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Implications of the Electric Vehicle Manufacturers' Decision to Mass Adopt Lithium-Iron Phosphate Batteries

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ABSTRACT Lithium-ion batteries are the ubiquitous energy storage device of choice in portable electronics and more recently, in electric vehicles. However, there are numerous lithium-ion battery chemistries and in particular, several cathode materials that have been commercialized over the last two decades, each with their own unique features and characteristics. In 2021, Tesla Inc. announced that it would change the cell chemistry used in its mass-market electric vehicles (EVs) from Lithium-Nickel-Cobalt-Aluminum-Oxide (NCA) to cells with Lithium-Iron-Phosphate (LFP) cathodes. Several other automakers have followed this trend by announcing their own plans to move their EV production to LFP. One of the reasons stated for this transition was to address issues with the nickel and cobalt supply chains. In this paper, we examine the trend of adopting LFP for mass-market electric vehicles, explore alternative reasons behind this transition, and analyze the effects this change will have on consumers.

INDEX TERMS Electric vehicles, lithium-ion batteries, battery performance, market trends.

I. INTRODUCTION

Lithium-ion (Li-ion) batteries currently dominate the market for commercial rechargeable batteries. Since the commercialization of the first Li-ion cells in the 1990s, improvements in cell components, materials, and mechanisms within these batteries have led to a steady increase of 3–5% annually in both cell-level specific energy (Wh/kg) and energy density (Wh/L) [1]. Although the gravimetric specific energy of Li-ion cells has achieved 300 Wh/kg [2], the batteries still comprise more than 25% of the curb weight of electric vehicles (EVs) and are important factors limiting driving range [3].

Li-ion cells are the individual building blocks of a battery pack and are available in various form factors, including prismatic, pouch, and cylindrical. Cylindrical cells are particularly well-suited for large scale manufacturing and hence, have been popular for EVs like Tesla [4], however, other companies like Nissan or Renault have moved to pouch cells while others like BMW have used prismatic cells [5].

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The family of lithium-ion batteries includes various types of electrodes (cathode and anode) materials. Cathode materials include Lithium Cobalt Oxide (LCO), Lithium Iron Phosphate (LFP), Lithium Manganese Oxide (LMO), Lithium Nickel Cobalt Aluminum Oxide (NCA), and Lithium Nickel Manganese Cobalt Oxide (NMC), while two popular (commercialized) anode materials are: Graphite, and Lithium Titanate Oxide (LTO). Currently, about 85% of all EVs use NMC or NCA cathode (NMC accounts for about 65-70% and NCA accounts for about 15-20% as of 2020) [6], while LFP accounts for another 10-20% of EVs [7]. For the anodes, graphite comprises the predominant majority (>99%) of all EVs [7]. Fig 1 depicts the historical evolution of the different types of battery technologies.

LCO was the cathode of choice for any application in the first decade after the introduction of Li-ion batteries. These cathodes contain ~0.95 kg of cobalt to achieve each kilowatt-hour available in energy capacity in the batteries [9], compared to 0.14 kg for NCA, and 0.4 kg for NMC [9], while LFP or LMO contain no cobalt at all. In the two decades after commercialization of Li-ion batteries [10], cobalt demand has

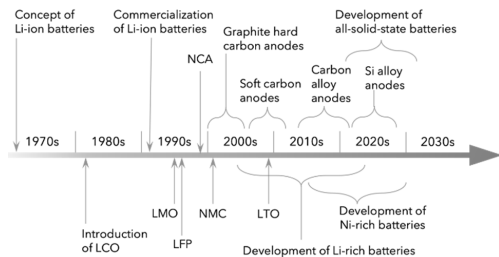


FIGURE 1. Historical evolution and advances of Li-ion battery technologies [8].

increased by ~ 5 times with over 70% of the cobalt supply chain concentrated in the Democratic Republic of Congo [9], [10]. The uneven distribution of cobalt supply has led to volatility in prices, and for cathodes such as LCO, the battery cost is extremely sensitive to changes in cobalt price [11]. Since cathodes like NCA, and NMC require a much lower amount of cobalt for every kilowatt-hour of energy contained in the battery, the cost of NCA or NMC cells has not been as sensitive to cobalt prices. Hence, the EV industry since 2010 has for the most part avoided the use of LCO cathodes, and has focused on NMC, NCA, LMO, and LFP.

