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Technical report

Battery Electric Locomotives

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Acronyms and Abbreviations

2170	21 mm by 70 mm cylindrical li-ion cell
AST	Automotive and Surface Transportation
BMS	battery management system
DOD	depth of discharge
FMMEA	failure modes, mechanisms, and effects analysis
LFP/LiFePO4	lithium iron phosphate
LIB	lithium-ion battery
LTO	lithium titanium oxide
NCA	nickel cobalt aluminium
NMC	nickel manganese cobalt
NRC	National Research Council
NSL	NRC National Science Library
SOC	state of charge
SOH	state of health
TC	Transport Canada

1 Introduction

The National Research Council Canada (NRC) Automotive and Surface Transportation (AST) has been tasked by Transport Canada (TC) to perform a risk assessment on the risks and hazards associated with the operation of hydrogen and battery-powered locomotives for the railway industry. The first phase of this project (2021-2022) focused on hydrail, a type of hydrogen-powered train that combines hydrogen fuel cells, batteries and electric traction motors in a hybrid configuration. As part of the second phase of this project (2022-2023), the NRC team working on this assignment was asked to perform a search of the existing literature to better understand the current technical trends and challenges associated with battery-powered locomotives.

Every battery-powered railway makes use of one or more battery-electric locomotives (BEL), and the latter are vehicles driven by electricity from an on-board battery. In this report, the concept of a BEL includes two configurations: a 100% battery-electric railway locomotive and a battery-catenary hybrid railway locomotive that can run both on routes with wires and on non-electrified sections. Other hybrid configurations with diesel or hydrogen fuel cells (hydrail) were not considered in this report. All types of train and locomotive were included: passenger trains (metro, tramways, commuter, intercity, regional and long distance), freight trains, specialty locomotives (e.g., mining industry), shunting locomotives and other yard services railway vehicles.

The NRC authors used a list of over 200 selected bibliographic references from an extensive search of scientific and technical databases. The list also includes references found in trade magazines as well as news and web sites to round off the BEL’s applications section. These references were found by the NRC National Science Library (NSL) in answer to the following questions:

1. What are the publications in scientific databases published in the last 8 years that discuss:
    a. the location of the battery in the locomotive;
    b. the batteries chemistry used in battery-driven locomotive;
    c. the failure modes, failure causes, failure consequences, severity of each failure mode and severity of failure rates for battery-electric locomotives;
    d. the way the battery applies power to a traction motor in the battery-operated locomotive;
    e. the operation, maintenance and recharging of battery-powered locomotives.

2. What are the studies for Codes, Standards and Regulations (CSR) on a battery-powered locomotive, train or switcher?

3. What are the existing battery-powered trains, locomotives or switchers applications across the globe (with a focus on North America, Europe, Australia, China, India and Japan)?

4. What are some "lessons learned" from existing battery-powered locomotive applications across the globe?

To find information on BEL technical features (question 1), the NRC-NSL conducted a literature search in six scientific and technical databases: Scopus, Elsevier, Engineering Collection (ProQuest), IEEE Xplore, TRID and SPARK. For question 2 associated to battery codes, standards and regulations (CSR), NRC-NSL searched the standards database ASTM Compass and conducted a web search (Google). To find applications and lessons worldwide (question 3 and 4), the search engine Google was queried. Company and train names found in the scientific and technical publications were also reused for the web searches. Finally, NRC-NSL consulted specific governments, associations and not-for-profit organizations websites. Those sources are synthetized in Table 1.

Table 1: Sources queried or consulted by NRC-NSL

Scientific & technical databases	Government sources	Associations / not-for-profit organizations
✓ ASTM Compass ✓ Engineering Collection ✓ IEEE Xplore ✓ Scopus ✓ SPARK ✓ TRID	✓ Science.gov ✓ U.S. Department of Transportation ✓ U.S. Department of Energy	✓ American National Standards Institute (ANSI) ✓ Association of American Railroads (AAR) ✓ Europe’s Rail (EU-Rail) ✓ International Electrotechnical Commission (IEC) ✓ International union of railways (UIC) ✓ Railway Technology

The author had several NRC researchers look over the sources and rank them in terms of relevance. The ranking system involved three levels, indicating sources as being relevant, maybe relevant, or not very relevant. A researcher then read all of the relevant papers and many of the maybe relevant papers to create this summary document. During this process, some other papers were also found that were relevant and were also read, with their findings summarized in this document.

2 Literature findings

2.1 Location of the Battery:

The location of the battery in a battery-powered railway is an important consideration in the design of the locomotive, as it can affect the locomotive's weight distribution, stability, and maintainability. There are several possible locations for the battery in the locomotive, including underfloor, roof-mounted, and a combination of both. Each location has its own advantages and disadvantages, which must be weighed against the specific requirements of the locomotive and its intended use.

Underfloor battery placement is a popular option, as it allows for a low centre of gravity and good weight distribution (Turnbull-Neep, 2021). The lower centre of gravity also provides greater stability for the locomotive, which is important for high-speed applications and tight corners. However, underfloor batteries can be more difficult to maintain, as they are not easily accessible and require more effort to replace or repair. Additionally, this can pose a challenge for mounting important components to the underframe due to limited space, although there are examples where some of these other components were mounted to the rooftop instead (Ogura, 2017). Despite these challenges, underfloor batteries remain the most popular choice since batteries do not need much maintenance other than replacing the cooling liquid once in a while, which can be done at a distance from the batteries.

Roof-mounted batteries, on the other hand, are easier to maintain and replace, as they are more accessible. They also offer better cooling and ventilation, which can improve battery performance and longevity. However, roof-mounted batteries can increase the height of the locomotive, which can make it more difficult to clear certain bridges or tunnels. They also add more weight to the top of the locomotive, which can affect stability, especially in situations with higher lateral forces such as tight turns or high winds (Turnbull-Neep, 2021). Furthermore, the locomotive structure also has to be improved to support the additional weight on the roof.

Another approach is to use a separate battery car, which can provide several benefits, such as modularity, easy maintenance, and flexibility in battery size and location. This approach can also provide better weight distribution and stability, as the battery car can be located at a distance from the locomotive, thus minimizing the weight and height of the locomotive. Research by the California Environmental Protection Agency (CalEPA, 2016) outlines advantages for separate battery cars, called tenders. It states that because there are limits on the size of a freight locomotive car body, there are limits to the amount of battery storage that can be present on the locomotive. The paper states that tenders are a good solution and claims that a series of tenders may be able to provide enough power to operate freight trains on shorter local or regional routes with no emissions. These battery tenders could store up to 5 MWh of electrical energy, based on current ideas. It involves dedicating one or more cars in a train for carrying batteries, with the battery car(s) connected to the locomotive by cables or electrical connections. One potential advantage of this approach is that it can allow for greater flexibility in terms of the amount of energy stored on the train, as the battery cars can be added or removed as needed. This can be particularly useful for longer routes, where the amount of energy required may vary depending on the terrain, distance, or other factors (CalEPA, 2016).

While the use of separate battery cars can offer some advantages, it also has some potential drawbacks. In order to run a freight train, multiple diesel locomotives are typically used. To replace these with battery electric ones, tender cars would need to be implemented to supply enough power, and multiple tender cars would be needed for each locomotive. This would mean that trains that are restricted in length or weight by regulations would not be able to carry as many freight cars since some of the cars on the train would be used to hold batteries. In addition, the use of separate battery cars can be less practical for shorter routes, as the additional weight and complexity may not be necessary ("Wabtec's All-Battery Locomotive, FLXdrive, Lowers Freight Train's Fuel Consumption by More Than 11 Percent in California Pilot," 2021).

Some battery powered locomotives utilize a diesel locomotive frame that has been converted to a battery electric. This is intended for a passenger train located in Calabria, Italy. Locomotive conversion allows a more cost competitive option than a new design. When a diesel locomotive is converted to battery power, the battery is usually located in the engine compartment or in the former fuel tank area due to space limitations in the rest of the locomotive. Removing the internal combustion engine clears enough room to easily install a battery. (Fragiacomo et al., 2022). According to Fragiacomo et al., the location of the battery in a locomotive can vary based on the type of battery and the design of the locomotive. Lithium-ion (Li-ion) batteries can be installed in the engine compartment, while other battery types may require more space and may be located in the fuel tank area due to their lower energy density. Lithium-ion batteries can be 15 times more energy dense than lead-acid, and this allows them to take less space in a vehicle. The location of the battery may also depend on the size and weight of the battery, as well as the layout of the locomotive. In some cases, the battery may be split between different locations in the locomotive to optimize the distribution of weight and minimize impacts on the centre of gravity.

2.2 Battery Chemistries and Alternative Technologies

There are many types of battery chemistries, but some are much more advanced and suited to a battery powered locomotive than others. Battery chemistries that may useful include nickel metal hydride (NiMH), lithium-ion (Li-ion). These are described in section 2.2.1 to 2.2.2, respectively. Some older chemistries like lead acid and nickel cadmium (Ni-Cd) were used in the past for traction vehicle but are not consider as a good option anymore.

Scalability and power, failure mechanisms, durability, supercapacitors and future battery technologies are described in sections 2.2.3 to 2.2.8, followed by a summary in section 2.2.9.

2.2.1 Nickel Metal Hydride Batteries

NiMH was the main chemistry used before lithium ion was created. It is still widely used in many electronics and until recently, in hybrid vehicles. This chemistry was interesting because of the improved energy density compared to Lead-acid batteries (around 60 Wh/kg) but the design suffers from charging memory effects that reduce its capacity quickly overtime. NiMH batteries involve a reversible reaction between nickel hydroxide ($Ni(OH)_2$) and a hydrogen-storage alloy electrode. During charging, nickel hydroxide is oxidized to form nickel oxyhydroxide (NiOOH) while the hydrogen-storage alloy electrode is oxidized to release hydrogen ions that combine with electrons to form hydrogen gas. The reverse reaction occurs during discharge (Cassayre et al., 2022). The performance of these batteries depends on many factors, including the composition of the hydrogen-storage alloy, the particle size, the morphology, and the electrochemical behavior of the nickel hydroxide electrode. Recent research has focused on developing new materials and improving the electrode design to enhance the performance of NiMH batteries (Li et al., 2016). One example of this is a study by Chen et. al. which focused on the use of nanoscale materials, which were used to increase the surface area and facilitate faster charge/discharge rates. The authors found that these materials demonstrated superior electrochemical properties, such as high specific capacity, good cycling stability, and excellent discharge capability at high current (Chen et al., 2015). The limited energy density at 60 Wh/kg and memory effect limited this chemistry for transport usage. Trains, cars or trucks require a higher capacity and no memory effect to achieve good performance in a vehicle and NiMH wasn't able to match the requirements.

2.2.2 Lithium-Ion Batteries

Lithium-ion batteries (LIBs) are rechargeable batteries that store energy by the transfer of lithium ions between two electrodes, usually a graphite anode and a metal oxide cathode. Each LIB chemistry discussed in this section corresponds to that description.

Table 2 has a brief summary of the five main LIB chemistries used in the vehicle market, (plus one that is not currently used there), and some relevant characteristics (Buchmann, 2017).

The most common battery technology used is lithium-iron battery chemistry and are known for having a high energy and power density, as well as high cycle life and charge retention when compared to other battery types not based on lithium. Therefore, these batteries are typically considered to be the best available battery technology for many applications including powering locomotives. However, they are typically very sensitive to being overcharged, which can create safety issues in the form of thermal runaway. For this reason, the use of battery management systems (BMS) is often necessary to prevent this and to help the batteries operate at peak performance levels (Barbosa, 2022).

Although the anode is typically made of graphite, lithium titanium oxide has also been used and can improve the battery cycle life, power, low temperature performance, and safety (Knibbe et al., 2022). On the other hand, it has about half the capacity of a lithium battery with a graphite anode. Several common lithium-ion battery cathode chemistries include lithium-nickel-cobalt-aluminum oxide (NCA), lithium-nickel-manganese-cobalt oxide (NMC), lithium manganese oxide (LMO), lithium-titanate-oxide (LTO), and lithium iron phosphate (LFP).

NMC batteries are composed of a cathode made of lithium, nickel, manganese, and cobalt (Li et al., 2018). Changing the percentages of these elements can change the properties and performance of the batteries. NCA batteries, on the other hand, are made with 80% nickel, 15% cobalt, and 5% aluminium. Both of these battery chemistries have relatively high energy densities and cycle life, but perform more poorly in terms of cost and safety.

LFP and LTO batteries typically have lower energy density, but have better useful lifespan and are safer. They also depend less on the depth of discharge of the discharge cycles and the charge and discharge rates. LTO batteries perform the best of all LIBs in terms of efficiency, and over-charge or discharge tolerance, but they are also very expensive. LFP batteries cost less than all of the other LIBs. They are also safer than most other LIBs because they are more thermally stable and do not produce toxic chemicals. In addition to the lower cost of LFP batteries, the materials are also easy to come by. Iron is plentiful and is relatively easy to obtain, which adds to the sustainability of using these batteries (Knibbe et al., 2022).

For this reason, LFP batteries are generally considered to be one of the most promising battery technologies, but some sources also claim LTO batteries to be the leading technology due to some of their advantages over LFP batteries that were previously mentioned (Thorne et al., 2019). This is despite the fact that both LTO and LFP batteries have a worse energy density than some other LIBs. Furthermore, LFP can exhibit worse performance in low temperatures when compared to other LIBs, which could be an important factor in Canada, where temperatures can be quite low (Brady, 2017). However, it has already been stated that LIBs typically require a battery management system to regulate the temperature for peak performance, so this may not be too much of a problem.

Table 2: Main Li-ion chemistries

Chemistry	**Main Formats**	**Manufac-turers**	**Energy density**	**Lifetime**	**Safety**	**Cold weather (C)**	**Availa-bility**	**Cost (/kWh)**
LFP (lithium iron phosphate) **LiFePO4**	Cylindrical (many sizes)	A123, CATL, CABL, EVE, BYD	Mid	mid	high	Charge: 0° or	high	low
	Prismatic		160 Wh/kg	5k cycles		-30° nano-phos-phate		≈140$US
						Discharge: -30°		
NCA (lithium-nickel-cobalt-aluminum oxide) **LiNiCoAlO2**	18650/2170 /4680	Panasonic, Tesla	High	Low	Low	Charge: 0°	high	low
			270 Wh/kg	1k-1.5k cycles		Discharge: -20°		≈140$US
NMC (lithium-nickel-manganese-cobalt oxide) **LiNixMnyCozO2**	18650/ Pouch	LG, SDI, Moli, SK	High	Low	Low	Charge: 0°	high	low
			260 Wh/kg	1.5k cycles		Discharge: -20°		≈150$US
LTO (lithium-titanate-oxide) **LiTiO Li4Ti5O12**	Pouch/ Prismatic	Toshiba, Yinlong	Low	high	Very high	Charge: -30°	low	high
			80 Wh/kg	+30 k cycles		Discharge: -50°		>500$US
LMO (lithium-Manganese-Oxide) **LiMn2O4**	Pouch	NEI	Low	Low	Low	Charge: 0°	low	high
			125 Wh/kg	500 cycles		Discharge: -20°		≈150$US

2.2.2.1 Electrochemical reactions

During the discharging process of a Li-ion battery, lithium atoms in the negative electrode are separated from their electrons (Savoye et al., 2011). These lithium ions travel from the negative electrode via the electrolyte to the positive electrode, where they recombine with their electrons and become electrically neutral. The tiny structure of Li-ion battery materials, shown in Figure 1, makes it possible to pass through a micro-permeable separator. Also, during charging, the opposite phenomenon occurs where the Li-ion moves from the positive side positive electrode to the negative side negative electrode (Sato, 2001). All Li-ion chemistries work the same way. The key element is the lithium so the reactions are all similar.

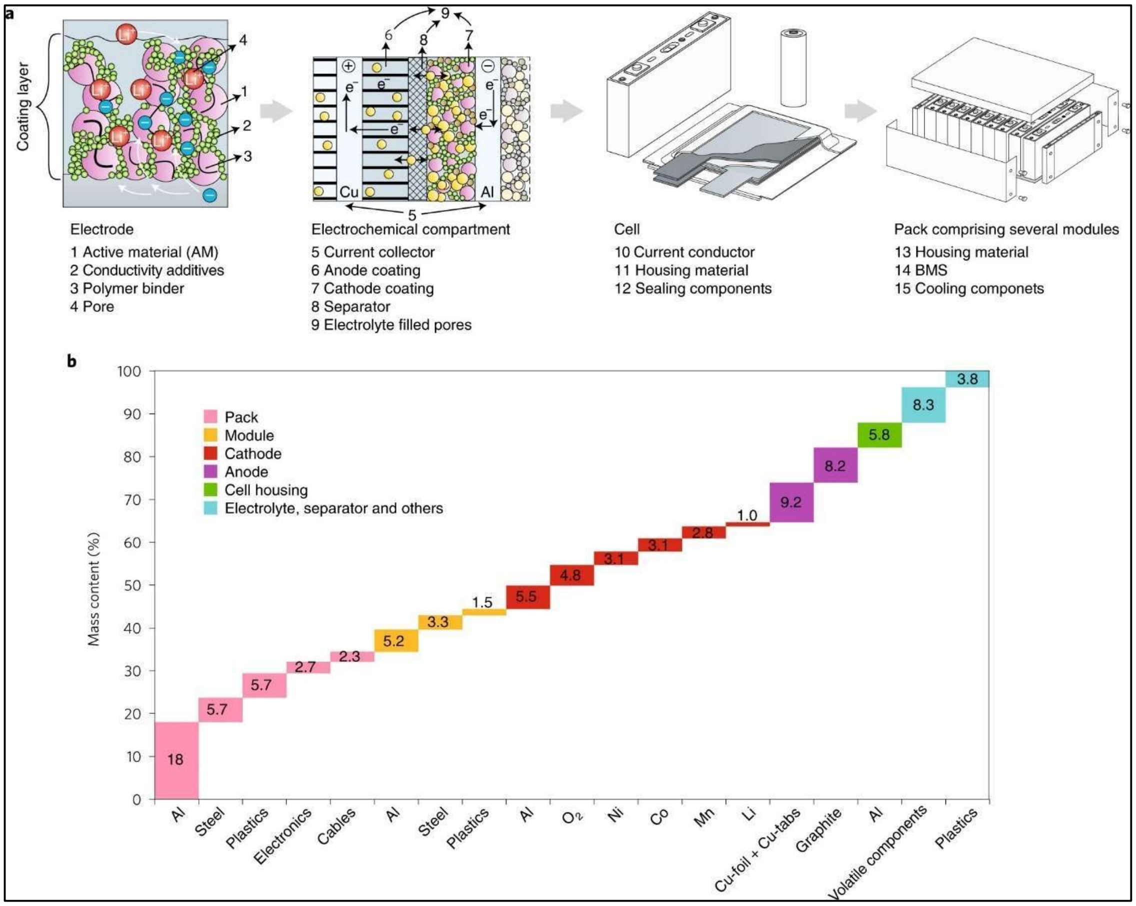


Figure 1: a Composition of the LIB electrode (including pores that are filled with electrolyte), electrochemical compartment, cell and modules as components of LIB packs. b, A breakdown of mass content at cell (cathode, anode, housing and electrolyte), module and pack levels are indicated. (Kwade et al., 2018)

2.2.2.2 Environmental impacts

The environmental impact of battery manufacturing depends mainly on the elements used in their manufacture. The proportions of each of the elements will also have an environmental impact because the more cobalt the NMCs contain, the larger the environmental impact will be. The industry has been working for several years to reduce the use of cobalt in NMCs and NCAs. The solution found for vehicles that don't require long autonomy is to use LFPs which offer good performance while not using cobalt and nickel.

2.2.2.3 Battery mix content 2014

The proportion of each material by weight in a battery from a 2014 analysis is shown in Table 3. These proportions may have changed since that time depending on the manufacturer as well as technological improvements.

Table 3: Li-ion battery components by weight percent (Gratz et al., 2014)

Battery component	Weight %
Casing	25
Cathode material	25
Anode material	14
Electrolyte	10
Copper electrolyte foil	8
Aluminium electrolyte foil	5
Separator	4
Other	9

It should be noted, however, that the example in Table 3 (Gratz et al., 2014) is from 2014 and the energy density was significantly lower than it is now in 2023; these values must therefore be tempered. The casing represents a smaller portion now due to the increase in energy density. However, it is reported that the cathode represents 25% of the remaining 75%, excluding the casing.

2.2.2.4 Battery mix content 2018

In another example from 2018, the mass proportion of each component of a battery consisting of NMC cells is shown in Figure 1.

Figure 1 shows the anode counts for 17.4%, the cell boxes for 5.8% and the electrolyte and other for 12.1% of the total mass of the battery. As per Table 3, the proportions of NiMnCo show that there is an equal share of Nickel, Manganese and Cobalt in the cathode (NMC111).

2.2.2.5 Battery mix content 2023

Current technology in 2023 is based on NMC811 so manganese and cobalt occupy only 10% each of the composition of the cathode. This chemistry was introduced in 2019 and became mainstream around 2021.

For comparison, a 77.4 kWh Hyundai Ioniq 5 battery in 2021 weighs about 450 kg (Kane, 2021). It is therefore possible to determine the quantity necessary for the manufacture of such a battery. The quantities this represents are shown in Table 4.

Table 4: Li-ion battery components for 2021 Hyundai Ioniq 5 NMC111 and 811 at 77.4 kWh battery.

Components	Weight %	Part	NMC111 Mass (kg)	NMC811 Mass (kg)
Al	18	Pack	81.0	81.0
Steel	5.7		25.7	25.7
Plastics	5.7		25.7	25.7
Electronics	2.7		12.2	12.2
Cables	2.3		10.4	10.4
Al	5.2	Module	23.4	23.4
Steel	3.3		14.9	14.9
Plastics	1.5		6.8	6.8
Al	5.5	Cathode	24.8	24.8
O2	4.8		21.6	21.6
Ni	3.1		14.0	33.5
Co	3.1		14.0	4.2
Mn	2.8		12.6	3.8
Li	1		4.5	4.5
Cu foil	9.2	Anode	41.4	41.4
Graphite	8.2		36.9	36.9
Al	5.8	Cell housing	26.1	26.1
Volatiles	8.3	Electrolyte, others	37.4	37.4
Plastics	3.8		17.1	17.1
Total			450.5	451.4

It is important to note that, as shown in Table 4, most of the weight of a LIB is aluminum (34.5% = 18% pack +5.2% module + 5.5% cathode + 5.8% cell housing for the XXX battery) followed by copper (9.2% = 9.2% anode for the XXX battery) and steel (9.0% = 5.7% pack + 3.3% module for the XXX battery). More delicate metals such as cobalt and lithium occupy 8.4 kg together in the new NMC811 battery. The proportions are very similar for an NCA-based battery because it uses aluminum instead of manganese, so the proportion of aluminum is slightly higher.

The composition of LFP cell is similar except for the cathode which is composed of iron and phosphate in molar equal portion and twice as much oxygen. Figure 2 shows that the amount of aluminum will remain the same because it acts as a collector and does not participate in the chemical reaction here. It is possible to extrapolate the weight of each main material based on a 100 kWh battery. The total weights of NMC and O2 are 88 kg. In the case of an LFP battery, this weight will be shared in equal molar proportion according to the formula $FePO_4$. The weights will therefore be about Iron at 41 kg, Phosphate at 23 kg and oxygen at 24 kg. However, a 600 kg LFP battery will not necessarily have 100 kWh because the energy density is lower than NMC or NCA. The value will be around 70 kWh depending on the technology available (see Table 2).

