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Navigating battery choices: A comparative study of lithium iron phosphate and nickel manganese cobalt battery technologies

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ABSTRACT

This research offers a comparative study on Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC) battery technologies through an extensive methodological approach that focuses on their chemical properties, performance metrics, cost efficiency, safety profiles, environmental footprints as well as innovatively comparing their market dynamics and technical performance to provide strategic recommendations and projections. Based upon an exhaustive examination into electrochemical attributes, thermal behavior, life cycle management aspects along with current trends within markets allow us to create a framework against which these most popular electricity storage alternatives might be assessed. Our results show LFP batteries are safer with life cycles beyond 2000 cycles at approximately 30 % lower costs than other similar battery technologies. They have enhanced heat resistance with the ability to operate effectively up to 60 °C besides having significantly reduced carbon footprints. On the other hand, NMC batteries have high energy densities, reaching 260 Wh/kg making them suitable for portable electronics and electric vehicles with a lot of power requirements although their costs are higher and there are environmental concerns associated with their cobalt and nickel content. The work confirms that LFP batteries are increasingly being adopted in markets due to cost advantages and safety improvements. We recognize the continued importance of NMC batteries in high performance areas due to their superior energy output ratings. LFP is recommended for applications requiring long lifetimes while NMC is ideal when high power is needed. The study indicates the need for better battery technology development towards improved efficiency and safety.

Introduction

As intermittent renewable sources including solar and wind are increasingly relied upon by the world, energy storage becomes important in balancing electricity supply and demand [102]. Furthermore, efficient methods of storing energy are important for improved grid reliability and efficiency [61]. With regard to capacity, scalability, efficiency, cost and applicability pumped hydroelectric storage (PHS), battery energy storage systems (BESS), thermal energy storages (TES), flywheel ESS, compressed air energy storage (CAES), hydrogen storages, super capacitors, mechanical storage are some of the options that exist today. These technologies provide backup power for grid stability in addition to integrating renewable sources like solar and wind into electric grids [126]. However, this does not mean that BESS power can be scaled down all the way to small gadgets or up for large-scale BESS projects due to a huge amount of stored energy at initial CAES compared with PHS.

Unlike pumped hydro storage which relies on specific geographical features only batteries have flexible land uses and climate conditions. For example, they can be used in rural areas where there may not be high mountains to construct dams or very large lakes near them. Large-scale lithium-ion battery projects such as the Moss Landing Battery project in the United States demonstrate how batteries' capacities can be harnessed in order to meet different types of electricity needs [73].

They become a focal point or part of broader initiatives aimed at reducing fossil fuel dependence, hence realizing environmental objectives. In today's LFP battery markets graphite helps make Nickel Manganese Cobalt better known among lithium-ion batteries users due to certain reasons such as advanced battery technology causing maturity Table 1.

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Table 1
Selected energy storage projects and product to demonstrate energy storage ranges.

Fig. 1 label	Energy storage system	Project/Product	Power capacity (MW)	Storage capacity (MWh)	Ref.
1	Battery	Moss Landing, United States	750	3000	[108]
2	Battery	LG Chem RESU, LG Chem	0.005	0.0095	[55]
3	CAES	Huntorf, Lower Saxony, Germany	290	580	[3]
4	CAES	Norton Energy Storage, Ohio, USA	110	1100	123
5	Electrolysis	Asian Renewable Energy Hub, Pilbara, Australia	14,000	420,000	[62]
6	Electrolysis	Linde Leuna, Leuna, Germany	24	720	[16]
7	Flywheel	Beacon Energy Storage, New York, USA	20	5	[34]
8	Flywheel	Piller Powerbridge, Germany	0.1	0.001	[44]
9	PHS	Fengning, China	3600	40,320	[146]
10	PHS	La Muela II, Spain	852	6360	[13]
11	Thermal	Hot water in rock caverns, Helsinki, Finland	11,600	120	[71]
12	Thermal	Drake Landing, Okotoks, Canada	1.5	1.5	[86]

Objective of study

This involves evaluating LFP- based batteries against NMC-based ones on their chemical characteristics i.e. effectivity levels; cost effectiveness; physical aspects etc needed when choosing between them within the energy field. Additionally, there is need to understand better operational risks associated with lithium-ion battery storage systems for safety checks [19]. For instance, this research examines how these batteries can be integrated into power systems to ensure grid stability during the integration of renewable energy sources [107]; and it explores how they can be optimized for frequency regulation and electricity arbitrage in the grid. This research also looks into whether or not battery technology is sustainable by evaluating multi-criteria decision-making that focuses on their long-term environmental benefits which include material recovery potentials [119] and possible applications suitable for each battery type according to several criteria such as cost, life cycle analysis and technical evaluation using a multi-criteria-decision making approach [133].

