OULUN AMMATTIKORKEAKOULU

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BATTERY CELL FIRE DETECTION AND SUPPRESSION SYSTEM

Commissioned by JOT Automation

BATTERY CELL FIRE DETECTION AND SUPPRESSION SYSTEM

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Litiumioniakkujen käyttökohteet ovat laajentuneet nykypäivänä aina työkaluista mobiililaitteisiin sekä sähköajoneuvoihin. Sähköautojen yleistyminen tieliikenteessä onkin moninkertaistanut litiumioniakkujen tuotannon. Vaikka litiumioniakkuja käytetäänkin monissa eri käyttökohteissa, on akkujen turvallisuudessa vielä kehitettävää. Tästä esimerkkinä ovat lukuisat sähköajoneuvojen tulipalot sekä Samsungin vialliset akut Galaxy Note 7 – mallin älypuhelimissa, joita ehdittiin myydä maailmanlaajuisesti 2,5 miljoonaa kappaletta vuonna 2016. Nämä sekä lukuisat muut tapaturmat liittyen akkutulipaloihin ovat malliesimerkki siitä, että litiumioniakkujen käyttöön liittyy selviä turvallisuusriskejä.

Tämän opinnäytetyön tarkoituksena on selvittää, millaisia palonhavaitsemis- ja sammutusjärjestelmäratkaisuja nykymarkkinoilla on tarjolla akkuja käsitteleville tuotantolaitteille. Työn tarkoituksena on myös tutkia, mitä viranomaisvaatimuksia Euroopan unioni asettaa tuotantolaitteille sekä tuotantoympäristölle. Opinnäytetyössä tarkastellaan myös muita nykypäivän sekä tulevaisuuden akkuteknologioita, sekä käsitellään litiumioniakkujen turvallisuusominaisuuksia sekä eri vikaantumistapoja huomioiden akkujen eri kennokoot. Lisäksi opinnäytetyössä tarkastellaan akkujen toimintaa useissa eri konteksteissa, kattaen monipuolisen näkökulman liittyen akkujen käyttökohteisiin sekä riskeihin.

Työn tuloksia voidaan hyödyntää alustan jatkokehitystyössä. Toimeksiantaja voi hyödyntää kehitettyä alustaa muille akkuja käsitteleville tuotantolaitteille. Lopuksi opinnäytetyössä käsitellään soveltuvia ratkaisuehdotuksia akkuja käsittelevälle tuotantolaitteelle.

Asiasanat: Litiumioniakku, akkukenno, akkuteknologiat, sammutusjärjestelmä, standardit, vikatilanne, sähköajoneuvo

ABSTRACT

Oulu University of Applied Sciences
Degree Programme in Electrical and Automation Engineering, Option of Electrical Engineering

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The applications of lithium-ion batteries have expanded recently, from tools to mobile devices and electric vehicles. The proliferation of electric cars in road transport has multiplied the production of lithium-ion batteries. Although lithium-ion batteries are used in many different applications, there is still room for improvement in battery safety, including numerous electric vehicle fires and Samsung's defective batteries in Galaxy Note 7 smartphones, which sold 2.5 million units worldwide in 2016. These and numerous other accidents related to battery fires show that there are clear safety risks associated with the use of lithium-ion batteries.

The purpose of this thesis is to find out what kind of fire detection and extinguishing system solutions are available in the current market for battery production machineries. The purpose of the thesis is also to study what regulatory requirements the European Union imposes on production equipment and the production environment. The thesis also examines other current and future battery technologies and discusses the safety properties of lithium-ion batteries and different failure modes, taking into account different cell sizes. The thesis also examines the operation of batteries in several different contexts, covering a versatile perspective related to battery applications and risks.

The results of the thesis can be utilized in the further development of the platform. The client can utilize the developed platform for other battery handling production machineries. The results of this thesis can be utilized when thinking about future prospects of battery manufacturing machineries. Finally, the thesis discusses suitable solution proposals for the battery assembly solution.

Keywords: Lithium-ion battery, battery cell, battery technologies, extinguishing system, standards, fault situation, electric vehicle

CONTENTS

LIST OF ABBREVIATIONS

A	Ampere; The unit of electric current.
Ah	Ampere hour or amp hour; the unit of electric charge, which amperes of electric current is transported during an hour.
Bar	Bar; The metric unit of pressure.
BESS/ESS	Battery energy storage system; An electrochemical device that charges from a power source, such as grid of a power plant, and discharges that energy later to provide electricity to services when needed.
BMS	Battery management system; An electronic system that controls and manages a rechargeable battery, by e.g. monitoring its state and authenticating or balancing the battery.
°C	Celsius; The unit of temperature.
CO2	Carbon dioxide; a chemical compound consisting of carbon and oxygen. Carbon dioxide emissions are involved in climate change, which is called the greenhouse effect. Also used as an extinguisher: Its effectiveness is based on suppressing the fire by lowering the oxygen content so that combustion cannot occur.
DOD	Depth of discharge; the percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity.
EV	Electric vehicle; A type of vehicle that uses one or more electric motors for propulsion.

GSD	General station description. Profinet GSD file type that describes the I/O device provided by the device manufacturer. GSD file consists of configuration information, modules, parameters, diagnostic and alarms, and vendor and device identification.
HEV	Hybrid electric vehicle; A type of hybrid vehicle that is powered by an internal combustion engine and an electric motor.
I/O	Input/Output; Describes any operation, program, or device that transfers data to or from a computer.
ICE	Internal combustion engine; an engine in which the energy obtained from burning fuel is converted into mechanical movement.
Kg	Kilogram; The unit of mass.
L	Litre; The unit for volume. A measure of volume that corresponds to one cubic decimeter.
Li-ion	Lithium-ion battery; A battery in which the lithium ion moves between the anode and the cathode. The lithium ion moves from anode to cathode during battery discharge and from cathode to anode during charging.
LWIR	Long-wave infrared; subset of the infrared band of the electromagnetic spectrum. Covers wavelengths from 8 micrometers to 14 micrometers. That range is the radiant heat that uncooled thermal imaging cameras see.
Pa, kPa	Pascal or kilopascal; the unit of pressure, that a force of one Newton causes when applied to a surface area of one square meter.

PHEV	Plug-in hybrid electric vehicle; A hybrid electric vehicle whose batteries can be recharged from an external electric power source, as well as its on-board engine and generator.
PKP	Purple-K; a dry-chemical fire suppression agent.
ROI	Region of interest; A sample within a data set identified for a particular purpose.
SEI	Solid electrolyte interphase; A layer formed on the surface of the electrode that prevents the electrode from disintegrating.
SOC	State of charge; an expression of the present battery capacity as a percentage of maximum capacity.
SOH	State of health; an expression of condition of a battery compared to its ideal conditions.
V	Voltage; The unit of electric potential.
Wh/kg, Wh/l	Watt-hour per kilogram or watt-hour per litre; a unit of specific energy that measures the density of energy in batteries.

1 INTRODUCTION

JOT Automation has identified the need for functioning gas, temperature and fire detection system as well as fast fire suppression and extinguishing system for battery cell testing and handling machine lines. The current gas detection is being monitored with Li-ion Tamer, which is designed to monitor off-gassing of Li-ion batteries. This thesis introduces different variations for monitoring the system, which can be delivered to JOT's machine lines as well as to JOT's own premises.

2 JOT AUTOMATION

2.1 History and background

The work was commissioned by JOT Automation, which designs and manufactures automatic testing and production equipment for the electronics industry. JOT's area of expertise includes final testing of smart devices, circuit board level testing equipment as part of a production line, and assembly equipment for use in the electronics industry. (1.)

JOT Automation was founded in 1988, and the company expanded very quickly after specializing in telecommunications. Rapid internationalization took place with the help of Nokia and the company was listed on the stock exchange in 1998. In 2000, JOT Automation was sold to Elektrobit, which is now known as Bittium. In 2011, JOT was acquired from the German Rohwedder Group, to which JOT was sold in 2007. Since 2018, JOT has been owned by a Chinese company in Jiangsu Province, Suzhou Victory Precision Manufacture Co., Ltd. (1.)

JOT’s headquarter locates in Oulu, Finland. JOT Automation also has a division, Bluelec, located in Salo, Finland, which supplies high-tech businesses with industrial electronics and test solutions (2.). JOT Automation has offices in Finland, Estonia, Germany, Hungary, China and in the United States of America. The company employs over 200 employees. (1.)

2.2 JOT Battery Assembly Solution

JOT Battery Assembly Solution is a fully customizable turnkey solution for automated battery assembly and production, that is also EV battery compatible. Highlights of the Battery Assembly Solution include automated unpacking of incoming materials and waste material recycling, battery testing, welding applications and finished product testing. The Battery Assembly Solution is fully comprehensive for automated prismatic battery assembly and has flexible customizability for multiple purposes and retrofits, due its modular and scalable design platform. (3.)

A demonstrative model of JOT Battery Assembly Solution is shown in Figure 1.

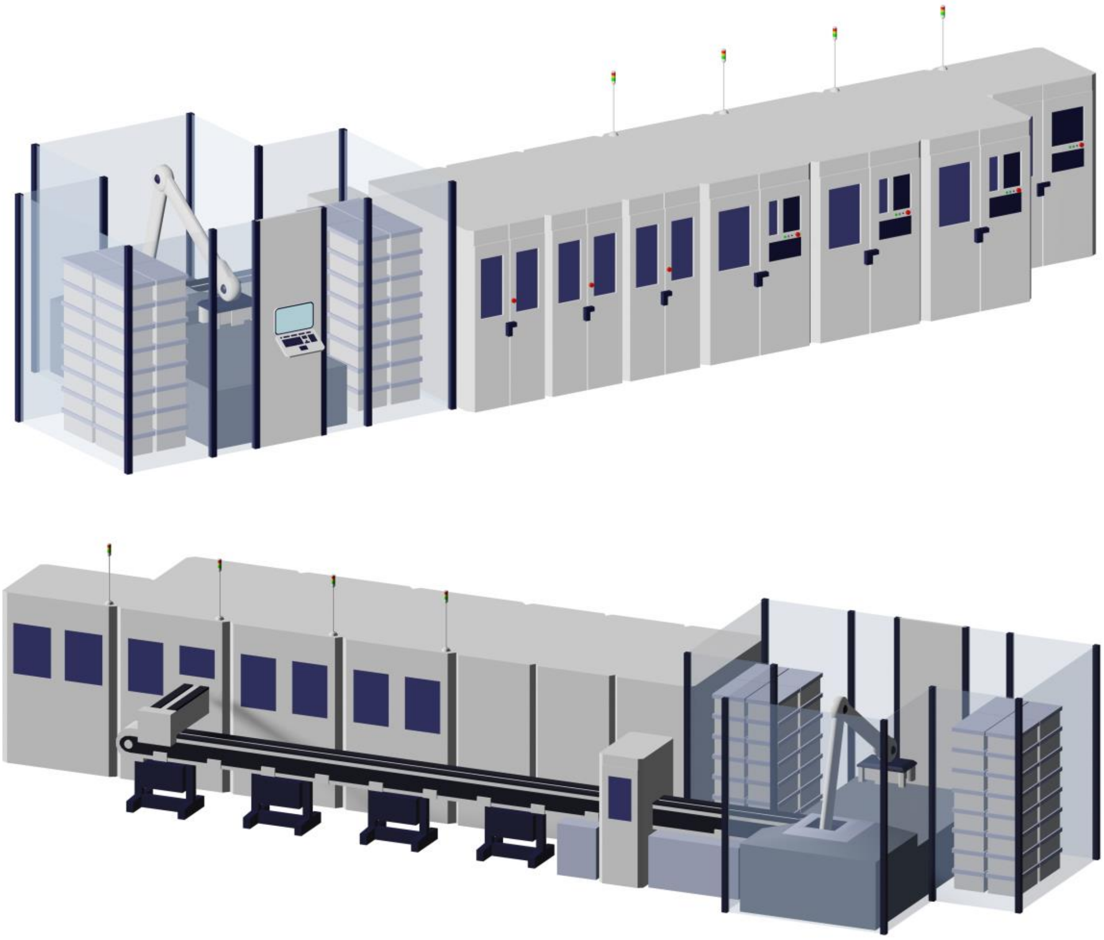


FIGURE 1. Three-dimensional model of JOT Battery Assembly Solution. The process starts where the robot arm is located, and finished product is removed from the final cabin. Above is shown the frontside and below is shown the backside of the machine line. (4.)

The Battery Assembly Solution is designed for handling batteries, chassis and cushion materials, assemble base plates to chassis, test out the batteries and place the batteries to the base plates. The multi-function gripper picks up and places the incoming material boxes and batteries. The material boxes are opened by the same gripper and the empty boxes are moved to shredder. The batteries are from there unloaded and placed to conveyor belt that moves the batteries to high-performance tester, which tests out the Alternating Current Internal Resistance (ACIR) and Direct Current Internal Resistance (DCIR). Single battery traceability and dimensional verification are also being done for the batteries. Besides testing out the batteries, the Battery Assembly Solution also sets up a complete base plate, where the batteries can be set up to. Once the batteries have passed the quality control, the batteries are placed to base plates, which consists of 30 prismatic batteries. The packed baseplate is then forwarded to a cabin, where the operator can pick up the finished product. (3.)

A demonstrative block diagram of the machine line functions is shown in Figure 2.

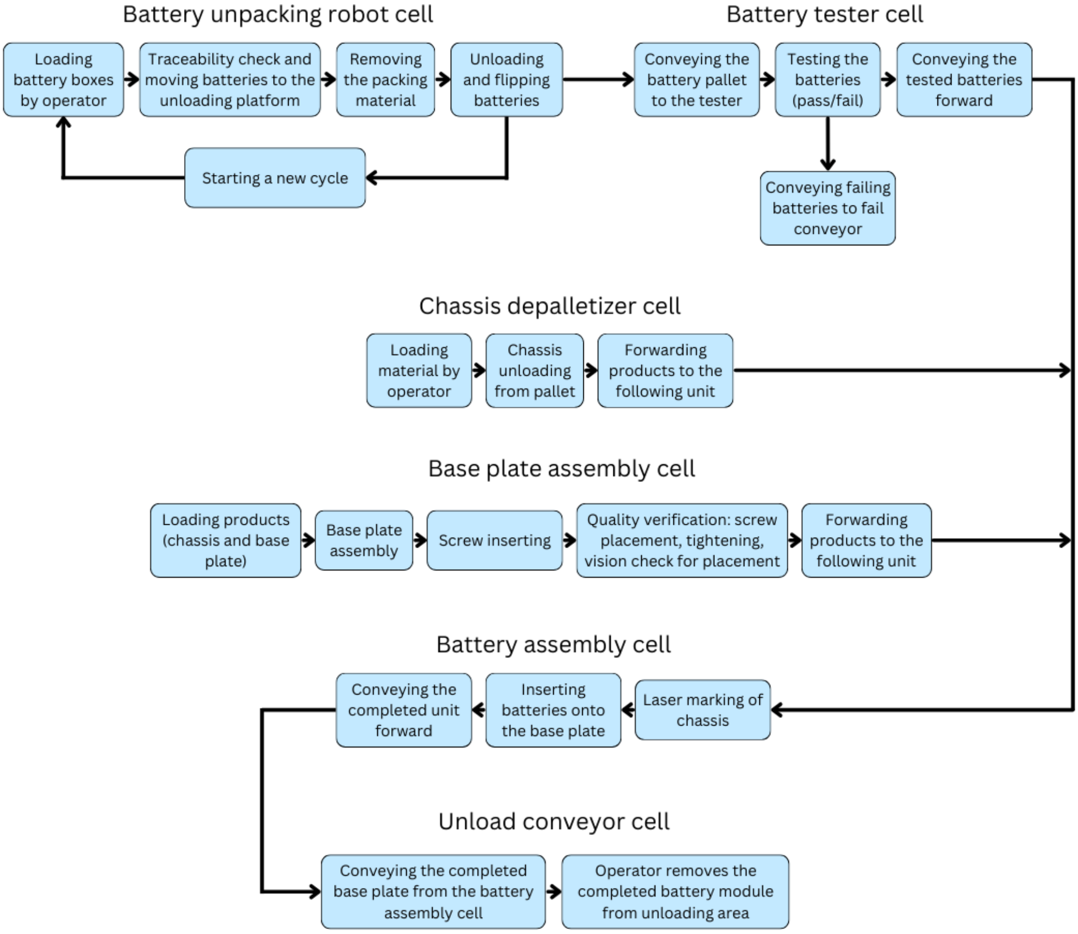


FIGURE 2. Block diagram of machine line functions. (4.)

3 BATTERY TECHNOLOGIES

In cars, the batteries are used to provide power to start the engine, and to the car’s lights and electronics when the car’s engine is not running. The car's thrust does not come from the battery but from the engine. The exceptions are electric or hybrid cars, or if the car runs out of fuel, in which case the internal combustion engine car can be driven for a short time.

Car batteries have a wider range of requirements to meet than any other application battery. To be used in cars, the battery must be able to discharge with an electric current of more than 1000 amperes for milliseconds and seconds, discharge with an electric current of 5 to 30 amperes for minutes, discharge with some amount of electric current for hours and days, charge with limited voltage, equalize voltage fluctuations in the electrical system, operate at temperatures between -30 and +75 °C and withstand vibrations according to the car model. (5, 149-150.)

In addition, the choice of battery must take into account car and situation-specific factors, such as the price, size and shape of the battery, and the desired performance requirements. Car engines and other parts are designed to work with a certain type of battery, so it is not easy to replace a different type of battery in the car than what was originally in it. (5, 149-150.)

Almost all car batteries have become maintenance-free in the sense that there is no need to add battery water to them. While most batteries are lead-acid batteries, only some heavy-duty batteries and old car batteries require such maintenance. The rest of the batteries in large cars will probably also become maintenance-free. (5, 149-150.)

3.1 Current automotive battery technologies

CO_2 emission, exhaust gas pollution and fuel consumption are real concerns in present time. In automotive industry, batteries have been one of the main focuses in recent years. Many of the technologies have been used for a long time and are still being used, such as lead-based batteries. These technologies have become indispensable, but they need improvement.

A battery is a device that stores direct current. When the battery is charged, it converts electrical energy into chemical energy. When discharged, the chemical energy is converted into direct current energy. Cost and performance have slowed the proliferation of batteries for use in mobile use. The energy density of the batteries (Wh/kg or Wh/l) has been quite low. Because of this, batteries have been needed a lot, which significantly increases the weight and size. (6.)