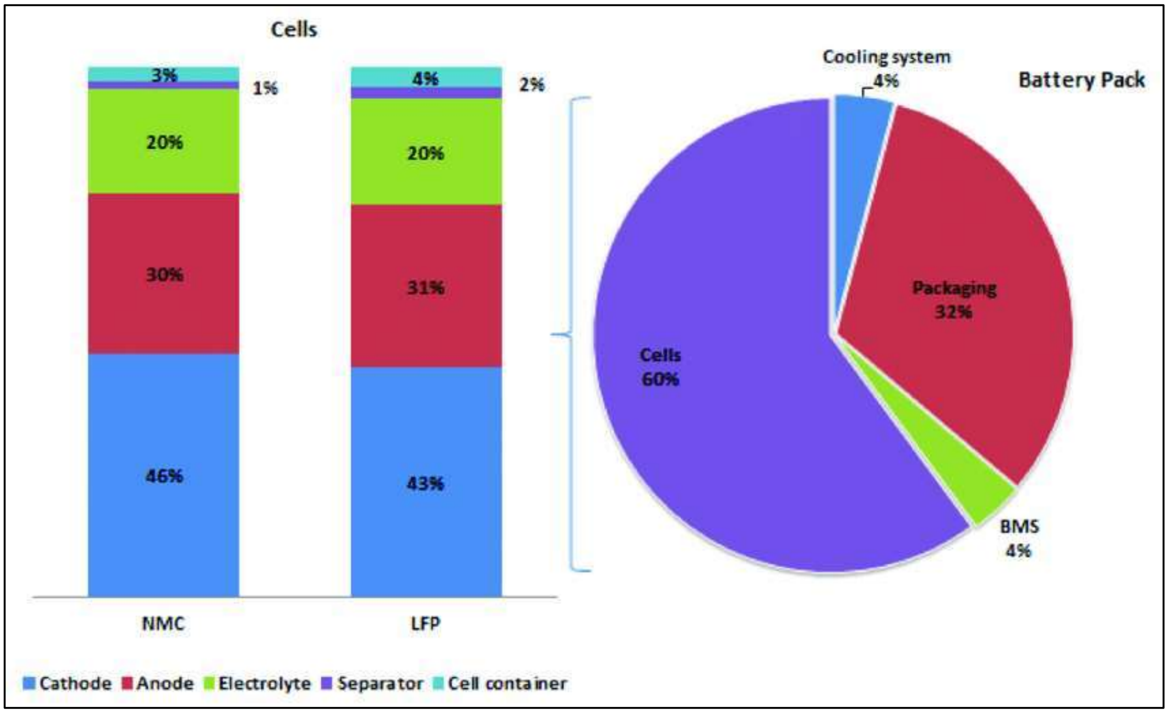


Figure 2: Battery pack and battery cell mass composition, by components, for LFP (lithium-iron-phosphate) and NMC (nickel-manganese-cobalt) batteries. (Carvalho et al., 2021)

The last main battery chemistry is LTO (lithium-titanate-oxide) LiTiO (Li4Ti5O12). As this chemistry is very rare and produced only by a few suppliers, it is difficult to know the exact proportion of the components. In these cells, graphite is replaced by a mixture of titanium, oxygen and sometimes a niobium addition. In one case, for example, this kind of mixture could replace the 49.2 kg graphite anode in a 600 kg, 2023 Tesla Model S battery as shown in Table 4: Li-ion battery components for 2021 Hyundai Ioniq 5 NMC111 and 811 at 77.4 kWh battery are shown in Table 4.

2.2.2.5.1 Mining of materials needed to facilitate material production in support of LIB manufacturing

Many of the materials identified in Figure 1 and Table 4 start with the mining of specific minerals, and each of those processes will have its own environmental impact, without even considering the environmental impacts of battery manufacturing itself. The sources of the needed minerals are widespread throughout the world with very uneven distribution according to the different minerals. Where each mineral comes from, and how it needs to be processed to produce a given material for LIB production will have different ethical, economic and environmental impacts (*Mineral Commodity summaries 2023*, 2023). However, it is necessary to relativize according to the origin, the main uses, the recyclability and the quantity necessary to determine the real environmental impact a given mineral and its manufacturing process has on manufacturing a battery.

The Aluminum section below lists a range of key facts about aluminum use in the U.S., and then also lists a range of factors that affect sustainable manufacturing of aluminum. The information focuses on producing aluminum as it would be used in the manufacture of a LIB, and looks at the use that has been made of it to date; its recycling; its sources of imports; the events, trends and issues; world resources; and finally, the refining process and GHG emissions related to the process.

The Aluminum section is followed by corresponding sections entitled Cobalt, Copper, Graphite, Iron & Steel, Lithium, Manganese and Nickel. That is followed by a Phosphate. That in turn is followed by a Titanium section that is relevant to the manufacturing of LTO batteries.

Having the ten separate sections makes it possible to understand where portions of the LIB manufacturing process can potentially be improved and how the resources can be problematic.

Overall, battery manufacture needs a lot of resources and energy sources but it highly depends on the countries where the resources come from and the countries where it is processed. The electricity GHG used depend on the local grid where the process occurs. There is also some big difference between the chemistry made. The amount of energy is much higher for LFP than NMC in the cell manufacturing process but much less intensive for the minerals process and use.

For more information about the Environmental impacts and the resources scarcity of each mineral present in Li-ion batteries, the Annex B goes more in details.

2.2.3 Scalability and Power

There is no limitation to the scalability and power of a battery assembly. A battery is an assembly of cells that in series adds the voltage and in parallel adds the current (Ah) The real limit is that of materials capable of supporting the potential and intensity. The volt potential is limited by the risk of loss through an insulator. The limitation in intensity is that of the conductive wires or plates. The internal resistance of each of the cells can become a problem to increase the voltage of batteries in series. This situation only concerns lead-acid batteries that are not designed to be installed in large series since it could cause too much internal resistance resulting in overheating.

Regarding power, this value depends on the ability of a cell to discharge or charge quickly without overheating and risking an uncontrolled thermal event. The C-value is the reference based on the total capacity of a cell. C means how many fractions of an hour a cell can completely discharge. For example, a value of 3 means that a cell can discharge in 20 minutes. There are also limited discharges as well as pulses. These limited discharges are usually about 30 seconds according to the manufacturers. The pulses are about 2 seconds. The details are in Table 5.

Table 5: Battery Voltage and power (batteryspace, 2023b; Buchmann, 2017; Toshiba, 2023)

Chemistry	Nominal voltage	Charge voltage	Charging C-rate	Discharging C-rate
NCA	3.6	4.2	0.5	2
NMC	3.6	4.2	0.5 to 2	2 to 10
LFP	3.2	3.65	1	2 (pulse 25)
LTO	2.4	2.85	1500 for 10 s	180 for 10 s

Lead-acid	2.1V	2.3V to 2.45V	0.1-0.05	n/a
NiMH	1.2	1.5	0.5-1	1

The C values shown in Table 5 are for reference purposes only and change according to the manufacturer's requirements. A higher capacity is reflected in a lower C-value and vice versa. The data can therefore change according to the needs as well as according to the manufacturers. They will also change in the future, following future technological improvements. For example, even if LFPs are generally limited to 2C, chemistry based on nanophosphate from A123 (Batteryspace, 2023a) allows a continuous value of 20C with pulses from 10 s to 48C. A good thermal management system will also better manage the rise in temperature and avoid a thermal event and premature aging of the cells.

Another limitation is the weight of a battery assembly. This situation affects any moving assembly but mainly acid-lead assembly due to their large weight.

There are currently systems in the world meeting huge power demand using li-ion batteries. Table 6 is listing some of these big projects around the world currently used.

Table 6: Battery Energy storage system (Shah, 2022)

Location	**Developer**	**Power, MW**	**Capacity, MWh**
California	Vista Energy Corp	400	1600
Florida	Florida Power&Light	409	900
Australia	Neoen	300	450
California	MextEra Energy Resources	290	920
California	PG&E	182.5	730

2.2.4 Failure mechanism with a particular focus on rail applications: focusing on the battery

A general Failure Modes, Mechanisms, and Effects Analysis (FMMEA) for commercially available lithium-ion batteries was developed on the individual cell level. The FMMEA is shown in Table 7, and it provides a comprehensive list of the parts within a lithium-ion battery that can:

- fail or degrade;
- the mode by which the failure is observed;
- the potential causes of the failure;
- whether the failure is brought on by progressive degradation (wearout) or abrupt overstress;
- the frequency of occurrence;
- the severity of failure; and
- the ease of detection of the failure mechanism.

This FMMEA was developed based on experience gained from years of reliability testing, battery disassembly, and failure analysis (Hendricks et al., 2015; Williard et al., 2011).

Table 7: FMMEA for lithium-ion batteries. (Ganesan et al., 2005; Hendricks et al., 2015)

Battery component	Potential failure mode(s)	Potential failure mechanism(s)	Mechanism type	Observed effect	Potential failure causes	Likelihood of occurrence	Severity of occurrence	Ease of detection
Anode (Active Material)	Thickening of solid electrolyte interphase layer	Chemical reduction reaction and deposition	Wearout	Increased charge transfer resistance, reduction of capacity, reduction of power	Chemical side reactions between lithium, electrode, and solvent	High	Low	High
	Particle fracture	Mechanical stress	Overstress	Reduction of capacity, reduction of power	Intercalation stress	Moderate	Low	Low
	Reduced electrode porosity	Mechanical degradation	Wearout	Increased diffusion resistance, reduction of capacity, reduction of power	Dimensional changes in electrode	Moderate	Low	Low
	Lithium plating and dendrite growth on anode surface	Chemical reaction	Wearout	Can cause short circuit if dendrites puncture separator	Charging the battery at low temperatures or high rates	Low	High	Low
Anode (Current Collector)	Free copper particles or copper plating	Chemical corrosion reaction and dissolution	Wearout	Increased resistance, reduction of power, reduction of current density	Overdischarge of the battery	Low	High	Low

Battery component	Potential failure mode(s)	Potential failure mechanism(s)	Mechanism type	Observed effect	Potential failure causes	Likelihood of occurrence	Severity of occurrence	Ease of detection
Cathode (Active Material)	Thickening of solid electrolyte interphase layer	Chemical reduction reaction and deposition	Wearout	Increased charge transfer resistance, reduction of capacity, reduction of power	Chemical side reactions between lithium, electrode, and solvent	High	Low	High
	Particle fracture	Mechanical stress	Overstress	Reduction of capacity, reduction of power	Intercalation stress	Moderate	Low	Low
	Reduced electrode porosity	Mechanical degradation	Wearout	Increased diffusion resistance, reduction of capacity, reduction of power	Dimensional changes in electrode	Moderate	Low	Low
	Gas generation and bloating of cell casing	Thermally driven electrode decomposition	Overstress	Reduction of capacity	Overcharge of the battery or short circuit	Low	High	Low
Cathode (Current Collector)	Pitting corrosion of aluminum	Chemical corrosion reaction	Wearout	Increased resistance, reduction of power, reduction of current density	Overcharge of the battery	Low	Moderate	Low

Battery component	Potential failure mode(s)	Potential failure mechanism(s)	Mechanism type	Observed effect	Potential failure causes	Likelihood of occurrence	Severity of occurrence	Ease of detection
Separator	Hole in separator	Mechanical damage	Overstress	High heat generation due to joule heating, bloating of cell casing, drastic voltage reduction	Dendrite formation, external crushing of cell	Low	High	Moderate
	Closing of separator pores	Thermally induced melting of separator	Overstress	Inability to charge or discharge battery	High internal cell temperature	Low	High	High
Lithium ions	Reduction in lithium ions, thickening of solid electrolyte interphase layer	Electrolyte reduction and solid product formation	Wearout	Reduction of capacity	Chemical side reactions between lithium, electrodes, and solvent	High	Low	High
Electrolyte salt	Decrease in lithium salt concentration	Chemical reduction reaction and deposition	Wearout	Increased diffusion resistance	Chemical side reactions between lithium, electrodes, and solvent	High	Low	High
Organic solvents	Gas generation and bloating of cell casing	Chemical decomposition of solvent	Overstress	Increased diffusion resistance, and may lead to thermal runaway	High external temperature, overcharging of the cell	Low	High	Low

Battery component	Potential failure mode(s)	Potential failure mechanism(s)	Mechanism type	Observed effect	Potential failure causes	Likelihood of occurrence	Severity of occurrence	Ease of detection
	Thickening of solid electrolyte interphase layer	Chemical reduction reaction and deposition	Wearout	Increased charge transfer resistance, reduction of capacity, reduction of power	Chemical side reactions between lithium, electrodes, and solvent	High	Low	High
Terminals	External corrosive path between positive and negative leads	Chemical corrosion reaction	Wearout	High heat generation due to joule heating, bloating of cell casing, drastic voltage reduction	Inadvertent shorting of the terminals	Low	High	Moderate
	Solder cracking	Thermal fatigue	Wearout	Loss of conductivity between battery and host device	Circuit disconnect	Low	Moderate	High
		Mechanical vibration fatigue						
Casing	Internal short circuit between anode and cathode	Mechanical stress	Overstress	High heat generation due to joule heating, bloating of cell casing, drastic voltage reduction	External load on cell	Low	High	

It is important to remember that despite this list of potential faults or problems of a lithium battery, each battery is equipped with a BMS to prevent or avoid many problems. The BMS is mainly used to prevent misuse of the battery by constantly managing the battery and limiting certain uses that could lead to a thermal runaway.

The BMS development is in the standard IEC/TS 61000-1-2 (Electromagnetic compatibility (EMC)—Part 1-2: General—Methodology for the achievement of functional safety of electrical and electronic systems including equipment with regard to electromagnetic phenomena) and include the safety functions for electromagnetic compatibility. They can be summarized as listed Table 8 below (Gabbar et al., 2021). Incorporating these BMS specifications will help to increase the life of a battery while increasing safety.

Table 8: BMS safety functions

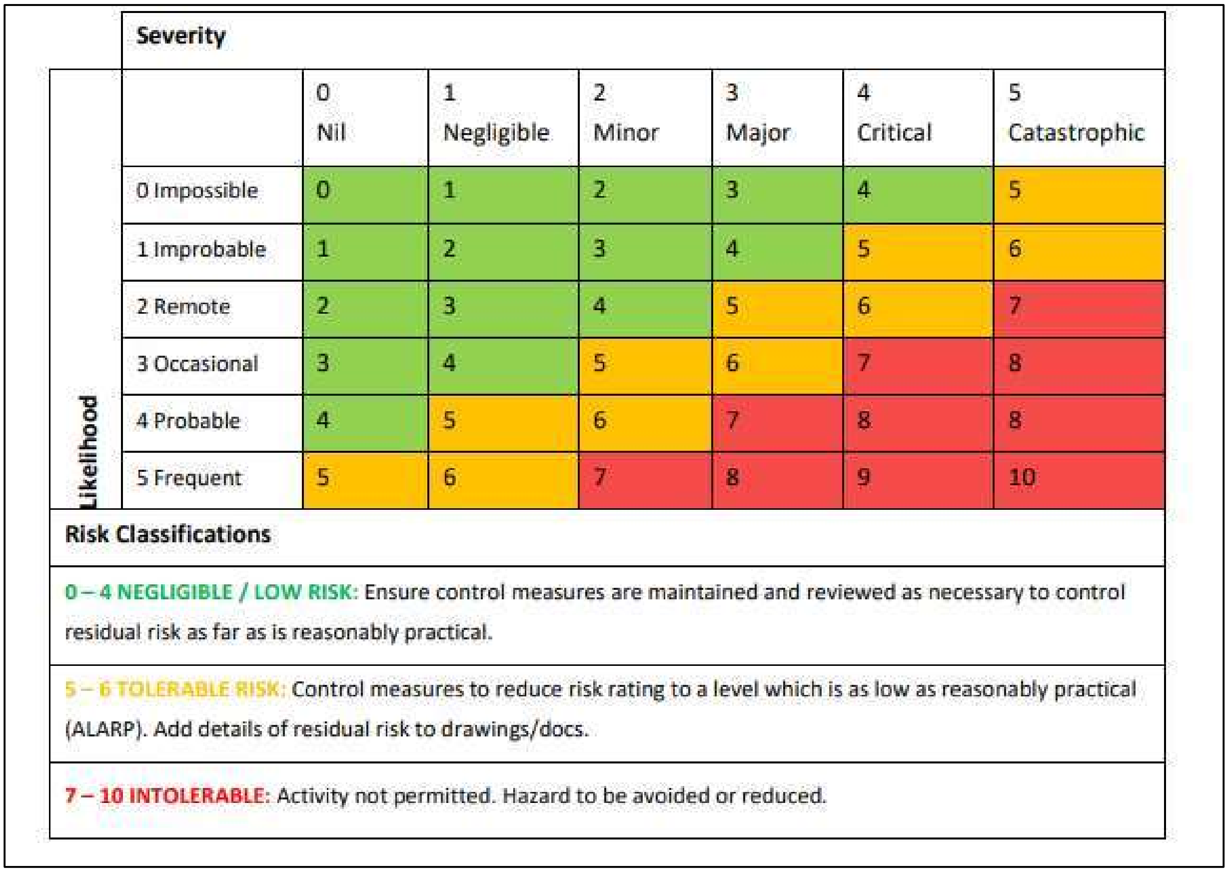
Nb	Function
1	Protect the battery pack.
2	Monitor the battery pack state.
3	Measure battery cells and pack voltage.
4	Measure battery cells and pack temperature.
5	Measure battery pack current flow.
6	Detect battery system leakage currents.
7	Determine battery pack critical state.
8	Manage operating modes.
9	Receive information from the master control system (EMS, VMS…).
10	Control the battery pack (dis)connection.
11	Control the (dis)connection of the electric line of charge.
12	Control the (dis)connection of the electric line of discharge.
13	Inform master control system (EMS, VMS…) of battery pack (dis)connection status.
14	Inform operators (HMI) of battery pack (dis)connection status.
15	Optimize battery lifetime and energy availability.
16	Monitor and control battery pack state of charge (SOC) and state of health (SOH).
17	Manage cell balancing.
18	Monitor and control non-safety battery support systems (BSS).
19	Diagnostic—record battery life history log.

2.2.5 Failure Modes and Rates

There have been some studies to investigate the various hazards associated with the use of a battery-electric locomotives. One study was done by Brown in Great Britain where a workshop was held with various stakeholders to try to determine all of the hazards associated with battery-electric locomotives (Brown, 2021). The report looked at risks associated with all operations scenarios including battery only, and combinations with diesel, hydrogen, or electrical power. It was also across all modes such as light rail, metro, freight, high-speed, and others. It considered all aspects of the lifecycle of the battery and battery-powered locomotives, including installation, charging, maintenance, etc. It also considered all the users of the system including operators, passengers, maintenance workers and even trespassers. They do note, however, that this was done generically. It did not consider site-specific factors. Therefore, they recommend a similar process of analyzing potential hazards for specific sites. Instead, they say this work can serve as a standard baseline from which organizations can work to create site-specific lists of potential hazards.

Brown's paper from the Rail Safety and Standards Board (RSSB) was accompanied by a separate document outlining the list of hazards that the workshop produced. The document also contained other information such as the cause of the hazard, the potential result of the hazard, the specific component or configuration that caused the hazard, and the persons that would be at risk from the hazard. Also included was a ranking of the likelihood and consequence (severity) of each of the identified hazards. These values were used to sort the hazards into categories as shown in Table 9 (Brown, 2021).

Table 9: Risk classification for ranking hazards (Brown, 2021).



	Severity					
Likelihood	0 Nil	1 Negligible	2 Minor	3 Major	4 Critical	5 Catastrophic
0 Impossible	0	1	2	3	4	5
1 Improbable	1	2	3	4	5	6
2 Remote	2	3	4	5	6	7
3 Occasional	3	4	5	6	7	8
4 Probable	4	5	6	7	8	8
5 Frequent	5	6	7	8	9	10

Risk Classifications

0 – 4 NEGLIGIBLE / LOW RISK: Ensure control measures are maintained and reviewed as necessary to control residual risk as far as is reasonably practical.

5 – 6 TOLERABLE RISK: Control measures to reduce risk rating to a level which is as low as reasonably practical (ALARP). Add details of residual risk to drawings/docs.

7 – 10 INTOLERABLE: Activity not permitted. Hazard to be avoided or reduced.

Brown's definition for an impossible likelihood level is "The event is highly unlikely to occur even by exception". While it may be highly unlikely, it is still possible and the NRC authors therefore believe a zero should not be used as it may give the false impression that it could never happen.

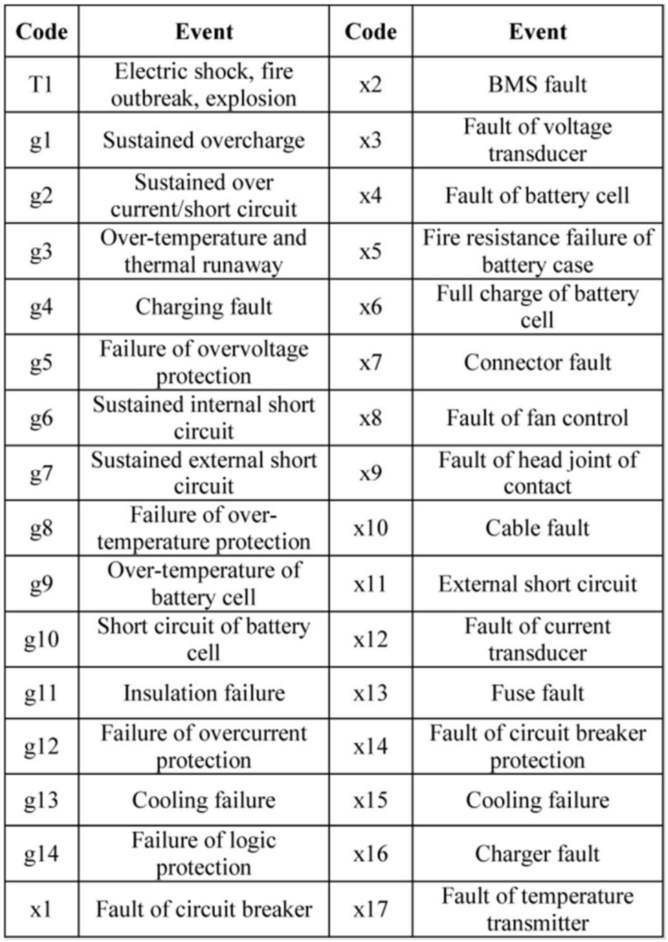
Many of the hazards in the list occur while charging the battery (electrocution or overheating batteries) or in the battery system (fire, release of chemicals). Also included are risks with the train getting stuck because of issues with the propulsion system (hybrid system). Some of the incidents could have been avoided by following standards, but for others, there is no applicable standard. The accompanying document in Brown’s study outlines the applicable standards that could be used for hazards, but often none were available (Brown, 2021).

Only two of the hazards fell into the category of “intolerable” in Brown’s study, which was conducted in Great Britain. Both received a score of 7, from Table 9. Both were identified as being caused by collisions with road users. One involved a collision between a battery powered locomotive and a road user, and the other involved a road user crashing into a charging station. Both of these could result in a fire or possible explosion. For the first case, the workshop identified a standard for diesel tanks (EN 45545 part 7:

https://standards.iteh.ai/catalog/standards/sist/110d8c2b-da8f-407a-b8bb-653a7410297b/sist-en-45545-7-2013) that could potentially be applied to contain the batteries. Some other measures are also mentioned such as having a battery management system that can detect damage to the battery and a system to isolate the battery if a problem is detected. Additionally, the workshop recommended locating the batteries away from areas on the locomotive which would be most likely to be impacted in a crash. For the second case, no standard was identified, but the workshop suggested installing physical barriers around the charging station (Brown, 2021).

Another study was done by Xueming et. al. to determine failure modes and rates (Xueming et al., 2019). This paper focused on three failure modes, namely electric shock, fire, and explosion. It also excluded factors such as manufacturing defects of batteries, bad installations, insufficient charge or discharge rates, and flaws in the design of the cooling system. With these assumptions, Table 10 was made with “T1” indicating the top event, “g1” to “g14” indicating intermediate events that can lead to the top event, and “x1” to “x17”, which indicate the most basic events that can lead to any of the intermediate events.

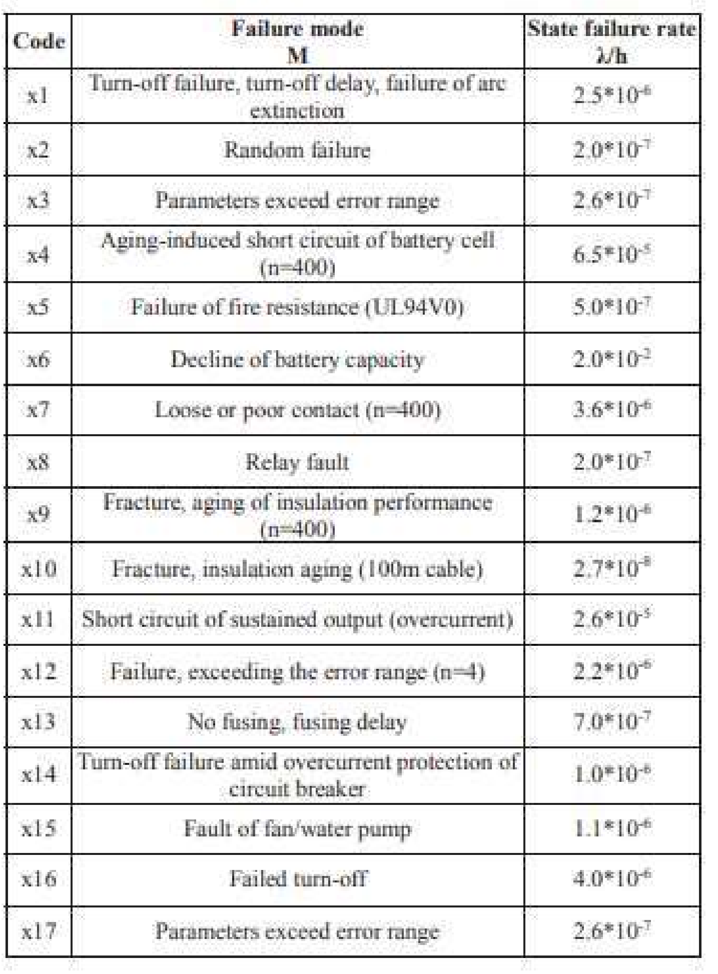
Table 10: List of battery electric locomotive failure modes including basic (x1 to x17), intermediate (g1 to g14), and top (T1) events (Xueming et al., 2019)



Code	Event	Code	Event
T1	Electric shock, fire outbreak, explosion	x2	BMS fault
g1	Sustained overcharge	x3	Fault of voltage transducer
g2	Sustained over current/short circuit	x4	Fault of battery cell
g3	Over-temperature and thermal runaway	x5	Fire resistance failure of battery case
g4	Charging fault	x6	Full charge of battery cell
g5	Failure of overvoltage protection	x7	Connector fault
g6	Sustained internal short circuit	x8	Fault of fan control
g7	Sustained external short circuit	x9	Fault of head joint of contact
g8	Failure of over-temperature protection	x10	Cable fault
g9	Over-temperature of battery cell	x11	External short circuit
g10	Short circuit of battery cell	x12	Fault of current transducer
g11	Insulation failure	x13	Fuse fault
g12	Failure of overcurrent protection	x14	Fault of circuit breaker protection
g13	Cooling failure	x15	Cooling failure
g14	Failure of logic protection	x16	Charger fault
x1	Fault of circuit breaker	x17	Fault of temperature transmitter

Table 11 shows the likelihood of each of these basic events occurring per hour of operation by relating them to information found in a reliability prediction handbook or from reliability tests.