NMC is a generalized class of cathode materials, which can be represented stoichiometrically as $\text{LiNi}_x\text{Mn}_y\text{Co}_z\text{O}_2$ where x , y , and z are the individual mole fractions of Ni, Mn, and Co. Among the commercially available NMC cathodes, NMC-111 or $\text{LiNi}_{0.33}\text{Mn}_{0.33}\text{Co}_{0.33}\text{O}_2$ with an equal amount of Ni, Mn, and Co, was the first to be commercialized. This was followed by NMC-532, NMC-622, NMC-721, and NMC-811 [9]. As the nickel mole fraction increases, the mole fraction of cobalt decreases and the specific capacity and operating voltage of the cathode increase, thereby, increasing the specific energy at the cell-level. In other words, the specific energy of $\text{NMC-811} > \text{NMC-721} > \text{NMC-622} > \text{NMC-532} > \text{NMC-111}$ [6],[12].

The NCA requires about 0.76 kg of nickel per kilowatt-hour of cell energy, followed by NMC-811 requiring 0.75 kg/kWh. NMC-622 and NMC-111 need 0.64 and 0.39 kg/kWh of nickel respectively since they have higher mole fraction of cobalt. The nickel supply chain is considerably more diverse with mining led by Indonesia (30.4%), Philippines (12.8%), and Russia (11.2%), although other important producers such as New Caledonia (8%), Australia (6.8%), Canada (6.7%), stand out [13]. Further, only about 7% of all the nickel end-use is EVs while over 70% is used in stainless steel, thereby leading to lower price volatility compared to cobalt. LFP and LMO require no cobalt or nickel, accounting for about 10% of the total EV market nowadays.

Each electrode, based on its intrinsic material properties and structure, has a set of unique performance metrics. LCO, NCA and NCM belong to the class of cathode referred to as layered oxides, $\text{Li}[\text{Metal}]\text{O}_2$, where the [Metal] is a transition metal. Li^+ ions diffuse in these cathodes through two-dimensional paths between layers of the transition metal oxide as the cathode is charged and discharged [14]. As Li^+ is extracted from an $\text{Li}[\text{Metal}]\text{O}_2$ cathode, the voltage increases

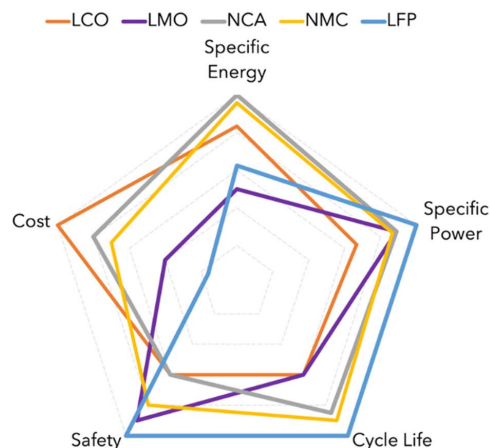


FIGURE 2. Comparison of the main performance metrics of popular Li-ion cathode chemistries [18]–[20].

up until a given value (dependent on the temperature) in which Li^+ extraction must be stopped to maintain the structure of the cathode. On the contrary, the electrode becomes unstable either due to loss of oxygen or by oxidizing the electrolyte. LMO presents a robust spinel structure $\text{Li}[\text{Metal}]\text{O}_4$ with a three-dimensional network of channels for fast Li^+ conduction but with also a serious transition metal dissolution as well as phase/surface stability problems [15]. LFP belongs to the class of cathodes called olivines, $\text{Li}[\text{Metal}]\text{PO}_4$, which are intrinsically stable at high temperatures [16]. Li^+ extraction is accompanied by a phase change from LiFePO_4 to FePO_4 which results in a flat voltage response. The lithium ions diffuse through LFP via one-dimensional channels [14], and it is important for LFP particles to be small enough not to have faults that could block these channels. Hence, LFP is generally manufactured as a nanoparticle which has a length scale of nanometers, unlike layered oxides which are 5–20 micron in size [17]. Due to the higher stability of LFP, an operating voltage of 3.4 V where there is minimal oxidation of electrolytes, LFP electrodes provide a quite constant reversible capacity over thousands of cycles.

The main metrics usually used for comparison of the different types of commercial cathodes are: specific capacity (Ah/kg), operating voltage (V), specific energy (Wh/kg), specific power (W/kg), cycle life (number of charge discharge cycles before reaching end-of-life), and cost per unit energy ($\$/\text{kWh}$). Fig. 2 shows a comparison of these performance metrics for the various popular electrodes [18]–[20].

Due to the nature of electrode particles used, whether they are nanoparticles or microparticles, and other material properties such as electronic conductivity, ionic conductivity and operating voltage, each cathode material has a different power capability. In terms of specific power, LFP and LMO cells have a highest specific power, followed by NCA, NMC, and LCO. At a high-level, specific power capability is closely tied to the acceleration and fast charging capability of the EV batteries.

