Batteries for electrical vehicles

Sähköajoneuvojen akut

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Tavoite pienentää ajoneuvojen päästöjä on saanut valtavasti huomiota, sillä liikenteen päästöt ovat olleet nousussa viime vuosina. Sähköajoneuvojen uskotaankin pienentävän merkittävästi nykyisiä päästöjä.

Tämä tutkimus käsittelee uusia ja nykyisiä akkuteknologioita. Siinä keskitytään tutkimaan akuista aiheutuvien jätteiden hävittämistä, akkujen elinikää, hintaa ja niiden tärkeimpiä ominaisuuksia, kuten kapasiteettia sekä energia- ja tehotiheyttä. Työ toteutettiin simulaatioiden ja kirjallisuuskatsauksen avulla. Tulokset ja aikaisemmat tutkimukset osoittavat nykyisten Li-ioni akkuteknologioiden olevan kilpailukyvyttömiä polttomoottoriteknologioiden suhteen, etenkin energiatiheyden osalta. Li-ioni akkutyypeistä saatujen tietojen perusteella kehiteltiin uusi mahdollinen akkuteknologia, jossa tehonlähdettä vaihdeltaisiin kulutuksen mukaan. Simulaatiot osoittautuivat toimiviksi, mutta asiaa pitää vielä tutkia tarkemmin. Uuden kehitetyn teknologian ohella Li-akut tarjoavat myös kilpailukykyä verrattuna polttomoottoriajoneuvoihin, etenkin energiatiheyden osalta. Nämä omaavat kuitenkin omat ongelmansa, mistä syystä niitä ei voida implementoida vielä ajoneuvoihin. Kehitetyn uuden akkuteknologian ohella, Li-akut tarvitsevat myös lisää tutkimusta koskien puutteita esimerkiksi eliniässä ja turvallisuudessa.

ABSTRACT

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The objective to reduce emissions in vehicles has got a lot of attention, as the amount of transport emissions have increased in the last few years. This bachelor thesis focuses on the analysis of the today's reality and the future trends related to the battery technology for the electrical vehicles. As the key factors, the study investigates the development of new materials and current ones, disposal of the elements of the battery technology, battery's lifetime and charge-cycles, expenses and parameters concerning capacity, energy density, and power density.

Study was done by using simulations and literature review. The results of the study show that the capacity of the conventional lithium-ion batteries has been developed almost as far as it can go, and it is clear new technologies and processes are needed to compete with internal combustion engines. However, simulations presented in this thesis show promise in combining two separate types of Li-ion batteries in order to counter out each of their deficiencies. The theoretical high energy density potential makes Li-batteries a promising solution, but they are in need of a significant further development to be utilized in electric vehicles.

CONTENTS

SYMBOLS AND ABBREVIATIONS

EU	European Union
EEA	European Economic Area
EV	Electric Vehicle
VOC	Open circuit voltage
DoD	Depth of Discharge
ISC	Internal Short Circuit
PCM	Parallel Cell Module
SCM	Series Cell Module
LCO	Lithium Cobalt Oxide
LMO	Lithium Manganese Oxide
NMC	Lithium Nickel Manganese Cobalt Oxide
LFP	Lithium Iron Phosphate
NCA	Lithium Nickel Cobalt Aluminum Oxide
LT	Lithium Titanate
Li-Air	Lithium-Air
Li_2O_2	Lithium Peroxide
Li-S	Lithium-Sulfur

Subscripts

C_A	Capacity	Ah
C_W	Capacity	Wh
C_n	Rated capacity of the battery	Ah
U_{nom}	Nominal Voltage	V

1. INTRODUCTION

Nearly 30 % of EU's emissions come from transport, and 72 % of these are from the road transportation [1]. In accordance with Paris Agreement, EU set the target to reduce its generated greenhouse gas emissions by at least 40 % below 1990 level by 2030, and carbon neutrality is a goal by 2050 [2]. The objective to reduce emissions has gotten a lot of attention, as the amount of transport emissions have increased in the last few years. European Economic Area (EEA) states in their 2018 report that Electric Vehicles (EVs) are the main component in the reducing of the pollutions and the improving of the air quality in the future [3]. The research results depict that EVs generate 17–30% lower emissions during their life cycle in comparison to petrol or diesel vehicles. EVs can also improve the local quality of the air, since all emissions are being generated during battery production stage and electricity generation at the power plant. The environmental stress related to the electrical vehicles comes from the battery charging, production stage of battery's components, and extraction of materials such as copper and cobalt. Further research is required to reduce negative effect related to electrical vehicles and their batteries.

This bachelor thesis focuses on the analysis of the today's reality and the future trends related to the battery technology for the electrical vehicles. As the key factors, the study investigates the development of the new materials and current ones, disposal of the elements of the battery technology, battery's lifetime and charge-cycles, expenses and parameters concerning capacity, energy density, and power density.

1.1 Study methods

Comprehensive literature review is used to investigate the nowadays development trends in the battery technology. The first chapter focuses on the basics of the battery technology and the nominal characteristics of a battery. This gives a better understanding for the next chapters where different battery types are being compared to each other. When comparing the different types, we are able to point out the pros and cons of each type, what is needed for future purposes in electrical vehicles (EV) and review new possible battery technologies. At the end of the thesis, several battery types are being reviewed in EVs. The battery statistics and information are based on the previous studies and the measurements.

The thesis focuses on the features and statistics of the batteries rather than chemical aspects and reactions inside the battery. More information about the chemical aspects of the batteries may be found elsewhere [4], [5].

2. BASICS OF THE BATTERY TECHNOLOGY

Battery is a storage unit that stores the electrical energy in electrochemical form. It comprises three main components: anode, cathode and electrolyte, which together are able to create electric potential difference in the battery. Working principle of rechargeable-battery is based on the oxidation-reduction reaction [6]. This reaction happens on cathodes and anodes in which one of the metals releases electrons (oxidation) and another one receives them (reduction). When applying external current to the battery, electrons flow through exterior routes to negative electrode. Simultaneously ion-compound called electrolyte carries the ions through to the same electrode. This creates potential difference between the electrodes, where another electrode has a greater number of electrons on the other side. During the discharge this operation is reversed. Electrolyte has an embedded separator, which inhibits the movement of the electrons through the substance. Thus, they flow through the external circuit and short circuit of the battery is prevented [7].

There are two types of batteries based on their ability to be recharged. Primary batteries are not rechargeable, thus having only one discharge cycle. Secondary batteries are rechargeable, i.e. chemical reactions are reversible with an external current.