Table 11: Failure rates for basic failure modes of a battery electric locomotive (Xueming et al., 2019)



Code	Failure mode M	State failure rate λ/h
x1	Turn-off failure, turn-off delay, failure of arc extinction	$2.5*10^{-6}$
x2	Random failure	$2.0*10^{-7}$
x3	Parameters exceed error range	$2.6*10^{-7}$
x4	Aging-induced short circuit of battery cell (n=400)	$6.5*10^{-5}$
x5	Failure of fire resistance (UL94V0)	$5.0*10^{-7}$
x6	Decline of battery capacity	$2.0*10^{-2}$
x7	Loose or poor contact (n=400)	$3.6*10^{-6}$
x8	Relay fault	$2.0*10^{-7}$
x9	Fracture, aging of insulation performance (n=400)	$1.2*10^{-6}$
x10	Fracture, insulation aging (100m cable)	$2.7*10^{-8}$
x11	Short circuit of sustained output (overcurrent)	$2.6*10^{-5}$
x12	Failure, exceeding the error range (n=4)	$2.2*10^{-6}$
x13	No fusing, fusing delay	$7.0*10^{-7}$
x14	Turn-off failure amid overcurrent protection of circuit breaker	$1.0*10^{-6}$
x15	Fault of fan/water pump	$1.1*10^{-6}$
x16	Failed turn-off	$4.0*10^{-6}$
x17	Parameters exceed error range	$2.6*10^{-7}$

From Table 11, the authors show that this leads to about a 1% (0.95%) chance of failure after 15,000 h of operation. The authors suggest that, upon reaching this time, this would justify a “thorough overhaul” of the battery. It is also noted that the failure would be mainly from three things, namely, “aging-induced short circuit of battery cell (x4)”, “decline of battery capacity (x6)” and “loose or poor contact of connector (x7)”, accounting for 43.3%, 25%, and 22.6% of failures respectively. Based on this, (Xueming et al., 2019) recommend that measures be taken to address these areas to reduce the hazard they pose. These measures would include regular inspection of connectors (x7), designing capacity redundancy for battery cells and the effective use of a BMS to control the state of charge (SOC) range of the cells (x6), and careful consideration and evaluation of the failure rates and expected life expectancy of the battery cells used (x4) (Xueming et al., 2019). It should be noted that decline of battery capacity isn’t a sudden event but a long coming event that provides lots of warning. It also doesn’t pose a risk to equipment or people in any way.

2.2.6 Durability / Lifetime:

Section 2.2.4 on battery failure mechanisms already mentions the degradation of lithium cells. However, this can be different according to many different specifications and factors.

Different chemistry is certainly the main factor influencing durability and lifetime. Table 12 shows the short life of a lead-acid battery depending on the depth of discharge. At 100% to zero, the number of discharge-recharge cycles barely reaches 15. These 15 cycles are under normal (e.g., room temperature) scenario without considering extreme temperature or high and low discharge and charge rates.

Table 12: Lead-acid battery cycling (Buchmann, 2017)

Depth of discharge	Starter battery	Deep-cycle battery
100%	12–15 cycles	150–200 cycles
50%	100–120 cycles	400–500 cycles
30%	130–150 cycles	1,000 and more cycles

While many different factors affect LIB battery life, one of the most important is number of discharge-recharge cycles, and the results for four LIB chemistries are shown in Table 13. Contrary to other chemistries like lead-acid, with all LIBs the battery is discharged from 100% to 0%, and 0% is the minimum charge level specified by the manufacturer. The battery is then recharged back to 100%. With each consecutive cycle, the battery tends have slightly less capacity, and the rated number of cycles is calculated when the battery capacity is down to 80% (of the original capacity).

The number of cycles presented in Table 13 were those found published in three papers between 2013 and 2023, and one set of 2021 specifications. If it is assumed that each researcher used test conditions that were not identical, then one can consider these results indicative rather than absolute. However, the large ratio between LTO cycles and the other three LIB technologies (NMC, LFP and NCA) is something that is widely observed.

Table 13: Li-ion battery cycles

Chemistry	Charge level (V)	Cut off (V)	Cycle (80%)	Ref.
NMC	4.2	2.5	1,000	(LG, 2013)
LTO	2.4	1.5	40,000	(Toshiba, 2023)
LFP	3.65	2	6,000	(Li et al., 2021)
NCA	4.2	2.5	500	(*Specifications for NCR18650BF*, 2021)

A second main advantage of the Li-ion batteries is the voltage quality during discharge. The voltage remains relatively flat compared to non-LIB chemistries. A flat voltage through to the end of the discharge phase helps equipment perform according to specification, without the need for electronics to deal with a sagging voltage.

2.2.6.1.1 Temperature

Li-ion batteries experience battery life degradation due to various reasons, including charging/discharging cycles, high current rates, and operating under excessively high or low temperatures (Vidal et al., 2019).

Although the acceptable temperature range of Li-ion batteries for EV applications is between -20 °C and 60 °C, the recommended operating temperature is from 15 °C to 35 °C (Liu et al., 2017). Therefore, most of the degradation processes in Li-ion batteries are temperature dependent. Low temperatures not only lead to a reduction of diffusion rates and intercalation but also growth of the lithium dendrite that might cause lithium plating (Waldmann et al., 2014) [65]. A significant cause of battery degradation might be the process of lithium plating in Li-ion batteries. Battery degradation leads to capacity loss, decreasing range and internal resistance, increasing energy power losses and overheating (Nadeau et al., 2013; Senol et al., 2023).

In battery aging tests (Timilsina et al., 2023) reported the results of storing batteries at five different temperatures from 15 °C to 55 °C. The results are shown in Figure 3, and it can be inferred that, as the temperature increases, the capacity loss (SOH) of the battery also increases. For all the temperatures examined, the SOC remains above 50% at the end of 5 years. Figure 3, shows the loss in capacity at different temperatures at a 50% SoC for a LMO battery. LMO battery is not used much anymore but was used in the Nissan Leaf. Durability and energy density were the main issues but this table give an example of what can happen at high temperature. Temperature greatly affects the life of the battery even in a storage situation. Data should be less impactful with NMC, NCA, LFP and LTO.

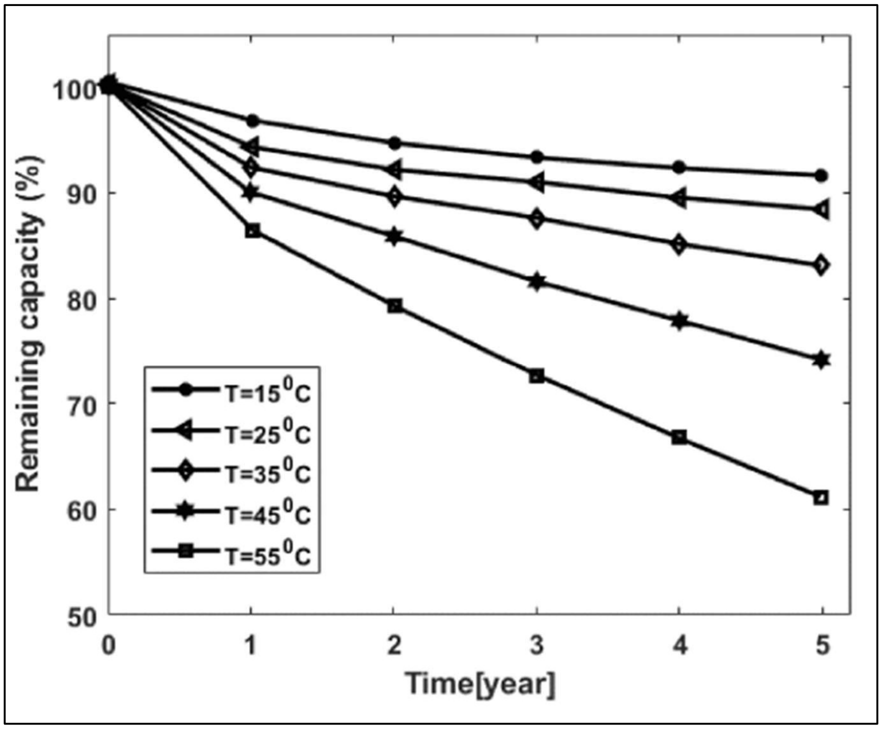


Figure 3: Effect of temperature on calendar aging (Timilsina et al., 2023)

There are also some battery degradation tests with different ambient temperature from the dataset. Figure 4 shows the capacity curve under different operating temperature. All the aging tests applied here is under 1C charge rate and 100% depth of discharge (DOD). From Figure 4, it can be observed that the higher ambient temperature leads to a higher battery degradation value. It takes more cycles for the battery test under 15 °C to degrade to the same capacity level as the battery aging test under 25 °C and

35 °C. The lowest ambient temperature test that is available is 15 °C. The extreme low temperature (lower than freeze point) will fast degrade the battery as well (Lyu et al., 2020). Unfortunately, there is no such real degradation data to prove it. Also, if we increase the discharging rate to 2C, the previous conclusion from Figure 4. is not true anymore. Figure 5 shows that the battery has the lowest degradation when the ambient temperature is at 25 °C. This may not be true if we switch to another type of battery. (Zhao et al., 2023)

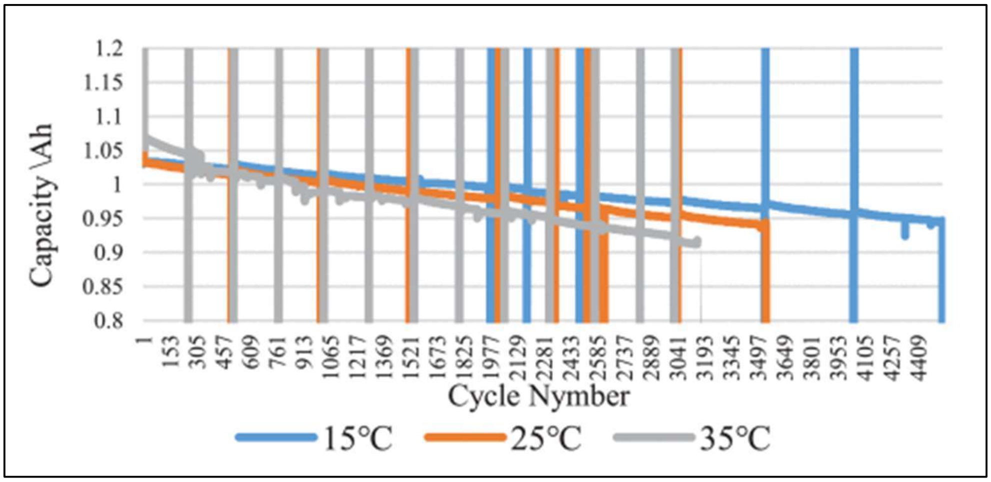


Figure 4: Battery capacity curve of LFP 0-100 1C

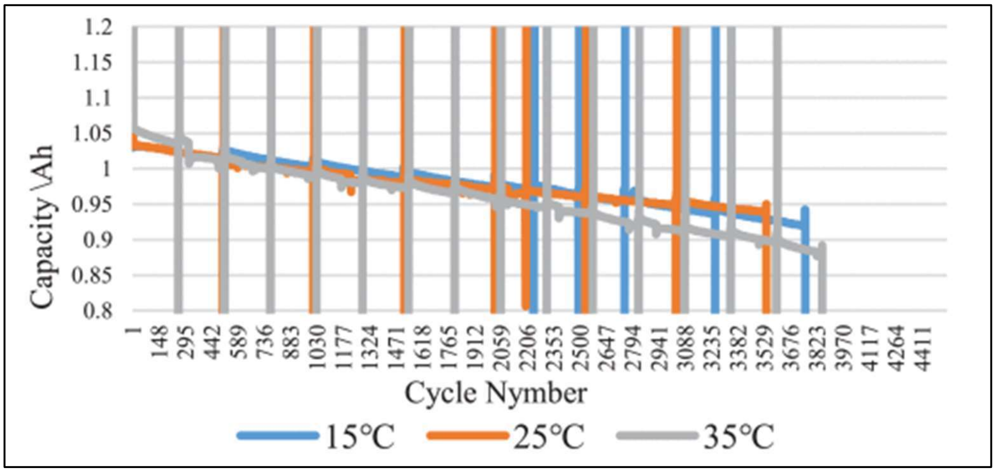


Figure 5: Battery capacity curve of LFP 0-100 2C

The change in cell capacity and resistance during discharge with a C-rate of 1C was measured at five different ambient temperatures. Figure 4 shows that the usable cell capacity increases significantly with T while the internal resistance of the Li-ion cell decreases. The cell has the maximum usable capacity in a range of 25 ˚C ≤ T ≤ 45 ˚C, where the internal resistance remains small. (Chacko & Chung, 2012)

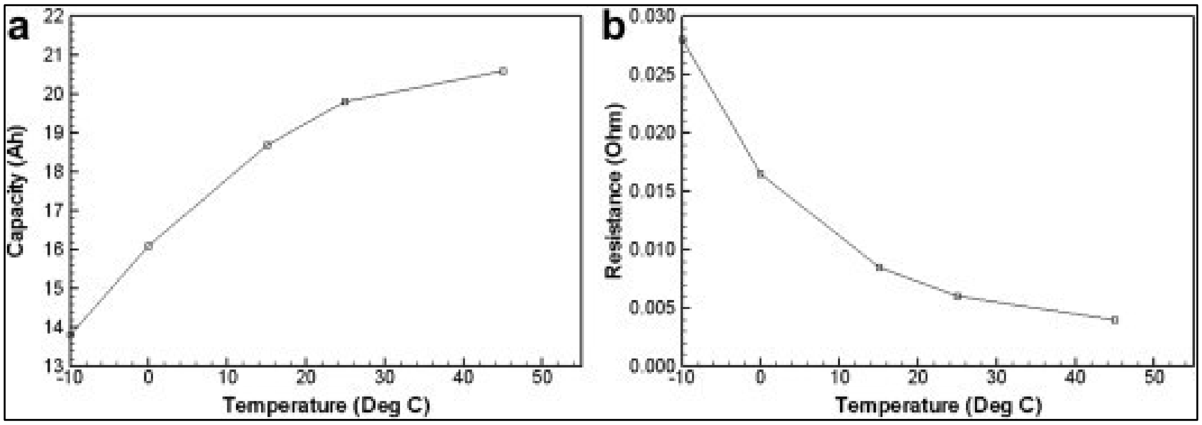


Figure 6: Li-ion cell characteristics at several ambient temperatures. a) Capacity, and b) resistance variation with T(Chacko & Chung, 2012)

The best way to avoid high temperatures is with a thermal management system. A good thermal management system will help cool or warm the cells temperature when require. Most of the electric vehicle on the market now have a similar system (Tesla, Chevrolet, Hyundai, etc), The only exception is the Nissan Leaf that does not have active cooling system and is causing the battery to suffering from overheating. Heat suffering could jeopardize the life of the cells by degrading the cathodes materials. A bigger system like on a train could eventually avoid the requirement of an active thermal system due to the large size of the battery. A bigger battery could greatly reduce the discharge rating and then avoid heat creation but it will remain a higher risk by the manufacturers and remain to be seen.

2.2.6.1.2 Aging over different State of charge

The SOC can affect degradation over time. As we can see in the Figure 7 and Figure 8, the SOC can impact on the SOH of the battery.

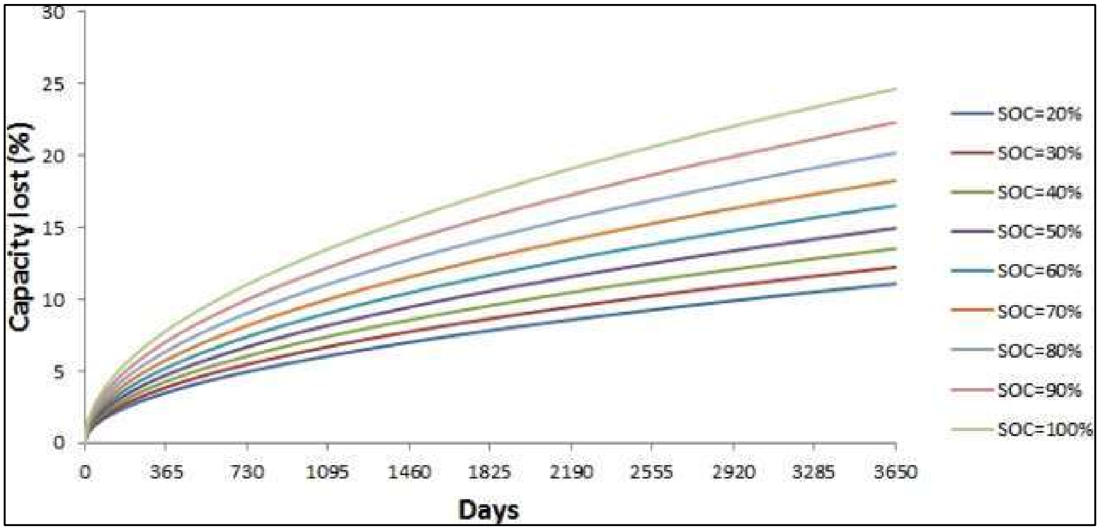


Figure 7: Capacity loss for different storage SOC values at 25 °C. (Pelletier et al., 2017)

A battery always kept at a high level of charge will allow the creation of dendrites on the anode and then reduce the performance of the cells. A higher SOC will slowly be steadily reducing the life of a battery pack entirely. It's an issue that's been seen on many of the first battery generation like the Leaf or the Chevrolet Spark EV. To avoid that issue, manufacturers sometimes limit the SOC by default at a lower charge or they recommend charging the battery at a lower level unless the full capacity is really required. There is some exception to that effect. LiFePO4 and LTO are not affected the same way with this issue or at least, they are affected much less. The chemical strong chemical bonding with the cathode elements and the oxygen makes it last longer. The recommendation is also not to leave a battery fully charge for a long period of time but the capacity lost is negligible.

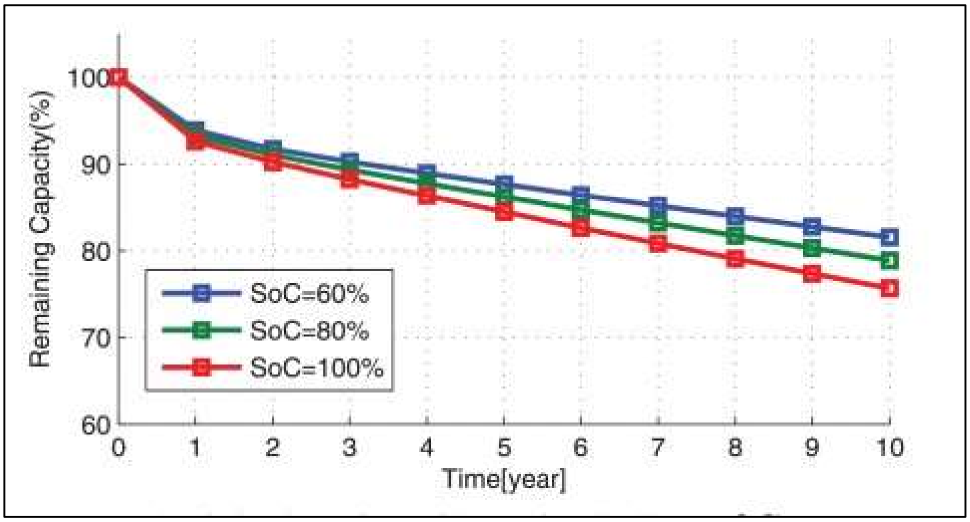


Figure 8: Calendar aging with varying SOC at 25C. (Xu et al., 2016)

2.2.6.1.3 Depth of Discharge

Li-ion batteries can be affected by the level of discharge apply to it. As we can see at the Figure 9, a battery life is reduced with the amplitude of capacity used. The smaller the amplitude is used, the longer the life of the battery will be and the higher the capacity will be. We can see that at 20% of uses, the cycles life can be as high as 15000 cycles but with a continuous use of 100%, the cycle life is only 2000.

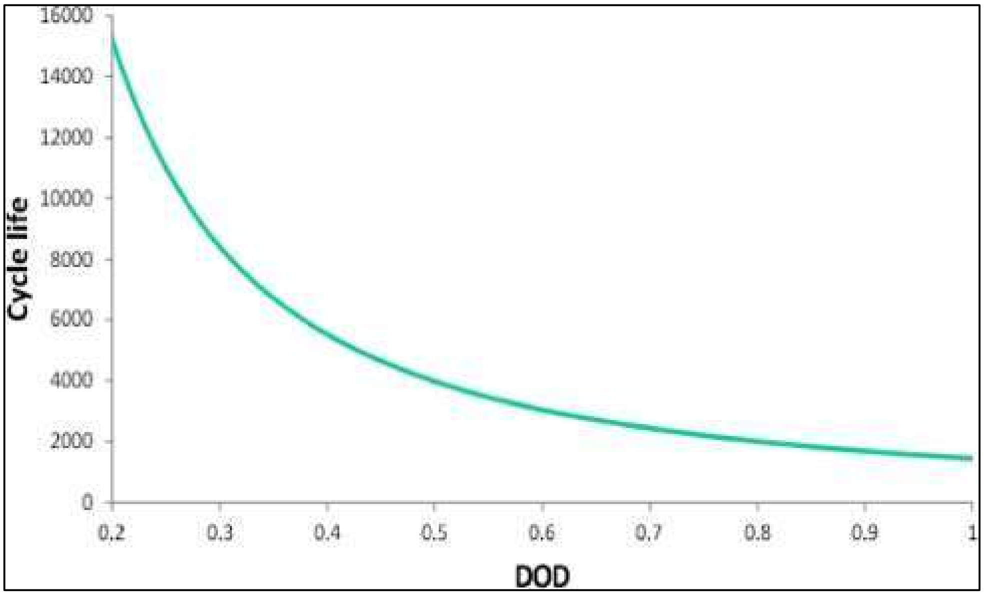


Figure 9: Cycle life versus DOD (Pelletier et al., 2017)

The Figure 10 is also showing the same type of capacity loss but for different chemistry: LMO, NMC and LFP. For any chemistry, the bigger DOD reduces greatly the cycle number. The NMC is the most affected by this process and LFP is the least affected. It’s important to note that the table is based on data from 2016. NMC and LFP have greatly improved since then although it is not the case for LMO. The NMC is probably the one that improved the most since then.

