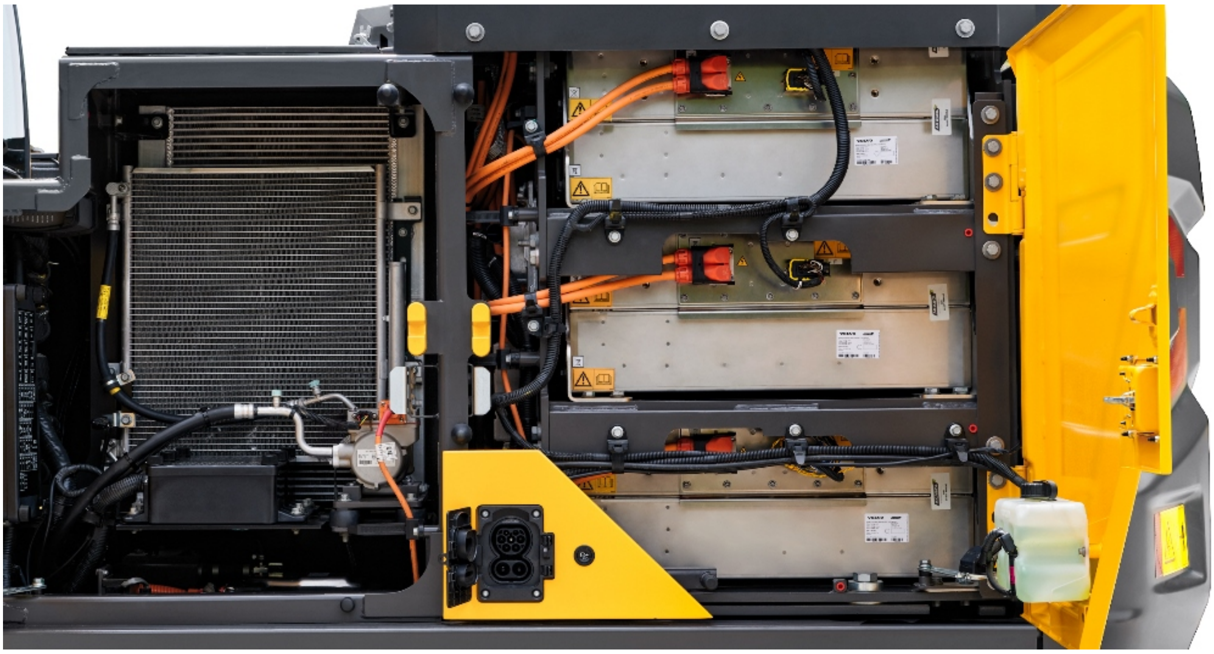

Study for development of a modular battery pack for use in off-highway vehicles at sub zero temperature

Degree Project in Electrical engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Degree Project 2024

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Cover: A photograph of the lithium-ion battery pack inside a Volvo EC230 electric excavator [1].

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Abstract

In this paper, a study regarding the possibility of using modular battery pack in OHVs at sub zero temperatures have been conducted. The paper looked into four different cathode chemistries, NMC, NCA, LFP, and PBa, as well as three different anode chemistries, graphite, TiO, and HC, and compared their traits once implemented in a full electrochemical cell. The report have also looked into three different cell form factor, cylindrical, prismatic, and pouch cells, and compared their cooling possibility and packaging constrains.

In order to get a accurate representation of the requirements for the battery pack, the paper looked into the specification of several electric and non-electric OHVs. From the specification it was concluded that the battery pack needed to have a 147.6 to 295.1 Wh/L energy density, a cycle life of 812.5 to 2500 cycles, a continuous and peak discharge rate of 0.4E to 1.3E and 0.6E to 1.67E respectively, as well as a charge rate of 0.125E.

By assuming a 60% package efficiency for cylindrical cells, as well as a 65% package efficiency for prismatic and pouch cells, thirteen out of twenty cells included in the paper met the requirements for them to be used in OHVs at sub zero temperature. Out of these thirteen cells, CATLs and Altris/Northvolts SIB cell using a PW cathode and a HC anode were the most promising cells to use due to their predicated lower cost of production per kWh compared to other cells.

Keywords: Study, Battery pack, Off-highway vehicle, Temperature, Lithium-ion, Sodium-ion, Form factor, Energy density, Cycle life, .

List of Acronyms

Below is the list of acronyms that have been used throughout this degree project listed in alphabetical order:

BMS	Battery management system
BOL	Begining of life
CO^2	Carbon dioxide
CTM	Cell-to-Module
CTMTP	Cell-to-Module-to-Pack
CTP	Cell-to-Pack
DOD	Depth of Discharge
EFC	Equivalent full cycle
EV	Electric vehicle
HC	Hard carbon
HV	Highway vehicles
LCO	Lithium cobalt oxide
LFP	Lithium iron phosphate
LIB	Lithium ion battery
MTP	Module-to-Pack
NCA	Lithium nickel cobalt aluminum oxide
NMC	Lithium nickel manganese cobalt oxide
OHV	Off-highway vehicles
PBa	Prussian blue analogue
PW	Prussian white
SIB	Sodium ion battery
SOC	State of charge
TiO	Titanium oxide

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Introduction

With the dangers of climate change, CO2 emissions and the rise of EVs on the global market [2], more and more research and development is being carried out on renewable energy sources [3], batteries [4], and the chemical structure that makes up the battery. One crucial area that gets quite a lot of attention is the automotive sector where a significant portion of the global CO^2 emission [5, 6, 7, 8, 9] comes from. A small sub-sector of the automotive sector that needs to be paid attention to is OHVs. These vehicles might not make up a large part of the vehicle market as HVs, but are still an important part of the economy in many countries.

As these vehicles perform a more utilitarian role as compared to HV, purchase price [10], operating cost, and efficiency becomes important factor when businesses and individuals are looking to add to, or replace part of their already existing OHV fleet in order to maximize profit. Therefore, for electrification to makes sense in this sub-sector of vehicles, the price, and the overall cost to operate these vehicles is an important factor to take into consideration.

With some of these models only selling in the hundreds, or thousands of units, a tailor-made battery pack for each individual model could become cost inhibited [11] as the cost to develop such a solution would not be recuperated during sales. A economically and commercially viable option when designing OHV for low production runs is to purchase an already finished battery system and design the vehicle around it.

1.1 Background

Battery systems comes in many different configuration, with different energy capacities, voltage levels, BMS, and cell chemistries to name a few, and with the broad definition of OHV, a single rigid solution for all possible OHV would not work. As such, a possible solution is a modular battery system where severally battery packs that can be assembled together either in series and/or parallel to achieve the desirable energy capacity for the vehicle, as well as the desired voltage level for the drive train.

With different cells containing different chemicals and material, they also come with different unique features and limitations that can make them more or less desirable to use in different vehicles and scenarios. Some of these features and limitations are operating temperature, energy density, specific energy and capacity degradation during use and storage to name a few. So choosing the correct cell chemistry is an important factor when designing a OHV.

1.2 Purpose

Hence, this degree project will be a study looking into modular battery pack for OHV for use in sub zero temperatures. The degree project will look in to the advantages and disadvantages of using different cell chemistries in colder climates. The advantages and disadvantages of using different cell form factors, and how they in turn effect the energy density and specific energy of the cell, the capacity retention and longevity of the cell, as well as the charge and discharge capability of the battery pack.

1.3 Limitation

Due to time restrain for the degree project, some limitations will occur.

- The degree project will only study modular battery pack for the heavy machinery sub-sector of OHVs.
- The degree project will not go over the physical layout of the internals in the battery pack nor will it go over the design of the physical battery pack.
- The degree project will not go over full cost calculations for the battery pack and will there for use already similar existing products [88, 133] to decide how large one battery pack should be in term of capacity.
- The degree project will only be conducted theoretically and is based on existing literature and research. As such a battery pack will not the built and tested.

2

Theory

2.1 OHV

OHV is a category of vehicles that includes a diverse number of vehicle types [12, 13, 14] that are design to a complete a variant of tasks. This means that they require different demands from their design and the components that make them up, and as such, can therefore be split further into two subcategories, recreational off-road vehicles and heavy machinery.

2.1.1 Recreational off-road vehicles

Recreational off-road vehicles is a subset of OHV that includes but are not limited to, sand and dune buggies [14, 15], quad bikes or all terrain vehicle (ATV) [13], dirt bikes, utility task vehicles (UTV), as well as homologated race vehicles. These vehicles are for the most part smaller, light-weight, competition vehicles, and as such put more emphasis on the weight and size of the drive train and energy storage, as compared to the longevity of the components.

2.1.2 Heavy machinery

Heavy machinery is the other subset of OHV and includes agricultural, construction, and forestry vehicles [12, 13]. This includes but are not limited to excavators [10, 14], wheel loaders, dump trucks, asphalt pavers, bulldozers, compactors, cranes, forklifts, snowcats, tractors, combine harvester, as well as drilling rigs. These vehicles are usually slower, heavier, and larger than that of recreational off-road vehicles and put more emphasis on the longevity, total energy, and reliability of their drive train and energy storage, and less emphasis on weight and size due.

2.2 Batteries

Batteries is a form of electrochemical cell [16] that stores their energy in the form of chemicals bonds and structures [17, 18]. In order to release this energy and generate current the internal chemicals of the cells needs to under go an chemical reaction. This chemical reaction can be achieved using different chemical structures and compositions and will in turn give the cell certain properties compared to other cell chemistries.

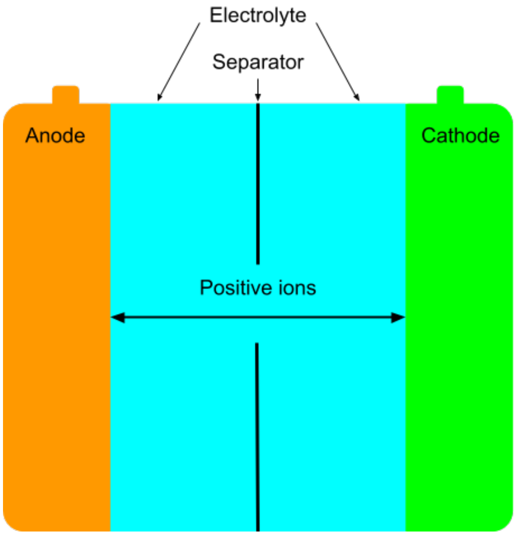

Figure 2.1: A general structure of a LIB and SIB cell

One of the most commonly used rechargeable batteries is ion batteries. Ion cells in general consists of three main parts [17, 18]. These have an anode (negative electrode) that stores electron and positive ions in its chemical structure when charged. A cathode (positive electrode) that have a higher electrochemical potential towards the electrons than that of the anode, and consequently provides the potential difference that allow the ions to flow from the anode to the cathode. The third part is a electrolyte solution or material that provides a barrier to prevent electron from traveling to, and from the anode and the cathode while still enabling the positive ions to pass through. A fourth part included in the cell but does not contribute to the reaction is a semi-permeable separator [19]. The separator provides a physical barrier between the anode and the cathode and prevents them from touching, and is there to ensure that the electrolyte barrier always exists between the anode and the cathode.