Study significance and motivation

There are various stakeholders in the energy industry who may want to compare LFP versus NMC batteries.:

1. Transportation Sector: This section accounts for almost one fifth of global CO2 emissions where road transport alone represents about 75 % constituting roughly a quarter of CO2 emissions that are linked to energy combustion [45]. This understanding will inform stakeholders' decision towards adoption of electric vehicles through better comprehension on LFP vs. NMC capabilities.
2. Policy Makers in Energy Storage Industry: Policy makers will find useful insights from this study on the impacts of different battery technologies on projects, supply chains and value chains helping strategic decision making and risk management.
3. Battery Technology's Place in a Sustainable Transition: Battery technology can contribute to more sustainable energy shifts by reducing dependence on certain materials while designing storage devices that are environmentally friendlier.
4. Global Market Demand: Expected global demand for lithium-ion batteries is projected to surpass 3 TWh per year by 2030 [93], which underscores the need for this study to facilitate scale up and market creation.

Hence, this research aims at improving energy storage mechanisms, encouraging sustainability as well as reducing business risks through a comprehensive comparison between LFP batteries and NMC batteries Fig. 1.

Methodology

In this study, LFP and NMC batteries were systematically compared in order to ascertain their suitability for energy power applications. The methodology was as follows:

1. Literature Review: We conducted a thorough review of current literature on the performance characteristics and advancements in LFP and NMC battery technologies from 2020 to 2024. They consisted of peer-reviewed articles as well as industry reports from Google Scholar, ScienceDirect, among others.
2. Search Strategy: Relevant studies were identified using keywords like "LFP," "LiFePO4," "NMC," and "Nickel Manganese Cobalt." This allowed us to determine recent developments and trends in battery research with a focus on sustainable energy solutions and electric vehicles.
3. Article Selection and Review: All articles selected had relevance to the research questions while exclusion criteria eliminated non-peer-reviewed publications or duplicate materials. A total of 105 key articles were extensively studied for their importance towards understanding battery performance, safety, and manufacturing processes.
4. Data Synthesis: Performance metrics; material availability; safety considerations; manufacturing techniques. By putting together all these details, we established a comprehensive knowledge about LFP's strengths vs NMC's strengths.
5. Analysis Framework: It guided how we carried out the systematic review using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework that ensured only reliable research was considered during the process (see Fig. 2).

This approach results in a concise examination of most critical factors affecting LFP's and NMC's applicability to power uses. By aligning with their various objectives including but not limited to providing basis for informed decision-making processes on technology selection

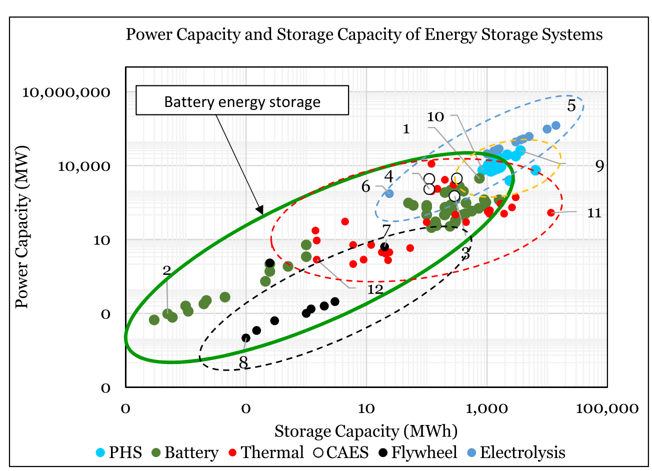

Fig. 1. Power and storage capacities of energy storage systems (Ref. Table 1).

