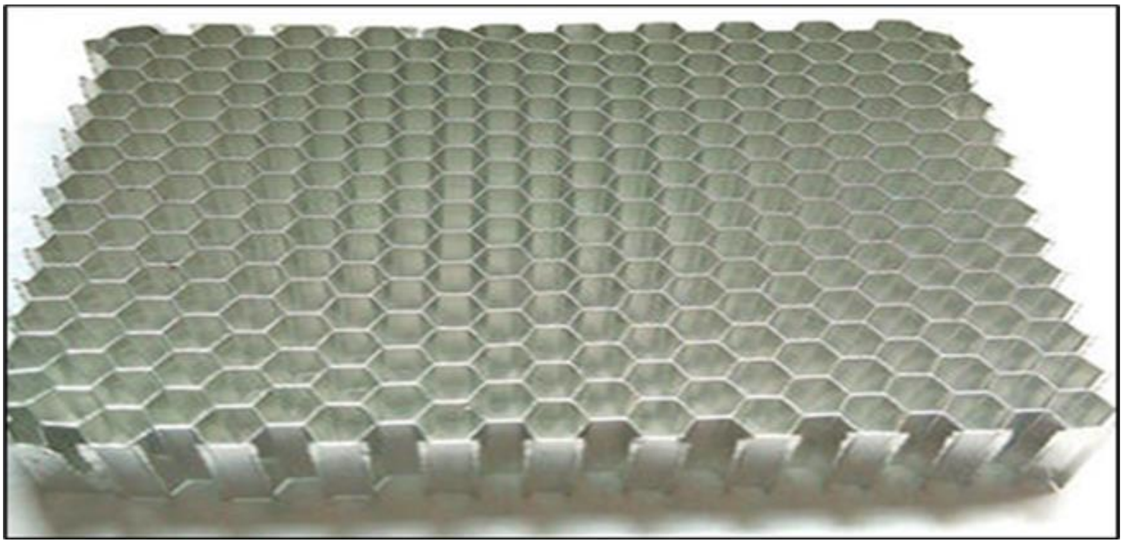


Figure 83*. An image of honeycomb fire material*
Source: : https://www.honeycombcompositepanels.com.

Expandable graphite has been used in numerous applications of fire safety, especially thermal insulators, and intumescent flame retardant for polymer composite (Wu et al., 2012). Expandable graphite (EG) is equivalent to a staged version of a graphite-sulfuric acid salt, i.e., the graphene layers all remain intact while bisulfate ions are intercalated between these layers (Camino. G et al., 1974) . The property of expandable graphite is the tendency to exfoliate when heated at high temperatures beyond a characteristic expansion onset temperature (. It expands rapidly in a worm-like manner to form vermicular graphite, with a low density. (Khalili et al., 2017) who have worked on expandable graphite -EG for polymer composite and compared flame retardant properties of the composite with a surface coating and matrix filling, found that the composites both coated and filled with EG could provide a significant improvement on flame retardant performance. Expandable graphite has features such as high temperature resistance, forms an effective insulating "char" layer that protects the substrate from heat and oxygen, Performance does not degrade with time or environmental exposure, reduces smoke evolution and its expandable temperature is 160°C to 280°C. One of the main applications of expandable graphite is as a flame retardant. When exposed to heat, expandable graphite expands and forms an intumescent layer on the material surface. This slows down the spread of fire and counteracts the most dangerous consequences of fire for humans, the formation of toxic gases and smoke.(Horold. A et al,2017) . The chromated XR1 coating offers excellent protection for honeycomb cores exposed to corrosive environments, meeting the requirements of AMS C7438, CL2.(Horold. A et al 2017) The table below shows the technical information of the honeycomb material.

Cell Size	(1/8-3/8)"
Densities	1.0 pcf-120 pcf
Sheet ''Ribbon" [L]	48''typical- 200 max
Sheet Transverse (W):	96 ''Typical -200'' max
Sheet Thickness (T)	(20/34)'' Max
Tolerance	Length= + 6-0'',Width= + 6-0, Thickness +/- 0.05, Cell size +/- 10%, Density, =10%

Table 20.- *Technical specifications of honeycomb material*
Source: https://www.honeycombcompositepanels.com.

Specification of aluminum honeycomb core:

Item	Unit	Specification								
Cell	inch		1/8"			3/16"		1/4"		
	mm	2.6	3.18	3.46	4.33	4.76	5.2	6.35	6.9	8.66
Side Length	mm	1.5	1.83	2	2.5	2.75	3	3.7	4	5
Foil Thickness	mm	0.03-0.05	0.03-0.05	0.03- 0.05	0.03-0.06	0.03-0.06	0.03-0.08	0.03- 0.08	0.03-0.08	0.03-0.08
Width	mm	≤440	≤440	≤440	≤1800	≤1800	≤1800	≤1800	≤1800	≤1800
Length	mm	≤1500	≤1500	≤2000	≤3000	≤3000	≤3200	≤4000	≤4000	≤5500
Height	mm	1.7~150	1.7~150	1.7~150	3~150	3~150	3~150	3~150	3~150	3~150

Item	Unit	Specification							
Cell	inch	3/8"		1/2"			3/4"		1"
	mm	9.53	10.39	12.7	13.86	17.32	19.05	20.78	25.4
Side Length	mm	5.5	6	7.33	8	10	11	12	15
Foil Thickness	mm	0.03-0.08	0.03-0.08	0.03-0.08	0.03-0.08	0.03-0.08	0.03- 0.08	0.03-0.08	0.03-0.08
Width	mm	≤1800	≤1800	≤1800	≤1800	≤1800	≤1800	≤1800	≤1800
Length	mm	≤5700	≤6000	≤7500	≤8000	≤10000	≤11000	≤12000	≤15000
Height	mm	3~150	3~150	3~150	3~150	3~150	3~150	3~150	3~150

Table 21 *.Technical datasheet for aluminum honeycomb core*
Source: https://www.honeycombcompositepanels.com.

6.1.7 LITHIUM-ION BATTERY MODULE DESIGN

The battery module design took into account, the weight, air-flow and heat dissipation, handling of the system, location of fire retardant material, the thickness of the fire retardant material, the cell configuration, location of the BMS board, location of high voltage busbars, the handling of the module, the anchoring of the sub module, the wire routing, location of multiple temperature sensors, the location of the honeycomb material and the weight of the metal to be used.

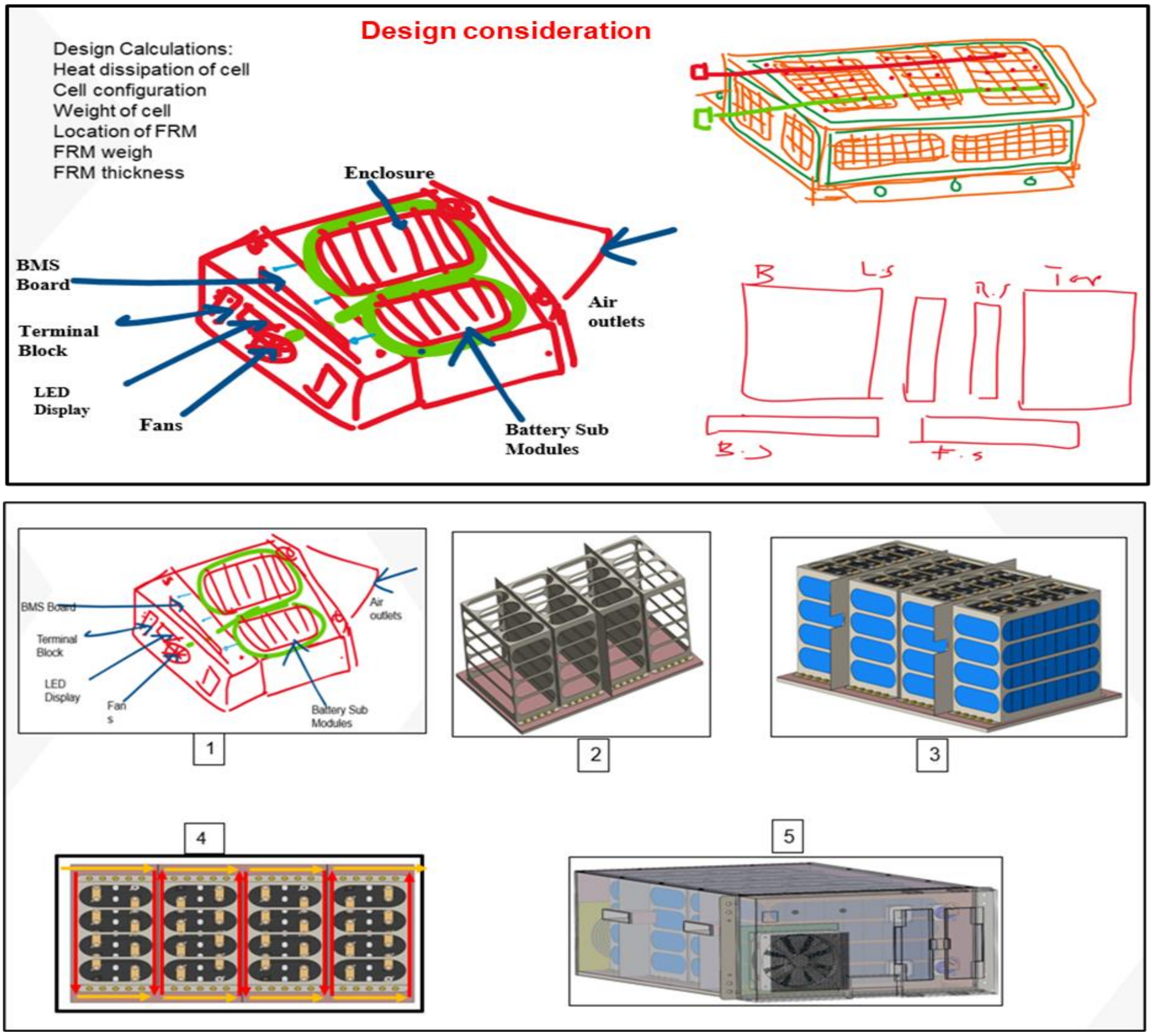


Figure 84. *Illustration of the process of designing the lithium-ion battery*
Source: Curtesy design process by Daniel Kelly Boakye Danquah, 2022.

Observation: A full temperature simulation was conducted to check on the airflow and heat dissipation impact to the cell, the resulting temperature from the simulation proves promising.

6.1.8 LITHIUM-ION BATTERY TEMPERATURE SIUMULATIONS

The experimental research entered a real temperature simulation to evaluate the impact of heat transfer during charging and discharging. Several parameters were considered during this temperature simulation. This includes the following module information found in table 70 below.

Parameters	Boundary Condition
Cell Capacity	144 Ah
Cell configuration	16S2 P
Module voltage	57.5 V
Cell total current	72 A
Total energy of full module	7.4 KWh
Thickness of metal plate	0.2 mm
Fan RPM	1000 RPM
Potential rack energy density	105 KW

Table 22*- Table of parameters for battery modules used in temperature simulation.*
Source: Created by Daniel K B Danquah

As heat is the principal killer of lithium-ion batteries, it was advisable to simulate the entire battery module based on heat transfer equation to understand the impact of adding fire retardant material and non-fire-retardant material under similar operating conditions.

from equation Stefan-Boltzmann (X.N Feng. et al, 2016)

$$\boxed{\rho C_p \frac{dT}{dt} = q_v + \frac{\partial}{\partial x}\left(\lambda_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda_z \frac{\partial T}{\partial z}\right)} \qquad (33)$$

where in the equation (ρ) is the material density, (Cp) is the heat capacity, (qv) is the heat-generating power per unit volume, and (λ) is the thermal conductivity coefficient.

Utilizing equation 36 by and breaking it down to heat transfer by radiation process, given by

$Q=ð(T_{Hot} -T_{Cold}) A.$ (34)

Where, Q is heating transfer, ð is Stefan Boltzmann constant. T_{Hot} is the Hot temperature, T_{Cold} is the cold temperature and A is the Area of the surface of the module.

6.1.9 ENGINEERING CALCULATION FOR ARRIVING AT SIMULATION.

Considering the module under construction for my research to be 50 Kg, with initial cell temperature of 32ºC, and cell temperature change to 55 ºC. Assuming the specific heat loss of battery module is 0.45KJ per Kg K.

From the equation $Q = ð(T_{Hot} -T_{Cold}) A$

$Q = m \times C\, \Delta T$ (35)

$Q = 50 \times 0.45 \times (32-28)$

$$Q = 90 \text{ J.}$$

Hypothetically, the module of 16s2p will generate this amount of heat through the calculation. This helped me in sizing the type of fan, the dimeter of inlet air gaps between cell to cell and the outlet air exit. Figure A and B are deep simulation to understand the impact of fire-retardant material, temperature sensors and honeycomb material on the lithium-ion battery module.

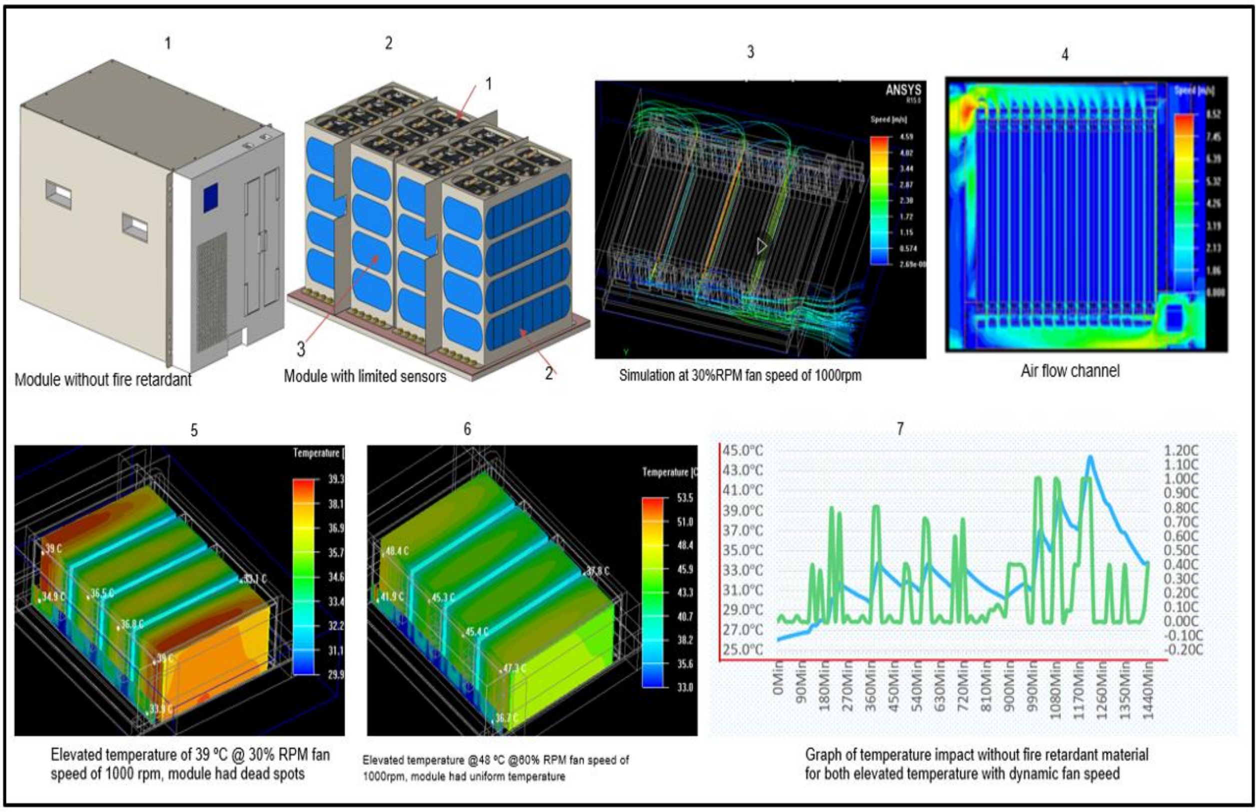


Figure 86 A. *An illustration of lithium-ion battery module without fire retardant with three sensors during simulation.*
Source: Image simulated and created by Daniel Kelly Boakye Danquah, 2022)

