Materials on Wheels: Batteries for Electric Vehicles

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Received: August 26, 2021 / Revised: September 24, 2021 / Accepted: September 28, 2021

***Abstract*—The Thai government is placing the advanced automotive industry sector among the 12-targeted industries as the key drivers for economic and social development. So, all kinds of Electric Vehicles (EV), namely, Battery Electric Vehicles (BEV), Hybrid Electric Vehicles (HEV), Plug-in Hybrid Electric Vehicles (PHEV), and Fuel Cell Electric Vehicles (FCEV) will be the focus for Thai automotive sector promotion by the government. Two key components of EVs are the motor and battery pack. Present battery types and major characteristics are elaborated and discussed with emphasis on materials development, obstacles, and appropriate solutions for the future sustainability of EV manufacturing and application.**

***Index Terms*—Materials on Wheels, Batteries for Electric Vehicles, Future Aspect of Batteries**

I. INTRODUCTION

Electric vehicles are typically classified into four general types [1], [2]:

- All-electric vehicles where the battery pack is the sole power source, hence these are termed Battery Electric Vehicles (BEVs). The battery is charged by the plug-in to an external source of electrical power. These vehicles reduce the consumption of oil and gas-based fuels and during driving they do not produce exhaust emissions.
- Hybrid Electric Vehicles (HEVs) are powered by a conventional Internal Combustion Engine (ICE) but are also fitted with an electric motor supplied via a relatively small battery pack. This battery is recharged while driving under ICE power and by regenerative braking during which the motor can act as a generator. The electric motor power enables the use of a smaller capacity ICE giving improved fuel consumption and reduced emissions without loss in performance.
- Plug-in Hybrid Electric Vehicles (PHEVs) are also powered by a conventional ICE and by an electric motor. The battery pack fitted is larger than in HEVs and is charged by plugging into an outside electrical power source, and as in HEVs via the ICE and during regenerative braking. When fully charged it is possible to drive under electric power only for up to about 50 km.
- Fuel Cell Electric Vehicles (FCEVs) are driven by an electric motor powered by electricity generated onboard from hydrogen-based fuel cells. A FCEV does not need a heavy energy storage battery but is normally equipped with a smaller battery to provide extra power for acceleration and to increase efficiency by regaining of energy via regenerative braking.

The need for and the increasing awareness of reducing carbon emissions combined with government incentives in many countries have resulted in greater public interest in and ever-increasing worldwide use of EVs [3]. As well as being free from exhaust emissions BEVs offer lower running and maintenance costs compared to ICE and hybrid vehicles. Forecasts estimate that, by the year 2040, EVs will account for around 55% of all new passenger cars [3], [4] and this figure may be as high as 66% if major car groups cease production of ICEVs by 2035. Projections for conservative and accelerated growth in zero and low emission vehicle (ZLEV) sales in the European market are illustrated in Fig. 1 [5]. The accelerated uptake prediction assumed that major car producers will cease ICEV manufacture from 2035 onwards.

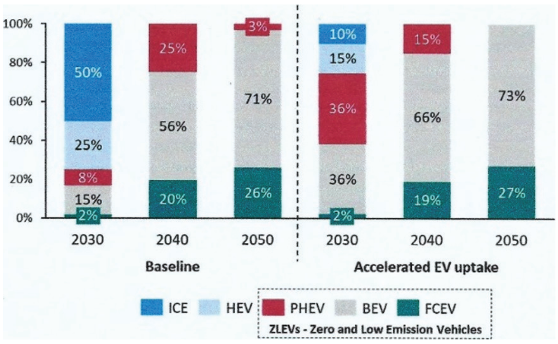

Fig. 1. Forecasts for vehicle sales in Europe under conservative baseline and accelerated EV uptake conditions [5].

One definite target is that of the EV30@30 Initiative which was launched in 2017 with current participation by Canada, China, Finland, France, India, Japan, Mexico, Netherlands, Norway, Sweden, and the United Kingdom [6]. The aim of this initiative is for all types of electric vehicles, apart from 2-wheeled, to collectively achieve a market share of 30% by 2030. A recent survey [7] suggests that continuing reductions in the price of battery packs will soon make EVs as affordable as comparable ICE models. In 2020 the average cost of a Lithium-ion battery pack was $137 per kWh approaching the $100 per kWh at which EVs cost roughly the same to manufacture as ICEVs.

In general, the continued developments in EV batteries and the materials used for their construction are aimed at:

- Increasing the driving range
- Reducing the time needed for recharge
- Improving safety by prevention of overheating
- Reducing cost of battery packs
- Solving environmental and ethical problems in the supply of raw materials
- Improving the working life and the potential for reuse and recycling.

Focusing on BEVs, this overview of materials for EVs considers the property requirements and availability of materials for the manufacture of anodes and cathodes for battery packs and comments briefly on the extra importance for light-weighting of body sections and other parts in order to compensate for the additional weight of the batteries. Material aspects of fuel cells are not included in this review and are covered elsewhere [8]-[10].

II. BATTERY TYPES AND CHARACTERISTICS

Electric vehicles need batteries that can supply high energy storage and high power. The energy storage capacity of a battery controls the potential charge-to-charge driving range and can be characterized by the specific energy in Wh./kg or by the energy density as Wh./l. Acceleration depends on battery power which can be described as specific power in W/kg or as power density in W/l. Hence, the relative performance of EV batteries is often compared on a Ragone type diagram [11] in which the specific energy or energy density is plotted versus the specific power or power density. An example of such representation (Fig. 2) from 2007 [12] illustrates the then required trade-off ranges between energy and power for HEV, PHEV, and BEV and indicates why more recent EV battery developments and usage have been focused on Li-Ion technology.

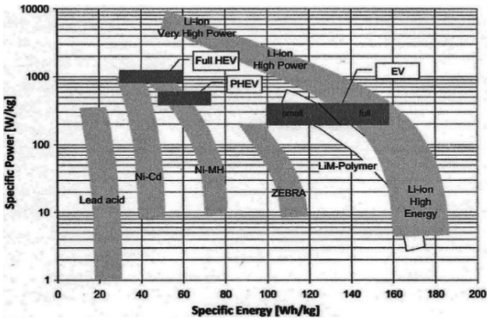

Fig. 2. Specific Power-Specific Energy relationships for various battery types in 2007 [12].

The characteristics of established and developing battery technologies are compared in Fig. 3, which plots energy density as Wh./l against specific energy [13]. The higher the value of power density, for a given acceleration, the smaller is the volume requirement for the battery while higher values for energy density reduce the mass of the battery enabling weight-saving and/or possible increased range.

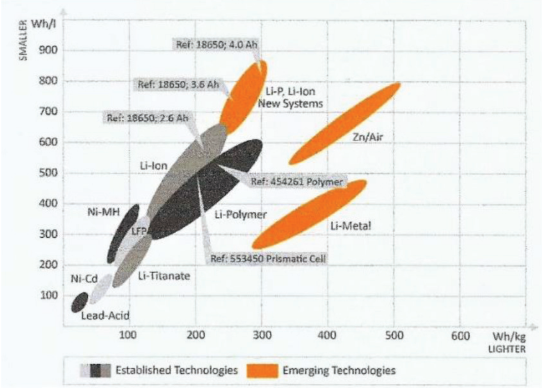

Fig. 3. Plot of energy density as (Wh./l) against specific energy (Wh./kg) for established and some emerging battery technologies [13].

The reference number indicated relate to battery cell size: 18650 is a cylindrical cell 18 mm in diameter with height of 65 mm; 454261 is rectangular with dimensions 45x42x61mm and 553450 is also rectangular 55x34x50 mm.

In addition to batteries, capacitors and fuel cells also have potential to provide power for EVs. Like batteries, capacitors store energy. They can supply this energy rapidly but unfortunately only in small amounts since they have lower specific energy than batteries [14].

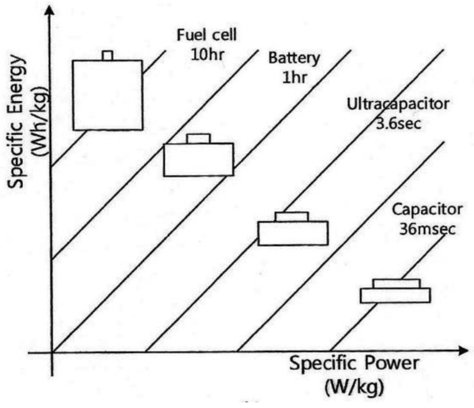

Fig. 4. The barrel model of Lee & Jung used to compare energy sources [15]. A capacitor has a small volume but a large opening area whereas a fuel cell has a large volume but only a small opening area.

Capacitors can be used in hybrid battery-capacitor systems where the capacitor can boost acceleration and store energy from regenerative braking. Fuel cells, like ICEs, generate energy and they offer high specific energy but this is offset by low specific power. Comparison between batteries, capacitors, and fuel cells can be conveniently made by reference to the barrel model proposed to supplement Rag one plots [15] as shown in Fig. 4.

III. LEAD – ACID BATTERIES

The history, present status and future of EV batteries can be considered with reference to Fig. 2 and 3. In the early days of the “horseless carriage” some 120-150 years ago, BEVs fitted with the first rechargeable lead-acid batteries provided strong competition for steam powered and ICE vehicles [16]. However, lead-acid batteries (LABs) have very limited levels of 20-35 Wh./kg for specific energy and hence are not suitable for use in traction applications, other than for golf and indoor carts and forklift trucks. To meet noise regulations and prevent exhaust fumes, electric forklifts and other off-road vehicles are increasingly replacing those powered by diesel or LPG, and as such are essential for indoor applications [17]. The weight of LABs is not a problem since the weight of the forklift must be sufficient to provide counterbalance during lifting operations. This is a complete contrast to automotive applications, where the weight of the battery is required to be as light as possible. However, even in forklifts, LABs can be replaced by hybrid Li-Ion/supercapacitor systems which offer improved power performance, energy efficiency, and cycle life plus reduced charging time and less maintenance [18]. It is recognized that, in addition to the larger traction battery, all electrified powertrains, HEVs and BEVs, retain a 12V start-up, board-net, and electronic component supply which continues to be provided by an auxiliary 12V LAB. This auxiliary is also used to maintain the safety management of the larger traction battery and, in start-stop systems store energy recovered via regenerative braking [19].

Ongoing LABs research is aimed at improving their capability in regenerative brake charging and motor assistance in hybrid vehicles [20], [22], applications in which they must be able to perform at high discharge and recharge rates. Unfortunately, at high rates of discharge, LABs suffer from irreversible growth of large, insulating lead sulfate crystals on the negative electrode, which subsequently reduces fast recharge ability. This problem can be reduced by adding carbon to the electrode to improve conductivity, to reduce sulfate crystal growth, and to provide capacitive behavior to buffer high charge and discharge rates [20], [21]. Although the negative electrode is improved in this lead-carbon battery, the positive electrode still suffers from softening and shedding. Further work is needed to provide additives to the positive electrode material to reduce this deterioration to further improve cycle life [22].

IV. NICKEL – METAL HYDRIDE (NI-MH) BATTERIES

A number of Ni-based alkaline battery systems have been developed including Ni-Cd, Ni-Fe, Ni-Zn, and Ni- metal hydride (Ni-MH). Of these, only the Ni-MH type became suitable for use in EVs. Ni-Cd batteries were originally considered as an alternative to lead-acid but their use in on the road automotive application is restricted due to toxicity issues. However, Ni-Cd batteries continue to be used in off the road industrial vehicles due to their insensitivity to external factors such as low temperatures, their wide operational temperature range of -40°C to +60°C, plus their lack of requirement for complex management systems [17]. Collection and recycling of used industrial alkaline batteries is close to 100% in Europe where the battery industry has set up a well-controlled closed-loop recycling system in which the battery manufacturer takes back used batteries which are then recycled at certificated companies [17]. Ni-Fe battery cells suffer from high self-discharge rate and hydrogen gassing, while Ni-Zn batteries are limited by the instability of the Zn electrodes under cycling conditions and dendritic growth causing short circuits [2], [23], [24].

Nickel-Metal Hydroxide (Ni-MH) battery cells consist of a metal hydroxide anode (negative electrode) plus a Ni hydroxide cathode (positive electrode) with a microporous polymer film separator and a potassium hydroxide-based electrolyte to provide ionic conductivity between the anode and cathode in the cell. The separator, which must be permeable to ions and be inert in the battery environment, acts as a physical barrier between the positive and negative electrodes to prevent electrical shorting. MH alloys are inter-metallics used for H storage, such as AB_5,

A_2B_7, and AB_2, where A is a combination of rare and alkaline earth elements, and B is mainly Ni with other transition metals. They are used as the active component in the anode since they are able to reversibly store hydrogen in an electrochemical environment [25]. The electrochemical reactions in Ni-MH, LAB, Li-Ion and other battery cells are compared in a number of reviews [25]-[28].

Reactions during the charging and discharging stages of a Ni-MH battery [28] are summarized as equations (1)-(3). In each case, the forward reaction occurs during charging and the reverse on discharge. On charging bivalent Ni is oxidized to become trivalent and M is reduced on absorbing H.

At the cathode: $Ni(OH)_2 + OH^- NiOOH + H_2O + e^-$ (1)

At the anode: $M + H_2O + e^- MH + OH$ (2)

Overall cell: $Ni(OH)_2 + M NiOOH + MH$ (3)

Ni-MH batteries have twice the specific energy combined with much higher energy density than lead-acid types, and have been used in EVs since the late 1990's [29], [30]. For example, the original Ford Ranger Electric pick-ups, made available in California to meet local environmental requirements, were fitted with a lead-acid battery pack which had mass of 870 kg. This was soon replaced by a Ni-MH pack weighing much less at 485 kg to give increases in payload and range [29]. Also, to be sold in California, the first electric version of the Toyota RAV4 SUV was powered by Ni-MH battery packs. Problems with patents and limitations to supply caused the brakes to be applied to the further development of Ni-MH large format battery packs for BEVs [30]. However, Ni-MH batteries continued to be fitted to hybrid vehicles having become the preferred power source in the hybrid Toyota Prius introduced in 1997 as the first mass-produced hybrid vehicle. Over the last 20 years, Ni-MH batteries have been used in many hybrid vehicles but in most current models they have been replaced by Li-Ion batteries which provide higher specific energy and energy density (Fig. 3).