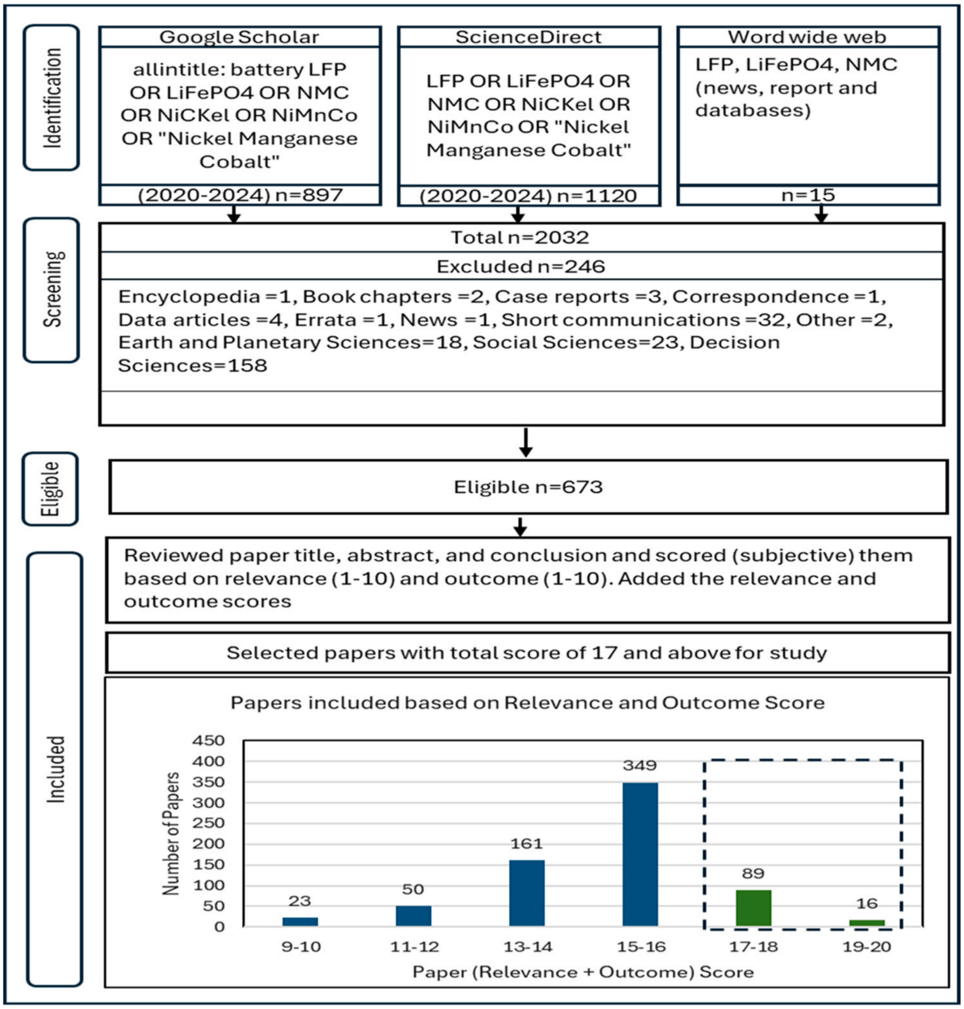

Fig. 2. PRISMA framework for systematic comparison of LFP and NMC battery technologies.

direction together with policy implications that are related to future forecast.

In terms of potential bias, there are no outside funding provided to us for this investigation. We did a thorough evaluation of LFP and NMC technologies, without restricting our investigation to any product made by particular manufacturers. We only looked at literature and public data our review, adhering to PRISMA rules. Nevertheless, the swift progress in battery technology poses a danger: an extended period of data gathering can overlook more recent innovations, which could make our conclusions outdated and less applicable to the present market. Furthermore, as China controls the LFP supply chain, Western policies meant to lessen Chinese influence may benefit NMC technology.

In line with the PRISMA checklists, the systematic screening process ensures that only valid research findings are used, which is consistent with the study objectives thus offering valuable insights into energy storage regarding battery technologies.

Literature review

The types of cathode materials chosen are important in the development of lithium-ion battery technologies as they directly affect their performance, cost and sustainability. Among the popular choices of cathodes are NMC and LFP batteries, which come with unique advantages and disadvantages. This article illustrates how energy density, cost-effectiveness, safety and environmental impact differs between LFP and NMC batteries. In this light it aims to examine the criteria used in selecting suitable cathode materials for lithium-ion batteries considering the changing market requirements as well as technological advancement. Lithium-ion batteries have been widely adopted due to their high energy density, long cycle life and low self-discharge rate hence being used in various fields [58,119]. In fact, they are so efficient that rechargeable batteries are considered synonymous with lithium-ion ones [96]. As an electrochemical element for battery applications researchers started exploring the use of Lithium in the 1970s which led to the development of lithium-ion batteries. However commercial Li-Ion cells only started appearing in the nineties [68]. This was a great innovation where intercalation—inserting or extracting lithium ions reversibly into their structure—were discovered allowing a possibility to insert or extract lithium ions reversibly during charge or discharge processes contact with other electrodes [144]. It is important to note that this was indeed the first time that we saw a version of rechargeable battery system with increased amount of stored energy at given mass ratio between electrode active material(s) and supporting media(s). As shown in Fig. 3, LIB consist of graphite anode, lithium metal oxide cathode and electrolyte facilitating movement of Li-ions between electrodes [103].