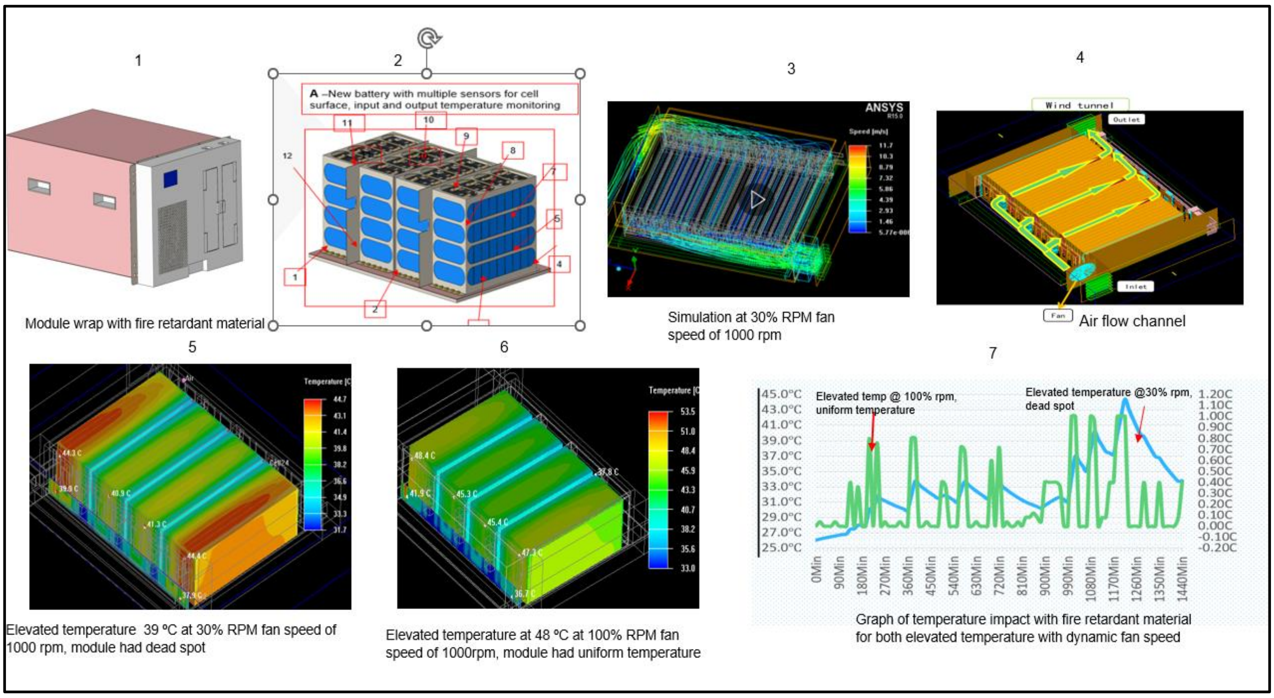


Figure 86 B. *An illustration of lithium-ion battery module with fire retardant and ten sensors during simulation.*
Source: Image created of Daniel Kelly Boakye Danquah, 2022)

Set Point	Air fluid From Front to Back			Air fluid From Front to Back		
	Module without FRM Design-1C @10Mins			Module with FRM Design-1C @ 10 mins		
	T	ΔT(K)	TR max	T	ΔT(K)	TR max
Cell Max	**32.5°C**			**33.°C**		
Cell Min	28.2°C	4.3K	**7.5K**	28.2°C	4.8K	**8.5K**
Air outlet	28.8°C			29.0°C		
Set Poins	Module without FRM- 2C@ 1hr Rest			Module with FRM Design-2C@1hr Rest		
Cell Max	**49.9°C**			**51.0°C**		
Cell Min	36.1°C	13.8K	24.9K	36.1°C	14.9K	27.4K
Air outlet	37.6°C			38.3°C		
Set Points	Module without FRM-2C@ 2h Rest			Module with FRM Design-2C @ 2h Rest		
Cell Max	**44.2°C**			**45.0°C**		
Cell Min	34.1°C	10.1K	19.2K	34.1°C	10.9K	20.0K
Air outlet	34.7°C			35.0°C		
Set Points	Module without FRM Design-3C@10Min Rest			Module with FRM Design-3C/10 Min Rest		
Cell Max	**70.7°C**			**73.0°C**		
Cell Min	46.4°C	24.3K	45.7K	46.4°C	26.6K	**48.0K**
Air outlet	48.6°C			49.7°C		
Fan	P=252.8Pa,Q=50.3CFM			P=252.8.6Pa,Q=50.3 CFM		

Table 22. *Table of simulation without fire retardant material and with fire retardant material to review change in temperature of cell and module.*
Created by Daniel Kelly Danquah

Number	Time	Voltage (V)	Current (A)	Power (kW)	Control Mode	Operating Mode	Highest Cell Voltage (V)	Lowest Cell Voltage (V)	Voltage Difference (V)	Highest Temperature (°C)	Voltage Upper Limit (V)	Voltage Lower Limit (V)
1	2019-11-05 09:27:49.9	99.4901	0	0	Stand by	Stand by	3.191	2.989	0.202	20	138	89.6
2	2019-11-05 09:27:50.9	102.35	0	0	Stand by	Stand by	3.264	3.091	0.173	20	138	89.6
3	2019-11-05 09:27:51.9	104.24	0	0	Stand by	Stand by	3.306	3.158	0.148	20	138	89.6
4	2019-11-05 09:27:52.9	105.526	0	0	Stand by	Stand by	3.334	3.209	0.125	24	138	89.6
5	2019-11-05 09:27:53.9	106.46	0	0	Stand by	Stand by	3.35	3.251	0.099	24	138	89.6
6	2019-11-05 09:27:54.9	107.105	0	0	Stand by	Stand by	3.364	3.281	0.083	25	138	89.6
7	2019-11-05 09:27:55.9	107.584	0	0	Stand by	Stand by	3.374	3.304	0.07	26	138	89.6
8	2019-11-05 09:27:56.9	107.941	0	0	Stand by	Stand by	3.386	3.338	0.048	27	138	89.6
9	2019-11-05 09:27:57.9	108.19	0	0	Stand by	Stand by	3.39	3.348	0.042	29	138	89.6
10	2019-11-05 09:27:58.9	108.406	0	0	Stand by	Stand by	3.394	3.357	0.037	30	138	89.6
11	2019-11-05 09:27:59.9	108.596	0	0	Stand by	Stand by	3.397	3.364	0.033	31	138	89.6
12	2019-11-05 09:28:00.9	108.721	0	0	Stand by	Stand by	3.4	3.369	0.031	32	138	89.6
13	2019-11-05 09:28:01.9	108.838	0	0	Stand by	Stand by	3.403	3.374	0.029	33	138	89.6
14	2019-11-05 09:28:02.9	108.938	0	0	Stand by	Stand by	3.405	3.377	0.028	35	138	89.6
15	2019-11-05 09:28:03.9	109.044	0	0	Stand by	Stand by	3.407	3.381	0.026	35	138	89.6
16	2019-11-05 09:28:04.9	109.105	0	0	Stand by	Stand by	3.409	3.384	0.025	34	138	89.6
17	2019-11-05 09:28:05.9	109.199	0	0	Stand by	Stand by	3.412	3.389	0.023	33	138	89.6
18	2019-11-05 09:28:06.9	109.294	0	0	Stand by	Stand by	3.413	3.391	0.022	32	138	89.6
19	2019-11-05 09:28:07.9	109.307	0	0	Stand by	Stand by	3.415	3.393	0.022	30	138	89.6
20	2019-11-05 09:28:08.9	109.374	0	0	Stand by	Stand by	3.416	3.395	0.021	28	138	89.6
21	2019-11-05 09:28:09.9	109.43	0	0	Stand by	Stand by	3.417	3.396	0.021	26	138	89.6
22	2019-11-05 09:28:10.9	109.462	0	0	Stand by	Stand by	3.418	3.398	0.02	25	138	89.6
23	2019-11-05 09:28:11.9	109.508	0	0	Stand by	Stand by	3.42	3.4	0.02	25	138	89.6
24	2019-11-05 09:28:12.9	109.537	0	0	Stand by	Stand by	3.42	3.401	0.019	25	138	89.6
25	2019-11-05 09:28:13.9	109.578	0	0	Stand by	Stand by	3.421	3.402	0.019	26	138	89.6
26	2019-11-05 09:28:14.9	109.626	0	0	Stand by	Stand by	3.423	3.404	0.019	27	138	89.6
27	2019-11-05 09:28:15.9	109.65	0	0	Stand by	Stand by	3.424	3.405	0.019	29	138	89.6
28	2019-11-05 09:28:16.9	109.691	0	0	Stand by	Stand by	3.425	3.406	0.019	30	138	89.6
29	2019-11-05 09:28:17.9	109.704	0	0	Stand by	Stand by	3.426	3.407	0.019	31	138	89.6
30	2019-11-05 09:28:18.9	109.743	0	0	Stand by	Stand by	3.426	3.408	0.018	33	138	89.6
31	2019-11-05 09:28:19.9	109.779	0	0	Stand by	Stand by	3.427	3.409	0.018	34	138	89.6
32	2019-11-05 09:28:20.9	109.795	0	0	Stand by	Stand by	3.427	3.41	0.017	234	138	89.6

Table 23. *-The table of simulated lithium-ion battery module for two scenarios, A for module without fire retardant material and Honeycomb material, and B, Simulation of temperature impact on module with both fire-retardant material and honeycomb. (Created by Daniel K B Danquah, software used ANSYT ,2022).*

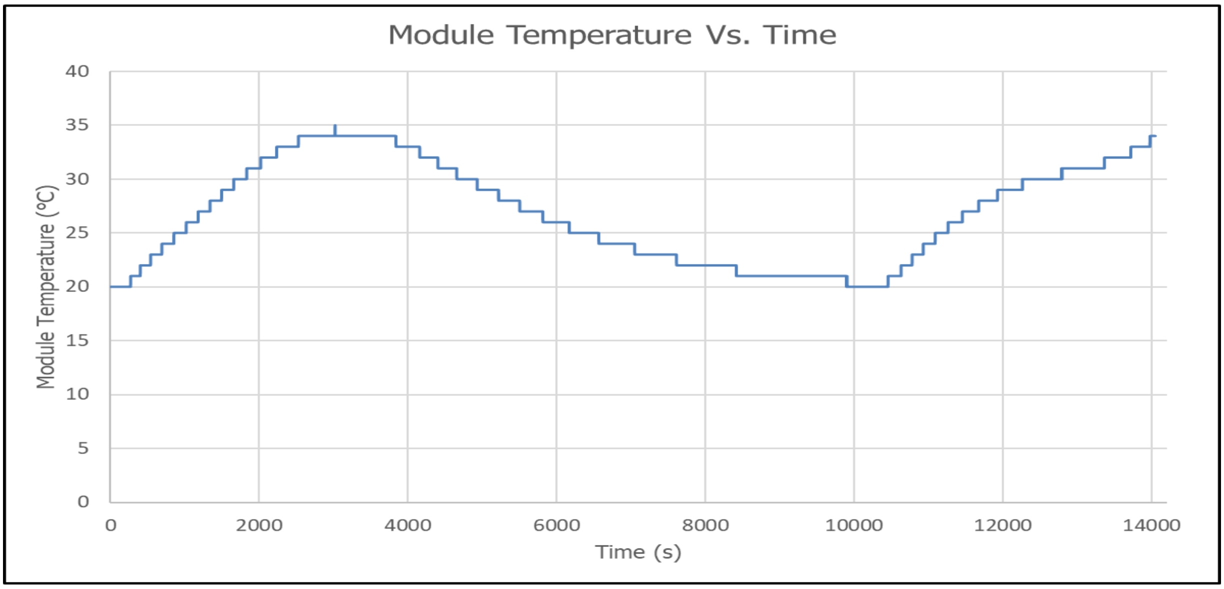


Table 25- *Table and graph of temperature impact on Battery module during charging and discharging.(Created by Daniel K. B Danquah, 2022)*

6.1.9 ANALYSIS OF SYSTEM SIMULATION RESULTS

The results from both temperature simulation from fig 68 (A), 68 (B) provide me with a clear result about the impact of temperature to the battery module, when the fire-retardant material, honeycomb and the multiple temperature sensors were introduced. In figure 68(A)

when the module was simulated at elevated temperature at 39 ºC, there were couple dead spot at the edge of the submodule, the fan speed was increased to 30% RPM to dissipate the built-up heat, as the module temperature increased to 48 ºC, the fan speed was increased to 60% RPM, this was done to achieved complete heat built up dissipation from the module. In scenario B, when fire retardant material, honeycomb and to-temperature sensors were introduced into the module, the at the same temperature condition, when the module temperature was elevated to 48 ºC, the fan was increased to 100% RPM, this happen as a result of the thermal insulating material obstructing some of the airflow in to the module, The tradeoff of introducing the fire retardant material is little obstruction of cold air into the battery module, this results in fan operating at higher RPM during operations at elevated temperature. The issue can be reverted by changing the type of fan to introduce a bigger fan with higher RPM to bring in more air to cool the module during elevated temperature. From the simulation. It is obvious that having multiple sensors will be able to record and alert the battery management system to shut down the battery operation to avoid further battery failure. The simulation provided a true result that, introducing the fire-retardant material and honeycomb did not necessarily negatively impact the operation of the battery module, as there was adequate airflow in the module to dissipate any potential built up of heat in the cell surface. The Delta in temperature from first module without fire-retardant material and the second module with fire-retardant material was not very big as presume. Figure (69) in appendix shows the two scenarios of temperature deviation for the two modules in the same operating conditions.

6.2.0 MECHANICAL RESOLUTION OF LITHIUM-ION BATTERY FAILURE

Choice of application mode without leaving any additional environmental burden either to lan d or the atmosphere.(Sravan.B et al, 2018.)

In my research to overcome the issue of fire propagation at the battery module level, A high rated fire-retardant material was used to provide a lamination in the metal enclosure. This will serve as a fire barrier to prevent the spread of fire from one module to another. From my design, the battery module has 4-sub modules, strap together by a firm and skeletal metal membrane, this gives the module absolute stability and firmness to the battery module during operation and in an abnormal vibration condition. Also, there is honeycomb material. with silicon and graphite impregnated chemical, expandable graphite which has the tendency to exfoliate when heated at high temperatures beyond a characteristic expansion onset temperature. The expandable graphite in the honeycomb material expands rapidly in a worm-like manner to form vermicular graphite, with a low density. (Khalili et al.2018). Expandable graphite has features such as high temperature resistance, forms an effective insulating “char” layer that protects the substrate from heat and oxygen, Performance does not degrade with time or environmental exposure, reduces smoke evolution and its expandable temperature is 160°C to 280°C . One of the main applications of expandable graphite is as a flame retardant.

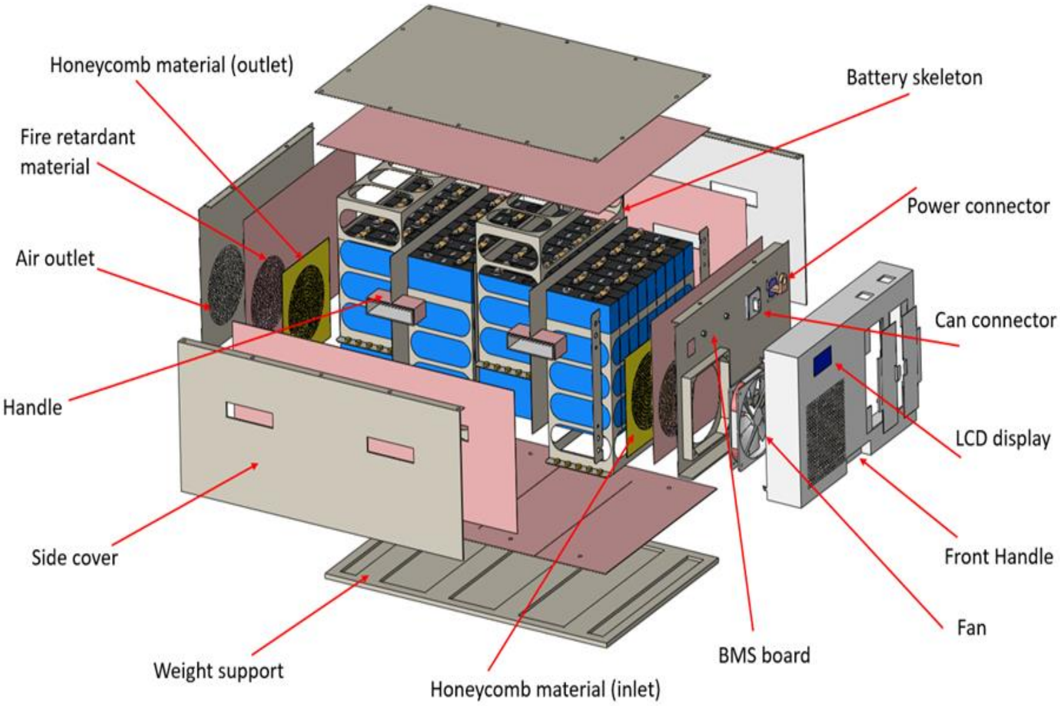


Figure 88. *An Overview of lithium-ion battery module with fire retardant material.*
Source: Designed by Daniel Kelly Boakye Danquah

When exposed to heat, expandable graphite expands and forms an intumescent layer on the honeycomb material surface. This will encapsulate the complete battery module and cut of supply of oxygen , since during abnormal battery operation such as high current that leads to battery electrolyte decomposition that results in temperature rise, the three main catalyst for fire explosions are oxygen, heat, and fuel. Once oxygen is removed from the combustion process, fire engulfment cannot continue to burn, this will suddenly curtail the spread of the fire. The technique of using fire blanket by firemen to subdue fire has been in use for long years and the concept employed in this application is similar, what makes this unique is the ability to have both honeycomb material impregnated with silicon and graphite material and fire-retardant material wrapped around the entire battery module to cut-off oxygen to stop further fuel to the battery module when it gets into combustions stage.