In order for the chemical reaction in the cell to take place, a external circuit consisting of conductive material will need to bridge the gap between the anode and the cathode. When the cell is discharging the anode will release electrons (e^-) and positive ions (in the case for LIBs and SIBs these positive ions will be lithium-ions (Li^+) and sodium-ions (Na^+) respectively). The free electrons will then be able to traverse the conductive material over to the cathode due to the difference in electrochemical potential each chemistry have with electron [17]. While the positive ions will traverse the electrolyte and the separator from the anode to the cathode in order to balance out the electrons that have traversed.

Due to the electrochemical potential being the factor for which cell discharge. By providing a potential difference between the anode and the cathode in the correct polarity, some cell chemistries allows for the reaction to take place in reverse and thus enabling the battery to be recharged. This is provided that the anode, cathode, or electrolyte did not become saturated or damaged during the discharge [17]. If the battery in question can not be recharged, the common name given to them is primary battery [20], while rechargeable batteries are also known as secondary batteries.

2.2.1 Lithium-ion cathodes

The most commonly used cell for high capacity energy storage is lithium-ion cells, with them accounting for more than 95% [21] of the global electrical vehicle market by 2019, as well as more than 90% [22] of the United States of Americas grid energy storage by 2021. This dominance can be attributed to their specific energy and energy density compared to other cells [20, 23], as energy density and specific energy is one of the largest weaknesses of cells for use in vehicle energy storage. This can be see when comparing cells to traditional fossil fuels, with gasoline having a energy density of 32 MJ/L [24] and specific energy of 43,5 MJ/kg, while diesel having a energy density of 36,4 MJ/L and specific energy of 42,8 MJ/kg. This gives the gasoline and diesel a ten time higher energy density, and a 40 time higher specific energy than that of any cell chemistry currently available.

2.2.1.1 NMC

One of the most commonly used cell cathode in EVs is NMC (also know as NCM) with a market share of 53% [21] as of 2019. The NMC cathode uses a lithium nickel manganese cobalt oxide [25, 26] ($\mathrm{Li_mNi_xMn_yCo_zO_2}$) material as a cathode that enables the cell to store energy. A feature of the NMC cathode is by changing the ratios [26, 27] of nickel ($\mathrm{Ni_x}$), manganese ($\mathrm{Mn_y}$), and cobalt ($\mathrm{Co_z}$) according to 2.1, the cell can be further adapted for different use cases, as different ratios enhances specific features of the cell.

The wide spread adoption of the NMC cell can be attributed to its high specific capacity ranging from 160 mAh/g to 260 mAh/g [27, 28]depending on what ratios of nickel, manganese and cobalt is being used as well as the potential of the battery, but also due to its half-cell potential of 3.8 V vs. $\mathrm{Li/Li^+}$ [28], thermal stability of 210°C [25, 29, 30] before thermal runaway occurs, and high cycle life [26] which enable it to reliably perform its task if manage correctly [31].

$$x + y + z = 1[26] \tag{2.1}$$

2.2.1.2 NCA

Another commonly used cell chemistry in EVs is that of NCA with it holding a market share of roughly 43% [21] as of 2019 with Tesla Inc. being the largest user of these cells in the EVs market. As for the chemical composition of the cathode, it consist of a lithium nickel cobalt aluminum oxide [25, 26] ($\mathrm{Li_mNi_xCo_yAl_zO_2}$) material as a cathode that enable the cell to store energy. A similar feature of NCA to that of NMC is the potential to use different ratios [16], in this case of nickel ($\mathrm{Ni_x}$), cobalt ($\mathrm{Co_y}$), and aluminum ($\mathrm{AL_z}$) according to 2.1 to enhance different features of the cell with $\mathrm{Ni_{0.8}Co_{0.15}Al_{0.05}}$ being the most common ratios in EVs.

With an similar specific capacity and half-cell potential to some NMC ratios of 180 mAh/g to 200 mAh/g [16, 26, 28] and 3.8 V vs. $\mathrm{Li/Li^+}$ [28] respectively, NCA provides a good proposition for similar usage as that of NMC. A effect of replacing manganese with aluminum is that of increase the lifespan of the battery [26, 32, 33], but with a lower thermal runaway temperature of 150°C [25, 30, 34], the NCA chemistry is less thermally stable and will achieve a higher peak temperature to that of NMC if not properly managed.

2.2.1.3 LFP

A third lithium based cell chemistry that have promising properties for use in vehicle energy storage is LFP. The cehmical composition of LFP consits of a lithium iron phosphate oxide [25, 26] ($LiFePO_4$) material for its cathode to enable the cell to store energy.

LFP does not have the same wide spread adoption for use in EVs [21] currently as NMC and NCA, this is due to its lower specific capacity ranging from 165 to 183 mAh/g [26, 28, 35], as well as lower half-cell potential of 3.45 V vs. Li/Li^+ [28] and as such can not reach the same level of energy density and specific energy once implemented in a full cell as NMC and NCA [21, 23, 25]. The key property that makes LFP appealing is its long cycle life [25], and high thermal stability [29, 30, 34] compared to NMC and NCA, with a thermal runaway temperature being as high as 250°C [25]. This makes LFP a more appealing option to use as grid energy storage and in none performance based applications [36, 37] where the lifespan of the battery is a more important criteria than size and weight.

2.2.2 Sodium-ion cathodes

Due to the high prices[38], geopolitical tension [38], and low abundance of lithium compared to sodium [38, 39], more research have been directed towards sodium-ion cells as an alternative solution to energy storage. With sodium atoms having a larger size and higher mass than that of lithium, sodium cells inherently comes with a lower energy density and specific energy [23] that can be a problem for high performance applications. But with a more abundant material as charge carrier, it could come with a lower price tag compared to that of lithium-ion cells, and can therefore be more suitable in grid storage [38], and low performance applications where space and weight are not limitations.

2.2.2.1 PBa

The most promising sodium-ion cell cathode is that of PBa, with the introduction of CATL [40] SIB in June of 2021, and Altris [41] and Northvolts [42] SIB in november of 2023, that promised a similar specific energy to that of LFP at 160 Wh/kg [23, 43, 44]. As for the chemical composition of PBa cathodes, it can vary due to the fact that PBa does not referee to one single chemical structure, but a variety of different chemical structures. PBas all centered around the chemical structure $A_1M_n(M^*{}_m(CN)_6)$ [45], where A represent a alkali metal and M and M* represent a transition metal. In the case for CATL, Altris and Northvolt, a variation called PW is being used and have a the chemical structure $Na_2Fe[Fe(CN)_6]$ [44].

With a theoretical specific capacity of 169 to 171 mAh/g [44, 46, 47], and a half-cell potential of ~3.15 V vs. Na/Na^+ [48, 49] for PW, as well as PBa providing a good cycle life and with a similar energy release during thermal runaway to that of NMC [50], the PBa cathode makes a case for it self as a replacement for LFP. However, as

PBas contains cyanide (CN), the potential of thermal runaway comes with inherent risk of releasing CN [51, 52] in to its surrounding if the form of hydrogen cyanide (HCN) and cyanogen ($(CN)_2$) if not sufficient safety precautions is taken.

2.2.3 Anodes

The choice of anode in a cell is just as an important choice, as that of cathode as it is the ability of the anode to bind and store positive ions and electrons in its structure that allows the cell to store energy. This topic have however not gotten the same attention as the development of cathodes due to the dominance of graphite anodes in LIBs.

2.2.3.1 Graphite

As previously stated, the most common anode being used in LIB is that of graphite, with it holding a 98% market share in LIB as of 2020 [28, 53], and started with the introduction of the first commercial LIB by Sony in 1991 [54]. This is down to the high specific capacity of ∼370 mAh/g and low potential of 0.15 V vs. Li/Li^+ [28]. Thus when combined with either a NMC, NCA, or LPF cathode, the full cell can achieve a high potential, as well as high energy density and specific energy.
As ion batteries work by intercalation, the positive ion gets stored in between the graphite layers. This unfortunately causes the graphite to expand and contract with charging and discharging [53], and causes the graphite to develop cracks which degrades the battery over time.

2.2.3.2 Hard carbon

Due to problem with intercalating sodium-ion into graphite anodes [39, 53], other material had to be used as anodes to make SIBs a viable battery type. It were not until year 2000 when Stevens and Dahn [55] successfully developed a SIB using a HC (or charcoal) anode with a high capacity close to that of graphite that enabled SIBs to be further develop [39] to compete with LIBs. With HC also being made of carbon, it also exhibits some of the same trait that graphite have, such as high specific capacity of 350 mAh/g, and a similar low potential vs. Na/Na^+ [55, 56].
With HC being a term used to describe the internal structure and the behavior of the material, it is not one single material, but a a range of various carbon based material that have undergone carbonization with the help of pyrolysis at ∼1000°C [57]. HC is also a more porous [39] material than that of graphite, and as such volumetric changes does not appear to be a problem, even with the larger sodium-ions that can degrade the battery, only starting to appear with even larger potassium-ions [56].

2.2.3.3 TiO_2

Another anode material that is used in LIBs and have the potential to be used in SIBs is that of TiO_2 [53, 58, 59]. Though not being as conductive and energy dense as that of graphite and HC with a capacity of ∼175 mAh/g, and a high potential of 1.5 V vs. Li/Li^+ [28] limits the energy density of a full cell using a

TiO_2 anode. The reason TiO_2 have gain attention is due to its higher cycle life than that of cells that uses an graphite anode [58], with Takami [60] showing the possibility to achieve 10000 full cycles before reaching 80% of the original capacity. A contributing factor to this is the almost none existing volumetric changes during charged or discharged cycles that graphite experience [53], the lack of lithium plating on during high current charging, as well as the high thermal stability.