During charge-discharge cycles, lithium ions are transported through electrolytes between positive and negative electrodes made up mostly by graphite with lithium cobalt oxide ($LiCoO2$). To generate electric current, these batteries have an electrolyte which allows ion transport without direct contact. As they are highly reactive there is no elemental form of lithium in them instead they employ intercalation-lithium metal oxides such as lithium-cobalt oxide ($LiCoO2$) for cathode and carbon compounds treated with lithium for the anodes, thus facilitating free

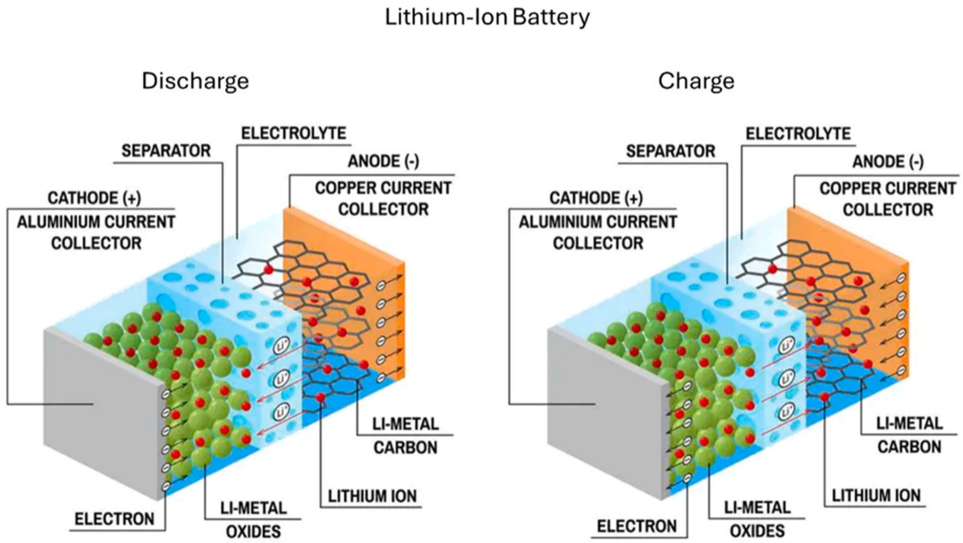

Fig. 3. Components of lithium-ion batteries [33].

movement of Lithium-ions between various types of electrode structures [57].

Eq. (1) represents what happens electrochemically when charging or discharging a Lithium-Ion Battery.

$$LiC_6 + CoO_2 \rightleftarrows C_6 + LiCoO_2 \tag{1}$$

During discharge process lithium ions (Li+) move from the negative electrode (LiC6) through the electrolyte towards positive electrode (CoO2), whereas at this time electrons (e-) flow through the external circuitry. In other words, it has to be both an ionic conductor and electronic conductor at a good level. Li-ion and electron flows destroy lithium-intercalated graphite (LiC6) into graphite (C6) at negative electrode and forms lithium cobalt oxide (LiCoO2) at positive electrode respectively [20]. This is a reversible reaction which can be reversed during charging where lithium ions move back from the positive to the negative electrode and graphite host structure C6 is intercalated with lithium ions in readiness for another discharge cycle [91]. Light weight as well as long life factors have made Lithium-ion batteries popular as power source in portable electronics such as cell phones, laptops, and tablets [76]. Additionally, they are used in EVs and grid scale storage systems for safe and greener modes of transportation and energy-consuming respectively [130].

Lithium-ion batteries have anode or cathode structures that contain lithium. According to Tran et al. [131] there are three types of cathodes in lithium-ion batteries: layered compounds; spinels; and olivines. As shown in Fig. 4, the arrangement of lithium and metal ions in alternate layers in a layered structure of lithium-ion batteries is responsible for its ability to store high energy, although it can become unstable under some circumstances. Olivine structure found in materials like Lithium Iron Phosphate (LFP) strongly holds lithium within a stable framework, thus resulting in excellent safety and long-life span, but with less energy usually stored. Spinel structure possesses a three-dimensional network that assists in promoting the fast movement of lithium through interconnected pathways leading to good power output and stability although it has lesser energy capacity than other structures.