Ni-MH batteries have proven durability and can be safely and profitably recycled to reclaim their high Ni content. Consequently, they continue to be subject to further development in China [31], Japan [32], Europe [33], and the US [27]. Continued developments [28], [34]-[39] are aimed at increasing energy density, improving charging efficiency, increasing cycle life and reducing self-discharge rates with materials research focused on the composition and structure of the anode and cathode materials. The most commonly used anodes have the general formula of AB_5 where B represent Ni and other elements such as Co, Al, Mn, and Cr while A represents Ce, Nd, La, Pr, Y, Hf, Zr, Ti, Nb, and Pd, etc. For example, one variant of AB_5 is $MmNi_{3.55}Co_{0.75}Mn_{0.4}Al_{0.3}$ where Mm refers to mischmetal containing a suitable combination of rare earth elements [25]. AB_2 Laves phase anodes have also been used in EV batteries, notably for the General Motors EV1 model, while A_2B_7 type are used in stationary applications [36]. Development to increase energy density is mainly focused on optimizing composition for the C14 hexagonal crystal structure of the AB_2 type. As for Li-ion packs, other work has examined ways of improving high-rate capability [38] and battery thermal management/cooling systems [39]. Although R&D on Ni-MH batteries continues, a survey by automotive battery manufacturers [19] has suggested that the potential for further market penetration by Ni-MH batteries has been reduced due to the increased performance and reduced cost of Li-Ion batteries coupled with concerns over Ni prices. Because Ni-MH batteries have already reached a relatively high degree of technological maturity, this survey expects that there will be only limited improvements in their performance by 2025.

V. Lithium – Ion (Li-ion) Batteries

Li-ion batteries have become preferred for EV applications since they have 2 times the energy density of the Ni-NH type, have a low self-discharge rate, can operate over a range of temperatures and have long cycle life [40]-[45]. Li-ion batteries are also the least affected by the memory effect by which some types of batteries gradually offer reduced maximum energy capacity with repeated charging. Li is the third lightest element, has a very small ionic radius and has the lowest reduction potential of all the elements enabling the highest possible cell potential, hence Li-based batteries have been developed for traction applications. A schematic view [40] of the electrochemical processes that take place in a basic Li-ion cell is given in Fig. 5 in which the cathode is represented as a layered lattice structure and the anode as a 2D graphite structure. Examples of basic cell arrangements in batteries are given as pouch, cylindrical and prismatic in Fig. 6. The main differences between these arrangements center on the dissipation of heat during charging and the relationship between packing arrangement of the cells in a battery module and cooling efficiency via thermal management, the pouch type cell enabling better heat dissipation [46]. Conventional cylindrical cells have a so called "swiss roll" construction and are encased in Al or steel, prismatic cells are encased in Al or polymer, and pouch cells in Al-polymer composite material which needs to be supported within a frame.

In a basic cell the anode consists of Li retained in graphite while the cathode has a layered structure of $LiMO_2$ where M is Co, Ni or Mn. The standard electrolyte is made up of Li salts such as $LiPF_6$ in a mixture of organic carbonate solvents such as ethylene carbonate and dimethyl carbonate. Because Li reacts with water, an aqueous electrolyte cannot be used. Both the anode and the cathode materials permit Li^+ ions to become intercalated or extracted from within their lattice structures during charging or discharge. During charging, the cathode provides Li^+ ions which move to the anode and are stored therein. As indicated in Fig. 5, during discharge electrons move from the anode to the cathode while Li^+ ions exit the anode to move simultaneously in the same direction through the electrolyte and back into the cathode lattice.

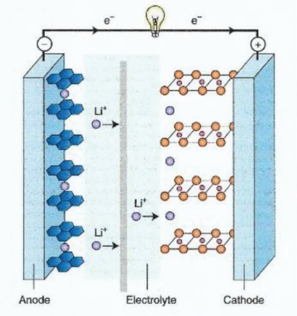

Fig. 5. Electrochemical processes in a Li-ion cell. After Goodenough [40].

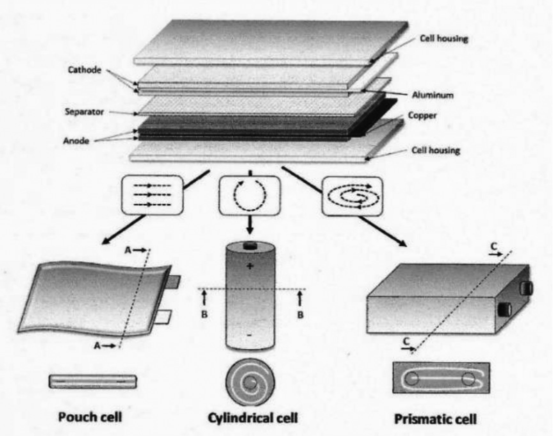

Fig. 6. Examples of lithium-ion cell arrangements: pouch, cylindrical and prismatic [46].

Reactions during the charging and discharging stages of the cell shown in Fig. 5 are summarized in equations (4)-(6). In each case, the forward reaction occurs during charging and the reverse on discharge.

At the cathode: $LiCoO_2\ CoO_2 + Li^+ + e^-$ (4)

At the anode: $C_6 + Li^+ + e^-\ LiC_6$ (5)

Overall cell: $C_6 + LiCoO_2\ LiC_6 + CoO_2$ (6)

The electrolyte contains a porous membrane, made of polyethylene and polypropylene, called a separator which allows passage of the Li^+ ions and is used to prevent any direct contact between the anode and the cathode [47]. As seen in Fig. 6, to allow electron transport, the anode is in contact with a Cu current collector and the cathode with one made of Al. Al cannot be used at the anode since it is reactive with Li. To produce the electrodes the active materials are mixed with binders and additives in a solvent to form a slurry that is coated onto the respective current collectors. A water-based solvent is used for the anodes and an organic solvent such as N-methyl pyrrolidone for the cathode. After drying the coated electrodes are roll-pressed and cut to size for final processing and cell assembly [48], [49].

VI. ANODE MATERIALS IN LI-ION CELLS

A. *Graphite Anodes*

Li metal cannot be safely used as an anode in conventional liquid electrolyte systems since during cycling it tends to form dendritic growths which can penetrate the separator material causing internal short circuits, thermal runaway on the cathode, and a risk of combustion [41], [42], [50]. Dendritic Li can also be detached to form "dead Li," gradually reducing performance. The large volume changes of the electrode during repeated dissolution and deposition of Li can also deteriorate the cell. Metallic Li is highly reactive such that surface corrosion in organic electrolytes can occur increasing interfacial resistance and reducing both efficiency and life of the cell [42]. Hence, graphite has become widely used as the anode material because Li ions can be intercalated into its layered structure between graphene plates and by this means Li dendrite growth can be prevented [51]. Graphite is an abundant relatively low-cost material with high electrical conductivity, high Li diffusivity and only undergoes small volume changes during loss and gain of Li atoms. Up to 1 Li atom per 6 C atoms can be stored. For EV batteries synthetic graphite is used due to its low impurity level which ensures less variation in production quality and greater stability when operating over a wide temperature range [41].

During the first few charging cycles, it is fortunate that a solid electrolyte interphase (SEI) layer is spontaneously generated on the graphite anode of lithium-ion batteries via the breakdown of the electrolyte. Although it reduces efficiency, the SEI layer allows through transport of Li ions while passivating the surface of the anode thus inhibiting any further decomposition of the electrolyte and increasing cycle life [52]-[54]. The SEI also controls the efficiency and safety of lithium batteries. The SEI is multiphase containing LiF, Li_2O, inorganic carbonates such as Li_2CO_3 and lithium ethylene di-carbonate (LiEDC). To improve the stability of the SEI, electrolyte additives such as vinylene carbonate and fluoroethylene carbonate can be used [55]. Volume changes in the anode can damage the SEI. The formation, nature and breakdown of the SEI layer is reported as complex and continues to be researched to determine the effects of electrolyte additives and formulation on Li ion conductivity and on potential improvement in SEI stability on conventional graphite anodes during long-term cycling [54], [56] and on other potential anode materials [57]. To develop an understanding of SEI formation and other electrode reactions requires the application of cryogenic high resolution electron microscopy [58], [59].

Graphite anodes tend to be intercalated with electrolyte as well as Li ions causing a reduction in capacity and strains in the graphite lattice and hence in the SEI layer. The intercalation with electrolyte is not reversible and causes volume expansion over charging and discharging cycles leading to exfoliation. Also, if battery cells become overheated C anodes can catch fire [44], [60]. Hence, there is continued development in the use of alternative anode materials such as lithium titanium oxide (LTO), conversion compounds, Li metal, and silicon.

B. Lithium Titanium Oxide Anodes

Lithium titanium oxide (LTO) with a formula $Li_4Ti_5O_{12}$ and a spinel structure has been used for anodes for some 30 years [61]. Like graphite, LTO is an intercalation anode since lithium ions can be inserted and removed from its lattice structure. Compared to graphite LTO has a lower specific capacity, a higher lithiation/de-lithiation plateau and lower conductivity of electrons, and diffusion rate of Li ions [60]-[63]. Graphite gives a specific capacity of 372 $mAhg^{-1}$ but LTO only 175 $mAhg^{-1}$. Graphite has a low working potential of about 0.2V couple whereas LTO operates at an excessively high potential of 1.55V vs Li^+/Li which limits output energy density. When paired with conventional cathodes LTO only provides a nominal cell voltage of 2.4 V compared to that of 3.7 V for graphite [42]. Nevertheless, LTO is reported to offer increases in power density, efficient charging at low temperatures, and improved cycling stability as a zero-strain material [41], [42], [44], [61]-[64]. Due to its higher Li insertion potential LTO is also less likely to form Li dendrites and whiskers than graphite [42], [62]. However, LTO can generate high gas volumes due to reaction between the organic electrolyte, and active material especially at higher temperatures of 40-60◦C [45], [65].

To improve the electrochemical properties and performance of LTO other elements such as Ru, W, Ce and La have been used to modify the lattice structure. For example, the inclusion of La can give rise to a perovskite lattice with a higher specific capacity of 225 $mAhg^{-1}$ and a lower potential of 1.0V vs Li^+/Li [64]. To improve conductivity, the forming of composites with better electronic conductors such as C has also been considered [45]. Another approach is to produce nano-structured material. In batteries, power output and minimum charging time both depend on movements of ions as well as electrons with ionic diffusion being the main factor that limits the rate of charge and discharge. Hence, to increase these rates, nanotechnology is being used to produce nano-sized crystal structures in active materials in order to reduce the Li+ diffusion distances [66], [67]. Nanotechnology is also being used in preparing LTO from $TiOSO_4$ which is said to be an inexpensive Ti-source produced during the mining process of ilmenite ($FeTiO_3$). The LTO is prepared as microspheres which are nucleated on small clusters of TiO_2 nanoparticles [68]. To improve the energy density of graphite anode cells carbon nano-structures have also been investigated but the production and handling of carbon nanotubes and graphene gives rise to environmental concerns such that nanostructured LTO is considered to a be a safer alternative [69].

For both graphite and LTO, anode materials surface coating can be applied to improve charge transfer between the anode and the electrolyte. Coating materials include Ag, C, Cu, Sn oxide, alumina and conductive polymers [45], [67], [70]-[72]. LTO can be coated with C to suppress the gas evolution that stems from reactions between the LTO and organic electrolyte although such coating can enhance electrolyte decomposition and cause SEI formation [70]. To reduce gassing, the use of electrolyte additives to form passivating surface films on LTO has also been investigated [73]. Nano-coatings of amorphous C, metal, metal oxides and polymers are used to protect graphite anodes from reactions with the electrolyte with application via wet chemical methods or vacuum deposition [67].

C. Conversion and Alloying Type Anodes

As potential alternatives to intercalation anodes there is continued development of conversion anodes and alloy type anodes [42], [44], [45], [57], [74]-[76]. Conversion reaction type anodes consist of M_aX_b where M represents transition metals such as Co, Cu, Fe, Mn and Ni, and X represents H, N, F, O, P, and S. Examples are Fe_2O_3, Co_2O_3, SnO_2, and CuO. Instead of intercalation a chemical reaction occurs such that all the M in the transition metal compound MaXb is fully replaced by Li forming metal nanoparticles M. Conversion anodes can offer high theoretical specific capacities of 500-1500 $mAhg^{-1}$ but suffer from low Li diffusion rates and large volume changes during cycling. Towards improvement, research is focused on optimizing their chemical composition and nanostructure [77]-[80]. Oxide nano-particles with hollow structures offer the ability to withstand stress from high volume changes and their high surface to volume ratio can increase Li mobility [80].

Other possible anode materials are the alloying-type which include Si, Sn, Pb, Sb, Zn, Al, Ag, Ge, and In and metal oxides, sulphides and phosphides [45], [57], [75], [76], [79]. This type can alloy with Li^+ to form Li-alloy compounds after lithiation and can exhibit discharge capacity of up to 4x higher than that of graphite since these anodes can store more Li^+ per unit (volume or mass) than intercalation anodes [75],

[76]. However, their practical application is restricted by slow Li^+ reaction rate and very large volume changes (>300%) during Li alloying and dealloying causing degradation and limited cycle life.