When coupled with graphite anodes, NCA cells have the highest specific energy (200–260 Wh/kg), followed by NMC

(150–250 Wh/kg), LCO (120–210 Wh/kg), LMO (100–130 Wh/kg) and, finally, LFP (80–150 Wh/kg) [2]. A higher specific energy leads to a lighter battery pack for a given energy capacity. This improves the energy efficiency and performance of the vehicle (greater energy stored for a given battery weight), thus enabling longer driving ranges.

LFP cells can deliver a higher number of charge-discharge cycles [20]–[22], compared to NCA or NMC cells. This is observed beyond lab tests in commercial products using both types of cells [23]–[27]. Longer cycle life implies a lower frequency of battery replacements, and hence lower operating costs for EV users. In terms of safety, NMC has a lower flash-point (the temperature at which a material will ignite) than LFP (215°C vs. 270°C), implying a lower risk of LFP cells catching fire due to thermal runaway [28]. This is due to the strong P–O covalent bonds in LFP cathodes' 3-dimensional structure that provide them much better thermal stability when compared to NCA and NCM based cathodes. The latter are thermally unstable upon heating and decompose with an oxygen release that acts as an internal oxidizer and provokes fast increase of internal temperature due to occurring undesirable exothermal reactions inside a sealed LIB.

In terms of cost, LMO cells were the cheapest and traditionally used for this reason in power applications, including power tools and some EVs like the Nissan Leaf. However, the very limited cycle life of LMO together with the price reduction in NMC and LFP diminished the use of LMO in the EV market. The LFP cost was initially assumed to be higher than that of NMC, due to cost reduction for NMC and NCA cells achieved due to the economies of scale associated with the rapid increase in demand for these batteries in EVs. Nonetheless, those early differences started diminishing from 2017 onward and a study by IHS Markit demonstrated LFP are already cheaper than NMC [29]. In fact, the price of LFP cathode active materials in China is reported to be 43% lower than NMC 811 cathode materials [30] on a per kWh basis. Mauler *et al.* [7] noted in 2022, but prior to the Russian war in Ukraine, that the falling battery cost has been put at risk by the increasing raw materials prices [7]. Clearly, the War has made this additionally more of a concern.

Although NMC has been the main cathode chemistry of use in the EV industry due to its specific energy and cost, different factors such as declines in LFP costs together with their better specific power, cyclability, and safety, together with the raw material price volatility, which influence the supply chain resilience and the eventual manufacturing cost of the battery pack, has paved way for an increased competition between NMC and LFP.

II. BATTERY CHEMISTRIES USED BY THE AUTOMOTIVE INDUSTRY: AN HISTORICAL PERSPECTIVE

Since 2010, the electric automotive industry has experienced an enormous change in conjunction with changes in the battery industry. In 2010, the Toyota Prius was the most sold electric (hybrid) vehicle and used a nickel metal hydride (NiMH) battery pack. Five years later, Toyota

launched its fourth-generation Prius which introduced Li-ion batteries.

During the 2010–2020 decade, more than 75,000 MWh of batteries were supplied and installed in EVs sold in the United States [31]. Fig. 3 shows the supplier-based breakdown of the total capacity supplied. Panasonic batteries accounted for nearly 74% of the total capacity installed in EVs in the USA during this period and were found in about 60% of total EVs sold [31]. These cells were predominantly used by Tesla and to a smaller extent by Toyota and Ford.

Another prominent battery supplier in the U.S. EV battery market during the period 2010–2020 was LG Chem, which provided blended NMC/LMO cathode cells to General Motors (GM) for use in its introductory Chevrolet Volt model. Later generations of the Volt kept with an NMC/LMO blend but increased the NMC content to extend the driving range [32].

Nissan initially chose LMO technology from its battery manufacturer AESC for the battery packs in its 2011 Leaf model. In 2016 Nissan announced that its Leaf models would feature extended driving range—made possible by battery packs with higher density NMC cells [33], [34].

Battery manufacturers Samsung SDI and SK Innovation also provided batteries to the U.S. EV market, mainly supplying to BMW and Kia, respectively [31].