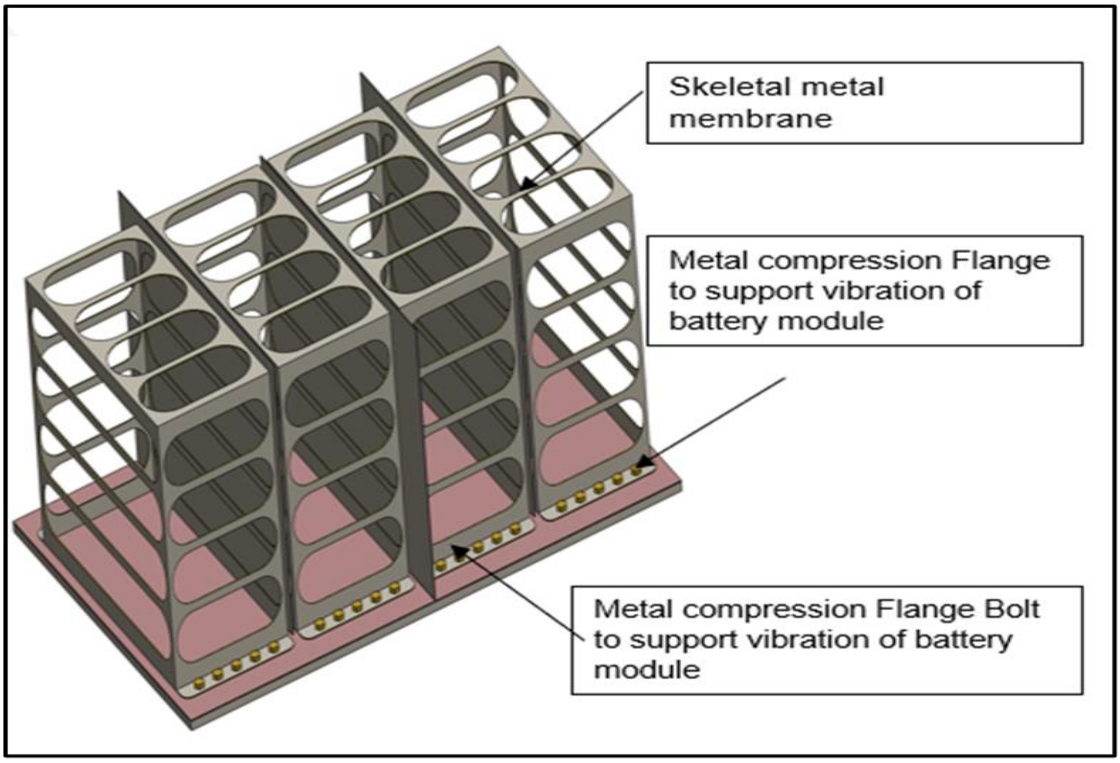


Figure 89. *An Overview of lithium-ion battery module skeletal structure.*
Source: Designed by Daniel Kelly Boakye Danquah

Research Question #3 Hypothesis

Introducing mill graded compression flange bolt and lug tight sealant on battery module and in rack reduce vibration shock in assembled battery module while in transit.

Test My Hypothesis-

Operation of the mill graded compression flange bolt and lug tight screw with sealant have been utilized in the military application for very long time but has not been introduce in the Lithium-ion battery industry. Flange bolts have a circular flange under the head that acts like a washer to distribute the load. These types of heavy-duty bolts have been used in automotive applications, plumbing, military equipment and more (Bing, 2022). Flange bolts feature a washer-like flange beneath the bolt head that speeds production time and distributes the clamping load, offering protection to the mating surface. To ensure a reliable, long-lasting connection between two sections of a large and enclosed area you will need to use a flange bolt. The best example, in this case, is the connection between the transmission and the engine in a vehicle.

Figure 90*. An image of flange compression bolt for securing the battery submodule to the base of the enclosure.*
Source: (engineeringchoice.com)

To maintain structural integrity of the battery module and avoid any potential lose joints that can cause short circuit during transport or in bad environmental conditions, structural analysis was done to establishes the relationship between an enclosure structural plate and expected external load of the battery module and the structure's corresponding developed internal stresses and displacements that occur within the enclosure when in service.

By applying the work-energy principle in structural engineering, as work is defined as the product of the force and the distance traveled by the force, while energy is defined as the ability to do work. Work can be transformed into various energy, including kinetic energy, potential energy, and strain energy (Felix Udoeyo, source content). In the case of a structural system, based on the law of conservation of energy, work done W is equal to the strain energy U stored when deforming the system. This is expressed mathematically as follows:

$$W=U \qquad \text{Equ 36}$$

$$DW=Fd\Delta$$

$$dW = Fd\Delta$$

The total work done is represented as follows:

$$W = \int_0^\Delta dW = \int_0^\Delta F d\Delta \qquad \text{Equ 37}$$

Thus, the strain energy is written as follows:

$$U = \int_0^\Delta F d\Delta$$

$$U = \frac{1}{2}F\Delta \qquad \text{Equ 38}$$

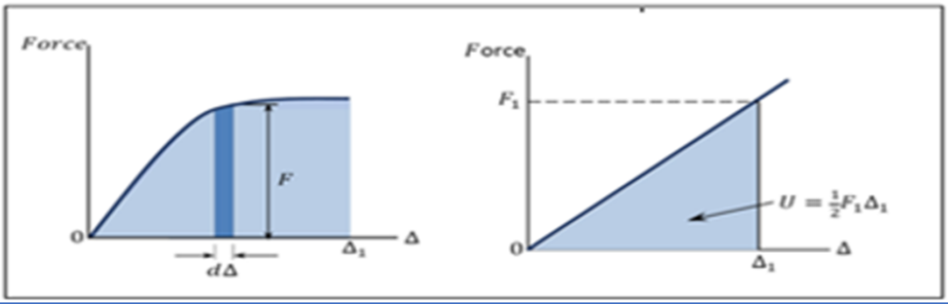


Figure 70*- An equation illustration of Newton second law, in application to weight and spread of force in the battery module.*
Source: https://www.eng.libretexts.org./Bookshelves/Civil_Engineering/Structural_Analysis)

After careful design consideration, such as the weight of the steel metallic material for the skeletal support, the weight of the flange bolt, the weight of the plate, weight of the battery module and vibration force, the weight of cables and BMS in the enclosure. A lab experimental vibration test was conducted to confirm the structural integrity of the skeletal weight of the membrane. The result after 5 minutes was successful. The lab experimental result supports the claim that, when the full module is built and lug tight with mill grade at 10 NM per bolt and supported with felt tape strap to bind all submodules together. Modules built to these standards will be able to support factory assembly and be able to be transported to site without disassembling the module for transportation.

6.2.1 SOFTWARE RESOLUTION OF BATTERY FAILURE

Research question # 3 Hypothesis

Introducing multiple sensors and writing high precision and fast acting algorithm in battery module BMS to alert and open contactors can stop further operation of batteries.

Software plays a key role in the operation and safety of the lithium -ion battery system, either by charging and discharging the battery pack, either for simple application such as mobile phone use or in a complex application such as large-scale utility energy storage system . My research employs the use of multiple precision sensors-thermocouples into the various cell surfaces to read and report the temperature of the battery cells which are above the set points in the battery module BMS. The module BMS will intern relay the temperature readings to the battery controller BMS to open all contactors and relays to stop operation for further failure.

The architecture of my research resolution with the software control to detect early fire in lithium-ion batteries was unique. As many researchers and battery engineers have tried with different software algorithm to resolve the problem, my technique to resolve the problem used the classical approach to capture data, process the data and use algorithm to determine the status and disengage the operation of the relay.

6.2.2 OPERATION OF SOFTWARE CONTROL TO RESOLVE FIRE DETECTION

The key algorithm of the battery system is used as a standard program interface function in my application layer to facilitate the project software I develop to easily implement the control strategy. The application software layer will take the battery parameters such as total voltage, total current, cell voltage, temperature, etc. by calling the relevant functions of the basic software layer and performs the issuance of control commands. Figure 89, illustrate the block design of the battery cells connected in series to multiple temperature sensors to report the status of the battery cells to the module BMS which will relay the information upstream to the rack controller for further storage and protection controls.

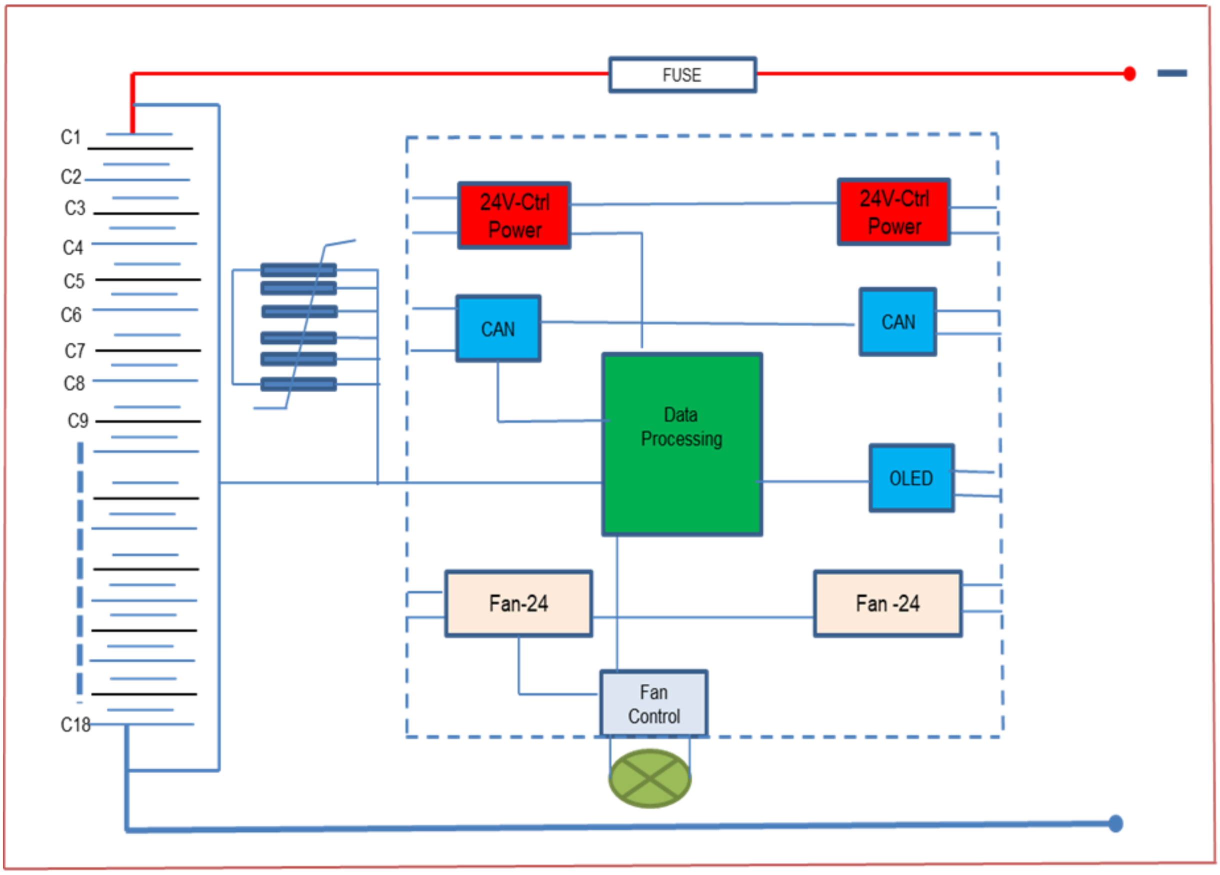


Figure 91. *An electrical design of the battery module with multiple sensors for control and detection*
Source*: written by Daniel Kelly B Danquah. 2022*

The battery management system employed in the battery will utilize system application software layer that will includes single voltage detection, temperature detection, total voltage detection, current detection, insulation resistance detection and supply voltage detection. management, thermal management, high voltage power-on management, charge management and SOC, Subsystems, and modules such as SOH and SOF estimation modules. The table below shows the algorithmic chart for the software control and early detection of failure.

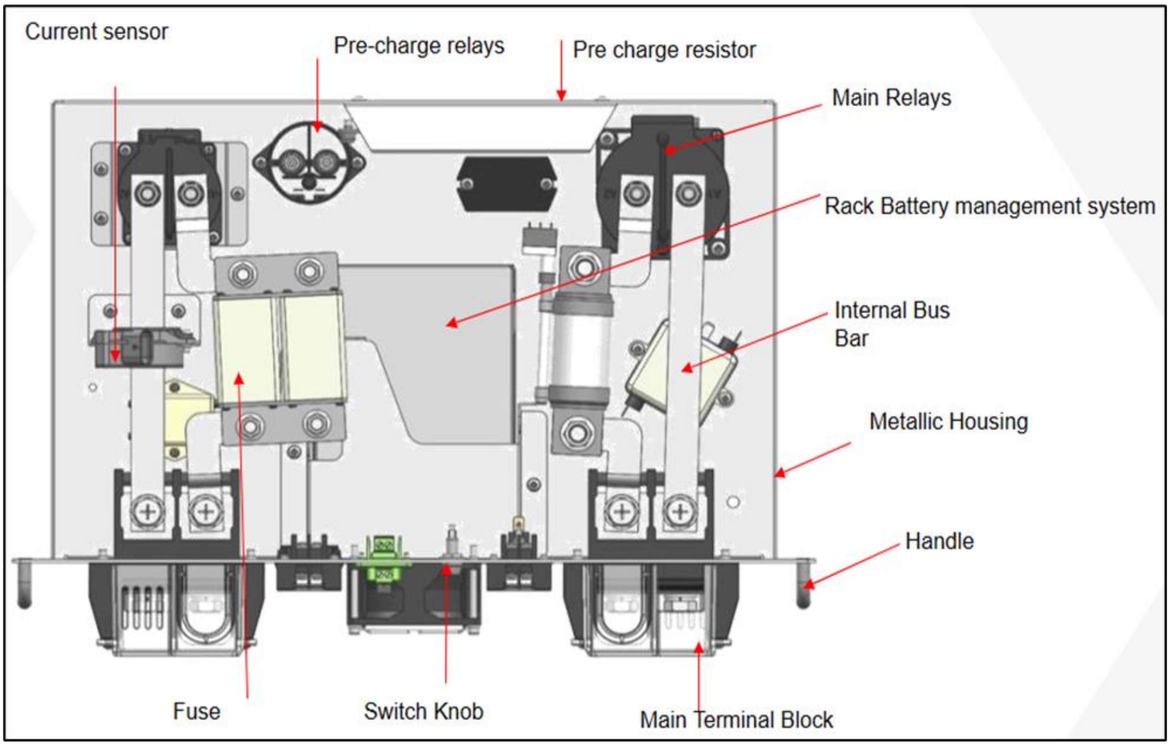


Figure 92. *Internal view the battery Controller*
Source: Designed by Daniel Kelly Boakye Danquah

Code N# API	Application Layer	Algorithm Operation	Initializing Task
Application software layer (C+)	Single voltage detection	Set over-voltage, under-voltage threshold;	Cell execution Module-High/Low
	Total voltage detection	Set over-voltage, under-voltage threshold;	Detection of threshold
	Multiple Temperature detection	Periodically detection interface function: periodically reading the temperature value, and updating the collected temperature value to the battery BMS module	Detection and repotting – Max/Min
	Insulation resistance detection	Fault alarm is reported according to the magnitude of the leakage resistance value and max charge voltage	Detection of set points
	Supply voltage detection	Periodically detection interface function: periodically read the internal and external total voltage	Sampling of voltage

	Current detection	Real-time monitoring of module failures;	Detection and reporting
	Thermal management	Use sensor for heat dissipation control and fan status	Detection and execution
	Charge management	Real time detection of the current of battery system-Highest and lowest	Balancing
	SOC Detection and estimation	It will use Amp hr. integra-charge and discharge	Detection and execution

Table 26. *A table of software algorithms for control and early fault detection .*
Source: written by Daniel Kelly B Danquah. 2022

6.2.2 BATTERY MANAGEMENT SYSTEM ALGORITM AND CONTROL

The battery management system is the controller of the battery and this records, computes, and store data in the memory of the battery and makes decisions to control the operations of the battery. It has single cell voltage detection that will operate to detect early failure by using microprocessor chip LTC6811.(Texas Instruments). The LTC6811 microprocessor is mainly used as a single-cell voltage detection chip. Each chip detects up to 12 strings of cells, and the communication interface with the microprocessor unit (MCU). For the chip to achieve single-cell detection, the chip initialization process and the main detection process must be implemented as follows per manufacture set points. The Initialization process enables the reference voltage and the software timer to select the conversion mode. This will set over-voltage, under-voltage threshold, Turn off the balancing switch and balancing timeout for all channels. To detect the voltage of the battery module, the following settings will need to be executed. The conversion of the ADC board must be initiated and wait for the conversion to complete, once completed, the following readings will be observed in the cell register:

Read the register value of the cell voltage group A, B,C and D

Once these registers are read, then we can move to the main to detection of power supply,

The module has the real-time detection function for each module battery management system (MBMS) and rack controller supply voltage, it uses the MCU's own ADC module to detect the supply voltage and updates it to the system status module. The resolution of the supply voltage detection is 0.1V. To achieve the above objectives, the function items implemented by this module are as follows, Once the BMS has been able to detect the voltage of the battery module, there are other functions that needs to be initialized, this includes Initializing the interface function. This function on the BMS will initiate a Periodic detection interface function periodically to read the supply voltage of the rack controller or MBMS board and update it to the system status module, Output version information of the module. Once that stage is completed. Temperature Detection is another critical function that the BMS will perform. The module performs the temperature detection function at different detection points within the battery pack, using multiple thermocouples inserted in between the cells and configured.