Si has a theoretical specific capacity of 3578 $mAhg^{-1}$, almost 10 x of that of graphite. Si is also non-toxic and has ready availability hence it is one of the most promising materials for anodes [46], [75]. Replacing the use of graphite with silicon could increase energy density and reduce costs. The large volume changes involved in repeated expansion and contraction of Si during battery cycling result in loss in capacity due to pulverization and electronic isolation of Si, and the instability in the SEI layer. To improve cycle life, attempts to minimize the effects of these large volume changes in Si when gaining or losing Li ions have led to the development of Si nanoparticle anodes [67], [79]. These employ nanostructured Si materials such as nanowires, hollow spheres, porous particles, and composite Si/C yolk–shell structures combined with polymer binders. The binders prevent disintegration of the anode and delamination from the current collector, and also improve the stability of the SEI layer thus preventing continuous exposure of fresh surfaces that could react consuming Li ions and electrolyte [81]-[84]. Recent binder research has examined the replacement of synthetic polymer binders, such as polyvinylidene fluoride and carboxymethyl cellulose, by natural biopolymers which have structural arrangements such as long chains that can better withstand strains from volume changes [83], [84].

In Si nanoparticle/C composites hollow or porous structures provide spaces for volume expansion with the inclusion of C improving electron conductivity. The combination of intercalation C material with a low content of alloy-type anode material such as silicon in mixed systems can increase theoretical capacity, for example, about 1000 $mAhg^{-1}$ can be achieved using mixed anode of 20% Si and 80% carbon [46]. To increase SEI stability also requires the development of improved interfacial polymer inorganic composite surface films which could be produced via decomposition of electrolyte additives or from preformed interfaces. In assessing the performance characteristics of anodes, it is expected that the silicon content in graphite or carbon-based anodes will gradually increase from the current 5-10% levels. Although Si–C and SiO_x–Si–C composite anode materials have been the subject of considerable R&D, there is little information on their commercial production [85], [86]. There is interest in silicon oxides (SiO_x) - based anode material since, although when compared to Si it has a lower initial theoretical capacity of 2615 $mAhg^{-1}$, it undergoes a significantly smaller volume change of 160% than the 300% for Si during lithiation/de-lithiation. Hence, SiO_x is more likely to provide better cycling performance since it should be less prone to pulverization and SEL instability [87], [88].

At the company's 2020 Battery Day to introduce a new tabless design for 46 dia.x80mm sized cylindrical cells, Tesla announced a move away from C-based materials such as graphitic carbon and graphene to Si-based material for anodes [89], [90]. To avoid Si expansion problems the COBRA battery consortium in Europe is focused on developing Si-C composite materials for anodes to be ready for commercialization by 2025 [91]. These nano-structured Si/C composites as for use with LNMO Co free cathodes as the EU funded COBRA protect is entitled "Cobalt-free Batteries for Future Automotive Applications". Other battery producers are also reported to be introducing Si-based anodes including NEO Battery Materials in Canada [92], Israel-based StoreDot, Gotion High-Tech in China and Enovix and Sila Nanotechnologies in the USA [93].

D. Li Metal Anodes

Li metal is an ideal candidate anode material for high energy density Li-Ion batteries since it exhibits a high theoretical capacity of 3860 $mAhg^{-1}$ and a low potential of -3.04 V vs SHE [50]. However, despite considerable R&D efforts practical application remains difficult due to a number of problems [94], [95]. These include high volume changes, dendrite formation, high reactivity, instability of the SEI, and the associated loss of active Li and degradation of the electrolyte [94]-[97]. The net effect is high internal resistance, low efficiency, shortened life, and not least concerns over safety if dendritic Li penetrates the cell separator. These problems are very difficult to overcome when using conventional liquid electrolytes [50], hence most research efforts have focused on replacement by solid-state electrolyte systems.

VII. CATHODE MATERISLS IN LI-ION CELLS

Cathode materials need high capacity for Li ions with minimum structural change during the removal and gain of Li ions and should offer a high potential vs Li^+/Li. Li-ion batteries can be conveniently classified according to their cathode chemistry with, in most cases, graphite serving as the anode material. Since the introduction of the original $LiCoO_2$ lithium cobalt oxide (LCO) cathode [40] a number of commercialized cathode materials have been developed. Most of these are based on layered or spinel transition metal oxides having a general formula of $LiMO_2$ where M signifies transition metals of which some examples are listed in Table I. As for anode materials, Li ions can be intercalated into the lattice structures of these cathode materials with Li stored between parallel MO_2 layers. NMC type cathodes have now become the most widely used for both PHEV and BEV electric vehicles. From a 2017-18 survey of 30 models from 17 major car manufacturers, it was reported [98] that 24 models used NMC batteries, 5 used NCA and only 1 used LFP. However, since then the manufacturing capability and use of LFP cathodes has significantly increased such that their estimated global market share was up to near 20% in 2020 and is forecast to increase to 25% in 2021 [99].

TABLE I
EXAMPLES OF CATHODE MATERIALS USED IN LI-ION BATTERIES. DATA FORM [41], [44], [106], [146].

Cathode Type	**Formula**	**Structure**	**Practical specific capacity (Ah/kg)**	**Discharge Potential v Li (V)**
LCO	$LiCoO_2$	Layered oxide	140-150	3.9
LNO	$LiNiO_2$	Layered oxide	220-240	3.75
NMC 111	$LiN_{0.33}Mn_{0.33}Co_{0.33}O_2$	Layered oxide	160	3.7
NMC 532	$LiN_{0.5}Mn_{0.3}Co_{0.2}O_2$	Layered oxide	165-170	3.7
NMC 622	$LiN_{0.6}Mn_{0.2}Co_{0.2}O_2$	Layered oxide	170-180	3.7
NMC 811	$LiN_{0.8}Mn_{0.1}Co_{0.1}O_2$	Layered oxide	190-200	3.7
NMC 955	$LiN_{0.9}Mn_{0.05}Co_{0.05}O_2$	Layered oxide	200-205	3.7
NCA	$LiN_{0.8}Co_{0.15}Al_{0.05}O_2$	Layered oxide	200	3.7
LMO	$LiMn_2O_4$	Spinel	110	4.1
LMNO	$LiMn_{1.5}Ni_{0.5}O_4$	Spinel	140	4.7
LFP	$LiFePO_4$	Olivine	165-170	3.45
LFMP	$LiMn_{0.7}Fe_{0.3}O_4$	Olivine	155	3.9

A. Lithium Cobalt Oxide (LCO) and Lithium Nickel Oxide (LNO) Materials

The original LCO type cathode material is no longer considered suitable for automotive applications due to safety concerns and the high and volatile cost of its high cobalt content. LCO has a high theoretical specific capacity of 274 Ah/kg but its reversible capacity is limited to 140 Ah/kg since irreversible structural collapse occurs if too much Li is removed when operated at potentials over 4.35 V vs Li/Li^+ [41], [44], [100]. LCO cathodes have high reactivity and suffer from low thermal stability such that thermal runaway can occur causing batteries to catch fire [41], [42]. However, small-sized LCO batteries continue to be used and developed for portable electronic equipment applications. Additions of Al, Cr, Fe, and Mn as dopants or as Co substitutes and oxide coatings such as Al_2O_3, TiO_2, and ZrO_2 have been made towards improving not only thermal stability but also structural stability especially at charging potentials of over 4.35V, the latter providing possible increases in useable capacity [100]-[103]. Since it has the same type of lattice structure and a similar theoretical specific capacity of 275 Ah/kg, $LiNiO_2$ (LNO) has also been investigated as a potential alternative to LCO. However, LNO is more thermally unstable than LCO and tends to form a self-passivating layer blocking Li ion diffusion [104], [105]. $LiNiO_2$ is difficult to produce with the correct stoichiometry and it also undergoes damaging irreversible structural changes during gain and loss of Li ions from its lattice [105]

It was found [106] that partial substitution of Co by Ni in LCO combined with small additions of Al could improve both electrochemical behaviour and thermal stability. This led to the development of the commercially used NCA cathodes which have a general formula of $Li(Ni_xCo_yAl_{1-x-y})O_2$ [107], [108]. Recent work [109] has found that the stability and cycling behavior of NCA became gradually improved with increasing Al content from 0 to 5.6%. However, Al contents above 5.6% gave deleterious effects, including increased residual lithium on the cathode surface and the formation of impurity phases ($LiAlO_2$ and Li_5AlO_4) which reduced cell capacity.

B. Lithium Manganese Oxide (LMO)

Lithium manganese oxide $LiMn_2O_4$ (LMO) has a spinel type lattice structure which allows improved ionic movement compared to a layered structure. LMO has better thermal stability and safety than LCO but has lower capacity and shorter life. Due to its low cost, non-toxicity and high rate of discharge capability, LMO was used in the first-generation Nissan Leaf but in later models has been replaced by NMC [110]. Wider use of LMO has been limited by its fast rate of fading in capacity during cycling which is associated with solution of Mn ions, distortion of its lattice, and side reactions between LMO, and the electrolyte [67], [111]-[114].

During discharge at high current, the diffusion rate of Li^+ ions in the electrolyte is higher than that in the bulk of cathode such that Li^+ ions accumulate on the surface of the cathode leading to the formation of a Mn^{3+} rich region and to the dissolution of Mn^{2+} into the electrolyte. The formation of Mn^{3+} results in the Jahn-Teller (J-T) distortion whereby distorted Mn^{3+} ions destabilize the lattice causing an irreversible cubic to tetragonal structural transformation which causes anisotropic volume changes [111]-[113]. This restricts the three-dimensional Li^+ diffusion pathways reducing capacity retention after repeated charge/discharge cycles and promotes cracking in the cathode particles. Performance is also reduced by the Mn^{2+} going into solution and then plating out in the SEI on the graphitic anode [112], [113]. The reduction in performance is much worse at temperatures over 50°C.

The JT distortion can be reduced by doping with Fe, Co, Al or Ni, while Mn^{2+} dissolution and other side reactions can be reduced by surface treatment of the cathode with nano-coatings of oxides such as ZrO_2 and TiO_2 [112]-[116]. Fluoride and phosphate coatings have also been used to prevent reaction with and decomposition of the $LiPF_6$-based carbonate electrolyte [117]. Doping with Ni can be used to form a core-shell type structure in which $LiMn_2O_4$ is protected by a shell of $LiNi_xMn_{2-x}O_4$ (LNMO) [118], [119]. Cathodes prepared from Ni doped LMO coated with $NiCo_2O_4$ have also been studied [120]. $LiMnPO_4$ (LMP) coating is also being examined as a potentially more effective alternative to coating with LNMO [121]. There is also interest in using carbon coating to protect LMO cathodes. A solvent-free mechanofusion method, which uses repeated strong centrifugal force combined with high shear and compression forces, has been shown to produce a uniformly dense, stable C coating [122]. This coating ensured no direct exposure of the core material to the electrolyte, ensuring minimal active metal dissolution with improved conductivity via interparticle contact and improved electrochemical and cycling performance.

It is also reported that the J-T distortion and Mn^{2+} dissolution can be suppressed by using composite cathodes in which there is a fine mixture of spinel and layered domains [113], [123]-[126], for example, nano-domains of layered Li_2MnO_3 can be embedded into micro-sized $LiMn_{1.5}Ni_{0.5}O_4$ to stabilize the structure [119]. Li_2MnO_3 has also been used to form experimental layered composite cathode material with $LiCoO_2$ [127]. For such layered structures, this work suggested that control of fine-scale microstructure, notably the domain size of the Li_2MnO_3-component, is the most important parameter to achieve improved electrochemical behavior.

C. Nickel-rich Cathode Materials, NCA and NCM.

To overcome problems associated with the thermal instability and limited life cycle of LCO and LNO materials layered ternary metal oxides with high Ni contents have been progressively developed as the NCA and NMC series of cathodes [128]-[133]. As commented earlier, controlled additions of Ni and Al to LCO to give NCA, normally with the ratio Ni:Co:Al as 0.8:0.15:0.05, are used to improve performance [107]-[109]. It was also found that including Co in LNO and $LiNi_xMn_{2-x}O_4$ (LNMO) material can help to maintain reversible capacity by preventing cation mixing in which Ni ions and Li ions can exchange their positions in the Ni-Mn mixed oxide lattice [130], [132].

Raising the Ni content increases the energy density and hence vehicle range [129], [130]. The Ni:Mn:Co ratio used in NMC cathodes was originally 1/3:1/3:1/3 but has gradually changed to become increasingly Ni rich to 5:3:2 then 6:2:2 and now 8:1:1 [133] and in the near future it is changing to 9:0.5:0.5 [108], [134]. The NMC cathodes are most frequently classified in terms of these compositional ratios as NMC111, NMC532, NMC622, and NMC81, but are sometimes referred to as NCM cathodes [132], [135]. High Ni contents also became necessary to replace Co due to increasing concerns over the cost and security of Co supplies and not least due to reported unethical and environmentally damaging mining practices used in the Democratic Republic of Congo (DRC) in central Africa, a region that supplies some 65% of the world's Co [133], [136]-[138]. The geographic distribution of Co is uneven with the other 35% coming mainly from China and Canada, each with 6%, and Russia, Cuba, and Australia. The supply of Co is dependent on Cu and Ni mining since 90% of Co is obtained as by-product [137]-[139]. With the expected rapid growth in EV production, it has been estimated that by 2030 the annual demand for Co just to be used in Li based batteries will be around 285,000 tons which is nearly twice the total world Co output of 145,000 during the year 2019 [139]. Naturally, there are additional concerns and predictive models for other critical elements such as Li, Ni, and Mn that are needed for EV batteries, and over suitable developments for efficient and safe recycling of end-of life batteries and recovery of all component elements [135], [139]-[142].

Increasing the Ni content improves capacity in NMC cathodes but it also has some adverse effects. It reduces thermal stability and resistance to cycling damage, and gives higher surface reactivity which can cause unwanted side-reactions, electrolyte decomposition and oxygen evolution [112], [143]-148]. With higher N contents in NMC the layered structure tends to become unstable during delithiation such that a surface layer of NiO can be produced together with outer layers of Li-P-O compounds and polycarbonates giving rise to a cathode electrolyte interface (CEI) [146]. Considerable research efforts have focused on degradation studies [112], [144], [147] towards improving NMC stability via the use of:

- doping agents such as Mg and Zr [149]
- coating materials such as C [150], phosphate [151], and polymers [152]-[154]
- tailored concentration gradients and core-shell structures [155], [156]
- grain boundary and particle size control [157]-[159].