In a lithium battery, the anode is the source of lithium ions while the cathode acts as sink for them, but it also needs to be optimized for other characteristics [131]. The modification of Li-ion battery's cathode materials can improve their specific energy capacity and reduce cost. The electrolyte plays an important role regarding separation between ionic conduction so that electrical conduction will not be interrupted by impurities within it. For a perfect battery, its transport number of lithium ions must be one in the electrolyte. This is particularly relevant to liquid organic and polymer gel-based electrolytes [128]. During passage of Li-ions through the electrolyte, the resulting electrons from a reaction (Li ⇄ Li+ + e-) are used to perform some work in the external circuit. This implies that there should be both electron and ion movement pathways in an electrode system so that their perfect coexistence can take place. It has to be an excellent ionic and electronic conductor.

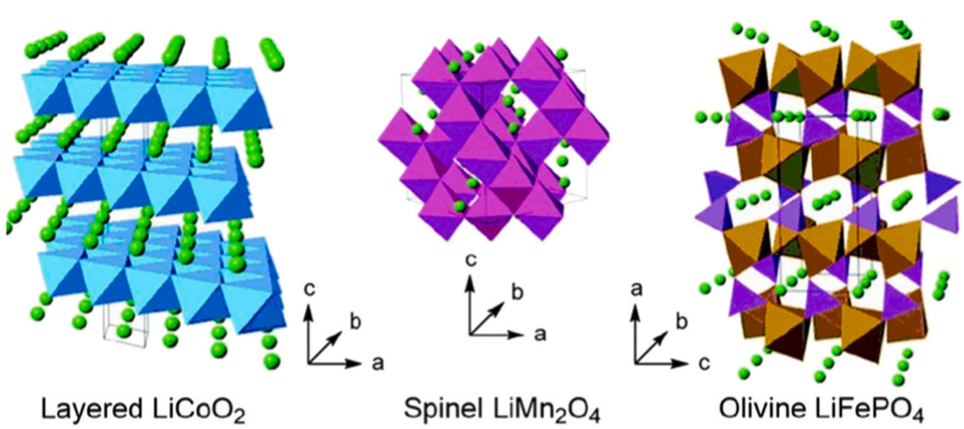

Fig. 4. Cathodes arrangements in lithium-ion batteries [97].

LFP and NMC electrochemical reactions

The general electrochemical reaction for NMC batteries involves the lithiation and delithiation of lithium ions in a layered oxide structure which corresponds with the movement of lithium ions into and out of the NMC cathode structure. These equations are represented as follows:

$$\text{Charge Reaction: } LiNiMnCoO_2 \rightarrow NiMnCoO_2 + Li+ + e- \quad (2)$$

$$\text{Discharge Reaction: } NiMnCoO_2 + Li+ + e- \rightarrow LiNiMnCoO_2 \quad (3)$$

NMC batteries are believed to offer high energy qualities largely due to the electrochemical behavior greatly provided by nickel thus making it possible to be applied in high energy volume applications such as electric powered vehicles and portable electronics. The LFP battery remains the one with the optimal thermodynamic stability and safety due to the presence of strong P—O bond within the phosphate structure and thus limiting the chances of thermal runaway compared to the NMC battery. LFP charging and discharging reactions are shown below.

$$\text{Charge Reaction: } LiFePO_4 \rightarrow FePO_4 + Li+ + e- \quad (4)$$

$$\text{Discharge Reaction: } FePO_4 + Li+ + e- \rightarrow LiFePO_4 \quad (5)$$

Over cycling, LFP retains its structural stability as a result of which the battery life is longer and there is less capacity fade compared to the NMC batteries which are more complex due to the composition of nickel, manganese and cobalt, which may lead to faster degradation of the battery. As these reactions are known, it is easier to select the battery types more adequate for further applications. Energy density, safety, cost, and longevity are optimized in this way. These electrochemical reactions enable lithium ions to shuttle between cathode and anode via an electrolyte in lithium-ion batteries. Graphite is typically used as anode, where lithium ions are usually intercalated forming substances like LiC6 still represented by Eq. (1) above. After discharging these moves back to cathode releasing energy stored in them [52]. Various compositions of the cathode allow for reversible reaction with lithium ions enabling multiple recharges over time. The electrochemical processes are key for efficient energy storage and discharge modes In both LFP and NMC batteries at the anode stage, lithium ions are intercalated into the graphite structure, in contrast to that which occurs when they store in graphite layers during charge and release them during discharge [60]. The anodic reactions do not differ between two types of batteries implying that both types use same anodes but different cathodes. Upon discharge lithium ions get inserted into the LFP structure at its cathode [6]. In contrast, at the NMC cathode, the electrochemical process shows that during discharge, lithium ions are incorporated into the NMC structure [81].