It is also good to note that by increasing the power density (W/kg or W/l), the battery can be used with higher charging and discharging capacities. The downside is that the energy density decreases. In mobile use, the battery pack consists of several individual batteries. Batteries can be divided into two categories, namely energy batteries and power batteries. Energy batteries can be discharged with much less power for a longer period of time. Power battery energy is obtained for a short time at high current. (6.)

The types of batteries used in mobile use are usually a lead-acid battery, a nickel metal hydride battery (NiMH) and a lithium-ion battery (Li-ion). Figure 3 shows the energy and power densities of a few battery types and energy sources.

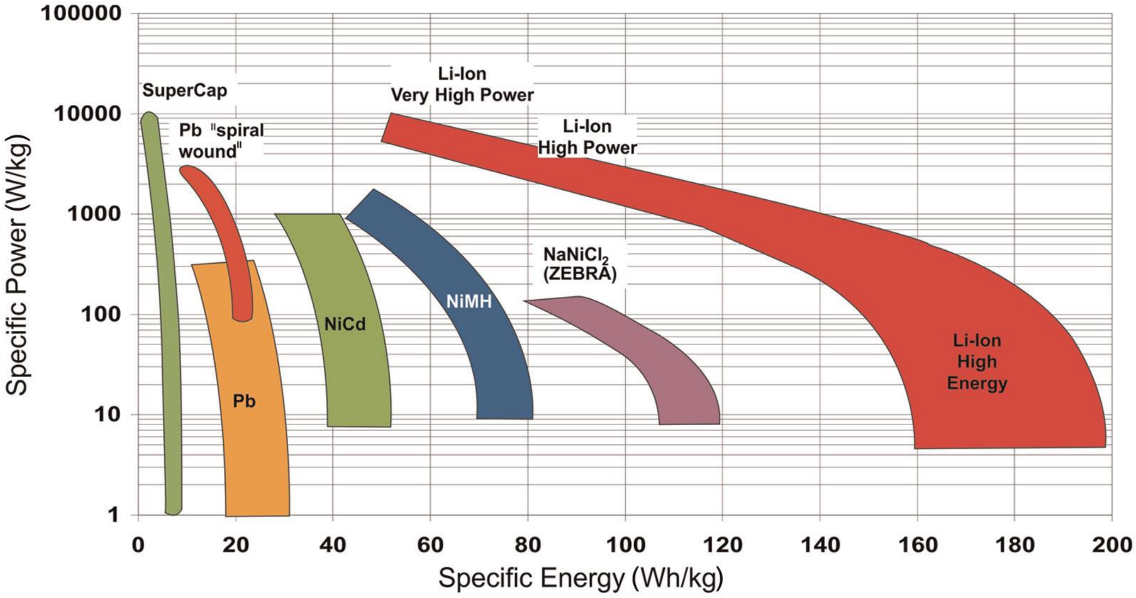


FIGURE 3. Ragone plot of various battery technologies with specification at cell level for automotive applications. (7, 766.)

3.2 Challenges in the development of Li-ion batteries

Production of Li-ion batteries for automotive technology has improved considerably over the past decade. However, the transfer of developments in materials, cell design and processes from lab scale to production scale remains a challenge due to the large number of consecutive process steps and the significant impact of material properties, electrode compositions and cell designs on processes (8, 4.). In order to support the fast-growing electromobility sector, climate change, energy transition and sustainability, all require innovative technologies. Alternative drive concepts must be discovered in order to slow down the climate change and reduce the CO2 emissions, and that's where development in battery manufacturing comes to a significant importance. The biggest challenges for battery design are energy and power density, charging time, life, costs, and sustainability. (8, 5.)

Battery life is crucial for optimizing applications and significant where safety and reliability are involved. Irregular current density distribution, inadequate control of the recharge and discharge cycles and thermal management may increase the risks of battery failure. Furthermore, metal deposition which creates short circuits can also decrease in productivity and increase runaway heating. (8, 7.)

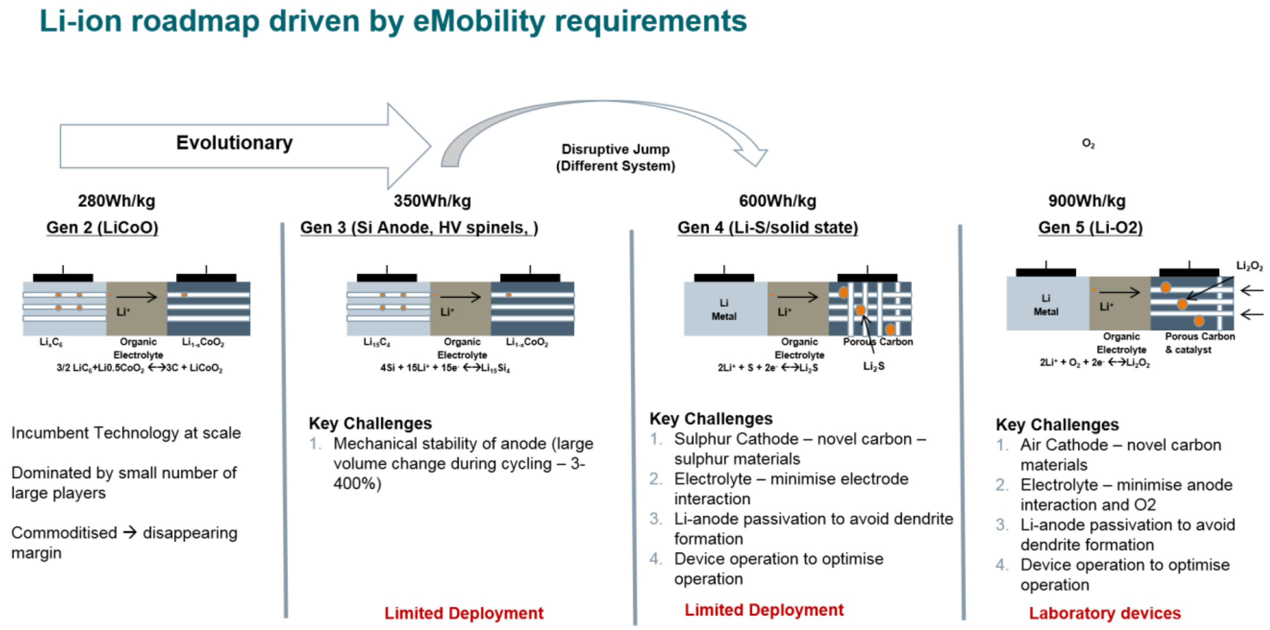
The development of new batteries also must include the aspect of sustainability. A well-planned strategy is needed for mining, recycling, producing, and disposing of new battery. The EV industry has pressure to figure out recycling and prevent unnecessary waste of batteries after their life cycle. Manufacturers and government need a well-planned strategy for mining, recycling, producing, and disposing of new battery types. (8, 7.)

Batteries are the most expensive components of an electric vehicle (7, 755.). Although the costs for batteries have reduced considerably over the last decade, the costs of batteries are still higher when compared to combustion engines. The manufacturing of high-power batteries and electric powertrains is not as optimized as for mechanical powertrains of combustion engines. Major technical breakthroughs are needed in rechargeable battery chemistries to make electric vehicles economically viable.

New battery designs are set to be lighter in weight and must carry more energy, but these outlines set many different challenges on the battery designs. The amount of energy that can be stored in the battery is dependent on the amount of lithium ions that can be stored in the anode, and this is the area where the new research and development is focused.

The chemistry and design of batteries limit the energy density, which limits the theoretical energy density, even without losses. Electrode material and the composition of the electrolyte defines the chemistry. For example, lithium-air batteries offer great potential efficient-energy storage applications because of their extremely high theoretical energy density, which is close to the energy density of gasoline. However, technical limitations have to be considered before their safe implementation, such as the components necessary for thermal management and the total weight of the battery system. The design of these components can substantially influence the energy density of a battery system. Additionally, a high-power density is needed for recapturing energy in a short period of time, such as through fast recharging or regenerative braking. This means that the battery must be able to cope with high current densities through recharge. (8, 10.)

Figure 4 illustrates Li-ion roadmap and key challenges for mobility applications.



Incumbent Technology at scale

Dominated by small number of large players

Commoditised → disappearing margin

Key Challenges
1. Mechanical stability of anode (large volume change during cycling – 3-400%)

Key Challenges
1. Sulphur Cathode – novel carbon – sulphur materials
2. Electrolyte – minimise electrode interaction
3. Li-anode passivation to avoid dendrite formation
4. Device operation to optimise operation

Key Challenges
1. Air Cathode – novel carbon materials
2. Electrolyte – minimise anode interaction and O2
3. Li-anode passivation to avoid dendrite formation
4. Device operation to optimise operation

FIGURE 4. A roadmap for Li-ion batteries for mobility applications. (9.)

3.3 Batteries used in electric cars

Electric cars very much determine the type of application required for the application of the electric vehicle. Good performance characteristics are required for batteries in both all-electric cars and plug-in hybrids.

Ten most sold electric vehicle models worldwide in 2019 and 2020 all use lithium-ion batteries (10, 3.). Lithium-ion batteries have technically replaced all other battery types used in electric vehicles, such as nickel-metal hydride (Ni-MH) batteries, but they remain in use as the main source of energy storage in some HEVs, such as in 2020 Toyota Highlander – model. The high charge-to-weight ratio of lithium makes the lithium-ion battery much lighter than the Ni-MH battery, which is desirable for powering electric vehicles (11.). Another disadvantage of Ni-MH battery is its “memory effect” which lithium-ion batteries don’t have. Patent encumbrances of Ni-MH batteries has also limited the use of these batteries in automotive industry (10, 3.).

3.4 Future battery prospects

The energy storage of electric cars has not yet reached such an extent that an electric car could be used in the same way as an internal combustion engine. Today, most common battery systems are Li-ion and lead-acid. Both systems have their own limitation and challenges, thus looking for a better solution is necessary. In following chapters are some of the most promising experimental batteries. (5, 601.)

3.4.1 Lithium-sulfur battery

In a lithium sulfur battery, the anode is made of lithium and the cathode of sulfur. The energy density of lithium-sulfur batteries is three times that of a lithium-ion battery. During the battery discharge cycle, the lithium dissolves from the surface of the anode, and during the charging cycle, the lithium attaches back to the anode. The challenge with lithium sulfur batteries is the limited cycle life of only 40-50 charges / discharges. The shortness of the cycle life is due to the release of sulfur from the cathode during the cycles and its contact with the lithium of the anode. Eventually, the lack of sulfur in the cathode will cause the battery to die. Lithium sulfur batteries also have problems staying stable at high temperatures. Researchers at Stanford University have conducted experiments with nanowire and graphene to get rid of the problems a lithium-sulfur battery has. They have obtained promising results from their experiments. (5, 75.)

Figure 5 shows the operating principle of lithium sulfur battery, how charging and discharging of the battery happens. When lithium-sulfur battery discharges, lithium dissolves from the anode surface and reverses itself when charging by plating itself back onto the anode.

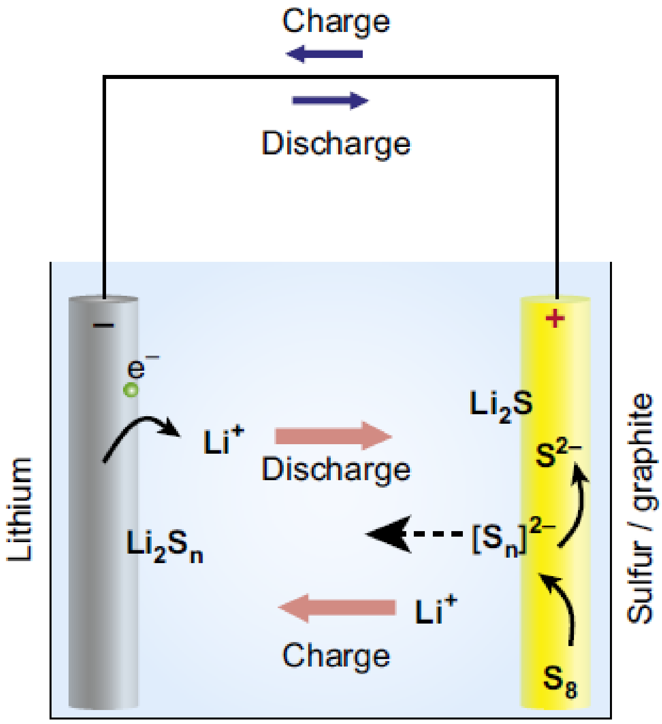


FIGURE 5. Lithium-sulfur battery operating principle. (5, 76.)

3.4.2 Lithium-air battery

In a lithium air battery, the anode is made of lithium metal and the cathode is typically a porous carbon material that brings oxygen from the surrounding air. The liquid electrolyte connects the anode and cathode while facilitating the movement of ions between them. When lithium is oxidized, electricity is discharged from it and during charging the process reverses. Lithium-air batteries could theoretically have an energy density of 13 kWh / kg, which roughly corresponds to the energy density of petrol. By comparison, Tesla Model S lithium-ion batteries produce 248 Wh / kg (8, 13.). The life cycle of a lithium-air battery also needs to be improved, as the battery cycle time is currently set at 50 charge-discharge cycles. (12.)

Air contaminants also cause problems for the lithium air battery, so the air must be filtered before it reaches the battery. One more problem is the sudden death of the battery due to lithium peroxide particles formed by lithium and oxygen. Lithium peroxide particles create a barrier that prevents the movement of electrons. As a result, the energy storage capacity of the battery collapses. Researchers are trying to solve this problem by adding additives to the battery to prevent the formation of particles. (12.)

Figure 6 shows the operating principle of lithium-air battery, and how air works with lithium in battery discharging and charging process. During battery discharge, the lithium in the anode is oxidized, and the positively charged lithium ions pass through the electrolyte to the cathode, where they react with oxygen molecules. Lithium oxide and lithium peroxide are formed in the cathode. During battery charge, the lithium metal plates onto the anode and frees dioxygen at the cathode. (13.)

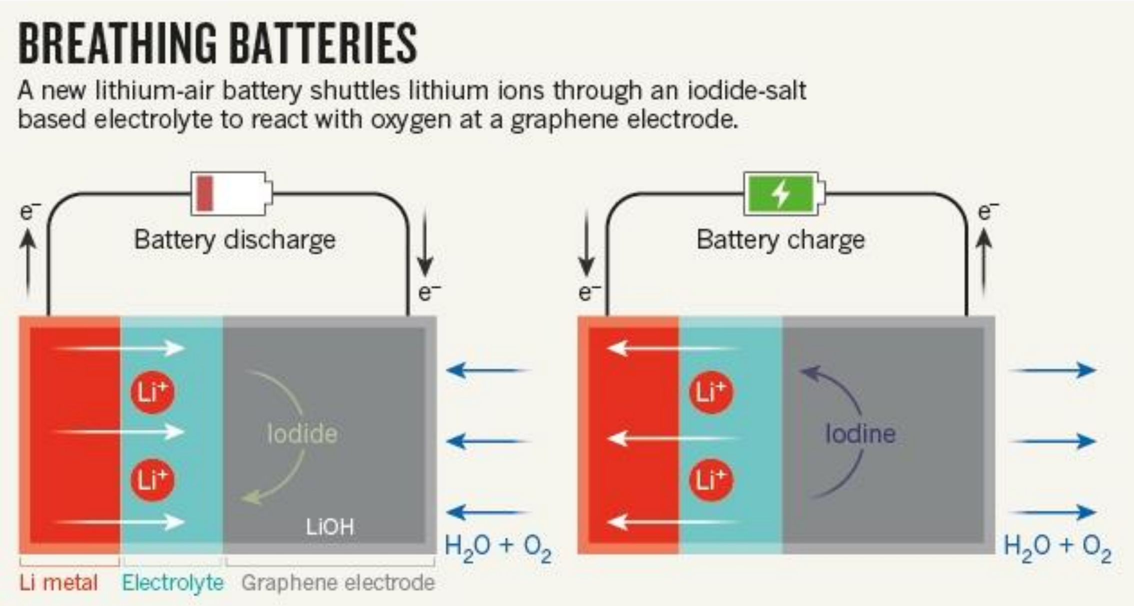


FIGURE 6. Lithium-air battery operating principle. (13.)

3.4.3 Solid-state battery

Solid-state lithium batteries have a solid lithium as an anode and a solid polymer composite as a cathode, and a separator is also solid. Solid-state batteries are promised to have twice the energy density of a lithium-ion battery, doubling the car's range without increasing car weight. Another problem with solid-state batteries is that solid lithium expands and contracts during charging and discharging cycles and this causes cracks on the lithium surface. Dendrites begin to accumulate in the cracks and eventually cause a short circuit in the battery. In addition, the challenges are to achieve sufficient electrical conductivity at cold temperatures and to increase the number of charge-discharge cycles. (12.)

Prototypes of solid-state batteries have reached a lifetime of only 100 charge-discharge cycles, so there is still a distance of about 1,200 to 1,500 charge-discharge cycle lines for a lithium-ion battery, equivalent to 366,000 miles (589,020km) in the car's odometer. According to Bosch, Solid-state batteries could be on the market in 2020 and car batteries in 2025. (12; 14.)

Figure 7 represents the operating principle of solid-state battery, and how charging and discharging of the battery works. Electrons move between cathode and anode, depending on the type of electrolyte chosen, either along inorganic crystal structures or polymer chains along.

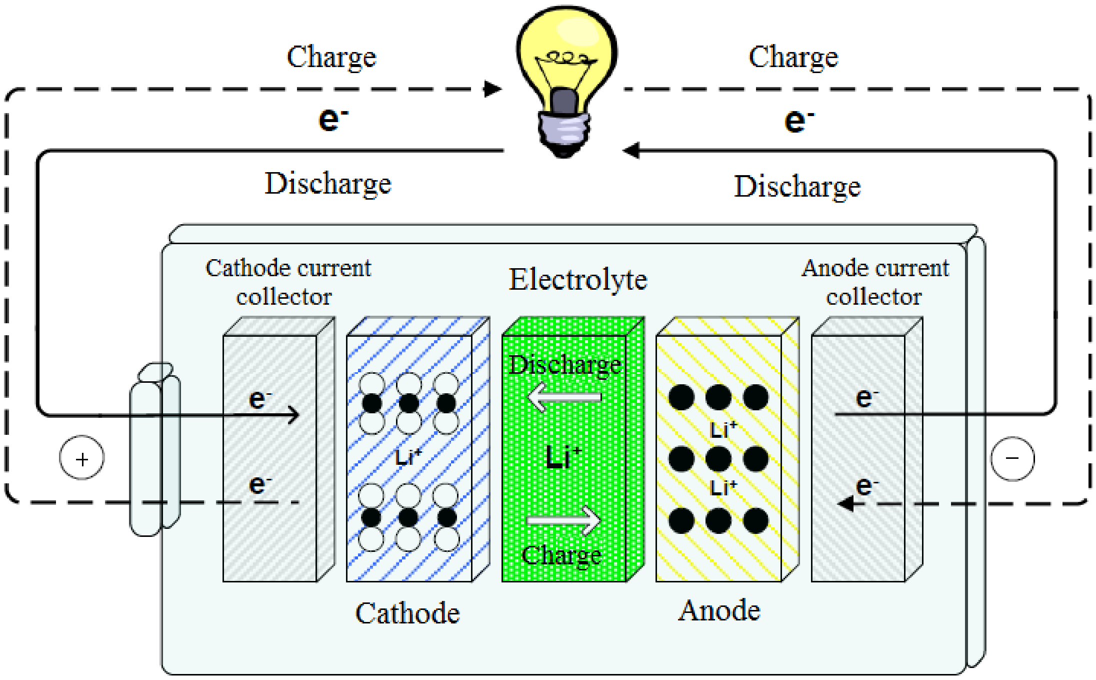


FIGURE 7. Representation of a solid-state battery charge/discharge. (15.)