2.1 Capacity

One of the most important parameters for batteries is the capacity, which is usually measured in ampere-hours (Ah). The capacity has a high effect to the driving range of the electric vehicle after the charging. Capacity determines the amount of charge the battery is able to deliver under the nominal voltage. Capacity can be calculated as follows:

$$C_{\mathrm{A}} = I \times t, \tag{1}$$

where C_{A} is the capacity (Ah), I is the charge or discharge current (A), and t is time (h). The capacity of a battery can be calculated when the charged battery is discharged with a constant load. As an example, the discharging with the current of 2 A for a 1-hour results in capacity of 2 Ah. The capacity can also be rewritten in Watt-hours, i.e. multiplying the Ampere-hour capacity with the nominal voltage U_{nom} of the battery:

$$C_W = C_A \times U_{nom}, \tag{2}$$

Capacity is affected by several factors, one of them being temperature at which it is being discharged [5]. Too high temperature causes decreasing of the capacity due to increase in internal resistance because of increase in chemical activity. Batteries are also subjected to self-discharge activity, which depend on the material used in batteries. Self-discharge is asymptotical meaning the loss of capacity is at highest rate right after charging [8]. The typical values of the self-discharge are around 5 to 10 %, 20 to 30%, and 15 to 20 % for Li-ion, Nickel Metal Hydride, and Nickel Cadmium battery, respectively [9]. The increase of the temperature facilitates the self-discharge activity [10]. On the contrary, the temperature decrease reduces ion mobility inside the battery. These factors affect the internal resistance.

Batteries are not an ideal voltage source. The chemical properties, aging, and operation temperature heavily affect the amount of the current battery can provide. The relatively reliable model of a battery is depicted in Fig. 1. The ideal voltage source is complemented with resistance in series to simulate the internal voltage drop inside the battery. The voltage at the battery terminals without the external load is called the open-circuit voltage (VOC). When added a load the voltage across it drops based on the internal resistance. This causes loss of electric power due to Joule loss on higher currents to heat and voltage drop across the circuit. Internal resistance varies across different batteries and it is affected by the discharge current. Higher current raises the value of internal resistance which lowers the voltage of the source.

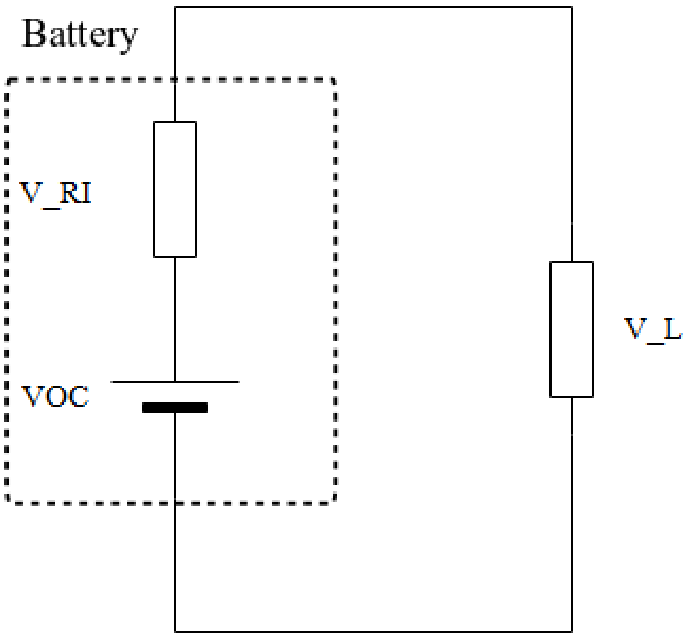

Fig. 1. Equivalent electric circuit of the battery with external load. Ideal voltage source VOC is complemented with resistance R_I to take into account the voltage drop inside the battery.

Another factor affecting batteries' capacity is their discharge rate, which is an important parameter to be considered when choosing battery for EV. The amount of current, which can be discharged from the battery in one hour while maintaining a nominal voltage range is measured with C-rating. It can be calculated as follows:

$$M = \frac{I}{C_n}, \tag{3}$$

where M is the C-rating, I is the discharge (A) and C_n is the rated capacity of the battery (Ah).

The nominal capacity will decrease when the battery is discharged at higher currents than the C-rating [5]. Internal losses transform some of the energy into heat, thus decreasing the capacity [11].

Nowadays, a standard electric car stores around 20 to 50 kWh in lithium-ion batteries [12] [13]. There are vehicles offering longer driving range, e.g. Tesla Model X 100 D and Tesla Model S 100 D with 100 kWh batteries [14].

2.2 Energy density

Energy density defines the battery's ability to storage energy per volume or mass unit [4]. Terms 'volumetric energy' and 'gravimetric energy' refer to the energy per volume and energy per mass, respectively. Gravimetric energy is measured in watt-hours per kilograms and can be calculated as following:

$$e = C_{\mathrm{A}} \times \frac{U_{\mathrm{nom}}}{m}, \tag{4}$$

where C_A is the capacity in (Ah), U_{nom} is the battery's nominal voltage and m (kg) is the mass of the battery.

The material of electrodes has the highest effect on the energy density. A high energy density is achieved with coupling high capacity and potential cathode with high capacity and low potential anode [15]. In electric vehicles energy density must be immense to establish long driving ranges. For reaching a certain speed, any excessive weight correlates to higher consumption. The low energy density means the higher mass for the desired capacity. This results in increased energy consumption for the desirable speed range. The energy density of Lithium-ion battery cell may be in the range 50–260 $\mathrm{Wh \cdot kg^{-1}}$ [16]. The battery pack has lower density in comparison to the single cell due to the cooling system and protective casing, which are used to satisfy the safety requirements.

2.3 Power density

Power density describes how quickly the battery is able to provide the energy. This relates to the C-rating and is measured with watts per kilogram. Batteries have internal resistance that turns into heat under the load. The resistive Joule loss can degrade the capacity of the battery. In lithium-ion batteries the increase in power density means lower specific energy and vice versa [15].

2.4 Charge cycles and lifetime

The charge cycle of battery is used to estimate the lifetime of battery by the amount of charges and discharges before the capacity drops under a certain value. This value is typically between 70 to 80 percent of the nominal capacity. Most batteries prefer small amount of discharge, low Depth-of-Discharge (DoD), rather than full discharge at once [17].