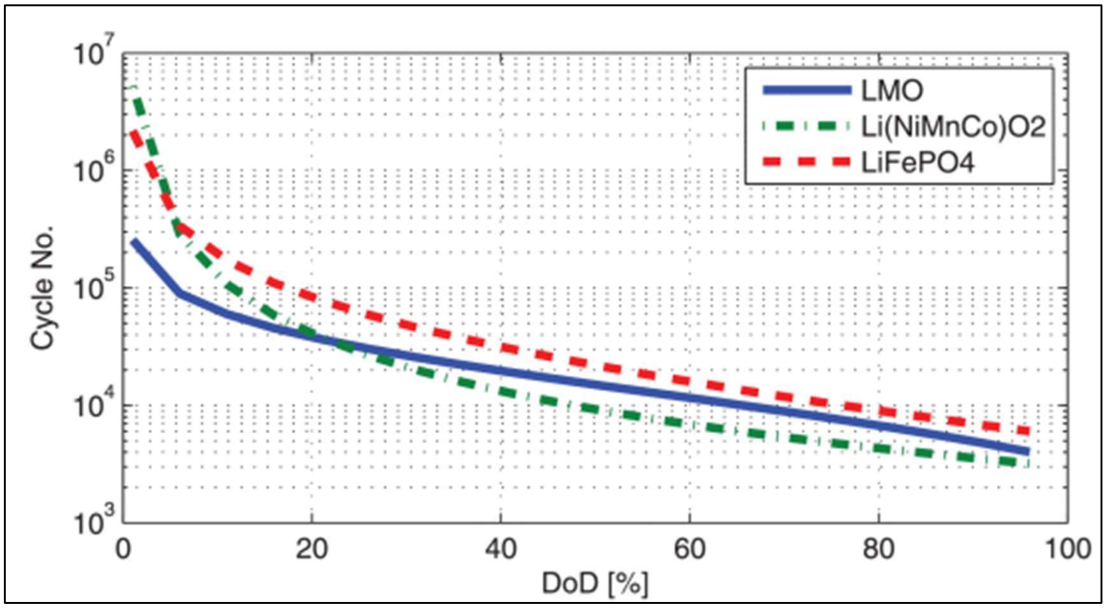


Figure 10: Comparison of cycle life for different types of lithium-ion batteries adjusted to reference conditions. (Xu et al., 2016)

Figure 11 is showing the effect of DOD for four different amplitudes. We can see in part a that a 50% amplitude of use offers a much better life than 80% or 100%. We can also notice that on longer term, a higher amplitude of 50 to 100% seems to be less damageable than an average amplitude of 50% around the 50% SOC. This information could deserve a deeper analysis to determine which level of DOD is more appropriate.

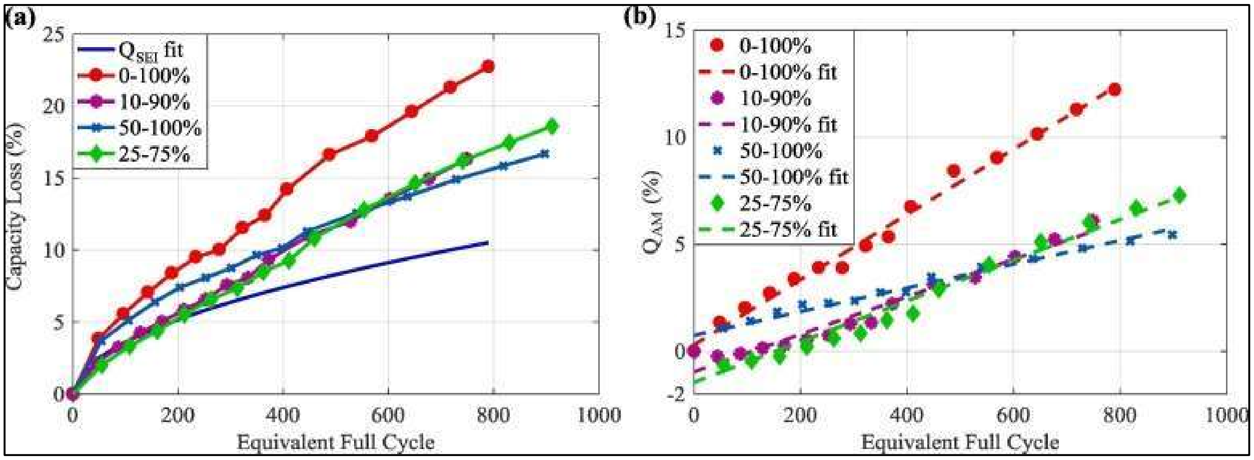


Figure 11: Capacity loss caused by: (a) solid electrolyte interphase (SEI) growth and AM loss; (b) AM loss. (Zhang et al., 2019)

2.2.6.1.4 Charging rates

The charging rate, like the discharging rate, impacts the life of a li-ion battery. The migration of lithium-ion from the cathode to the anode and vice versa affects the structure of the electrodes over time and reduces their life. Figure 12 is showing the impact of the charging rate over the cycle number. Faster charging rate decreases the cycles but this impact can be mitigated with a good thermal management system and good quality cells. Some cells are now manufactured to easily take more power without much reduction in performance but all these cells/batteries have improved thermal management systems.

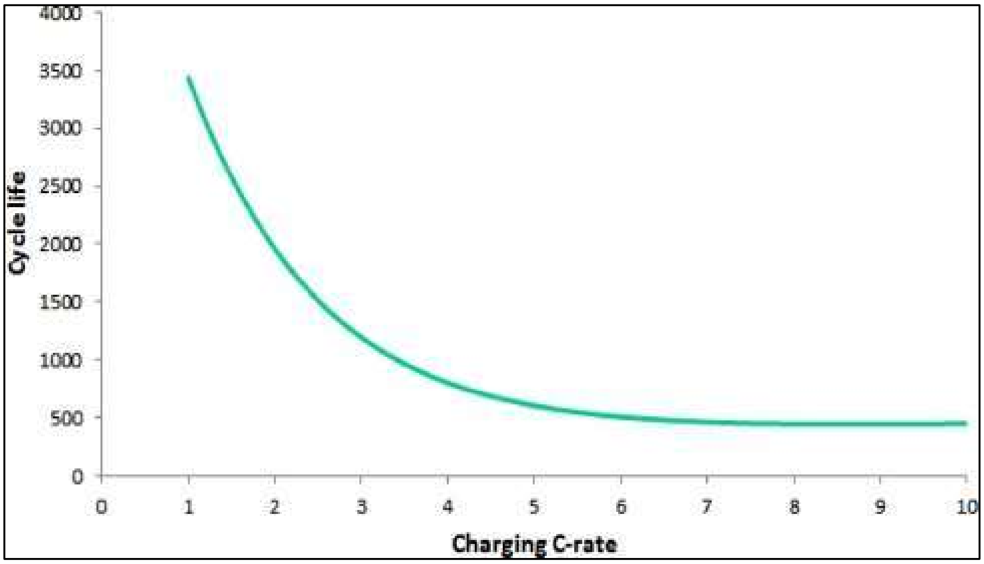


Figure 12: Cycle life versus fast charging rate. (Pelletier et al., 2017)

2.2.7 Supercapacitors

An alternative to batteries that has been used in some applications is supercapacitors. Supercapacitors typically have higher power density than batteries, which means they can deliver higher power. However, their energy density is lower than batteries, meaning they cannot store as much energy per unit weight or volume (Olabi et al., 2022). The chemistry of supercapacitors involves the reversible adsorption of ions at the electrode-electrolyte interface. Supercapacitors typically use two electrodes, separated by an electrolyte, and the energy is stored in the form of an electric field at the interface between the electrode and the electrolyte. During charging, ions from the electrolyte adsorb onto the surface of the electrode, creating a double layer of charge separation. During discharge, the ions desorb from the surface of the electrode, releasing their stored energy (Miller & Simon, 2008). This form of supercapacitor is typically referred to as an electrical double-layer capacitor (EDLC). Another form that can be used is a pseudo-capacitor, which stores energy through reversible faradaic redox reactions that occur at the electrode surface (Wahab et al., 2022).

Supercapacitors are used for many electronics due to their advantages over batteries. These advantages include a specific high power, efficiency, fast charging, cycle life, and low temperature performance. However, the limitations in specific energy and relatively high cost and self-discharge rate make it much less appealing for rail applications where a high amount of energy storage is required (Brady, 2017).

One study by Sigle et. al. was done that investigated the use of hybrid energy storage systems (HESS) that compared NMC and LFP batteries with and without supercapacitors integrated to form a HESS. The study focused on the lifetime of the batteries. For NMC, HESS helped in terms of capacity and resistance lifetime (i.e., when battery internal resistance doubles). For LFP, HESS did not help the capacity lifetime and had a negative effect on the resistance lifetime (Sigle et al., 2017).

2.2.8 Future Battery Technologies

Current LIBs have a cap on energy density of around 350 Wh/kg. However, research into silicon (Si)-rich anode materials and solid-state batteries could help to raise this to around 500 Wh/kg. Additionally, research on Li-air batteries is being conducted (Knibbe et al., 2022).

Current LIBs carry their own oxidant, and therefore have an energy density limit for safety reasons. This limit is 1,000 Wh/kg by regulation. This is higher than can currently be obtained, but could eventually restrict the potential of battery technology. Li-air batteries or other metal-air batteries have been theorized to be able to produce up to 11,000 Wh/kg, which would be comparable to that of fossil fuels (Turnbull-Neep, 2021). These could also be much safer due to the dependence on air as an oxidant. However, this technology is very far from being ready and would likely not be able to obtain this level of energy density in practice due to limitations in efficiency (Knibbe et al., 2022).

Recently, two companies, Amprius Technologies, Inc. in California and Contemporary Amperex Technology Co., Limited (CATL) based in Ningde, China, announced a new NMC product with an energy density of 500 Wh/kg and that will be ready for aerospace usage in the coming years (Amprius, 2023; CATL, 2023). Both these companies are preparing for large-scale production planned for next year. It is doubtful that this technology will be seen soon for use in trains due to the cost issue being more in the aerospace range cost than trains. CATL also announced (Agatie, 2023) a new development in LFP chemistry that involved replacing iron in the cathode with zinc-magnesium-aluminum. The improvement should allow for an energy density around 210 Wh/kg and could increase battery adoption in transport due to low cost and relatively high energy density. These improvements could jeopardize the pertinence of the future solid-state cells that might be already outdated when their technology will be market ready (P et al., 2022). One other future chemistry that could emerge is the sodium ion battery. Na-ion batteries can have specific energies approaching 200 Wh/kg. (Abraham, 2020). Both CATL and BYD are coming up with new Na-ion batteries dedicated for transport. BYD is expected to start this year by producing the first car with this technology (Hanley, 2023).

2.2.9 Summary

In summary, section 2.2 has shown that LIBs are the most promising battery technology available for battery electric locomotives right now. This is mainly due to their high energy density, cycle life, and relative environmental friendliness. LFP and LTO are among the best options currently available for LIBs because of their relative safety when compared with other LIBs. However, other LIBs can obtain a higher energy density. LFPs are of particular interest since they are made of fairly common materials and are relatively inexpensive. The table below from a study by Li et. al. shows a comparison of some key factors for some of these battery technologies (Li et al., 2023). One of the battery technologies is Lithium Manganate (LMO). It was not introduced in Table 2 with the other other LIB technologies, but has not been discussed in detail.

Table 14: Comparison of battery technologies

Index	Lead-acid	Ni-Cd	Ni-MH	LMO (Lithium Manganate Oxide)	LFP (Lithium Iron Phosphate)	NMC (Nickel Manganese Cobalt)	LTO (Lithium Titanate Oxide)
Energy density (Wh/kg)	25	40	60	120	110	250	80
Cycle life	300	500	800	1,000	1,500	1,000	6,000
Self-discharge rate (%/month)	5	25	25	5	5	5	5
Operating temperature range	Wide	Moderate	Moderate	Narrow	Narrow	Moderate	Wide
Memory effect	No	Yes	No	No	No	No	No
Environment pollution	Moderate	Severe	No	No	No	No	No

Figure 13 show the safety, power density, energy density, cost and lifetime on a web chart. NMC appears on the figure but not in Table 14 because it is not seen as a good option for locomotives due to cost and lower lifetime. The NMC energy density, on the other hand (shown in the figure but not the table), is the highest at 250 Wh/kg (Warner, 2019). Until 2021, a patent limited the adoption of LFP. LFP was, until 2021, limited to China but since then, it spread all around the world as one of the best options for heavy land transport. Even if NMC was widely used in western countries, LFP was dominating and still does in terms of numbers because of the Chinese market.

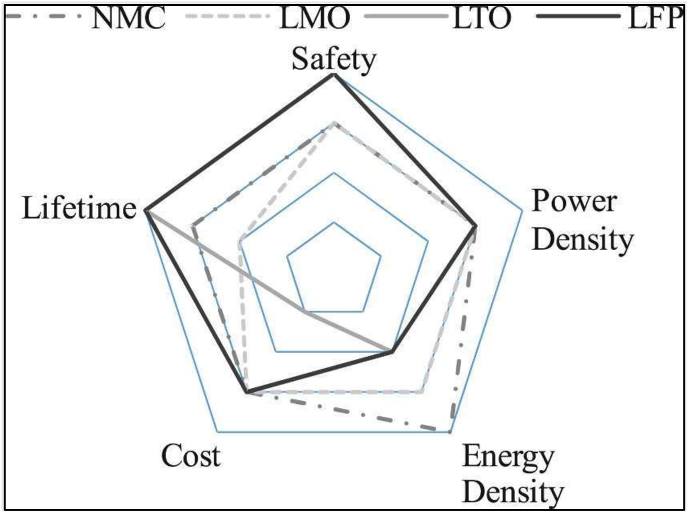


Figure 13: Comparison of some primary Li-ion battery chemistries .LFP, lithium-iron-phosphate; LMO, lithium-manganese-oxide; LTO, lithium-titanate; NMC, nickel-metal-cobalt (IRENA, 2017)

Table 15 shows more details about different lithium-ion batterychemistries. The LFP, LTO, NCA and NMC chemistries were introduced early in the report in Table 2 and discussed extensively. The LMO chemistry has been referred to a few times, including in Table 15. The LCO chemistry is discussed for the first time with this table.

The energy density of some chemistries like NCA and NMC can be very high and achieve a decent cycle life. Those chemistries come at a higher price but could offer higher range due to higher specific energy and power density. It is also possible to see the temperature range of each chemistry. Any lithium-ion chemistry can function at least in the range of -20 °C to 55 °C.

Table 15: Comparison of lithium-ion battery chemistries (Warner, 2019)

	Li iron phosphate	**Li manganese oxide**	**Li titanium oxide**	**Li cobalt oxide**	**Li nickel cobalt aluminum**	**Li nickel manganese cobalt**
Chemistry descriptor	LFP	LMO	LTO	LCO	NCA	NMC
Specific energy (Wh/kg)	90-120	100-150	60-80	150-200	200-300	150-280
Energy density (Wh/L)	190-300	250-360	170-230	400-600	490-675	325
Specific power (W/kg)	4,000	4,000	1,000	1,000	1,000	1,000-4,000
Power density (W/L)	10,000	10,000	2,000	2,000	2,000	2,000-10,000
Volts (per cell)	3.3	3.7	2.3	3.6	3.6	3.7
Cycle life	5,000-6,000	300-700	>15,000+	500-1,000	500	3,000-4,000
Self-discharging (%/month)	<1%	5%	2-10%	1-5%	2-10%	1%
Operating temperature range	-20°C to 60°C	-20°C to 60°C	-30°C to 75°C	-20°C to 60°C	-20°C to 60°C	-20°C to 55°C

2.3 Costs

It is important to compare different battery chemistries at the same ampere-hour (Ah) capacity to show the cost differences due solely to chemistry and performance. For this example, an LTO, an LFP and an NMC chemistry are used, as seen in Table 16, to show the differences and impact that chemistry has on cost. Although material costs can vary significantly, this example assumes that the material cost for each of these cells is the same (Warner, 2019). Next, it is assumed that in each case the cell is a 20 Ah cell with the standard nominal voltages for those chemistries, from which the cost per Wh of energy for each chemistry is calculated. The resulting calculations show that on a Wh basis, the NMC has the lowest cost per Wh of the three chemistries because it has the highest energy.

One other methodology for evaluating cell costs that has been gaining some interest recently is comparing cost per Wh per charge-and-discharge cycle. This methodology is used to try to bring in the full life cycle value of the cell into the spotlight for comparison and not just the initial investment. Table 16 shows that while NMC proves to be the lowest cost per Wh, once the average number of cycles that each can achieve is considered, LTO comes in with the lowest cost per Wh per cycle due to its ability to provide such high life cycle. The cost per Wh per cycle for LFP is 55% higher, and the cost for NMC is 120% higher.

The last four rows of Table 16 introduce the amount of energy that is usable in each chemistry and associated costs that begin to get close to the real costs that would be critical in an application. For this example, 80% was used as the available energy for each chemistry, but this percentage will vary greatly with different chemistry and applications, as discussed previously. Once again, due to its very high cycle life the LTO chemistry comes out as the lowest cost per cycle of usable Wh of energy. It Is important to note that this example is for demonstration purposes. If these three cells were taken and actual materials costs, cycle life, and usable depth of discharge were applied, the accuracy could be improved significantly. For the purposes of this report, this serves to describe the effects of adding cycle life and usable energy into the comparison.

Table 16: Sample life cycle costs of different lithium-ion chemistries at different DOD (Warner, 2019) (i.e., usable energy (%))

	LTO	**LFP**	**NMC**
Material cost	$22.50	$22.50	$22.50
Capacity (Ah)	20	20	20
Voltage (V)	2.5	3.2	3.7
Energy (Wh)	50	64	74
Cost/Wh	$0.45	$0.35	$0.30
Cycles	10,000	5,000	3,000
Cost/Wh/cycle	$0.000045	$0.000070	$0.000010
Usable energy (%)	80	80	80
Usable energy (Wh)	47.5	57.6	59.2
Cost/Wh of usable energy	$0.47	$0.39	$0.38
Cost/Wh/cycle of usable energy	$0.000056	$0.000088	$0.000127

2.4 Hazards

The use of locomotives in general is not without safety risks. This is true regardless of the method by which the locomotive is powered. Diesel, for example, is known to be flammable and diesel-powered locomotives have a higher energy density than battery-powered locomotives. However, as has previously been mentioned, batteries carry their own oxidant. This means that in a failure, the energy can be released in an uncontrollable way. The energy density of batteries will eventually hit a cap of about 1,000

Wh/kg. Because this is a value typical of high explosives with transportation capabilities (Turnbull-Neep, 2021), at this value, a battery is potentially transportable and handleable, but needs special safety arrangements to mitigate the risk of explosions because it is consider as an explosive material.

The main failure mechanism of batteries in general is thermal runaway. The thermal runaway occurs when a battery cell cannot dissipate heat fast enough due to exothermic side reactions, which lead to an uncontrollable temperature rise and often result in a fire. The mechanism for this typically starts when the solid electrolyte interphase layer on the anode breaks down, often due to a rise in temperature, but also possible from being pierced by an object (e.g., something striking the battery) or from manufacturing defects, which lead to the release of flammable gases. The separator then breaks down and a short circuit is caused. This, in turn raises the temperature. This causes the cathode to break down and release oxygen. At this point, flammable gases from the anode and the oxygen from the cathode have been released, and a heat source is present from the shorted circuit. This creates the conditions for combustion, which can heat up the surrounding battery cells and cause the same process to initiate in them (Turnbull-Neep, 2021).

The risk of thermal runaway increases as the state of charge increases. This is especially true if a battery is overcharged. LIBs are much more sensitive to overcharge than other batteries, which is why a battery management system (BMS) is required to help manage this. The BMS will manage many cells that are connected in series and parallel in the battery and will perform state of charge balancing, which ensures the state of charge of all of the cells is similar. It also ensures the normal voltage range of each battery is not exceeded. At charging stations, battery management is of critical importance. Therefore, additional sensors are typically used here. One type of sensor is a current sensor that ensures that charging only happens as long as the demand is within a certain range. A second type is a sensor that ensures the BMS is controlling the process (Turnbull-Neep, 2021). Avoiding overcharging is also important if the batteries are being charged by regenerative braking.

Short circuits leading to a fire can also be caused by other factors such as internal dendrite growth. Internal dendrite growth, even if it does not cause a short circuit can reduce the lifespan of the battery (Lu et al., 2014). Dendrites are microscopic lithium metal fibres that grow from the anode surface and can pierce the separator between the anode and cathode. Dendrite growth has also been shown to be more prevalent when charging at low temperatures, so proper temperature management of the battery cells is also important (Li et al., 2023).

Various studies have been conducted to investigate the causes and mechanisms of dendrite growth, as well as potential solutions to mitigate its effects. One study found that dendrite growth is strongly influenced by the microstructure of the anode material, as well as the applied current density and temperature (Katalenich & Jacobson, 2022). Another study found that the presence of a solid electrolyte interphase (SEI) layer on the anode surface can suppress dendrite growth, by providing a stable surface for lithium deposition (Meyerson et al., 2020).

Several techniques have been proposed to prevent or reduce dendrite growth, such as the use of additives in the electrolyte, the application of external pressure to the electrodes, and the use of three-dimensional (3D) electrodes (Wu et al., 2022). One study found that the use of a 3D carbon nanotube (CNT) electrode can reduce dendrite growth and improve the cycling stability of lithium-ion batteries (Zhang et al., 2021).

Research has also been done on fire suppression systems for when batteries do catch on fire. The idea is to suppress the fire before it can spread to too many cells and potentially cause an explosion. Studies have been done to compare different compounds for fire suppression such as carbon dioxide, ultrafine dry powder and HFC-227ea. Of these, HFC-227ea was found to be most effective (Yang et al., 2022). Some work has also been done by Liu et al. on dodecafluoro-2-methylpentan-3-one and found that large amounts can help to stop a battery fire (Liu et al., 2018). Other studies have shown that water mist can be effective and can be enhanced by adding some other chemicals such as dodecafluoro-2-methylpentan-3-one (T. Liu et al., 2020; Y. Liu et al., 2020; L. Zhang et al., 2020). Another paper has recommended measures such as including fuses that can help mitigate short circuits (Weiss et al., 2018). The paper also recommends subdividing the battery unit into separated containers as well as the use of a pressure relief valve in battery cells. Additionally, to prevent access to external air that could grow a fire, an automatic closing vent on the battery rack is recommended.

Some new fire suppression products based on AVD (aqueous vermiculite dispersion) are coming. A study (Wang et al., 2020) shows the effects of the AVD fire extinguishing agent on inhibiting the combustion efficiency of the materials in three batteries were studied along with the composition of the fuel gas. Furthermore, AVD was compared with typical clean fire extinguishing agents, namely, Novec 1230. As quoted from the main results of the study Wang et al.:

> “In terms of cooling, regarding the NMC pouch cells, the AVD fire extinguishing agent demonstrated a maximum cooling rate of 84.45 °C/s after thermal runaway (TR) occurred for 2 s. In contrast, regarding the LFP pouch cells, the AVD fire extinguishing agent was applied after 2 s of TR and demonstrated a maximum cooling rate of 202.440 °C/s. For the 21700 (the result of a joint effort between Panasonic and Tesla, and introduced in 2017 (Beck)) cylindrical cells, the AVD fire extinguishing agent demonstrated a maximum cooling rate of −22.975 °C/s after TR occurred for 2 s. In terms of the cooling effect, the cooling rate of the AVD fire extinguishing agent for the three types of batteries, from highest to lowest cooling rate is LFP, NMC, and 21700. In the same environment, typical clean fire extinguishing agents, Novec 2130 and 2-BTP, were used to suppress battery fires. The fire extinguishing experiment of the 21700 cylindrical cells showed that with the same dose (500 ml) of Novec 2130 and 2-BTP released after 2 s of TR, the maximum cooling rates were 9.050 °C/s and 10.010 °C/s. Therefore, the temperature of the battery fire was reduced. In terms of cooling rates, the AVD fire extinguishing agent exhibited clear advantages.”

Another potential preventative measure is to detect when thermal runaway is becoming more likely to occur. One study uses a data-driven approach to detect problems in a battery pack using voltage and temperature data (Bhaskar et al., 2022). The method uses principal component analysis (PCA). The proposed method was shown in the simulation to have a low false positive rate. It also detected problems faster and missed fewer problems than some other methods that have been used in the past.

Risk is not all equal with lithium chemistry. There are many different lithium-ion chemistries and each of them have different specifications including different risk level. Lithium Cobalt as an example is one of the least safe in case of thermal runaway, but LTO and LFP are two of the safest. As previously shown in Figure 13, LFP and LTO are safer chemistries than NMC or LMO. The reason is that lithium iron phosphate is more stable than nickel manganese cobalt at higher temperatures. LFP doesn’t release oxygen when it catches on fire so this is safer than other LIB chemistry. LFP batteries can burn but will not be as uncontrolled as an NMC or NCA battery exploding. LTO is the safest lithium-ion chemistry while offering the lowest energy density and highest cost (Toshiba). LTO uses a LFP cathode but an LTO anode instead of graphite, making it even safer.

2.5 How Batteries Apply Power to Traction Motors

The exact components used for transmitting power to the traction motors on a battery electric locomotive vary depending on the type of train (European Investment Bank, 2022). However, there are some commonalities between them. For example, a battery management system is a critical component to ensure that the charge and discharge rates of the batteries are managed in a way that results in both safe and effective performance of the batteries and locomotive. The system will also have a traction inverter of some kind as well as the traction motors themselves (Turnbull-Neep, 2021). An inverter is necessary to help control the supply of power from the battery to the traction motor and to convert the direct current (DC) power from the batteries to the alternating current (AC) power required by most traction motors. The traction motors themselves are also essential. These are the three critical components of the system. Figure 14 shows a diagram of this (Mwambeleko et al., 2016). It also includes an auxiliary power unit, which represents the power requirement of auxiliary systems in the locomotive such as lighting, heating, etc. The AC power used by the traction motors is three-phase, often abbreviated as 3φ or 3~, and results in smoother torque and higher efficiency than would be obtained with single phase AC motors.