The lithium iron phosphate (LFP) and nickel manganese cobalt (NMC) batteries degradation mechanisms differ due to the difference in their chemical composition and structural features [38]. This is attributed to the strong iron phosphate bond in LFP batteries which enhances electrochemical stability, thus prohibiting breakdown under normal charge/discharge conditions. Their crystalline structure is also comparatively well and hence spared of the adverse effects of mechanical forces. The NMC batteries on the contrary are susceptible to changes in the electrode structure as well as phase changes that make their use over a long period impossible [152]. Such loss of cobalt from the NMC cathode causes damage to the cathode structure leading to a decrease in the overall capacity of the battery. The interface of the cathode and the electrolyte becomes unstable which gives rise to a resistive layer on NMC batteries that blocks ions transport leading to quick loss of capacity.

To explain the aging factors affecting LFP and NMC batteries, the experimental results and models have been adopted. Some important techniques include Accelerated Aging Tests, EIS, Cyclic Voltammetry, and Capacity Testing, Post-Mortem Investigation, and Mathematical Modeling and Simulation 408995. These approaches assist in measuring the quantifiable effects of different degradation mechanisms and creating ways in which they can be controlled. For example, it has been demonstrated that stabilizers can be introduced into the ceasing chambers of the NMC batteries in order to improve the storage life of the batteries [122]. On the next hand, these LFP batteries are improved through the developments in the formulation of the electrodes and the design of the cell to extend its use. Thus understanding these deterioration processes and experienced evidence is essential for advancing the design of the battery, the operation systems which will be good for managing the systems as why they were said to be good for using LFP and NMC batteries in more applications, is their life and reliability.

LFP and NMC characteristics based on the bond theory

Regarding ionic and covalent bonding, this study used bond theory to investigate LFP and NMC batteries. These unique characteristics are determined by the bond lengths and energies, especially between lithium and oxygen as well as nickel manganese cobalt with oxygen [17]. Fig. 5 illustrates that LFP batteries exploit the low energy needed for lithium to bond with oxygen around 340 kJ/mol to shuttle Li-ions across the cells making them more stable. Shorter bonds have greater bond energies hence stronger overlap in atomic orbitals [63]. This increased overlap results in a more stable connection between atoms as they approach each other thus leading to better interaction and energy exchange among them. The length of the phosphorus-oxygen bond in LFP batteries ranges from 150–160 pm indicating a strong bond is present here. Ramasubramanian et al. [105] state that this characteristic enhances its longevity as well as thermal resistance [105]. Conversely, stronger metal-oxygen bonds such as those between nickel to oxygen (400–430 kJ/mol), manganese to oxygen (380–405 kJ/mol), and cobalt to oxygen (385–410 kJ/mol) enable NMC batteries achieve better energy density and capacity while at the same time enhancing their electrochemical performance 67151. Consequently, their presence leads to higher storage of energy thus an increase in power output due to higher potential energy per unit volume. Therefore, these metals' bonds with oxygen contribute significantly towards NMC having bigger storage capacity than LFP batteries do. It proves again that atomic or molecular interactions play an important role in determining how efficient lithium-ion batteries are.

Due to these molecular interactions, the LFP batteries are safer and more thermally stable due to the strong covalent P═O bond in their phosphate structure. Their stronger electronegativity of oxygen compared to phosphorus led to a higher bonding energy of about 460–490 kJ/mol between these atoms, which made them less likely to

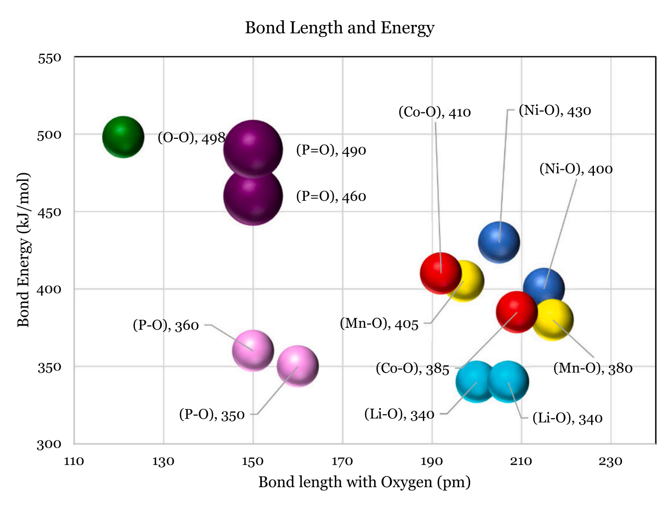

Fig. 5. Bond energy and bond length.

undergo structural failure or thermal runaway during charge-discharge cycles 2250.