DoD affects the lifetime of the battery; smaller discharges increase the cycle life. Batteries have the suggested depth of discharge that inform the lowest capacity which it can be reduced to without harming the cell and affecting its cycle life. This is indicated in percentages. The battery stress may be reduced if battery’s full charging and discharging is avoided. For example, a battery may have 15 000 cycles at a DoD of 10 percent, but only 3 000 cycles at 80 percent DoD [18].

The voltage in which the battery is charged may affect the cycle life. Every reduction in peak charge voltage of 0.1 V/cell is said to double the cycle life. However, lowering the voltage causes loss in capacity, 70 mV reduction from peak voltage drops capacity by 10 percent [17].

2.5 Safety

Safety issues for batteries are mechanical deformation, Internal Short Circuit (ISC), thermal runaway and explosion/fire. Mechanical deformation of battery packs from the external damage may be prevented with protective casing. The casing protects the cooling system and electronics in the pack in addition the protection of the cells. In case of accident, e.g. collision, it is important to keep the battery pack protected to mitigate the risk of fire and the leakage of chemicals.

Internal Short Circuit is a serious safety concern in Li-ion batteries. In case of ISC electrons flow from one electrode to other because of latent flaw. In minor cases this can only lead to devices getting extremely hot. In worst case scenario it can lead to a thermal runaway.

Thermal runaway occurs when cell reaches the temperature at which the chemical reactions promote the further increase in temperature. The raise in chemical reactions further raises temperature and that again increases the chemical reactivity in the cell. If the temperature of the battery reaches a specific temperature the separator between the electrodes melt, creating ISC inside the battery. At these temperatures electrolyte starts to form gases inside the battery, which can lead to an explosion or a fire [19]. Thermal runaway for Lithium-ion batteries usually happens between 150–270 °C, depending on the battery type. The rise of temperature can be caused by charge or discharge current and external temperature of the battery. This is the reason all EVs need a cooling system. The conventional cooling techniques used in EVs are passive or forced convection, circulating water-based coolant through battery structure, and flooding the battery with a dielectric oil. Placing of the cooling system also has an impact on the characteristics of the battery. The tab cooling offers benefits in usable capacity when discharged at higher currents in comparison to the surface cooling technique. This is because of more uniform distribution of heat in the cell. Tesla Model S uses a surface cooling system, where water glycol coolant flows through next to battery cells [20].

Lithium-ion batteries require the overcharge protection to prevent thermal runaway and failure of the cell. At the overcharge state the average temperature rises immensely, and when overcharged over a critical degree, battery failure occurs [21].

2.6 Disposal

Lithium-ion batteries can be recycled, but the recycling procedure is energy intensive. Recycled batteries undergo a high-temperature melting-and-extraction process [22]. The plants are expensive to build, and they require sophisticated equipment to capture emissions generated during recycling process. Recycling reduces the amount of batteries that end up in a landfill. In landfills, the battery casing corrodes that may lead in releasing toxic chemicals into the soil and water [23]. Recycling can prevent this. Some of the recycled materials cannot be applied in the manufacturing of the batteries of the same quality. However, recycled materials might be used in less demanding battery applications [24]. The process starts with deactivation with full discharge to prevent undesired thermal events. The electrolyte may be frozen to prevent electrochemical reactions. Following steps include mechanical, pyrometallurgical and hydrometallurgical treatments. The mechanical treatment involves crushing of battery cells. The pyrometallurgical process extracts the metals by the thermal treatment. The hydrometallurgical treatment involves aqueous process. The hydrometallurgical process is necessary to recover lithium and pyrometallurgical process can recover nickel, cobalt and copper [25].

2.7 Cost

Among other characteristics the cost is a major element to be considered when selecting the battery of an EV. The battery cost comprises of the materials being used in a cell and the production process. Materials used in cathode, e.g. cobalt and nickel are expensive metals, which prices have fluctuated much in recent years. Tesla Model 3’s 90 kWh battery costs around $18,000 [26]. This limits their competitiveness at the automobile market. The cost of the battery pack should drop at least 25 % to compete with the internal combustion engine technology.

3. CURRENT STATE

Electric vehicle battery is divided into three sub-assemblies – cells, modules and packs. First one being the smallest component. It is used to create modules, which create the pack. The module is a combination of cells in series and parallel. The pack is formed by the arrangement of modules. There are two main design techniques in creating of packs called Parallel Cell Module (PCM) and Series Cell Module (SCM) [27]. In PCM, modules are created by placing cells in parallel. Modules are then wired in series to form a battery pack. The SCM approach is to put cells in series to form a module with specific voltage and wire the modules together in parallel to build the pack. This way the capacity of the pack can be later altered.

The most used battery technology in nowadays electric vehicles is lithium-ion [28]. Lithium is flammable and highly reactive alkali metal. The high reactiveness correlates to low electronegativity, meaning they readily form bonds with electronegative atoms [29]. Lithium is main element in the cathode, which plays a key role in the battery affecting its capacity and cost. Current Li-Ion energy density stands between 90–235 $Wh \cdot kg^{-1}$. Lithium has low electrochemical potential –3.04 V and specific capacity of 3.86 $Ah \cdot g^{-1}$ [4].

There are different types of materials besides lithium used to create cathodes. The most used types for the cathode are Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Iron Phosphate (LFP), Lithium Nickel Cobalt Aluminum Oxide (NCA) and Lithium Titanate (LT) [7]. Each of these have their own advantages and disadvantages, which are listed in the Table I.

Name	Energy Density Wh/kg	Power Density, W/Kg	Cycle Life	Cost of active materials, E/kg (**)	Nominal Voltage, V	C-Rate Discharge
LCO	150-200	Low	500-1000	NA	3.6 V	1
LMO	100-135	Medium	300-700	14	3.7 V	1, (10)*
NMC	150-220	Medium	1000-2000	27	3.6 V	1, (5)*
LFP	90-120	High	>2000	18.5	3.3 V	1, (25)*
NCA	200-260	Medium	500	33	3.6 V	1
LTO	50-80	Medium	3000-7000	NA	2.4 V	10

Table I Statistics of different Lithium batteries [30]. ** Data is adopted from [31]. * Possible on some cells

3.1 Lithium Cobalt Oxide

Lithium Cobalt Oxide cathodes are manufactured from lithium carbonate and cobalt. They have high energy density and decent cycle life, but suffer from poor thermal stability and, therefore, they need to be monitored for safe usage. Cobalt is also very expensive material, making utilizing them in electric vehicles unfavorable. This battery type is used in Tesla Roadster 1.5, which has a driving range of 372 kilometers with the battery pack size of 53 kWh [7], [32].