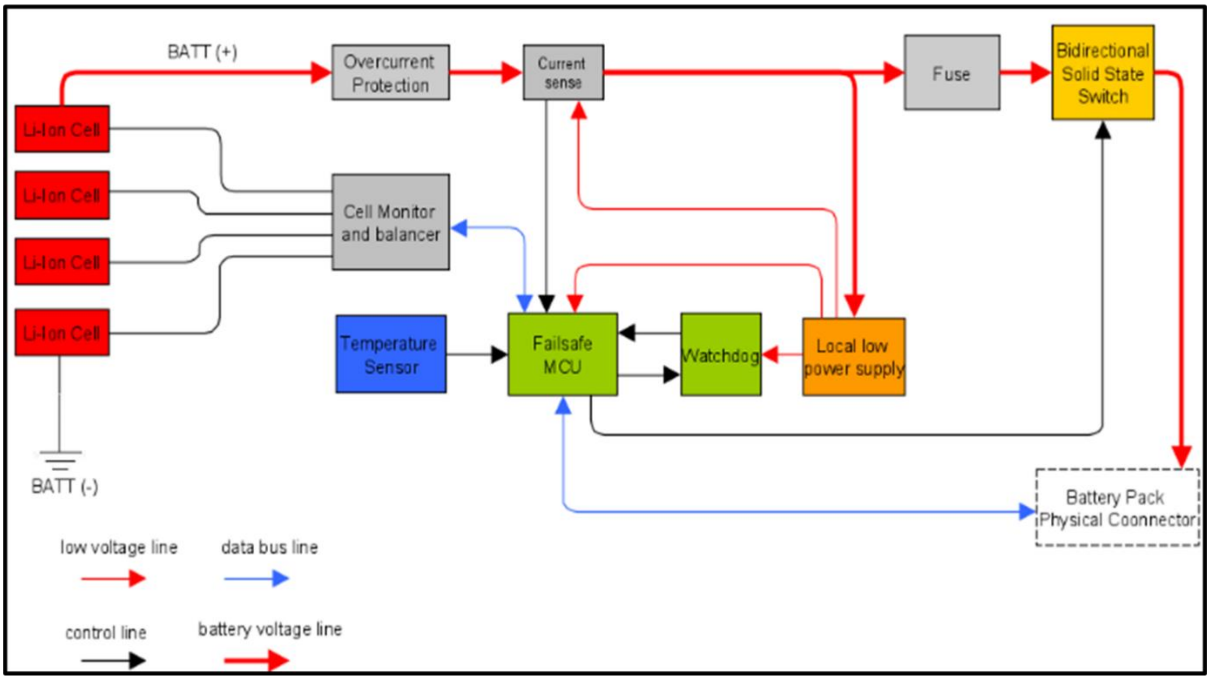


Figure 93*. This illustrates the structural appearance of the battery management system block diagram: this is used in the battery. nodule for energy storage system (Daniel kelly Boakye Danquah,2023)*

To realize the battery pack temperature collection function, this module needs to design the following functions: Initialize interface function is used to initialize the parameters required for temperature acquisition.

- ❖ Periodic detection interface function: periodically reading the temperature value and updating the collected temperature value to the battery BMS module.
- ❖ Version read interface function: used to output the version information of the module.

To achieve total voltage detection, The battery module implements periodic detection of the internal and external total voltage of the battery pack. At power-on initialization, the gain and offset of the voltage obtained from the normal voltage measurement (NVM) are used for the calculation of the actual total voltage; during the operation of the system, the gain and offset can be modified in real time by the host computer. A version read interface is provided.

To achieve the above target functions, this module needs to perform the following function design, Initialize the interface function: read the gain and offset from the (NVM) and initialize the chip. Periodic detection interface function: periodically read the internal and external total voltage and update the total voltage information of the battery.

6.2.3 CURRENT AND SAFETY DETECTION BATTERY MODULE

The design of the algorithm is such that when the module realizes the detection of the charging current and the discharging current of the battery pack. When the detection result is positive, the detected current is the discharging current, and when the detection result is negative, the detected current is the charging current. The detected current can be used for battery real-time power calculation and ampere-hour integration estimation. To achieve the above target functions, this module needs to perform the following function design:

1. Initialize the interface function: read the gain and offset from the NVM and initialize the chip.
2. Periodically detection interface function periodically reads the real-time value and average value of the current and updates it to the current information of the battery.
3. Parameter calibration interface function: used for calibration of shunt gain value and offset value and saved to NVM.
4. Real-time monitoring of module failures.
5. Version read interface function: Output version information of the module.

6.2.4 INSULATION RESISTANCE DETECTION AND CALCULATION

The main function of this module is to calculate the insulation resistance value periodically according to the voltage signal and total voltage of the sampling resistor, to perform the fault alarming function, this module performs the following functions: Fault type determination: the system changes the topology of the resistor network by controlling the combination of the closed and open states of the switch. According to the voltage signal on the sampling resistor, it can determine whether it is single-ended leakage, double-ended leakage, or not. to perform the Insulation resistance calculation, this will be done based on the type of fault, the voltage signal and the total voltage on the sampling resistor, an independent equation can be designed, and then the magnitude of the leakage resistance can be calculated.

Fault alarm: The insulation fault is reported based on the magnitude of the leakage resistance value and the maximum allowable total charging voltage.

The main function of this module is to periodically perform the control and execution functions of battery pack balancing calculation, balancing on, balancing stop and forced clear according to the current state and operating conditions of the battery pack, and control the balancing time. To achieve the above objectives, this module performs the following function: Balancing command transmission: send balancing calculation, balancing on, balancing stop, and forced clear command according to the current state and operating conditions of the battery pack. Balancing command execution: Receive balancing command, perform balancing calculation, balancing on, balancing stop, and forced clear operation according to command and battery status. Balancing time control: During balancing calculation, the required balancing time is calculated. When the balancing is turned on, the battery balancing time is set and controlled.

6.2.5 CHARGING MECHANISM OF CONTROLLER

The charging and discharging of the battery system is based on an algorithm programmed into the control board processor. The main function of this module is to send the status information parameters of the battery system to the Advanced Control Unit (ACU) and execute the charging control commands issued by the advanced control unit. A real-time detection of the current of the battery system is achieved when the charging current reaches the set alarm threshold and alarm information for decision making is triggered.

Also, the charging power calculation for real-time charging power of the battery system according to the charging voltage and charging current of the battery system is achieved when the charging power reaches the set alarm threshold and alarm information for Advance Control

Unit decision is also triggered. The highest/lowest cell voltage detection calculates the highest and lowest cell voltages based on the detected cell voltage values of each cell. When the highest cell voltage reaches the set alarm threshold, information to advanced control unit-(ACU) of decision-making charging command execution: After the RMSC sends the battery system status information to AUC,(the ACU decides to charge or stop charging according to the battery system status. PCS status and its own status, and delivers the determined charging control command, RMSC The command is executed by closing or opening the relay after receiving the charge control command. (Texas Instrument,2022).

Thermal Management. The thermal management of the battery pack mainly refers to heat management, and the functions include heat dissipation control and fan status detection. The purpose of battery pack thermal management is to control the battery pack to work in a suitable temperature environment to maximize battery performance.

High-voltage power-on and power-off management means that the BMS controls the high-voltage power-on and power-off of the battery system according to the state of the battery system. It mainly includes condition determination for allowing high voltage power-on, control of high-voltage relay, detection of high-voltage relay status, life update, fault diagnosis of high-voltage power-on failure, and condition determination of high voltage power off.

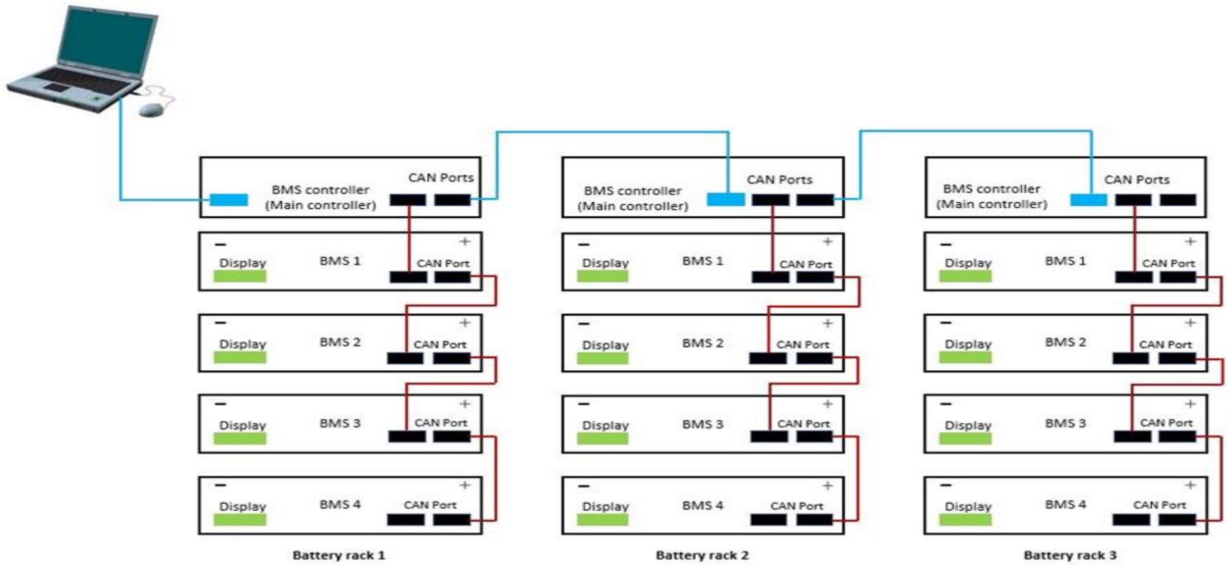


Figure 94. *An illustration of communication topology of the battery management system. Source which uses three tier topology system : Designed by Daniel Kelly Boakye Danquah, March 2023).*

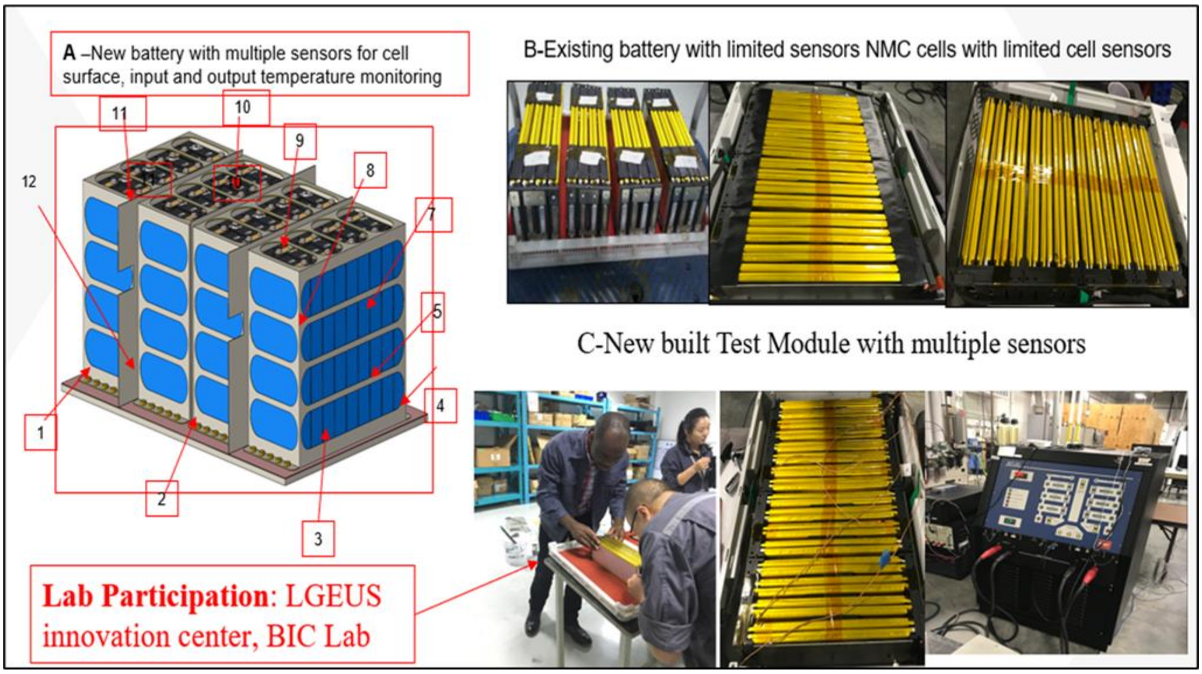


Figure 95 *. A stage process of building and assembling the battery module to introduce multiple thermocouples to read various temperature points. Source : DFD lab in Jouzu, China, Daniel kelly Danquah, November,2020)*

6.2.6 FAULT AND ALGORITHM OF BATTERY MANAGEMENT SYSTEM

The battery management system (BMS) monitors the state of the battery during the use of the energy storage power station in real time to ensure the safety of the battery use process and improve the battery use efficiency, thereby prolonging the battery life. More importantly, the BMS accurately evaluates the battery usage status in the battery pack, and the battery information can be accurately provided to the energy storage system control center for more scientific and rational decision-making, control, and protection. The battery module system based on the design algorithm to detect failure will utilize fault alarms to a single cell voltage that is too high/low, temperature too high/low, total voltage too high/low, pressure difference too large, temperature difference too large, charge current too high, discharge current too high , Insulation is too low, single voltage collection disconnection, temperature collection disconnection and other 10 categories 35 fault alarms.