Beyond the American market, NMC cathodes, specially the 111 generation, have been the main type of cell used in EV batteries worldwide (e.g., in the Nissan Leaf, Renault Zoe, BMW i3, and GM Chevrolet Bolt [35]). In 2017, battery manufacturers evolved toward low cobalt content batteries [36] due to cost, supply challenges [37], and issues with the mining of cobalt [38]. As a result, new NMC versions that contain more nickel and less cobalt were developed including NMC 433, NMC 532, NMC 622, and NMC 811 [35]. The major advantage of using nickel in batteries is that it helps deliver acceptable energy density and storage capacity at a lower cost [37], [39]. For example, SK Innovation, which serves EV makers beyond Kia at a global scale including Daimler, Ford, and Hyundai [40], announced in 2020 that it would start implementing NMC 9.5.5 cathodes—instead of the commonly used NMC 622—in its commercial EV cells as early as 2023 [41]. Other producers such as Samsung SDI (serving BMW, Ford, Stellantis, and Volkswagen [VW] [40]) or LG Chem (serving GM, Groupe Renault, Stellantis, Tesla, Volvo, or VW Group [40]) are also in the race.

At a global scale, the primary LFP cell manufacturer worldwide is Contemporary Amperex Technology Co., Limited (CATL), which is the largest cell manufacturer in the world with a 26% of the global market and provides cells to Honda, BMW, Dongfeng Motor Corp., SAIC Motor Corp., Stellantis, Tesla, VW Group, and Volvo Car Group [40]). CATL has also been pushing hard toward new cell developments implying sodium ion cell technology [42].

Apart from improving the cell chemistry and its characteristics, the EV industry has also looked at increasing the specific energy of the battery packs by using the batteries as

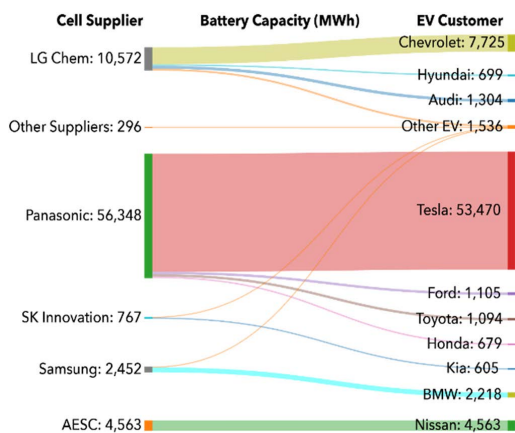


FIGURE 3. Total capacity (MWh) of Li-ion batteries supplied to the U.S. EV market by manufacturer in the period 2010–2020, based on [31].

a structural element in the vehicle [43]. Tesla announced the adoption of this philosophy—the so-called “cell-to-chassis design”—in its 2020 Battery Day event [44]. This design incorporates the Panasonic cylindrical cells as a body structure linking the front and rear underbody parts [45]. Similarly, VW started using its concept of Modular Electric Drive Matrix (MEB) in June 2020, and later that year GM introduced in the fall 2020 its Ultium Platform developed with LG Chem [30]. While VW uses NMC cells in its MEB platform (already implemented in its ID3 model), GM is employing an NMCA prismatic cells with 89% nickel in its Ultium Platform. Both BYD and CATL are developing new LFP battery packs equally formed by prismatic cells to optimize packaging and facilitate system cooling. BYD calls this architecture “BYD’s Blade Battery,” which is used in models such as the BYD Han EV [46].

In summary, as of 2021, NMC technology dominates the EV industry, accounting for 71% of the EV market. Follows NCA cells used in Tesla models with most of the rest. LFP has regained sales share but kept representing less than 4% in 2021 [47]. Although LFP Li-ion batteries have advantages over NMC batteries in terms of cycling life and power density, their lower energy density requires more space and weight to achieve the same capacity as NMC Li-ion batteries. This has traditionally posed a barrier to their large-scale introduction into the EV industry, and it is a reason they have been usually constrained to low-range cheap cars and to lower energy density applications, including uninterruptible power supply, UPS, and home storage systems, which often require the ability to cycle more and deeper over their lifetime and do not have constraints on size and weight. Nevertheless, due to cost and safety reasons, the mass adoption of LFP cells might be coming to the EV industry.

III. TESLA’S MOVE TO LFP

Tesla has been leading the global electric vehicle market during the last 5 years [48], and with its continuous increase in sales has become a catalyst that has moved the whole car manufacturing sector towards electrification. In this sense, it is not only a market leader but also a trendsetter. In this context,

Tesla announced in February 2020 it would transition away from the Panasonic cylindrical NCA cells it used and toward CATL’s prismatic LFP technology to produce Model 3 EVs in its Chinese factory [49]. Although the internal cobalt mining in China only represents 1% of the global industry [50], this announcement ultimately affected commercial Chinese cobalt miners whose shares dropped by 8% that day [51]. In January 2022, CATL delivered its first LFP cells to the Tesla factory in Shanghai [52].