2.3 Cell form factor

Cells comes in three different form factor, these are the cylindrical cell, the prismatic cell and the pouch cell. With each form factor providing different packed requirements, cooling possibilities, price points and sizes.

2.3.1 Cylindrical cells

The first form factor is the cylindrical cell being first used for LIBs by Sony in 1992 [61, 62]. The cylindrical cell uses a ridged outer casing in the shape of a cylinder, with the anode and cathode being wound around a central core [63]. With a simple and standardized shape for manufacturing [62, 64], the most commonly used being either 18 mm and 65 mm (18650) in diameter and length respectively or 21 mm and 70 mm (21700) in diameter and length respectively. The cylindrical cells is the cheapest way of making cells with a high energy density and high specific energy due to "...the high volume nature of the manufacturing process" [64]. But due to their small physical size, in order to achieve larger capacities using cylindrical cells, the BMS needs to monitor a larger amount of cells [61] and consequently requiring more computational power.

Figure 2.2: Polymer Lithium Ion Battery - 18650 Cell (2600mAh). [65], CC BY 2.0

With the symmetrical design of a cylinder in a radial direction, the cylindrical cell provides good mechanical strength from internal pressures, [62, 66] from both gas build up [67], and volumetric changes in the anode as mentioned in chapter 2.2.3.3. By the inherent shape of being a cylinder comes packaging constraint [62, 64], as only ∼90,69% of the area is covered when placed in a hexagonal pattern (not taking in to account the edges of the rows). These voids in between the cells could be both an advantage [62, 66] and a disadvantage [64], depending on what type of cooling system is being used to cool the battery pack.

2.3.2 Prismatic cells

The second form factor is the prismatic cell, and were introduced in the early 1990 [66]. The prismatic cell consists of a ridged outer casing [61, 68] in the shape of a rectangular prism, with the anode and cathode wounded around a central core [61, 62, 63, 68], same as with the cylindrical cell, that is then flattened and placed in side the hard casing. This form a production causes the anode and cathode material to be under large mechanical stress in the bends and causes "...problem for the electrode coating or electrolyte distribution" [62], as well as increasing the internal pressure that the outer casing needs to support. An alternative way to produce a prismatic cell is to stack the anode and cathode material in an alternating pattern before being placed inside the case [61, 68]. With prismatic cell reaching larger sizes [69] as to that of cylindrical cells, and being thicker, the thermal management difficulty increases [62] as the temperature different between the core and the surface of the prismatic cell is larger, consequently the BMS need to be more complex in order to monitor the cells temperature.

Figure 2.3: Lithium Energy Japan LEV50 Rechargeable Li-ion cell in Tokyo Motor Show 2011. [70], CC BY-SA 3.0

Due to the inherent shape of a rectangular prism, prismatic cells have large flat sides, this allows the prismatic cells to be efficiently stacked and placed inside a battery pack. With straight lines and large flat areas exposed in between the cells, the cooling possibility of prismatic cells are great and allows for better cooling solutions on the surface of the cell [61] to that of cylindrical cells. But as compared to cylindrical cell, prismatic cells with its large, flat, unsupported area on its outer casing does not have the inherent mechanical strength to withstand the internal pressure, and are as such susceptible to swelling and buckling [66] from gas build up [67], and volumetric changes in the anode during charge and discharge. Another consideration of prismatic cells is that unlike the cylindrical cell with standard sizes [64, 66, 71], there exist no standardised dimension for a prismatic cell. So each manufacture of prismatic cells have their own dimensions for their cells, and potential changes in supplier would come with the risk of needing to redesign parts of the battery pack.

2.3.3 Pouch cells

The third cell form factor being used is the pouch cell with it being introduced in 1995 [66]. The pouch cell, unlike the cylindrical cell and the prismatic cell, does not use a ridged outer casing [62, 68], instead opting for a flexible outer film [61, 66]. This enable the the pouch cell to reach higher energy density and specific capacity than that of cylindrical and prismatic cells [64], but does instead require more external support [61, 66] from the battery pack and negates some of the benefit of the higher energy density and specific capacity.

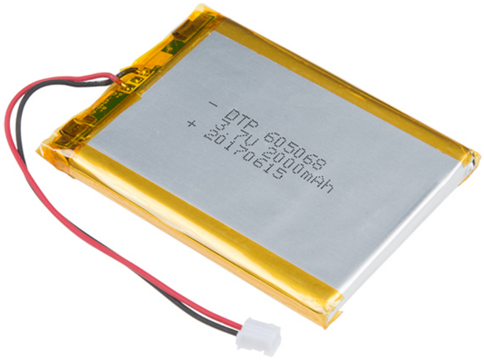

Figure 2.4: Lithium Ion Battery - 2Ah. [72], CC BY 2.0

The production method use for pouch cells is by stacking anode and cathode material in an alternating pattern [28, 64], the same as mentioned in the production of prismatic cells. Another similarity between prismatic cell and pouch cells is the lack of standard sizes and as with the prismatic cell [64, 66], with each manufacture have their own dimensions for their cells, and as such comes with the same risk of needing to redesign parts of the battery pack in the case of changing supplier.
Without a outer casing surrounding the cell, pouch cells can be placed closer to one and other, this enables efficient stacking [66] inside a battery pack and enables it to reach higher energy density and specific capacities [64]. As well as with a large flat area enables for good thermal regulation and management [64]. As with the prismatic cell, pouch cell have flat unsupported area and with no ridged outer casing, the pouch cell will experience significant swelling and deflation [64, 66], due to

gas build up [67] and anode expansion and contraction during charge and discharge cycles as mention in chapter 2.2.3.3.

3

Battery pack demands

The battery pack for heavy machinery have some specific requirements that need to be meet. This is to ensure that battery pack will be able to withstand the forces and size constrains of the vehicle. Theses include the energy density and specific energy of the battery pack in order to fit in the vehicle. The longevity of the battery pack, and its ability to withstand stresses and last the life of the vehicle. The safety of operating the vehicle, The power the battery pack needs to provide the vehicle in order for it to complete its task. The temperature the vehicle will operate in. The downtime the vehicle have in between tasks to be able to the charged. And lastly, the voltage the drive train and other components will operate at.

3.1 Energy density & specific energy

The energy density needed for the battery pack can be determined by use cases where diesel motors and fuel tank can be replaced by electric drive trains and battery packs, one such scenarios is in forklifts. The chosen forklift to calculate the energy density needed in the battery pack is the Linde H45D [73, 74] due to information access. The Linde H45D uses a 55 kW diesel motor and have a 50 L fuel tank. This correspond to a volume of 343,2 L [75] for the engine, excluding the gearbox, and 50 L for the fuel tank. A similarly powerful electric motor, including inverter, excluding the gearbox [76, 77, 78] have a volume of 34 L. This gives the forklift a remaining volume of ∼359,2 L (3.1) that can be used for the battery pack.

$$343,2L + 50L - 34L = 359,2L \tag{3.1}$$

When in use, the Linde H45D roughly uses 50-100 L of diesel per week [74] which corresponds to 10-20 L of diesel per day. As mentioned in chapter 2.2.1, diesel fuel have a energy density of 36,4 MJ/L [24], and with on-road heavy duty diesel engine achieving a brake thermal efficiency between 42% [79] to 46% [80], while the best diesel engines achieves 53.09% [81] as of April 2024. Assuming in this case a brake thermal efficiency of 46%, this equates to 46,5 kWh to 93 kWh (3.2) of energy being used to perform useful work.

$$10 \leftrightarrow 20L * 36.4MJ/L * 0.46 = 167.4 \leftrightarrow 334.9MJ = 46.5 \leftrightarrow 93kWh \tag{3.2}$$

As there also exist thermal efficiency factors for both the battery pack during charge and discharge, as well as for the electric motor, the energy figure needed in the vehicle will be higher. For the electric motor the thermal efficiency is ≥90% [82, 83, 84], while for the cell, the discharge thermal efficiency is 97,5% for for LFP/C cell when discharge at a C-rate of 1C [85, 86, 87].

$$\frac{46.5 \leftrightarrow 93kWh}{0.9 * 0.975} = 53 \leftrightarrow 106kWh \tag{3.3}$$

$$\frac{53 \leftrightarrow 106kWh}{359.2L} = 147.6 \leftrightarrow 295.1Wh/L \tag{3.4}$$

This equates to a required battery pack size of between 53 kWh and 106 kWh (3.3) in order for the forklift to be able to operate for one day without needing to charge, and is in line what Kalmar [88] uses for their forklift when equiped with a lead-acid battery required to operate for eight hours. When divided with the remaining volume of 359.2 L in the forklift, a energy density of 147.6 Wh/L to 295.1 Wh/L (3.4) is than the required of the battery pack.

As for the specific energy of the battery pack. A limit will not be set as most OHVs are heavy to ensure that the center of gravity does not shifting significantly as load is add or removed. As such the difference in specific energy between the cells would in this case have minimal to no effect on the overall weight of the vehicle.

3.2 Longevity

As for how long the vehicle should last and consequently how long the battery pack should last is a delicate subject. But as every heavy machinery is used, wear and tear will be an inevitability that can not be avoided. As such, a realistic target need to be meet.

According to dealers and service provider [89, 90, 91], heavy machinery will last about 6500 to 20000 hours depending on the vehicle in question. If assuming that the battery pack is adequate for one days of work, or 8 hours of use if in use continuously. The battery pack will need to support 812,5 to 2500 (3.5) EFCs in order for the battery pack to last the lifetime of the vehicle.

$$\frac{6500 \leftrightarrow 20000h}{8h} = 812,5 \leftrightarrow 2500 \tag{3.5}$$

3.3 Safety

With the use of battery pack as energy storage, their exist a few hazards that need to be addressed [92, 93, 94]. This includes, vibrational and external damage to the battery pack, short circuit between the anode and the cathode, toxic and flammable gases and liquids being released from the cells, and in worst case scenario thermal runaway and fire. The most prevalent of these categories is vibrational and external damage due to the environment these vehicles operate in, as well as the possibility for this kind of damage to lead to other forms of damage if something is shaken loose or penetrates the battery pack. This can in turn lead to short circuit, electrolyte leakage, fire, explosions and thermal runaway if not addressed in the design stage of the battery pack.