Fault alarm items			Level		
Failure category	Fault types	Failure form	Level I	Level 2	Level 3
Battery Failure Mode	Cell voltage	Over voltage	❖ √	❖ √	❖ √
		Under voltage	❖ √	❖ √	❖ √
		Module voltage variance	❖ √	❖ √	❖ √
		Rack voltage variance	❖ √	❖ √	❖ √
	Total voltage	Over voltage	❖ √	❖ √	❖ √
		Under voltage	❖ √	❖ √	❖ √
	Temperature	High temperature	❖ √	❖ √	❖ √
		Low temperatures	❖ √	❖ √	❖ √

		Module temperature variance	❖ √	❖ √	❖ √
		Rack temperature variance	❖ √	❖ √	❖ √
	Current	Over charge current	❖ √	❖ √	❖ √
		Over discharge current	❖ √	❖ √	❖ √
	Battery SOC	Too high	❖ √	❖ √	❖ √
		Too low	❖ √	❖ √	❖ √
BMS Failure	Cell voltage detection	Power-on self-test error			❖ √
		Communication error			❖ √
		Data update error			❖ √
		Calibration error		❖ √	❖
		Voltage reversed			❖ √
		Communication cable failure			❖ √
	Temperature Detection	Power-on self-test error			❖ √
		Abnormal temperature jump			❖ √
		Communication error			❖ √
		Signal cable short to power			√
		Signal Cable Short to Ground			√
		Signal cable failure			➢ √
		Self-test error			➢ √

	Insulation Detection	Calibration error		√	➢
		Front-end Detection Resistor Failure			➢ √
	Current Detection	Power-on self-test error			➢ √
		Calibration error		√	
		Data update error			➢ √
		Abnormal parameter		√	
		Communication cable disconnected			➢ √
	Total Voltage Detection	Power-on self-test error			➢ √
		Communication error			➢ √
		Data update error			➢ √
		Calibration error		➢ √	
		Voltage reversed			➢ √
Battery systems Faults	Positive Relay	Sticky			➢ √
		Pull-in failure			➢ √
		With current cut-off	➢ √		
	Negative Relay	Sticky			➢ √
		Pull-in failure			➢ √
		With current cut-off	➢ √		
	Power supply	Over voltage	➢ √	➢ √	➢ √
		Under voltage	➢ √	➢ √	➢ √
		Positive terminal insulation fault		➢ √	➢ √

	Battery system insulation	Negative terminal insulation fault		➢ √	➢ √
		Intermediate position insulation fault		➢ √	➢ √
		Insulation fault		➢ √	➢ √

Table 27. *This table represents the overall fault level int the BMS algorithm, starting from warning, alarm to final stage of fault. Created by Daniel Kelly Boakye Danquah, 2022.*

6.2.7 BMS EARLY WARNING DETECTION AND PROTECTION SET POINTS

Fault types	**Threshold**			**Notes**
	First-level	**Second level**	**Third level**	
High Cell Voltage	≥ 3.60V	≥3.65V	≥3.70 V	Error: ± 0.005V
Low Cell Voltage	≤2.0V	≤2.05V	≤2.10V	Error: ± 0.005V
High Total Voltage	≥57.5V	≥58.0V	≥58.5V	——
Low Total Voltage	48V	≤46.4V	≤44.88V	——
Cell Voltage Variance	≥300mV	≥400mV	≥500mV	——
High Temperature	≥50℃	≥55℃	≥59℃	Error: ±1 ℃
Low Temperature	≤0℃	≤-5℃	≤-9℃	Error: ±1 ℃
Low Insulation Resistance	≤500Ω / V	——	≤100Ω / V	——
High Charging Current 0≤ T<12 ℃	≥31A	≥32A	≥32.6A	Error: ±1%
High Charging Current 12≤T≤40 ℃	≥105A	≥107A	≥109A	Error: ±1%

Large Discharge Current	≥155A	≥160A	≥163.5A	Error: ±1%

Table 28*- This is a table of battery safety control setpoints threshold to maintain the safe operation of the battery module. designed and written by Daniel Kelly Boakye Danquah 2022.*

CHAPTER SEVEN

7.0 RECOMMENDED TEST AND VALIDATION PLAN FOR BATTERY MODULE

This chapter of my research explains the proposed test and evaluation to be used to test the battery system. The test process explains details on all potential operational and fire propagation mitigation strategies proposed in my research. I used multiple test references and standards to support the process, this included the UL9540A,NFPA 70 and NEC.

7.1.0 REFERENCE STSANDARDS

The following documents are essential for the application of this document. For reference files with note dates, only the version of the date you are noted is applicable to this file. The latest version of a reference file that does not note the date (including all modification orders) applies to this file.

Standard Number	Standard Name
UN38.3	United Nations Manual of Recommendations, Tests and Standards on the Transport of Dangerous Goods, Chapter 38.
GB/T31467.3-2015	Lithium-ion power battery packs and systems for electric vehicles Part 3: Safety requirements with the test method

UL 991	Tests for Safety - Related Controls Management Solid - State Devices
UL 1998	Standard for Software in Programmable Components
IEEE 693	Recommended Practice for Seismic Design of Substations: "Seismic design recommendations for substations, including qualification of different equipment types are discussed
NFPA 70	National Electrical Code® : "Adopted in all 50 states, NFPA 70, National Electrical Code is the benchmark for safe electrical design, installation, and inspection to protect people and property from electrical hazards."
UL 1973	Standard for Batteries for Use in Stationary, Vehicle Auxiliary Power, and Light Electric Rail (LER) Applications: "These requirements cover battery systems as defined by this standard for use as energy storage for stationary applications such as for PV, wind turbine storage or for UPS, etc. applications.(ww.sandia.gov)
NFPA 855	Standard for the Installation of Stationary Energy Storage Systems: "This standard provides the minimum requirements for mitigating the hazards associated with ESS." The standard addresses where the technology is located, how it is separated from other components, the suppression systems in place, as well as ventilation, detection, signage, listings, and emergency operations associated with energy storage systems

Table 29*- A reference table for testing and safety standards in battery testing.*
Source: www.ul.com/service/UL-9540a-test method.

As the recommended reference from UL and test reference for UL9540A. I prepared this test procedure to test the designed battery module to operate and function without any technical issues and withstand fire propagation.

Serial number	Project classification	Pilot project	Number	Important levels
1	Security testing	Highly simulated	5.1	B
2		High and low temperature test	5.2	B
3		Salt Mist Test	5.3	B
4		**Shell stress testing (Accelerated aging)**	5.4	B
5		Vibration	5.5	B
6		Impact	5.6	B
7		Impact (UN38.3)	5.7	B
8		Impact Test (UL1973)	5.8	B
9		Static force testing	5.9	B
10		Drop test	5.10	B
11		Fixture test	5.11	B
12		Heat out of control	5.12	A
13		Forced discharge	5.13	B
14		Warm-up test	5.14	B

15		Insulation pressure-resistant test	5.15	A
16		Continuity testing	5.16	A
17		Cooling / thermal stabilization system fault test	5.17	B
18		Operating voltage measurement	5.18	A
19		Outer short circuit (UN38.3)	5.19	A
20		Short-circuit test (UL1973)	5.20	A
21	Electrical performance and Fire propagation test	Charge and discharge efficiency	6.1	D
22		Low-temperature discharge capacity	6.2	D
23		High-temperature discharge capacity	6.3	D
24		Load retention and resilience	6.4	D
25		Normal temperature cycle life test	6.5	C
26		Stores	6.6	C
27		Total pressure	6.7	C

		measurement and accuracy requirements		
28		Charge and discharge current accuracy	6.8	C
29		Insulation resistance sampling function and accuracy verification	6.9	C
30	Functional testing	High-voltage circuit contactor control function	7.1	C
31		Emergency stop protection and signal diagnostics	7.2	C
32		Unbalanced charging test	7.3	B
33		Overcharging protection test	7.4	B

Table 30 *- This is the table illustrating the overall test set that will be conducted on the battery module .Source: Compiled and designed by Daniel Kelly Boakye Danquah*

7.1.1 TEMPERATURE TEST

This test is to evaluate the sealing perfection of the battery and battery pack and the internal electrical connection. The experiment will be conducted using rapid and extreme temperature changes.

TEST METHOD

The test battery or battery pack is stored for at least 12 hours at 75±2 °C, followed by at least 12 hours at -40±2 °C. The maximum time interval between two temperatures is 30 minutes. This process is repeated 10 times. Store all test batteries and battery packs at ambient temperatures (20 ±5 °C) for 24 hours.

7.1.2 TEST REQUIREMENTS-RESULTS

No weight loss, no leakage, no exhaust, no disintegrating, no rupture and no combustion, and the open circuit voltage after the test is not less than 90% of the voltage before the test.

NB: if the results prove otherwise negative, then components need to be replaced and tested again.

7.1.3 TEST REQUIREMENTS/RESULTS FOR SALT MIST TEST

This test determines that, the energy storage system can safely withstand the expected salt spray conditions when used in the vicinity of the marine environment and is suitable for fixed systems installed near the marine environment, whose internal components may be damaged by perforation caused by the opening of the salt spray through the housing.

TEST METHOD

- The test parts shall be subject to visual inspection, electrical and mechanical inspection in accordance with the relevant specifications.
- Place the test piece in a salt mist cabinet and hold it for 2 hours at a temperature of 15 to 35 °C, with a salt mist concentration of 5%.
- After the spray, the test piece should be moved into the humidity cabinet at a temperature of 40 °C and the corresponding humidity of 93% (the transfer process is as far as possible to avoid the loss of salt water on the test piece), and the humidity storage shall be carried

out in accordance with the specified residence time.

- Repeat step band step c) according to the prescribed number of cycles; The relevant specifications should describe whether the test parts are cleaned after the test.

The relevant specifications should describe whether the test parts are cleaned after the test. If cleaning is required, the test piece is placed under the tap for 5 minutes, and after washing with distilled water or mineral water, shake with your bare hands or remove the moisture with a blower, and dry for 1 hour at a temperature of 55 to 2 °C, for cleaning the water temperature must not be higher than 35 °C. Place the specimen under standard atmospheric conditions (approximately 1 to 2 hours) to return to the original condition, but must perform a visual, electrical, and mechanical inspection before and after the reply.

discharge and charging cycles and test for an insulated pressure-resistant test (AC3000V)

There is one of the following that is determined to be unqualified:

An explosion, fire, combustible gas concentration. Toxic gas leakage, risk of electric shock (dielectric breakdown), leakage (outside the shell, Damage , the shell breaks, exposing dangerous parts.

7.1.4 STRUCTURAL INTEGRITY TEST

Determine whether the housing made of molded polymer material can withstand the accelerated aging test without affecting the safety of the housing. This structural test is for the molded pieces inside the battery pack and can be conducted at the mold facility to confirm the integrity of the parts.

7.15 TEST METHOD

Place a fully discharged sample in a fully ventilated circulating air oven, which should be kept at an average temperature of at least 10degrees C(18degrees F) higher than the maximum temperature in the 18-section temperature and operating limit test, but not less than 70degrees C (158degrees F). Samples should be placed in the oven for 7 hours. After removing from the oven, the sample to be tested is observed at the end of the observation. The sample to be tested should be checked for signs of rupture and leakage.

7.1.6 TEST REQUIREMENTS

Samples should not show signs of mechanical damage, as well as signs of rupture or leakage.

7.1.7 VIBRATION TEST

This test is designed to confirm that the battery module would be able withstand vibration and be able to be transported from factory to installation site without disassembling it. Various simulations would be employed to test the system.

TEST METHOD

a) The battery and battery pack are confined to the vibrator plane in a way that does not deform the battery to correctly propagate the vibration. 1 to go-check-frequency sine vibration within 15min from 7Hz to 200Hz, 12 vibrations in 3d direction in 3 hrs., and the vandal sweep is: maintains the maximum acceleration of 1gn from 7 Hz until the frequency Rate reached 18 Hz.

b) Then keep the amplitude at 0.8 mm (1.6 mm total) and increase the frequency until the maximum acceleration

8gn (frequency is approximately 50 Hz). Keep the maximum acceleration at 8gn until the frequency increases to 200 Hertz.

7.1.8 TEST REQUIREMENTS/RESLTS

No weight loss, no leakage, no exhaust, no disintegrating, no rupture and no combustion, and the post-test voltage is not less than 90%before the test.

7.1.9 IMPACT TEST

The purpose of the Simulated impacts test is to confirm that, the module may be able to withstand vibration and impact during transport.

TEST METHOD

a）The test battery and battery pack are fastened to the test unit with a hard bracket that supports all mounting surfaces of each test battery pack. Each battery and battery pack are subjected to a semi-sine impact of 6 milliseconds between a maximum acceleration of 150gn and a pulse duration of 6 milliseconds. Each battery or battery pack must be secure d'or Ceding in three perpendicular batteries or battery packs. The positive direction of the orientation undergoes three shocks, followed by three shocks in the opposite direction, with a total of 18 punches.

b）Large batteries and large battery packs are subjected to a half-sine wave impact with a maximum acceleration of 50gn and a pulse time of 11 milliseconds. Each battery or battery pack must withstand three shocks in the positive direction of the three perpendicular battery mounting orientations, followed by three shocks in the opposite direction, for a total of 18 shocks.

7.2.0 TEST REQUIREMENTS/RESULTS

No weight loss, no leakage, no exhaust, no disintegrating, no rupture and no combustion, and the open circuit voltage of each test cell or battery pack after the test is not less than 90% of its pre-test voltage.

7.2.1 SYTEM IMPACT TEST

The impact test is conducted to confirm the durability of the lithium-ion battery,

TEST METHOD

a）The specimen battery cabinet or battery pack is placed on a flat surface. A bar with a diameter of 15.8mm is placed horizontally in the center of the specimen. A 9.1kg hammer fell from 61cm to 2.5cm to the specimen.

b）The vertical shaft of the cylindrical or prism-shaped battery to be hit should be parallel to the flat surface and perpendicular to the vertical shaft of the 15.8mm curved surface with a diameter placed horizontally at the center of the specimen.

c）The prismatic battery must also rotate 90 degrees around the vertical shaft so that its wide and narrow sides are subjected to impact. Each specimen only suffered one impact. Different specimens are used for each impact.

7.2.2 TEST REQUIREMENTS

The battery or battery pack housing temperature does not exceed 170degrees C and is free of disintegration, no rupture, and no combustion within 6 hours of testing.

7.2.3 DROP TEST

Modules intended for on-site installation on rack-mounted or similar equipment should be tested for drop impact to ensure that unintentional drops during installation or removal do not pose any danger.

TEST METHOD

a）Impact on concrete or metal surfaces at a location where adverse results are most likely to occur and in a manner that best represents what may occur during maintenance and handling/removal of the battery system during installation and maintenance.

b）At least one not flat drop should be performed, the concrete surface should be at least 76mm (3 inches) thick, and the concrete or metal drop surface should be large enough to cover the sample to be tested.

c）If the device under test is operational after testing, it should be discharged and charged in accordance with the manufacturer's specifications. Then observe for 1 hour and monitor for an external temperature anomaly.

d）The insulation pressure test AC 3000Vis was carried out.

7.2.4 TEST REQUIREMENTS

The following must not occur explosion, fire, combustible gas concentration, toxic gas leakage, Risk of electric shock (dielectric breakdown), leakage (outside the sample housing to be tested).

7.2.5 FIXTURE TEST

The handles of modules/components used to carry the modules/components on site / rack slots should be sufficiently strong to support the battery system or to allow the handling of modules/ components.

TEST METHOD

a）Apply a force to the center of the mounting device that is three times the weight of the battery system. Keep the force for 1 minute. For modules/packs with handling handles, the handle should be used to support the sample under test and apply an additional force equivalent to three times the weight of the sample to be tested in the downward direction.

b）If more than one handling handle is provided, additional weight should be distributed between the handles.

7.2.6 TEST REQUIREMENT/RESULTS

Test requirements: The force applied shall not damage the mounting device and its fixtures when testing the wall clamp. The applied force should not damage the handle or handle installation/fixing of the device under test.

7.2.7 CRITICAL FIRE PROPERGATION CONTROL TEST PROCESS

Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems: “The test methodology in this document evaluates the fire characteristics of a battery energy storage system that undergoes thermal runaway. The data generated will be used to determine the fire and explosion protection required for an installation of a battery energy storage system intended for installation, operation, and maintenance. This test is not a substitute for 9540A but to prove that.

TEST METHOD.

a. Prepare fully assemble battery module.
b. De-energize the battery module and place on a test area-(Test room)
c. Connect two cables of positive and negative terminal with a switch into the module.
d. Insert thermocouple to record battery internal temperature.
e. Verify that all the conditions in the room/test chambers are set out.
f. Press the switch to short circuit the battery module.
g. Record when the battery module reaches 230 degrees Celsius and catches on fire.
h. Observe and record if the battery module honeycomb material melts to encapsulate and cut off oxygen!
i. Record the unit fire behavior if the battery module continues to burn or the fire dies.

7.2.8 TEST REQUIREMENTS/ RESULTS

The short circuit applied will ignite the fire, but the fire-retardant material and honeycomb material will prohibit the spread of fire and eventually kill fire.

7.2.9 COOLING /THERMAL STABILIZATION SYSTEM FAULT TEST

Test that the energy storage system is functioning properly when the cooling/thermal stabilization system fails, or when the temperature reaches the upper limit, the system is protected.

TEST METHOD

a) The sample is fully charged and stored at a maximum operating temperature for 7 hours. Discharge until the protective device of the empty or sample is activated.

b) The sample is empty and stored at a maximum operating temperature for 7 hours. Charge until it is fully charged, or the sample's protective device is activated.

7.2.8 TECHNICAL REQUIREMENTS

There is one of the following that is determined to be unqualified:

Explosion, fire. Combustible gas, Concentration, Toxic gas leakage, Risk of electric shock (dielectric breakdown), Leakage (outside the shell), Damage (broken housing, exposure of dangerous parts), Loss of protection control.

7.3.0 OUTER SHORT CIRCUIT

For this experiment, verify short-circuit protection (UN38.3).