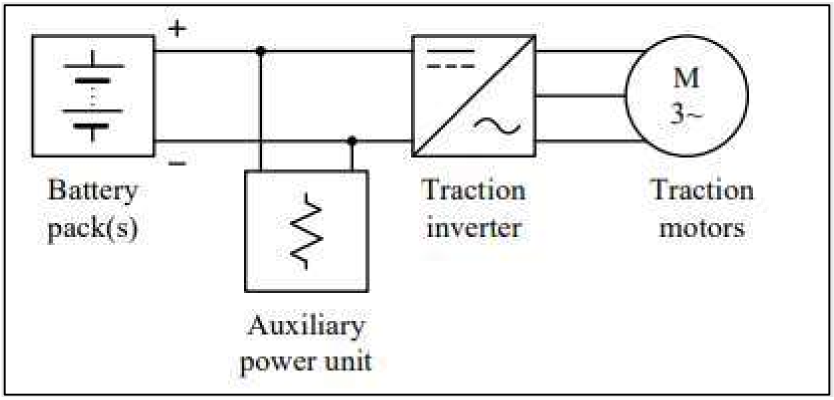


Figure 14: Basic battery connections to traction motors on a battery electric locomotive (Turnbull-Neep, 2021)

The arrangement in Figure 14 is the most basic configuration. However, a DC/DC converter is often used in addition to this in order to help regulate the DC-bus voltage of the inverter, as shown in Figure 15 (Mwambeleko et al., 2016). This arrangement can reduce the voltage required by the battery pack, but can come at a cost in terms of efficiency (Turnbull-Neep, 2021).

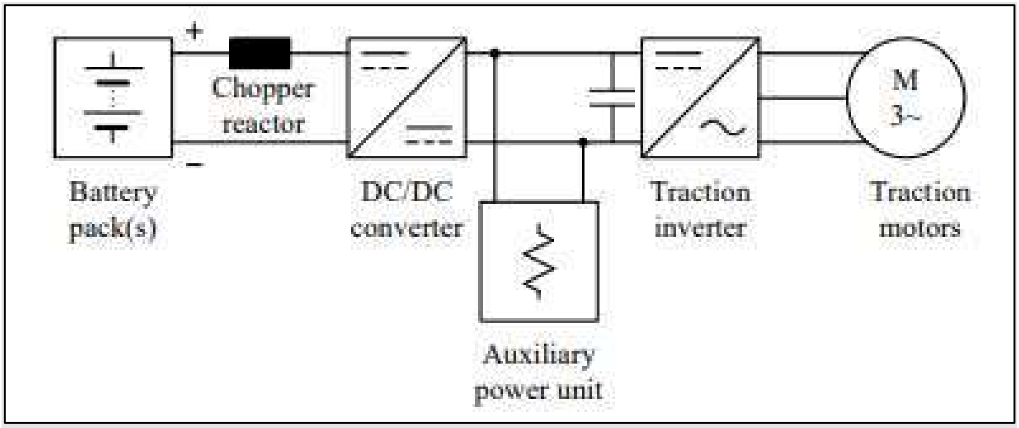


Figure 15: Basic battery connection to traction motors with DC/DC converter (Mwambeleko et al., 2016).

However, it should also be noted that many battery electric locomotives around the world are meant to be used only between electrified lines of track. Therefore, the battery packs and DC/DC converter are often connected in parallel to the electrified contact system. Additionally, the system allows for regenerative braking, which means that power can be fed from the traction motors back into the battery packs.

Figure 16 shows a diagram of the power flow for various conditions when operating Figure 15 configurations on battery power alone. Figure 17 shows a similar diagram for when the battery powered locomotive is also connected to an electrified line (Ogura, 2017). The configurations in both figures use variable-voltage variable-frequency (VVVF) inverters that convert from DC to AC when the batteries are driving the locomotive, and from AC to DC when regenerative braking is taking place.

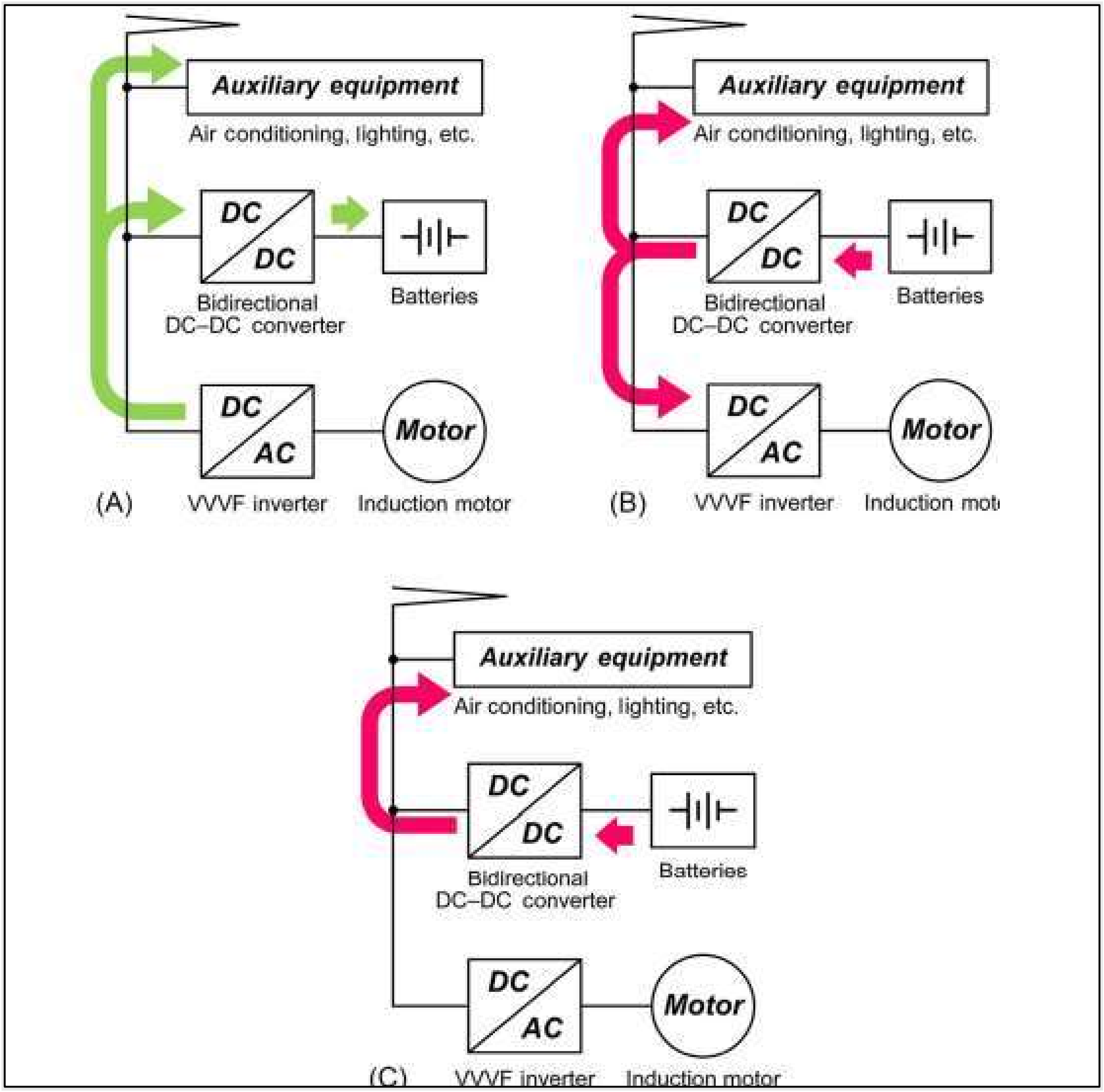


Figure 16: Power flow in battery electric locomotives in the following conditions: (A) regenerative braking, (B) accelerating, and (C) waiting/coasting (Ogura, 2017)

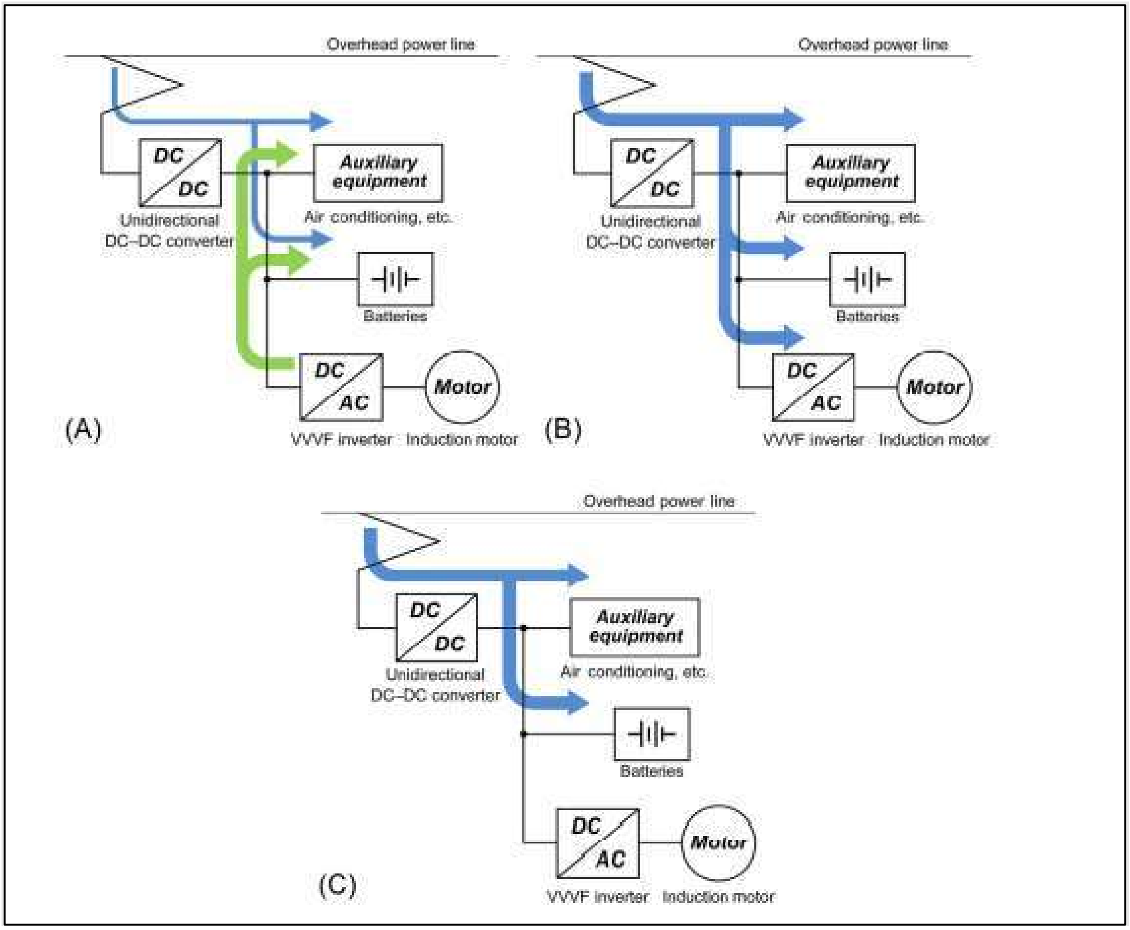


Figure 17: Power flow in battery electric locomotives also connected to an electrified line in the following configurations: (A) regenerative braking, (B) accelerating, and (C) waiting/coasting (Ogura, 2017)

One additional component that should be included is a braking resistor to help dissipate extra energy in the batteries This is important when the batteries are fully charged and are not capable of storing more power; they risk becoming overcharged in a situation where the process of regenerative braking is also charging the batteries (Al-Ezee et al., 2015). These are generally quite large because they have to transfer a lot of heat to the ambient air while the locomotive is moving or stopped.

2.6 Operation, Maintenance, and Recharging

As mentioned in the section 2.5, charging of batteries can be done using regenerative braking. During this process, the dynamic brakes of the locomotive generate electric energy that can potentially be stored in the batteries. Apart from this method, there are three main methods of charging batteries that involve taking electricity from an outside source. The first method is full charging during periods of time when the locomotive is not in use. For example, if a train is not operated for a couple hours a day, the locomotive could go to a charging site and stay there while it is charged. This method is the most efficient in terms of preserving battery life since charging does not typically need to be done as quickly.

The second method is where the locomotive batteries are charged while in-service. This can only be done on electrified lines or using a generator on a hybrid diesel electric train. In this case, the batteries are charged using the power provided by the electrified line or generator. There are many examples (see Annex A) around the world of battery electric locomotives being used in order to allow a train to go from one section of electrified track to another. With this method of charging, when the train leaves one electrified line (or stops a generator), the batteries need to have a level of charge that allows the train to operate using battery power alone for the section of track that it needs to cover before reaching the next electrified line (or restarts a generator).

The third charging method is referred to as opportunity charging. This typically takes place at stations along the train's route. As an example, a passenger train would need to stop at stations periodically to allow passengers to enter and exit the train. The batteries in the locomotive could be charged to some degree during this time. However, this charging would likely need to be done more quickly, which would have negative effects on battery life.

With all methods of charging, the battery management system plays a key role to help ensure that all of the battery cells have a similar state of charge. This is important to make sure none of the battery cells experience a discharge that is too deep, since this will have an adverse effect on battery life. It is also to avoid safety issues associated with overcharging the battery cells.

At current levels of technology charging at a charging location will not happen as quickly as refueling a diesel locomotive. A diesel locomotive has an equivalent charging power of around 60 to 78 MW when the energy density of fuel and the refueling rate are factored in (Turnbull-Neep, 2021). The thermodynamic efficiency of diesel engines is limited. As a result, a battery electric train should operate more efficiently and only require about a third of the energy of a diesel train. Therefore, to match the rate of charging of a diesel train, a battery electric train would need to charge with a power of 20 to 26 MW. The current technology cannot come close to matching this as the current charging power can be as high as around 1.2 MW. This means that, even if a battery electric locomotive could store as much energy as a diesel locomotive, it would take more than 20 times as long to recharge as it would to refuel the diesel locomotive. Recharge time will be limited by the charger capacity so it will take hours instead of less than one hour with diesel. However, this time could be somewhat offset by the ability to recharge the train using other methods such as regenerative braking, opportunity charging, and charging while driving if some portions of the track are electrified.

One solution, that has been investigated for the automotive sector is the idea of switching out discharged batteries for fully charged ones and charging the discharged batteries before putting them back on another train and swapping them for that train's discharged batteries (Turnbull-Neep, 2021). This could theoretically allow "charging" (i.e., switching) to be done quite quickly. However, there are several practical problems with this strategy. For one, it would require standardized batteries to allow the swapping to be done efficiently across locomotive models and operators. Additionally, the batteries may be quite difficult to remove and reinstall. They would be quite large and take up a lot of space. They would also be mechanically and electrically connected to the locomotive. These factors could mean swapping out batteries takes a lot of time and effort. However, it is important to note that swapping out batteries will have to happen a some point anyway since the batteries will reach their end of life long before the rest of the locomotive.

As previously mentioned, a battery has a longer life when it is charged and discharged more slowly. Additionally, the more charge and discharge cycles the battery experiences, the shorter its life. This means that trade-offs have to be made between battery performance and service life. Some studies have been done to analyze this. One study done by Royston et. al. was done using simulation for a particular route in the UK to determine the ideal charging rate for a battery electric multiple unit locomotive set up in order to meet the requirements of the route and maximize battery life (Royston et al., 2019). This route was partly on electrified lines so the charging rate when the train was on these lines needed to be determined to both make sure the batteries were charged enough to transport the train to the next electrified line and to minimize the charging rate to maximize the battery life. Another study focused on opportunity charging, and used simulation to determine if using it was worth it (Olmos et al., 2021). Using opportunity charging can have negative effects on battery life, since it increases the number of cycles and is usually done at a high charging rate. The study showed that opportunity charging is worth doing in terms of cost as long as the right batteries and number of charging stations for opportunity charging are carefully selected based on calculations.

Several studies have been done in the past to evaluate batteries in terms of their lifetime with respect to variables such as depth of discharge. One such study was done by Shtang and Yaroslavtsev and showed that a lithium polymer battery was able to operate for 5,000 cycles with an 80 % depth of discharge, and for 7,000 cycles if the depth of discharge was limited to only 70% (Shtang & Yaroslavtsev, 2017). Based on this, the authors show that if a train with these batteries were operated year-round with one discharge cycle in the 70 % to 80 % range occurring three times per day, the batteries would last about 6.5 to 9 years. This is in agreement with other studies that expect batteries to last around 8 years when managed correctly (Turnbull-Neep, 2021).

Another important factor for the operation of battery electric locomotives is the self-discharge. This is the energy lost from chemical reactions inside the battery itself. This has a negative effect on the battery capacity. It has also been shown to be largely dependent on the environmental temperature (Omar et al., 2015). At a temperature of 25 °C there was a 10% self-discharge in 44 weeks, whereas the self-discharge was 20% in 24 weeks at 40 °C and 20% in only 4 weeks at a temperature of 60 °C. The self-discharge rate was also shown to be dependant on the state of charge. As a result, the authors of the study conclude that a battery management system should have a health monitoring system to report the capacity of the battery in comparison to the original capacity. This self-discharge in any LIB batteries was recently identified as having been caused by the presence of dimethyl terephthalate polyethylene terephthalate (PET) contained in the tape used to secure the ends of the roll. The tape decomposes and creates the molecule that leads to the self-discharge. The molecule is called a redox shuttle because it can travel to the positive side of the electrode, then to the negative side and then back to the positive side. It shuttles between the electrodes and that creates the self-discharge, just like lithium is supposed to do. The problem is that the shuttle molecule is doing it all the time in the background, even when no lithium is supposed to move when the battery just sitting there (Buechele et al., 2023).

One method to significantly extend the range of battery electric locomotives is to install electrified lines in areas where the train needs to accelerate, such as at stations or other locations the train needs to stop. One study done by Mwambeleko and Kulworawanichpong showed that a battery electric tram system was able to reduce the power draw from the battery from 300 kW to only 100 kW when just 200 m of catenary was used at the stations to aide in acceleration (Mwambeleko et al., 2020). After this 200 m, the

100 kW was more than enough as well. This setup significantly reduced the required power and discharge rate of the battery. Another study simulated the energy savings associated with using a catenary system for acceleration (Mwambeleko et al., 2020). The authors call this system a battery and accelerating contact line (BACL) hybrid system. Their simulations showed that the required battery size could be reduced by 62.5% using this system.

When charging the batteries, there are two main methods. One is a constant voltage mode and the other is a constant current mode (Turnbull-Neep, 2021). The constant voltage mode does not easily allow the batteries to be overcharged, but occurs much more slowly than the constant current charging mode. For this reason, a combination of the two is often used, where a constant current mode of charging is done until the voltage reaches a set value, at which point constant voltage charging is used to finish the process. This takes advantage of the faster charging speed of the constant current method, while also limiting the risk of overcharging by use of the constant voltage method. Some research has also been done on a constant current charging method that is controlled by a battery system charging control method (Duan et al., 2020). This system involves multiple battery packs being connected in parallel to limit the charging current of each battery pack. In this way, the system helps ensure that the charging current does not exceed the limit.

It is also important to mention that the power grid at charging stations may not be able to provide the power required to charge the battery electric locomotives (Guerrieri, 2019). As mentioned in paragraph 5 above, this is currently limited to 1.2 MW, but will likely increase in the future. Therefore, it may be necessary to store energy using large batteries at the charging stations so they can be used to charge the locomotive batteries with the appropriate power and energy. The power for these batteries may still come from the power grid, but would be able to steadily store the energy and discharge it at a faster rate when needed than the grid could have done it without overheating. The battery allows the power demand from the grid to be leveled and stable.

It has also been suggested that the power could come from decentralized renewable energy sources to help ensure the energy is generated in an environmentally friendly way (Streuling et al., 2021). One study done by Guov et. al. studied the batteries that would be required at different stations to provide more that 1 MW of power for charging (Guov et al., 2022). The authors ran simulations to determine the best battery energy storage system (BESS) that could be used for different stations. They found that lithium-ion batteries and vanadium redox flow batteries were two of the best options. The lithium-ion batteries were found to be effective for many reasons including those outlined in the battery chemistries section of this document, whereas the redox flow batteries were found to be useful for large stationary energy storage because of the easily scalable capacity and long cycle life.

Another factor to consider in charging the locomotive batteries is the temperature. At temperatures below freezing or above 50 °C, an efficient thermal management system is required, since lithium-ion batteries perform quite poorly and sometimes even dangerously when outside these values (Chatterjee et al., 2019). Furthermore, a thermal management system can help to keep the lithium-ion batteries operating in their optimum range of around 30 to 40 °C. This optimum range takes into account the efficiency and energy storage ability. The optimum charging rate has also been found to be around 0.5 C, meaning that the batteries could be fully charged in 2 h. However, these optimal conditions would have to be tailored to specific battery types and the charging rate is often required to be greater to allow for faster charging.

In general, charging can happen in many ways. However, careful consideration needs to be given to determining the optimal charging strategies for a given train and route. Research done by Bedell showed the importance of modelling in the design stage in order to optimize charging of battery electric locomotives (Bedell, 2017). In the study, the author showed that failing to effectively model and plan charging, as well as battery sizing and lifetime estimation led to an increase in cost of 13.7%. In the case of this study, this difference in cost was obtained when comparing a common lifetime estimation method with a more accurate one. Therefore, it can be concluded that careful planning of a battery electric locomotive train and route is worthwhile and very important.

3 Codes, Standards, and Regulations

There are not many codes, standards, or regulations specific to battery electric locomotives. However, there are some that have been made in the past number of years for the batteries in particular. The International Electrotechnical Commission (IEC) has produced IEC 62928 (initially published in 2017 and revised later in 2018)(*Railway applications - Rolling stock - Onboard lithium-ion traction batteries*, 2018), which is a technical specification that outlines the design, operation parameters, safety recommendations, data exchange, routine and type tests, as well as marking and designation for rolling stock (Mazzone et al., 2018). It covers various aspects such as general safety, electrical requirements, mechanical requirements, performance requirements, and storage and transportation conditions. In order to meet all of these requirements, the specification defines several types of tests, including electrical tests, mechanical tests, and safety tests.

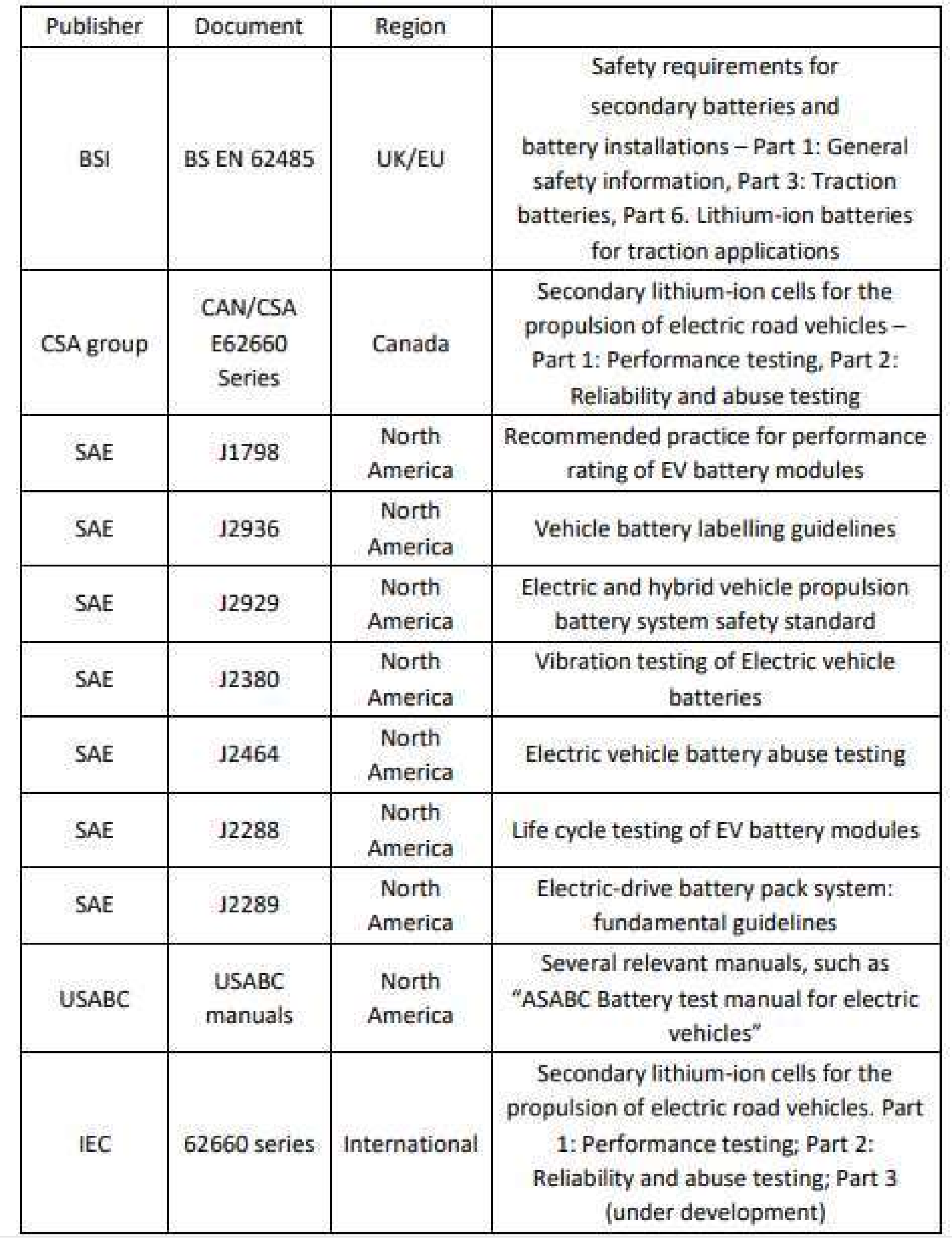
The electrical tests include discharge performance, charge retention and recovery, and endurance in cycles, among others. The mechanical tests involve measuring the physical appearance, mass, and shock and vibration tolerance of the battery. The safety tests, as outlined in IEC 62619 (last revised in 2022), involve external short circuit, impact and drop tests, thermal abuse tests, and tests to ensure the battery can withstand internal short circuits.