Another major hazard which is crucial that it is taken care of during design stage is adequate cooling of the battery pack, as it is possible for cells to enter thermal runaway [29, 34, 30, 94] by just heat alone due to the small inefficiencies during charging and discharging mention in chapter 3.1.

3.4 Power demand

The power demand for a heavy machinery can vary significantly depending on what task the vehicles is subject to complete. As such a single battery module can not provide ample power for each and all vehicles to complete its work, and power demand will therefore be subject the number of battery modules each vehicle uses. The power demand each battery pack needs to withstand can therefore be described using E-rate [87] (Power draw/Rated energy capacity), which is subject to the number of battery modules in each vehicle. By looking at the example given in chapter 3.1, as well as existing electric heavy machinery, the E-rating spans a range between 0.4E to 1.3E for continuous use [95, 96, 97, 98, 99, 100], and 0.6E to 1.67E for peak power usage [95, 98, 99]. As such the battery pack should be able to handle at least a E-rating of 1.67E without compromising the longevity and safety of the battery pack.

3.5 Temperature

As mentioned in the chapter 1.2. The vehicle in question should be able to operate at sub zero temperature without any disturbance to the task at hand, this of course also extends to the temperature of the battery pack modules, and the cells. The low temperature of the cells introduces a problem to the operation of the battery pack as a whole, as operating the cells at a suboptimal temperature accelerates the degradation [31, 101] of the cells. In order to protect the cells from operating at suboptimal temperature and damaging the cells, the cells would either need to be heated before any current can flow to or from them, or to be kept at an increased temperature for the life of the vehicle. Another option is to choose cells chemistries that have a decreased accelerated degradation due to operating at a suboptimal temperature.

Another issue with operating cells at a low temperature is decreased capacity [102] for some types of cells chemistries, consequently a variation in capacity will in turn change the C-rate of the battery and the associated degradation of the battery due to the increased C-rate, this will therefore need to be taken into consideration regarding the choice of cell chemistry.

3.6 Charging

Another aspect of operating a electric OHV that a business is dependent on to function is the downtime due to charging. As such, a certain amount of time each day need to be allocated towards this task. This time is not only dependent on the

amount of work a particular vehicle performs during operation, but also the level of current the battery can receive without damaging the cells.
As for the case in Sweden, the usual amount of time a person will work for, and be able to operate a vehicle is eight hours per day, this is also confirmed by M.Åkesson [103] to be the usual amount of time his excavator operates during peak season. This is of course not always the case as businesses and corporations can employ shifts and therefore increase the time the vehicle is in operation, as well as decreasing the amount of time can be allocated to charging. This scenario though be fixed by designing the battery pack in the vehicle to be able to be swapped out for another battery pack that is ready to be used. Due to the inconvenience of having multiple battery packs charging and taking up space. If possible to avoid, the charging time should therefore be capped to a level that is equal or lower to the maximum operating time for the battery pack. This is to ensure that with a two battery pack setup, the limiting factor in operation is not the charge time of energy in battery pack.
As determined in previously in chapter 3.1, a smaller forklift will consume 53 kWh to 106 kWh during 8 hours of operation. By the same equations used in chapter 3.1, a Liebherr 914 compact, with a 250 liter tank [104], consuming seven liter of diesel fuel per hour [103] during operation will consume 296.8 kWh in the same amount of time. But with a 5 times larger fuel tank, the Liebherr is probably expected to have 5 times as many battery pack modules, and therefore bring down the equivalent energy consumption per number of battery pack modules to 59.4 kWh, which is on par with previously calculated values.
Therefore, by assuming the maximum charge time to be eight hours, and energy consumption of 106 kWh. The charging power for the amount of battery modules in a small forklift should therefore be 13.3 kW or 0.125E (3.6).

$$\frac{106kWh}{8h} = 13.3kW \tag{3.6}$$

$$\frac{1\ Battery\,pack}{8h} = 0.125E \tag{3.7}$$

3.7 Voltage

A fundamental part of the battery pack and the vehicle as a whole is the voltage level the vehicle and battery pack will operate at. As the current is the main contributing factor to losses in a electrical system, increasing the voltage of battery pack would therefore decrease the losses in the system, and make the system as a whole more efficient and cheaper to operate. Another positive effect from increasing the voltage is the possibility to charge and discharge at higher power, and in turn reduces charging time and increase the longevity of the battery pack.
Though with a higher voltage level comes two concerns that needs to be addressed. The first is that of isolation [105], as with a higher voltage comes a increased risk of arcing occurring as a result of improper isolation. This would therefore increase the cost of components [105] and the overall cost of construction the vehicle. Some of this cost would though be recuperated as a lower current will also allow for the use

of thinner wires. This however is a path of diminishing return as the limiting factor for how thin a wire can be shifts from the current going through it, to the external stresses on the connections and wire itself it needs to endure.

A second concern is that of voltage drop in the battery pack due to increased internal resistance. With higher voltage being achieved by connecting several cells in series, the internal resistance of the battery pack would therefore increase at the same rate as the voltage. This would lead to a larger voltage drop between the open circuit voltage and the load voltage, and as a result the components would furthermore need to have a larger operating window.

These concern are fortunately minuscule in comparison to the upside of using a higher voltage, as such a battery pack with a nominal voltage of at least 800V would therefore be a suitable solution in this situation.

4

Comparison

As laid out previously in chapter 3, the cell chosen for the battery pack will need to adhere to a couple of demands. As such, twenty cells (table 4.1) have been chosen to represent a variety of configuration of cathodes, anodes, and form factors to be compared, and to get a overview over the potential configurations that could work for a battery pack to be used in a OHV at sub zero temperatures.

Table 4.1: Cell models and their configuration being compared

Manufacturer	Model	Cathode	Anode	Form factor
LG	INR18650HG2 [106]	NMC	Graphite	Cylindrical
Samsung	INR18650-30Q [107]	NMC	Graphite	Cylindrical
Samsung	INR21700-53G [108]	NMC	Graphite	Cylindrical
Samsung	SDI 94Ah [109, 110]	NMC	Graphite	Prismatic
LG	LGX E78 [111]	NMC	Graphite	Pouch
Leclanche	GL60 [112]	NMC	Graphite	Pouch
Panasonic	NCR18650GA [113, 114]	NCA	Graphite	Cylindrical
Panasonic	NCA103450 [115]	NCA	Graphite	Prismatic
Panasonic	UPF359191Z [116]	NCA	Graphite	Pouch
Samsung	IFR18650-11Q [117, 118]	LFP	Graphite	Cylindrical
BYD	FC4680P [119]	LFP	Graphite	Cylindrical
CATL	CB260 [120, 121]	LFP	Graphite	Prismatic
BYD	Blade [122]	LFP	Graphite	Prismatic
EEMB	LP7568130F [123]	LFP	Graphite	Pouch
CTS	CTS-S86117169 [124]	LFP	Graphite	Pouch
YinLong	YLE-LTO-66160 [125]	-	TiO_2	Cylindrical
Toshiba	20Ah SCiB [126, 127]	-	TiO_2	Prismatic
Leclanche	LT34 [128]	-	TiO_2	Pouch
CATL	- [40]	PBa	HC	-
Altris	Energy optimized sodium-ion battery cell gen1 [129]	PBa	HC	Pouch

4.1 Energy density & specific energy

The first aspect to look at is the energy density and specific energy of different cells depending on the choice of cathode, anode and form factor. The most energy dense cell is that of NMC cathode with a graphite anode in a cylindrical form factor with a energy density of 766 Wh/L (appendix A.2). This is followed by NCA/graphite in

a cylindrical form factor with a energy density of 676 Wh/L, while the least energy dense cell is the lithium TiO_2 cells as to be expected with a energy density ranging from 116 Wh/L to 187 Wh/L.
But a more important factor to consider is the energy density of the battery pack as a whole instead of the individual cells. A study by Löbberding et al. [130] showed that the package efficiency for CTM and MTP for cylindrical cells were 36.2% and 83.4% on average respectively. While for prismatic and pouch cells the package efficiency for CTM and MTP were 73.2% and 47.7% on average respectively. This gives the cylindrical form factor a combined CTMTP efficiency of 30.2%, while the prismatic and pouch form factor achieved a combined efficiency of 34.9% on average. But by ditching the CTMTP design altogether, another study [131] showed that by adapting a CTMTP design to a CTP design in a Volkswagen ID.3, the package efficiency could be increased by 25% from 41% to 51.3%. So by adopting a CTP design from the beginning, BYD [132] claims to achieve a 50% increase in package efficiency by using their blade cell in a CTP configuration, Torqeedo [133] achieved a ≥60% package efficiency, and CATL [134] achieved a 72% package efficiency using their CTP 3.0 Qilin battery design with prismatic cells, which they claim is 9 percentage points higher than using cylindrical cell at 63%.

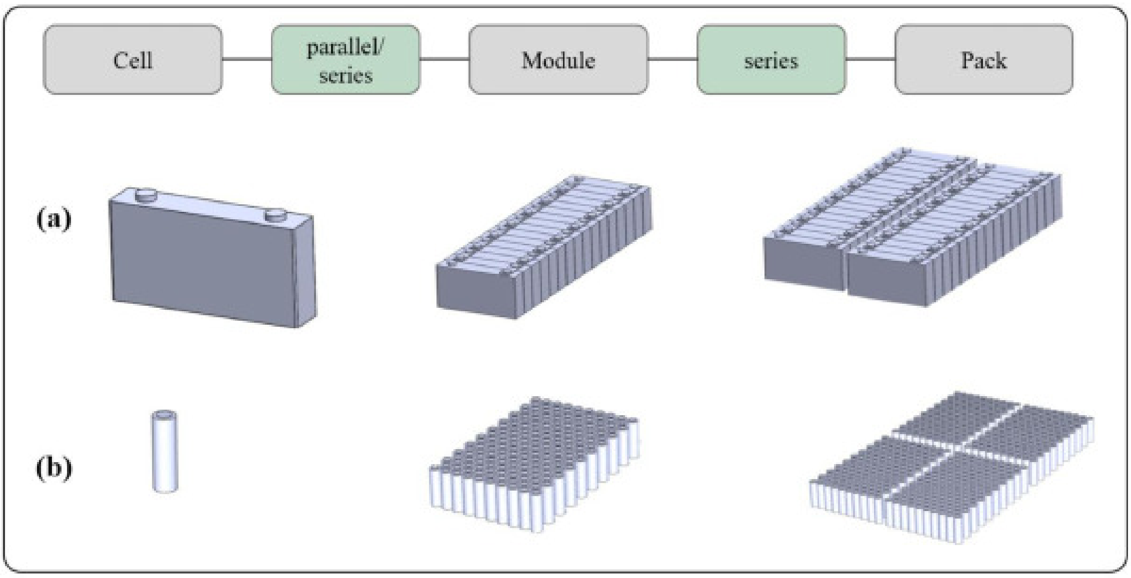

Figure 4.1: Overview of battery packs indicating two constructions with (a) cylindrical and (b) prismatic cells. [135], CC BY-NC-ND 4.0

As such, by assuming a 60% package efficiency for cylindrical cell, and a 65% package efficiency for prismatic cells as well as pouch cells is achievable, the minimum required energy density for the cells would therefore be 246 Wh/L and 227.1 Wh/L respectively by the requirement set out in chapter 3.1. Out of the twenty cells being compared, sixteen have a high enough energy density. It should be noted that the energy density values for the cells are assuming that the battery operates at a temperature of 20°C to 25°C, and as such will decrease if the cell temperature deviants from this temperature. Out of the five cells with insufficient energy density on their own, two are LFP/graphite cells, as well as all three of the cells using TiO_2 as the anode.