TEST METHOD

a) Short-circuit ingests at 55±2 °C, external resistances and 0.1 Ω, and the short-circuit time lasts until the battery temperature returns to 1hafter 55±2 °C and Observe for 6 hours.

The battery or battery pack housing temperature does not exceed 170degrees C and is free of disintegration, no rupture, and no combustion within 6 hours of testing.

7.3.1 EXTERNAL SHORT CIRCUIT

For the experiment, verify short-circuit protection (UL1973).

TEST METHOD

a) Positive and negative poles are connected to an external circuit no larger than 20ms.

c) Charge-discharge cycle.

d) Insulation pressure-resistant test (AC3000V).

7.3.2 TEST REQUIREMENTS

There is one of the following that is determined to be unqualified: Explosion, fire, combustible gas concentration, toxic gas leakage, risk of electric shock (dielectric breakdown); leakage (outside the shell), Damage (broken housing, exposure of dangerous parts), loss of protection control.

7.3.3 ELECTRICAL PERFORMANCE TESTING

This is a test in the project that will test the electrical performance of the battery module , this will account for the charging and the discharge capabilities of the battery module and test the electrical component stress points.

7.3.4 CHARGE AND DISCHARGE EFFICIENCY

Test the charge and discharge performance of the battery system and confirm the operational capabilities of the battery.

TEST METHOD

a) Set the ambient temperature to 25 °C

b) Drain the sample for testing and charge it fully in a recommended charging manner and record the charged energy (kWh.)

c) Discharge the sample to 100% to the cut-off discharge condition and record the discharge energy (kWh).

d) Calculates the ratio of discharge energy to charged energy.

7.3.5 HIGH TEMPERATURE DISCHARGE CPACITY TEST

To the experiment, it is to satisfy that, the battery module can be charged and discharged at higher temperature without any operational defect. To achieve these test results, all test conditions should be set to achieve optimal results.

TEST METHOD

a) The battery system is fully charged at room temperature.

b) Store/Shelve the battery module at 24 hr. at 45 degrees C.

c) At room temperature, empty at 100A and record the discharge capacity.

Requirement: The discharge capacity is not less than 90%of the initial capacity

CHAPTER EIGHT

8.0 CONCLUSION

Chapter 8 provides an overarching conclusion to the research work summarized concisely in four main points. **Point one** will clearly answer the hypothesis. The opportunities and shortfalls of the energy storage industry and will provide a reasonable assessment and contribution. **Point two** will summarize and reflect on the research process. Benefits and limitations from each core component of the research will be discussed. **Point three** will present opportunities in future research to build upon the work presented in this thesis. **Point four** will reveal contributions to the field, research and development and general application and problem this research will address in the industry.

8.1.0 GENERAL CONCLUSION TO RESEARCH HYPOTHESIS

The research is based on a quantitative and experimental analysis, in addition to an on-site case study, this thesis has shown how introducing a fire retardant and honeycomb material into lithium-ion battery can mitigate the spread of fire and detect failure at the early stage. Lithium-ion fires have long characterized the industry and UL has enacted stronger testing rules and certification to curtail that. In my research to find an alternative solution to fire safety, I had to derive the three-point strategy to resolve that, and this included the following:

Firstly, Identifying the problems that lithium-Ion batteries fires bring to the energy storage community, the general society and how through classical research and experiment, I will be able to provide solution to mitigate that.

Secondly, Developed and designed a patent pending lithium-Ion battery module with fire retardant ,honeycomb material and precision multiple sensors to detect battery fire failure and cut oxygen in the battery module to resolve the potential to spread fire when there is thermal run away.

Finally, Analyze the past, current, and future state of lithium-Ion battery fire failures, what resolution has been employed to mitigate before. I conducted qualitative and quantitative research to determine that, developing such engineering solution in mitigating the fire safety in batteries will demystify the fears surrounding lithium-Ion batteries for the society to embrace it and help engineering and procurement construction companies be able to build battery system in a ruggedized manner and transport to site without dismantling, this will bring a relief and safe huge cost in the energy storage industry..

8.1.1 RESEARCH PROCESS REFLECTION

I chose to conduct this research as it is relevant to the world, industry, the University of North Dakota and to me. Lithium-ion battery fire safety has been the top concern in the energy storage industry, as we transition into alternative source of energy and want to help in the decarbonization. Currently, there is one clear solution to resolve lithium-ion fires, either in electric mobility or in utility energy storage application. So, it is important to study this topic and provide a practical solution to the industry to show how this potential problem can be mitigated. My main aim was to show that there is a problem, and we need to do something about it, either starting at the smaller stage or bigger stage. I took the approach I mentioned in the three-point strategy above, as these are the key areas surrounding reducing potential lithium-ion battery fire failures.

I blended quantitative, qualitative, experimental, simulation and exploratory research. Ultimately I governed the project utilizing a project management approach, aiming to technically answer the problem. This proved to be beneficial in answering each research question and ultimately the hypothesis. I expected to find out that the energy storage industry and society industry could make a difference and the results solidified my expectation.

Prior to my research performed, I expected to find for my first strategy that one of the most catastrophic failures of a lithium -Ion (LIB) system is the cascading thermal runaway event, which is considered the main cause of battery safety concerns. Studies such as this are crucial to educating and bringing awareness to the world and industry. I agree with findings by (Doughty D. H., Roth E. P., A general discussion of Li ion battery safety. *Electrochemical. Soc. Interface* 21, 37–44 (2012). (Google Scholar).

In Strategy two, I expected to find that activities within the energy storage industry through the development of high precision thermocouples and writing software algorithm will be able to detect battery higher temperatures and report the status to the Battery management system to shut off for further operation, also designing battery with fire retardant material and honeycomb to encapsulate the battery module will subdue potential battery fire propagation. The results to this matched with what I expected to find, however, implementation of this finding is key in the energy storage industry as many researchers have done research to propose other solutions but making it a national policy or code standards has not been materialize.

In strategy three, I expected that, with the numerous ways that other scientist and researchers have contributed to solving fire issues in the lithium-Ion battery industry, continuous review of their solutions and improving on it, will help to uncover some of the things that they did not do. Also bring this into my solution for the fire mitigation in lithium-ion batteries for energy storage.

8.1.2 FUTURE RESEARCH & OPPORTUNITIES

Upon conclusion of this research, answering the research questions and ultimately the hypothesis, further research should be considered in the following seven key areas.

1. Explore education into lithium-Ion Cell development and technology optimization, since there is a growing demand in this area of technology, further education and research needs to be explored into different anode and cathode material.
2. Further research should be done into the area of fire safety, code, and standards and how these standards could be implemented into the battery industry.

3. Another area of opportunity to research is the area of electric fast charging technologies and protection and control of lithium-ion batteries.
4. Again, another key area of research should be aimed at the strategic application of lithium-ion, such as :
   a. *Higher military use in lesser weapon technology*
   b. *Expand research into another known cell materials-Cathode/Anode*
5. Final opportunity in understanding of Energy Storage Code and Standards and standardization of battery modules and EMS for the industry,
6. Research into the area of energy storage cyber security and its economic impact in grid modernization.

8.1.3 CONTRIBUTION AND SIGNIFICANCE

The research presented supports the hypothesis. *"Developing high precision sensors, module's structure and introducing high fire-retardant material to encapsulate battery modules and systems can resolve the problem of fire safety and early fault detection in lithium-Ion batteries."* This research, through literature review shows that there have been many attempts by other researchers and industry players to resolve the problem of fire safety. The research set forth was to determine if introducing fire retardant, precision sensors, honeycomb material and Mil standard with lug-tight bolt would be able to mitigate fire propagation should there be fire outbreak, throughout the long research and experiment conducted, it is obvious that, introducing such proposed hardware-Fire retardant and honeycomb material into lithium-ion battery module design would indeed mitigate fire propagation. This is evident in the findings section based on *Figure 88 and figure 89*. As the industry continues to grow and more people grow appetite to adopt electric vehicles and energy storage technologies, the research will play a vital role in both industrial and economic sense. this will help to unlock the answer and fears in energy storage industry for fire propagation at the module level by providing a solution with the introduction of FRM for complete encapsulation and standard temperature sensors at the battery module level. Which will be cheaper in cost for the industry to pass the safety test by UL for UL9540A?

Also, in academics, my research will serve as a foundation for future building blocks for students to explore other aspects of energy storage technologies. My research will also serve as a technology and knowledge base for the University of North Dakota and other public universities about the need to introduce FRM in lithium-ion batteries. My research project will advance UND current research on development of electrode materials for lithium-ion battery from lignite coal., and that will trigger a chain reaction in the entire LIB industry, improving the competitiveness of existing LIB products and promote innovative products by domestic business. Finally, my research outcome has uncovered new way of developing new lithium-ion battery module with introduction and battery management system in details and how they can detect early failure in the battery system for safety and built to ruggedization to be transportable without disassembling the modules. This will be a relief to industry.

8.1.4 NEXT OPPORTUNITIES FOR THE RESEARCH

I use this knowledge, technical knowhow, and experience gain in these studies to propose changes to UL, NFPA, NEC and Legislature to enforce changes and standards in standardizing module manufacturing process by introducing fire retardant material- FRM, defined number of temperature sensors in all lithium-ion- modules that is being produced to the market.

Also Develop course program for both my university-University of North Dakota (UND) and the co-operate environment energy industry on the need train more people and make them aware of lithium-ion as an alternative energy source to drive us to clean energy transition and e-mobility drive.

8.1.5 CONCLUDING STATEMENT.

Fire Safety is the most concerned problem in the large-scale and small application of Lithium-ion batteries and thermal runaway is the most common and catastrophic form of battery safety accidents. There have been many fire outbreaks in some major installed ESS system across the globe, China, USA, and Korea. This has led the certification body underwrite laboratory (UL) to enact a certification code UL9540A and 9450 based on the NFPA fire code. Batteries are not used alone, it is always interconnected with other power conversion system, such as inverter, power supply, fuse and AC panel, DC panels, and each of these are contributing factors to battery system failure, hence introducing early fault detection and fire-retardant materials to encapsulate the battery to cut of oxygen will help protect battery and system from causing fire explosion and stop battery module from burning during battery thermal runaway. It is paramount to have very strong detection, identification, and containment of internal short circuits in its early and middle stages that will prevent ISC from developing into thermal runaway.

Therefore, I conclude in my research by proposing three techniques:

1. By using the high-grade fire-retardant material to wrap and encapsulate all sub-modules to contain fire where and should there be an outbreak or thermal runaway.
2. Using aluminum honeycomb material as part of the module enclosure to melt and seal all ventilated vent to cut out oxygen into the battery module during the event of thermal runaway or fire outbreak.
3. Introducing multiple temperature sensors to detect early temperature deviation and send signal to the battery BMS to open contactors to stop battery operation.

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APENDICES

Report Attribute	Details
Market size value in 2022	USD 350.42 million
Revenue forecast in 2030	USD 737.99 million
Growth rate	CAGR of 9.8% from 2022 to 2030
Base year for estimation	2021
Historical data	2019 - 2020
Forecast period	2022 - 2030
Quantitative units	Revenue in USD million, Power Capacity in kW and CAGR from 2022 to 2030
Report coverage	Revenue forecast, capacity forecast, company ranking, competitive landscape, growth factors, trends
Segments covered	Application, region
Region scope	North America; Europe; Asia Pacific; Central & South America; Middle East & Africa
Country scope	U.S.; Germany; UK; South Korea; Japan; Brazil
Key companies profiled	Langley Holdings plc, Amber Kinetics, Inc., Stornetic GmbH, POWERTHRU, Energiestro, VYCON, Inc., Bc New Energy (Tianjin) Co., Ltd. (BNE), Beacon Power, LLC, PUNCH Flybrid, Kinetic Traction Systems, Inc.

Customization scope	Free report customization (equivalent up to 8 analyst's working days) with purchase. Addition or alteration to country, regional, and segment scope.
Pricing and purchase options	Avail customized purchase options to meet your exact research needs.

Table 1.0. *Table of Application and regional Flywheel energy storage market outlook and use of magnetic flywheels technology.(Contributed by Daniel Kelly Danquah)*

Source: https://www.fortunebusinessinsights.com/industry-reports/segmentation/flywheel-energy-storage-market-100756.

Lithium-ion Technology	**Uses**	**Advantages**	**Drawbacks**	**Voltage Range**
Lithium-ion phosphate (LFP)	In energy storage, in cars and computers	Cheaper, longer life, durable and higher tolerance to temperature	Relatively low specific energy, it can suffer low temperature in operation	(2.0-3.6)V
Lithium Cobalt Oxide (LCO)	Cell phones, tablets, laptops, cameras	High specific energy	Short lifespan, low thermal stability, and expensive	(2.5-4.3)V
Lithium Manganese Oxide(LMO)	Medical instruments and power tools and other hybrid cars	Fast charge, handle high load application,	Lower cycle life	(3.0-4.2)V
Lithium Nickel Cobalt Aluminum oxide(NCA)	Electric vehicle application	Higher energy density, longer lifespan	Not very safe, very expensive	(3.0-4.2)V
Lithium Titanate (LTO)	Used in electric vehicle, energy storage telecommunication,	Very safe, long-life span. Very safe and wide	Low energy density,	(2.4-3.0)V

	and aerospace and military application	temperature range	expensive and very heavy	
Lithium Nickel cobalt oxide (NMC)	Energy storage, vehicle application and military application	Higher energy density, smaller footprint, lighter weight	Expensive, weakness to higher temperature	(2.8-4.2)V

Table 9. *Analysis of various known lithium-ion technologies*
Source: Daniel Kelly Boakye Danquah, UND 2023

Battery system	Transformation of energy	Types of technology
Primary systems	One-time transformation of chemically stored energy	Leclanché Alkaline zinc manganese dioxide and various lithium systems
Accumulators	Repeatable transformation-reversible from chemical to electrochemical energy	Lead accumulators, Nickel accumulators NiCd, NiFe, NiZn, NiMh, Lithium-ion systems, CNM, FePO4, Sodium accumulators
Double layer storage	Repeatable highly reversible storage of electrical energy through physicochemical boundary process	Aqueous and non-aqueous
Renewable systems	Transformation of chemically stored energy re-generability through external process	Zinc air
Fuel Cells	Continuous transformation of chemically stored energy	PEM,MCFC,SOFC,AFC,PAFC
Flow systems	Transformation of electrically and chemically stored energy by separation of the converter from the storage	Zinc Bromine, Vanadium flow system

Figure 96. *Fig 1. A cut view of magnetic flywheel for storing energy for use.*
Source: https://www.greenbuildingadvisor.com/article/power-storage-in-flywheels

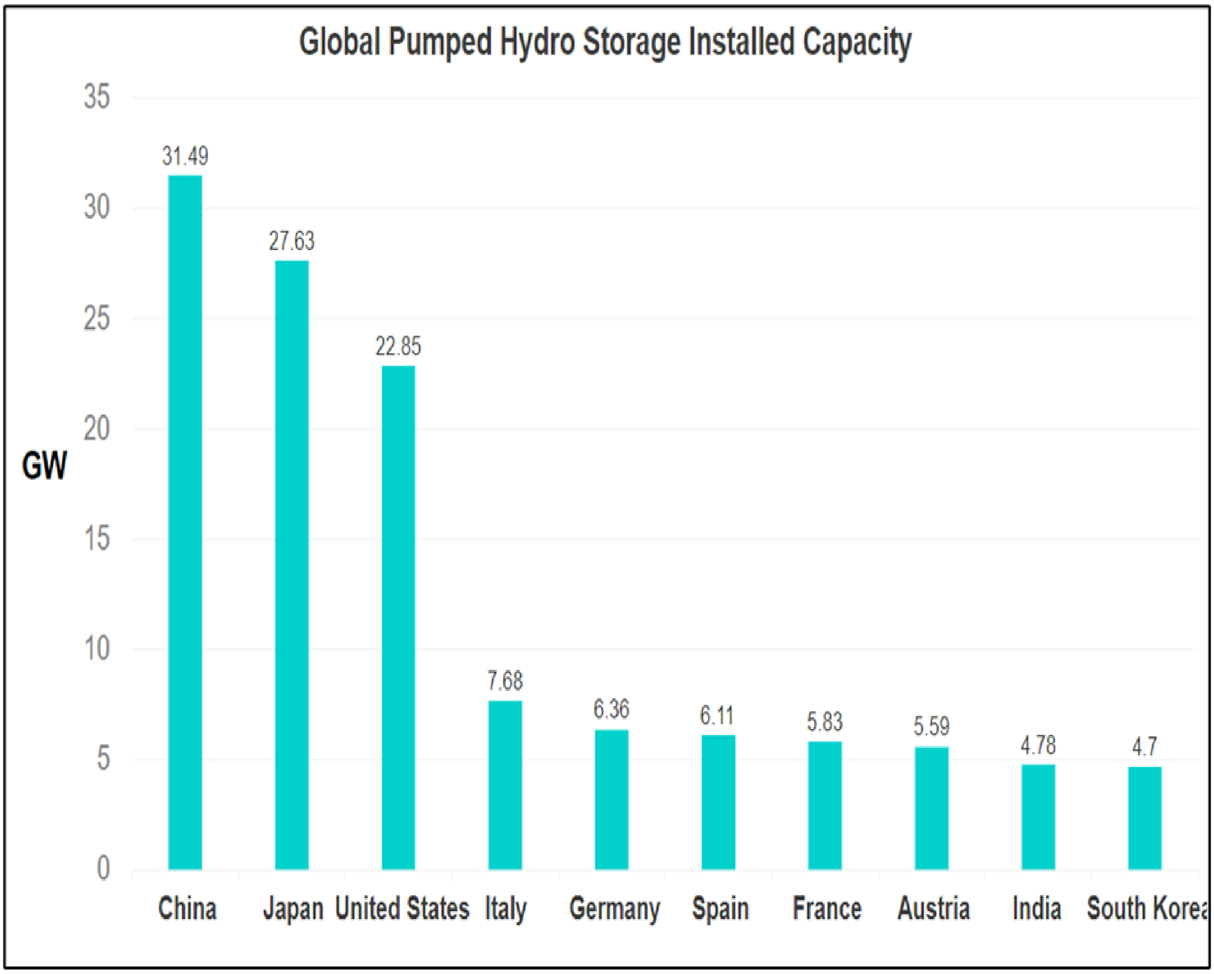

Figure 98*. A graph of Global Pumped Hydro Storage*
Source: https://www.blackridgeresearch.com/reports/global-pumped-hydro-storage-phs-market