Although doping of NMC622 with Mg and Zr, performed during the NMC622 synthesizing co-precipitation process reduced capacity, it improved stability by inhibiting structural changes and prevented collapse of the layered structure. The effects of such doping were said to be complex and difficult to predict [149].

Uncoated cathodes are prone to degradation of active materials and hence capacity fade due to their reaction with hydrofluoric acid containing electrolytes. Coating of the cathode may reduce or prevent such reactions with the thickness, uniformity and ionic and electronic conductivity of the coating being the main factors in coating selection [130], [143], [150]-[153]. Ultrathin thin rough surface coatings have been the subject of considerable development [130] with atomic layer deposition (ALD) being of most interest to provide effective thin layer coatings consisting of Al_2O_3 [143]. Phosphate coatings based on Li_3PO_4 may be used to provide not only protection of the active material but also to themselves act as active layers to improve electrochemical properties [143], [151]. Cathode particles can be encapsulated with a S-containing polymer called PERDOT which unlike conventional coatings can penetrate the interior of the particle aggregates to give additional protection [153], [154]. The coating allows transport of Li ions and electrons and is also said to prevent both structural conversion to spinel phase and oxygen release thus enabling the battery to operate at higher voltage to increase energy output or promote longer life [154].

Concentration gradient structures have been produced in LMNO type cathode particles in which the surface of each particle is Mn rich while the core is Ni rich with each particle containing tailored near linear concentration gradients for both Mn and Ni [155]. The higher Ni level at the surfaces is designed to reduce capacity fade, Mn ion solution and side reactions [111]-[114] outlined earlier. In contrast to LMO and LNMO, for improved stability and cycle life in the Ni rich NMC materials the surface of each particle needs to be Mn rich with the high-capacity core being Ni rich. This is achieved by producing particles having core-shell structures [156]. Using the core-shell approach, which is said to be easier to achieve than controlled concentration gradients, cathode particles with overall composition equivalent to NMC811 but with Ni rich core compositions near to NMC9.5.5 and Mn rich surfaces equivalent to NMC111 have been reported to provide significantly improved capacity retention when compared to homogeneous NMC811 material [156].

In conventional polycrystalline NMC the cathode particles consist of near-spherical aggregates of small sub-micron crystals. During cycling, volume changes occur causing cracking of these particles leading to isolation of the active material and capacity loss. The cracking may be reduced by infiltration along grain boundaries of low melting point oxides or Li_3PO_4 solid electrolyte [157] or by producing the cathode particles as single crystals of 2-10 micron in size. The use of single crystals not only suppresses cracking but also significantly increase Li ion diffusivity raising power density [158]-[160].

D. Lithium Iron Phosphate (LFP) Cathodes.

Unlike the layered cathode materials, LFP, with a formula $LiFePO_4$, has an olivine type lattice structure. It is one of a group of polyanion compounds based on $(XO_4)^{3-}$ where X=P, S, Si, As. Mo or W [41]. The main advantages of LFP as a cathode include good thermal stability, high safety, Co free, environmentally friendly, non-toxic, long cycle and shelf life, and relative low cost since it contains abundant elements [41], [131]-[133], [146]. LFP has higher resistance to heating effects than other cathode materials and is much less likely to suffer thermal runaway. However, LFP has limited electronic and ionic conductivity and hence is difficult to charge at high rates, has low nominal voltage of 3.4V versus Li/Li^+, and limited practical specific capacity of 120-160 mAh/g, the latter giving a shorter range per charge compared to NMC types [131], [132], [136], [161], [162]. The performance of LFP can be improved by reducing particle size to nano-scale, by C coating, by doping and by producing composites with various forms of C [146], [161]-[164]

The advantages offered by LFP, especially regarding safety aspects, have outweighed its disadvantages for applications in hybrids such as BMW 3 and 5 Series, motor-homes, forklifts, tourist boats, and especially for public transport buses in China [132], [133], [146]. Over the last 2 years, the increased need for reduction in the use of Co and Ni in order to lower costs has renewed interest in batteries fitted with LFP cathodes. In China, it is reported that LFP batteries now have 47% of the market and that Tesla is now using LFP in its China-made Model 3 saloon while Volkswagen is also planning for its use in entry level models [165], [166]. Although Ni based cathode batteries can offer ranges of 450 km, for economic reasons, in spite of its limited range of only about 160 km, the current best-selling car in China is the Hong Guang Mini, produced by a GM joint venture [165]. In a recent techno-economic report it has been predicted that, in the light of increasing safety standards, LFP could become increasingly used after 2022 when patent restrictions that currently limit its production to China are due to expire [167].

LFP batteries suffer from lower performance and reduced range in cold climatic conditions, however the recent reported development in thermally modulated (TM) LFP batteries is claimed to be a solution to this problem [168]. The TM-LFP battery which operates safely at 60°C in all types of ambient conditions is said to offer equivalent performance to NMC622 and additionally can be fast-charged in 10 minutes to provide suitable cruising range.

For future alternatives to LFP there are some other olivine type structures that could be developed as cathode materials include $LiMnPO_4$ (LMP), $LiFeSPO_4$ (LFSP) and $Li_3V_2(PO4)_3$ (LVP) [41], [146], [169].

VIII. A NOTE ON FUTURE DEVELOPMENT

A 2021 battery technology roadmap has highlighted some potential future developments [170]. Examples of such developments include improvements in solid state batteries, Li-O and Li-S batteries, Al- and Zn-air batteries, and Na, K, Mg and Ca based batteries. It is estimated that during the last 20 years around 170,000 scientific/technical papers have been published on battery developments [170]. Although about 45% of this work has focused on Li-Ion batteries there is increasing R&D interest in Na-ion, Li-S, and other metal-ion types [170], [171], and for safety reasons in batteries that can use aqueous electrolytes [172].

At present and over the next few years the move to use solid state electrolytes in Li-ion batteries will improve safety since these electrolytes, when compared to flammable organic liquid or gel media-based electrolytes, can inhibit the growth of Li dendrites, do not pose leakage problems and reduce fire risk [42], [89], [173]-[176]. They can operate at higher voltage, be charged at high rates and require less space in the vehicle. The solid electrolyte also acts as a separator. Solid electrolytes may allow the use of thin Li films as the anode decreasing the weight and volume of the battery in comparison with conventional anodes [95], [96]. Developments in solid-state electrolytes are focused on a variety of inorganic materials such as complex Li metal oxides, sulphides, halides and phosphates, garnets, perovskites [177]-[179], and also on polymer composites [180]-[182]. Of particular importance is the study of the behaviour of solid electrolytes at their interfaces with the electrodes and effects on performance and life [183], [184]. In composite solid electrolytes, the polymer provides flexibility and effective interfacial contact with the electrodes while the inorganic gives higher ionic conductivity [182]. On an industrial scale the handling and processing of such materials and the manufacture of solid-state cells presents a number of practical difficulties, for example, during sintering after conventional slurry-based processing [179]. In laboratory and pilot scale development of batteries a number of different processing routes, such as tape casting, wet powder spraying, roller coating, hot pressing and physical/chemical deposition, are used. However, the choice of both materials and processing methods can become much narrower when a particular development needs to be scaled up for manufacturing [185], [186]. Problems related to scaling up of processing for mass production are nevertheless being solved such that Toyota and Volkswagen expect to have solid state batteries in some of their EVs before 2025, with other manufacturers to follow. The Toyota battery is reported to provide 500 km range per charge and a full recharge capability within 10 minutes [187]. Since Na is an abundant low-cost resource, it is an attractive substitute for Li in the development and commercialization of Na-ion type batteries [170], [188]-[191]. Na is chemically similar to Li but has a larger ionic diameter such that diffusion rates of Na ions are relatively slow, even when cathodes with sufficiently large enough space to accommodate within their lattice can be found [170]. The larger Na ion also results in larger volume changes during cycling. With further development it is predicted that Na-ion batteries with hard C anodes and Co-free cathodes will be suitable for applications in short range EVs and in large-scale stationary energy storage applications [188], [189].

As other alternatives to conventional Li-ion batteries, there is growing research interest in the use of metal anodes such as Li, Na, Al, and Zn in combination with cathodes such as S, Se, and O_2. [170]. Of these Li-S batteries are believed to offer the greatest potential since not only can they offer a theoretical energy density of $2600Whkg^{-1}$ (about 5x higher than for conventional Li-ion) but also S can be readily sourced at low cost. At present Li-S batteries remain limited by low ionic conductivity, the short life of Li anodes and precipitation and transformational changes within electrolytes [192], [193].

Al metal anodes have also shown promise to deliver high-capacity cells but their development continues to be restricted by difficulties in finding suitable cathode materials and in formulating electrolytes which are not corrosive to current collector and battery container materials [170], [194]. For metal-air batteries which use oxygen-permeable cathodes, and safe, aqueous electrolytes, Zn may prove to be the most suitable anode material. However, the main problems to be overcome include the formation of Zn dendrites and passivation by Zn oxide [170], [195]. There is also interest in developing organic electrode materials [196] and in anionic batteries [197]. For all types of battery developments, the characterization, production, and control of consistent nano-structured materials continues to be of increasing significance in seeking to improve performance and safety [67], [69], [198]-[200].

Sustainability is the rationale for the change from internal combustion engines to electric vehicles. Battery developments must continue to focus on sustainability with the need to conserve, recover, reclaim and re-use critical materials [135], [136], [140], [142], [201]-[209] and, linked to the re-use of materials, on the need to further develop efficient and environmentally safe manufacturing processes [210], [211]. Data from a 2020 Greenpeace report on EV batteries reinforces the need for sustainability research and action. Greenpeace estimate that between 2021 and 2030 there will be 12.85 million tons of "spent" EV lithium-ion batteries while during the same period some 10.35 million tons of lithium, cobalt, nickel, and manganese will be mined for new batteries [212]. By 2030, lithium use for global battery production is projected to be 29.7 times higher than in 2018. In addition, from 2021 to 2030, EV battery production will use up 30% of the world's current proven cobalt reserves.

EV battery packs are heavy, hence for efficiency and environmental reasons, the light-weighting of body and other parts in EVs is essential to offset this extra weight. Light-weighting allows the use of smaller battery packs thus reducing materials usage and costs. Alternatively, it may enable an increase in vehicle range per charge by allowing an increase in battery pack size. Over the last 50 or so years, the auto-industry has gained considerable experience in weight saving from their efforts in reducing body-in white (BIW) mass of ICE and hybrid vehicles [213]. These advances in light-weighting together with improvements in IC engine efficiency and more effective use of catalytic converters have reduced the amount and toxicity of harmful exhaust emissions. Vehicle weight reduction and emission controls will continue to be key drivers in ICE and hybrid vehicle development as the gradual transition to BEV and FCEV usage takes place over the next 2 or 3 decades. BIW weight savings have been achieved via the use of advanced high-strength steels and by replacement of steels by Al alloys in sheet and extruded form and as die-castings. First generation EVs made use of steels but the trend for BIW is now to completely replace steels by Al alloys [214]. For lightness and impact resistance, Al alloys are also used for the enclosures or housings needed to contain and protect the battery modules. Al alloys also provide sufficiently high thermal conductivity required for thermal management of battery temperature and by providing an electromagnetic shield avoid interference effects with other electrical and electronic vehicle systems [215]. Battery enclosures are normally constructed from hollow extruded sections and/or sheet material and are integrated into the body structure of the vehicle. In a novel recent development by Tesla, very large high-pressure die cast Al alloy parts are used for single-piece front and rear underbody. These 2 sections are joined with a honeycomb type Al alloy battery enclosure such that the enclosure actually contributes to the strength of the vehicle structure rather than just containing the battery cells [89], [216].

IX. OUTLOOK OF EV BATTERY INDUSTRY IN THAILAND

According to the ERIA (Economic Research Institute for ASEAN and East Asia) research project report [217], Thailand has a strong position in conventional starter battery production and exports. In terms of trade value, NiMH batteries are not a significant item with 0.1 million US dollars in exports value and 21 million dollars imports value in 2019. A significantly higher import level of 122.5 million US dollars than exports of 8.4 million US dollars for Li-ion batteries suggests that Thailand does not play a significant role in the global supply chain for this type of battery.

On the other hand, the numbers for import and export values for battery modules, cells, and components are significant (110.0 vs 112.2 million US dollars) which could be interpreted as Thailand being a source of EV batteries assembly.

According to the Kasikorn Research Center (K-Research), Thailand's assembly and output of EV batteries are predicted to reach 430,000 units by 2023 which would account for three percent of global EV battery production, placing Thailand in the top four in Asia. Sales of the three types of EVs; HEV, PHEV, and BEV in the country will account for 25% of the total car market. In addition, Thailand will be the hub for EV battery export in ASEAN with 40% of the production or 170,000 units intended for export in 2023. Battery EVs will be mainly delivered to Japan, Oceania, Singapore, and Malaysia due to the rising income growth and government's support for EV facilities [218]. Battery manufacturers in Thailand consist of both multinational companies from Europe and Japan and domestic companies stimulated by the strong investment promotion incentives by the government [219].

X. CONCLUSION

This general review has covered the battery materials that have and are being used in electric and hybrid vehicles, and has outlined some possible future developments. It is believed that Li-ion battery technology will continue to dominate the EV market for at least the next decade. Several new promising battery technologies continue to be increasingly researched. In 2015 the number of academic papers on battery developments was 15,000 but by 2020 this number had increased to 23,000 [170]. Potential new battery technologies such as Li-S, Zn-Air, Al-Ion and capacitors and fuel cells require long times to commercialize since the transition from laboratory scale studies to production viable battery cells is a very arduous process.

Li-ion batteries will continue to be improved, in particular by developments in nano-materials for anodes and cathodes and by improvements in solid state electrolytes. There needs to be further studies into degradation mechanisms especially in countries like Thailand where ambient temperatures can be well above 25^{o}C. However, it is equally if not more important for the industry R&D to pay more attention to the recycling and next-life reuse of EV spent batteries in order to conserve critical materials and avoid further damage to the environment. In terms of raw material supply, in the future production of Ni-rich cathodes Thailand has to face possible strong competition from the Philippines and Indonesia, who unlike Thailand have natural reserves of Ni.