3.2 Lithium Manganese Oxide

Lithium Manganese Oxide has low internal resistance making it ideal for the fast charging and high current discharging. It also has a high thermal stability and an enhanced safety, although scarce cycle life. The capacity of Li-manganese is around 1/3 of LCOs. Design flexibility allows to optimize LMO to its suitable purpose for either optimal longevity (cycle life), maximum load current (specific power) or high capacity (energy density). For example, the long-life version of 18650 cell has the capacity of 1500 mAh and the regular has 1100 mAh [30].

3.3 Lithium Nickel Manganese Cobalt Oxide

According to data in Table I Lithium Nickel Manganese Cobalt Oxide (NMC) has approximately the same energy density as LCO and a higher power density. It can also be tailored to provide either higher capacity or discharge current. For example, NMC 18650 cell designed to act as a power cell can have continuous discharge current of 20 A and capacity of 2000 mAh. As energy cell it can deliver 4 to 5 Amperes with the capacity of 2800 mAh. Nickel has a high specific energy but poor stability, when manganese has the ability to lower the internal resistance but offers low energy density. Combining these two, enhances each other’s strengths making them suitable for EVs. NMC has been used in electric vehicles such as Nissan Leaf of which the 2018 model offers driving range of 243 kilometers with 40 kWh battery pack [33], [34].

3.4 Lithium Iron Phosphate

The key benefits of Lithium Iron Phosphate batteries are the high current rating and the long cycle life [30]. The phosphate in the cathode makes LFP withstand the high temperatures better than the other Li-ion batteries. These batteries have wide temperature range and are less likely to suffer from thermal runaway [7]. On the downside, the voltage of the cell is lower compared to others reducing its specific energy. LFP also has higher self-discharge than the other Li-ion batteries [30].

3.5 Lithium Nickel Cobalt Aluminum Oxide

Providing high energy density and decent power density Lithium Nickel Cobalt Aluminum Oxide (NCA) has potential being used in electric vehicles. On the downside, they have high manufacturing cost and are not as safe as the other battery types, requiring special monitoring measures to be employed for use in EVs [7], [34]. This battery technology is used in Tesla Model 3 Long Range RWD which has driving range of 523 kilometers and capacity of 79.5 kWh [35].

3.6 Lithium Titanate

In LTO the usual graphite as anode material is replaced with Li-titanate. Lithium manganese oxide or lithium nickel manganese cobalt oxide may be used as an option for cathode material. LTO has a highly lower specific energy compared to other five battery types and lowest nominal cell voltage of 2.4 V. It compensates the lack of characteristics with high discharge rate and fast recharge time. Other major qualities of the battery type are high safety, performance, and long cycle life. The estimated cost per kWh for LTO-based batteries is higher than carbon-based ones because LTO offers lower specific energy in comparison to graphite [36]. One reason why LTO lacks in specific energy is the low nominal voltage. Applying (2), even if the two cells capacity and mass would be the same the lack in voltage makes the specific energy smaller for the desired voltage in LTO. LTO battery type is used in i-MiEV cars by Mitsubishi. The nominal capacity of the battery unit is 16 kWh, which provides around 160 km driving range [37].

3.7 Comparisons and simulations

The comparison of basic properties of these Li-ion batteries is depicted in Fig. 2.

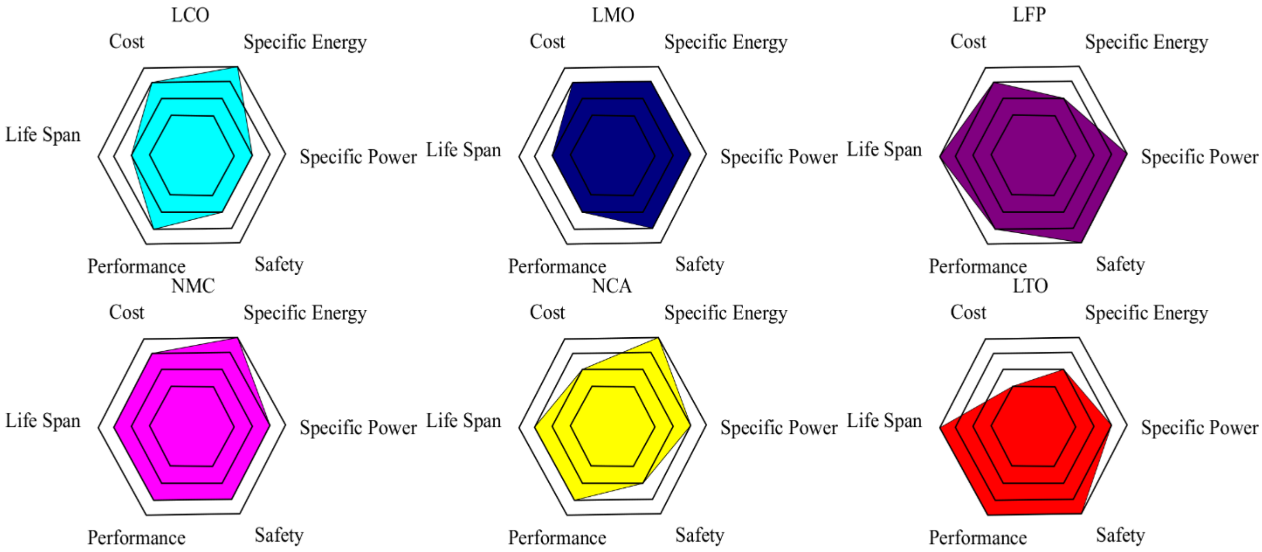

Fig. 2. Hexagons for each battery type showing characteristics under discussion *[7]*.

NMC battery type offers the reasonable balance in basic characteristics in comparison to the other battery types. Every other type is lacking on at least one of the characteristics majorly.

For example, LCO and NMC share approximately the same energy density (around 150–200 Wh·kg^{-1}), but LCO has lower cycle life. LFP has immensely larger cycle life but majorly lower energy density. Performance describes how well the specific battery type is able to perform under extreme temperature conditions [7].

Simulation was done using Matlab Simulink to study the importance of discharge current to state of charge. Battery types LCO and LFP were discharged with 5C current and state of charge was monitored in relation to time. Simulation was done according to the model in Fig. 3.