3.5 Types of Lithium-ion batteries

Lithium-ion batteries are considered the leading battery technology for many portable electrical devices, tools and electric cars, and increasingly for electricity storage (11.). Millions of people around the world use lithium-ion batteries, e.g. in cell phones, laptops and cameras, and hybrid and electric cars.

Lithium has a high electrochemical voltage and therefore a high energy density. Lithium is also the lightest of the metals, making it well suited for battery use. Lithium-ion batteries use a wide variety of electrodes and electrolytes. Compounds such as Lithium cobalt oxide (LiCoO2), Lithium manganese oxide (LiMn2O4), Lithium nickel oxide (LiNiO2), Lithium iron phosphate battery (LiFePO4) and various lithium manganese oxide compounds are used as the positive electrode. As the positive electrode, graphite, amorphous carbon, lithium titanate, tin, silicon alloys, silica and tin dioxide are used. Electrode selection has an effect on battery characteristics such as service life, price, safety, individual cell voltage, energy density, and specific energy. There are also a wide variety of electrolytes used. There are organic liquid electrolytes consisting of carbonates or esters, as well as salts. Solid electrolytes are also used. (5, 542.)

On the downside, lithium-ion batteries have a higher price than lead-acid batteries, the inconvenience of the recycling process, and safety risks. Some lithium-ion batteries deteriorate when discharged to a voltage of less than 2 volts (V), while poorly withstand excessive charging. Lithium-ion batteries do not withstand high temperatures (65 °C) as well as lead-acid batteries and can be dangerous if charged quickly at low temperatures (<0 °C). (16, 727.)

3.5.1 Lithium Manganese Oxide - LMO

The cathode of the LMO battery consists of lithium manganese oxide (LiMn2O4) and the anode is graphite. The battery has a nominal cell voltage of 3.7 V and an operating range of 3.0 to 4.2 V. The energy density is 100 to 150 Wh. The advantages of battery chemistry are safety and high instantaneous current dissipation. The disadvantages are low energy density and short service life. (17, 24.)

LMO battery chemistry has been used in Nissan Leaf's first-generation battery pack (24 kWh, manufactured by AESC). According to some sources, this is a mixture of LMO and LNO chemistry based on LMO chemistry. LMO batteries have also been improved by combining LMO and NCM chemistry to combine the strengths of both chemistry, such as the momentary current carrying capacity of the LMO and the energy density of the NCM. (17, 24; 18.)

Figure 8 shows the marginal characteristics of lithium manganese oxide battery.

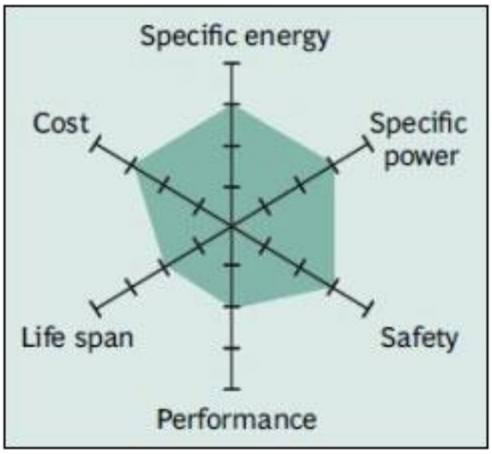


FIGURE 8. Characteristic representation of lithium manganese oxide battery. (18.)

3.5.2 Lithium Nickel Manganese Cobalt Oxides - NCM

Lithium nickel manganese cobalt oxides (abbreviated Li-NMC, LNMC, NCM or NMC) battery chemistry is based on a combination of nickel, cobalt, and manganese. The cathode type is lithium-nickel-cobalt-manganese oxide with the chemical formula $LiNi_xCo\text{-}_yMn_zO_2$. In the formula, x, y, and z are the ratios of nickel, cobalt, and manganese relative to each other (x + y + z = 1). Previously, the most common NCM compound was NCM111 (Lithium-Nickel $_{0.33}$, Cobalt $_{0.33}$, Manganese $_{0.33}$, Oxide $_2$) with equal amounts of nickel, cobalt, and manganese. (18.)

Due to the high price of cobalt, battery manufacturers have sought to increase the proportion of nickel in the compound. Today, the most common compounds are NCM523 (Nickel 50%, Cobalt 20%, Manganese 30%) and NCM622 (Nickel 60%, Cobalt 20%, Manganese 20%). The latest compound, NCM811 (Nickel 80%, Cobalt 10%, Manganese 10%), is fast becoming the most popular NCM compound. In September 2019, 18% of the batteries for electric cars manufactured for the Chinese market were NCM811 chemical batteries, calculated based on battery capacity. Globally, production volumes of batteries for this chemical are growing and at 7%, it is expected to increase in 2020 in Europe as well as in North America. The advantages of NCM chemistry are the high energy density of 150–220 Wh / kg and the instantaneous current transfer capacity. (18; 19.)

Figure 9 shows the marginal characteristics of lithium nickel manganese cobalt battery.

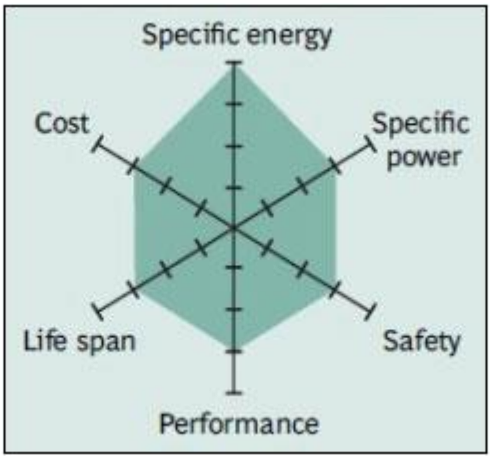


FIGURE 9. Characteristic representation of lithium nickel manganese cobalt battery. (18.)

3.5.3 Lithium Nickel Cobalt Aluminium Oxides - NCA

The lithium-nickel-cobalt aluminum battery (LiNiCoAlo2), or NCA for short, is one of the major lithium-ion motion-based technologies currently on the electric vehicle market. The NCA battery was developed in 1999 as a follow-up to lithium nickel oxide. Aluminum was added to the cathode to stabilize the cell. Cobalt increases the energy storage capacity of the cell. The nominal voltage of the NCA cell is 3.6 V with a voltage ranging from 3.0 V to 4.2 V. The advantages of the battery are a high energy density of 200 to 260 Wh / kg and a long service life. The disadvantages are considered to be safety due to the low thermal escape temperature, the high cost and the unethical production of cobalt. The amount of nickel in the cells has been increased at the expense of cobalt. (18.)

Figure 10 shows the marginal characteristics of lithium nickel cobalt aluminum battery.

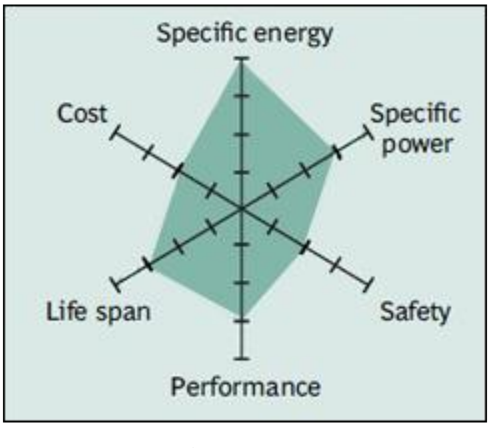


FIGURE 10. Characteristic representation of lithium nickel cobalt aluminum battery. (18.)

3.6 Lead-acid battery

The vehicle's starter battery, also called SLI battery, consists of six lead-acid cells with a nominal voltage of 2 V connected in series. Lead cells are composed of positive and negative plates, which in turn consist of a lead lattice and an active substance of about 37% sulfuric acid. Lead-acid batteries have become known, for example, as starter batteries. They are designed to provide momentarily hard currents. These types of batteries are also called power batteries. The car's lead-acid battery can momentarily supply up to 800 A. Starter batteries must not be discharged very much and a deep discharge will significantly shorten the life of the battery. Starter battery capacities are typically about 40-200 Ah. (20, 107.)

Batteries used in local batteries, such as photovoltaic systems, and batteries in trucks and other mobile devices are energy batteries. The energy battery and the power battery are similar in structure. Energy batteries have a large capacity, meaning they can store more energy than power batteries. An energy battery like this cannot momentarily provide as much power as a power battery. (20, 108.)

3.7 Nickel-based batteries

Nickel batteries came after lead-acid batteries as a new battery technology. The most common of these are nickel-metal hydride (Ni-MH) and nickel-cadmium (Ni-Cd) batteries. The advantage of nickel-cadmium is a higher charging and discharging current and a longer life cycle compared to a nickel-metal hydride battery. The positive electrode of the Ni-Cd battery is made of nickel hydroxide and the negative one is made of cadmium. The electrolyte is a potassium hydroxide solution. The positive electron of the Ni-MH battery is nickel hydroxide, and the negative electron is a metal hybrid. Potassium hydroxide also acts as an electrolyte in the nickel-metal hydride battery. (21.)

The self-discharge of Ni-Cd batteries is relatively high. The first time you charge the battery, you usually need to charge it for a relatively long time, about 24 hours. Only after 2-3 charges the battery reaches its full capacity. Capacity decreases over time, but lasts well for about 800 to 1000 cycles, i.e., charge and discharge cycles. One of the disadvantages of a nickel-cadmium battery is its memory. If it is continuously discharged in the same amount and sometimes not completely discharged, its electrical charge capacity decreases to the amount of discharge used. Nickel-cadmium batteries have been banned in the EU since autumn 2009, except for specifically stated uses. The reason for the ban is the cadmium it contains, which is a poison that is dangerous to humans and the environment. (21.)

A nickel-metal hydride battery also suffers from a memory phenomenon like a nickel-cadmium battery, but the phenomenon isn’t that strong. A Ni-MH battery has a higher capacity but a shorter life than Ni-Cd batteries. The nickel-metal hydride battery suffers from severe self-discharge and has a low current carrying capacity compared to a nickel-cadmium battery. A nickel-metal hydride battery is also toxic to the environment because of the nickel it contains, which is why it is classified as hazardous waste. (21; 22.)

3.8 Types of battery cells

The batteries are divided into different types of construction, the most popular of which are prismatic, cylindrical and pouch cell constructions, but the final choice between construction types is made according to the application. For example, the design of pencil-sized batteries is a cylindrical cell model, and this is also the design model favored by the electric vehicle and battery manufacturer Tesla (8, 15.). The characteristic shape of prismatic batteries is a rectangle of varying thickness. This battery model can be found, for example, in phones, tablets and some laptops. Pouch cells are most often used in vehicles because of their compactness and lightness. The actual outer shell does not weigh very much and allows more life for the battery during use. However, living results in delamination of the cathode, anode, and insulator within the battery, resulting in clearly impaired battery performance. It is therefore good for batteries to have compression so that they do not swell so easily, and therefore the pouch cells have one bigger common case to protect them. Designs of mentioned battery cells are seen in Figure 11.

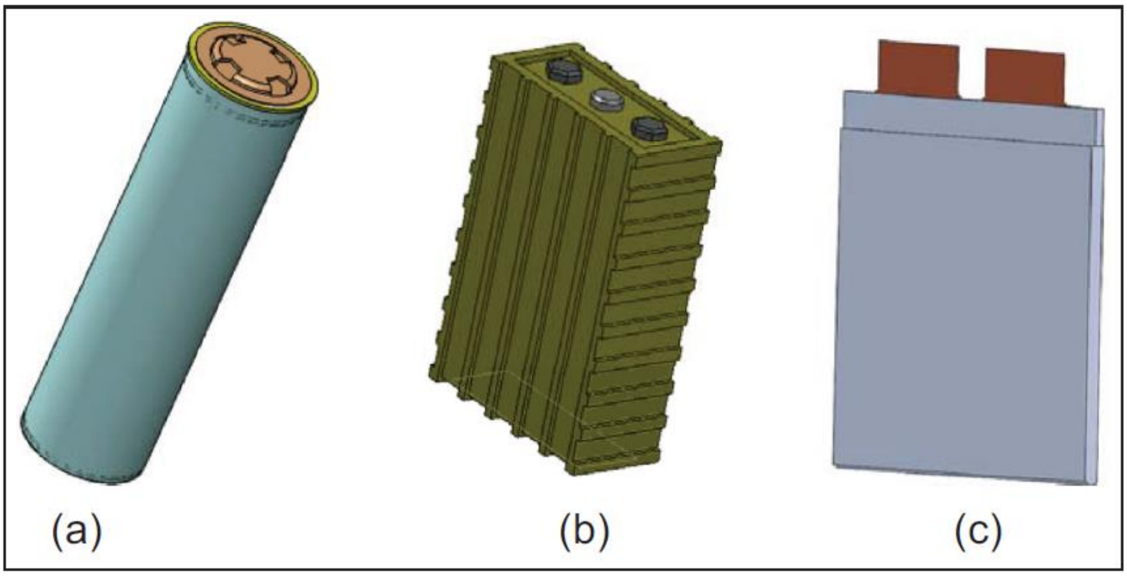


FIGURE 11. Various cell designs: (a) cylindrical; (b) prismatic; (c) pouch. (7, 768.)

3.8.1 Cylindrical cell

The cylindrical cells are layered with a metal rod-like structure. They consist of a metal outer shell with a cathode and an anode wound inside it, with insulation between them. The insulator is a very thin perforated plastic and is impregnated with ether electrolyte. At one end the cell has a negative anode and at the other a positive cathode pole. Cylindrical batteries withstand physical stress very well, and because of their construction, they also withstand internal pressure well, which prevents delamination, which would result in reduced battery life. For this reason, cylindrical batteries do not usually swell, but they have a pressure relief valve for safety. In some models, the valve closes again when pressure has been released from the battery, but in most models, the valve acts as an electrical fuse and is disposable at the same time. At the same time as the valve opens, liquid, electrolyte in this case, may leak from the battery and the battery may dry out, either partially or completely, after which the battery will either not work, or its function will deteriorate substantially. (23.)

Some cylindrical models also have a PTC - switch, which stands for Positive Thermal Coefficient Switch, which switches to a non-conductive state due to excessive heating of the battery. Heating is often caused by a short circuit in the device, which causes the current delivered by the cell to become too high. When the short circuit is removed and the battery has cooled down sufficiently, the PTC – switch returns to the conductive state. It is worth noticing, however, that not all cylindrical batteries have this PTC – switch, although it is being installed to majority of cylindrical cells. (23.)

An exploded-view drawing of a cylindrical cell is shown in Figure 12.

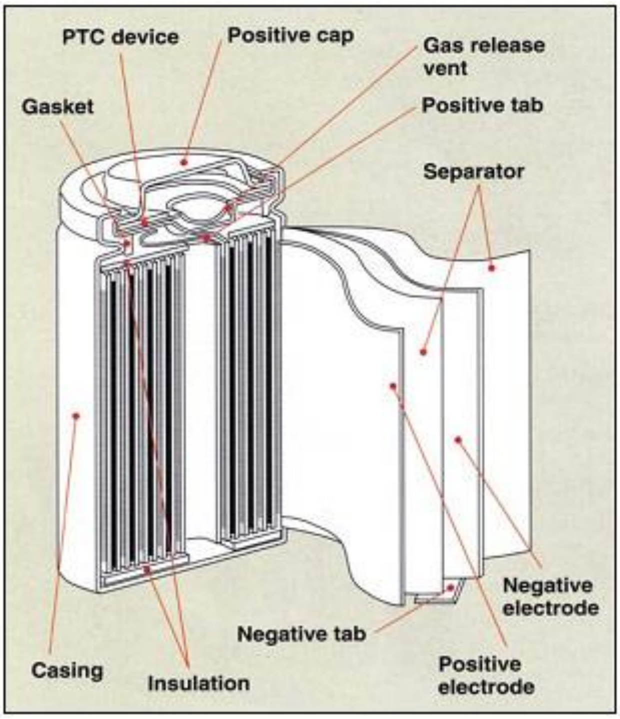


FIGURE 12. Cross section of a lithium-ion cylindrical cell. (23.)

3.8.2 Prismatic cell

Prismatic batteries are very similar in content to cylindrical ones, but the interior materials are layered in a box-like shape. Batteries are often thin packages designed to fit directly into a device. This is a design that is less commonly used in passenger vehicles, but there are also larger in-vehicle batteries that are commonly used in heavy equipment. Prismatic batteries used in vehicles are often packages made in a welded aluminum housing. (23.)

The most common use for prismatic batteries is with portable electronics such as computers, phones and tablets. The prismatic design of the battery allows the battery to swell somewhat well thanks to the two larger sides. For example, you can find cells about five millimeters thick in cell phones, for which it is normal to swell up to eight millimeters after 500 cycles, which means that it is normal for a battery to swell up to 60%. At this point, however, the battery is still delaminated and its capacity has been significantly reduced. In many cell phones and other everyday electronic devices (tablets, laptops, etc.), the battery is encased in plastic, allowing it to have some compression to keep the lamination piled up. The most important thing when swelling is to make sure that the battery itself does not press on the electronics of the device after swelling, and if the battery swells even more, it should be taken out of service due to the risk of explosion. (23; 24, 7.)

An exploded-view drawing of a prismatic cell is shown in Figure 13.