4.2 C-rate

The second aspect to look at for the cells is the rate the cells can be charged and discharged at. In chapter 3.4 & 3.6 the minimum charging capability of 0.125E, and minimum discharging capability of 1.3E for continuous use, and 1.67E for peak use was determined. Assuming that the motor voltage is the same as battery pack voltage, 1E in this case describes the same amount of current as 1C does. As such the minimum charging current, continuous discharging current and peak discharge current is 0.125C, 1.3C and 1.67C respectively.
For the minimum charging current, all of the twenty cells (appendix A.3) are capable of receiving substantial higher current, and as such this is not a determining factor when choosing a cells to use for the battery pack. The same can not be said about the discharging current as two LFP/graphite cells can not achieve a continuous discharging current higher than 1C without potential damage or rapid aging occurring to the cell. As for the PBa/HC cells, a conclusive result can not be derived as no data from the manufactures is able to be found. Although a study [136] done on PBa with an unknown anode (PBa/-) show that 4C during continuous usage is possible to achieve with out rapid aging occurring, as well as a peak of 20C for short periods of time.

4.3 Temperature

A third aspect to look at is the range of temperatures the different cells can operate at, as well as the capacity retention when the cells are not at a optimal temperature. The first notable common characteristic between the different cells (appendix A.4) is that of minimum charging temperature, as all but cells using TiO_2 as the anode, or PBa as the cathode are recommended to not be charged at a temperature lower than 0°C. This would in turn require the cells to be have a higher temperature than the ambient temperature before charge can be accepted.
Another common characteristic between the cells is the minimum discharging temperature of -20°C, where in this case the cells using TiO_2 as the anode is the only outlier as it is able to operate at further reduced temperatures. However discharging at these reduced temperature will incur rapid aging and degradation for NMC/graphite [31, 32], NCA/graphite [32] and LFP/graphite [101] cells. As such, in both the discharging and charging scenario, the cells would need to have a higher temperature than the surrounding ambient temperature to not damage the cells.
A byproduct of operating the cells at a higher temperature is that of capacity retention, with NMC/graphite [106, 107, 109] cells losing 15% to 40% at -10°C (figure 4.2), NCA/graphite [113, 115] cells losing 12% to 27% at -10°C (figure 4.3), LFP/graphite [117, 120, 123] cells losing 25% to 40% at -10°C (figure 4.4), -/TiO_2 [125] cells losing 30% at -20°C (figure 4.5), and PBa/HC [40, 137] cells losing $\leq$ 10% and 21% at -20°C and -25°C respectively (figure 4.6), which is in line what studies has

shown [102]. As such, not operating the battery at increased temperatures would therefore affect both the effective energy density (chapter 4.1) of the battery, as well as the C-rate (chapter 4.2) of the battery significantly. Thus there is a risk that this could tip the battery for being sufficient to insufficient for the task at hand to be performed.

This increased temperature can either be achieved by heating the cells before each use and letting it cool down in between. This would introduce extra operational expense for the operator, either by needing to use energy from the grid to heat the cells, or by using energy from the battery and reducing the both the energy being able to be used for productive work, as well as the life time of the cells for needing to operate at reduced temperatures. It would also introduce unwanted delay and hindrance to the operation of the vehicle as during heating, none or limited amount of productive work can be done, this drawback can be mitigated substantially if the vehicle have known operating hours.

The higher temperature can also be achieved by constantly keeping the cells at a elevated temperature. This would reduce the operating cost of the vehicle, but by keeping the cells at elevated temperature constantly, research has shown that NMC/-graphite [33, 138], NCA/graphite [33], LFP/graphite [33, 139] and $Na_3V_2(PO4)_2F_3$/HC [140] will all experience faster aging and degradation, as such the cells might not be able last the life time of the vehicle.

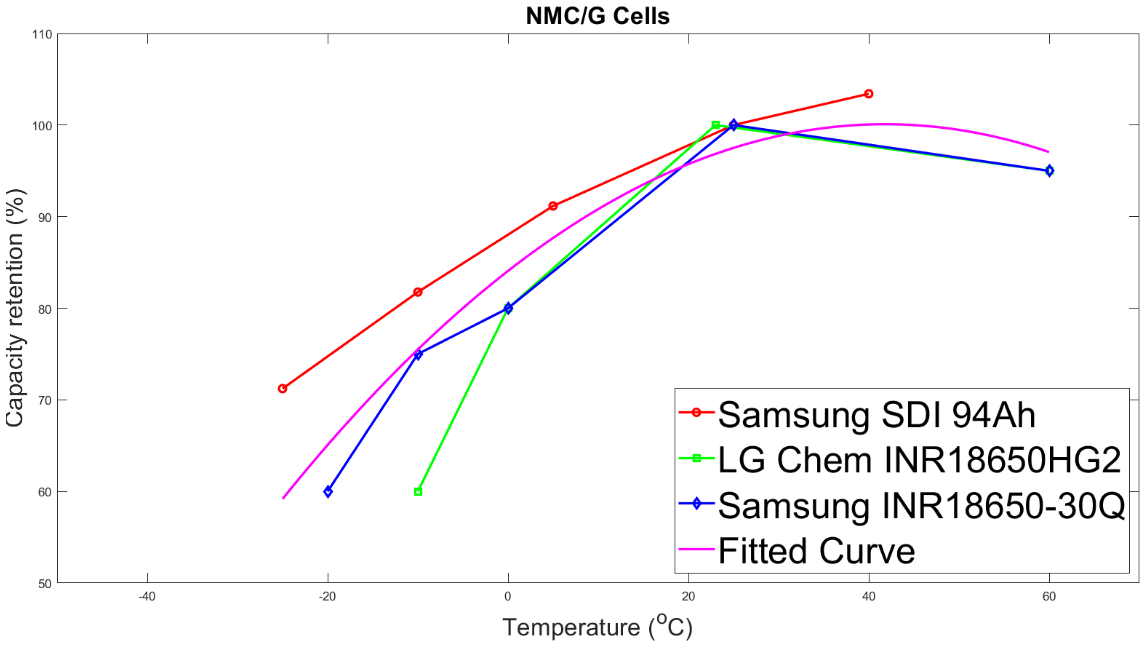

Figure 4.2: Claimed discharge capacity by the manufacturer and fitted curve for NMC/graphite at different temperature.

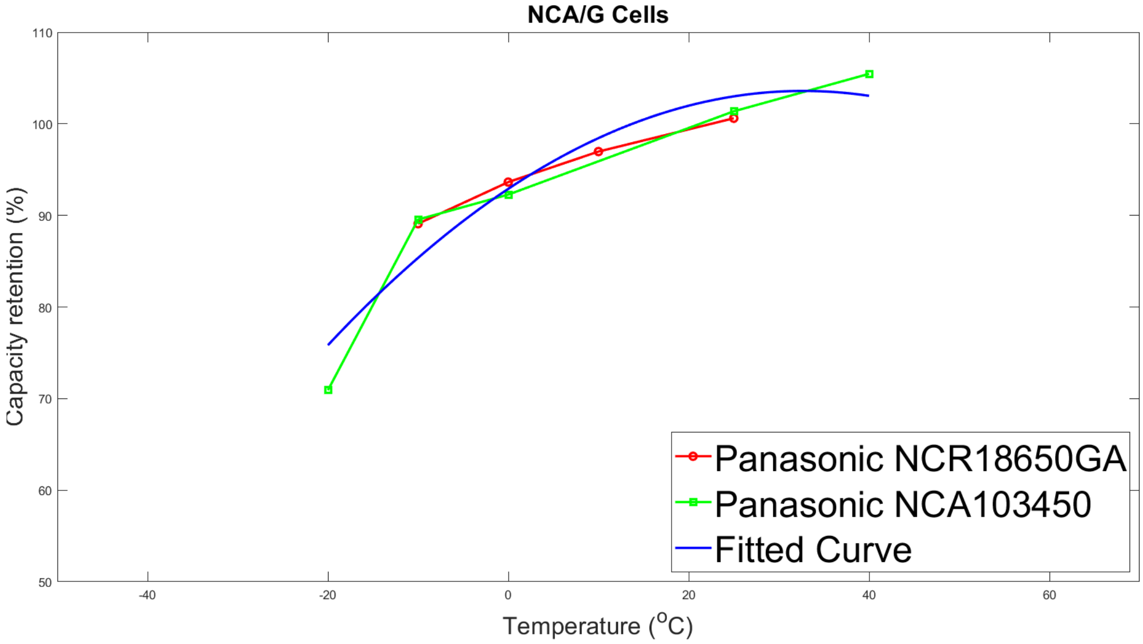

Figure 4.3: Claimed discharge capacity by the manufacturer and fitted curve for NCA/graphite at different temperature.