With regards to recycling and reuse there is the question of who is to be responsible for these activities. Will the OEM vehicle builder be liable to finance recycling at the end of life of the battery and who will be responsible for the collection and testing, etc., of batteries from vehicles at the end of their lives? In Europe, for example, there is the Extended Producer Responsibility (EPR) scheme which is part of the Waste Framework Directive 2008/98/EC (WFD). This scheme is to ensure that producers of products bear financial responsibility or financial and organizational responsibility for the management of the waste stage of a product's lifecycle [220]. For Thailand, the Ministry of Higher Education, Science, Research and Innovation (MHESI), in collaboration with the Electric Vehicle Association of Thailand (EVAT) and a number of science and academic institutions have recently joined forces to form the Thailand Energy Storage Technology Alliance (TESTA) to create a collaborative platform and network as well as ensuring that R&D, especially on Lithium-ion batteries, is fully commercialized. [221] Meanwhile, the Department of Industrial Works, Ministry of Industry (MOI) is preparing the plan for EV battery end-of-life management and the Pollution Control Department, Ministry of Natural Resources and Environment (MONRE) is enacting the Acts for the EV battery end-of-life management [222].

RERERENCES

[1] C. E. Thomas, "Fuel Cell and Battery Electric Vehicles Compared," *International Journal of Hydrogen Energy*, vol. 34, no. 15, pp. 6005-6020, Aug. 2009.

[2] F. Un-Noor, S. Padmanaban, L. Mihet-Popa et al., "A Comprehensive Study of Key Electric Vehicle (EV) Components, Technologies, Challenges, Impacts and Future Direction of Development," *Energies,* vol. 10, no. 8, p. 84, Aug. 2017.

[3] International Energy Agency. (2021, Jul. 5). *Global EV Outlook 2020*. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2020

[4] S. Baltac and S. Slater. (2021, Jul. 10). *Batteries on Wheels: The Role of Battery Electric Cars in the EU Power System and Beyond*. [Online]. Available: https: www.elementenergy.co.uk/wordpress/wpcontent/upload/2019/06/Batteries on wheelsPublicreport 4th-June-2019.pdf

[5] S. Baltac and S. Slater. (2010, Jun. 4). *Batteries on Wheels: The Role of Battery Electric Cars in the EU Power System and Beyond*. [Online]. Available: http://www.elementenergy.co.uk/wordpress/wpcontent/uploads/2019/06/Batteries_on_wheels Public-report_4th-June-2019.pdf

[6] Clean Energy Ministerial. (2021, Jul. 10). *EV30/30 Increasing*. [Online]. Available: https://www.cleanenergyministerial.org/compaign-clean-energy-ministerial/ev3030-campaign

[7] I. Boudway. (2021, Jul. 10). *Batteries for Electric Cars Speed Towards a Tipping Point*. [Online]. Available: https://www.bloomberg.com/news/articles/2020-12-16/electriccars-are-about-to-be-as-gas-powered models

[8] J. Kurtz, S. Sprik, G. Saur et al., "On-Road Fuel Cell Electric Vehicles Evaluation: Overview," Technical Report National Renewable Energy Laboratory Golden, Co., USA, Re. NREL/TP-5400-73009. May 2019.

[9] Y. Manoharan, S. E. Hosseini, B. Butler et al., "Hydrogen Fuel Cell Vehicles; Current Status and Future Prospect," *Applied Sciences,* vol. 9, p. 17, Jun. 2019.

[10] Y. Wang, D. F. R. Diaz, K. S. Chen et al., "Materials, Technological Status and Fundamentals of PEM Fuel Cells-a Review," *Materials Today*, vol. 32, pp. 178-203, Feb. 2020.

[11] T. Christen and M.W. Carlen, "Theory of Ragone Plots," *Journal of Power Engineering*, vol. 91, p. 216, Dec. 2000.

[12] F. R. Kalhammer, B. M. Kopf, D. Swan et al. (2007, Apr. 10). *State of California Air Resources Board Sacramento, California, USA*. [Online]. Available. http://w2agz.com/Library/Storage/EV%20Batteries/Kalhammer_2007_zev_panel_report.pdf

[13] E. Rahimzei, K. Sann, and M. Vogel. (2015, May 2). *Kompedium: Li-Ionen Betterien, Frankfurt-am-Main, Germany: Verband der Elctrotechnik*. [Online]. Available: https://www.dke.de/resource/blob/933404/3d80f2d93602ef58c6e28ade9be093cf/kompendium-li-ionen-batterien-data.pdf

[14] B. D. McCloskey, "Expanding the Ragone Plot: Pushing the Limits of Energy Storage," *Journal of Phys, Chem, Letters*, vol. 6, pp. 3592-3593, Jun. 2015.

[15] S. C. Lee and W. Y Jung, "Analogical Understanding of the Ragone Plot and a New Categorization of Energy Devices," *Energy Procedia*, vol. 88, pp. 526-530, Jun. 2016.

[16] M. Guarnieri, "Looking Back to Electric Cars," in *Proc. 3rd IEEE Hist. Electro-Technol*, 2012, pp. 1-6.

[17] EUROBAT. (2017, Jun. 20). *Battery Technology for Motive Off-Road Application*. [Online]. Available: https://www.eurobat.org/images/news/publications/final_eurobat_motive_power_report_lores.pdf

[18] T. Paul, T. Mesbahi, S. Durand et al., "Sizing of Lithium-Ion Battery/Sup Ercapacitor Hybrid Energy Storage System for Forklift Vehicle," *Energies,* vol. 13, p. 18, Jul. 2020.

[19] EUROBAT. (2014, May 14). *A Review of Battery Technologies for Automotive Applications*. [Online]. Available: https://www.acea.auto/publication/a-review-of-battery-technologies-for-automotive-applications/

[20] P. T. Moseley, D.A. Rand, and K. Peters. “Enhancing The Performance of Lead-Acid Batteries with Carbon-In Pursuit of Understanding,” *Journal of Power Sources,* vol. 295, pp. 268-274, Nov. 2015.

[21] J. Yang, C. Hui, H. Wang et al., “Review on the Research of Failure Modes and Mechanisms for Lead-Acid Batteries,” *International Journal of Energy Research*, vol. 41, pp. 336-352, Mar. 2017.

[22] H. Hao, K. Chen, H. Liu et al., “A Review of the Positive Electrode Additives in Lead-Acid Batteries,” *International Journal of Electrochemical Science*, vol.13, no. 3, pp. 2329-2340, Mar. 2018.

[23] S. F. Tie and C. W. Tan, “A Review of Energy Sources and Energy Management Systems in Electric Vehicles,” *Renewable & Sustainable Energy Reviews*, vol. 20, pp. 82-102, Apr. 2013.

[24] M. A. Hannan, M. M. Hoque, and A. Mohamed “Review of Energy Storage Systems for Electric Vehicle Applications: Issues and Challenges,” *Renewable & Sustainable Energy Reviews*, vol. 69, pp. 771-789, Mar. 2017.

[25] C. C. Yang, C. C. Wang, M. M. li et al., “A Start of the Renaissance for Nickel Metal Hydride Batteries: A Hydrogen Storage Alloy Series with an Ultra-Long Cycle Life”, *Journal of Materials Chemistry A*, vol. 5, pp. 1145-1152, Dec. 2017.

[26] B. G. Pollet, I. Staffell, and J. L. Shang, “Current Status of Hybrid, Battery and Fuel Cell Electric Vehicles: From Electrochemistry to Market Prospects,” *Electrochimica Acta,* vol. 84, pp. 235-249, Dec. 2012.

[27] S. Chang, K. H. Young, and C. Fierro, “Reviews on the US Patents Regarding Nickel/Metal Hydride Batteries,” *Batteries*, vol. 2, no. 10, p. 29, Apr. 2016.

[28] K. H. Young and S. Yasuoka, “Capacity Degradation Mechanisms in Nickel/Metal Hydride Batteries,” *Batteries*, vol. 2, no. 3, p. 28, Mar. 2016.

[29] B. Sanchez, J. C. Argucha, and J. W. Smith. (2021, Jul. 22). *Performance Characterization of 1998 Ford Ranger Electric with Nickel/Metal Hydride Battery*. [Online]. Available: https://avt.inl.gov/sites/default/files/pdf/fsev/ranger_nimh_report.pdf

[30] S. Boschert, *Plug-in Hybrids: The Cars that Will Recharge America*, New Society Publishers, Gabriola Island, Canada, 2006, p. 213.

[31] K. H. Young, X. Cai, and S. Chang, “Reviews on the Chinese Patents Regarding Nickel/Metal Hydride Batteries”, *Batteries,* vol. 3, no. 24, p. 60, Aug. 2017.

[32] T. Ouchi, K. H. Young, and D. Moghe, “Reviews on the Japanese Patent Applications Regarding Nickel/Metal Hydride Batteries,” *Batteries,* vol. 2, no. 21, p. 30, Jun. 2016.

[33] S. Chang, K. H. Young, and Y. L. Lien, “Reviews of European Patents on Nickel/Metal Hydride Batteries,” *Batteries,* vol. 3, no. 25, p. 16, Aug. 2017.

[34] K. H. Young, “Research in Nickel/Metal Hydride Batteries 2017”, *Batteries,* vol. 4, no. 1, p. 5, Feb. 2018.

[35] S. B. Cao and F. Y. Huang, “Analysis of the Status Quo and Development of Ni-MH Batteries for Hybrid Electric Vehicles,” *Batteries Bimonthly*, vol. 46, pp. 289-291, Apr. 2016.

[36] K. H. Young, S. Chang, and X. Lin, “C14 Laves Phase Metal Hydride Alloys for NI/MH Batteries Applications,” *Batteries*, vol. 3, no. 27, Sep. 2017.

[37] X. Sun, Z. Li, X. Wang, and C. Li, “Technology Development of Electric Vehicles: A Review,” *Energies*, vol. 13, no. 90, p. 29, Aug. 2020.

[38] K. Liu, W. Zhou, D. Zhu et al., “Excellent High-Rate Capability of Micron Sized Co-Free A-Ni $(OH)_2$ for High Power Ni-MH Battery,” *Journal Alloys & Compounds*, vol. 768, no. 5, pp. 269-276, Nov. 2018.

[39] A. Chu, Y. Yian, J. Zu et al., “The Design and Investigation of a Cooling System for a High-Power Ni-MH Battery Pack in Hybrid Electric Vehicles,” *Applied Sciences*, vol. 10, p. 1660, Mar. 2020.

[40] J. B. Goodenough, “How We Made the Li-Ion Rechargeable Battery,” *Nature Electronics*, vol. 1, p. 204, Mar. 2018.

[41] N. Nitta, F. Wu, J. T. Lee et al., “Li-ion Battery Materials: Present and Future,” *Materials Today*, vol. 18, pp. 252-264. Jun. 2015.

[42] Y. L. Ding, Z. P. Cano, A. Yu et al., “Automotive Li-Ion Batteries: Current Status and Future Perspectives,” *Electrochemical Energy Reviews*, vol. 2, no. 1, pp. 1-28, Mar. 2019.

[43] Z. P. Cano, D. Banham, S. Ye et al., “Batteries and Fuels Cells for Emerging Electric Vehicle Markets,” *Nature Energy*, vol. 3, pp. 279-289, Apr. 2018.

[44] Y. Miao, P. Hynan, A. von Jouanne et al., “Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancement,” *Energies*, vol. 12, p. 20, Mar. 2019.

[45] X. Zeng, M. Li, D. A. El-Hady et al., “Commercialization of Lithium Battery Technology for Electric Vehicles,” *Advanced Energy Materials*, vol. 9. No. 27, Jul. 2019.

[46] P. V. Tichelen, “Preparatory Study on Ecodesign and Energy Labeling of Batteries,” *European Commission Report*, Brussels, BE. Rep. FWC ENER/C3/2015-619-Lot 1, Aug. 2019.

[47] A. Li, A. C. Y. Yuen, W. Wang et al., “A Review of Lithium-Ion Battery Separators Towards Enhanced Safety Performance and Modelling Approaches,” *Molecules*, vol. 26, pp. 15, Jan. 2021.

[48] H. C. Kim, T. J. Wallington, R. Arsenault et al., “Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis,” *Environmental Science & Technology*, vol. 50, pp. 7715-7722, Jun. 2016.

[49] M. Schönemann, *Battery Production and Simulation*. Brussels, BE: Springer, Cham, 2017, pp. 11-37.

[50] W. Xu, J. Wang, F. Ding et al., “Lithium metal Anodes for Rechargeable Batteries,” *Energy & Environmental Science*, vol. 7, pp. 513-537, Oct. 2014.

[51] Y. Li, Y. Lu, P. Adelhelm et al., “Intercalation Chemistry of Graphite: Alkali Metal Ions and Beyond,” *Chemical Society. Review*, vol. 7, p. 34, Jul. 2019.

[52] E. Peled and S. Menken, “Review-SEI: Past, Present and Future,” *Journal of the Electrochemical Society*, vol. 164, no. 7, pp. 1703-1719, Jun. 2017.

[53] S. K. Heiskanen, J. Kim, and B. L. Lucht, “Generation and Evolution of the Solid Electrolyte Interphase of Lithium-Ion Batteries,” *Joule*, vol. 3, pp. 2322-2333, Oct. 2019.

[54] J. F. Ding, R. Xu, C. Yan et al., “A Review on the Failure and Regulation of Solid Electrolyte Interphase in Lithium Batteries,” *Journal of Energy Chemistry,* vol. 59, pp. 306-319, Aug. 2021.

[55] M. J. Lain, I. R. Lopez, and E. Kendrick, “Electrolyte Additions in Lithium-Ion EV Batteries and the Relationship of the SEI Composition to Cell Resistance and Lifetime”, *Electrochem*, vol. 1, pp. 200-216, Jun. 2020.