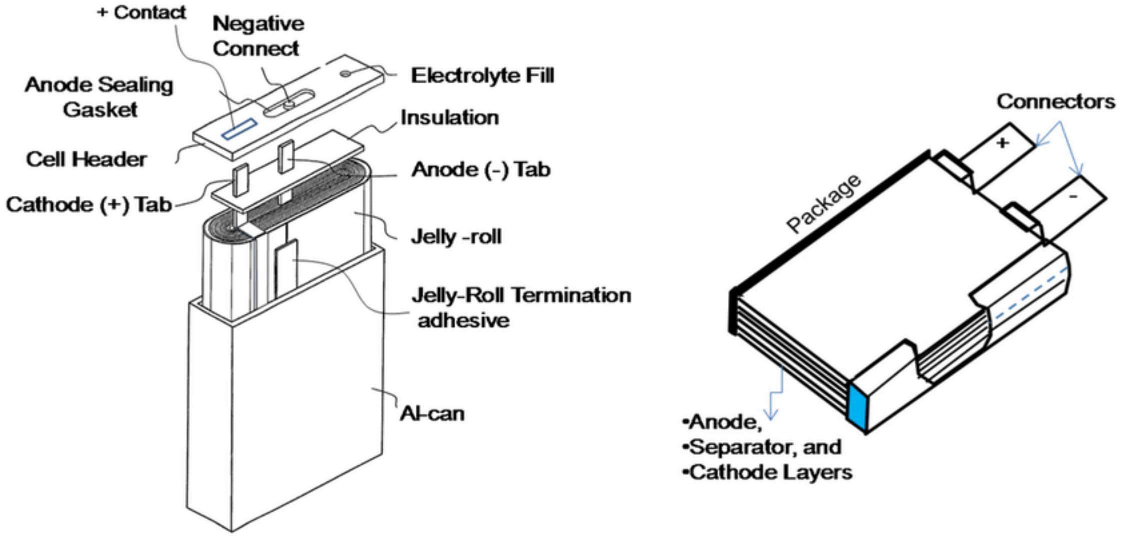


FIGURE 13. Cross section of a lithium-ion prismatic cell. (25, 10.)

3.8.3 Pouch cell

The pouch cells are the lightest in terms of construction and space management, as well as a really popular solution for vehicle use, as battery packs can weigh several hundred pounds. For example, if the pouch cell achieves a weight gain of 20% compared to cylindrical and prismatic ones, which is achieved with polymer batteries, the benefit is already with a 300 kg package of 75 kg, which corresponds almost to the weight of an adult man. Often, battery packs weigh even more, so any weight that is removed from the batteries is an advantage to the economy, controllability, and performance of the vehicle. The structure of the pouch cell with respect to the cathode, anode and insulator differs somewhat from the cylindrical and prismatic cell structures in that there is insulation between the cathode and anode parts as in other solutions, but it is possible to have two layers of each material and a collector between them. Both collectors are thus both between the two cathodes and the anode and are routed outside the bag as poles. The disadvantage of the pouch structure is especially the swelling of smaller cells. Already after 500 cycles, 8–10% swelling of the cells has been observed, but the corresponding swelling of the larger 40 Ah cells occurs at 5,000 cycles. Therefore, when making the battery, it is necessary to take into account the swelling in the housing and the tearing in the bag caused by possible sharp edges. (23.)

An exploded-view drawing of a pouch cell is shown in Figure 14.

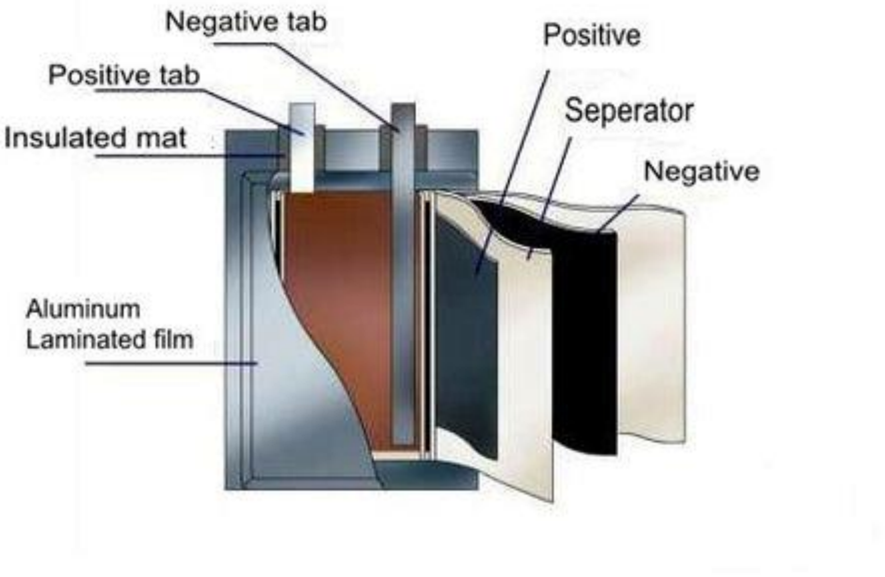


FIGURE 14. Cross section of a lithium-ion pouch cell. (26.)

3.9 Internal protection devices in 18650 Li-ion batteries

Battery packs that use Li-ion, require a mandatory protection circuit to ensure safety under all circumstances. The name “18650” derives from the battery’s specific measurements, 18 millimeters by 65 millimeters. Governed by international standard IEC 62133-2, the safety of Li-ion cells or packs begins by having some or all of the following safeguards. (23.)

1. Built-in PTC (Positive Temperature Coefficient), which protects the battery against current surges.
2. CID (Current Interruption Device), opens the circuit at a cell pressure of 1,000 kPa.
3. Safety vents that release gases on excessive pressure buildup at 3,000 kPa.

The placement and representation of safety mechanisms of 18650 cylindrical battery cell is shown in Figure 15.

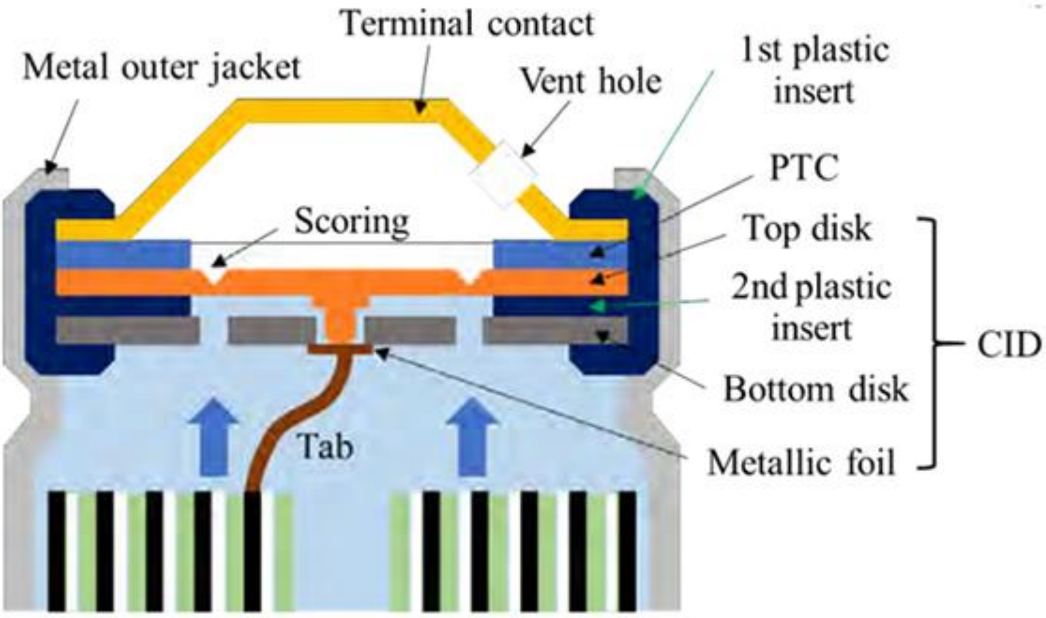


FIGURE 15. Typical safety mechanisms of the 18650 battery cell. (27.)

Although cylindrical 18650 batteries have these internal protection devices, there have been controversial results on the safety of PTC and CID in multi-cell configurations. Series and/or parallel configurations have experienced thermal runaway under various test conditions. (28.)

3.9.1 Positive Temperature Coefficient - PTC

A positive temperature coefficient (PTC) thermistor is a small round disk located inside of the cylindrical battery, on the positive terminal side. PTC protects against overheating and indirectly overcurrent. PTC works as an internal protective device that are found in majority of 18650 batteries. PTC is designed to cut off the circuit when the temperature rises abnormally and is resettable; if the battery temperature decreases back to its normal range, the PTC thermistor will revert to the low resistance state and this way, the battery is able to operate the normal way (29, 1.). A PTC thermistor reduces the flow of electrical current when an external short occurs. The PTC thermistor's resistance increases when the battery temperature increases due to an external short circuit. In this way, the battery current and the corresponding ohmic heating effect is greatly reduced. (23.)

3.9.2 Current Interruption Devices – CIDs

The current interrupt device (CID) acts as a fuse-type device that permanently cuts off the electrical circuit into an open circuit state when triggered either by excessive cell pressure, high temperature, or high voltage, depending on the design. As seen in Figure 15, the CID operates by pressure. When the internal pressure in cylindrical cell increases to around 1,000 kPa, the scored top disk (orange disk) breaks and separates from the metallic foil (brown tab) and disconnects the current flow. After breakage of the top disk, the gas is able to be vented out. (29, 1.)

3.9.3 Protection Circuit Board – PCB

Fairly uncommon protection device and that is not under any standards is Protection Circuit Board, referred as PCB, which some cylindrical cell models have installed inside them. Mainly used in lower voltage battery packs, protection circuit board or module (PCB or PCM) works quite much the same way as the battery management system does, detecting the overvoltage, overcurrent, overtemperature, undervoltage and short circuit and protecting from them. PCB monitors the status of each single cell in the battery pack. PCB is mainly used in flashlights and is highly recommended for older Li-ion batteries, and is not recommended for high-drain applications, as it limits the battery's discharge to 6A. (30; 27.)

3.10 Batteries used in solar energy storage systems

There are no batteries suitable only for solar energy storage systems, but there are many batteries suitable for use in photovoltaic systems. In photovoltaic systems, the goal of electricity storage is to stabilize the electricity grid or to transfer revenue over time. The battery is always system-specific, as the controls and the scope of the system impose requirements on the battery that the selection must be made. Batteries can be divided into three main groups according to their structure: flooded, sealed and gel batteries. Leading charge controller manufacturers have taken these structural differences into account. In a grid-scale production plants, Li-ion battery is the most common type of battery used. (33.)

Flooded lead-acid batteries have traditionally been used in cottage applications based directly on their purchase price and functionality. For maintenance, the charge level of an open battery can be measured with an acid meter, and water can be added after a charging failure, which is usually the result of an incorrect or faulty charging controller. These batteries are also referred to as maintenance-free batteries, as the advanced cap and lid design of existing batteries recycles hydrogen gas, keeping water addition to a minimum. An open local battery is characterized by its good cyclic durability and long service life and the disadvantage of low charge voltage maintenance. (34, 2.)

There is no need to add water to sealed batteries throughout their life cycle, and their low gas evolution and placement in different positions allow for optimal space utilization. Following the battery manufacturer's charging instructions, a sealed battery requires a more precise charge controller due to its design. This information can usually be found in the battery manual. (34, 3.)

AGM (Absorbed Glass Mat) batteries are sealed batteries, but they absorb battery acid in fiberglass sheets installed between the lead plates. This structure achieves a high current output structure and more lead plates can be placed in the battery, as the fiberglass plate is much thinner as an insulator than liquid alone. The AGM battery works well as a starter battery. The AGM battery does not leak acids or release hydrogen gases into the environment during charging, so it can be installed in any position without a separate battery box. The AGM battery has a long life when used properly and has a better charge capacity than a traditional sealed battery. (31; 34.)

In a gel battery, the electrolyte is absorbed into the jelly-like gel. The gel battery is suitable for use with fast cycles and can withstand undervoltage. They must be charged with temperature compensation and must not be installed unless you are sure that they are suitable for charging. The gel battery can be placed in a position-free manner and without a separate battery box, as it does not emit hydrogen gas or leak acids. Gel batteries are very resistant to cold, so frost does not break them in itself. (32; 16, 74; 34.)

4 BATTERY FAILURE

The design and use of batteries must consider the specific safety features of the batteries. High energy density, high short-circuit currents, high voltages in the batteries pose electrical risks, and there are other safety risks associated with batteries, in addition to which five well-known risk factors are:

- chemical risks
- electronic risks
- the risks posed by the circumstances
- risks due to malfunctions
- ageing (35, 10.)

In the following chapters, the common causes of battery failure, which include the five above-mentioned are explained.

4.1 Chemical risks

Chemical risks in Li-ion batteries are caused by the chemicals they contain, such as the electrolyte, which can be corrosive as well as flammable. If the battery is subjected to excessive mechanical stress and breaks or tears, the electrolyte may leak out, causing damage to surrounding materials or people. If a battery is exposed to fire or other exposure to high temperatures, gaseous and combustible compounds will produce toxic combustion gases. (35, 11.)

4.2 Electronic risks

Li-ion batteries contain a considerable amount of electrical energy, which is why, for example, short-circuit currents are considerable. High currents can cause the conductors to heat up, which can result in fires or other thermal damage, or they can break other electrical systems. Batteries also use high voltages, which can be hundreds of volts and, due to the high voltage, pose a risk of electric shock. (35, 10.)

Battery management systems control the discharge and charging currents of the batteries, but in the event of a fault condition or an internal short circuit, the protection may not work. The Li-ion battery also poorly tolerates overcharging and deep discharge, which can cause heating during charging and thermal hardening as a result of heating. Overcharging or deep discharge also causes internal damage to the battery electrodes, which shortens the battery life and increases the risk of an internal short circuit, especially at the end of the battery life. Overcharging or deep dis-charge may occur when using the wrong type of charger or when using the battery in the wrong type of device. (35, 11.)

4.3 The risks posed by the circumstances

The conditions surrounding the batteries have a significant effect on their lifespan and safety. In humid conditions, the insulation resistance of batteries can deteriorate and thus cause leakage currents in parts originally designed to be de-energized, where there is a risk of electric shock. If moisture comes in contact with the lithium in the battery, the lithium will react violently with combustion. (35, 11.)

High temperatures can lead to thermal eruption, which can cause the battery to burn out uncontrollably and may even explode. Thermal hardening can result from a chain reaction in which a single exothermic reaction produces heat that triggers the next reaction. Thermal hardening can also occur when the battery is exposed to an external heat source. (35, 11.)

4.4 Risks due to malfunctions

The charging, discharging currents, temperature and voltages of Li-ion batteries are monitored by control systems connected to the batteries, so that the battery can be used safely and has the longest possible service life. Malfunctions of these systems can expose the battery to excessive stress, which can cause the battery to become unstable or shorten its life. For example, battery management systems monitor charging voltages for each battery cell. This prevents overcharging of individual cells. (35, 11.)

4.5 Ageing

The aging of the battery affects its operation. First, this occurs at the electrolyte-electrode interface due to the chemical composition of the cell electrolyte. Aging can be mechanical or chemical and largely depends on the structure/composition of the electrodes. The two main effects are an increase in impedance and a decrease in capacity. (35, 11.)

A solid electrolyte interphase (SEI), i.e. a so-called passivation layer, is formed on the surface of the anode, increasing the impedance of the anode. Formation begins in the early stages of aging and continues to grow with battery use. The SEI increases at the anode as the electrolyte oxidizes to the oxide surface structure, resulting in a decrease in the amount of lithium recycled in the battery. The impedance of the anode increases as the contact surface decreases. In addition to this, the electrodes undergo dissolution, structural degradation and disorganization of the material. In addition to the decrease in capacity due to the decrease in active material, the increase in battery resistance can have a direct effect on the power loss. (35, 11.)

The two types of aging that occur in batteries are calendar and cycle aging. Calendar aging refers to battery storage and the capacity that is permanently lost during use due to low usage. High storage temperatures accelerate side reactions such as metal dissolution, which accelerates the deterioration of battery capacity. Another significant factor is the charge level of the cell. A high charge level generally means a higher amount of lithium ions at the electrodes, which in turn promotes the formation of SEI. (36.)

Cycle aging occurs when a cell is charged or discharged. The same factors mentioned above are also involved in cycle aging, i.e. generally high temperatures increase the loss of charging capacity as well as the increase in impedance. In addition to high temperatures, very cold conditions increase the formation of metallic lithium on the surface of the electrodes. The charge of the cell is of great importance in this case, because at worst, aging can be very rapid. The amount of battery power discharged before the next charge is also important. The study compared the behavior of Li-ion batteries in long-term use by discharging them to a certain level before the next charge. Based on the results, it was possible to find a clear difference in the battery charging capacities with the same number of discharges. A fully discharged battery had significantly more capacity loss compared to a 30% discharged battery. High charging voltages have also been found to contribute to the rapid aging of the battery. (35, 17; 36.)

Studies have identified the need for advanced model-based thermal management strategies. Utilizing these models provides a better understanding of, among other things, the causes of battery degradation and its other internal processes that allow for optimal performance and longevity. (35, 15; 36.)

4.6 Stages of battery failure

Understanding the behavior of Li-ion battery will help in early detection of upcoming failure and possible preventive action if failure is noticed in early stage. Lithium-ion batteries have several ways to fail, and the stages of failure vary somewhat depending on the failure mechanism. A broad definition of stages of failure is possible. (35, 17.)

4.6.1 Initiation abuse factor

A Li-ion battery failure is initiated by a certain type of abuse, whether it’s chemical, electrical or thermal abuse. This stage (Stage 1) of a failure is normally detectable by a battery management system, which is constantly monitoring the physical characteristics of the individual lithium-ion batteries. The amount of time between the initiating abuse factor and the next stage, off-gas generation, largely depends on the type of abuse. For mechanical abuse, such as penetration, where the insides of the cell are immediately exposed, there will be essentially no time between Stage 1 and Stage 2. (37.)

4.6.2 Off-gas generation

The following stage (Stage 2) after initiation abuse factor is off-gas generation. Different form factors lend to different reasons why this happens. For example, cylindrical cells generate off-gassing compounds because of a vent feature of the lithium-ion battery cell. In a pouch or prismatic cell, this will result in cell swelling. For a typical cylindrical design, appreciable swelling will not occur. However, if a cylindrical cell has been sufficiently heated (usually from an external source), the case walls may soften sufficiently to allow bulging of the cell base (38, 27.). Prismatic cell cases may have a vent port installed, usually in large format cells, or may incorporate score marks in them to provide a weak point for case venting (38, 72.). Pouch cells don’t have a vent port, so the cell starts to swell when the gas is being generated. At some point the pouch cell will rupture in the seal which leads to an off-gassing event. When battery management system is not practical, e.g. in shipping or in storage of batteries, an off-gas monitoring should be taken into account and should be detectable by either with smoke alarm which isn’t the greatest solution, or by a third party provider. Off-gas monitoring also provides a viable redundant sensing technique that can be used in conjunction with battery management systems in operational batteries. If the off-gas generation is detected in early phase, a battery failure may be prevented. (37.)