Tesla’s CEO (officially Technoking) Elon Musk mentioned in October 2020 that he believed “the energy density of LFP batteries has improved enough to enable the use of cheaper and cobalt-free batteries in its lower-end vehicles,” saying, “This is actually good because there’s plenty of iron in the world” [53]. Furthermore, in February 2021, Musk expressed concerns regarding the availability and cost of nickel. He urged mining companies to mine more nickel and indicated Tesla would give them “a giant contract for a long period of time” if they “mine nickel efficiently and in an environmentally sensitive way” [54]. There has been a 16% surge in nickel prices from 2020 to 2021 alone, which is partly due to demand for EVs [54]. At the same time, lithium price indices have grown by over 200%, thereby increasing the cost of raw materials required for manufacturing Li-ion cells overall [55]. For reference, the active material cost for LFP cathodes is about US\$10/kg compared to over US\$35/kg for NMC cathodes [55].

In September 2021 Tesla offered Model 3 reservation-holders the option to expedite delivery of their vehicles if they would accept LFP batteries in their cars instead of NCA cells. Until this point, NCA packs had been promoted and installed in all Model 3 sedans sold in the North America region [56].

Tesla’s 2021 Q3 investor deck disclosed that all its standard-range cars would shift to LFP battery packs, although the date for the shift or the specific EV models were not announced. [56]. Tesla produces two categories of EVs: long-range and standard range. Long-range vehicles can travel over 350 miles on a single charge while standard-range vehicles, on the other hand, provide between 200 to 300 miles of driving range. Tesla’s October 2021 announcement regarding the shift to LFP battery packs pertains to the standard-range segment of vehicles. However, this new announcement would be signaling the global scale of the move.

IV. RATIONALE BEHIND TESLA’S MOVE

Tesla likely made the switch because LFP batteries do not require scarce metals like nickel or cobalt but rather use mainly iron, which is available in abundance at a significantly lower cost. In 2021, the volume-weighted average cost of LFP cells was about 30% less than NMC cells [57]. The result is cheaper batteries [58].

Tesla’s threefold technical rationale for the shift appears similar to that from other EV manufacturers, including Honda, Ford, BYD, GAC Motor, and Zhejiang Geely Holding Group Co. LFP cells are currently a more affordable chemistry, they last longer nowadays than their NCA or

NMC counterparts, and—above all—they are safer and more stable. However, LFP also present limitations as a cathode material compared to NMC or NCA. These specially involve lower specific capacity (165 mAh/g for LFP compared to 170 mAh/g and 200 mAh/g for NMC and NCA respectively) and a lower average voltage of 3.4V for LFP compared to 3.7V for NMC and NCA [59]. The specific capacity and average voltage of LFP coupled with the similar density of Fe, Co, Ni, and Mn (7.2–8.9 g/cm³), result in a lower gravimetric energy (Wh/kg) and lower volumetric energy density (Wh/L) than those for NMC or NCA. In the case of Tesla, the U.S. Environmental Protection Agency (U.S. EPA) rated the specific energy of its LFP battery pack at 126 Wh/kg while the previous NCA battery pack was rated at 145 Wh/kg [60]. At the vehicle curb weight level, the 2022 Model 3 (RWD) weighs 3880 lb. compared to the 3616 lb. of the 2021 version. A higher weight implies a lower driving range for the car.

EPA tests vehicles by running them through a series of driving routines, or schedules, that specify vehicle speed for each point in time during the laboratory tests. EPA homologated efficiency ratings providing data on the impact of the heavier battery on the vehicle's driving range is published and categorized in a year-by-year manner [61]. On examining the EPA data, we find that the heavier battery pack in the 2022 Tesla Model 3 has resulted in increased energy consumption of about 8% in city schedule (244 Wh/mi in 2022 vs. 225 Wh/mi in 2021) and about 5% in highway schedule (267 Wh/mi in 2022 vs. 253 Wh/mi in 2021) [62], Fig.4. Independent testing reports suggest the vehicle's acceleration from 0 to 60 mi/hour has also been reduced by about 10% (5.8 s in 2022 vs. 5.3 s in 2021), which means it will take longer for vehicles with LFP batteries to achieve the same driving speed compared to the vehicles with lighter NCA batteries.