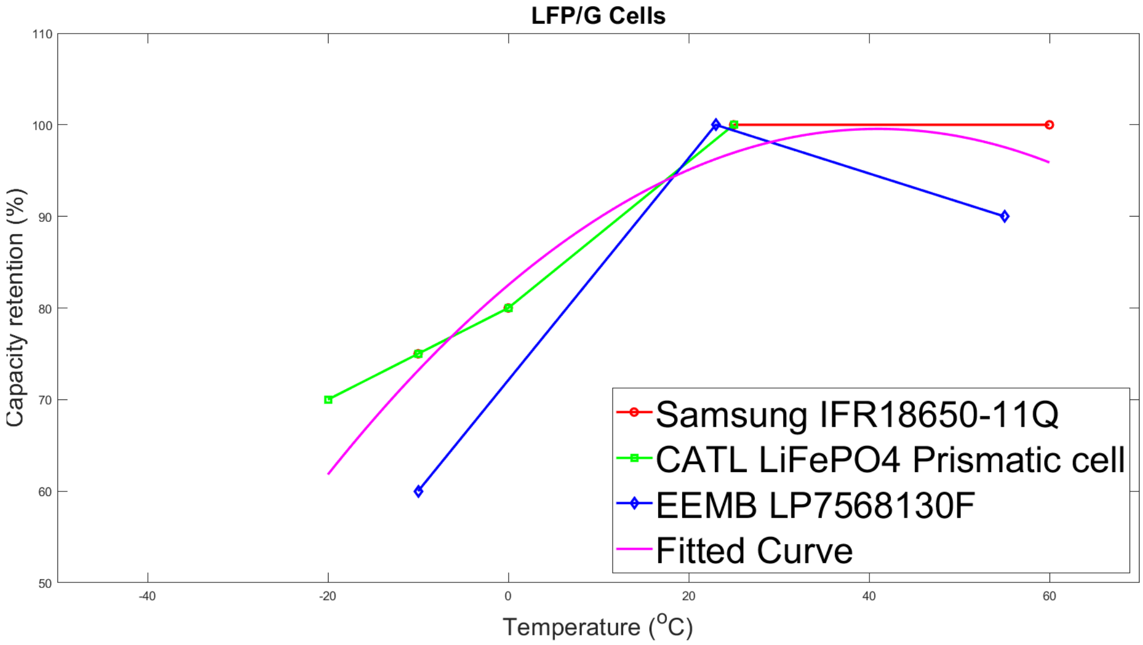

Figure 4.4: Claimed discharge capacity by the manufacturer and fitted curve for LFP/graphite at different temperature.

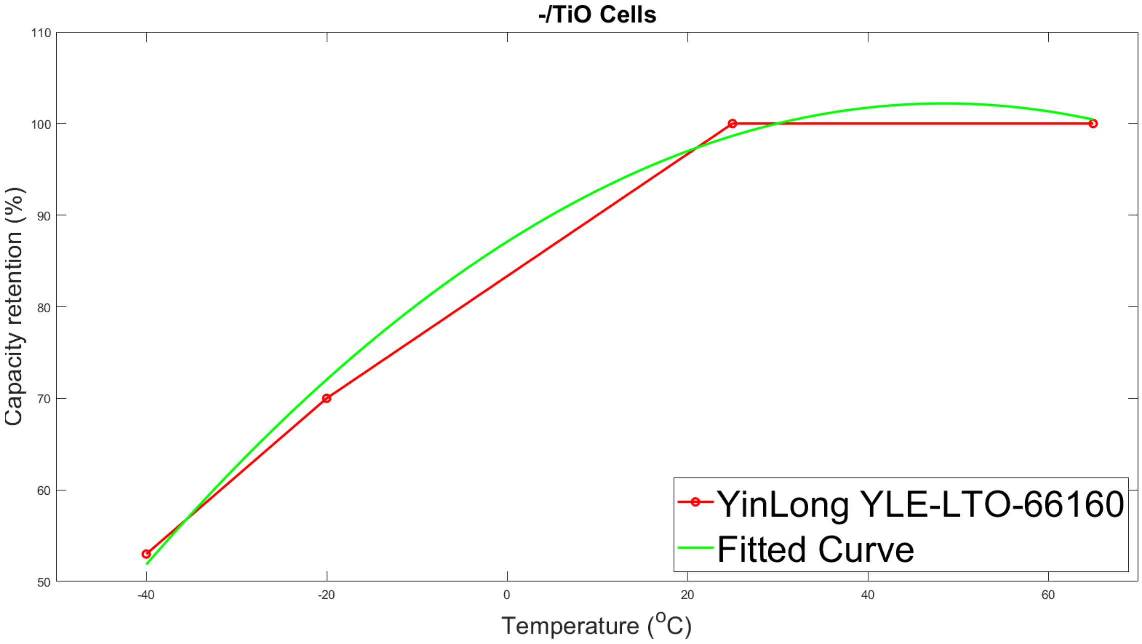

Figure 4.5: Claimed discharge capacity by the manufacturer and fitted curve for -/TiO_2 at different temperature.

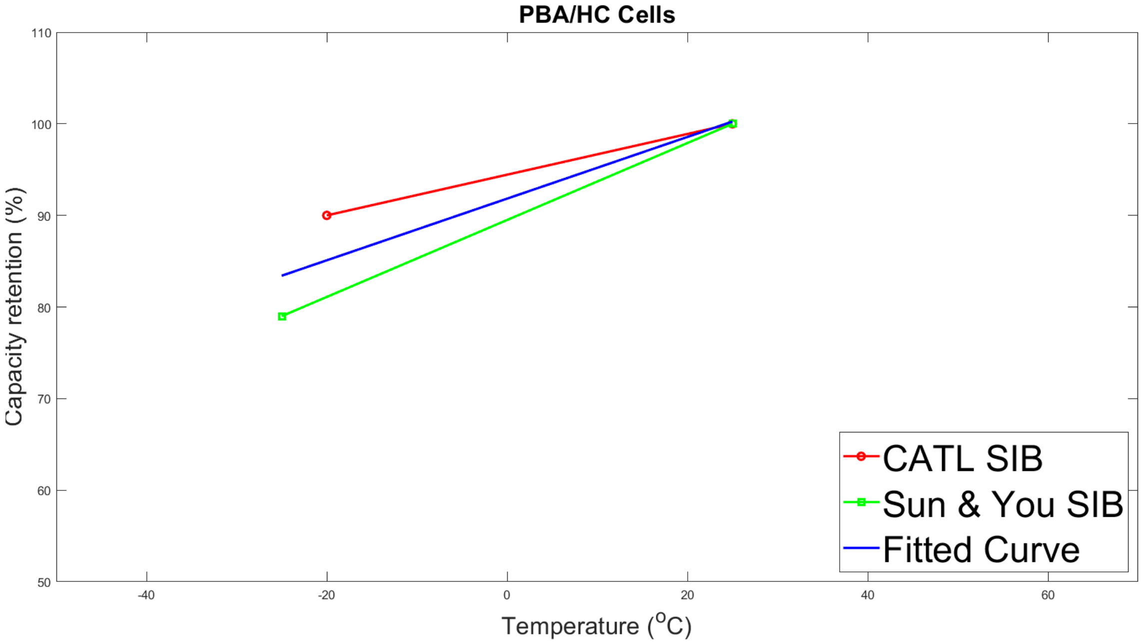

Figure 4.6: Claimed discharge capacity by the manufacturer and fitted curve for PBa/HC at different temperature.

4.4 Longevity

The fourth aspect to look at when comparing different cells is that of longevity in term of cycle life and calendar life (storage degradation). Here different cells have drastically different expected cycle life (appendix A.5), with NMC/graphite cells losing up to 40% in its capacity in just 250 cycle when tested by Samsung, while -/TiO_2 can reach 10 000 cycle with less than 20% capacity reduction when tested by YinLong. It is important to take into consideration the C-rate, DOD, and temperature during which these test were carried out at as different amount of C-rate [31, 101], DOD [31, 101, 141, 142], and temperature [31, 32, 101, 140, 143] can drastically change the expected cycle life, as well as it might not be representative of the real world, and what the cells is expected to handle. The effect C-rating has on the cycle life of the cells can be most clearly seen i table 4.2 when comparing LG INR18650HG2 cell, Samsung INR18650-30Q cell, and INR21700-53G cell, as well as comparing Samsung IFR18650-11Q cell, and CATL CB260 cell, as different discharging rate changes the amount of cycle the cell performed as well as the capacity retention at the end of the cycles.

Table 4.2: Claimed energy density and cycle life of different cells assuming certain charge, discharge and temperature criteria.

	Energy density	Cycle life	Charging current	Discharing current	Capacity retention	Test temperature
LG INR18650HG2 (NMC/graphite, Cylindrical) [106]	616 Wh/L	300	4 A (1.33C)	10 A (3.33C)	≥ 70%	-
Samsung INR18650-30Q (NMC/graphite, Cylindrical) [107]	624 Wh/L	250	1.5 A (0.5C)	15 A (5C)	≥ 60%	25°C
Samsung INR21700-53G (NMC/graphite, Cylindrical) [108]	766 Wh/L	1000	1.75 A (0.33C)	5.3 A (1C)	≥ 80%	-
Samsung SDI 94Ah (NMC/graphite, Prismatic) [109, 110]	355 Wh/L	≥ 3200	47 A (0.5C)	94 A (1C)	80%	25°C
Panasonic NCR18650GA (NCA/graphite, Cylindrical) [113, 114]	676 Wh/L	500	1.65 A (0.5C)	6 A (1.8C)	63%	25°C
Panasonic NCA103450 (NCA/graphite, Prismatic) [115]	460 Wh/L	500	1.645 A (0.7C)	6.462 A (2.75C)	83%	25°C
Samsung IFR18650-11Q (LFP/graphite, Cylindrical) [117, 118]	203 Wh/L	1000	1.5 A (1.3C)	10 A (9.1C)	≥ 75%	25±5°C
CATL CB260 cell (LFP/graphite, Prismatic) [120, 121]	345 Wh/L	≥ 3500	150 A (1C)	150 A (1C)	80%	25°C

Another notable correlation seen in table 4.2 is that of energy density and cycle life, with Samsung SDI 94Ah cell able to achieve three times as many cycle compared to Samsung INR21700-53G cell with similar testing conditions and capacity retention. As well as Panasonic NCA103450 cell able to endure the same amount of cycles as Panasonic NCR18650GA cell while using a higher C-rating and retaining a higher capacity. However, as showing in studies [31, 101, 141, 142], reducing the DOD could increase the number of cycles the cells can endure. As such, both Samsung INR21700-53G cell and Panasonic NCR18650GA cell could therefore increase the number of cycles and capacity retention if DOD is limited, and they are capped to similar levels of energy density to that of Samsung SDI 94Ah cell and Panasonic NCA103450 cell.