4.6.3 Smoke generation

If no mitigating action is taken after off-gas generation, the battery failure continues to progress. The generation of smoke (Stage 3) is an indication that the cell has reached the stage of thermal runaway and the cell can experience rapid disassembly at any moment. The smoke is being generated from the inside of the battery and because the cell has already experienced a vent or rupture from the off-gassing event, the smoke will be present outside of the cell, similarly to the off-gassing compounds in Stage 2. A smoke detector would be able to detect this stage of a lithium-ion battery failure and differentiate between Stage 2 and Stage 3. (37.)

4.6.4 Fire generation

Once smoke has been generated, the battery cell is in a very unstable state and can experience fire generation (Stage 4) or rapid disassembly at any moment. The cell is in fully developed thermal runaway and is generating its own heat and energy. The cells have metal oxide electrodes which generate their own oxygen during decomposition, adding energy and fuel to the battery fire. In a lithium-ion battery pack, where there are several cells, fire generation from a single cell greatly increases the likelihood of cell-to-cell propagation, where one failing cell can propagate its failure to other cells in the pack, creating a very large and destructive event. This stage of a Li-ion battery failure is detectable by a heat detector. (37.)

4.7 Causes of failure

Battery failures can be roughly set to two basic types. One occurs at a predictable interval-per-million and is connected with a design flaw involving the electrode, separator, electrolyte or processes, and these defects often involve a recall to correct a discovered flaw. The more difficult failures are random events that do not point to a design flaw. It may be a stress event like charging at sub-freezing temperature, vibration, or a fluke incident.

A mild short will only cause elevated self-discharge and the heat buildup is minimal because the discharging power is very low. If enough microscopic metallic particles converge on one spot, a sizeable current begins to flow between the electrodes of the cell, and the spot heats up and weakens. Heat buildup damages the insulation layer in a cell and cause an electrical short. The temperature can quickly reach up to 500°C, at which point the cell catches fire or it explodes. (39, 56.)

4.8 Effects on the health

Lithium-ion battery fires are known to release several toxic gases, such as carbon monoxide (CO) and hydrogen fluoride (HF). According to study made by Nano Energy, Li-ion batteries can emit more than 100 gaseous products, most of which are hazardous to the human beings and trigger negative impact on the environment (40, 3-4.). Toxic emissions highly depend on the battery materials, and state of charge (SOC) as well. The 100% SOC is found to be the most dangerous state in terms of toxicity (40, 5.).
As the safety hazards of Li-ion batteries have been known for years, imposingly shown by several burning devices and cars, the need for further enhancement and research of the safety of these systems are rising.

Toxic emission from lithium-ion battery fires and their health effects are shown in Table 1.

Substance	**Hazards - Effect on Health**
Ethyl Methyl Carbonate (EMC)	Eye irritation; flammable liquid; Skin irritation, specific target organ toxicity-single exposure
Diethyl Carbonate (DEC)	Eye irritation; flammable liquid; Skin irritation, specific target organ toxicity-single exposure
Ethylene Carbonate (EC)	Eye irritation; skin irritation; specific target organ toxicity-single exposure.
Benzene	Aspiration hazard; carcinogenicity; eye irritation; germ cell mutagenicity.

Toluene	Aspiration hazard; flammable liquid; reproductive toxicity; skin irritation; specific target organ toxicity-repeated exposure.
Styrene	Acute toxicity; eye irritation; flammable liquid; Specific target organ toxicity-repeated exposure.
Biphenyl	Aquatic acute toxicity; aquatic chronic toxicity; eye irritation.
Acrolein	Acute toxicity; aquatic acute toxicity; aquatic chronic toxicity; carcinogenicity; corrosive to the respiratory tract; eye damage; flammable liquid; germ cell mutagenicity; skin corrosion; skin sensitization.
Carbon Monoxide (CO)	Acute toxicity; flammable gases; reproductive toxicity; specific target organ toxicity-repeated exposure.
Carbonyl Sulfide (COS)	Acute toxicity; eye irritation; flammable gases; Gases under pressure.
Hydrogen Fluoride	Acute toxicity; corrosive to the respiratory tract; skin corrosion.

TABLE 1. Eleven crucial gas mixture constituents and their hazards. (41, 6.)

Flammable gases are not the only toxic substances in batteries, but the electrode and electrolyte can also be toxic to humans. The risk of contact with electrodes or electrolyte is small but still exists. For example, a leaked battery may come into contact with the electrolyte, so this risk should not be overlooked when handling batteries. Lead-acid batteries use sulfuric acid as an electrolyte, and if the battery is not maintenance-free, there is a risk of contact with sulfuric acid. These risk factors should always be considered when handling batteries. Proper protective equipment reduces the risk of contact with toxic substances. (40, 7.)

4.8.1 Lead

Lead is a toxic metal that can enter the body by inhalation of lead dust or ingestion when touching the mouth with lead-contaminated hands. If leaked onto the ground, acid and lead particles contaminate the soil and become airborne when dry. In adults, lead can cause memory loss and lower the ability to concentrate, as well as harm the reproductive system. Lead is even more harmful for children; excessive levels of lead can affect a child’s growth, cause brain damage, harm kidneys, impair hearing and induce behavioral problems. Lead is also known to cause high blood pressure, nerve disorders, and muscle and joint pain. (42.)

4.8.2 Sulfuric acid

The sulfuric acid in a lead acid battery is highly corrosive and is more harmful than acids used in most other battery systems. Contact with eye can cause permanent blindness; swallowing damages internal organs that can lead to death. First aid treatment calls for flushing the skin for 10–15 minutes with large amounts of water to cool the affected tissue and to prevent secondary damage. Immediately remove contaminated clothing and thoroughly wash the underlying skin. Always wear protective equipment when handling sulfuric acid. (42.)

4.8.3 Cadmium

Cadmium used in nickel-cadmium batteries is considered more harmful than lead if ingested. Workers at Ni-Cd manufacturing plants in Japan have been experiencing health problems from prolonged exposure to the metal, and governments have banned disposal of nickel-cadmium batteries in landfills. The soft, whitish metal that occurs naturally in the soil can damage kidneys. Cadmium can be absorbed through the skin by touching a spilled battery. Since most Ni-Cd batteries are sealed, there are no health risks in handling intact cells; caution is required when working with an open battery. Nickel-metal-hydride is considered non-toxic, and the only concern is the electrolyte. Although toxic to plants, nickel is not harmful to humans. (42.)

4.9 Means of suppression

The lithium-ion battery has several cells depending on the size of the battery. The laptop battery has 6 to 12 cells and the car battery up to thousands. The voltage of one cell is about 3.6 V. The required battery voltage is obtained by connecting the cells in series and the charging capacity by connecting the cell sets in parallel. (43.)

The anode of the cell is graphite that can burn. The electrolyte is a lithium salt dissolved in an organic solvent. The electrolyte can also burn. The cathode is a variety of oxides or phosphates of lithium and other metals that cannot burn. There is nothing in the battery that would cause a hazard when reacting with water. (43.)

The operating temperature of a lithium-ion battery is up to 60 ºC. Its cells can self-heat for several reasons (fault, misuse, short circuit, compression, puncture, high temperature). If the ambient temperature of the cell is above 150 ºC, it will start to heat itself. The temperature of the heating cell rises to about 650 ºC. If nothing is done, cell after cell will heat up inside the battery. (44, 2.)

Extinguishing flames burning outside the battery with an initial extinguisher or suppression does not stop the cells from heating up. Instead, pouring the battery case with water cools it and, indirectly, the heated cells. An additive that reduces the surface tension of the water speeds up cooling, as the extinguisher gets inside the battery to cool the heated cells.

Current standards do not have specific requirements for extinguishing Li-ion battery fires (42.). Standards for Li-ion batteries are published by the Institute of Electrical and Electronics Engineers (IEEE), Underwriters Laboratories (UL), and the United Nations (UN), but they focus only on battery abuse testing to ensure that Li-ion batteries are safe during transportation (45, 8.). Very little research has been made of fire suppression of Li-ion batteries on cell, module and pack levels. Public information on Li-ion battery fire suppression is very limited, and large companies may have good understanding and knowledge of the processes involved and the performance of different extinguishing agents, but the knowledge is most often proprietary information. There are some general advice on how Li-ion safety should be taken into account on various situations, but there is a lack of test methods for fire-fighting systems to be used. Research-based information must be used and utilized in the design of fire-fighting equipment, but the design must always be done on a device-based basis. (44, 14.)

4.9.1 Fire suppression at cell level

A small Li-ion fire on a cell level can be seen as a regular combustible fire. Foam extinguishers or water-based products should be used when putting out a battery cell fire, but dry chemical-based extinguishers can also be used. Water-based products are readily available and are also appropriate to use for extinguishing since Li-ion contains very little lithium metal that reacts with water. Water also cools down the adjacent area and prevents the fire from spreading. (46.)

If the battery cell is in an enclosed space and a battery failure can be detected at an early stage, water or foam extinguishers work the most efficiently, as the active substance in the enclosed space cannot drain off the cell, which contributes to fire suppression and cooling. (46.)

Research Institutes of Sweden has made a research of simulated battery cell fire suppression experiment, where they tested the performance differences of total compartment systems versus direct injection from the top of the battery module with water, foam, inert gas and Li-ion battery developed agent. The test setup included 19.7 Ah pouch type battery cell and a dummy cell consisting of a plate thermometer, which was used to evaluate the degree of fire control in the tests and to indicate the heat exposure towards neighboring cells. The cells were placed inside a cubic box, in order to mimic a more realistic situation, where the battery cells would be inside a battery module. An electric heating element was used to initiate thermal runaway and a small propane gas flame was used as a pilot flame in order to ignite the combustion gases released from the cell during heat-up. Thermal runaway initiation by overcharge was omitted as it typically results in more vigorous and rapid fire and the effectiveness of fire suppression agents are more difficult to compare that way. (47, 9.)

The results show that it is possible to observe that the tests indicate that fire extinguishment of a battery cell fire inside a battery module is unlikely when using total compartment water spray or water mist fire protection systems. Instead, fire extinguishing agents will more likely have an effect on suppressing the fire if it is distributed evenly inside the battery module. Out of several extinguishing agents, which included plain water, Class A and Class F foams, nitrogen gas, compressed air foam system (CAFS) and an agent designed for Li-ion fires (Aqueous Vermiculite Dispersion, shortened as AVD), pure water proved to be the most effective out of all extinguishing agents. The application of water also provided the necessary cooling for the battery cells, which lowers the chance of cells reigniting. Class A and Class F foam agents showed similar results to that of water, although they prove improved extinguishment of their own classed fires. The benefit of Class F foam for the battery module protection may be its improved cooling abilities, but a disadvantage could be the content of salts which may increase the likelihood of short-circuiting non-fire affected cells, as it is impossible to de-energize the cells. (47, 24.)

4.9.2 Fire suppression at module and pack level

There is no direct answer which extinguishing agent would be most suitable on module and pack level. The choice of extinguishing equipment must take into account whether water, inert gas or chemical-based extinguishing agents are to be used. Every system has their advantages and disadvantages. Some systems may produce more immediate effects, but not all systems are able to both put down the flames and cool down the cells. The other equipment around batteries should also be taken into account when choosing the extinguishing agent, whether the equipment carry a fire hazard risk or can be damaged by extinguishing agent.

Fire suppression experiments on module and pack level is as limited as on cell level. The main difference between battery cell fire and battery module/pack fire is the extinguishing time. Battery modules and packs contains several battery cells inside their casing, so one major difference is extinguishing time: modules and packs require longer extinguishing time, as the cells need to cool down in order to exclude the chance of cells reigniting. In order to fully extinguish a fire inside the LIB pack, a direct access to the battery cells is needed. (48, 6.)

To achieve the extinguishment of a fire inside a LIB pack, direct access to the battery cells is needed (49, 6.). As the modules and battery pack are compactly designed with a high tightness level and may locate in places with difficult access, access to the seat of fire inside LIB pack can be challenging.

The choice of extinguishing equipment must take into account whether water, inert gas or chemical-based extinguishing agents are to be used. Every system has their advantages and disadvantages. Some systems may produce more immediate effects, but not all systems are able to both put down the flames and cool down the cells. The other equipment around batteries should also be taken into account when choosing the extinguishing agent, whether the equipment carry a fire hazard risk or can be damaged by extinguishing agent.

The results of various studies also make it difficult to apply the available data. A research made by Si et al. where they compared effectiveness of inert gases as extinguishing agents (CO2 and HFC-227ea) show that CO2 provide better cooling effect compared to HFC-227ea (50, 634.), whereas in research made by Mikolajczak et al. show that carbon dioxide can be used to suppress the fire, but it does not cool the battery down. (51, 97-98.)

Research made by DNV GL where they tested the effectiveness of total flooding systems and direct injection systems on a module level show that out of total flooding systems Hi-Fog had the best results on cooling down the neighboring modules and putting out the flames. From direct injection systems, direct water injection showed most effective results on reducing the temperature compared to foam-based systems. (52.)

5 REQUIREMENTS FOR THE PRODUCTION LINE

Many different factors are contemplated in the requirements of the production line. The European Standard sets some regulations related to production equipment and their operation. Above all, considering the customer's requirements, the battery chemistry of the batteries should be considered when considering, for example, suitable extinguishing options. Electrical devices and related data transfer can also alternatively set requirements.

5.1 Fire suppression agents for electrical fires

Electrical fire means a fire that receives ignition energy directly from electricity. The most common cause of a fire in an electrical appliance is negligence, non-compliance with the operating and installation instructions, neglect of maintenance, or electric shock due to damage to the appliance. Electrical fires in electrical equipment (in wires or in switchboards) may have been caused by, for example, misuse, insulation failure, loose connections, and overloaded electrical cables or short-circuiting machinery. (53, 14-15.)

Electric fire can be fought in the same way as ordinary fire, but water, foam and other conductive substances should not be used, as electricity may be conducted from the fire thought conductive fire suppression agency, such as water. Conductive substances also have the potential of faulting electronic parts inside the machinery, which is another reason why they should be avoided. Although the fire can potentially be electrical, it can be extinguished with any extinguishing agent classified as electrical fires. Carbon dioxide CO_2, Novec 1230, FM-200 and dry chemical powder extinguishers such as PKP (Purple-K) are particularly well suited for extinguishing such a fire. PKP should be the last resort to put out a fire because of its corrosive tendencies. When electricity is turned off for those devices, it usually becomes a normal burning fire. (54, 8-9.)

5.2 Standards, regulatory and equipment requirement

Even the general safety requirements for lithium-ion batteries are not currently in the legislation, but the most important legislation for batteries is the Batteries Directive (520/2014). The purpose of the Batteries Directive is, among other things, to prevent the use of hazardous substances in batteries and to promote the recycling of batteries. The Finnish Government has initiated the National Battery Directive, which deals with batteries and accumulators. An important addition is that the Batteries Directive is not a general safety directive. The directive does not address or consider the safety of batteries during use. Thus, lithium-ion batteries, like all other batteries, do not in themselves require the CE marking. Otherwise, the CE marking can be found on lithium-ion batteries, for example in connection with battery electronics. CE marking indicates that the manufacturer assures that the product meets the requirements of the relevant EU directives, and that the product has undergone any required checks. (55, 26.)

There is also no specific standard guidance on battery storage; the obligation to notify the rescue service or Tukes (Finnish Safety and Chemicals Agency) is exceeded only on the basis of battery chemicals in really large quantities of batteries. An important general guide is to follow any instructions that come with the battery or the device for charging, using, storing, and storing the battery. The instructions for use of the battery and the device using it should considered different safety aspects and should mention, for example, suitable operating temperatures and other conditions. The battery manufacturer should be able to provide similar instructions if the instructions do not provide an answer to the various safety considerations. (55, 22.)

Staff training and guidance also play an important role in safety, both in the use of the device and in the correct handling of batteries. Human error can also be a significant risk factor. For example, a faulty Li-ion battery can inadvertently end up unprotected between electrical and electronic waste, where it can be further damaged, drift into thermal escape, and ignite the surrounding fire load. The possibility of an incident in question can be minimized by proper training of staff and by highlighting various risk and hazard factors. (55, 16.)

The instructions show a general guidance, and adequate consideration of the safety aspects of Li-ion batteries also requires case-specific safety planning. Regulatory requirements do not comment on battery products or lithium technology. In this respect, the legislation is lagging behind. The requirements for the production line and production equipment are based on the company's own risk assessments and the measures and solutions generated from them. The fire and rescue service are interested in the amount and location of the fire load in the building and the fire compartments generated from it. The governing regulations are the Rescue Act (379/2011) and the Collection of Building Regulations. (56.)

One of the key regulatory requirements for a safe production environment and the use of production equipment is the Machinery Directive, which obliges the manufacturer to carry out a risk assessment setting out the health and safety requirements applicable to the machinery. The machinery must then be designed and constructed in such a way that these requirements are met, taking into account the results of the risk assessment. For electrical hazards, the safety targets set in the Low Voltage Directive are met. The essential requirements of the Directives shall be deemed to be fulfilled if the design complies with the harmonized standards referred to in the Official Journal of the European Union. (56.)

Using a safety programmable logic controller (PLC) to perform safety functions places demands on how the software should be developed and validated. A safety PLC is like a standard PLC. It can be used to control and automate pieces of industrial equipment. A safety PLC supports all the applications that a standard PLC does; however, a safety PLC contains integrated safety functions that allow it to control safety systems as well (57.). To avoid mistakes the software must be readable, understandable and the software must be possible to test and maintain. Specifications for the software must be prepared to ensure that you can check the functionality of the program. It is also important to divide the program into modules that can be tested individually. PLC’s should cover the following standards for safety use; SFS-EN ISO 13849-1 and SFS-IEC 61508. SFS is the Finnish central organization for standardization. SFS is a member of International Organization for Standardization (ISO) and European Organization for Standardization (CEN). (56.)

If a possible extinguishing solution is considered as part of the machine line, this is affected by the standards SFS-EN 54-5, SFS-EN 15276-1 and SFS-EN 12094-9, which define the requirements for fire detectors and fixed firefighting systems. These standards should be examined on a case-by-case basis, depending on what kind of extinguishing solution you want to apply in the production equipment. (56.)