Battery system	Transformation of energy	Types of technology
Primary systems	One-time transformation of chemically stored energy	Leclanché Alkaline zinc manganese dioxide and various lithium systems
Accumulators	Repeatable transformation-reversible from chemical to electrochemical energy	Lead accumulators, Nickel accumulators NiCd, NiFe, NiZn, NiMh, Lithium-ion systems, CNM, FePO4, Sodium accumulators
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Fuel Cells	Continuous transformation of chemically stored energy	PEM,MCFC,SOFC,AFC,PAFC
Flow systems	Transformation of electrically and chemically stored energy by separation of the converter from the storage	Zinc Bromine, Vanadium flow system

Table 2. *Illustration of types of chemical energy storage*
Source: (Handbook of energy storage, 2015)

Battery	NCA-Graphite	LFP-Graphite	LMO(Spinel)-Graphite	LMO (Spinel)-TiO
Cathode	LiNiCoAlO2	LiFePO4	LiMn2O4	LiMn2O4
Anode	Graphite	Graphite	Graphite	Li4TiO12
Battery mass(kg)	75.9	81.6	62.6	106.2
		Material Composition(mass%)		
Cathode active material	24.8 %	22.2%	24.4%	28.3%
Anode active material	16.5%	15.3%	16.3%	18.9%
		Electrode Elements		
Lithium (Li)	1.9%	1.1%	1.4%	2.8%
Nickel(Ni)	12.1%	0.0%	0.0%	0.0%
Cobalt (Co)	2.3%	0.0%	0.0%	0.0%
Aluminum (Al)	0.3%	0.0%	0.0%	0.0%
Oxygen (O)	8.3%0.0%	9.0%	12.4%	2.3%
Iron (Fe)	0.0%	7.8%	0.0%0	0.0%
Phosphorous (P)	0.0%	4.4%	0.0%	00.0%
Manganese (Mn)	0.0%	0.0%	10.7%	12.4%
Titanium(Ti)	0.0%	0.0%	0.0%	9.8%
Graphite (c)	16.5%	15.3%	16.3%	0.0%
Carbon	2.4%	2.1%	2.3%	4.5%
Binder	3.8%	3.4%	3.7%	4.5%
Copper Parts	13.3%	13.8%	13.5%	2.6%

Aluminum parts	12.7%	13.3%	12.5%	13.7%
Aluminum casing	8.9%	9.4%	9.2%	8.8%
Electrolyte Solvent	11.7%	14.2%	11.8%	13.4%
Plastics	4.2%	4.6%	4.5%	3.6%
Steel	0.1%	0.1%	0.1%	0.1%
Thermal insulation	1.2%	1.3%	1.2%	1.2%
Electronic parts	0.3%	0.3%	0.4%	0.2%

Table 10. *Mechanical composition of Lithium-ion battery cell*
Source: https://www.researchgate.net/publication/265158823_Paper_No_11-38911

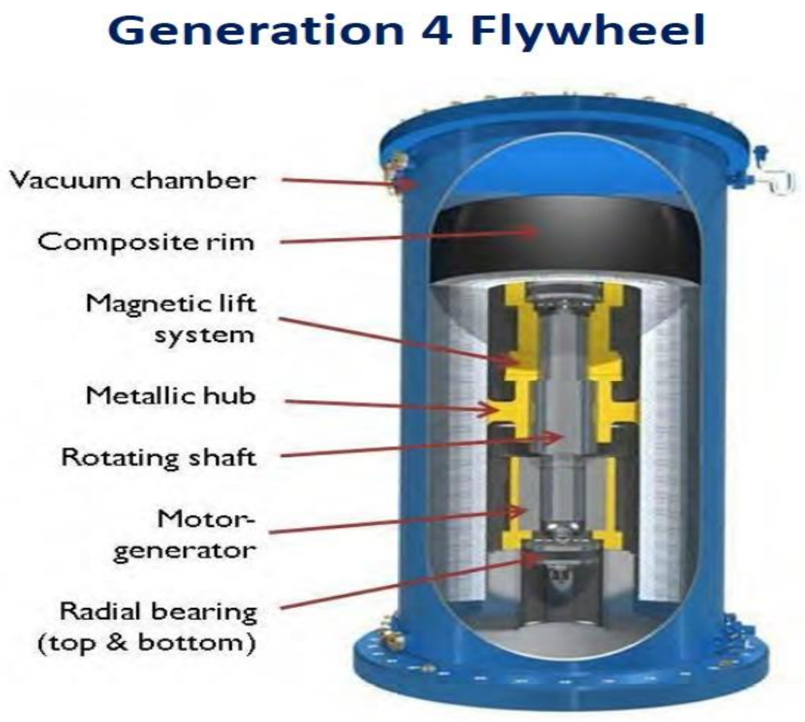

Figure 1. *A cut view of magnetic flywheel for storing energy for use.*
Source: https://www.greenbuildingadvisor.com/article/power-storage-in-flywheels

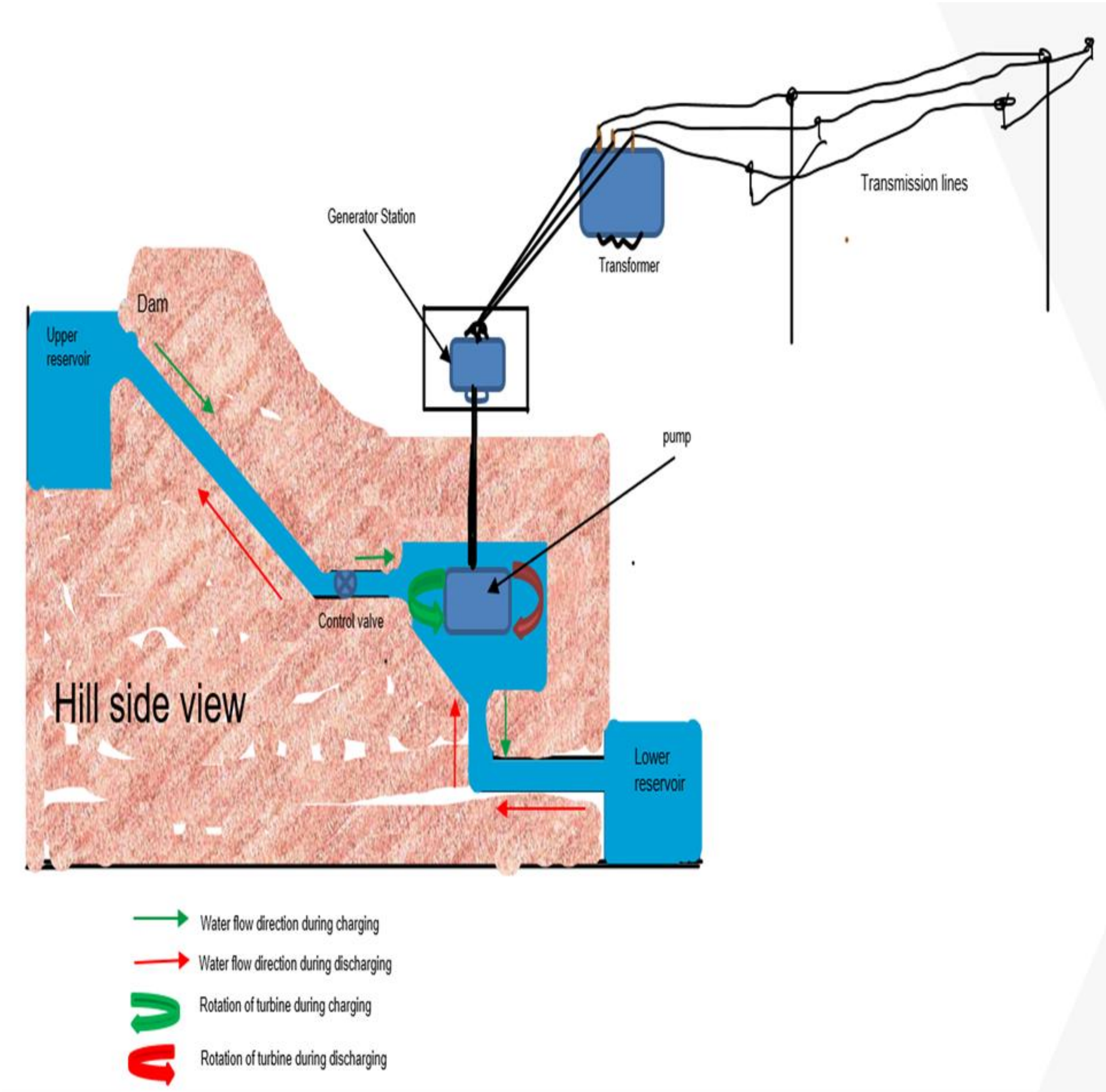

***Figure 97**: Illustration of Pump hydro energy storage plant*
Source: Created by Daniel Kelly Danquah

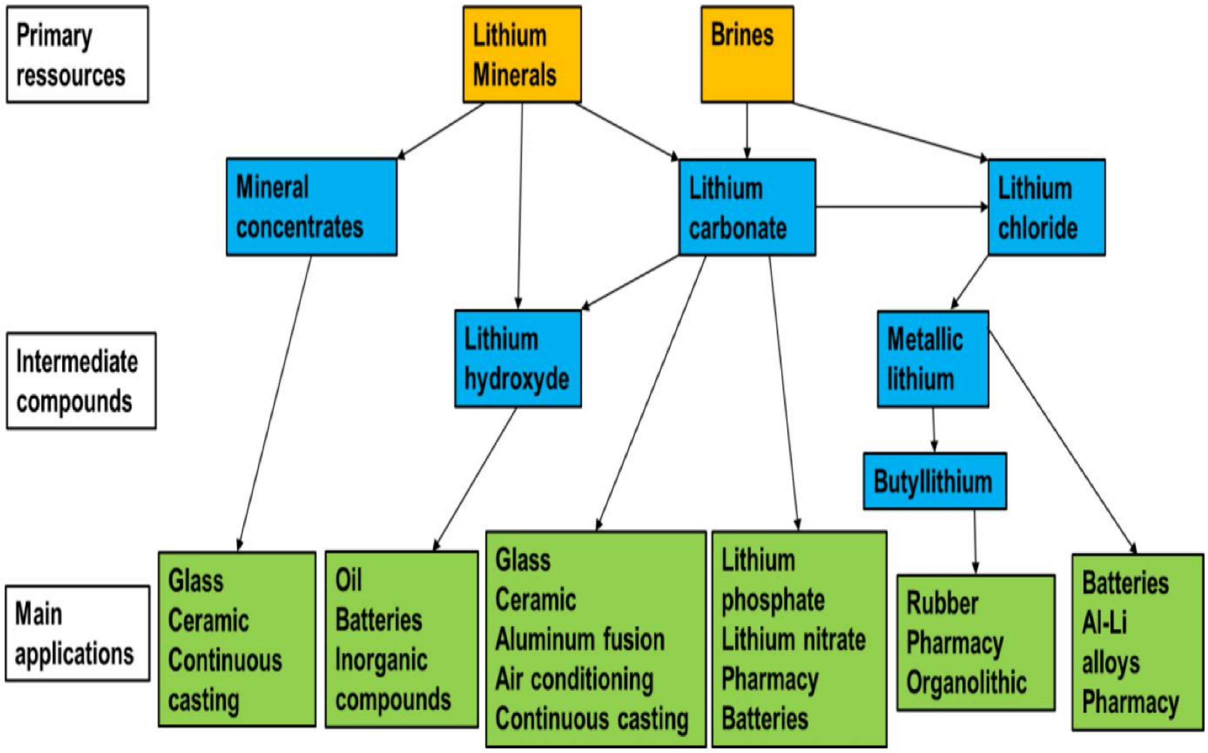

Figure 99. *Diagram showing Lithium sources and application.*
Source: https://www.mdpi.com/minerals/minerals

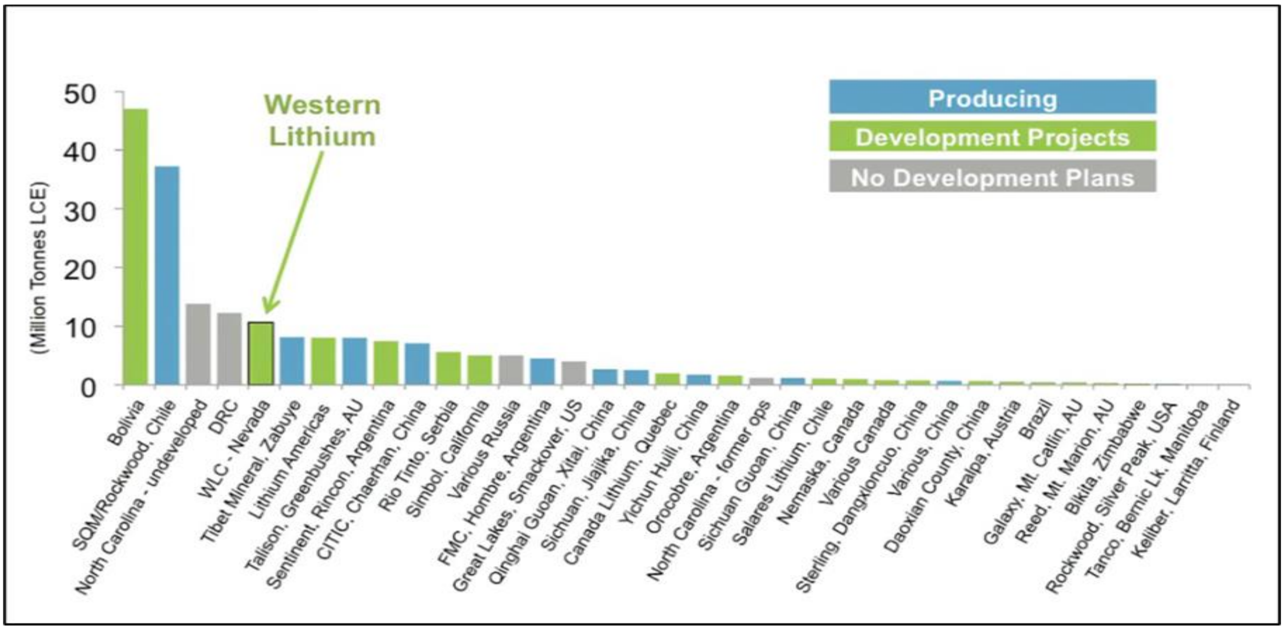

Figure 100. *A graph showing world lithium Resource availability.*
Source: Brine Lithium Deposits | Geology for Investors

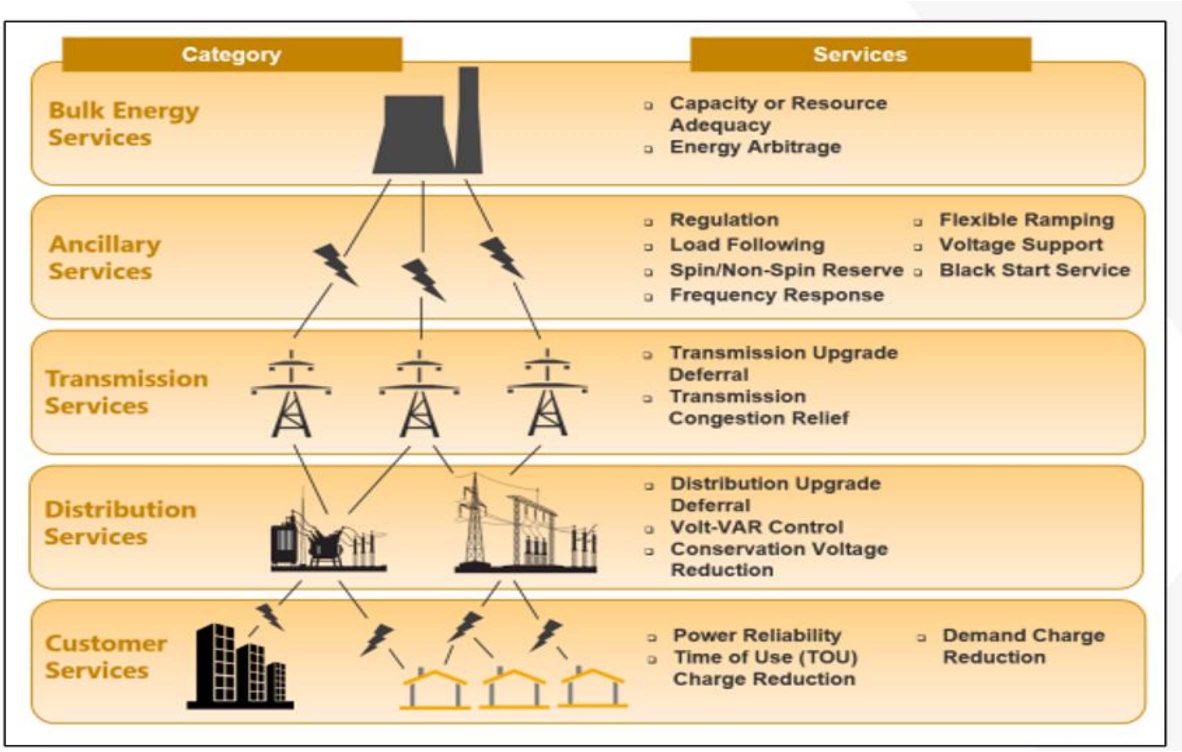

Figure 25. *Taxonomy of Energy Storage Services*
Source: Pacific Northwest National Laboratory (PNNL).