[56] M. A. Gialampouki, J. Hashemi, and A. A. Peterson, “The Electrochemical Mechanisms of Solid–Electrolyte Interphase Formation in Lithium-Based Batteries,” *The Journal of Physical Chemistry*, vol. 123, pp. 20084-20092, Aug. 2019

[57] M. Li, J. Lu, and X. Ji, “Design Strategies for Nonaqueous Multivalent-Ion and Monovalent-Ion Battery Anodes,” *Nature Reviews Materials*, vol. 5, 276-294, Feb. 2020.

[58] W. Huang, P. M. Attia, H. Wang et al., “Evolution of the Solid–Electrolyte Interphase on Carbonaceous Anodes Visualized by Atomic-Resolution Cryogenic Electron Microscopy,” *Nano Lett*ers, vol. 19, pp. 5140-5148, Jul. 2019.

[59] Y. Yuan, K. Amine, J. Lu et al., “Understanding Materials Challenges for Rechargeable Ion Batteries with in Situ Transmission Electron Microscopy,” *Nature Communications*, vol. 8, p. 14, Aug. 2017.

[60] J. Duan, X. Tang, H. Dai et al., “Building Safe Lithium-Ion Batteries for Electric Vehicles,” *Electrochemical Energy Reviews*, vol. 3, pp. 1-42, Dec. 2020.

[61] T. Ohzuku, A. Ueda, and N. Yamamoto, “Zero-Strain Insertion Material of Li (Li1/3Ti5/3) O4 for Rechargeable Lithium Cells,” *Journal of the Electrochemical Society*, vol. 142, pp. 1431-1435, May. 1995.

[62] T. D. H. Nguyen, H. D. Pham, S-Y. Lin et al., “Featured Properties of Li^+-Based Battery Anode $Li_4Ti_5O_{12}$,” *RSC Advances*, vol. 10, pp. 14071-14079, Apr. 2020.

[63] T. Nemeth, P. Schroer, M. Kuipers et al., “Lithium Titanate Oxide Battery Cells for High-Power Automotive Applications: Electrothermal Properties, Aging Behavior and Cost Considerations,” *Journal of Energy Storage*, vol. 31, p. 101656, Oct. 2020.

[64] L. Zhang, X. Zhang, Q. Zhang et al., “Lithium Lanthanum Titanate Perovskite as an Anode for Lithium-Ion Batteries,” *Nature Communications*, vol. 11, p. 8, Jul. 2020.

[65] Y. B. He, B. Li, M. Liu et al., “Gassing in $Li_4Ti_5O_{12}$-Based Batteries and Its Remedy,” *Scientific Reports*, vol. 2, p. 913, Dec. 2012.

[66] F. Wang, L. Wu, C. Ma et al., “Excess lithium Storage and Charge Compensation in Nanoscale $Li_4+xTi_5O_{12}$,” *Nanotechnology*, vol. 24, no. 24, p. 9, Sep. 2013.

[67] J. Lu, C. Chen, Z. Ma et al., ‘The Role of Nanotechnology in the Development of Battery Materials for Electric Vehicles,” *Nature Nanotechnology*, vol. 11, pp. 1031-1038, Dec. 2016.

[68] H-J. Hong, G. Ban, S-M. Lee et al., “Synthesis of 3D-structured $Li_4Ti_5O_{12}$ from Titanium (IV) Oxysulfate ($TiOSO_4$) Solution as a Highly Sustainable Anode Material for Lithium-Ion Batteries,” *Journal of Alloys & Compounds*, vol. 844, p. 156203, Dec. 2020.

[69] L. A. Ellingsen, C. R. Hung, G. Majeau-Bettez et al., “Nanotechnology for Environmentally Sustainable Electromobility,” *Nature Nanotechnology*, vol. 11 no. 12, pp. 1039-1051, Dec. 2016.

[70] X. Li, P. Huanga, W. Yang et al., “In-situ Carbon Coating to Enhance the Rate Capability of the $Li_4Ti_5O_{12}$ Anode Material and Suppress the Electrolyte Reduction Decomposition on the Electrode,” *Electrochimica Acta*, vol. 190, pp. 69-75, Feb. 2016.

[71] J. K. Yoon, S. Nam, H. C. Shim et al., “Highly-Stable $Li_4Ti_5O_{12}$ Anodes Obtained by Atomic-Layer-Deposited Al2O3,” *Materials*, vol. 11, p. 10, May. 2018.

[72] N. Delaporte, P. Chevallier, and S. Rochon, “A Low-Cost and Li-Rich Organic Coating on a $Li_4Ti_5O_{12}$ Anode Material Enabling Li-Ion Battery Cycling at Subzero Temperatures,” *Material Advances*, vol. 1, pp. 854-872, Jun. 2020.

[73] M. S. Milien, J. Hoffmann, M. Payne, “Effect of Electrolyte Additives on Cycling Performance and Gas Evolution,” *Journal Electrochemical Society*, vol. 165, no. 16, pp. A3925-A3931, Dec. 2018.

[74] M. R. Palacin, “Recent Advances in Rechargeable Battery Materials: A Chemist’s Perspective,” *Chemical Society Reviews*, vol. 38, pp. 2565-2575, Jun. 2009.

[75] R. Borah, F. R. Hughson, J. Johnston et al., “On Battery Materials and Methods,” *Materials Today Advances*, vol. 6, p. 22, Jun. 2020.

[76] Y. Wu, X. Huang, L. Huang et al., “Strategies for Rational Design of High-power Lithium-Ion Batteries,” *Energy & Environmental Materials*, vol. 4, pp. 19-45, May 2021.

[77] S-H. Yu, S. H. Lee, D. J. Lee, et al. “Conversion Reaction-Based Oxide Nanomaterials for Lithium-Ion Battery Anodes,” *Small*, vol. 12, pp. 2146-2172, Dec. 2016.

[78] S-H. Yu, X. Feng, N. Zhang et al., “Understanding Conversion-Type Electrodes for Lithium Rechargeable Batteries,” *Accounts of Chemical Research*, vol. 51, no. 2, pp. 273-281, Jan. 2018.

[79] Q. Cui, Y. Zhong, L. Pan et al., “Recent Advances in Designing High-Capacity Anode Nanomaterials for Li-Ion Batteries and Their Atomic-Scale Storage Mechanism Studies,” *Advanced Science*, vol. 5, p. 22, Apr. 2018.

[80] T. W. Kwon, J. W. Choi, and A. Coskun, “The Emerging Era of Supra-Molecular Polymeric Binders in Silicon Anodes,” *Chemical Society Reviews*, vol. 47, pp. 2145-2164, Feb. 2018.

[81] N. Yuca, O. S. Taskin, and E. Arici, “An Overview of Efforts to Enhance the Si Electrode Stability for Lithium-Ion Batteries,” *Energy Storage*, vol. 2, no. 94, pp, 15, Oct. 2020.

[82] Y-M. Zhao, F-S. Yue, S-C. Li et al., “Advances of Polymer Binders for Silicon-Based Anodes in High Energy Lithium-Ion Batteries,” *InfoMat*, vol. 2, pp. 460-501, Mar. 2021.

[83] S. Li, Z-Gu. Wu, Y-M. Liu et al., “A Compared Investigation of Different Biogum Polymer Binders for Silicon Anode of Lithium-Ion Batteries,” *Ionics*, vol. 27, pp.1829-1836, Mar. 2021.

[84] R. Schmuch, Z. G. Wu, Y-M. Liu et al., “Performance and Cost of Materials for Lithium-Based Rechargeable Automotive Batteries,” *Nature Energy*, vol. 3, pp. 267-278, Apr. 2018.

[85] J. Asenbaue, T. Eisenmann, M. Kuenzel et al., “The Success Story of Graphite as a Lithium-Ion Anode Material-Fundamentals, Remaining Challenges, and Recent Developments Including Silicon (Oxide) Composites,” *Sustainable Energy Fuels*, vol. 4, pp. 5387-5416, May 2020.

[86] T. Chen, J. Wu, Q. Zhang et al., “Recent Advancement of Siox Based Anodes for Lithium-Ion Batteries,” *Journal of Power Sources*, vol. 363, pp. 126-144, Sep. 2017.

[87] Z. Liu, Q. Yu, and Y. Zhao, “Silicon Oxides: A Promising Family of Anode Materials for Lithium-Ion Batteries,” *Chemical Society Reviews*, vol. 48, pp. 285-309, Dec. 2019.

[88] J. Frazelle, “Battery Day,” *ACM Queue*, vol. 8, no. 5, pp. 5-25, Oct. 2020.

[89] E. Fox. (2020, Sep. 28). *Tesla Silicon Anode for 4680 Battery Cell: What’s the Secret?* [Online]. Available: https://www.tesmanian.com/blogs/tesmanian-blog/tesla-silicon-the-new-4680-battery-cell-anode

[90] COBRA. (2021, Jul. 10). *Tesla vs COBRA: A look at Tesla’s Battery Day*. [Online]. Available: https//projectcoobra.eu/2020/10/10/tesla-vs-cobratesla-vs-cobra-battery-day

[91] MINING.COM. (2021, Mar. 30). *NEO’s Silicon Anodes Achieve Long-Term Cycling*. [Online]. Available: https://www.mining.com/neos-silicon-anodes-achieve-long-term-cycling/

[92] N. Willing. (2021, Jan. 29). *Battery Makers Expand Silicon Anode Production*. [Online]. Available: https://www.argusmedia.com/en/news/2182042-battery-makers-expand-silicon-anode-production

[93] Y. Che, Y. Luo, H. Zhang, “The Challenge of Lithium Metal Anodes for Practical Applications,” *Small Methods*, vol. 3, no. 7, p. 23, Apr. 2019.

[94] R. Wang, W. Cui, F. Cu et al. “Lithium metal Anodes Present and Future,” *Journal of Energy Chemistry*, vol. 48, pp. 145-159, Sep. 2021.

[95] D. Lin, Y. Liu, and Y. Cui, “Reviving the Lithium Metal Anode for High-Energy Batteries,” *Nature Nanotechnology*, vol. 2, pp.194-206, Mar. 2017.

[96] Y. Han, B. Liu, Z. Xiao et al., “Interface Issues of Lithium Metal Anode for High-Energy Batteries: Challenges, Strategies, and Perspectives,” *InfoMat*, vol. 3, pp. 155-174, Jan. 2021.

[97] G. Zubi, R. Dufo-Lópeza, M. Carvalho et al., “The Lithium-Ion Battery: State of the Art and Future Perspectives,” *Renewable & Sustainable Energy Reviews*, vol. 89, pp. 292-308, Jun. 2018.

[99] K. Shang. (2021, Jul. 20). *Lithium-ion Batteries: LFP Cathode Materials Market Share Forecast to Increase in 2021*. [Online]. Available: https://roskill.com/news/lithium-ion-batteries-lfp-cathode-materials-market-share-forecast-to-increase-in-2021/

[100] J. Li, M. Weng, Y. Qiu et al., “Structural Origin of The High-Voltage Instability of Lithium Cobalt Oxide,” *Nature Nanotechnology*, vol. 16, pp. 599-605, Feb. 2021.

[101] J-N. Zhang, Q. Li, C. Ouyang et al., "Trace Doping of Multiple Elements Enables Stable Battery Cycling of Licoo2 at 4.6V," *Nature Energy*, vol. 4, pp. 594-603, Jun. 2019.

[102] K. Wang, J. Wang, Y. Xian et al., "Recent Advance and Historical Developments of High Voltage Lithium Cobalt Oxide Materials for Rechargeable Lithium-Ion Batteries," *Journal Power Sources*, vol. 460, p. 228062, Jun. 2020.

[103] Y. Lyu, X. Wu, K. Wang et al., "An Overview of the Advances of LicoO$_2$ Cathodes for Lithium-Ion Batteries," *Advanced Energy Materials*, vol. 11, no. 2, p. 2000982, Jun. 2020.

[104] S. Muto, Y. Sasano, K. Tatsumi et al., "Capacity-Fading Mechanisms of LiNiO$_2$-Based Li-ion Batteries. II. Diagnostic Analysis by Electron Microscopy and Spectroscopy," *Journal of Electrochemical Society*, vol. 156, pp. A371-A377, Mar. 2009.

[105] J. Xu, F. Lin, M. M. Doeff et al., "A Review of Ni-based Layered Oxides for Rechargeable Li-ion Batteries," *Journal of Materials Chemistry A*, vol. 5, pp. 874-901, Nov. 2017.

[106] C. H. Chen, J. Liua, M. E. Stoll et al., "Aluminium-Doped Lithium Nickel Cobalt Electrodes for High-Power Lithium-Ion Batteries," *Journal of Power Sources*, vol. 125, no. 2, pp. 278-285, Apr. 2004.

[107] A. Purwanto, C. S. Yudha, U. Ubaidillah et al., "NCA Cathode Material: Synthesis Methods and Performance Enhancement Efforts," *Materials Research Express*, vol. 5, no. 2, p. 122001, Sep. 2018.

[108] C. M. Julien and A. Mauger, "NCA, NCM 811 and the Route to Ni-Richer Lithium-Ion Batteries," *Energies,* vol. 13, no. 23, p. 46, Dec. 2020.

[109] K. Zhou, Q. Xiea, B. Li et al., "An In-Depth Understanding of The Effect of Aluminum Doping in High-Nickel Cathodes for Lithium-Ion Batteries," *Energy Storage Materials*, vol. 34, pp. 229-240, Jan. 2021.

[110] NISSAN. (2021, Jul. 10). *Accelerating Toward Carbon Neutrality*. [Online]. Available: https://www.nissan-gloobal.com/ENTECHNOLOGY/li on ev.thml

[111] X. Li, Y. Yu, and C. Wang, "Suppression of Jahn-Teller Distortion of Spinel Limn$_2$O$_4$ Cathode," *Journal of Alloys & Compounds*, vol. 479, pp. 310-313, Jun. 2009.

[112] J. P. Pender, "Electrode Degradation in Lithium-Ion Batteries," *ACS Nano*, vol. 14, pp. 1243-1295, Jan. 2020.