5.2.1 EN ISO 13849-1

ISO 13849 provides safety requirements and guidance on the principles for the design and integration of safety-related control system components, including software development. The standard specifies the characteristics of these safety-related parts of the control system, which include the level of performance required to perform the safety function. The standard applies to safety-related parts of the control system for all types of machinery in dense and continuous operation, regardless of the technology or energy used (electrical, hydraulic, pneumatic, mechanical, etc.), for all kinds of machinery. (58.)

5.2.2 IEC 61508

The IEC 61508-1:2010 standard covers aspects to consider when electrical/electronic/programmable electronic (E/E/PE) systems are used to carry out safety functions. An important goal of this standard is to facilitate the development of international standards for the product or application sectors of the technical committees responsible for the product or application sector. This allows all relevant factors related to the product or application to be fully considered and thus meets the specific needs of the product users and the application sector. (59.)

5.2.3 EN 54-5

The EN 54 standard defines the requirements, testing methods and performance criteria for spot heat detectors used in fire detectors installed in and outside buildings. The standard presents the evaluation and verification of the permanence of the performance level of spot heat detectors that comply with the standard. Based on the EN 54 standard, the functionality and reliability of the components of the fire detection and fire alarm system are evaluated and reported. (60.)

5.2.4 EN 15276-1

The EN 15276 standard defines requirements and test methods for condensed aerosol extinguishing systems and components. This document covers the use of condensed aerosol extinguishing systems in total flood situations. The standard does not cover all legal requirements and some countries exceptionally apply specific national regulations. Users of this standard are advised to contact their national authorities regarding the applicability or inapplicability of the standard. (61.)

5.2.5 EN 12094-9

The EN 12094 standard specifies requirements and test methods for electronic control and delay devices used in conjunction with automatic fire detection systems and inert extinguishing systems, such as CO2, installed in buildings. The standard has been prepared based on the mandatory functions and optional functions and possible requirements of all electronic control devices. The standard has been prepared based on the mandatory functions and optional functions and possible requirements of all electronic control devices. The standard also defines the product characteristics, testing methods and performance criteria, according to which the efficiency and reliability of the components of gas extinguishing systems can be evaluated and explained. (62.)

5.3 Internal battery faults

The operation inside the Li-ion cell is still not fully understood, which complicates the detection of internal battery faults. Some of the internal battery faults are overcharge, overdischarge, internal and external short circuit, overheating, accelerated degradation, and thermal runaway. All these faults affect the battery operation, but most dangerous ones are accelerated degradation and thermal runaway since they directly harm the battery users and affect the Li-ion battery applications. Abnormal battery operations can be signs of internal faults, which include voltage drop, state of charge (SOC) drop, temperature rise, increase in internal resistance, and physical transformation, such as swelling.

5.3.1 Overcharge

Accelerated degradation and thermal runaway are usually the result of overcharging a battery. Overcharging may also occur in Li-ion cells due to the cell capacity variations, erroneous current and voltage measurement, or defective SOC estimation. Breaking battery charger can also overcharge a normal Li-ion battery. Overcharging of Li-ion batteries leads to electrochemical reactions between battery components and the loss of active materials (63, 16.). The building of gases in sealed batteries may cause the gases to burst out of the battery. Before the overcharging starts to happen in the battery, the surface temperature of the battery typically increases. This results in an internal short circuit inside the battery and thick solid electrolyte interphase layer. (64, 2-3.)

5.3.2 Overdischarge

Defective SOC estimation, erroneous current and voltage measurement can be the reasons for overdischarging, such as for overcharging. Overdischarge impacts the battery lifespan and thermal stability of a Li-ion cell, and these result substantial cell swelling. Although a single overdischarge does not necessarily cause a safety hazard, it forces electrodes outside their safe potential range and adversely affects the integrity of cell components (65, 2.). During overdischarging, the anode potential increases, which eventually may lead to internal short circuit. (64, 3.)

5.3.3 Internal short circuit

Li-ion battery internal short circuiting may occur internally and externally. The failing insulating separator layer between electrodes is a phenomenon of an internal short circuit. This failing separator layer may be attributed due to high temperature, cell deformation, the formation of dendrite, or compressive shock. These can lead to penetration through the separator layer which will eventually lead to internal short circuiting. As this event takes place, the electrolyte tends to decompose which causes thermal runaway. Thermal runaway is usually the result of heat build-up inside the battery from the short circuit. (64, 3-4.)

5.3.4 External short circuit

External short circuit typically occurs then the sheets are connected by a low resistance path. Cell swelling due to gas generation from other side reactions during overcharge result to electrolyte leakage, which is another cause for external short circuit. When an external heat-conducting material contacts with both positive and negative terminals, this causes an electrical connection between the electrodes. Stored energy in the cell gets discharged during an external short circuit. (64, 4.)

5.3.5 Overheating

Overheating can be a result of many reasons, such as failing voltage regulator, which sends a high amount of voltage back to the battery, leading to overheating. External and internal short circuits can also be caused by overheating. Cathode typically degrades during battery overheating, which leads to solid electrolyte interphase (SEI) growth at the anode. Battery also losses its capacity significantly due to the result of overheating. Materials inside Li-ion battery can lead them to break down and produce toxic gases, which is most cases causes the pressure to build-up inside the battery, leading to swelling and possible explosion of the Li-ion battery. Other aftermath of overheating is thermal runaway, which happens because at a demanding temperature, a runaway reaction happens ad the heat cannot breakout as rapidly as it is formed inside the battery. (64, 4.)

5.3.6 Accelerated degradation

A common distinctive in many batteries is cell degradation, which occurs as a result of variety of reasons, such as battery aging and self-discharging mechanisms. Accelerated degradation is however abnormal and may cause harsh problems in Li-ion battery. During storage, elevated temperatures, but also impedance increase, change in SOC, higher frequency of cycle and voltage rates, accelerate the degradation process. Accelerated degradation shortens the battery lifespan, which is a major issue in EV applications. (64, 4.)

5.3.7 Thermal runaway

All of the discussed internal battery faults may cause thermal runaway in Li-ion battery. During the battery charging, high charging currents and high temperatures also can lead this phenomenon. When the temperature is risen and metallic lithium becomes molten, it causes violent reactions. Limited air circulation is another cause for thermal runaway. Probability for thermal runaway increases with the amount of charge/discharge cycles on Li-ion battery. Thermal runaway is related to exothermic reactions in the batteries. When the first exothermic reaction occurs, SEI layer decompositions, and it increases the heat release at the beginning of thermal runaway. Pressure and temperature increase in Li-ion cell is a consequence of thermal runaway, which may lead to annihilation of the Li-ion cell container. When this happens, a large amount of flammable and toxic gases is released from the blasted Li-ion cell. Battery heating up and explosion is often the result of a thermal runaway. (64, 4-5.)

5.4 External battery faults

External battery faults can cause internal battery faults to occur. There are several types of external faults, which are temperature, voltage and current sensor faults, cell connection fault, and cooling system fault. The cooling system fault can be seen as the most severe fault as it leads to a direct thermal failure, more specifically to thermal runaway, as the system fails to provide adequate cooling. (64, 5.)

5.4.1 Sensor fault

Reliable sensor fault diagnostic scheme is crucial for ensuring the battery safety and performance. This helps prevent many internal faults, such as overcharge and overdischarge, overheat, internal and external short circuit, and especially thermal runaway. Sensor faults include failure of temperature, voltage and current sensors that monitor batteries. Vibration, collision electrolyte leakage and other physical factors cause sensor faults. They can also be attributed to the loose battery terminals or battery sensor corrosion. Degradation process of the battery can be accelerated by sensor fault which can lead to other internal battery faults. Battery management system (BMS) functions can also be hindered due to incorrect state estimation of a sensor fault. (64, 5.)

The temperature sensor holds an essential role in the Li-ion battery system, as it transfers crucial temperature data, which helps the battery operations to work effectively. Incorrect temperature data from a faulty temperature sensor can cause malfunction of BMS, which can lead to further problems due to ineffective thermal management. Inaccurate thermal management function in BMS can significantly decrease the battery life. Short-circuiting, overheating, aging under high temperatures, capacity fade due to high temperature and thermal runaway can also happen due to temperature sensor fault. (64, 5.)

The voltage sensor monitors the voltage of cells. A voltage sensor fault can cause a battery cell or the entire battery pack to exceed the upper and lower voltage limits specified by manufacturers, which can result in overcharge and overdischarge. A voltage sensor fault can lead to inaccurate state of charge and state of health (SOH) estimation, which can result in an internal fault, as the battery suffers from overcharge and overdischarge. (64, 5.)

The current sensor monitors the upcoming and outcoming current that enters the battery and sends the data to the BMS. A current sensor fault is important to detect as early as possible, as it can lead to further problems. The current can bypass the sensor and inaccurate the readings, which raises the importance of the current sensor. Inaccurate SOC and other parameter estimations can also be signs of current sensor fault, which impacts the control actions in the BMS, that can cause the cells to overcharge, overdischarge or overheat. (64, 5.)

5.4.2 Cooling system fault

Cooling system takes place when talking about batteries that are being installed to an application, such as an electric vehicle. Thermal aspects of the battery are being managed with the cooling system. The main purpose of the cooling system is to transfer the heat away from the battery cell or packs and ensure that the battery remains in the optimal temperature range. When the cooling motor or fan fails to operate due to sensor fault, outdated fan wiring or a broken fuse, cooling system faults occur. Allowed battery temperature range depends on both temperature sensor and cooling system fault, thus these cannot be separated from each other. Cooling system faults lead to direct system failures which leads to battery overheating, that eventually ends up to thermal runaway. By this reason alone, cooling system faults are one of the most severe faults. Due to this reason, it is important to diagnose system faults as early as possible. (64, 5.)

5.4.3 Cell connection fault

Poor electrical connections between cell terminals are the cause of battery or cell connection faults. These connections may become loose from vibration or terminal corrosion, by impurities over time. When cell connections faults occur, the cell resistance can increase radically. Risen cell resistance can lead to cell imbalance, due to uneven current or overheating of the faulty cell. With voltage and temperature sensors, cell connection fault is simple to detect. If this is left unresolved, can it lead to more harsh consequences, such as thermal runaway or external short circuit. (64, 5-6.)

5.5 Controlling faulty situation

If the lithium-ion battery starts to fail inside the production unit or during its process, it is advisable to get the battery out of the process as early as possible. A faulty battery should be removed from the vicinity of other batteries to minimize the risk of thermal runaway, which could potentially ignite the surrounding batteries. If this happens, there is an increased risk of a large battery fire, which can be difficult, if not impossible, to manage. When direct cooling is the most effective way to cool down the battery, it is easier to remove one faulty battery from the line and try to cool it, rather than trying to control multiple burning batteries at the same time. Material damage is increasing and the risk of fire is increasing significantly.

Appropriate measuring equipment can reduce the risk of failure and fire when a failing battery can be detected in an early stage. When considering a production facility where battery cells are stacked on a base plate, a sensible solution would be to remove a single failing battery from the production line, such as inside of a water-filled box, where the battery can fail in by itself and the process does not have to stop due to a single failing battery. This could be accomplished cost-effectively, for example, using artificial intelligence, when a single failing battery could be removed from the production line, and thus there is no need to stop the production line and run the process down due to a single failing battery.

With the help of artificial intelligence, it is possible to detect a questionable fault situation in a more versatile way, rather than using traditional measuring devices. When a certain set limit value of a measuring device is exceeded or exceeded, this will cause a possible undue alarm to the system, even if there is no fault condition itself. The in-depth learning system is able to detect an anomaly, which is not necessarily a battery fault in itself.

In the current market, there are systems utilizing artificial intelligence that can be applied in the battery industry and in the production equipment dealing with the thesis, for example from Siemens. The Siemens S7-1500 Learning Artificial Intelligence is able to identify and learn anomalies that are not exceedances due to battery failure (66.). The artificial intelligence combined with the thermal imager would be able to map the source of escaping heat from outside the battery and thus determine whether the battery is operational. Sufficiently developed artificial intelligence is a cost-effective and ecological addition to production, as working batteries that would otherwise be removed from the line do not unnecessarily incur measures and additional costs.

6 IMPLEMENTATIONS PROPOSAL

JOT Automation has expressed the need to find out extinguishing methods and equipment solutions that can detect a battery fire in the battery assembly solution during the process and implement an extinguishing solution for it. During the thesis, solution to the problem has been tried to find through different companies and their services. Many companies were contacted in this matter, trying to find a suitable and functional solution for the production equipment, and a few companies expressed their solution proposals related to the different extinguishing methods and equipment solutions.

Next, the solutions offered by different companies regarding the extinguishing and equipment solutions that the companies have offered as part of JOT Automation's Battery Assembly Solution are discussed. The companies have covered various solutions, but not all companies have the ability to offer a comprehensive solution as part of the battery assembly solution. Companies offered proposals for separate equipment solutions and extinguishing solutions, and one company offered a comprehensive equipment solution as part of the battery assembly solution.

6.1 AGIS Fire & Security

AGIS Fire & Security is a company producing firefighting and security system services, whose roots in Finland go back to the 1960s. The company's goal is to offer efficient and competitive solutions and to find customers technologies suitable for their needs (67.). AGIS has offered versatile information and proposed solutions to the research problem that this thesis deals with. In its private message (68.), AGIS opens solutions for different areas that are connected to device solutions. On the detection side, AGIS suggests the Xtralis® VESDA sense point XCL gas detector, which is installed in the pipeline of the Xtralis® VESDA VEP sampler. The gas detector in question therefore also requires a Xtralis® VESDA VEP sampler to function, but this enables early smoke detection. However, the detector in question does not have a sensor for hydrogen fluoride, instead it detects gases that are formed as a result of the heating and burning of the battery.

AGIS also opens solutions for heat detection: they offer different point detectors and thermal wire solutions based on the rate of heat rise, alarming at a certain temperature. AGIS suggests that the most suitable option for JOT Automation's battery production equipment would be a solution based on ramp speed. In addition to this, AGIS offers solutions that can be connected to a fire detector or a trigger center, and they have both addressable and conventional solutions available. Regarding the fire extinguishers themselves, AGIS does not offer a clear solution for the thesis, but it presents inert fire extinguishing systems, carbon dioxide systems and chemical Novec 1230 fire extinguishing systems that can contribute to minimizing risks. However, from these solutions only the carbon dioxide system works in an open space, as the other systems require a tight space to function optimally. According to AGIS, carbon dioxide also cools the burning object, which in this case would be a prismatic battery.

In addition to this private message, AGIS opens in a private message (69.) the components that make up their extinguishing system. According to the message, the tanks are installed in a rack, which includes a trigger delay device (electrically or pneumatically triggered), CO2 racks, and a nozzle. AGIS also provides a general description of the system's operation in the email attachment. With the ZETTLER® MZX-e extinguishing control panel, triggering is possible either based on one detector information, or alternatively with double detection, in which case two separate detections are required for triggering. A sampler, a gas detector and, according to the company, actually anything that can be used to get a closing relay tip data can be connected to this. A manual release button can also be connected to the center, and there is one already integrated in the cover of the center. In this way, AGIS came up with the idea of a simple passage of the pipe in the roof of the modules. AGIS uses electro-galvanized steel pipe with a threaded or bead connection for the extinguishing pipeline. AGIS estimates that three times 67.5 Litre/50Kg 50 Bar tanks would go into the system.

Figure 16 shows an illustrative picture of the extinguishing system provided by the company in an isometric description for JOT Automation’s battery assembly solution.

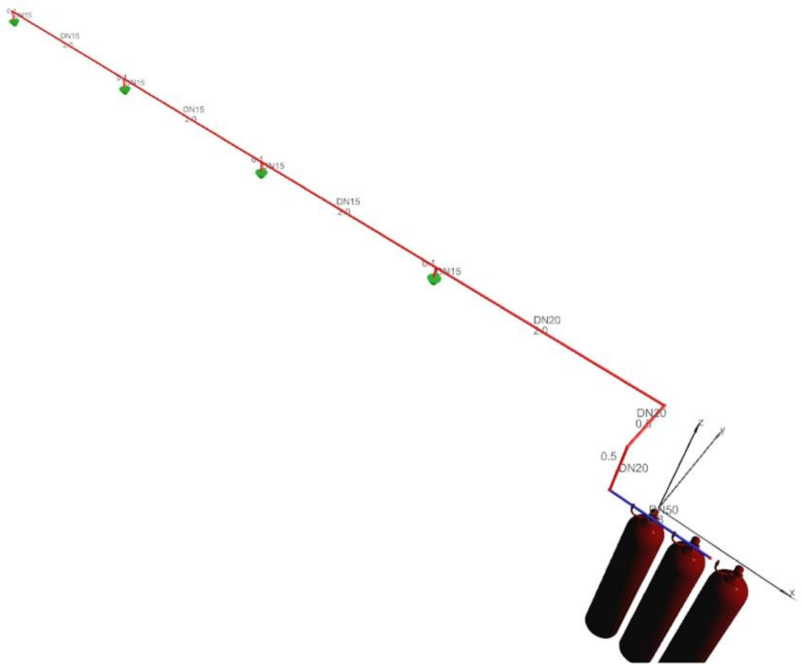


FIGURE 16. Surface isometric description of the battery assembly solution extinguishing piping. (70.)

6.2 Stemmer Imaging

Stemmer Imaging is a company founded in 1998, whose main business is machine vision systems. The company's other businesses are electronics and components, vision components and optoelectronics components for the needs of industry and research (71.). In its private message (72.), Stemmer Imaging has offered an application regarding to battery temperature monitoring. For monitoring the battery cell temperature: As the designated temperature specification is not determined, but assuming the monitored temperature development and eventually triggering the alarms would happen around 100°C or below, the company recommends for monitoring of battery cell temperature a camera with long wave infrared (LWIR) sensitivity. This is based on the fact that LWIR gives the most accurate response in these temperature ranges, with black body spectrum attached. For the estimated matrix of 30 cells in 1x1 meter matrix, the company recommends a camera with enough resolution. The camera they suggest is the AT IRSX-1640. The camera is readily radiometrically calibrated to give accurate temperature readout.

The software for analyzing the matrix image with the cells and reading the temperature of the cells itself, they recommend MvTec HALCON software. HALCON is a comprehensive standard software for machine vision with an integrated development environment (73.).

The long wave infrared camera provides a picture and an intensity map, where the intensity of each pixel strictly corresponds to the temperature. When using the HALCON, one can easily divide the image into regions-of-interest (ROI), where each region corresponds to one battery cell. With HALCON, both the average and the peak temperature of each cell can be tracked.