Additionally, IEC 62864-1 (last revised in 2016) outlines the requirements for hybrid railway systems, including energy management, energy consumption, and vehicle characteristics for energy management. The goal of these specifications is to ensure the safety and reliability of the batteries used in railway applications and promote the development of more sustainable and efficient energy storage solutions for the industry.

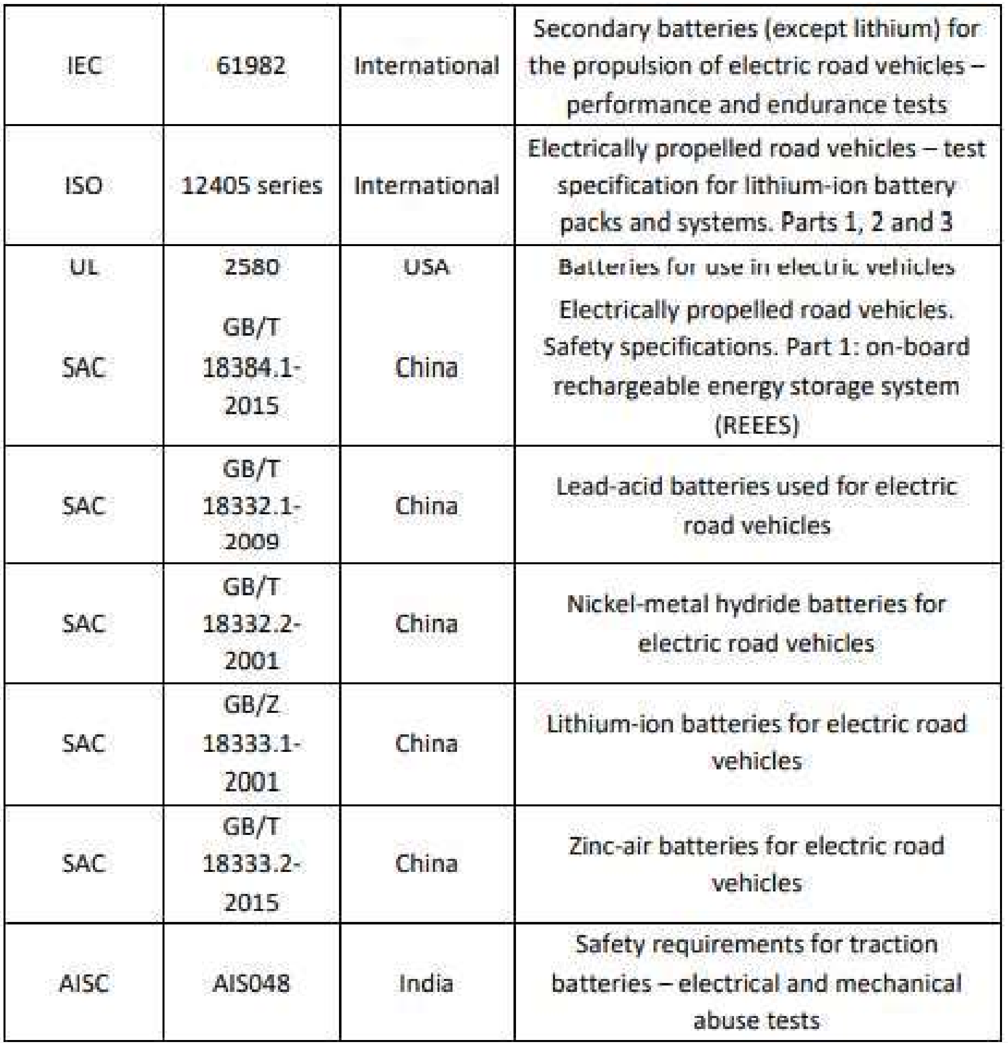
Another relevant standard is the UL 1973 (last revised in 2022) standard for batteries in light electric rail and stationary applications (UL Standards, 2018). They cover batteries used in light electric rail substations or on the rail cars themselves. The standard evaluates the system based on charge and discharge parameters provided by the manufacturer. It does not evaluate performance or reliability under different charge and discharge cycles or under different environmental conditions though.

Although there are some standards for batteries in battery electric locomotives, there is not much for the locomotives themselves. There are many standards from various sources and countries on locomotives in general, but not on battery electric locomotives in particular. Additionally, there are codes, standards, and regulations for batteries in general, but again, none of these are directly tailored for battery electric locomotives. One similar field is the use of batteries in electric vehicles. Table 17 shows a 2016 list of some relevant standards from around the world that could be used and perhaps adapted to battery electric locomotives.

Table 17: Codes, standards, and regulations for electric vehicles (Green et al., 2016)



Publisher	Document	Region	
BSI	BS EN 62485	UK/EU	Safety requirements for secondary batteries and battery installations – Part 1: General safety information, Part 3: Traction batteries, Part 6. Lithium-ion batteries for traction applications
CSA group	CAN/CSA E62660 Series	Canada	Secondary lithium-ion cells for the propulsion of electric road vehicles – Part 1: Performance testing, Part 2: Reliability and abuse testing
SAE	J1798	North America	Recommended practice for performance rating of EV battery modules
SAE	J2936	North America	Vehicle battery labelling guidelines
SAE	J2929	North America	Electric and hybrid vehicle propulsion battery system safety standard
SAE	J2380	North America	Vibration testing of Electric vehicle batteries
SAE	J2464	North America	Electric vehicle battery abuse testing
SAE	J2288	North America	Life cycle testing of EV battery modules
SAE	J2289	North America	Electric-drive battery pack system: fundamental guidelines
USABC	USABC manuals	North America	Several relevant manuals, such as "ASABC Battery test manual for electric vehicles"
IEC	62660 series	International	Secondary lithium-ion cells for the propulsion of electric road vehicles. Part 1: Performance testing; Part 2: Reliability and abuse testing; Part 3 (under development)



IEC	61982	International	Secondary batteries (except lithium) for the propulsion of electric road vehicles – performance and endurance tests
ISO	12405 series	International	Electrically propelled road vehicles – test specification for lithium-ion battery packs and systems. Parts 1, 2 and 3
UL	2580	USA	Batteries for use in electric vehicles
SAC	GB/T 18384.1-2015	China	Electrically propelled road vehicles. Safety specifications. Part 1: on-board rechargeable energy storage system (REEES)
SAC	GB/T 18332.1-2009	China	Lead-acid batteries used for electric road vehicles
SAC	GB/T 18332.2-2001	China	Nickel-metal hydride batteries for electric road vehicles
SAC	GB/Z 18333.1-2001	China	Lithium-ion batteries for electric road vehicles
SAC	GB/T 18333.2-2015	China	Zinc-air batteries for electric road vehicles
AISC	AIS048	India	Safety requirements for traction batteries – electrical and mechanical abuse tests

Standard EN 50155 (published initially in 2017 and revised in 2021) addresses DC/DC converters and outlines the requirements that are used for rail applications and how to comply with DC/DC modules from GAIA Converter, a leading manufacturer of these modules (Gaïa Converter, 2022).

Despite the standards present, there are still many gaps that need to be addressed. One study by Tindall and Burton listed several gaps that should be addressed (Tindall & Burton, 2021). The first set of gaps identified are due to the fact that most work has been focused on lithium-ion batteries. While this makes sense due to the fact that they are mostly the batteries of choice, some other batteries are used and may be used in the future. The authors say that the standards for battery management systems, a critical component for safety, currently apply only to lithium-ion batteries. Additionally, the standards for the environmental conditions for battery power systems on trains also apply only to lithium-ion batteries. These are both included in IEC 62928, which was previously mentioned.

The study also identified the following gaps in the current codes, regulations, and standards (Tindall & Burton, 2021):

1. There is a risk of toxic gas leaks in passenger and workforce areas due to battery system faults or collisions, and there are no standards in place to mitigate this risk.
2. Procedures have not been developed for emergency services to respond to fires on battery powered trains.
3. There are no standards specifying how battery powered trains should be designed to support emergency services operations.
4. Standards are not in place to ensure that the necessary measures are taken in battery storage locations to detect and suppress fires.
5. There is a risk of vehicle collisions with light rail battery charging systems leading to an unsafe environment for people nearby, and there are no standards in place to mitigate this risk.
6. The design of battery charging systems needs to ensure that battery powered trains do not become connected to incompatible chargers.
7. There are no standards specifying crashworthiness requirements for large batteries on trains.
8. Standards have not been put in place to limit the current supplied to the battery through the pantograph while a battery powered train is stationary.
9. There is no standardization for the additional information to be displayed to the driver to support battery powered train operation.
10. Procedures for operating trains based on the information provided to the driver or attendant relating to the battery system are not standardized.
11. There is no agreed upon methodology for rating traction power supply systems for hybrid electric and battery powered trains.
12. Procedures will need to be developed to manage how Train Operators and Maintenance Staff work with and near to battery powered trains.

4 Battery Electric Locomotive Applications

While the technology exists to have battery electric locomotives, there are not currently many in service. All battery trains found by the NRC NSL currently working in the world are listed in Annex A. The current section lists some of the ones that are in service as well as some that are planned to be in service. There are several companies and countries using this technology. One such company is Alstom, who purchased Bombardier Transport in 2021. Alstom has developed a battery electric locomotive that will be used in a passenger application in Ireland (May, 2022). Ninety-five of these trains were sold and will likely be in service by 2025. Another 90 should be in service by 2026.

An example of a train that is already in service is the Talent 3 that was produced by Bombardier and used starting in 2019 ("Bombardier Talent 3 Battery Train," 2020). The train operates in several regions in Europe and consists of a three-car battery electric multiple unit (BEMU) as the locomotive. It can run at a speed of 140 km/h and has a maximum acceleration of 1.1 m/s^2. It also has a range of 100 km when running on battery power. Like many current examples of battery electric trains, this one is for passenger rail and is designed to run between electrified lines.

Alstom has also developed a locomotive called Traxx that will use battery power in freight applications (Geerts, 2022). However, it is only for last mile applications, meaning that it will run using power from an overhead catenary system for most of the time, but, when necessary, can operate for short distances in regions such as ports that do not have electrified lines. The locomotive is not in use yet, but has been designed and should be in service in Luxembourg, France and Germany by 2025.

Brookville is another company that has developed a battery electric locomotive that is used in the US. This is the Liberty NXT streetcar platform (Perrero, 2022). It is for passenger applications and can be used on electrified line or can be run on battery power between electrified lines. The streetcar is not large, with a length of 20.3 m, and does not operate on a long line. One example where it is used is in Detroit, where it is used on a 5.3 km line, 60% of which is not electrified (Barrow, 2015).

Construcciones y Auxiliar de Ferrocarriles (CAF) has also made a battery electric BEMU that will operate in Germany ("CAF wins battery-electric trains contract in Germany," 2022). Again, this train will operate on battery power between electrified lines. However, it is not be expected to be in service until 2024.

CRRC is a Chinese company that has developed a fully battery powered locomotive (Moore, 2022). It uses lithium-ion batteries with a storage capacity of 1,000 kWh. The locomotive is capable of operating for 10 h without recharging. The locomotives are used in China in some switchyards, but also in some mines for low-speed and shunting applications. CRRC has also developed some battery electric locomotives for use in Europe that will operate using the power from electrified lines when available, but on battery power between electrified lines ("CRRC Zhuzhou exports a set of electric trains to the EU," 2021). This will again be mainly for shunting purposes.

Hitachi Rail is a Japanese company that has developed several products including a battery tram, a battery electric locomotive and a battery-diesel hybrid locomotive. The battery electric locomotive is currently in use in Scotland and can operate at speeds of up to 144 to 162 km/h with a maximum range of around 90 km on the batteries. Again, this locomotive is designed for passenger applications and only operates on batteries between electrified lines. There are also some other similar battery powered locomotives the company has produced for use in other areas in the past, but this is the newest.

Wabtec is an American company that has developed the EMD Joule (BHP, 2022) and also the FLXdrive battery-electric locomotive that Canadian National Railway and Union Pacific use. This is a battery electric locomotive that has been used and purchased for use in many locations. The locomotives are a hybrid between diesel and electric. The use of these has brought the fuel consumption down by double digits in terms of percentage ("Roy Hill Buys Industry's First B-E Locomotive for Ore Transport," 2022). The company also produces battery electric shunting locomotives.

One Canadian company called Medatech has developed a fully battery electric system for transporting freight in a mine (Medatech, 2021). However, this is a monorail system and works with one unit at a time. The units are quite small with the base being only 14 by 4 feet. It is also limited to a speed of 25 km/h.

Many other examples exist from other companies and from other regions. However, the NRC authors were not able to find any examples of battery electric locomotives being used for freight applications on rail networks without the use of a hybrid system. There are some examples of shunting locomotives being powered exclusively by batteries. Additionally, there are several examples of battery electric locomotives being used for passenger transport, but even these rely on electrified lines to provide power for some portions of the route.

The lack of any battery powered locomotives being used for freight applications on rail networks around the world constitutes a significant gap in the current literature. The probable cause for this gap is that the energy storage, power, and range of battery electric locomotives is not yet high enough to be used for freight applications that typically involve high loads over long distances.

5 Lessons Learned and future work

This document has shown some specific examples and applications of battery electric locomotives in service, as well as some studies that modelled and investigated different battery and charging scenarios on different routes. These highlight the need for battery electric locomotives as well as the track side systems around them to be well planned out and designed so that the needs of the intended application are met and costs and replacements of parts do not exceed expected values. This likely means that, with current technology, the trains and routes would need to be planned and designed together (Barbosa, 2022)]. Unfortunately, this would mean that they would be customized for certain areas and factors such as speeds, grades, temperatures, distances, and loads. This customization would be required as part of the design process to achieve the range required. The problem with this is that there would be less flexibility in terms of the battery electric locomotives potentially only being able to be used in one region. This could be limiting in large scale operations.

Weight doesn’t affect fuel efficiency (FE) linearly. The following analysis is for trucking but could also apply for trains. In Figure 18 (Franzese & Davidson, 2011), the raw data was fitted with linear regression lines which presented similar coefficients of determination as the ones obtained when the data was fitted with polynomial lines (note: neither regression line types were a good fit for the data). The chart shows that the FE decreases as the vehicle weight increases. Figure 18 also shows that, in general, for any given vehicle weight level, the FE decrease as the vehicle speed increases. However, a close examination of the raw data graphed indicates that there are overlaps in FE for any given vehicle weight, at least between adjacent speed ranges.

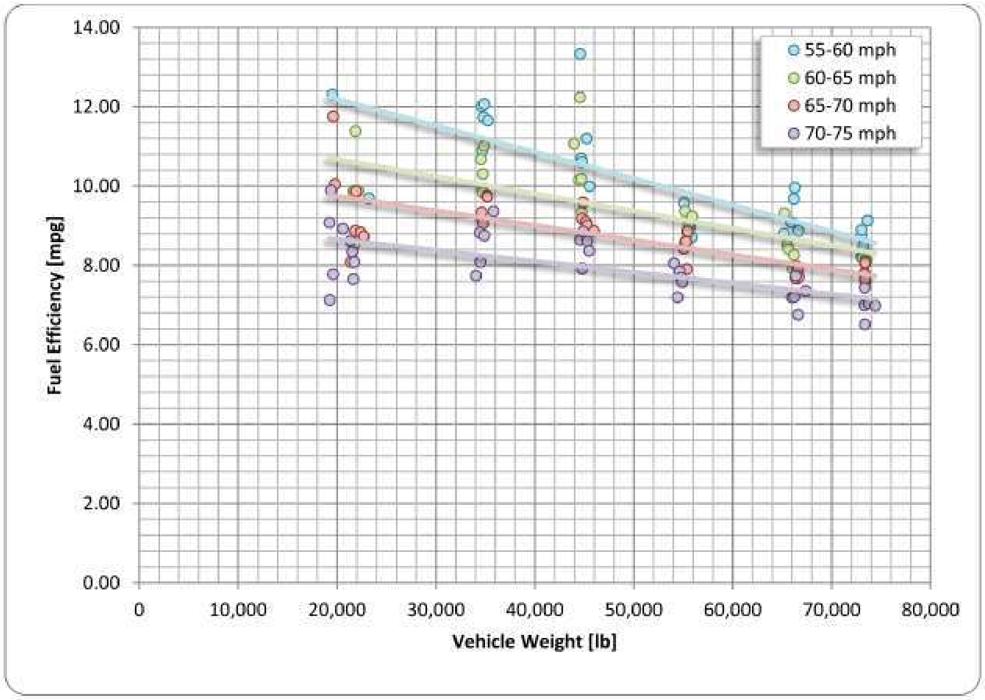


Figure 18: Fuel efficiency vs. vehicle weight for different speed intervals (with polynomial regression lines), for flat terrain

Table 18: Fuel efficiency vs. vehicle weight range for speeds of 65 mph on flat terrain

Weight Range [lb]	Average Weight [lb]	Distance Traveled [miles]	Fuel Consumed [gal]	Fuel Efficiency [mpg]	Average Speed [mph]
20,000-30,000	21,222	51.4	5.4	9.5	65.0
30,000-40,000	34,285	505.9	53.0	9.5	65.0
40,000-50,000	44,911	537.8	58.7	9.2	65.0
50,000-60,000	55,468	541.2	63.3	8.6	64.9
60,000-70,000	66,558	1356.9	171.9	7.9	65.0
70,000-80,000	73,248	1363.1	172.3	7.9	65.0

At any given speed, FE decreases as vehicle weight increases, although the relationship between FE and vehicle weight is not linear, especially for vehicles above 65,000 lb as seen in Table 18. A FE prediction model as a function of the vehicle weight was also developed using the flat-terrain data, for vehicle speeds of 65 mph. The model predicts a decrease of about 24% in FE when the vehicle weight is increased from the current limit to 96,000 lb (Franzese & Davidson, 2011).

The analysis of the information collected while the vehicles were traveling on mild upslope terrains showed that the FE of Class-8 trucks decreases abruptly with vehicle weight ranging from light loads up to medium-heavy loads. After that, increases in the vehicle weight only decrease FE slightly. FE also decreases significantly with speed, but only for light and medium loads. For medium-heavy and heavy loads, FE is almost constant for speeds ranging from 57 to about 66 mph. For speeds higher than 66 mph, the FE decreases with speed, but at a lower rate than for light and medium loads.

With this analysis, it would be interesting to see how much energy is required for a long-haul train and estimate the energy requirement, and then determine the feasibility of battery trains. This topic is not covered in this review but could be done in the future perhaps in a collaboration with NREL who have been performing research in this area. Also, rail efficiency is less affected by aerodynamics and weight than trucks – steel wheels on rails are very low rolling resistance for the weight being moved.

Regarding the choice of lithium battery chemistry, LFP and LTO technologies are often used because of their very high life-cycles. However, the lower energy density makes them less attractive for long-haul trains. NMC chemistry is sometimes quickly set aside because of its higher material cost, but has some advantages too. First of all, the higher energy density would allow for greater range due to the higher amount of energy stored. In addition, despite the higher price of NMCs, the end-of-life value at recycling is more attractive. The cobalt and nickel container represents a much more significant value than iron and phosphate. On March 31, 2023, cobalt in the markets was US$33,865/tn and nickel was US$23,288/tn. In comparison, pure iron is not listed and phosphate was US$345/tn. The residual value is therefore more interesting. A more in-depth cost study taking into account the advantages for long-haul could therefore be carried out to better assess energy needs. None of the current chemistries should set aside too quickly to avoid any mistakes. Each chemistry has its own advantages and inconvenient and each of then can be use for different applications at their best.

6 Conclusion

This report summarized the different types of batteries that could be used in the design of a battery powered locomotive. Li-ion batteries are known for having a high energy and power density, as well as high cycle life and charge retention and therefore are typically considered to be the best available battery technology for many applications including powering locomotives. Research in Great Britain by Brown (ref) has shown that many of the hazards of a battery locomotive occur while charging the battery and are related to the battery system (fire, release of chemicals). There are also risks with the train becoming immobile because of issues with the propulsion system (hybrid system).

Only two hazards fell into the category of “intolerable” in Brown’s study. One involved a collision between a battery powered locomotive and a road user, and the other involved a road user crashing into a charging station. Both of these could result in a fire or possible explosion. This risk isn’t limited to battery trains but to any trains.

There are currently few codes, standards, or regulations specific to battery electric locomotives. However, there are some that have been made in recent years for transporting the batteries, and although there are some standards for batteries with the chemistries used in battery electric locomotives, no standardization has been made for battery locomotives themselves. Voltage, capacity, chemistry, form factors are all variables decided by the manufacturers, and not standardize. There are many standards from various sources and countries on locomotives in general, but not on battery electric locomotives in particular.

Tindall and Burton identified various gaps in the codes and standards for battery powered locomotive. The first set of gaps identified are due to the fact that most work has been focused on lithium-ion batteries. The standards for the environmental conditions for battery power systems on trains also apply only to lithium-ion batteries. Twelve additional gaps were found:

1. There is a risk of toxic gas leaks in passenger and workforce areas due to battery system faults or collisions, and there are no standards in place to mitigate this risk.
2. Procedures have not been developed for emergency services to respond to fires on battery powered trains.
3. There are no standards specifying how battery powered trains should be designed to support emergency services operations.
4. Standards are not in place to ensure that the necessary measures are taken in battery storage locations to detect and suppress fires.
5. There is a risk of vehicle collisions with light rail battery charging systems leading to an unsafe environment for people nearby, and there are no standards in place to mitigate this risk.
6. The design of battery charging systems needs to ensure that battery powered trains do not become connected to incompatible chargers.
7. There are no standards specifying crashworthiness requirements for large batteries on trains.
8. Standards have not been put in place to limit the current supplied to the battery through the pantograph while a battery powered train is stationary.

9. There is no standardization for the additional information to be displayed to the driver to support battery powered train operation.
10. Procedures for operating trains based on the information provided to the driver or attendant relating to the battery system are not standardized.
11. There is no agreed upon methodology for rating traction power supply systems for hybrid electric and battery powered trains.
12. Procedures will need to be developed to manage how Train Operators and Maintenance Staff work with and near to battery powered trains.

The future work for battery powered locomotive could include:

- Working towards standards for batteries in locomotive and shunters:
    - Including standards for charging the batteries at a station and through catenaries
- Research on the crashworthiness of a battery only locomotive
- Research on the lifecycle of a battery powered locomotive and the components affected by vibration
- Work in collaboration with NREL or other research bodies on researching how much energy is required for a long-haul train and estimating the energy requirement, and then determining the feasibility of battery trains as applied to a Canadian operating environment.
- Research the effect of a large-scale battery fire, for the purpose of understanding fire-fighting requirements.
- Research design methods to improve crash-worthiness of battery systems installed on freight locomotives; identify methods to contain damage and reduce the scale of thermal runaway fires.