Despite the higher energy consumption of the 2022 or the LFP-Model 3, the U.S. EPA rated range of the Tesla 2022 Model 3 (RWD) is 9 miles (about 3%) higher than that for the 2021 Model 3 Standard Range Plus, or NCA-Model 3 [61]. The range based on city duty cycle is about 6 miles higher for the LFP-Model 3 than the NCA-Model 3, while the highway duty cycle offered about 26 miles more range for the LFP-Model 3. The higher driving range for the LFP-Model 3 compared to NCA-Model 3, despite the higher battery weight for the LFP battery pack, can be attributed to improvements in powertrain efficiency governed by motors and power electronics. Therefore, these technological improvements could compensate and even enhance the performance of new Tesla EVs despite their weight gain. In this way, consumers do not realize about the driving range handicap associated with the in-efficiency of added weight from the LFP battery pack nor they will enjoy extended driving range achieved with new control and electronic developments. If the powertrains efficiency between the NCA-Model 3 and the LFP-Model 3 were the same, Fig. 5 shows that the NCA-Model 3 would have more than 10 miles more driving range for a given battery pack size.

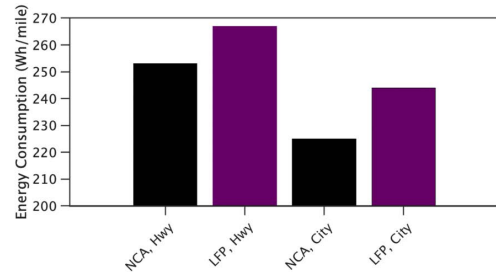


FIGURE 4. Comparison of U.S. EPA energy consumption ratings of the 2022 Tesla Model 3 with an LFP battery pack and 2021 Tesla Model 3 with an NCA battery pack. The comparison is shown over highway (Hwy) and city driving schedules.

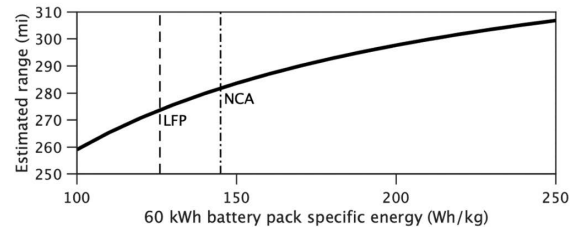


FIGURE 5. The estimated range of a Tesla Model 3 vehicle with a 60-kWh battery pack tested under the U.S. EPA federal test procedure schedule. The estimation was performed using a vehicle dynamics model which uses driving schedules and vehicle parameters as input and provide energy consumption and power requirements as output [68]. The analysis here was performed by holding the total energy in the battery constant at 60-kWh, while the weight of the battery pack varies with the specific energy.

Apart from the specific energy limitation, LFP batteries' do also present electronic and ionic conductivity issues. These have been largely addressed for room temperature operation [63]–[65]; however, issue persists at lower temperatures where LFP batteries charge more slowly [66]. Cold weather performance complaints for LFP-based batteries have forced Tesla to fit the new Model 3 vehicles with a heat pump [67].

When compared with other Li-ion cell types, despite their lower gravimetric energy and the issues they face under cold weather (significant reduction of the instantaneous retained capacity), LFP batteries are gaining traction in the EV market. This is mainly due to two out of the three reasons: price associated with the scarcity of raw materials [7] safety and liability.

Regarding the scarcity and price of raw materials, according to estimates by EV market analysis firm RhoMotion, the present-day utilization of cathode materials would be: NMC 60%, LFP 25%, NCA 14%, and others less than 1% [69]. With this distribution and the significant presence of nickel in most of the chemistries, the availability of this metal worldwide is becoming a cause of concern. The nickel content in NMC batteries is 33% or more (depending on the cell type), while the nickel content in NCA batteries is 80–85%. With the current nickel shortage, battery manufacturers are struggling to procure large quantities of nickel for their batteries. Rising demand for nickel—paired with scarcity issues, supply problems, and the associated increase in the cost of nickel—pushes up the overall cost of the battery, reducing profit margins and creating an additional source of concern for carmakers. Thus, companies may prefer to implement

LFP batteries, which do not contain nickel, because their raw materials are available in abundance at a remarkably lower cost. Still, the limited availability of raw materials also causes delays in production, which in turn affects delivery. This could be the reason for Tesla asking its customers in North America if they would like to go ahead with LFP batteries in their cars rather than NCA batteries. Avoiding such supply chain issues could be another related reason for car manufacturers to go with LFP batteries, which grant availability right now.

V. SAFETY AND LIABILITY ISSUES

There are concerns associated with incidents involving explosions and fires after a crash and with mass recalls of cars due to battery failures. These are important reasons for Original Equipment Manufacturers (OEMs) to empower a shift from NMC or NCA to LFP batteries.

For Tesla, their Model S vehicles, which use NCA cells, were involved in several well-publicized fire incidents in 2013. Most of the fires were allegedly triggered by road debris unexpectedly puncturing the battery pack. Tesla responded by adding a titanium shell that reduced the likelihood of such punctures. In Shanghai in 2021, a Tesla Model 3 (again, with NCA cells) exploded in an underground residential parking garage. Preliminary analysis allegedly indicated the incident was caused by an impact to the vehicle's underside that damaged the battery pack and produced the accident [70].