The position of each cell remains more or less constant. But even in the case of small deviations in the position of the frame with cells, the ROIs can be aligned using the HALCON shape matching methods, so the temperatures of each cell can be monitored. The HALCON provides a fairly flexible way to communicate with the PLC using a TCP-socket. TCP, which stands for Transmission Control Protocol, is a network protocol that transfers data on the internet from your device to a web server. Through the TCP-socket, one can regularly send the current temperature of each cell, or just the index of the faulty cell when its temperature exceeds. With industrial computers, the images can be grabbed from the LWIR camera, perform the vision algorithms in HALCON and output the required results to PLC.

Illustrative images of the operation of the LWIR camera in the JOT Automation's battery assembly solution have not been provided on behalf of the representative company.

6.3 NoFire Systems

NoFire Systems has offered the most versatile device solution package. NoFire Systems delivers extinguishing solutions to its customers and partners internationally, and thanks to its extensive network, the company also acts as a communicator between the various key parties in the industry. (74.)

NoFire Systems will share the solution proposal with a private email message (75.). In the message, the company provides information on how to identify lithium battery fires using the NoFire TM system. As already stated in earlier chapters, when dealing with lithium batteries and the risks to them, the so-called thermal runaway produces many harmful gases that are formed in several different stages of the fire. According to a private solution proposal, it is possible to detect these highly flammable gases with NoFire TM, and with this to react for thermal escape up to several minutes before a more violent gas discharge and flame fire.

Figure 17 represents the reaction time of their gas sensor detecting toxic gases in an early phase, where voltage change in gas sensor can be detected early on before thermal runaway starts.

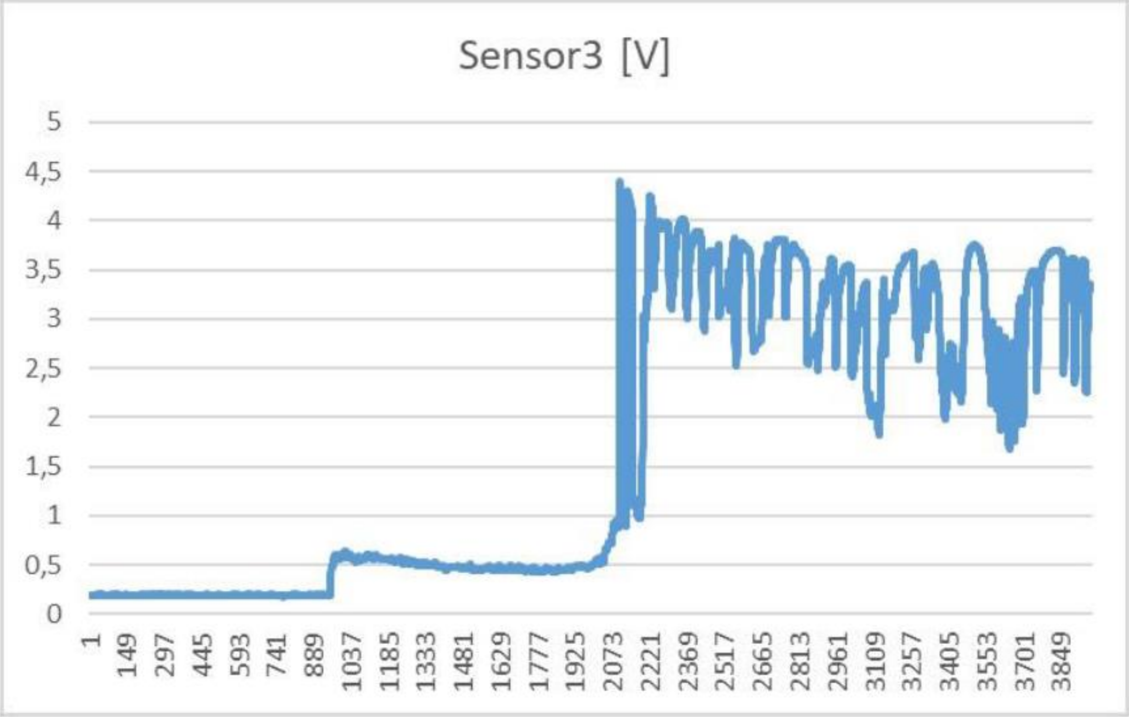


FIGURE 17. NoFire TM controlling thermal runaway due to overcharging. Time in seconds on the lower axis, voltage (V) on the upper axis. The first observations are obtained well in advance. (75.)

According to the company's solution proposal, the gas sensor used by NoFire TM has been selected from among several potential candidates based on thorough tests. The resolution of the sensor is described as accurate, which is especially effective in industrial environments, where it is required to monitor the ambient air quality and relate observations to previously observed ones. Monitoring and observation have been implemented algorithmically in such a way that longer-term and short-term values are used to detect genuinely unusual observations, e.g. thermal runaway, and on the other hand to exclude other relevant exceptions (false positives). The versatility, accuracy, and speed of the equipment in question is also increased by, for example, its ability to utilize data from thermal camera sensors.

NoFire TM system consists of following equipment and sensors, such as analytics section, gas sensor unit, thermal camera sensor, battery-backed power supply, fire detection and extinguishing central unit, aerosol fire extinguishing unit, flash buzzer, physical isolation switch and manual call point. The proposed solution consists of several gas sensor units, one AI-based analytics unit, several thermal camera sensors as well as aerosol suppressor units. The system can be expanded either wired or wireless. The devices' modest power consumption enables very flexible placement even in challenging locations.

The company states that, for example, aerosol-based extinguishing equipment can be used without significant disadvantages to prevent or at least limit the spread of a possible fire to only one battery module or battery rack. The aerosol also equalizes the distribution of excess heat within the protected volume.

The completed setup of gas detectors, thermal cameras, AI-based analytics unit and aerosol suppressor units is represented in Figure 18.

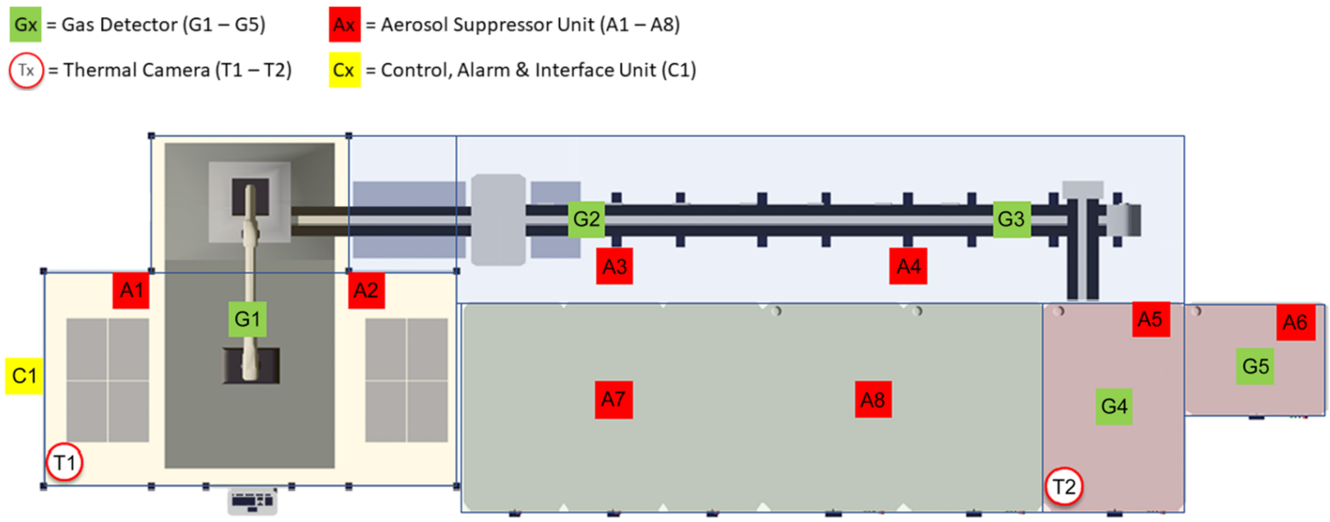


FIGURE 18. Two-dimensional model of JOT Automation's battery assembly solution, where No-Fire's proposed setup of sensors and AI-unit are placed. The figure illustrates the positioning of the different components seen from above of the machine line. (76.)

The company states that aerosol-based extinguishing systems act quickly, on average within 2-8 seconds from the command, are long-lived up to dozens of years, relatively inexpensive and almost maintenance-free. They are compact and can be flexibly arranged, potentially improving the efficiency of for example container-based energy storages. Aerosol systems do not displace the oxygen and are not subject to pressure equipment legislation or require complete tightness of the protected volume. Modern aerosols also do not cause short circuits or corrosion, and simply ventilating the protected space is usually sufficient as a follow-up measure. When planning the amount of aerosol required for protecting a structure or room, the volume, possible leaks and openings and ventilation must be taken into account, together with manufacturer, product, environment and standard-specific concentration guidelines.

For compliance with standards, the company states that there is currently no comprehensive European standard for battery fire prevention, but NoFire actively participates in standardization groups at both Finnish and EU level. In Finland, the revised Equipment Act, which should be completed by the end of 2023, will not take a position on battery fire prevention. NoFire TM with its peripherals is supported and, depending on the implemented entity, is compatible with e.g. with EN 54, EN 15276 and BRL K23001 standards, and the progress of its development work and tests is reported at regular intervals, to for example TUKES (The Chemical and Safety Agency of Finland) and Kiwa Inspecta, who are inspection, testing and certification service company. The European Standard EN 54 defines the requirements, testing methods and operational criteria for point heat detectors used in fire detectors and fire alarm systems installed in and outside buildings. The European Standard EN 15276 defines the requirements and test methods for condensed aerosol extinguishing system components. Kiwa Inspecta's BRL K23001 certification scheme covers product certification of condensed aerosol generators and separate components.

However, the prerequisite for success in extinguishing and containing challenging lithium-ion-based fires is to intervene as early as possible, and NoFire TM makes this possible. The information produced by the system about the different alarm levels and potential faults can be also transmitted to the fire detector and building automation for alarm actions and, for example, cutting off ventilation.

In the offered configuration, the analytics unit uses not only gas sensors but also data produced by thermal cameras to support its decisions. The detected fire event can be responded to with aerosol-based extinguishing, which enables production to continue with as little inconvenience and short interruptions as possible. The intelligent central device ensures expandability and flexible integration with surrounding systems.

Up to this point, NoFire's system has been used in such a way that alarms to other devices in the system have been sent through the tip of a potential-free relay. Preliminary information, a rise in the gas level in the customer's system, as well as an alarm, a rise in the gas level and temperature in the customer's system, are also sent to the external system via the tip of its own potential-free relay. Exporting this data to another device can be challenging when using I/O, so the benefits of Profinet would come to the fore in this case when, for example, measurement data can be transferred along the bus. The importance of the bus is emphasized if sensors are added to the device and the data is also exported to other units or devices for viewing. The device could be connected to the JOT Automation’s system using different interfaces.

In the following topics, different interfaces for connect applications are discussed.

6.4 Input/Output

One option is to implement the solution using I/O. I/O, i.e. Input/Output, consists of physical wires and system inputs and outputs. Data such as sensor measurement data and various limits, such as safety limits, are imported into the inputs. Devices are controlled with the outputs or an alarm can be given to another device, i.e. information or commands are sent forward with the outputs.

The benefits of the I/O solution are usability in devices from many different manufacturers. In this case, when a limited amount of data is transferred, I/O can be a more economical solution. As a disadvantage, I/O does not provide as extensive diagnostics of the hardware. Depending on the amount of data, I/O may require more cables and therefore more physical installation.

With I/O, we depend on the fact that the I/O modules, which for example read voltage messages or current messages, are compatible with the outputs of e.g. NoFire's device. Unlike with Profinet, data could always be imported along the Profinet bus, regardless of the I/O modules.

JOT Automation mainly uses logic from Siemens, Beckhoff and Omron. The previously mentioned security standards, which are required from manufacturers' equipment when security-related data is processed. All three manufacturers have logics that are included in section 5.2. declared safety standards. The requirement for safety standards is that the equipment used in the system covers the required safety standards. In this case, using general station description (GSD) would make sense, because it can be used in the engineering softwares of these logics.

6.5 Profinet & PROFIsafe

Another option is to implement a solution using Profinet and PROFIsafe. In PROFIsafe, communication takes place via telegrams and there is a separate telegram for safety functions. Using ProfiSAFE requires software expertise from the device manufacturer, in this case NoFire, to create a GSDML file. The GSD file is a standardized way of describing the device information to the engineering tool and the I/O controller (PLC/PAC/DCS) and can work across a variety of engineering tools as a standard set of device information. A GSD file will be imported into the Profinet configuration tool of the controller. Once the GSD file has been imported you can set up the Profinet I/O device and will be able to configure, parameterize, and choose diagnostic options in the tool. (77.)

Depending on the manufacturer of the logic, the manufacturer's design program is used, into which the GSD file is imported. When the GSD file has been imported, it is possible to read, for example, measurement data or device diagnostics via telegrams. For example, information on the state of the UPS battery charge could be imported, in this case, for example, if an error occurs in the power source of NoFire's system, and the system power transfer moves to the battery. This information is brought to the logic by means of a telegram, where the logic processes the data and performs the necessary actions, for example giving an alarm to the system or closing a valve.

Basic I/O must be kept alongside the system for applicability and scalability. For example, systems such as fire alarm systems do not necessarily support GSD files, so data transfer must be carried out using IO in this situation.

The company needs to see if it is profitable to spend time and money to prepare the GSD file, if the benefits that would be obtained through GSD would be large enough. Here you also have to take into account the fact that the network card of the device must meet the Profinet standards, so that it can be used in the Profinet bus. The company must investigate the situation on a case-by-case basis, whether this is profitable in the environment of the equipment being used.

7 PRACTICAL IMPLEMENTATION

The cooperation between the service provider and the buyer of the service requires consideration of many different areas before pilot production is reached. Design work from many different areas comes to the fore, including process design, electrical design, automation design and mechanical design. Process planning considers physical and chemical phenomena related to products, in this case lithium-ion batteries. Battery chemistries should be considered and based on them, for example, necessary combustion tests should be carried out in order to better understand the fire behavior of the battery chemistry. This is linked, among other things, to the electrical design, in order to guarantee the correct functionality of the components in a fire situation, for example. Electrical design also involves the electrical functionality of the entire equipment and the compatibility of components and other peripherals. Cabling also plays a big role. In order for the equipment to work in the event of a fault, the fire resistance of the cables can be considered. The circuit diagrams, which are part of the hardware documentation, are linked under the electrical design. The functionality of the hardware as desired and the software implementation are part of the automation design. The automation designer must consider the requirements set by the process designer so that the automation corresponds to the implementations carried out by the process designer. Mechanical design involves the physical sizes and limitations of components and equipment, such as considering the pressure of water extinguishing and what kind of sprinkler covers a large enough extinguishing area.

The testing of failure situations must be considered, as well as the repair of the failure situation. This involves spare parts and the availability of components, as components can have long delivery times, and the production equipment may not work as desired if certain components are missing. For this reason, the production equipment can be idle for no reason, which is reflected in the running costs. Thinking about pilot production, all possible malfunctions must be taken into account and reviewed in order to get the production equipment into continuous production. Malfunctions include, for example, power outages and the functionality of the equipment during that time, incorrect positioning of the battery in the process, and possible bugs in the software. When planning the amount of aerosol required for protecting a structure or room, the volume, possible leaks and openings and ventilation must be considered, together with manufacturer, product, environment and standard-specific concentration guidelines. An aerosol suppression unit disperses not unlike a smoke machine, therefore normally not requiring strengthening the protected structure. If necessary, installation and maintenance of an aerosol-based suppression system can through training also be delegated to customer personnel. Depending on the regulations, an inspection by a third party might be required.

When thinking about installation work, you should consider whether you want to carry out the installation work through a subcontractor or the service provider's employees. Mechanical challenges can also be part of the installation work, such as possible welding and installation of mechanical parts related to the device, as well as possible replacement and maintenance work.

The operation of the equipment in terms of various standards, regulations and regulations must be considered, which involves compliance with standards and third-party inspections. For example, the safety of the equipment and the proper functioning of fire protection in the event of a failure are defined in terms of different standards, the proper functioning of which is checked by authorized inspectors.

If the comprehensive solution offered by NoFire is decided to be used, development targets for the production equipment include, for example, the complete isolation of the conveyor belt and the robot cell with plexiglass walls and roof, so that a reacting battery can be detected as early as possible. When the space is closed, the gas sensors are able to observe the escaping gases better than in an open space, and thus a fire situation can be avoided and malfunctions can be detected at an early stage.

For the conclusion, the buyer of the service itself determines which services they want to buy from the service providers, and this does not necessarily include all the services offered by the service provider. For example, electrical designing, automation designing, and mechanical designing can be carried out on behalf of the buyer of the service itself, if the necessary conditions are met. In this situation, the buyer of the service only buys the product offered by the service provider and carries out all the other planning by themself. The buyer of the service may also have to be responsible for compliance with standards, which may be part of the service provider's product, if they do not want to buy this service from them. In this situation, the services provided by the third party are responsible for compliance with the standards.

8 CONCLUSION

Although there are many fire suppression agents available in today’s market focused for electrical and battery fires and for places where electricity and batteries are used, every suppression agent has its own advantages and disadvantages. A case-by-case assessment must be made of the planned equipment, to determine which extinguishing solutions can be used, considering the surrounding workspace as well as the equipment.

It was difficult to get information from the companies regarding for the implementation proposals, as well as the unsuitability of the available public information for the topic of the thesis. Appropriate information exists, but this information is not public but corporate confidentiality information that is not intended to be made available to the public. The information available is limited and this information may not be applicable to the topic of the thesis. In the thesis, batteries and related theory are discussed in various environments in accordance with the JOT Automation's premises. Current, international and scientific sources were used in a variety of ways in the thesis, so that the theory part was sufficiently comprehensive and wide-ranging, which promotes the understanding of how batteries work. The topic of the thesis is broad, which is essential for the nature of the thesis. The topic for the thesis itself was interesting as it included contacting companies and trying to find a suitable implementation solution for the battery assembly solution. However, the cooperation with service provider companies delayed the planned schedule.

Many companies were able to offer a variety of measuring devices as well as sensors but did not guarantee the functionality of the measuring devices for the battery assembly solution. This was understandable since these measuring devices or sensors had not previously been used in a similar production environment. These measuring devices are not further documented in this thesis.

The thesis also examines different fieldbuses and their benefits from different service providers for connecting the system to JOT Automation's system. Interpretations were made in which situation any fieldbus solution would be the best option. Different fieldbuses enable compatibility with equipment manufacturers' devices, and different fieldbus possibilities are taken into account in the implementation proposal. Implementation proposal and practical implementation were able to be documented.