Moreover, LFP is able to intercalate lithium through a reversible cell-life that is further enhanced by using conductive materials in order improve its performance as an electrical device [23]. On the other hand, LFP batteries have low energy density and capacity compared to NMC batteries because they are composed of transition metals such as nickel (Ni), manganese (Mn) and cobalt (Co). These metals exist in different oxidation states that increase their electrochemical activity thus facilitates efficient intercalation and deintercalation of lithium ions during charge-discharge process of battery cycles (M. [70,131]). For example, nickel can have + 2 and + 3 oxidation states, manganese ranges from + 2 to + 7 with common applications at + 4 in batteries while cobalt is found in + 2 and + 3 oxidation states. This complex electrochemical behavior is responsible for high performance of NMC batteries enabling them to have more capacity and stability. The interaction among these metals promotes not only improved storage properties but also enhances the structural integrity by preventing any crystal instability leading to long-life cycle of a battery system [80,82].

Comparative analysis of LFP and NMC lithium-ion batteries

This detailed comparative analysis between LFP and NMC batteries will be provided based on their chemical composition and material properties, electrochemical performance, safety considerations, cost and resource availability, applications and use cases, environmental and sustainability factors, market trends and future outlook.

Chemical composition and material properties

The chemical composition in LFP as well as NMC cells is a basic factor that determines their performance as well as suitability for various uses. For instance, a cathode material used in LFP battery is mostly lithium iron phosphate (Q. Cheng et al., 2021). It is worth noting that the stability of phosphate structure particularly strong P═O bond imparts higher thermal stability as well as longer lifecycle to the LFP batteries making them suitable for stationary energy storage systems or a specific kind of EVs with defined safety requirements. On the other hand, NMC cells typically employ nickel-manganese-cobalt combination in their cathode materials (Wen et al., 2020). The combination gives higher energy density than what can be got from using LFP thus make them better suited for high-power electric vehicles like those for portable electronics requiring high energy storage capacity or power density such as high-performance electronic devices like smartphones which need constant recharge due to their heavy usage (Wen et al., 2020). This has implications for weight-conscious applications where smallness combined with huge energy output is desired.

The elemental composition of LFP and NMC batteries also plays a significant role in their performance characteristics. For instance, LFP batteries employ lithium iron phosphate which forms a stable olivine structure as stated by Jiang et al. [58]. This structure is crucial for long-lasting LFP batteries even under harsh thermal/structural pressures. It must be noted that the stability of the layered oxide structure in which nickel, manganese and cobalt are found in NMC cells is much less than that of the olivine structure typical for LFP batteries featuring lithium iron phosphate. Such stability prevents heat-releasing reactions from propagating towards uncontrollable overheating of the battery thus preventing thermal runaway condition. In contrast, NMC batteries rely on an interplay between nickel, manganese and cobalt to optimize their performance properties. The role of high energy density is assigned to nickel, while cobalt improves stability and manganese provides a better thermal stability as shown by Jiang et al. [58]. Nevertheless, layered oxide structure characteristic for these NMC cathodes whereas enhancing energy density makes them less stable under high thermal stress than olivine structure seen in LFP cathodes having lithium iron phosphate (Wen et al., 2020). This difference in composition and structure is one reason why applications requiring higher thermal stability rather than more energy density choose LFP instead of NMC.

The mechanical stability after cycling of a battery's cathode material is highly dependent on the crystal structure. This is one of the reasons why LFP batteries are so popular since these materials can resist structural modifications during a cycle. On Table 2, LFP batteries can withstand more mechanical abuse before failure than other lithium-ion battery types as revealed from our analysis. Thus, this makes them more suitable for heavy-duty applications where reliability and long-term performance are vital (see Table 2). However, NMC batteries with high nickel content, especially those prone to degradation over time but rather slowly. Cracking and crumbling as common failure modes in NMC batteries as observed by Teichert et al. [129] especially large amounts of nickel. The effect of such a mechanical instability may result in higher rates of NMC battery degradation which consequently shortens their lifetime dramatically creating high likelihood that they will require recycling or disposal at some stage in their lifecycle. Therefore, when assessing their long-term reliability, it is important to consider the susceptibility of NMC batteries to structural changes during cycling, particularly for demanding applications such as electric vehicles where battery durability is crucial. The difference between LFP and NMC batteries also extends to material stability; the latter are less stable than the former. In fact, inherent stability is part of any phosphate-based chemistry in LFP batteries while LiMPO4 has very strong P═O bonds that resist thermal decomposition making them nearly indestructible at different working environments as well as temperatures extremes. In contrast, despite having higher energy density levels compared LFP, NMCs face problems relating to material stability; they do not experience thermal or cyclic change without breakage due to presence of nickel that might help them gain more energy density but under high thermally or cycling conditions can lead to an unstable disintegration phase noted by Teichert et al. [129] for example through cracks and metal dissolution. However, these degradation pathways shorten the lifespan of NMC batteries and also make their end-of-life management even more difficult and costly.