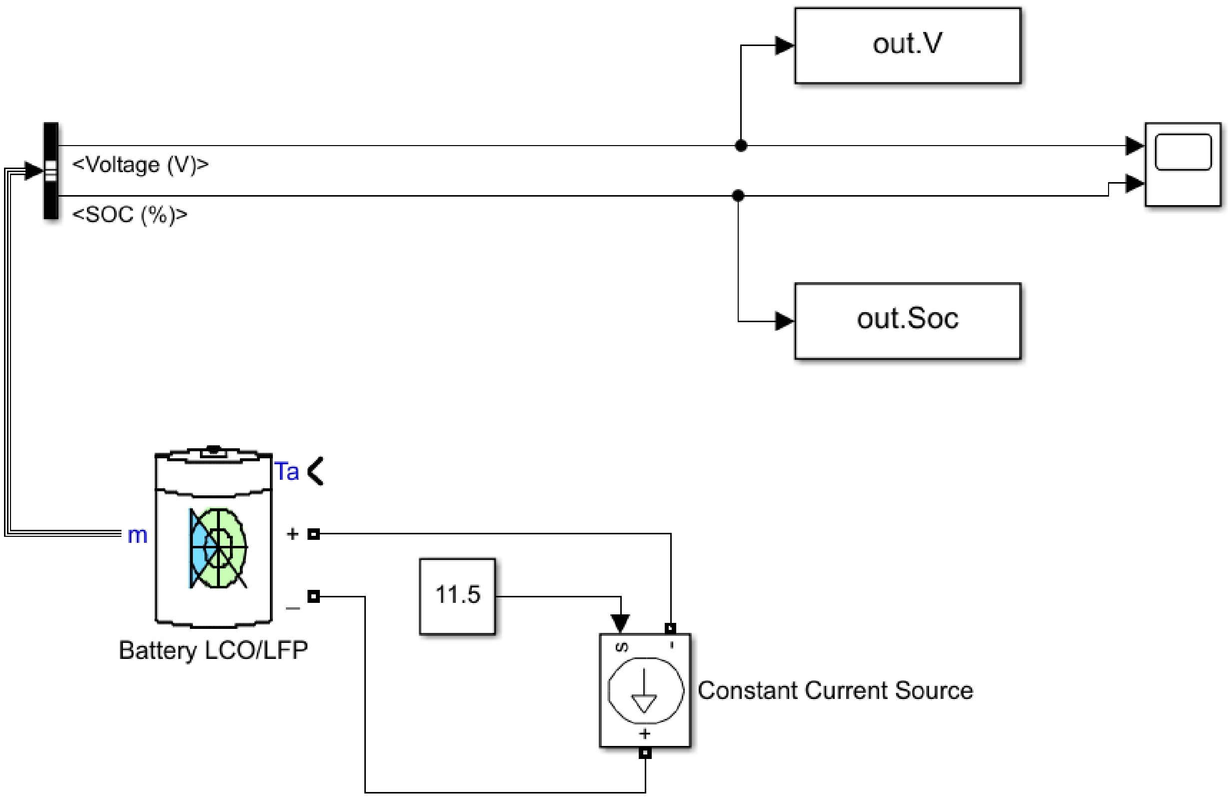

Fig. 3. Simulation of battery cell under constant discharge current.

LCO and LFP type of batteries were preset by the software used. LCO cell was rated at 2.05 Ah with nominal voltage of 3.35 V. LFP had nominal voltage of 3.3 V and a capacity of 2.3 Ah. Discharge currents were 10.25 A and 11.5, respectively. Results of the simulation are presented in Figs. (4)-(5).

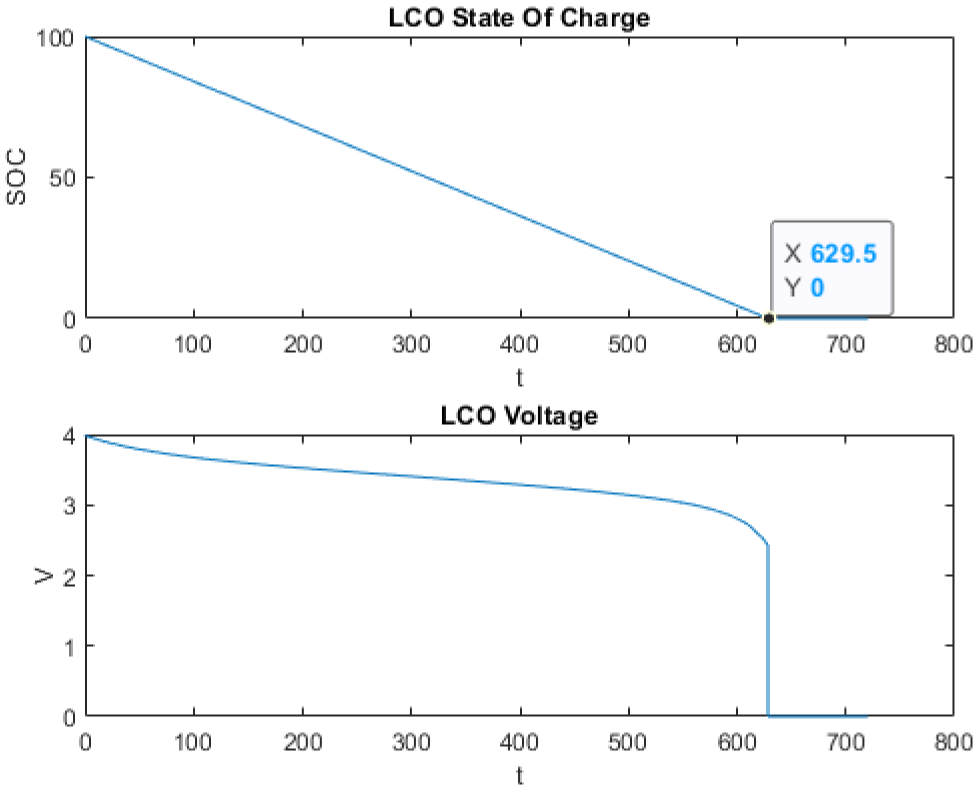

Fig. 4. LCO State of charge and voltage over time. The LCO cell is being discharged at 5C rating (10.25 A).