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Appendix A List of existing battery powered locomotives

Country	Year	Use	Application	Railway company	Locomotive manufacturer	Ownership
Ireland	2026	Passenger	Revenue	DART+	Alstom	public
Luxemburg, France, Germany	2022	freight	Revenue	CFL Cargo	Traxx locomotive, Alstom	private
USA	2015	Passenger	Revenue	Brookville Equipment Corporation	Siemens	private
UK	2015	Passenger	Revenue	Network Rail	Bombardier	public
Germany	2022	Passenger	Revenue	Rhein-Ruhr and Westfalen-Lippe transport authorities	CAF	public
Thailand	2023	freight	Revenue	State Railways of Thailand	CRRC Dalian Co.	public
Brazil	2022	freight	Revenue	National Agency of Land Transport	CRRC Zhuzhou Locomotive	public
Hungary	2022	freight	Revenue	Rail Cargo Hungaria	CRRC Zhuzhou	private
France	2021	freight	Revenue	Paribus Rail Investment Management and Vossloh Loco	CRRC Zhuzhou Locomotive	private
Austria	2021	Passenger	Revenue	n/a	CRRC Zhuzhou	public
UK Scotland		Passenger	Revenue	n/a	Hitachirail	public
Italy	2021	Passenger	Revenue	Gestione Servizio tramviario	Hitachirail	private
Denmark	2021	Passenger	Revenue	Midtjyske Jernbaner	Siemens	private
Germany	2021	Passenger	Revenue	Niederbarnimer Eisenbahn	Siemens	private
Switzerland	2022	Passenger	Revenue	Nahverkehrsverbund Schleswig-Holstein GmbH	Stadler	private
Australia	2022	mining	Test/ Revenue	BHP/Western Australia Iron Ore rail network	Progress Rail, Caterpillar	private
Australia	2022	mining	Test/ Revenue	BHP/Western Australia Iron Ore rail network	Wabtec	private
Australia	2022	mining	Revenue	Iron ore producer Roy Hill	Wabtec FLXdrive	private
Kazakhstan	2022	shunter	Revenue	Kazakhstan Temir Zholy	Wabtec FLXdrive	private
USA	2019	freight	Test	BNSF	Wabtec FLXdrive	private
Canada	2021	freight	Revenue	CN	Wabtec FLXdrive	private
UK	2022	shunter	Test	GB Railfreight	Clayton Equipment Ltd	private

Country	**Year**	**Use**	**Application**	**Railway company**	**Locomotive manufacturer**	**Ownership**
UK	2022	shunter/conv	Revenue	Bure Valley Railway	Clayton Equipment Ltd	private
Singapore	2027	Passenger	Revenue	Singapore CRRC Sifang Railway Vehicles Service Pte. Ltd	CRRC Qingdao Sifang Co	public
USA	2011	Passenger	Test/ Revenue	Charlotte Area Transit System	ameriTRAM LFX-300	public
Canada	2021	mining	Revenue	Torex Gold Resources	Muckahi System	private
USA	2022	powered cart	Test	n/a	Parallel	private
USA	2022	freight conv	Revenue	Metra	Progress Rail	private
USA	2022	freight	Revenue	UP	Wabtec FLXdrive	private
USA	2020	freight	Revenue	Anacostia Rail Holdings subsidiary Pacific Harbor Line	EMD® Joule, Progress Rail	private
Sweden	2020	MPV	maintenance	Railcare Group	Trafikverket	private
Czech Rep	2022	Passenger	Revenue	n/a	Škoda	n/a
France	2018	Passenger	Revenue	Métropole Nice Côte d’Azur	Alstom	public
Lux, Fr, Ge	2017	Passenger	Revenue	Luxembourg City	CAF	public

Appendix B Resource analysis

The following data for every specific mineral comes from the U.S. Geological Survey (Mineral Commodity summaries 2023, 2023) with the exception of the refining process and GHG emissions that come from different sources cited in each section.

Aluminum:

Table 4 showed the different content of a li-ion battery including aluminum. Aluminum accounts for 108 kg, or 18%, of a 600 kg NCA or NMC battery. Table 19 shown some of the key facts about aluminum resources and treatments in the industry. The first five rows summarize key factors about aluminum (use; recycling; import source; events, trends and issues; world resources), based on a 2023 U.S. Geological Survey Mineral Commodity summary for aluminum. The last row (refining processes and GHG), is based on sources cited in that row.

Table 19: Key facts about aluminum from the U.S. Geological Survey (Mineral Commodity summaries 2023, 2023), with additional refining-processes-and-GHG information

Operation	Specifications
Use	Transportation applications accounted for 35% of domestic consumption; the remainder was used in packaging 23%; building 16%; electrical 10%; machinery 7%; consumer durables 6%; and other 3%.
Recycling	In 2022, aluminum recovered from purchased scrap in the United States was about 3.4 million tons, of which about 56% came from new (manufacturing) scrap and 44% from old scrap (discarded aluminum products). Aluminum recovered from old scrap was equivalent to about 29% of apparent consumption.
Import source	Canada 50%; United Arab Emirates 9%; Russia 5%; China 4%; and other 32%.
Events, Trends, Issues	In June, a 250,000 tons per year primary aluminum smelter in Hawesville, KY, idled its full production for an estimated 9 to 12 months owing to high energy costs. In July, a 161,000 tons per year primary aluminum smelter in Newburgh, IN, curtailed one of three operating aluminum smelting lines, citing operational challenges. In July, force majeure was declared at a rolling mill and aluminum packaging products manufacturer in Newburgh, IN, that produced approximately 310,000 tons per year of rolled aluminum. A shortage of magnesium, an essential component of aluminum packaging products, was cited for the declaration. Production at the plant was reduced by up to 50% before the declaration was lifted in September. In August, low local demand led to the permanent closure of aluminum beverage can manufacturing facilities in Phoenix, AZ, and St. Paul, MN.
World Resources	Global resources of bauxite are estimated to be between 55 billion and 75 billion tons and are sufficient to meet world demand for metal well into the future.
Refining process and GHG	It is important to note that aluminium is highly linked to electricity generation in the area where it is produced. China is the main producer of aluminum, and the CO2 emission from their production are very high. However, if China started using a lower emission electric grid or the production was moved to one (e.g., in Quebec), the aluminum produced would have a lower CO2 impact. More on this and other sustainability issues for aluminum are given in Table 20

Some of the key sustainability issues associated with producing aluminum are described in Table 20. Aluminum production has impact on many aspects including climate, biodiversity, human rights and more. Number of FTEs in the Employment row refers to the number of employees in the U.S. related to aluminum. Biodiversity Risk Area at 17% is consider very high.

Table 20: Aluminum sustainability assessment (Gregoir & van Acker, 2022)

Impact	Definition	Quantity
Climate	CO_2 (tons CO_2/tons metal)	18
Waste	Tailings waste (tons waste/tons metal)	13.7
	Acidic waste (tons waste/tons metal)	N.A.
Water (scarcity)	Production in high or medium risk areas	35%
	WWF Water Scarcity	2.3
Biodiversity	Biodiversity risk areas	17%
	Volume moved (tons waste/tons metal)	15
Environment	Eutrophication (tons PO_4^{-3}/tons metal)	1%
	Acidification (tons SO_2/tons metal)	0.03
Human rights	HR (% of mine output in low score countries)	19
	ASM (% of mining and metal production)	8
Employment	Employment (# FTE) (upstream and downstream, including recycling)	1.6k
Economic benefits	Mining royalty (%)	N.A.
By-products	% of raw ore shared	0

Cobalt:

Table 21 showed the different content of a li-ion battery including cobalt. Cobalt is essential for the manufacturing of NCA and NMC batteries and accounts for around 18.6 kg or 3.1% of a 600 kg NCA battery and 5.6 kg or 0.93% of a 600 kg NMC battery. Some of the key sustainability issues associated with producing cobalt are described in Table 21.

Table 21: Cobalt sustainability assessment (Gregoir & van Acker, 2022)

Impact	Definition	Quantity
Climate	CO_2 (tons CO_2/tons metal)	5 to 12.5 (sulphate) 5 to 38 (metal)
Waste	Tailings waste (tons waste/tons metal)	35.9
	Acidic waste (tons waste/tons metal)	3.6
Water (scarcity)	Production in high or medium-risk areas	6%
	WWF Water Scarcity	2.2
Biodiversity	Biodiversity risk areas	80%
	Volume moved (tons waste/tons metal)	64
Environment	Eutrophication (tons PO_4^{-3}/tons metal)	6%
	Acidification (tons SO_2/tons metal)	0.62
Human rights	HR (% of mine output in low score countries)	80
	ASM (% of mining and metal production)	10
Employment	Employment (# FTE) (upstream and downstream, including recycling)	15 k
Economic benefits	Mining royalty (%)	0.057
By-products	% of raw ore shared	98

The first five rows of Table 21 summarize key factors about cobalt (use; recycling; import source; events, trends and issues; world resources), based on a 2023 U.S. Geological Survey Mineral Commodity summary for cobalt. The last row (refining processes and GHG), is based on sources cited in that row.

Table 22: Key facts about cobalt from the U.S. Geological Survey (Mineral Commodity summaries 2023, 2023), with additional refining-processes-and-GHG information

Operation	Specifications
Use	An estimated 40% of the cobalt consumed in the United States was used in superalloys, mainly in aircraft gas turbine engines; 35% in a variety of chemical applications; 15% in various other metallic applications; and 10% in cemented carbides for cutting and wear-resistant applications. The total estimated value of cobalt consumed in the U.S. in 2022 was US$530 million.
Recycling	In 2022, cobalt contained in purchased scrap represented an estimated 24% of the total estimated cobalt consumption.
Import source	Cobalt contained in metal, oxide, and salts: Norway 22%; Canada 16%; Finland 12%; Japan 12%; and other 38%.
Events, Trends, Issues	Global cobalt mine and refinery production were forecast to increase to record-high levels in 2022. The increase in mine production was mainly in Congo (Kinshasa) and in Indonesia, where new mining and processing projects were starting production. Congo (Kinshasa) continued to be the world's leading source of mined cobalt, accounting for about 70% of world cobalt mine production. With the exception of some production in the United States, production in Morocco, and artisanally mined cobalt in Congo (Kinshasa), most cobalt is mined as a by-product of copper or nickel. China was the world's leading producer of refined cobalt, most of which was produced from partially refined cobalt imported from Congo (Kinshasa). China was the world's leading consumer of cobalt, with about 80% of its consumption used by the rechargeable battery industry.
World Mine Production and Reserves Resources	Reserves for Australia, China, and Congo (Kinshasa) were revised based on company and Government reports.
World Resources	Nine identified cobalt resources of the United States are estimated to be about 1 million tn. Most of these resources are in Minnesota, but other important occurrences are in Alaska, California, Idaho, Michigan, Missouri, Montana, Oregon, and Pennsylvania. With the exception of resources in Idaho and Missouri, any future cobalt production from these deposits would be as a by-product of another metal. Identified world terrestrial cobalt resources are about 25 million tn. The vast majority of these resources are in sediment-hosted stratiform copper deposits in Congo (Kinshasa) and Zambia; nickel-bearing laterite deposits in Australia and nearby island countries and Cuba; and magmatic nickel-copper sulfide deposits hosted in mafic and ultramafic rocks in Australia, Canada, Russia, and the United States. More than 120 million tn of cobalt resources have been identified in polymetallic nodules and crusts on the floor of the Atlantic, Indian, and Pacific Oceans.
Refining process and GHG	See U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Copper:

As noted in Table 4, cables in the pack (expected to be mostly copper) account for 13.8 kg, or 2.3%, of a 600 kg NCA or NMC battery. In addition, copper foil in the anode accounts for 55.2 kg, or 9.2%, of the same battery. The copper thus totals 69 kg, or 11.5% of a 600 kg NCA or NMC battery. Table 23 corresponding key facts about copper, together with additional refining-processes-and-GHG information.

Table 23: Key facts about copper from the U.S. Geological Survey (Mineral Commodity summaries 2023, 2023), with additional refining-processes-and-GHG information

Operation	Specifications
Use	Copper and copper alloy products were used in building construction 46%; electrical and electronic products 21%; transportation equipment 16%; consumer and general products 10%; and industrial machinery and equipment 7%.
Recycling	Old (post-consumer) scrap, converted to refined metal, alloys, and other forms, provided an estimated 160,000 tons of copper in 2022, and an estimated 670,000 tons of copper was recovered from new (manufacturing) scrap derived from fabricating operations. Of the total copper recovered from scrap, brass and wire-rod mills accounted for approximately 85%; smelters, refiners, and ingot makers 10%; and chemical plants, foundries, and miscellaneous manufacturers 5%. Copper recovered from scrap contributed 32% of the U.S. copper supply.
Import source	Copper content of blister and anodes: Finland 90%; and other 10%. Copper content of matte, ash, and precipitates: Canada 34%; Belgium 17%; Japan 15%; Mexico 11%; and other 23%. Copper content of ore and concentrates: Mexico 82%; Canada 18%; and other <1%. Copper content of scrap: Canada 51%; Mexico 37%; and other 12%. Refined copper: Chile 64%; Canada 20%; Mexico 11%; and other 5%. Refined copper accounted for 86% of all unmanufactured copper imports.
Events, Trends, Issues	In 2022, the largest increase in mined copper output in the United States was at the Bingham Canyon Mine in Utah, where ore grades and recovery rates were higher than those in 2021 following the transition to mining a new area of the open pit. Copper production also rose significantly at the Morenci and Safford Mines in Arizona, reflecting increased mining, milling, and (or) leaching rates. Owing to labour shortages and lower copper ore grades, the most significant decrease in mined copper output was at the Mission Mine in Arizona. The ramp ups of the Gunnison Mine in Arizona and the Pumpkin Hollow Mine in Nevada continued to be delayed by technical issues. Refined copper production in the United States increased by an estimated 3% in 2022 compared with that in 2021 because of a greater supply of copper concentrates to the Miami smelter in Arizona, which was partially offset by unplanned stoppages and labour shortages at the Garfield smelter in Utah. A new smelter in North Carolina designed to produce copper anodes from scrap was in the process of ramping up as of September, and at least five other domestic facilities that would recover copper from scrap were expected to begin operating within the next few years. In August, a leading copper wire-rod plant in Amarillo, TX, was indefinitely shut down owing to high production costs, maintenance issues, and labour shortages. The annual average The Commodity Exchange, Inc. exchange (COMEX) copper price was projected to be about $4 per pound in 2022, 6% less than that in 2021. Analysts attributed the decreased price primarily to widespread global expectations for reduced economic growth and lower demand for copper in the near future, coronavirus disease 2019 (COVID-19) mitigation measures in China, and increased strength of the U.S. dollar relative to other currencies.
World Mine Production and Reserves Resources	Reserves for Australia, Canada, Chile, China, Peru, Poland, the United States and Zambia were revised based on company and Government reports.
World Resources	A U.S. Geological Survey study of global copper deposits indicated that, as of 2015, identified resources contained 2.1 billion tons of copper, and undiscovered resources contained an estimated 3.5 billion tons
Refining process and GHG	See U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Some of the key sustainability issues associated with producing copper are described in Table 24.

Table 24: Copper sustainability assessment (Gregoir & van Acker, 2022)

Impact	Definition	Quantity
Climate	CO_2 (tons CO_2/tons metal)	4.8
Waste	Tailings waste (tons waste/tons metal)	139.7
	Acidic waste (tons waste/tons metal)	66.9
Water (scarcity)	Production in high or medium-risk areas	39%
	WWF Water Scarcity	2.5
Biodiversity	Biodiversity risk areas	20%
	Volume moved (t waste/t metal)	468
Environment	Eutrophication (tons PO_4^{-3}/tons metal)	0%
	Acidification (tons SO_2/tons metal)	0.061
Human rights	HR (% of mine output in low score countries)	28
	ASM (% of mining and metal production)	1
Employment	Employment (# FTE) (upstream and downstream, including recycling)	1.1k
Economic benefits	Mining royalty (%)	0.046
By-products	% of raw ore shared	65

Graphite:

Table 4 shows the graphite in the anode accounts for 49.2 kg, or 8.2%, of a 600 kg NCA or NMC battery. Similar to the first table in the aluminum, cobalt and copper sections above, Table 25 lists corresponding key facts about graphite, together with additional refining-processes-and-GHG information.

Table 25 Graphite First

Operation	Specifications
Use	The major uses of natural graphite were batteries, brake linings, lubricants, powdered metals, refractory applications, and steelmaking.
Recycling	Refractory brick and linings, alumina-graphite refractories for continuous metal castings, magnesia graphite refractory brick for basic oxygen and electric arc furnaces, and insulation brick led the way in the recycling of graphite products. Recycling of refractory graphite material is increasing, with material being recycled into products such as brake linings and thermal insulation. Recovering high-quality flake graphite from steelmaking kish is technically feasible, but currently not practiced. The abundance of graphite in the world market inhibits increased recycling efforts. Information on the quantity and value of recycled graphite is not available.
Import source	China 33%; Mexico 18%; Canada 17%; Madagascar 10%; and other 22%.

Operation	Specifications
Events, Trends, Issues	U.S. natural graphite imports decreased by 29% and 28% in 2019 and 2020, respectively, and then increased by 48% in 2021, and by 55% in 2022. U.S. imports for consumption and U.S. apparent consumption increased by 16% and 19%, respectively, for the 5-year period of 2018 to 2022. The increase in consumption is likely due to rising demand from the lithium-ion battery industry. In 2022, China was the world's leading graphite producer, producing an estimated 65% of total world production. Approximately 24% of graphite produced in China was amorphous and about 76% was flake. China produced some large flake graphite, but much of its flake graphite production was very small, in the +200-mesh range. China also processed most of the world's spherical graphite.
World Mine Production and Reserves	Reserves for Brazil, China, and Russia were revised based on company and Government reports.
World Resources	Domestic resources of graphite are relatively small, but the rest of the world's resources exceed 800 million tn of recoverable graphite.
Refining process and GHG	See U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Iron and Steel:

As noted in Table 4, casing in the pack account for a big part of the material used and can also be used in different quantity in the battery chemistry depending the chemistry used. battery. Iron can be a big part of the cathode in a Lithium Iron Phosphate battery.

Table 26: Key factors about iron and steel from the U.S. Geological Survey (Mineral Commodity summaries 2023, 2023), with additional refining processes and GHG information

Operation	Specifications
Use	Construction accounted for an estimated 46% of total domestic shipments by market classification, followed by transportation (predominantly automotive), 26%; machinery and equipment, 8%; energy, 6%; appliances, 5%; and other applications, 9%.
Recycling	See the Iron and Steel Scrap and Iron and Steel Slag chapters. (*Mineral Commodity summaries 2023*, 2023)
Import source	Canada, 21%; Brazil, 15%; Mexico, 14%; Republic of Korea, 9%; and other, 41%.

Operation	Specifications
Events, Trends, Issues	The World Steel Association forecast global finished steel consumption to decrease by 2.3% in 2022 and increase by 1.0% in 2023. End-use consumption of steel products was expected to decline in 2022 following concurrent events affecting consumer demand, including the conflict in Ukraine, continuing coronavirus disease 2019 (COVID-19) mitigation measures in China, rising energy costs and interest rates, and global inflation. In the United States, the apparent consumption of finished steel products was estimated to have increased by 2% in 2022 owing to strong economic recovery from COVID-19 supply disruptions. The Infrastructure Investment and Jobs Act was expected to spur growth in the energy and construction sectors. The economic conditions in China significantly affected steel production, with finished steel production decreasing by 4% in 2022 and expected to remain unchanged in 2023 owing to extended COVID-19 mitigation strategies that led to decreased demand for real estate and construction investments. In Japan and the Republic of Korea, steel demand was estimated to be lower in 2022 owing to decreases in the construction sector. Production of finished steel products in India was expected to increase by 6% in 2022 owing to infrastructure spending, strong demand for consumer goods, and increased demand in the automotive sector.
World Resources	Not applicable
Refining process and GHG	Iron and steel production create 1.39 tn of CO2 per ton of crude steel. The production process currently requires the use of coal to split the bond between oxygen and iron to fix the oxygen on the carbon and then create CO2.

Table 27: Energy and greenhouse gas results(Norgate & Haque, 2010)

Ore mined	Mining method	Stage	Inventory		
			Item	Value	Units
Iron ore	Open-cut	Drilling	Diesel	0.03	kg/tons ore
		Blasting	Explosives	0.5	kg/tons ore
		Loading & hauling	Diesel	2.2	kg/tons ore
		Crushing & screening	Electricity	2.5	kWh/tons ore
		Stacking & reclaiming	Electricity	0.5	kWh/tons ore
		Rail transport	Diesel	0.5	kg/tons ore
		Port operationsb	Electricity	0.8	kWh/onst ore
		Overall	Water	0.21	m3/tons ore
			Diesel	3.4	kg/tons ore
				135	MJ/tons ore
			Electricity	3.8	kWh/tons ore
			Explosives	0.5	kg/tons ore
			Waste rock	1.3	tons/tons ore

Table 28: Inventory data for mining and mineral processing operations used in study.(Norgate & Haque, 2010)

Metal ore	Energy (MJ/tons ore[a] or conc.[b])	GWP (kg CO2e/tons ore[a] or conc.[b])
Iron ore	(%)	(%)
Drilling	1.3 (0.9)	0.1 (0.8)
Blasting	3.3 (2.2)	0.7 (5.9)
Loading & hauling	92.1 (60.3)	6.0 (50.5)
Crushing & screening	23.1 (15.1)	2.5 (21.0)
Stacking & reclaiming	4.6 (3.0)	0.5 (4.2)
Rail transport	20.9 (13.7)	1.3 (10.9)
Port operations	7.4 (4.8)	0.8 (6.7)
- Total	152.7	11.9

Lithium:

Table 29: Lithium from the U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Operation	Specifications
Use	Although lithium markets vary by location, global end-use markets were estimated as follows: batteries, 80%; ceramics and glass, 7%; lubricating greases, 4%; continuous casting mold flux powders, 2%; air treatment, 1%; medical, 1%; and other uses, 5%. Lithium consumption for batteries increased significantly in recent years because rechargeable lithium batteries have been used extensively in the growing market for electric vehicles and portable electronic devices, and increasingly have been used in electric tools, and grid storage applications. Lithium minerals were used directly as ore concentrates in ceramics and glass applications.
Recycling	Construction of lithium battery recycling plants increased at a rapid pace. As of November 2022, about 44 companies in Canada and the United States and 47 companies in Europe recycled lithium batteries or planned to do so. Automobile companies and battery recyclers partnered to supply the automobile industry with a source of battery materials.
Import source	Argentina, 51%; Chile, 40%; China, 4%; Russia, 3%; and other, 2%.