In the case for calendar life, it will also have a impact on the longevity of the cells, as heavy machinery, if not used in shifts, will be idle for most of its existence. As such, calendar aging has to be taken into consideration. In chapter 4.3, the effect temperature have on calendar aging have been discussed and that higher temperature will increase the rate at which calendar aging occur. The same research

[33, 138, 139, 140] also shows that SOC also have a impact on the rate at which cells degrade in storage, with higher SOC degrading faster. NMC/graphite, NCA/-graphite and LFP/graphite all show similar degradation pattern for SOC when kept at a constant temperature of +20°C, with the exception of LFP/graphite at 0% SOC which shows close to zero degradation in storage.

5

Result

5.1 Requirements

When comparing between the different cells, three criteria seems to have the largest impact on the feasibility of using the cells when constructing a battery pack for heavy machinery. They being, energy density (chapter 4.1), maximum continuous discharge current (chapter 4.2), and cycle life (chapter 4.4). Out of the twenty cells (table 4.1) being compared, all of the NMC/graphite cells, NCA/graphite cells and PBa/HC cells, as well as two of the LFP/graphite cells have enough energy density, and maximum continuous discharge current to satisfy the requirements in chapter 4.1 & 4.2. As for the longevity of the cells, both LFP/graphite (table 4.2), and PBa/HC [136] can effortless clear the upper limit of 2500 EFC set out in chapter 3.2. As for NMC/graphite and NCA/graphite, by limiting the DOD [141, 142] just enough in order to satisfy the energy density, these cells could in theory accomplish the upper limit of 2500 EFC. As such, the cells that meet all the requirements and are able to be used in the battery pack is.

- LG INR18650HG2 (NMC/graphite, Cylindrical) [106]
- Samsung INR18650-30Q (NMC/graphite, Cylindrical) [107]
- Samsung INR21700-53G (NMC/graphite, Cylindrical) [108]
- Samsung SDI 94Ah (NMC/graphite, Prismatic) [109, 110]
- LG Chem LGX E78 (NMC/graphite, Pouch) [111]
- Leclanche GL60 (NMC/graphite, Pouch) [112]
- Panasonic NCR18650GA (NCA/graphite, Cylindrical) [113, 114]
- Panasonic NCA103450 (NCA/graphite, Prismatic) [115]
- Panasonic UPF359191Z (NCA/graphite, Pouch) [116]
- BYD FC4680P (LFP/graphite, Cylindrical) [119]
- EEMB LP7568130F (LFP/graphite, Pouch) [123]
- CATL SIB (PBa/HC, -) [40]
- Altris gen1 SIB (PBa/HC, Pouch) [129]

5.2 Price & Availability

With the battery pack being a product meant for the open market, reducing the price of constructing and material cost is a key aspect. As such, with thirteen cells meeting the requirements of the battery pack, choosing the cheapest is the obvious choice. Out of the four cathode and anode paring that meet the requirements, PBa/HC is expected to be the cheapest [2, 144, 145] with it expecting to cost 20%

[146] to 30% [2] less than LFP/graphite cells as of 2025, with NMC/graphite being an additional 32% [144] more expensive than LFP/graphite, and NCA/graphite being marginally cheaper [147] than NMC/graphite.
Therefore the choice of cell to use in the battery pack is either CATLs SIB cell [40], or Altris gen1 SIB cell [129], but due to the lack of data on the form factor and specification for the Catl SIB, this degree project will as such assume that the cell of choice is the Altris gen1 SIB. However, it should be noted that as of late 2023, the average price for a battery pack in China is 11% lower than that of in Europe [144]. In turn the CATL SIB cell would therefore in theory be the cheaper option when constructing a battery pack. It should also be noted that at the time of writing this degree project, neither CATL or Altris have yet to released their PBa/HC cells on the open market, with Altris set to release their cell in the fourth quarter of 2024 [129]. As such, pricing is unknown and may change in relation to LFP/graphite cells, as well as each other cells.

5.3 Layout

With a nominal voltage of 3.0 V, that is in accordance with chapter 2.2.2.1 and 2.2.3.2. As well as a total energy of 353 Wh [129], the Altris gen1 SIB cell have a standard discharge capacity of 117.6 Ah.
With these two parameters set, a ∼80 kWh battery pack as set out in chapter 1.3 can be conceived. As such, by placing 250 cells in series and one in parallel (250s-1p), a 87.7 kWh, 750 V, and 117 Ah battery pack can be designed.

5.4 Temperature

Deciding on what temperature to keep the cells and pack at is a crucial decision as that will affect the cycle life, the C-rate and energy density. With a C-rate of 4C for continuous usage, and 20C for peak usage achieved in [136] being significantly higher than the 1.3C and 1.67C set out in chapter 3.4, this is not a limiting factor for the determination of operating temperature. As for the energy density of the battery pack, allowing for a lower temperature of -20°C will be an issue in the long run as the battery pack starts to degrade. With a lower limit for the energy density of 227.1 Wh/L set out in chapter 4.1 for pouch cells, which is 78.3% of the battery packs BOL capacity, operating at -20°C will not work, as a degradation of only 2.2% to the capacity will as such bring the capacity below the lower limit. As such the main factor to the determine the operational temperature of the cells and battery pack is cycle life and degradation. As shown in [136] and [137], with a discharge rate of 4C, a capacity retention of 85.7% and 79.3% can be achieved respectively from 1500 EFC and 3000 EFC, as well as 86% capacity retention from 1000 EFC at -25°C. With this level of degradation, it is clear that in order for the battery pack to remain above the lower limit for energy densityset out in 3.2, the battery pack must operate at its optimal temperature, in this case, 15°C to 40°C [129].

6

Conclusion & discussion

This report have looked into the possibility of using battery packs to power OHVs in sub zero temperatures. It is shown that NMC/graphite, NCA/graphite, LFP/-graphite, and PBa/HC all have enough energy density, longevity, and C-rate to be used in a battery pack for OHV in sub zero temperature, as such, the main factor determining the best cell to use in the battery pack is price. Out of the four different cathode and anode combination, PBa/HC is shown to be the cheapest, as such is the cell of choice. With this, a 87.7 kW, 750 V, and 117Ah battery pack could be designed using a 250s-1p CTP layout.

In the choice of only including only four cathodes and three anodes in this degree project, some potential alternative might have been over looked. In the case of left out cathode, layered oxide [148], polyanionic, and organic cathodes for SIB might have promising traits that could make them functional, but where left out due to lower theoretical specific capacity or worse capacity retention during cycles then that of PBa. Further more, LMO and LCO cathodes for LIB were not taken into consideration due to lack of representation in current EVs. As for in the case of anodes, lithium metal anode were left out due to lack of commercialisation. As such, further study could look into the feasibility of using these chemistries for OHVs operating at sub zero temperatures.

One area not covered at all in this degree project is the electrolyte and the impact it has on the cells attributes. As such, this is an area of further studies.

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A

Electrochemical cells

Table A.1: The voltage range different electrochemical cells operate at during charging and discharging.

	Nominal voltage	Maximum charge voltage	Minimum discharge voltage
LG INR18650HG2 (NMC/G, Cylindrical) [106]	3.6 V	4.2 V	2.5 V
Samsung INR18650-30Q (NMC/G, Cylindrical) [107]	3.6 V	4.2 V	2.5 V
Samsung INR21700-53G (NMC/G, Cylindrical) [108]	3.63 V	4.2 V	2.5 V
Samsung SDI 94Ah (NMC/G, Prismatic) [109, 110]	3.68 V	4.15 V	2.7 V
LG LGX E78 (NMC/G, Pouch) [111]	3.67 V	-	-
Leclanche GL60 (NMC/G, Pouch) [112]	3.65 V	4.2 V	3.0 V
Panasonic NCR18650GA (NCA/G, Cylindrical) [113, 114]	3.6 V	4.2 V	2.5 V
Panasonic NCA103450 (NCA/G, Prismatic) [115]	3.6 V	-	-
Panasonic UPF359191Z (NCA/G, Pouch) [116]	3.85 V	-	-
Samsung IFR18650-11Q (LFP/G, Cylindrical) [117, 118]	3.2 V	3.6 V	2.0 V
BYD FC4680P (LFP/G, Cylindrical) [119]	3.2 V	3.65 V	2.0 V
CATL LiFePO4 Prismatic cell (LFP/G, Prismatic) [120, 121]	3.2 V	3.65 V	2.0 V
BYD Blade (LFP/G,Prismatic) [122]	3.2 V	3.8 V	2.0 V
EEMB LP7568130F (LFP/G, Pouch) [123]	3.2 V	3.65 V	2.0 V
CTS CTS-S86117169 (LFP/G, Pouch) [124]	3.2 V	3.65 V	2.0 V
YinLong YLE-LTO-66160 (-/TiO, Cylindrical) [125]	2.3 V	2.8 V	1.5 V
Toshiba LTO cell (-/TiO, Prismatic) [126, 127]	2.4 V	-	-
Leclanche LT34 (-/TiO, Pouch) [128]	2.2 V	2.8 V	1.5 V
CATL SIB (PBa/HC, -) [40]	-	-	-
Altris gen1 SIB (PBa/HC, Pouch) [129]	3.0 V*	3.8 V*	2.0 V*

*Target specification

Table A.2: Energy density and specific energy of different commercially available electrochemical cells.