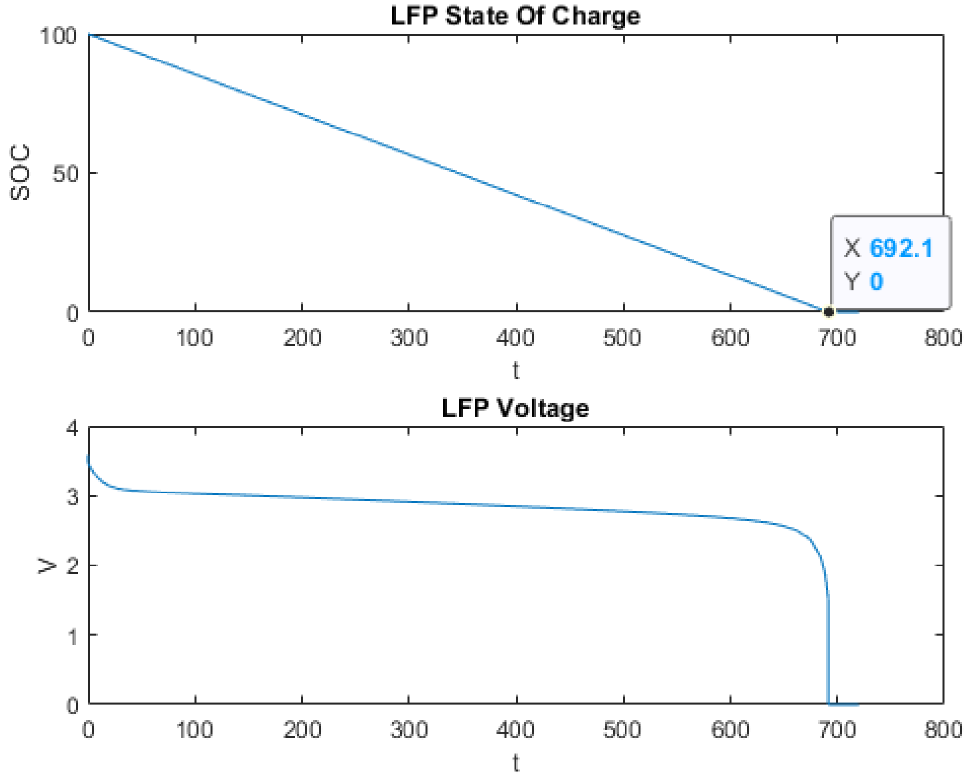

Fig. 5. LFP State of charge and voltage over time. The LCO cell is being discharged at 5C rating (11.5 A).

According to the simulation it takes 629.5 seconds for LCO and 692.1 seconds for LFP to reach zero capacity under the 5C discharge current. With 5C discharge current the battery ideally should reach zero state of charge at 720 seconds. In this simulation LCO reaches zero state of charge approximately one minute before LFP. Capacity is lost due to thermal reactions and energy is lost into heat. Different batteries are able to provide power longer than others at higher discharge currents, in this case LFP. With this information it is important to consider the choice of battery for the vehicles consumption to maximize usable capacity to provide longer driving ranges.

The Li-ion batteries have been used successfully in cars. Nevertheless, only around 2 % vehicles are electric in Europe [38]. The energy density of the batteries must increase at least up to 700 Wh·kg^{-1} to compete with internal combustion engine technology [15]. At the moment, one of the other main problems for commercializing EVs are the cost of vehicles and the charge time. Therefore, different types of battery technologies are being developed to create a solution for this problem.

4. FUTURE

Nowadays, a standard electrical car stores around 20 to 50 kWh in lithium-ion batteries. Larger vehicles are expected to have battery capacity around 200–1000 kWh [12]. The battery-powered train and mining truck require a battery capacity around 200 kWh and 500 kWh, respectively. This puts the weight of the energy storage at over 1000 kg according to Table I for the train and over 2000 kg for the mining truck.

Some studies report that the capacity of the conventional lithium-ion batteries has been developed almost as far as it can go. This is because the positive electrode (anode) in lithium metal batteries is made from lithium instead of graphite which weighs more, meaning higher specific energy [39]. Carbon-based anodes have a capacity of about 370 $Ah \cdot kg^{-1}$, which is about the tenth of Lithium Metals capacity of 3860 $Ah \cdot kg^{-1}$ [7]. At the moment, Lithium Metal unfortunately has safety hazards, one of them being generation of dendrite. Dendrite can cause short circuits between the two electrodes, therefore leading up to thermal runaway and possible fire or explosion. Silicon based anodes are also viable option for future EV purposes with the theoretical capacity of 4200 Ah kg^{-1}. Based on these electrode types most prominent future battery technologies for Electric Vehicles involve Lithium-Air, Lithium-Sulfur, and Solid-State Lithium.

4.1 Lithium-Air

Lithium-Air (Li-air) battery is a type of metal-air battery, in which during discharge lithium-ions flow from anode to cathode and react with oxygen molecules (O_2) to form lithium peroxide (Li_2O_2) in a non-aqueous electrolyte. If Li_2O_2 can no longer be generated in the cathode the battery is empty. Compared to Lithium-ion batteries Li-air batteries have much higher theoretical energy density at 11430 $Wh \cdot kg^{-1}$, excluding the oxygen. That is comparable to energy density of fossil fuels. However, this value lowers as the cell discharges and more oxygen enters the cathode, increasing its mass. [15, p. 1 and 4]. Li-air has some deficiencies which are yet to be solved caused by impure air leading up to the cathode and on to react with the lithium metal. Reactions with carbon dioxide, nitrogen and water at the electrolyte/lithium interface lead to unwanted results. These problems include lithium corrosion, decomposition of the electrolyte and decomposition of the air electrode carbon material during charging process. [4] These have an effect on short shelf lifetime and poor cycle performance.

4.2 Lithium-Sulfur

Lithium-Sulfur-based batteries have also much higher theoretical energy density compared to Li-ion batteries at 2566 $Wh \cdot kg^{-1}$ [15]. The anode consists of lithium metal and the cathode of sulfur-carbon composite. Sulfur is cheaper and lighter in comparison to Li-ion metal oxides and offers better safety. Sulfur is also more environmentally friendly element than lithium. Challenges related to Li-S battery technology include poor conductivity of sulfur polysulfide shuttle and large volume change of sulfur electrode [4].