Finally, I would like to thank my thesis supervisor Ensio Sieppi for all the help with the thesis and JOT Automation for the interesting and challenging topic. I greatly appreciate the cooperating companies and their staff who offered their implementation proposals for the battery assembly line. Doing the thesis broadened my understanding of batteries and their challenges. Batteries have developed a lot over time, but versatile and comprehensive additional information about their operation will be needed in the future.

REFERENCES

1. JOT Automation Ltd. (2022). About Us. Retrieved January 14, 2022, from https://www.jotautomation.com/about-us

2. Bluelec. (2022). About Us. Retrieved January, 14, 2022, from https://bluelec.com/about-us/

3. JOT Automation Ltd. (2022). Battery Assembly Solution. Retrieved January 14, 2022, from https://www.jotautomation.com/solutions/ev-battery-assembly-solution

4. Picture. Sakari Palokangas. 2022.

5. Garche, J. & Karden, Eckhard & Moseley, P.T. & Rand, David. (2017). Lead-Acid Batteries for Future Automobiles. Retrieved January 19, 2022, from https://www.researchgate.net/publication/319269812_Lead-Acid_Batteries_for_Future_Automobiles

6. Alanen R. & Koljonen T. & Hukari S. & Saari P. (2003). Energian varastoinnin nykytila. Retrieved February 3, 2022, from https://www.vttresearch.com/sites/default/files/pdf/tiedotteet/2003/T2199.pdf

7. Budde-Meiwes, Heide & Drillkens, Julia & Lunz, Benedikt & Muennix, Jens & Lehner, Susanne & Kowal, Julia & Sauer, Dirk. (2013). A review of current automotive battery technology and future prospects. Retrieved February 3, 2022, from https://www.researchgate.net/publication/258177713_A_review_of_current_automotive_battery_technology_and_future_prospects

8. Kwade, Arno & Haselrieder, Wolfgang & Leithoff, Ruben & Modlinger, Armin & Dietrich, Franz & Droeder, Klaus. (2018). Current status and challenges for automotive battery production technologies. Retrieved February 4, 2022, from https://www.researchgate.net/publication/324499759_Current_status_and_challenges_for_automotive_battery_production_technologies

9. Hughes T. (2018). Beyond Li-ion – batteries for transportation. Retrieved February 4, 2022, from https://ingenuity.siemens.com/2018/07/beyond-li-ion-batteries-for-transportation/

10. Salgado, Rui & Danzi, Federico & Oliveira, J. & El-Azab, Anter & Camanho, Pedro & Braga, Maria. (2021). The Latest Trends in Electric Vehicles Batteries. Retrieved February 7, 2022, from https://www.researchgate.net/publication/351906536_The_Latest_Trends_in_Electric_Vehicles_Batteries

11. Goonan, T.G. (2012). Lithium use in batteries. Retrieved February 7, 2022, from https://pubs.usgs.gov/circ/1371/pdf/circ1371_508.pdf

12. Battery University. (2021). BU-212: Future Batteries. Retrieved February 8, 2022, from https://batteryuniversity.com/article/bu-212-future-batteries

13. Ball, P. (2015). 'Breathing battery' advance holds promise for long-range electric cars. Retrieved February 8, 2022, from https://www.nature.com/news/breathing-battery-advance-holds-promise-for-long-range-electric-cars-1.18683

14. Lombardo T. (2015). Solid State Battery Could Double Electric Vehicle Range. Retrieved February 8, 2022, from https://www.engineering.com/story/solid-state-battery-could-double-electric-vehicle-range

15. Sousa, Rui & Sousa, J. A. & Ribeiro, J. & Goncalves, L.M. & Correia, J.H.. (2013). All-solid-state batteries: An overview for bio applications. Retrieved February 9, 2022, from https://www.researchgate.net/publication/257266663_All-solid-state_batteries_An_overview_for_bio_applications

16. Reddy T. (2011). Linden's Handbook of Batteries, Fourth Edition. Retrieved February 9, 2022, from https://vdoc.pub/documents/lindens-handbook-of-batteries-4th-edition-6nh4os1iu1o0

17. Hietaniemi M. (2015). Thermal Stability Of Chemicals Used In Lithium- Ion Batteries. Retrieved February 10, 2022, from http://jultika.oulu.fi/files/nbnfioulu-201512032229.pdf

18. Battery University. (2021). BU-205: Types of Lithium-ion. Retrieved February 11, 2022, from https://batteryuniversity.com/article/bu-205-types-of-lithium-ion

19. Kane M. (2019.) NCM 811 Almost Account For A Fifth Of EV Li-Ion Deployment In China. Retrieved February 15, 2022, from https://insideevs.com/news/382356/ncm-811-ev-li-ion-deployment-china/

20. Rand D. & Dell R. (2001). Understanding Batteries. Retrieved February 15, 2022, from https://pubs.rsc.org/en/content/ebook/978-0-85404-605-8

21. Battery University. (2021). BU-203: Nickel-based Batteries. Retrieved February 17, 2022, from https://batteryuniversity.com/article/bu-203-nickel-based-batteries

22. EUR-Lex. (2020). Disposal of spent batteries. Retrieved February 18, 2022, from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=LEGISSUM:l21202

23. Battery University. (2019). BU-301a: Types of Battery Cells. Retrieved February 21, 2022, from https://batteryuniversity.com/article/bu-301a-types-of-battery-cells

24. Romare M. & Dahllöf L. (2017). The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries. Retrieved February 22, 2022, from http://www.energimyndigheten.se/globalassets/forskning--innovation/transporter/c243-the-life-cycle-energy-consumption-and-co2-emissions-from-lithium-ion-batteries-.pdf

25. Landini, Stefano. (2019). A Review of Phase Change Materials for the Thermal Management and Isothermalisation of Lithium-Ion Cells. Retrieved October 15, 2022, from https://www.researchgate.net/publication/335365432_A_Review_of_Phase_Change_Materials_for_the_Thermal_Management_and_Isothermalisation_of_Lithium-Ion_Cells

26. Grepow. (2019). 3 Different Shapes Lithium Battery Structure. Retrieved October 15, 2022, from https://www.grepow.com/blog/3-different-shapes-lithium-battery-structure.html

27. Battery University. (2019). BU-304: Why are Protection Circuits Needed? Retrieved February 23, 2022, from https://batteryuniversity.com/learn/article/safety_circuits_for_modern_batteries

28. Battery University. (2021). BU-304b: Making Lithium-ion Safe. Retrieved February 25, 2022, from https://batteryuniversity.com/article/bu-304b-making-lithium-ion-safe

29. Yao, Xingyan & Kong, Lingxi & Pecht, Michael. (2020). Reliability of Cylindrical Li-ion Battery Safety Vents. Retrieved February 28, 2022, from https://www.researchgate.net/publication/341657945_Reliability_of_Cylindrical_Li-ion_Battery_Safety_Vents

30. Batterybro. (2015). Battery Safety 101: Anatomy - PTC vs PCB vs CID. Retrieved February 28, 2022, from https://batterybro.com/blogs/18650-wholesale-battery-reviews/18306003-battery-safety-101-anatomy-ptc-vs-pcb-vs-cid

31. Battery University. (2021). BU-201: How does the Lead Acid Battery Work? . Retrieved February 28, 2022, from https://batteryuniversity.com/article/bu-201-how-does-the-lead-acid-battery-work

32. Akkupojat. (2013). Akut. Retrieved February 28, 2022, from https://web.archive.org/web/20131111095235/https://www.akkupojat.fi/index.php/site/aurinkopaneelit/akut-3

33. Shama & Saha, Sajeeb & Haque, M.E. & Mahmud, Md. Apel. (2019). Comparative Analysis of Commonly used Batteries for Residential Solar PV Applications. Retrieved March 1, 2022, from https://www.researchgate.net/publication/337819254_Comparative_Analysis_of_Commonly_used_Batteries_for_Residential_Solar_PV_Applications

34. Spiers, D. (2017). Batteries in PV systems. Retrieved March 2, 2022, from https://www.researchgate.net/publication/328248394_Batteries_in_PV_systems

35. The European Association for Advanced Rechargeable Batteries. (2013). Safety of Lithium-ion batteries. Retrieved March 3, 2022, from https://batteryrecycling.org.au/wp-content/uploads/2020/11/Li-ion-safety-July-9-2013-Recharge-.pdf

36. Battery University. (2021). BU-808: How to Prolong Lithium-based Batteries. Retrieved March 3, 2022, from https://batteryuniversity.com/article/bu-808-how-to-prolong-lithium-based-batteries

37. Frank N. (2017). Stages of a Lithium Ion Battery Failure. Retrieved March 4, 2022, from https://liiontamer.com/lithium-ion-battery-failure-stages/

38. The Fire Protection Research Foundation. (2011). Lithium-Ion Batteries Hazard and Use Assessment. Retrieved March 7, 2022, from https://www.nrc.gov/docs/ML1719/ML17192A237.pdf

39. Doughty D. & Pesaran A. (2012). Vehicle Battery Safety Roadmap Guidance. Retrieved March 7, 2022, from https://www.nrel.gov/docs/fy13osti/54404.pdf

40. Sun, Jie & Li, Jigang & Zhou, Tian & Yang, Kai & Wei, Shouping & Tang, Na & Dang, Nannan & Li, Hong & Qiu, Xinping & Chen, Liquan. (2016). Toxicity, a serious concern of thermal runaway from commercial Li-ion battery. Nano Energy. Retrieved March 8, 2022, from https://www.researchgate.net/publication/304907208_Toxicity_a_serious_concern_of_thermal_runaway_from_commercial_Li-ion_battery

41. Nedjalkov, Antonio & Meyer, Jan & Köhring, Michael & Doering, Alexander & Angelmahr, Martin & Dahle, Sebastian & Sander, Andreas & Fischer, Axel & Schade, Wolfgang. (2016). Toxic Gas Emissions from Damaged Lithium Ion Batteries—Analysis and Safety Enhancement Solution. Retrieved March 10, 2022, from https://www.researchgate.net/publication/297657770_Toxic_Gas_Emissions_from_Damaged_Lithium_Ion_Batteries-Analysis_and_Safety_Enhancement_Solution

42. Battery University. (2021). BU-703: Health Concerns with Batteries. Retrieved March 11, 2022, from https://batteryuniversity.com/article/bu-703-health-concerns-with-batteries

43. Battery University. (2021). BU-302: Series and Parallel Battery Configurations. Retrieved March 16, 2022, from https://batteryuniversity.com/article/bu-302-series-and-parallel-battery-configurations

44. Ghiji M. & Novozhilov V. & Moinuddin K. & Joseph P. (2020). A Review of Lithium-Ion Battery Fire Suppression. Retrieved March 17, 2022, from https://www.researchgate.net/publication/344448023_A_Review_of_Lithium-Ion_Battery_Fire_Suppression

45. Kong, Lingxi & Li, Chuan & Jiang, Jiuchun & Pecht, Michael. (2018). Li-Ion Battery Fire Hazards and Safety Strategies. Retrieved March 18, 2022, from https://www.researchgate.net/publication/327162650_Li-Ion_Battery_Fire_Hazards_and_Safety_Strategies

46. Battery University. (2019). BU-304a: Safety Concerns with Li-ion. Retrieved March 22, 2022, from https://batteryuniversity.com/learn/article/safety_concerns_with_li_ion

47. Andersson P. & Arvidson M. & Evegren F. & Jandali M. & Larsson F. & Rosengren M. (2018). Lion Fire: Extinguishment and mitigation of fires in Li-ion batteries at sea. Retrieved March 23, 2022, from https://www.diva-portal.org/smash/get/diva2:1273584/FULLTEXT01.pdf

48. Willstrand O. & Bisschop R. & Rosengren M. (2019). Fire Suppression Tests for Vehicle Battery Pack. Retrieved March 25, 2022, from https://www.researchgate.net/publication/337330881_Fire_Suppression_Tests_for_Vehicle_Battery_Pack

49. Petit Boulanger C. & Thomaza J. & Azmi B. & Labadie O. & Poutrain B. & Gentilleau M. & Bazin H. (2015). A partnership between renault and french first responders to ensure safe intervention on crash or fire-damaged electrical vehicles. In: The 24th ESV conference proceedings (ESV2015), Göteborg, SE. Retrieved March 28, 2022, from https://www-esv.nhtsa.dot.gov/Proceedings/24/files/24ESV-000252.PDF

50. Si, Rong-jun & Liu, De-qi & Xue, Shao-qian. (2018). Experimental Study on Fire and Explosion Suppression of Self-ignition of Lithium Ion Battery. Retrieved March 30, 2022, from https://www.researchgate.net/publication/322995532_Experimental_Study_on_Fire_and_Explosion_Suppression_of_Self-ignition_of_Lithium_Ion_Battery

51. Mikolajczak, C. & Kahn, M. & White, K. & Long, R.T. (2011). Lithium-ion Batteries Hazard and Use Assessment. Retrieved March 31, 2022, from https://www.nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Hazardous-materials/rflithiumionbatterieshazard.ashx

52. Gully B. & Helgesen H. & Skogtvedt J.E. & Kostopoulos D. (2019). Technical Reference for Li-ion Battery Explosion Risk and Fire Suppression. Retrieved April 1, 2022, from https://safety4sea.com/wp-content/uploads/2020/01/DNV-GL-Technical-Reference-for-Li-Ion-Battery-Explosion-Risk-and-Fire-Suppresion-2020_01.pdf

53. Babrauskas V. (2009). Research on Electrical Fires: The State of the Art. Retrieved April 4, 2022, from https://www.researchgate.net/publication/250275720_Research_on_Electrical_Fires_The_State_of_the_Art

54. Kumar A. & Prasad N. (2010). Industrial Fire Fighting System Using PLC with SCADA. Retrieved April 4, 2022, from https://www.guardsafetysaudi.com/pdf/Fire-fighting.pdf

55. Pitkämäki A. & Bröckl M. & Raivio T. (2018). Opas teollisuuden litiumioniakkujen turvalliseen käyttöön. Retrieved April 4, 2022, from https://tukes.fi/documents/5470659/8237195/Opas+teollisuuden+litiumioniakkujen+turvalliseen+k%C3%A4ytt%C3%B6%C3%B6n/c5c7fefe-7979-4344-ba25-ba18a6f9f234/Opas+teollisuuden+litiumioniakkujen+turvalliseen+k%C3%A4ytt%C3%B6%C3%B6n.pdf?t=1529565473000

56. Directive 2006/42/EC of the European Parliament and of the Council of 17 May 2006 on machinery, and amending Directive 95/16/EC. (2006). Retrieved April 5, 2022, from https://eur-lex.europa.eu/legal-content/FI/ALL/?uri=CELEX%3A32006L0042

57. Huffman Engineering. (2017). What Are Safety PLCs? Retrieved April 6, 2022, from https://huffmaneng.com/what-are-safety-plcs/

58. Finnish Standards Association SFS. (2020). SFS- EN ISO 13849-1. Retrieved April 11, 2022, from https://sales.sfs.fi/fi/index/tuotteet/SFS/CENISO/ID2/1/400493.html.stx

59. Finnish Standards Association SFS. (2020). SFS-EN 61508-1. Retrieved April 11, 2022, from https://sales.sfs.fi/fi/index/tuotteet/SFSsahko/CENELEC/ID2/6/160758.html.stx

60. Finnish Standards Association SFS. (2020). SFS-EN 54-5. Retrieved November 14, 2022, from https://sales.sfs.fi/fi/index/tuotteet/SFS/CEN/ID2/5/700974.html.stx

61. Finnish Standards Association SFS. (2020). SFS-EN 15276-1. Retrieved November 14, 2022, from https://sales.sfs.fi/fi/index/tuotteet/SFS/CEN/ID2/1/758752.html.stx

62. Finnish Standards Association SFS. (2020). SFS-EN 12094-9. Retrieved November 14, 2022, from https://sales.sfs.fi/fi/index/tuotteet/SFS/CEN/ID2/1/4186.html.stx

63. Xie J. & Liu Y. (2015). Failure Study of Commercial LiFePO 4 Cells in Overcharge Conditions Using Electrochemical Impedance Spectroscopy. Retrieved April 12, 2022, from https://www.researchgate.net/publication/282939617_Failure_Study_of_Commercial_LiFePO_4_Cells_in_Overcharge_Conditions_Using_Electrochemical_Impedance_Spectroscopy

64. Fowler M. & Tran M-K. (2020). A Review of Lithium-Ion Battery Fault Diagnostic Algorithms: Current Progress and Future Challenges. Retrieved April 15, 2022, from https://www.researchgate.net/publication/339793410_A_Review_of_Lithium-Ion_Battery_Fault_Diagnostic_Algorithms_Current_Progress_and_Future_Challenges

65. Robles J. & Vyas A. & Fear C. & Jeevarajan J. A. (2020). Overdischarge and Aging Analytics of Li-Ion Cells. Journal of the Electrochemical Society. Retrieved April 15, 2022, from https://www.researchgate.net/publication/342500485_Overdischarge_and_Aging_Analytics_of_Li-Ion_Cells

66. Siemens. (2022). SIMATIC S7-1500 TM NPU. Retrieved April 26, 2022, from https://new.siemens.com/global/en/products/automation/systems/industrial/plc/simatic-s7-1500/simatic-s7-1500-tm-npu.html

67. AGIS Fire & Security. (2022). Tietoa meistä. Retrieved April 26, 2022, from https://agisfs.fi/tietoa-agis-fire-security/

68. Pahnila, Heikki. (2022). Engineer. AGIS Fire & Security. Email, April 3, 2022.

69. Pahnila, Heikki. (2022). Engineer. AGIS Fire & Security. Email, April 11, 2022.

70. Pahnila, Heikki. (2022). Engineer. AGIS Fire & Security. Email, April 12, 2022.

71. Stemmer Imaging. (2022). About Stemmer Imaging. Retrieved April 26, 2022, from https://www.stemmer-imaging.com/en-fi/about-stemmer-imaging/

72. Staudinger, Max. (2022). Manager Finland & The Baltics. Stemmer Imaging. Email, April 25, 2022.

73. MVTec. (2022). HALCON – The power of machine vision: MVTec Software. Retrieved April 26, 2022, from https://www.mvtec.com/products/halcon

74. NoFire Systems. (2021). NoFire Systems – Applications and advantages. Retrieved April 26, 2022, from https://www.nofire.fi/

75. Sovinen, Tatu. (2022). Senior Advisor. NoFire Systems. Email, October 11, 2022.

76. Sovinen, Tatu. (2022). Senior Advisor. NoFire Systems. Email, November 28, 2022.

77. Profinet University. (2022). Profinet GSD File Basics. Retrieved April 26, 2022, from https://profinetuniversity.com/profinet-basics/profinet-gsd-file-basics/