In May 2012, a Nissan GTR crashed into a BYD e6 taxi in Shenzhen, China. The BYD e6, which uses LFP cells, caught fire after hitting a tree, killing all three occupants. A Chinese team concluded that the cause of the fire was "electric arcs caused by the short-circuiting of high voltage lines of the high voltage distribution box ignited combustible material in the vehicle including the interior materials and part of the power batteries" [71]. In the accident, the vehicle's power batteries did not explode, and 72 single-cell batteries (accounting for 75% of the 96 power batteries) did not catch fire. The design of the battery system in relation to the installation layout on the vehicle, the insulation protection, and the high-voltage system were all reasonable [72].

There have also been several documented cases of Chevy Bolt vehicles, using NMC pouch-cell-based battery packs, catching fire while parked and plugged in to charge in enclosed spaces like garages [73]. One of the attributed reasons for these incidents was the release of oxygen due to the battery pack overheating when overcharged [74]. GM announced in August of 2022 that it was recalling all Chevy Bolts made after 2017, including the new versions released earlier that year, after multiple fires in the EVs' battery packs were found to have been caused by defects in the LG Chem cells inside [75]. There were issues with the LG Chem batteries in Hyundai Kona EVs as well [76]. After 16 Kona EVs caught fire in Korea, Canada, and Europe over a period of two years, Hyundai also announced a similar recall for 82,000 EVs worldwide, including 75,000 Kona



FIGURE 6. Examples of failures (fires) in Nissan and Tesla EVs, images from [83]–[85].

EVs [76], to update the BMSs [77]. The mass recall to replace the affected batteries cost Hyundai \$900 million [76] while GM's recall of the more than 140,000 affected Bolt EVs cost the automaker an estimated \$1.8 billion [76]. The cost was shared in this case by the battery manufacturer, LG Energy Solutions, which offset the total loss by \$0.1 billion. In April 2022, the U.S. National Highway Traffic Safety Administration (NHTSA) announced an investigation to ensure that all defective batteries produced by LG Chem (now rebranded as LG Energy Solution) have been recalled by automakers [78].

For the case of Tesla, although the EV maker has had numerous recalls during the last two years, with at least 10 between Q3 and Q4 2021, none of them has been directly related to the batteries or fire hazards [79]. Tesla is facing issues with windshields, suspension knuckles, airbags, and cameras, but apparently not with batteries. In fact, doubts introduced about Tesla's high-voltage batteries by the investigation requested in October 2019 to the NHTSA were dispelled in October 2021. Furthermore, NHTSA declined to address a formal investigation into fire risks involving Tesla cars, after finding no relevant incidents in the USA from 2019 [80].

Beyond the cases pointed out, concerns about fires and explosions might be overstated. Although EV accidents involving fires are catastrophic—with fires that are extremely difficult to extinguish due to the presence of cobalt and the low flashpoint in NCA and NMC cells (see Fig. 6), such occurrences are uncommon, and rare for LFP battery packs. An analysis by AutoinsuranceEZ updated in January 2022 indicates that despite increasing concerns among car-makers, EV fires present a much lower rate of occurrence per 100,000 vehicle sales when compared with hybrid or gasoline-powered vehicles [81].

The same study from AutoinsuranceEZ also presents summarized data on the latest recalls from 2020 that involved potential fire hazards and it indicates that just the two cited cases involved pure EVs (Volt and Kona models) [81]. Two more cases also related to the batteries involved hybrid models from BMW and Chrysler. No recalls were attributed to LFP-based EVs in 2020.

In summary, liability issues might compel car-makers to move to a safer choice that does not necessitate a large expenditure in quality assurance. Additionally, although these recalls come at a cost to EV makers and battery suppliers, the benefits may outweigh the costs [82].

VI. IMPLICATIONS OF TESLA'S DECISION

The previous sections outlined the general implications of Tesla's decision based on techno-economic reasons. Other

OEMs including Ford Motors and VW [86], and Rivian Automotive [87] have followed Tesla by stating that their mass market battery vehicles will shift to LFP batteries. Here, we delve into the wider implications the decision has on subsidies, manufacturability of batteries, and intellectual property rights.