4.3 Solid State Lithium

Solid State Lithium uses solid electrolytes instead of liquids which are found in Li-ion batteries. Reportedly using solid electrolytes instead of liquids could offer major advantages for safety and capacity [40]. Using solid electrolytes such as ceramics could prevent start of fire better than liquid electrolytes, which are usually flammable. Other types of electrolytes being tested are lithium phosphorus sulfur and metal oxides. These materials have shown to be inconsistent and unreliable. Providing pathways for the ions to flow between electrodes, solid state electrolyte also serves as a separator simplifying the cell architecture. At the moment, the manufactured cells suffer from dendrite forming inside the cell. This creates ISCs in battery which damages the cell performance [41].

4.4 Comparisons

Characteristics of the mentioned Li-batteries are presented in Table II.

Name	Energy density Wh/kg	Power density W/kg	Cycle life	Cost of active materials	Nominal voltage	C-rate
Li-Air	13 000 theoretical	Low	50	N/A	1.7–3.2	Unknown
Li-S	500	2500	50	N/A	2.1	0.2
Solid State Lithium	300	Low when cold	100	N/A	3.6	Rapid

Table II Li-metal battery statistics. Data is adopted from [16].

At the moment, all listed Li-batteries listed in Table II are not ready to be used in electric vehicles. Apart from issues facing each battery type they also share low cycle life, making them inappropriate for electric vehicles. Besides, the high energy density of Li-ion batteries is currently superior among all available Li-based battery alternatives. The theoretical high energy density potential makes them a promising solution, but they are in need of a significant further development.

5. RESULTS

As mentioned in this study there are different pros and cons considering different types of batteries. Usually at least one of the six main characteristics in Fig. 2 is insufficient (e.g. energy density, power density, safety, performance, cost or cycle life). Lithium-Sulfur has the highest specific energy, but too low of a charge cycle at this instant and has a lot of safety related issues. Lithium Iron Phosphate has high power density and cycle life, but its specific energy reduces the range of the electric vehicles. Motorhome Iridium E Mobil uses LFP as a power source but it only has a range of about 100 kilometers under optimum conditions [42]. Lithium Cobalt Oxide is an unlikely energy storage solution because of the limited availability of cobalt, which result in higher costs and the low power density restricts its use in heavier vehicles. Considering each of these battery types having their own disadvantages, but lots of potential usages for EVs, using two different power supplies could counter out these disadvantages.

Since LFP battery type has high power density and LCO batteries have high energy density it should be taken in consideration using these two, or any two battery types which support each other, in powering of electric vehicle. LFP would provide the power for heavy loads (e.g. acceleration) and LCO would be in charge of the driving range. In this arrangement LCO would not suffer from the high current causing losses which include decreasing capacity, as depicted in Fig. 3 simulation results. The switching between battery packs would change with a switch when a certain threshold such as high current occurs and vice versa. The system is depicted in the Fig. 6.

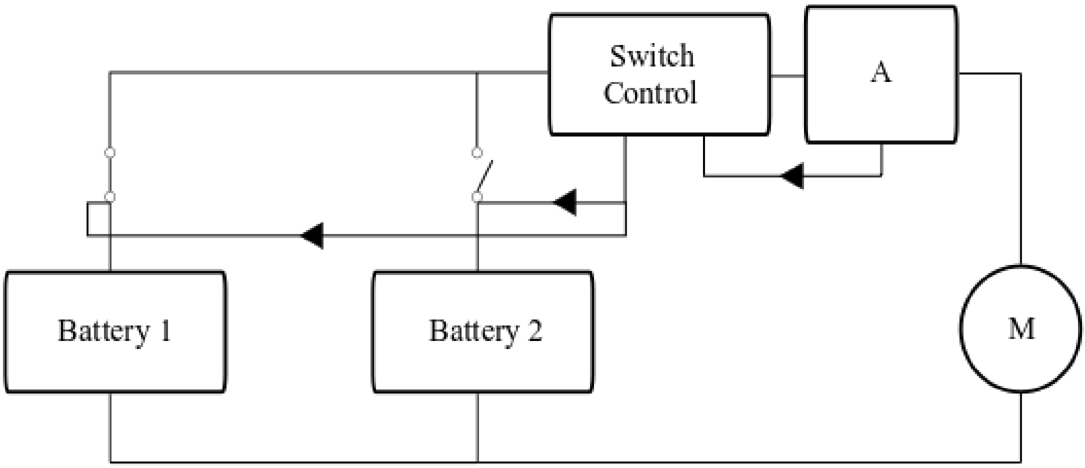

Fig. 6. Control circuit for batteries.

In the Fig. 6, A stands for ampere meter and M for the motor. The ampere meter could be replaced with temperature meter. As the current rises high enough, it sends a signal to the control unit which operates the switches linked to the batteries. This way only one of the batteries will be active as a power source. As presented in simulation with discharging of LFP and LCO with 5C current, this system could potentially increase the capacity and driving range of the electric vehicles.

As battery type, which is able to provide high discharge currents, would mainly be used for acceleration it would not need that much of capacity and would be smaller in comparison to the battery type with high specific energy. This could make the whole battery pack more affordable and prevent capacity loss caused by too high discharge current and possible temperature related problems.

6. CONCLUSION

Current and possible future battery types were listed and compared to show possibilities and inconsistencies in these. At the moment, Li-ion and Li-batteries are unable to compete with conventional internal combustion engine technology due to low specific energy and high cost. As some studies report that the capacity of the conventional lithium-ion batteries has been developed almost as far as it can go, and it is clear new technologies and processes are needed. With the higher energy density of Li-batteries in comparison to Li-ion batteries it is likely for those to replace current technology. It is unclear how long this breakthrough would take in time and for Li-batteries to be used in electric vehicles.

Another possible solution for EVs to better compete with internal combustion engines and become more commercialized it should be taken into consideration to use two different battery types which support each other as shown in Fig. 6. This requires more investigation and testing as it was only briefly tested with simple simulation (Fig. 3.). This solution would possibly reduce the cost of the battery pack with being able to use more affordable materials and avoid thermal stress from high discharge currents. These characteristics would make them more desirable for customer purposes.

7. REFERENCES

[1] E. Parliament, "CO2 emissions from cars: facts and figures (infographics)," 18 April 2019. [Online]. Available: https://www.europarl.europa.eu/news/en/headlines/priorities/climate-change/20190313STO31218/co2-emissions-from-cars-facts-and-figures-infographics. [Accessed 06 January 2020].

[2] "European Parliament," 18 April 2019. [Online]. Available: https://www.europarl.europa.eu/news/en/headlines/priorities/climate-change/20180305STO99003/reducing-carbon-emissions-eu-targets-and-measures. [Accessed 20 January 2020].