Operation	Specifications
Events, Trends, Issues	Excluding U.S. production, worldwide lithium production in 2022 increased by 21% to approximately 130,000 tons from 107,000 tons in 2021 in response to strong demand from the lithium-ion battery market and increased prices of lithium. Global consumption of lithium in 2022 was estimated to be 134,000 tons, a 41% increase from 95,000 tons in 2021. Spot lithium carbonate prices in China (cost, insurance, and freight [c.i.f.]) increased from approximately $35,000 per ton in January to about $67,000 per ton in November. For fixed contracts, the annual average U.S. lithium carbonate price was $37,000 per ton in 2022, almost three times higher than that in 2021. Spot lithium hydroxide prices in China (free on board) increased from approximately $35,300 per ton in January to about $78,000 per ton in November. Spot spodumene (6% lithium oxide) prices in China (c.i.f.) increased from approximately $4,900 per ton in January to about $5,800 per ton in November. Six mineral operations in Australia, one mineral tailings operation in Brazil, two brine operations each in Argentina and Chile, and three mineral and two brine operations in China accounted for the majority of world lithium production. Additionally, smaller operations in Brazil, Canada, China, Portugal, the United States, and Zimbabwe also contributed to world lithium production. Owing to the rapid increase in demand and prices of lithium in 2022, established lithium operations worldwide increased or were in the process of increasing production capacity. The U.S. Department of Energy selected 12 lithium-based projects funded with $1.6 billion from the 2022 U.S. Bipartisan Infrastructure Law to support new commercial-scale domestic facilities to extract and process lithium, manufacture battery components, recycle batteries, and develop new technologies to increase U.S. lithium reserves. Lithium supply security has become a top priority for technology companies in Asia, Europe, and North America. Strategic alliances and joint ventures among technology companies and exploration companies continued to be established to ensure a reliable, diversified supply of lithium for battery suppliers and vehicle manufacturers. Brinebased lithium sources were in various stages of development or exploration in Argentina, Bolivia, Chile, China, and the United States; mineral-based lithium sources were in various stages of development or exploration in Australia, Austria, Brazil, Canada, China, Congo (Kinshasa), Czechia, Ethiopia, Finland, Germany, Ghana, Kazakhstan, Mali, Namibia, Nigeria, Peru, Portugal, Russia, Serbia, Spain, Thailand, the United States, and Zimbabwe; lithium-clay sources were in various stages of development or exploration in Mexico and the United States.
World Mine Production and Reserves Ressources	Reserves for Argentina, Australia, Brazil, Canada, Chile, China, the United States, Zimbabwe, and "Other countries" were revised based on information from company and Government reports.
World Ressources	Owing to continuing exploration, identified lithium resources have increased substantially worldwide and total about 98 million tons. Identified lithium resources in the United States—from continental brines, claystone, geothermal brines, hectorite, oilfield brines, and pegmatites—are 12 million tons. Identified lithium resources in other countries have been revised to 86 million tons. Identified lithium resources are distributed as follows: Bolivia, 21 million tons; Argentina, 20 million tons; Chile, 11 million tons; Australia, 7.9 million tons; China, 6.8 million tons; Germany, 3.2 million tons; Congo (Kinshasa), 3 million tons; Canada, 2.9 million tons; Mexico, 1.7 million tons; Czechia, 1.3 million tons; Serbia, 1.2 million tons; Russia, 1 million tons; Peru, 880,000 tons; Mali, 840,000 tons; Brazil, 730,000 tons; Zimbabwe, 690,000 tons; Spain, 320,000 tons; Portugal, 270,000 tons; Namibia; 230,000 tons; Ghana, 180,000 tons; Finland, 68,000 tons; Austria, 60,000 tons; and Kazakhstan, 50,000 tons.
Refining process and GHG	See U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Table 30: Lithium sustainability assessment (Gregoir & van Acker, 2022)

Impact	Definition	Quantity
Climate	CO_2 (tons CO_2/tons metal)	3.5-8.2 (brine) 17.8-22.5 (hard rock)
Waste	Tailings waste (tons waste/tons metal)	20.5
	Acidic waste (tons waste/tons metal)	2

Impact	Definition	Quantity
Water (scarcity)	Production in high or medium-risk areas (%)	75%
	WWF Water Scarcity	2.5
Biodiversity	Biodiversity risk areas (%)	2%
	Volume moved (tons waste/tons metal)	359
Environment	Eutrophication (tons PO_4^{-3}/tons metal)	2%
	Acidification (tons SO_2/tons metal)	0.038
Human rights	HR (% of mine output in low score countries)	14%
	ASM (% of mining and metal production)	0%
Employment	Employment (#FTE) (upstream and downstream, including recycling)	8.4k
Economic benefits	Mining royalty (%)	0.0763
By-products	% of raw ore shared	0%

Manganese:

Table 31: Manganese from the U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Operation	Specifications
Use	Most ore consumption was related to steel production, either directly in pig iron manufacture or indirectly through upgrading the ore to ferroalloys. Additional quantities of ore were used for nonmetallurgical purposes, such as in the production of animal feed, brick colorant, dry cell batteries, and fertilizers. Manganese ferroalloys were produced at two plants.
Recycling	Manganese was recycled incidentally as a constituent of ferrous and nonferrous scrap; however, scrap recovery specifically for manganese was negligible. Manganese is recovered along with iron from steel slag.
Import source	Manganese ore: Gabon, 67%; South Africa, 19%; Mexico, 12%; and other, 2%. Ferromanganese: Australia, 19%; Malaysia, 18%; South Africa, 17%; Norway, 15%; and other, 31%. Silicomanganese: Georgia, 28%; South Africa, 22%; Australia, 21%; and other, 29%. Manganese contained in principal manganese imports:8 Gabon, 25%; South Africa, 19%; Australia, 12%; Georgia, 8%; and other, 36%.
Events, Trends, Issues	Global production of steel, the leading use of manganese, decreased in 2022 compared with production in 2021 owing to supply chain disruptions resulting from the conflict between Russia and Ukraine and intermittent coronavirus disease 2019 (COVID-19) pandemic-related lockdowns in China. Global production of manganese ore was estimated to be unchanged from that in 2021. The leading countries for manganese ore production were, in descending order on a contained-weight basis, South Africa, Gabon, and Australia. On a contained-weight basis, total U.S. manganese imports were estimated to have increased by almost 20% in 2022 compared with those in 2021. By September 2022, average spot market prices for manganese ore, 44% grade, from China had increased by 23% compared with the annual average spot price in 2021.
World Ressources	Land-based manganese resources are large but irregularly distributed; those in the United States are very low grade and have potentially high extraction costs. South Africa accounts for an estimated 70% of the world's manganese resources.
Refining process and GHG	See U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Table 32: Life cycle inventory. Values are presented per functional unit.(R. Zhang et al., 2020)

Empty Cell		Unit	Amount
Raw materials	Explosive a	kg	0.65
	Tungsten carbide a	g	1.3
	Continuous casting billet a	g	39.06
	Crude oil a	kg	0.43
	Wood a	cm3	1.30 × 103
	Manganese (Mn) a	tons	1.5
	Sulfuric acid d	tons	0.81
	Ammonia d	kg	50.5
	Sodium dimethyl dithiocarbamate (SDD) d	kg	2
	Selenium dioxide (SeO2) d	kg	1.1
	Chemicals organic a	g	10.87
	Potassium dichromate (K2Cr2O7) d	kg	0.57
	Calcium carbonate (CaCO3) d	kg	9.07
	Coal c,d	tons	0.5
	Fresh water a,b,c,d	tons	4.24
	Tap water c,d	tons	0.25
	Electricity a,b,c,d	kWh	7385.24
Emission to air	Particulates a,b,c,d	kg	3.71
	Nitrogen dioxide (NO2) a	g	186.74
	Sulfur dioxide (SO2) c	g	32.24
	Nitrogen oxides c	g	28.28
	Sulfuric acid d	g	132.93
	Ammonia d	g	21.37
	Dimethylamine d	g	2.5
	Carbon disulfide d	g	4.2
	Hydrogen sulfide d	g	1.00 × 10−3
	Direct air emissions c,d	tons	0.5
Emission to water	Suspended solids b	g	12.63
	COD b	g	26.91
	Ammonia b	g	0.2
	Phosphate b	g	2.89 × 10−2
	Mercury b	g	2.38 × 10−4
	Znic b	g	0.25
	Copper b	g	2.38 × 10−2
	Sulfide b	g	1.74 × 10−2
	Lead b	g	2.38 × 10−2
	Cadmium b	g	7.13 × 10−2
	Arsenic b	g	2.38 × 10−4
	Nickel b	g	9.50 × 10−2
	Chromium b	g	2.38 × 10−2

Empty Cell		Unit	Amount
	Manganese b	g	6.33 × 10−2
Waste to treatment	wastewater treatment a,b,c,d	kg	261.37
	Secondary sedimentation tank emissions a	kg	168.74
	Sewage treatment plant emissions b	kg	20
	Tailings wastewater b	tons	2.34
	Tailings storage b	tons	4.1
	Municipal solid waste (MSW) to landfill a,b,c,d	kg	209.98
	Industrial hazardous waste (IHW) incineration c	kg	0.22

Table 33: Sensitivity analysis of main contributors. (R. Zhang et al., 2020)

Empty Cell	**Electricity**	**Direct emission**	**Manganese concentrate**	**Manganese oxide**	**Ammonia**	**Coal mining**	**Others**
Variation	−5%	−5%	−5%	−5%	−5%	−5%	−5%
Mineral resource scarcity	−1.91 × 10 −3	0	−3.95	−1.81	−1.57 × 10−6	−3.46 × 10−6	−6.79 × 10 −4
(kg Cu eq)	0%	0%	(-3.43%)	(-1.57%)	0%	0%	0%
Fossil resource scarcity	−63.91	0	−6.68	−6.75	−2.48	−7.07	−1.43
(kg oil eq)	(-3.62%)	0%	(-0.38%)	(-0.38%)	(-0.14%)	(-0.40%)	(-0.08%)
Terrestrial ecotoxicity	−0.02	−10.01	−3.66 × 10−3	−1.82 × 10−3	−4.57 × 10−4	−1.27 × 10−4	−0.02
(kg 1,4-DCB eq)	(-0.01%)	(-4.98%)	0%	0%	0%	0%	(-0.01%)
Global warming (kg CO2 eq)	−353.67	−24.61	−37.56	−33.92	−10.31	−6.91	−12.71
Empty Cell	(-3.69%)	(-0.26%)	(-0.39%)	(-0.35%)	(-0.11%)	(-0.07%)	(-0.13%)

Nickel:

Table 34: Nickel from the U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Operation	Specifications
Use	The leading uses for primary nickel are alloys and steels, electroplating, and other uses including catalysts and chemicals. Stainless and alloy steel and nickel-containing alloys typically account for more than 85% of domestic consumption.
Recycling	Most secondary nickel was in the form of nickel content of stainless-steel scrap. Nickel in alloyed form was recovered from the processing of nickel-containing waste. Most recycled nickel was used to produce new alloys and stainless steel. In 2022, as part of the Bipartisan Infrastructure Law, more than $600 million was allocated to projects to recover nickel from spent lithium-ion batteries and for the synthesis of nickel-containing precursor and cathode active materials. In 2022, recycled nickel in all forms accounted for approximately 56% of apparent consumption.
Import source	Primary nickel: Canada, 45%; Norway, 9%; Australia, 8%; Finland, 7%; and other, 31%. Nickel-containing scrap, including nickel content of stainless-steel scrap: Canada, 38%; Mexico, 26%; United Kingdom, 9%; and other, 27%.
Events, Trends, Issues	In 2022, the annual average LME nickel cash price was estimated to have increased by 35% compared with that in 2021 which was attributed to increasing use of nickel in electric vehicle batteries and continued strong demand for stainless steel. Nickel prices were particularly volatile early in the year. In March, after the onset of the conflict between Russia and Ukraine, prices surged, which disrupted nickel trading on the LME for approximately two weeks. Monthly average prices peaked in March, but began to decline through July, and stabilized for the remainder of the year. Estimated global nickel mine production increased by about 20%, with almost all of the increased production attributed to Indonesia. The largest share of the increase was facilitated by the ongoing commissioning of integrated nickel pig iron and stainless-steel projects. In addition, several companies continued to develop projects to produce intermediate matte or mixed nickel-cobalt hydroxide that were intended to be used as feedstock to produce batterygrade nickel sulfate. On February 24, 2022, a U.S. critical minerals list was published in the Federal Register (87 FR 10381). The changes in the 2022 list from the prior list published in 2018 (83 FR 23295) were the addition of nickel and zinc and the removal of helium, potash, rhenium, strontium, and uranium. The list is to be updated every 3 years and revised as necessary consistent with available data.
World Mine Production and Reserves Ressources	Reserves for Canada, China, New Caledonia, and the United States were revised based on company and Government reports.
World Ressources	Identified land-based resources averaging approximately 0.5% nickel or greater contain at least 300 million tons of nickel, with about 60% in laterites and 40% in sulfide deposits. Extensive nickel resources also are found in manganese crusts and nodules on the ocean floor.
Refining process and GHG	See U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Table 35: Nickel sustainability assessment (Gregoir & van Acker, 2022)

Impact	Definition	Quantity
Climate	CO_2 (tons CO_2/tons metal)	18 (Class 1) - 69 (Class 2)
Waste	Tailings waste (tons waste/tons metal)	29.6
	Acidic waste (tons waste/tons metal)	17.6
Water (scarcity)	Production in high or medium-risk areas (%)	9%
	WWF Water Scarcity	2.3

Impact	Definition	Quantity
Biodiversity	Biodiversity risk areas (%)	54%
	Volume moved (tons waste/tons metal)	242
Environment	Eutrophication (tons PO_4^{-3}/tons metal)	0.005-0.016
	Acidification (tons SO_2/tons metal)	0.17-1.4
Human rights	HR (% of mine output in low score countries)	31%
	ASM (% of mining and metal production)	2%
Employment	Employment (#FTE) (upstream and downstream, including recycling)	158k
Economic benefits	Mining royalty (%)	0.065
By-products	% of raw ore shared	N.A.

Phosphate:

Table 36: Phosphate from the U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Operation	Specifications
Use	More than 95% of the phosphate rock mined in the United States was used to manufacture wet-process phosphoric acid and superphosphoric acid, which were used as intermediate feedstocks in the manufacture of granular and liquid ammonium phosphate fertilizers and animal feed supplements. About 25% of the wet-process phosphoric acid produced was exported in the form of upgraded granular diammonium phosphate (DAP) and monoammonium phosphate (MAP) fertilizer and merchant-grade phosphoric acid. The balance of the phosphate rock mined was for the manufacture of elemental phosphorus, which was used to produce phosphorus compounds for industrial applications, primarily glyphosate herbicide.
Recycling	None
Import source	Peru, 95%; and Morocco, 5%.
Events, Trends, Issues	Domestic production and consumption of phosphate rock were lower in 2022, owing to slightly lower production of elemental phosphorus and phosphoric acid. Domestic fertilizer production and consumption also were lower because of adverse weather conditions in some areas of the United States during the spring planting season, rail delays, high fertilizer costs, and hurricane damage to some production facilities. In Idaho, all three producers continued to develop new mines that will replace existing mines within the next decade. World production of phosphate rock was estimated to have been slightly lower in 2022. The conflict between Russia and Ukraine caused some reduction of exports of phosphate rock and fertilizers from Russia. Although fertilizer materials were exempt from sanctions, some countries did not allow Russian ships in their ports. In 2022, the global phosphate fertilizer market experienced supply disruptions, high fertilizer prices in the first half of the year, and lower consumption in some regions. The most significant supply disruption was from China placing restrictions on exports of DAP and MAP. This reduced Chinese exports by about 5 million tons. Other countries increased exports but were unable to compensate for the loss to the world market. Global consumption of P2O5 contained in fertilizers was estimated to have decreased slightly to about 48 million tons in 2022.
World Ressources	Some world reserves were reported only in terms of ore tonnage and grade. Phosphate rock resources occur principally as sedimentary marine phosphorites. The largest sedimentary deposits are found in northern Africa, the Middle East, China, and the United States. Significant igneous occurrences are found in Brazil, Canada, Finland, Russia, and South Africa. Large phosphate resources have been identified on the continental shelves and on seamounts in the Atlantic Ocean and the Pacific Ocean. World resources of phosphate rock are more than 300 billion tons. There are no imminent shortages of phosphate rock.

Titanium:

Table 37: Titanium from the U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Operation	Specifications
Use	Abrasive sands, monazite, and zircon were coproducts of domestic titanium minerals mining operations. More than 95% of titanium mineral concentrates were consumed by domestic TiO2 pigment producers. The remainder was used in welding-rod coatings and for manufacturing carbides, chemicals, and titanium metal.
Recycling	None
Import source	South Africa, 39%; Australia, 15%; Madagascar, 14%; Canada, 10%; and other, 22%.
Events, Trends, Issues	Consumption of titanium mineral concentrates is tied to production of TiO2 pigments that are primarily used in paint, paper, and plastics. Demand for these primary uses is related to changes in the gross domestic product. Domestic apparent consumption of titanium mineral concentrates in 2022 was estimated to have been unchanged from that in 2021. Inventory changes were not included in the apparent consumption calculation. Exports of titanium mineral concentrates increased significantly owing to increased recovery from mine tailings. In 2022, as of September, South Africa (37%), Madagascar (16%), Mozambique (15%), and Australia (9%) were the leading sources of titanium mineral concentrates imports to the United States. Mining and heavy-mineral-sandprocessing operations were expanded near Starke, FL, and preliminary technical and economic study studies were completed at a heavy-mineral-sands project near Camden, TN. The project plans also included production of synthetic rutile from ilmenite using a proprietary process. In 2022, China continued to be the leading producer and consumer of titanium mineral concentrates, accounting for more than one-third of global production of ilmenite. Mozambique and South Africa also were leading producers of titanium mineral concentrates. China's imports of titanium mineral concentrates were about 3.4 million tons in gross weight, a decrease of 10% compared with those in 2021. As of October, Mozambique (47%), Kenya (9%), and Vietnam (8%) were the leading sources of titanium mineral concentrates to China. In Saudi Arabia, commissioning of a project to produce up to 500,000 tons per year of titanium slag resumed in 2022 after being delayed in 2021. Exploration projects for heavy-mineral sands were being developed in Australia, Brazil, Canada, China, Finland, Greenland, Kenya, Malawi, Mozambique, Norway, Papua New Guinea, Russia, Senegal, and Tanzania.
World Ressources	Ilmenite accounts for about 90% of the world's consumption of titanium minerals. World resources of anatase, ilmenite, and rutile total more than 2 billion tons.
Refining process and GHG	Refining process of the Titanium sponge are describe at See U.S. Geological Survey (Mineral Commodity summaries 2023, 2023)

Table 38: The titanium sponge is produced by Kroll process i.e. heating reduction with magnesium, which includes five major steps.

Task	Description
1	The first step is dedicated to the mining and dressing of ilmenite concentrate. Currently, the ilmenite concentrate used in China's titanium sponge manufacturing enterprise typically comes from vanadium titano-magnetite, which is obtained from the iron middling ore through the high-intensity magnetic separation and flotation after the iron separation.
2	The second step involves the process of titania slag smelting. The ilmenite concentrate as the raw material, blending with petroleum coke as the reducing agent and pitch as the bonding agent, was smelted in an electric furnace so as to separate iron from the ilmenite concentrate and to obtain high-grade slag with high titania content.

Task	Description
3	The third step focuses on the chlorination and refining of titania slag. Specifically, the mixture of petroleum coke and high-grade titania slag is placed in a chlorination furnace, where crude titanium tetrachloride ($TiCl_4$) is produced through the chlorination reaction with chlorine. Subsequently, a refining process is conducted to obtain high-purity $TiCl_4$.
4	The fourth step involves the reduction and distillation process, where high-purity $TiCl_4$ obtained from the previous step is reduced with magnesium followed by a vacuum distillation so as to generate the titanium sponge.
5	The fifth step carries out the electrolysis of magnesium chloride ($MgCl_2$) as an important auxiliary process. At present China's major titanium sponge manufacturing enterprises mainly adopt the joint production project of titanium and magnesium, where magnesium chloride, a by-product from the titanium reduction reaction, is fully utilized to produce magnesium and chlorine via electrolysis process. The magnesium is refined and recycled back to the distillation and reduction process for producing titanium sponge, and chlorine is recycled back to the chlorination process after filtration and purification for the production of $TiCl_4$. Such processes constitute a closed-loop system of chlorine and magnesium. This circulation greatly simplifies the process for producing titanium sponge, with the production cost greatly reduced as well.

Table 39: Life cycle inventory of 1t titanium sponge production.

Life cycle inventory of 1t titanium sponge production.								
Empty Cell	**Item**	**Unit**	**Ore mining and dressing**	**Titanium slag smelting**	**Chlorination and refining**	**Reduction and distillation**	**Electrolysis of MgCl2**	**Total**
Input	Raw ore	kg	9.11E+04					9.11E+04
	Fresh water	kg	3.01E+04		4.40E+02			3.06E+04
	Flotation agent	kg	3.44E+01					3.44E+01
	Pitch	kg		2.79E+02				2.79E+02
	Petroleum coke	kg		5.02E+02	6.51E+02			1.15E+03
	Graphite electrode	kg		6.69E+01				6.69E+01
	Sodium hydroxide	kg			4.52E+03			4.52E+03
	Magnesium (make up)	kg				4.10E+01		4.10E+01
	Chlorine (make up)	kg			1.62E+03			1.62E+03
	Sulfuric acid	kg					6.98E+01	6.98E+01
	Raw coal	kg	3.71E-01	9.19E+00	3.53E+03			3.54E+03
	Crude oil	kg	1.62E+01	5.69E+02	8.51E+02			1.44E+03
	Natural gas	m3	2.64E-03	2.99E+01	9.16E+01			1.22E+02
	Electric power	kWh	1.05E+03	4.70E+03	2.55E+03	4.85E+03	1.45E+04	2.77E+04
Output	CO2	kg	1.11E+03	3.87E+03	8.42E+03	4.00E+03	1.19E+04	2.93E+04

Life cycle inventory of 1t titanium sponge production.

Empty Cell	Item	Unit	Ore mining and dressing	Titanium slag smelting	Chlorination and refining	Reduction and distillation	Electrolysis of MgCl2	Total
	SO2	kg	2.15E+00	2.63E+01	5.17E+01	2.71E+01	8.11E+01	1.88E+02
	NOx	kg	2.37E+00	1.79E+01	4.60E+01	1.84E+01	5.51E+01	1.40E+02
	CO	kg	1.19E+00	1.17E+03	6.15E+02	5.62E+00	1.68E+01	1.81E+03
	CH4	kg	1.81E-02	7.25E-02	1.66E+01	5.31E-02	1.59E-01	1.69E+01
	N2O	kg	1.58E-02	7.14E-02	3.96E-02	7.33E-02	2.19E-01	4.19E-01
	NMVOC	kg	3.18E-02	1.43E-01	1.60E+01	1.47E-01	4.40E-01	1.67E+01
	HCl	kg					3.92E+00	3.92E+00
	HF	kg					6.36E-01	6.36E-01
	As	kg	1.63E-03	7.33E-03	4.03E-03	7.56E-03	2.26E-02	4.31E-02
	Cd	kg	1.04E-05	4.80E-05	2.75E-05	4.81E-05	1.44E-04	2.78E-04
	Cr	kg	1.38E-04	6.18E-04	3.40E-04	6.38E-04	1.91E-03	3.64E-03
	Hg	kg	7.16E-05	3.22E-04	1.77E-04	3.32E-04	9.92E-04	1.89E-03
	Ni	kg	2.04E-04	9.34E-04	5.29E-04	9.47E-04	2.83E-03	5.44E-03
	Pb	kg	1.43E-03	6.48E-03	3.61E-03	6.63E-03	1.98E-02	3.80E-02
	V	kg	2.35E-03	1.06E-02	5.82E-03	1.09E-02	3.26E-02	6.22E-02
	Zn	kg	1.96E-03	8.80E-03	4.84E-03	9.08E-03	2.71E-02	5.18E-02
	Particulates	kg	8.59E-01	7.60E+01	7.95E-01	1.51E+00	4.52E+00	8.37E+01
	COD	kg	6.07E-02	2.75E-01	1.53E-01	2.81E-01	8.41E-01	1.61E+00
	Spent alkali liquor	kg			4.60E+03			4.60E+03
	Waste water	kg	1.44E+03					1.44E+03
	Tailings	kg	2.41E+04					2.41E+04
	Waste rock	kg	2.39E+04					2.39E+04
	Other residue	kg		4.16E+01		9.30E+01	1.62E-01	1.35E+02
	Hydrochloric acid (concentration: 20%) by-product	kg			5.13E+02			5.13E+02

Battery assembly (Feng et al., 2022):

Assembling the battery requires additional resources. The article used here takes into account the resource and manufacturing impact of a typical battery. Although each of the minerals have already been presented separately, it is still important to demonstrate the overall impact in a finished product. The NCM battery and the LFP battery were both studied in 1 kWh as a functional unit, with a total driving range of 200,000 km during the Electric Vehicles (EV) life cycle (Deng et al., 2017; Ellingsen et al., 2014).

The life cycle inventory (LCI) analysis of a product following the standard ISO 14040 should include detailed material and energy flow within the system boundaries of the corresponding link of the product. Inventory data includes the whole lifetime data including raw materials, energy use, pollution emissions, and additional products in the manufacturing, using, and EOL recycling phases of two kinds of power batteries. Data is obtained from national statistics, government annual reports, industry association survey reports, enterprise reality surveys, relevant patent literature, etc.

Table 40: Inventory data for NCM and LFP batteries in the manufacturing phase.(Feng et al., 2022)

Empty Cell		**Parameter name**	**Unit**	**NCM**	**LFP**
Input	**Energy and Power**	Electricity	kWh	1.17E−02	3.76E+00
		Natural gas	kg	2.93E−01	1.08E+00
	Materials	Water	kg	2.13E+02	1.99E+01
		NMP	kg	3.33E+00	2.37E+00
		electrolyte	kg	2.05E+00	1.88E+00
		Cathode material	kg	4.60E+00	2.41E+00
		Anode material	kg	2.37E+00	1.05E+00
		Carbon nanotubes	kg	1.83E−01	1.45E−01
		Graphite	kg	5.50E−02	9.44E−01
		Pure water	kg	2.04E+01	1.39E+01
		Aluminum foil	kg	4.67E−01	6.02E−01
		Copper foil	kg	1.13 + 00	9.04E−01
		Battery separator	cm2	3.25E+01	2.82E+01
		Shell	p	6.27	1.75
Output	**Atmospheric Pollutant**	Dust	g	7.61E+00	–
		Non-methane hydrocarbons	g	1.49E+00	–
	Water pollutants	Chemical Oxygen Demand (COD)	g	4.49E+00	1.51E−01
		Biological Oxygen Demand (BOD)	g	1.36E+00	–
		Suspended Solids	g	5.00E−01	9.41E−02
		Volatile Organic Compounds (VOC)	g	–	3.58E+00
		Ammonia Nitrogen	g	2.22E−02	–
		Fluoride	g	3.33E−02	–
	Production	Battery cells	kg	6.27E+00	1.75E+00