A. LFP AS A CHEAPER ALTERNATIVE TO OPEN NEW MARKETS

Analysts have posited that a shift to LFP batteries provide a way for Tesla to increase profit margins at the same market price of the vehicle, [88] or in some scenarios, even lowering prices. Tesla could be seeking to lower its Model 3 price below the level required to meet requirements for subsidies in regions like China (price tag under 300,000 yuan) [30], Spain (subsidized vehicles cannot cost more than €35,000) [89], or the United Kingdom. Due to the deceleration in Li-ion cells' price drop, and even with a price increase in Li-ion raw materials, as experienced in 2021, migrating to cheaper cell materials might be a reliable way to manufacture cost-competitive vehicles. In addition, the use of LFP in standard-range vehicles could free up nickel for use in the other long-range vehicles. As a result, the company could invest less money to obtain nickel for its high-energy-density batteries.

B. EXISTING PATENT LAWS NOW FAVOR MANUFACTURING LFP BATTERIES OUTSIDE CHINA

There are three major patents that govern the use of LFP technology [90]: The first was filed by Nobel Prize winner John Goodenough in 1996 and granted in 2003. The patent described the performance of the material and its use in batteries; it expired in 2017 [91]. The second was filed by the University of Montreal and granted in 2008. It described how the performance of LFP, which has low electronic conductivity, can be improved by coating it in carbon. This patent expired in 2021 [92]. The third governing patent was from Hydro Quebec and the National Centre for Scientific Research (CNRS), filed in 2001 and granted in 2007. It brings together the two aforementioned patents and describes a method to synthesize the coated material. This patent is due to expire in the United States in 2022 and already expired in Europe in 2021 [93]. The three patents were tied together to create a license under the consortium "LiFePO₄+C AG". This owns and licenses the worldwide rights to LFP. This was never defended in China and battery manufacturers like CATL and BYD have already commercialized LFP battery packs in EVs in China. It has been licensed around the world to companies like BASF, Aleees and Mitsui.

With the last of the three patents that control LFP production outside China set to expire in 2022, the restrictions they enacted will soon lapse, and the use of LFP batteries in EV is projected to skyrocket [94]. Tesla estimates its batteries will eventually shift to roughly two-thirds iron-based and one-third nickel-based [95]. With the patents still under effect, Tesla will not be able to achieve significant savings because

it will have to purchase the batteries from China and incur the associated costs: a 10% import tariff, around 1% shipping costs, and a 3% licensing fee due to the patents. With all the additional costs, Tesla saves only 6% by moving from NCA to LFP batteries, when the original cost of LFP batteries should result in savings of 20% [53]. When the patents expire, however, Tesla will be able to manufacture its own batteries, getting closer to its goal of "localizing all key parts of the vehicles on the continent" (i.e., moving battery production closer to its factories) [96]. This should result in significant cost savings because of the streamlined logistics.

VII. CONCLUSION

In 2020, Tesla shifted to LFP batteries away from NCA cells. LFP cathodes are identified to have lower gravimetric specific energy compared to NMC and NCA solutions. Tesla's leadership has stated that LFP provides a path to using cheaper and cobalt free batteries as well as avoiding other supply chain constrained metals like nickel. This transition to LFP chemistry is taking place with the backdrop of raw material price spikes and supply chain issues, especially with cobalt, nickel, and lithium. It is suspected that there may be additional reasons behind this strategy while the company also has concerns about missing delivery deadlines due to the shortage of raw materials.

Tesla's decision sparked interest among other OEMs such as Ford Motors and Volkswagen in 2021, and more recently by Rivian Automotive in 2022 who have all announced a similar focus on LFP chemistry for their vehicles. Liability issues related to large-scale vehicle recall might be compelling carmakers to move to safer battery systems that do not necessitate a large expenditure on quality assurance. LFP may be the easy choice for EV manufacturers to keep prices down (making EV cars susceptible to receive subsidies) or increase the profit margin while reducing potential safety and supply issues. Finally, EV manufacturers are also likely looking to locally manufacture LFP given that the last of the three patents that control LFP production outside China are set to expire this year.

On the vehicle performance front, the move to LFP reduces the efficiency due to the lower specific energy and higher battery and overall vehicle weight. While there are continuous performance and efficiency improvements of other non-battery EV powertrain components, the higher battery weight with LFP could lead to a stagnation in the overall driving range and performance of EVs in the market.

Shifting from one common battery type to another may serve to obscure the actual necessity which could be to invest in developing modern technologies to mitigate known issues of safety. While EV firms reach or surpass the market share currently held by conventional vehicle manufacturers, they must demonstrate a competitive driving range, develop safe and reliable systems, enforce improved quality control measures, and enhance battery management capabilities. Choosing a battery type based solely on economic considerations could hinder the user experience, and delay progress

in developing EV competent technologies, thus, delaying the industry consolidation.

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