[3] EEA, "Electric vehicles from life cycle and circular economy perspectives," EEA, 2018.

[4] Z. Zhengcheng, Rechargable batteries, Springer, 2015.

[5] L. David, Handbook of Batteries, McGraw-Hill, 2001.

[6] PVEducation, "Basic Battery Operation," [Online]. Available: https://www.pveducation.org/pvcdrom/battery-basics/basic-battery-operation. [Accessed 26 March 2020].

[7] Y. Miao, P. Hynan, A. von Jouanne and A. Yokochi, "Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements," MDPI, 2019.

[8] "Battery University," 16 November 2018. [Online]. Available: https://batteryuniversity.com/learn/article/elevating_self_discharge. [Accessed 3 February 2020].

[9] C. Simpson, "Characteristics of rechargeable batteries," Texas Instuments, 2011.

[10] V. Muenzel, M. Brazil and I. Mareels, "Modeling Reversible Self-Discharge in Series-Connected Li-ion Batteries," IEEE, 2013.

[11] BatteryUniversity, "BU-402: What is C-rate?," 09 March 2017. [Online]. Available: https://batteryuniversity.com/learn/article/what_is_the_c_rate. [Accessed 08 January 2020].

[12] H. Weiss, "Large Lithium-Ion Battery-Powered Electric Vehicles - From Ideoa To Reality," IEEE, 2018.

[13] B. University, "BU-1003: Electric Vehicle (EV)," 27 November 2019. [Online]. Available: https://batteryuniversity.com/learn/article/electric_vehicle_ev. [Accessed 26 March 2020].

[14] D. Yoney, "Inside EVs," 18 June 2018. [Online]. Available: https://insideevs.com/features/336680/7-electric-cars-with-the-biggest-batteries/. [Accessed 5 February 2020].

[15] N. Imanishi and A. C. Lutz, "The Lithium Air Battery: Fundamentals," Springer, 2014.

[16] "BU-218: Summary Table of Future Batteries," Battery University, 2016.

[17] "Battery University," 10 July 2019. [Online]. Available: https://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries. [Accessed 21 January 2020].

[18] K. Thaubborn, "Energy Sage," 3 June 2019. [Online]. Available: https://news.energysage.com/depth-discharge-dod-mean-battery-important/. [Accessed 20 January 2020].

[19] C. Zhao, J. Sun and Q. Wang, "Thermal runaway hazards investigation on 18650 lithium-ion battery using extended volume accelerating rate calorimeter," Elsevier, 2019.

[20] R. Maughan, "AVID Technology," 26 July 2017. [Online]. Available: https://avidtp.com/what-is-the-best-cooling-system-for-electric-vehicle-battery-packs/. [Accessed 3 February 2020].

[21] D. Ouyang, M. Chen, J. Liu, R. W. Wei, J. Weng and J. Wang, "Investigation of a commercial lithium-ion battery under overcharge/over-discharge failure conditions," RSC Advances, 2018.

[22] M. Jacoby, "It's time to get serious about recycling lithium-ion batteries," *Chemical And Engineering News*, 14 July 2019.

[23] K. Kattenburg, "What Do Batteries Do to the Environment If Not Properly Recycled?," Sciencing.

[24] "BatteryUniversity," 13 September 2019. [Online]. Available: https://batteryuniversity.com/learn/article/recycling_batteries. [Accessed 2020 January 24].

[25] Z. Xiaohong, Z. Zewen, L. Xiao, Z. Yi, H. Yi, C. Hongbin and S. Zhi, "A Mini-Revie on Metal Recycling from Spent Lithium Ion Batteries," Elsevier, 2018.

[26] C. Campbell, "Lithium-ion Battery Cells: Cathodes and Costs," the deep dive, 2019.

[27] L. Gregory, M. Plett and K. J., "Simulating Battery Packs Comprising Parallel Cell Modules and Series Cell Modules," University of Colorado at Colorado Springs, 2009.

[28] B. Kennedy, D. Patterson and S. Camilleri, "Use of lithium-ion batteries in electric vehicles," Elsevier, 2000.

[29] A. M. Helmenstine, "Most reactive metal on the periodic table," ThoughtCo, 2019.

[30] B. University, "BU-205: Types of Lithium Ion," 10 July 2019. [Online]. Available: https://batteryuniversity.com/index.php/learn/article/types_of_lithium_ion. [Accessed 17 January 2020].

[31] G. Patry, A. Romagny, S. Martinet and D. Froelich, "Cost modeling of lithium-ion battery cells for automotive applications," Energy Science and Engineering, 2015.

[32] E. Specifications, "2008 Tesla Roadster 1.5 - Driving Range," 2020. [Online]. Available: https://www.evspecifications.com/en/model-driving-range/0f3a60.

[33] "2018 Nissan Leaf SL - Driving Range," EV Specifications, 2020.

[34] C. Atwell, "Power Elelctronics," 24 April 2018. [Online]. Available: https://www.powerelectronics.com/technologies/alternative-energy/article/21864146/six-lithiumion-battery-chemistries-not-all-batteries-are-created-equal. [Accessed 17 January 2020].

[35] E. Specifications, "Tesla Model 3 Long Range RWD - Driving range," 2020. [Online]. Available: https://www.evspecifications.com/en/model-driving-range/3c3b98.

[36] X. Gaojie, H. Penxian, D. Shanmu, L. Haisheng, C. Guanglei and C. Liquan, "Li4Ti5O12-based energy conversion and storage systems: Status and Prospects," Elsevier, 2017.

[37] "Green Car Congress," 14 May 2008. [Online]. Available: https://www.greencarcongress.com/2008/05/the-battery-pac.html. [Accessed 3 February 2020].

[38] "Electric vehicles as a proportion of the total fleet," European Environment Agency.

[39] M. Golden, "New coating developed by Stanford researches brings lithium metal battery closer to reality," *Stanford News,* 2019 August 2019.

[40] D. L. Chandler, "MIT News," 12 July 2017. [Online]. Available: https://news.mit.edu/2017/solid-electrolyte-improving-rechargeable-lithium-batteries-0713. [Accessed 03 26 2020].

[41] C. Stoldt and S.-H. Lee, "All-solid-state lithium metal batteries for next generation energy storage," IEEE, 2013.

[42] "BatteryUniversity," 23 January 2020. [Online]. Available: https://batteryuniversity.com/learn/article/experimental_rechargeable_batteries. [Accessed 24 January 2020].