	Energy density	Specific energy
LG INR18650HG2 (NMC/G, Cylindrical) [106]	616 Wh/L	229 Wh/kg
Samsung INR18650-30Q (NMC/G, Cylindrical) [107]	624 Wh/L	225 Wh/kg
Samsung INR21700-53G (NMC/G, Cylindrical) [108]	766 Wh/L	267 Wh/kg
Samsung SDI 94Ah (NMC/G, Prismatic) [109, 110]	355 Wh/L	164 Wh/kg
LG Chem LGX E78 (NMC/G, Pouch) [111]	603 Wh/L	264 Wh/kg
Leclanche GL60 (NMC/G, Pouch) [112]	340 Wh/L	195 Wh/kg
Panasonic NCR18650GA (NCA/G, Cylindrical) [113, 114]	676 Wh/L	247.5 Wh/kg
Panasonic NCA103450 (NCA/G, Prismatic) [115]	460 Wh/L	207 Wh/kg
Panasonic UPF359191Z (NCA/G, Pouch) [116]	618 Wh/L	274 Wh/kg
Samsung IFR18650-11Q (LFP/G, Cylindrical) [117, 118]	203 Wh/L	81 Wh/kg
BYD FC4680P (LFP/G, Cylindrical) [119]	350 Wh/L	142 Wh/kg
CATL LiFePO4 Prismatic cell (LFP/G, Prismatic) [120, 121]	345 Wh/L	161 Wh/kg
BYD Blade (LFP/G,Prismatic) [122]	378 Wh/L	161 Wh/kg
EEMB LP7568130F (LFP/G, Pouch) [123]	228 Wh/L	128 Wh/kg
CTS CTS-S86117169 (LFP/G, Pouch) [124]	376 Wh/L	158 Wh/kg
YinLong YinLong YLE-LTO-66160 (-/TiO, Cylindrical) [125]	187 Wh/L	81 Wh/kg
Toshiba LTO cell (-/TiO, Prismatic) [126, 127]	177 Wh/L	93 Wh/kg
Leclanche LT34 (-/TiO, Pouch) [128]	116 Wh/L	69 Wh/kg
CATL SIB (PBa/HC, -) [40]	-	160 Wh/kg
Altris gen1 SIB (PBa/HC, Pouch) [129]	290 Wh/L*	160 Wh/kg*

*Target specification

Table A.3: The charge and discharge current different electrochemical cells is claimed to be able to handle.

	Nominal charging current	Maximum charging current	Maximum continuous discharging current	Peak pulsating discharging current
LG INR18650HG2 (NMC/G, Cylindrical) [106]	1.5 A (0.5C)	4 A (1.33C)	20 A (6.67C)	-
Samsung INR18650-30Q (NMC/G, Cylindrical) [107]	1.5 A (0.5C)	4 A (1.33C)	15 A (5C)	-
Samsung INR21700-53G (NMC/G, Cylindrical) [108]	1.75 A (0.33C)	5.3 A (1C)	10.6 A (2C)	-
Samsung SDI 94Ah (NMC/G, Prismatic) [109, 110]	72 A (0.76C)	270 A (2.87C)	150 A (1.6C)	409 A (4.3C)
LG Chem LGX E78 (NMC/G, Pouch) [111]	-	184 A (2.3C)	234 A (3C)	496 A (6.3C)
Leclanche GL60 (NMC/G, Pouch) [112]	-	120 A (2C)	180 A (3C)	300 A (5C)
Panasonic NCR18650GA (NCA/G, Cylindrical) [113, 114]	1.475 A (0.44C)	-	10 A (3C)	17.5 A (5.3C)
Panasonic NCA103450 (NCA/G, Prismatic) [115]	1.589 A (0.72C)	1.589 A (0.72C)	-	-
Panasonic UPF359191Z (NCA/G, Pouch) [116]	-	-	-	-
Samsung IFR18650-11Q (LFP/G, Cylindrical) [117, 118]	0.55 A (0.5C)	3 A (2.7C)	10 A (9.1C)	17.5 (15.9C)
BYD FC4680P (LFP/G, Cylindrical) [119]	0.75 A (0.5C)	15 A (1C)	45 A (3C)	-
CATL LiFePO4 Prismatic cell (LFP/G, Prismatic) [120, 121]	75 A (0.5 C)	150 A (1C)	150 A (1C)	450 A (3C)
BYD Blade (LFP/G,Prismatic) [122]	27.6 A (0.2C)	207 A (1.5C)	-	276 A (2C)
EEMB LP7568130F (LFP/G, Pouch) [123]	-	5 A (1C)	10 A (2C)	-
CTS CTS-S86117169 (LFP/G, Pouch) [124]	10 A (0.5C)	20 A (1C)	20 A (1C)	40 A (2C)
YinLong YLE-LTO-66160 (-/TiO, Cylindrical) [125]	45 A (1C)	270 A (6C)	270 A (6C)	450 A (10C)
Toshiba LTO cell (-/TiO, Prismatic) [126, 127]	-	-	-	200 A (10C)
Leclanche LT34 (-/TiO, Pouch) [128]	-	204 A (6C)	204 A (6C)	340 A (10C)
CATL SIB (PBa/HC, -) [40]	-	-	-	-
Altris gen1 SIB (PBa/HC, Pouch) [129]	-	-	-	-

*Target specification

Table A.4: The temperature range different electrochemical cells is claimed to be able to handle.

	Maximum charging temperature	Minimum charging temperature	Maximum discharging temperature	Minimum discharging temperature	Maximum storage temperature	Minimum storage temperature
LG INR18650HG2 (NMC/G, Cylindrical) [106]	+50°C	0°C	+75°C	-20°C	+60°C	-20°C
Samsung INR18650-30Q (NMC/G, Cylindrical) [107]	+50°C	0°C	+75°C	-20°C	+60°C	-30°C
Samsung INR21700-53G (NMC/G, Cylindrical) [108]	+50°C	0°C	+60°C	-30°C	+60°C	-20°C
Samsung SDI 94Ah (NMC/G, Prismatic) [109, 110]	+65°C	0°C	+55°C	-20°C	+65°C	-20°C
LG Chem LGX E78 (NMC/G, Pouch) [111]	-	-	+55°C	-30°C	+60°C	-30°C
Leclanche GL60 (NMC/G, Pouch) [112]	+45°C	0°C	+55°C	-20°C	+60°C	-20°C
Panasonic NCR18650GA (NCA/G, Cylindrical) [113, 114]	+45°C	+10°C	+60°C	-20°C	+50°C	-20°C
Panasonic NCA103450 (NCA/G, Prismatic) [115]	+45°C	0°C	+60°C	-20°C	+50°C	-20°C
Panasonic UPF359191Z (NCA/G, Pouch) [116]	-	-	-	-	-	-
Samsung IFR18650-11Q (LFP/G, Cylindrical) [117, 118]	+60°C	0°C	+80°C	-20°C	+25°C	-20°C
BYD FC4680P (LFP/G, Cylindrical) [119]	+55°C	0°C	+60°C	-20°C	+25°C	-20°C
CATL LiFePO4 Prismatic cell (LFP/G, Prismatic) [120, 121]	+60°C	0°C	+60°C	-30°C	-	-
BYD Blade (LFP/G,Prismatic) [122]	+50°C	-10°C	+55°C	-20°C	30°C	-10°C
EEMB LP7568130F (LFP/G, Pouch) [123]	+45°C	0°C	+60°C	-10°C	+60°C	-20°C
CTS CTS-S86117169 (LFP/G, Pouch) [124]	+55°C	0°C	+60°C	-20°C	-	-
YinLong YLE-LTO-66160 (-/TiO, Cylindrical) [125]	+65°C	-40°C	+65°C	-40°C	+28°C	-5°C
Toshiba LTO cell (-/TiO, Prismatic) [126, 127]	+65°C	-50°C	+65°C	-50°C	+65°C	-20°C
Leclanche LT34 (-/TiO, Pouch) [128]	+55°C	-20°C	+55°C	-20°C	+60°C	-20°C
CATL SIB (PBa/HC, -) [40]	-	-	-	≤ -20°C	-	-
Altris gen1 SIB (PBa/HC, Pouch) [129]	+60°C*	- 20°C*	+60°C*	- 20°C*	+55°C*	-20°C*

*Target specification

Table A.5: Claimed cycle life of different electrochemical cells assuming certain charge, discharge and temperature criteria.

	Cycle life	Charging current	Discharing current	Capacity retention	Test temperature
LG INR18650HG2 (NMC/G, Cylindrical) [106]	300	4 A (1.33C)	10 A (3.33C)	≥ 70%	23±2°C
Samsung INR18650-30Q (NMC/G, Cylindrical) [107]	250	1.5 A (0.5C)	15 A (5C)	≥ 60%	25°C
Samsung INR21700-53G (NMC/G, Cylindrical) [108]	1000	1.75 A (0.33C)	5.3 A (1C)	≥ 80%	-
Samsung SDI 94Ah (NMC/G, Prismatic) [109, 110]	≥ 3200	47 A (0.5C)	94 A (1C)	80%	25°C
LG Chem LGX E78 (NMC/G, Pouch) [111]	-	-	-	-	-
Leclanche GL60 (NMC/G, Pouch) [112]	4500	60 A (1C)	60 A (1C)	-	-
Panasonic NCR18650GA (NCA/G, Cylindrical) [113, 114]	500	1.65 A (0.5C)	6 A (1.8C)	63%	25°C
Panasonic NCA103450 (NCA/G, Prismatic) [115]	500	1.645 A (0.7C)	6.462 A (2.75C)	83%	25°C
Panasonic UPF359191Z (NCA/G, Pouch) [116]	-	-	-	-	-
Samsung IFR18650-11Q (LFP/G, Cylindrical) [117, 118]	1000	1.5 A (1.3C)	10 A (9.1C)	≥ 75%	25±5°C
BYD FC4680P (LFP/G, Cylindrical) [119]	2000	15 A (1C)	15 A (1C)	-	25±2°C
CATL LiFePO4 Prismatic cell (LFP/G, Prismatic) [120, 121]	≥ 3500	150 A (1C)	150 A (1C)	80%	25°C
BYD Blade (LFP/G,Prismatic) [122]	≥ 4000	-	-	-	-
EEMB LP7568130F (LFP/G, Pouch) [123]	≥2000	-	2.5 A (0.5C)	70%	-
CTS CTS-S86117169 (LFP/G, Pouch) [124]	∼2000	10 A (0.5C)	20 A (1C)	-	25°C
YinLong YLE-LTO-66160 (-/TiO, Cylindrical) [125]	10000	45 A (1C)	45 A (1C)	≥ 80%	25±5°C
Toshiba LTO cell (-/TiO, Prismatic) [126, 127]	20000	60 A (3C)	60 A (3C)	75%	25°C
Leclanche LT34 (-/TiO, Pouch) [128]	15000	136 A (4C)	136 A (4C)	-	-
CATL SIB (PBa/HC, -) [40]	-	-	-	-	-
Altris gen1 SIB (PBa/HC, Pouch) [129]	≥5000*	-	39 A (0.33C)*	70%*	+25°C*

*Target specification

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