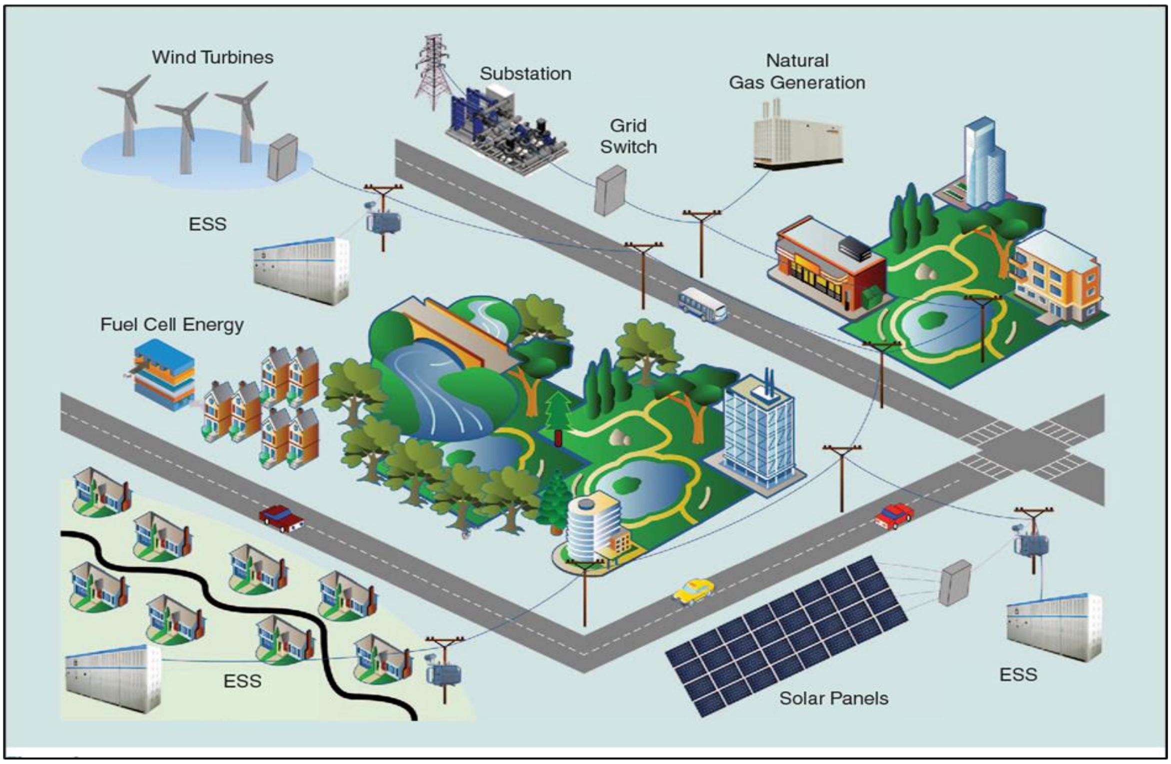

Figure 28. *Image of Energy storage in Micro grid Applications*
Source: https://www.bing.com/images/search?view

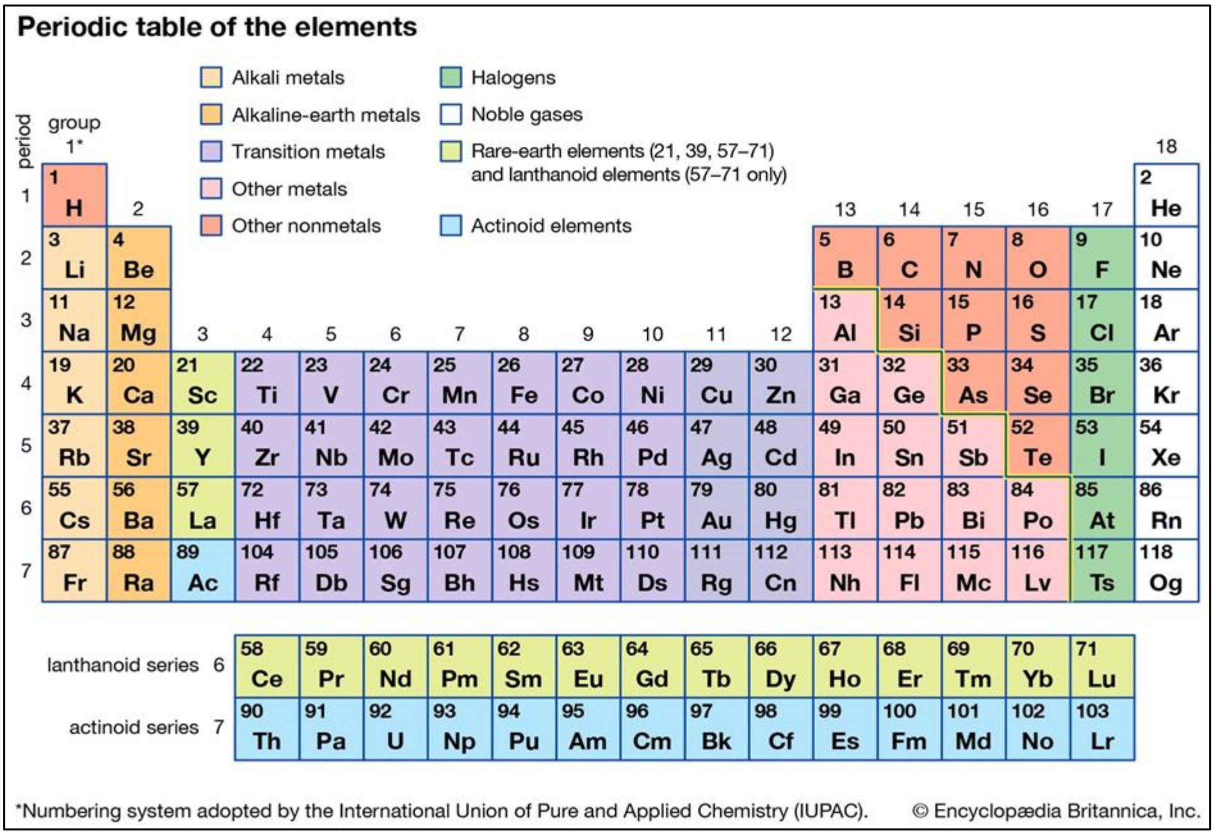

Figure 15. *The periodic table showing all elements of Global deposits of lithium minerals. Source: Global Deposit of Lithium Materials (Royal Society of Chemistry (rsc.org)*

Figure 32. *An image of cluster of commercial lithium-ion batteries to support a substation. Source: https://www.solarpowerworldonline.com/2020/06/fluence.*

Figure 58. *Image of electric vehicle catching fire, a total of 80kWh of lithium-ion.*
Source: battery guy.com

Figure 56. *Image of a yacht catching on fire.*
Source:bing.com

Federal Aviation Administration

Lithium Battery Air Incidents

involving smoke, fire, or extreme heat

Click the funnel to filter data. Hover over text for more information

Click to reset filters

Note: These are verified lithium battery related events involving smoke, fire, or extreme heat that the FAA is aware of and should not be considered a complete listing of all such incidents. The methods of collecting and recording these incidents and the data involved has changed over the life span of this chart as the FAA's Office of Hazardous Materials Safety has evolved. The incident summaries included here are intended to be brief and objective. They do not represent all information the FAA has collected, nor do they include all investigative or enforcement action taken. Verified incidents will be uploaded by the fifth of the month. Processing time varies.

Incident Date	New	Reporter	Carrier Type	Category	Reported Description
3/7/2023	New	Air Transport International	Cargo	Laptop	During ground handling process, Air Transport International facility located in Rockville, IL ground personnel observed a parcel containing a laptop computer making a popping sound during ULD loading into the aircraft. Th..
3/1/2023	New	Spirit Airlines	Passenger	Other Electronic Devices	Spirit Airlines reports a passenger hand carried bag was stowed in the overhead bin on a flight from Dallas, TX to Orlando, FL. During the flight smoke was observed emitting from the overhead bin. The bag was remov..
2/24/2023	New	Spirit Airlines	Passenger	Battery Pack/Battery	Passenger offered her checked bag to the air carrier and it contained a USB connected power bank Lithium Ion Battery. During ground operations airline personnel observed a bag smoking, they removed the bag to a safe..
2/8/2023	New	United Airlines	Passenger	Battery Pack/Battery	The air carrier reports a passenger possessed a power bank that smoked during a flight, the power bank was placed in Thermal Containment Bag. The aircraft continued to its destination without further incident and no rep..
1/25/2023	New	Sun Country	Passenger	Battery Pack/Battery	Sun Country Airlines reports a thermal event involving power bank charging a passenger cell phone in-flight. The operating crew took possession of the power bank and secured it in a Thermal Containment Bag. The flight conti..
1/24/2023	New	American Airlines	Passenger	e-Cigarette/ Vape Device	The air carrier reports a thermal event involving a passenger vape device. The device became hot to touch during flight, the vape device was placed in a Thermal Containment Bag. The aircraft continued to its destination wit..
1/9/2023	New	Southwest Airlines	Passenger	Battery Pack/Battery	Southwest Airlines reports during taxi operations a passenger was charging a cell phone with a portable battery pack causing a thermal event. Airline personnel safely secured the device within a Thermal Containment Bag. N..
1/8/2023	New	American Airlines	Vape	e-Cigarette/ Vape Device	The air carrier reports a thermal event involving a passenger vape device. The device became hot to touch during flight, the vape device was placed in a Thermal Containment Bag. The aircraft continued to its destination wit..
12/29/2022	New	Alaska Airlines	Passenger	Laptop	Alaska Airlines reports a thermal incident occurred inflight when a passenger laptop began to smoke. Flight crew safely secured the laptop in a Thermal Containment Bag. The flight continued without further incident...
12/26/2022	New	Lufthansa Airlines	Passenger	Laptop	Lufthansa Airlines reports a thermal event involving Lap Top computer possessed by a passenger in-flight. The Lap Top was stowed in a back pack within the overhead bin in "hibernation mode". The operating crew e..
12/24/2022	New	Jet Blue Airlines	Passenger	Battery	Media reported a hazardous materials incident involving Jet Blue Airlines.

Table 55. *A graph of lithium-ion Battery air incidents*
Source: Federal Aviation Administration, security and Hazardous Materials safety, Last updated March 2023

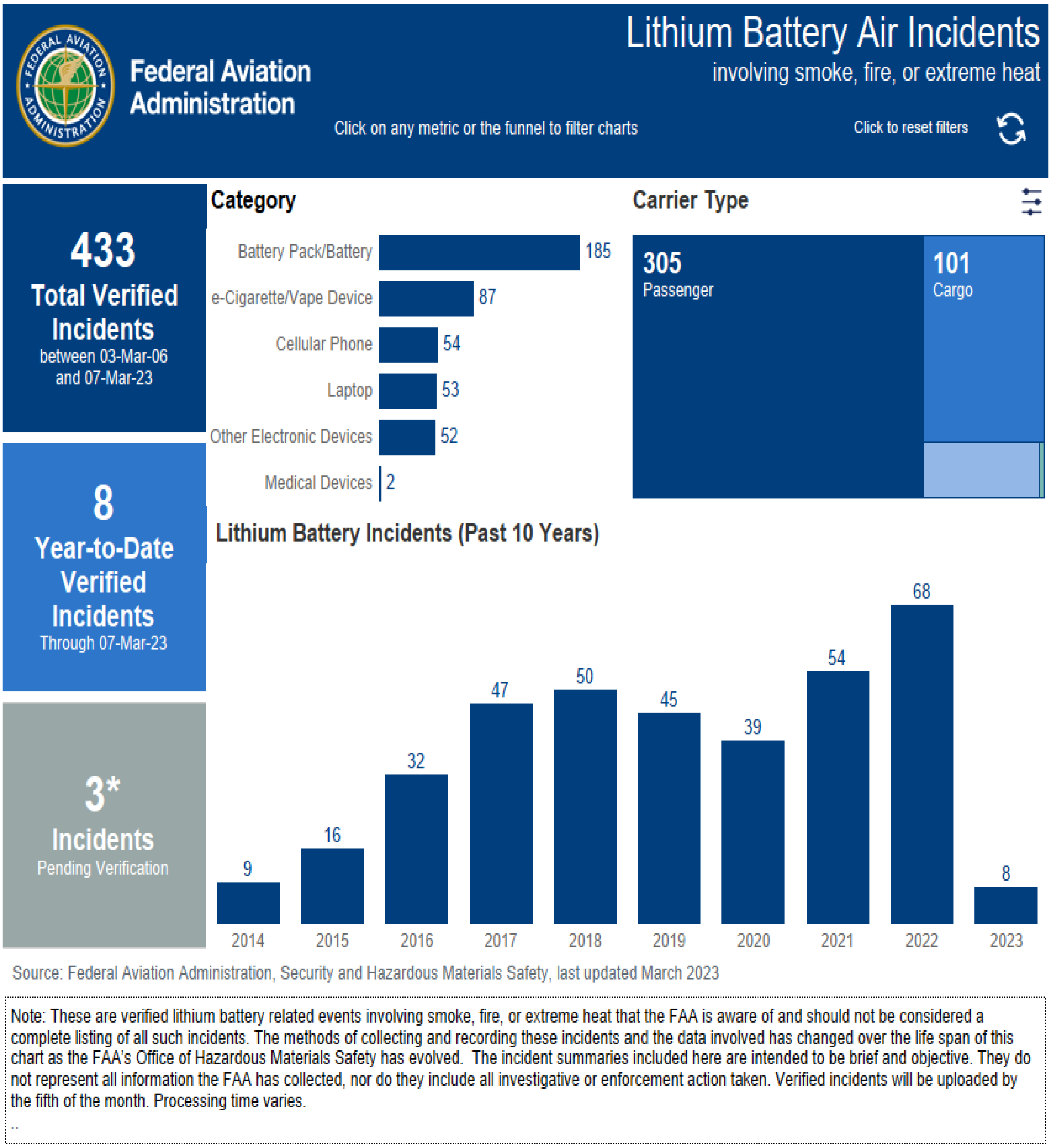

Figure 54. *A list of samples lithium-ion battery air incidents*
Source: Source: Federal Aviation Administration, security and Hazardous Materials safety, Last updated February 2023