[113] C. Zuo, Z. Hu, R. Qi et al., "Double the Capacity of Manganese Spinel for Lithium-Ion Storage by Suppression of Cooperative Jahn-Teller Distortion," *Advanced Energy Materials*, vol. 10, no. 34, p. 10, Sep. 2020.

[114] A-H. Marincas, F. Goge, S. A. Dorneanu et al., "Review on synthesis methods to obtain LiMn$_2$O$_4$-Based Cathode Materials for Li-ion Batteries," *Journal Solid State Electrochemistry*, vol. 24, pp. 473-497, Jan. 2020.

[115] S. Lui, B. Wang, X. Zhang et al., "Reviving the Lithium-Manganese -Based Layered Oxide Cathodes for Lithium-Ion Batteries," *Matte*r, vol. 4, no. 5, pp. 1511-1527, May 2021.

[116] L. Yang, K. Yang, and J. Zhang, "Harnessing Surface Structure to Enable High-Performance Cathode Materials for Lithium-Ion Batteries," *Chemical Society Reviews*, vol. 49, pp. 4667-4680, Jan. 2020.

[117] G. Xu, C. Zhang, C. Cui et al., "Strategies for Improving the Cyclability and Thermo-Stability of LiMn$_2$O$_4$-Based Batteries at Elevated Temperatures," *Journal Materials Chemistry A*, vol. 3, pp. 4092-4123, Feb. 2015.

[118] W. Liu, J. Chen, S. Ji et al., "Enhancing the Electrochemical Performance of the LiMn$_2$O$_4$ Hollow Microsphere Cathode with LiNi$_{0.5}$Mn$_{1.5}$O$_4$ Coated Layer," *Chemistry Europe Journal*, vol. 20, no. 3, pp. 824-830, Jan. 2014.

[119] L. Wen, X. Wang, G. Q. Liu et al., "Novel Surface Coating Strategies for Better Battery Materials," *Surface Innovations*, vol. 6, no. 1-2, pp.13-18, Mar. 2018.

[120] P. Ye, H. Dong, Y. Xu et al., "Nico$_2$O$_4$ Surface Coating Li [Ni0.03Mn1.97] O$_4$ Micro-/Nano-Spheres as Cathode Material for High-Performance Lithium-Ion Battery," *Applied Surface Science*, vol. 428, pp. 469-477, Sep. 2018.

[121] T. Kozawa, T. Harata, and M. Naito, "Fabrication of an LiMn$_2$O$_4$@LiMnPO$_4$ Composite Cathode for Improved Cycling Performance at High Temperatures," *Journal of Asian Ceramic Societies*, vol. 8, no. 2, pp. 309-317, Mar. 2020.

[122] V. Selvamani, N. Phattharasupakun, J. Wutthipron et al., "High-Performance Spinel LiMn$_2$O$_4$@Carbon Core-Shell Cathode Materials for Li-Ion Batteries," *Sustainable Energy & Fuels,* vol. 3, pp. 1988-1994, May. 2019.

[123] J. Lu, B. Song, H. Xia et al., "High Energy Spinel-Structured Cathode Stabilized by Layered Materials for Advanced Lithium-Ion Batteries," *Journal Power Sources,* vol. 271, pp. 604-613, Dec. 2014.

[124] J. Wu, Z. Cui, J. Wu et al., "Suppression of Voltage-Decay in Li$_2$MnO$_3$ Cathode via Reconstruction of Layered-Spinel Co-exist Phases," *Journal Materials Chemistry A*, vol. 8, pp. 18687-18697, Aug. 2020.

[125] S. Liu and H. Yu, "Toward Functional Units Constructing Mn-Based Oxide Cathodes for Rechargeable Batteries," *Science Bulletin*, vol. 66, no. 13*,* pp. 1260-1262, Jul. 2021.

[126] X. Zhu, F. Meng, Q. Zhang et al., "LiMnO$_2$ Cathode Stabilized by Interfacial Orbital Ordering for Sustainable Lithium-Ion Batteries," *Nature Sustainability*, vol. 4, pp. 392-401, Dec. 2021.

[127] S. Kaewma, N. Wiriya, P. Chantrasuwan, "Multiscale Investigation Elucidating the Structural Complexities and Electrochemical Properties of Layered-Layered Composite Cathode Materials Synthesized at Low Temperatures," *Physical Chemistry Chemical Physics*, vol. 22, no. 10, pp. 5439-5448, Jan. 2020.

[128] D. Andre, S. J. Kim, P. Lump et al., "Future generations of Cathode Materials: An Automotive Industry Perspective," *Journal Material Chemistry A*, vol. 3, pp. 6709-6732, Feb. 2015.

[129] Y. Chen, S. Song, X. Zhang et al., "The Challenges, Solutions, and Development of High-Energy Ni-rich NCM/NCA Lib Cathode Materials," *Journal of Physics: Conference Series*, vol. 1347, p. 9, Jun. 2019.

[130] J. L. Choi, "Recent Progress and Perspective of Advanced High-Energy Co-Less Ni-Rich Cathodes for Li-Ion Batteries: Yesterday, Today and Tomorrow," *Advanced Energy Materials*, vol. 10, p. 31, Sep. 2020.

[131] N. Mohamed and N. K. Allam, "Recent Advances in the Design of Cathode Materials for Li-Ion Batteries," *RSC Advances*, vol. 10, pp. 2162-21685, Jun. 2020.

[132] X. Shen, "Advanced Electrode Materials in Lithium Batteries: Retrospect and Prospect," *Energy Material Advances*, vol. 2021, p. 15, Jun. 2021.

[133] S. W. D. Gourley, T. Or, and Z. Chen, "Breaking Free from Cobalt Reliance in Lithium-Ion Batteries," i*Science*, vol. 23, no. 9, p. 16, Aug. 2020.

[134] K. B-wook. (2021, Jul. 10). *SK Makes World's 1st NCM Battery with 90% Nickel*. [Online]. Available: https//www.koreaherald.com/view.php?ud=20200810000683

[135] H-J. Kim, TNV. Krishna, K. Zeb et al., "A Comprehensive Review of Li-Ion Battery Materials and Their Recycling Techniques," *Electronics*, vol. 9, p. 45, Jul. 2020.

[136] S. Duhnen, J. Betz, M. Kolek et al., "Towards Green Battery Cells: Perspective on Materials and Technologies," *Small Methods*, vol. 4, pp. 1-38, Apr. 2020.

[137] D. Matthews, "Global Value Chains: Cobalt in Lithium-ion Batteries for Electric Vehicles," U.S. International Trade Commission, Washington DC, USA, Rep. ID-067, May 18, 2020.

[138] M. Azevedo, N. Campagnol, and T. Hagenbruch. (2018, Jun 22). *Lithium and Cobalt-A Tale of Two Commodities*. [Online]. Available: https//www.mckinsey.com/industries/metals-and-mining/our-insights/lithium-and-cobalt-a-tale-of-two-commodities

[139] I. Belharouak, J. Nanda, E. Self et al., "Operation, Manufacturing and Supply Chain of Lithium-Ion Batteries for Electric Vehicles," Oak Ridge National Laboratory, Oak Ridge, USA, Rep. ORNL/TM-2020/172955, Jan. 1, 1996.

[140] J. Baars, T. Domenech, R. Bleischwitz et al., "Circular Economy Strategies for Electric Vehicle Batteries to Reduce Reliance on Raw Materials," *Nature Sustainability*, vol. 4, pp. 71-79, Sep. 2021.

[141] UNCTAD, "Commodities at a Glance: Special Issue on Strategic Battery Raw Materials," UNCTAD, Geneva, CH, Rep. No. 13, Jun. 13, 2020.

[142] X. Yu and A. Manthiram, "Sustainable Battery Materials for Next-Generation Electrical Energy Storage," *Advanced Energy Sustainability Research*, vol. 2, pp. 2-12, Jun. 2021.

[143] S-T. Myung, F. Maglia, and K-J. Park "Nickel-Rich Layered Cathode Materials for Automotive Lithium-Ion Batteries: Achievements and Perspectives," *ACS Energy Lett*., vol. 2, no. 1, pp. 196-223, Dec. 2017.

[144] T. Li, X-Z. Yuan, L. Zhang et al., "Degradation Mechanisms and Mitigation Strategies of Nickel-rich NMC-Based Lithium-Ion Batteries," *Electrochemical Energy Reviews*, vol. 3, pp. 43-80, Oct. 2020.

[145] P. Teichert, G. G. Eshetu, H. Jahnke et al., "Degradation and Aging Routes of Ni-Rich Cathode Based Li-Ion Batteries," *Batteries*, vol. 6, no. 8, Jan. 2020.

[146] M. Armand, P. Axmannb, D. Bresser et al., "Lithium-Ion Batteries-Current State of the Art and Anticipated Developments," *Journal of Power Sources*, vol. 479, p. 26, Dec. 2020.

[147] L. Liu, M. Lia, L. Chu et al., "Layered Ternary Metal Oxides: Performance Degradation Mechanisms as Cathodes, and Design Strategies for High-Performance Batteries," *Progress in Mat. Science*, vol. 111, p. 85, Jun. 2020.

[148] L. Song, J. Du, Z. Xiao et al., "Research Progress on the Surface of High-Nickel-Cobalt-Manganese Ternary Cathode Materials: A Mini Review," *Frontiers in Chemistry*, vol. 8, p. 8, Aug. 2020.

[149] A. L. Lipson, J. L. Durham, M. LeResche et al., "Improving the Thermal Stability of NMC622 Li-ion Battery Cathodes Through Doping During Coprecipitation," *ACS Applied Material Interfaces*, vol. 12, pp.18512-18518, Apr. 2020.

[150] X. Chen, F. Ma, Y. Li et al., "Nitrogen-Doped Carbon Coated $LiNi_{0.6}Co_{0.2}Mn_{0.2}O_2$ Cathode with Enhanced Electrochemical Performance for Li-Ion Batteries," *Electrochimica Acta*, vol. 284, pp. 526-533, Sep. 2018.

[151] L. Zhu, T. F. Yan, D. Jia et al., "$LiFePO_4$-Coated $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ Cathode Materials with Improved High Voltage Electrochemical Performance and Enhanced Safety for Lithium-Ion Pouch Cells," *Journal Electrochemical Society*, vol. 166, pp. A5437-A5444, Jan. 2019.

[152] Y. B. Cao, X. Qi, K. H. Hu et al., "Conductive Polymers Encapsulation to Enhance Electrochemical Performance of Ni-rich Cathode Materials for Li-Ion Batteries," *ACS Applied Materials & Interfaces*, vol. 10, pp. 18270-18280, May 2018.

[153] G. L. Xu, Q. Liu, K. K. S. Lau et al., "Building Ultraconformal Protective Layers on Both Secondary and Primary Particles of Layered Lithium Transition Metal Oxide Cathodes," *Nature Energy*, vol 4, pp. 484-494, May 2019.

[154] J. Sagoff. (2019, May 14). *New Argonne Coating Could Have Big Implications for Lithium Batteries*. [Online]. Available: https://www.anl.gov/article/ new-argonne-coating-could-have-big-implications-for-lithium-batteries

[155] T. Wu, X. Liu, X. Zhang et al., "Full Concentration Gradient-Tailored Li-rich Layered Oxides for High-Energy Lithium-Ion Batteries," *Advanced Materials*, vol. 33, no. 2, p. 10, Nov. 2020.

[156] S. Maeng, Y. Chungb, S. Min et al., "Enhanced Mechanical Strength and Electrochemical Performance of Core-Shell Structured High-Nickel Cathode Material," *Journal of Power Sources,* vol. 448, no. 1, p. 227395, Feb. 2020.

[157] P. Yan, J. Zheng, J. Liu et al., "Tailoring Grain Boundary Structures and Chemistry of Ni-rich Layered Cathodes for Enhanced Cycle Stability of Lithium-Ion Batteries," *Natural Energy*, vol. 3, pp. 600-605, Jul. 2018.

[158] C. Wang, R. Yua, S. Hwang et al., "Single Crystal Cathodes Enabling High-Performance All-Solid-State Lithium-Ion Batteries," *Energy Storage Materials*, vol. 30, pp. 98-103, Sep. 2020.

[159] L. Zheng, J. C. Bennett, and M. N. Obrovac, "All-Dry Synthesis of Single Crystal NMC Cathode Materials for Li-Ion Batteries," *Journal Electrochemical Society*, vol. 167, p. 130536, Oct. 2020.

[160] Q. Wu, S. Mao, Z. Wang et al., "Improving $LiNi_xCo_yMn_{1-x-y}$ Cathode Electrolyte Interface Under High Voltage in Lithium-Ion Batteries," *Nano Select*, vol. 1, pp. 111-134, Jun. 2020.

[161] Z. Ahsan, B. Ding, Z. Cai et al., "Recent Progress in Capacity Enhancement of $LiFePO_4$ Cathode for Li-Ion Batteries," *Journal Electrochem, Energy Conservation & Storage*, vol. 18, p. 15, Feb. 2021.

[162] R. Zhao, J. Liu, and F. Ma, "Cathode Chemistries and Electrode Parameters Affecting the Fast Charging Performance of Li-Ion Batteries," *Journal Electrochem, Energy Conservation & Storage*, vol. 17, p. 13, May 2020.

[163] J. Hu, W. Huang, L. Yang et al., "Structure and Performance of The $LiFePO_4$ Cathode Material: From the Bulk to the Surface," *Nanoscale*, vol. 12, pp. 15036-15044, Jun. 2020.

[164] Y-M Xin, H-Y. Xu, J-H Ruan et al., "A Review on Application of $LiFePO_4$ Based Composites as Electrode Materials for Lithium-Ion Batteries," *International Journal of Electrochemical Science*, vol. 16, p. 18, Jun. 2021.

[165] Wall Street Journal. (2021, Jul. 10). *Low-cost EV Battery Wins Fans in China*. [Online]. Available: https//www.wsj.com/article/elon-musk-linkk-this-ev-battery-and-it-costs-lessbut-the-u-s-isnt-on-it-11616929201

[166] E. Els. (2011, Mar. 11). *Cobalt, Nickel Free Electric Car Batteries are a Runaway Success*. [Online]. Available: https://www.mining.com/cobalt-nickel-free-electric-car-batteries-are-a-runaway-success/

[167] ROSKILL. (2020, Jun. 25). *Batteries: The True Drivers Behind LFP Demand-New Safety Standards, Costs, IP Rights, ESG & Simplified Battery Pack Designs*. [Online]. Available: https://roskill.com/news/batteries-the-true-drivers-behind-lfp-demand-new-safety-standards-costs-ip-rights-esg-simplified-battery-pack-designs/

[168] X-G. Yang, T. Liu, and C-Y Wang, "Thermally Modulated Lithium Iron Phosphate Batteries for Mass-Market Electric Vehicles," *Nature Energy*, vol. 6, pp.176-185, Jan. 2021.

[169] N. Tolganbek, Y. Yerkinbekova, S. Kalybekkyzy et al., "Current State of High Voltage Olivine Structured $LiMPO_4$ Cathode Materials for Energy Storage Applications: A Review," *Journal Alloys & Compounds*, vol. 882, p. 16, Nov. 2021.

[170] J. Ma, Y. Li, N. S. Grundish et al., "The 2021 Battery Technology Roadmap," *Journal of Physics D: Applied Physics*, vol. 54, p. 44, Sep. 2021.

[171] A. E. Kharbachi, O. Zavorotynska, M. Latroche et al., "Exploits, Advances, and Challenges Benefiting Beyond Li-Ion Battery Technologies," *Journal Alloys & Compounds,* vol. 817, p. 26, Sep. 2020.

[172] D. Chao, W. Zhou, F. Xie et al., "Roadmap for Advanced Aqueous Batteries: From Design of Materials to Applications," *Science Advances*, vol. 6, no. 21, pp. 1-19, May 2020.

[173] J. Janek and W. G. Zeier, "A solid Future for Battery Development," *Nature Energy*, vol. 1, p. 16141, Sep. 2016.

[174] S. Randau, D. A. Weber, O. Kotz et al., "Benchmarking the Performance of All-Solid-State Lithium Batteries," *Nature Energy*, vol. 5, pp. 259-270, Mar. 2020.

[175] Z. Wang, J, Liu, M, Wang et al., "Toward Safer Solid-State Lithium Metal Batteries," *Nanoscale Advances*, vol. 5, p. 9, Apr. 2020.

[176] S. Ferrari, M. Falco, and A. B. Munoz-Garcia, "Solid-State Post Li Metal Ion Batteries: A Sustainable Forthcoming Reality," *Advanced Energy Materials*, vol. 10, p. 30, Jun. 2021.

[177] Z. Zhang, Y. Shao, B. Lotsch et al., "New Horizons for Inorganic Solid State Ion Conductors," *Energy & Environmental Science*, vol. 11, pp. 1945-1976, Jun. 2018.

[178] G. Yang, C. Abraham, Y. Ma et al., "Advances in Materials Design for All-Solid-State Batteries: From Bulk to Thin Films," *Applied Sciences*, vol. 10, 4727, p. 50, Jul. 2020.

[179] S. Ball, J. Clark, and J. Cookson, "Battery Materials Technology Trends and Market Drivers for Automotive Applications," *Johnson Matthey Technology Review*, vol. 64, no. 3, pp. 287-297, Jul. 2020.

[180] D. Karabelli, K. P. Birke, and M. Weber, "A Performance and Cost Overview of Selected Solid-State Electrolytes: Race between Polymer Electrolytes and Inorganic Sulphides," *Batteries,* vol. 7, no. 18, p. 13, Mar. 2021.

[181] T. Zhang, W. He, W. Zhang et al., "Designing Composite Solid-State Electrolytes for High Performance Lithium Ion or Lithium Metal Batteries," *Chemical Science*, vol. 11, pp. 8686-8707, Jul. 2020.

[182] S. Li, S-Q Zhang, L. Shen et al., "Progress and Perspective of Ceramic/Polymer Composite Solid Electrolytes for Lithium Batteries," *Advanced Science*, vol. 7, p. 22, Jan. 2020.

[183] Z. Ding, J. Li, J. Li et al., "Review-Interfaces: Key Issue to be Solved for All Solid-State Battery Technologies," *Journal Electrochemical Society*, vol. 167, p. 19, Jun. 2020.

[184] S. Lou, F. Zhang, C. Fu et al., "Interface Issues and Challenges in All-Solid-State Batteries: Lithium, Sodium and Beyond," *Advanced Materials*, vol. 33, no. 6, p. 29, Jul. 2020.

[185] C. Singer, J. Schnell, and G. Reinhart, "Scalable processing Routes for the Production of All-Solid-State Batteries-Modeling Interdependencies of Product and Process," *Energy Technologies*, vol. 9, p. 14, Oct. 2021.

[186] K. J. Huang, G. Reder, and E. A. Olivetti, "Manufacturing Scalability Implications of Materials Choice in Inorganic Solid-State Batteries," *Joule*, vol. 5, no. 3, pp. 564-580, Mar. 2021.

[187] E. Sugiura. (2021, May 28). *Can Japan and Toyota win the Solid-State Battery Race?* [Online]. Available: https://asia.nikkei.com/Business/Business-Spotlight/Can-Japan-and-Toyota-win-the-solid-state-battery-raceToyota solid state

[188] K. Chayabuka, G. Moulder, D. L. Danilov et al., "From Li-Ion Batteries Toward Na-Ion Chemistries: Challenges and Opportunities," *Advanced Energy Materials*, vol. 10, p. 11, Aug. 2020.

[189] K. M. Abraham, "How Comparable are Sodium-Ion Batteries to Lithium-Ion Counterparts?," *ACS Energy Letters*, vol. 5, pp. 3544-3547, May 2020.

[190] M. Mirzaelan, Q. Abbas, M. R. C. Hunt et al., "Na-Ion Batteries," in *Encyclopedia of Smart Materials*, A. G. Olabi, Ed. Amsterdam, NLD: Elsevier, 2021, p. 14.

[191] M. Arnaiz, J. L. Gomez-Camer, N. E. Drewett et al., "Exploring Na-ion Technological Advances: Pathways from Energy to Power," *Materials Today Proceedings*, vol. 39, pp. 1118-1131, Apr. 2021.

[192] H. Zhao, N. Deng, J. Yan et al., "A Review on Anode for lithium-Sulphur Batteries: Progress and Prospects," *Chemical Engineering* Journal, vol. 347, pp. 343-365, Sep. 2018.

[193] M. Zhao, B-Q. Li, X-Q. Zhang et al., "A Perspective toward Practical Lithium-Sulphur Batteries," *ACS Central Science,* vol. 6, p. 1095-1104, Jun. 2020.

[194] N. R. Levy and Y. Ein-Eli, "Aluminium-Ion Battery Technology: A Rising Star or a Devastating Fall," *Journal Solid State Electrochemistry*," vol. 24, pp. 2067-2071, Apr. 2020.

[195] S. Hosseini, S. M. Soltani, and Y. Y. Li, "Current Status and Technical Challenges of Electrolytes in Zinc-Air Batteries: An in-Depth Review," *Chemical Engineering Journal*, vol. 408, p. 127241, Mar. 2021.

[196] B. Esser, F. Dolhem, M. Becuwe et al., "A Perspective on Organic Electrode Materials and Technologies for Next Generation Batteries," *Journal Power Sources*, vol. 482, p. 24, Jan. 2021.

[197] G. Karkera, M. A. Reddy, and M. Fichner, "Recent Developments and Future Perspectives of Anionic Batteries," *Journal of Power Sources*, vol. 481, no. 22, p. 17, Jan. 2021.

[198] M. M. Rahman, I. Sultana, Y. Fan et al., "Strategies, Design and Synthesis of Advanced Nanostructured Electrodes for Rechargeable Batteries," *Materials Chemistry Frontiers*, vol. 16, p. 35, Jun. 2021.

[199] D. E. Demirocak, S. S. Srinivasan, and E. K. Stefanakos, "A Review on Nanocomposite Materials for Rechargeable Li-ion Batteries," *Applied Sciences*, vol. 7, no. 7, p. 731, Jul. 2017.

[200] J. E. Knoop and S. Ahn, "Recent Advances in Nanomaterials for High-Performance Li-S Batteries," *Journal Energy Chemistry*, vol. 47, pp. 86-106, Aug. 2020.

[201] J. B. Dunn, L. Gaines, J. C. Kelly et al., "The Significance of Li-Ion Batteries in Electric Vehicle Life-Cycle Energy and Emissions and Recycling's Role in its Reduction," *Energy & Environmental Science*, vol. 8, pp. 158-168, Nov. 2015.

[202] G. Harper, R. Sommerville, E. Kendrick et al., "Recycling Lithium-Ion Batteries from Electric Vehicles," *Nature*, vol. 575, pp. 75-86, Nov. 2019.

[203] L. C. Casals, B. A. Garcia, and C. Canal, "Second Life Batteries Lifespan: Rest of Useful Life and Environmental Analysis," *Journal Environmental Management*, vol. 232, pp. 354-363, Nov. 2019.

[204] J. Bacher, E. Pohjalainen, E. Yli-Rantala et al., "Environmental Aspects Related to the use of Critical Raw Materials in Priority Sectors and Value Chains," European Environment Agency, Copenhagen, DNK, Re. ETC/WMGE 2020/5, Dec. 15, 2020.

[205] H. E. Melin. (2029, Mar. 29). *State-of-the-Art in Reuse and Recycling of Lithium-Ion Batteries*. [Online]. Available: https://www.linkedin.com/pulse/state-of-the-art-lithium-ion-battery-reuse-recycling-research-melin

[206] A. Beaudet, F. Larouche, K. Amouz et al., "Key Challenges and Opportunities for Recycling Electric Vehicle Battery Materials," *Sustainability*, vol. 12, no. 14, p. 12, Jul. 2020.

[207] X. B. Cheng, H. Liu, H. Yuan et al., "A Perspective on Sustainable Energy Materials for Lithium Batteries," *SusMat.* vol. 1, pp. 38-50, Mar. 2021.

[208] X. Yu and A. Manthiram, "Sustainable Battery Materials for Next-Generation Electrical Energy Storage," *Advanced Energy Sustainability Research*, vol. 2, no. 5, p. 12, Jan. 2021.

[209] S. Doose, J. K. Mayer, and P. Michalowski, "Challenges in Ecofriendly Battery Recycling and Closed Materials Cycles: A Perspective on Future Lithium Battery Generations," *Metals*, vol. 11, p. 17, Feb. 2021.

[210] Y. Liu, R. Zhang, J. Wang et al., "Current and Future lithium-Ion Battery Manufacturing," *iScience*, vol. 24, p. 17, Apr. 2021.

[211] P. Cooke, "Gigafactory Logistics in Space and Time: Tesla's Fourth Gigafactory and Its Rivals," *Sustainability,* vol. 12, p. 16, Mar. 2020.

[212] Greenpeace. (2021, Jul. 10). *Greenpeace Report Troubleshoots China's Electric Vehicles Boom, Highlights Critical Supply Risks for Lithium-Ion Batteries*. [Online]. Available: https://www.greenpeace.org/eastasia/press/6175/greenpeace-report-troubleshoots-chinas-electric-vehicles-boom-highlights-critical-supply-risks-for-lithium-ion-batteries/

[213] P. Bhandubanyong and J. T. H. Pearce, "Materials on Wheels: Moving to Lighter Auto-Bodies," *International Scientific Journal of Engineering and Technology*, vol. 2, no.1, pp. 27-36, Jun. 2018.

[214] P. Bhandubanyong and J. T. H. Pearce, "Going Electric: Some Materials Aspects for the Thai Automotive Industry," *Materials Science*, vol. 36, pp. 4-6, Jan. 2019.

[215] A&L. (2020, Nov. 23). *Aluminium for Battery Containers in Electric Cars*. [Online]. Available: https://www.publiteconline.it/ael/aluminium-for-battery-containers-in-electric-cars-3/

[216] F. Lambert. (2021, Jan. 19). *First Look at Tesla's New Structural Battery Pack that will Power its Future Vehicles*. [Online]. Available: https://electrek.co/2021/01/19/tesla-structural-battery-pack-first-picture/

[217] M. Schröder, "Electric Vehicle and Electric Vehicle Component Production in Thailand," ERIA, Jakarta: IDN, Re. FY2021 no. 03, May 7, 2021.

[218] Kasikorn. (2029, Jan. 30). *Thailand is Poised to Produce over 430,000 units of EV Batteries in 5 Years, Becoming 4th Largest Production Base in Asia*. [Online]. Available: https://www.kasikornresearch.com/en/analysis/k-econ/business/Pages/z2960.aspx

[219] Thailand Board of Investment. (2021, Jul. 20). *Thailand Car Makers Ramp Up Electric Vehicle Production Capacity in Thailand, Investment Board Says*. [Online]. Available: https://www.boi.go.th/un/boi_event_detail?module=news&topic_id=125377

[220] Batteries Directive. (2021, Jul. 10). *European Parliamentary Research Service*. [Online]. Available: https://www.europarl.Eu/RegData/etudes/BRIE/2020/654184/EPRBRI(2020)654184_EN.pdf

[221] TGGS. (2021, Jul. 10). *NSTDA in collaboration with KKU KMUTT KMUTNB and EVAT to find Thailand Energy Storage Technology Alliance (TESTA).* [Online]. Available: https://tggs.kmutnb.ac.th/nstda-in-collaboration-with-kku-kmutt-kmutnb-and-evat-to-find-thailand-energy-storage-technology-alliance-testa

[222] EVAT. (2021, Jul. 10). *Thailand's Automotive Industry and Current EV Status*. [Online]. Available: https://www.boi.go.th/upload/content/2.%20[PPT]%20Thailand's%20Automotive%20Industry%20and%20Current%20EV%20Status_5c864c90761f6.pdf

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