Electrochemical performance

For batteries, energy density is an important performance indicator especially when space and weight are constraints (Maxwell and Tabor, 2021). Such high energy densities for NMC batteries ranging from 150 to 260 Wh/kg were also emphasized by Aguiló-Aguayo et al. [5] and Hemavathi et al. [47]. This feature has made them ideal for applications requiring high energy storage in a small volume like EVs and portable electronic gadgets since the battery would have compact dimensions but still stores a lot of power [25]. Additionally, while this can be viewed as a disadvantage due to its low energy density, it is compensated for by other advantages such as longer cycle life and thermal stability in LFP batteries. Furthermore, the other benefits of LFP batteries, which include better thermal stability and long-life cycle among others, compensates their low energy density compared to their competitors with higher ones like NMC cells.

The efficiency of a battery may widely differ depending on the conditions under which it is used. For example, LFP batteries have shown outstanding performance in urban drive cycles, especially when using a small battery. It can be said that this excellence is attributed to the specific physical properties of LFP chemistry, which enable stable and reliable operation over wide operating conditions. Understanding non-uniformity in the internal state of large format lithium-ion batteries is important in optimization of cell and battery module design. In contrast, LFP batteries are less susceptible to internal state changes that can affect the life and performance of different types of cells. This makes them extremely appropriate for environments where consistent performance is required even if there are fluctuating surroundings.

Although aging and degradation processes happen inevitably in lithium-ion batteries, these processes tend to be very different across

Table 2
Comparing effects of ageing and degradation on LFP and NMC batteries.

Aspect	LFP	NMC
Cycle Life and Capacity Fade	Longer cycle life and less capacity fade over time [50].	Shorter cycle life and, more rapid capacity fade [69].
Thermal Stability and Heat Generation	Higher thermal stability; less prone to overheating [56].	Lower thermal stability since they are more susceptible to heat generation and thermal degradation [27].
Mechanical Stability and Structural Changes	Better mechanical stability, minimal structural changes during cycling [6].	Cells are known for their tendency to undergo structural changes such as cracking or particle disintegration which leads to faster degradation rate [129].
Electrochemical Stability and Side Reactions	More stable electrochemical environment, fewer side reactions contribute to degradation [137].	Prone to side reactions such as electrolyte decomposition and transition metal dissolution [87].
State of Charge (SoC) & Depth of Discharge (DoD) Effects	SoC and DoD resilient, with less degradation from deep cycling [2].	More sensitive to high SoC and deep DoD, faster degradation under extreme cycling conditions [134].
Charge Rate & Charging Protocol	can withstand different rates of charge but fast charging should be done in order to minimize degradation [31].	More sensitive to high charge rates than any other type thereby having potential for accelerated degradation from fast charging protocols [31].
Environmental Conditions	It is less affected by adverse environmental conditions and performs well across broader temperature ranges [36].	Controlled environments may be necessary during operation, to avoid extreme or abnormal conditions which could lead into further instability besides this also minimizing their lifespan [72].

various battery chemistries. According to Nájera et al. [90], aging models developed for both LFP and NMC chemistries show that both types of experience capacity fade due to age as a result of calendar and cycling effects. Nevertheless, under various operational modes these errors do not exceed 3 % at most indicating that these chemistry concepts are robust enough [90]. This suggests that any BMS strategy should consider age patterns inherent in both LFP and NMC batteries. Although NMC designs could degrade faster under some circumstances, it takes an effective BMS system to limit such impacts hence prolonging life span of such systems. Similarly, for LFP systems with slow degradation rates provide opportunities for BMS strategies that maximize their performance over longer time frames as per Table 2.

Battery charging rate as well as charge protocols applied significantly determine its serviceability and functioning ability over time. Dufek et al. [31] has identified how LFP batteries can sustain different types of charges without considerable degradation making them ideal for multiple uses [31]. However, fast charging protocols must handle carefully especially concerning quick degradation in NMC cells that are more vulnerable to high charge rates. Choosing batteries with the ability to withstand different charging rates is a critical consideration for specific applications. For instance, there may be a requirement of more stringent management practices in NMC batteries under circumstances where fast charging is necessary so as not to accelerate its depreciation. Conversely, LFP batteries can last longer and operate more flexibly in instances where charging conditions have varied due to their ability to accommodate diverse charging protocols as per Table 2).

Safety factors

Thermal runaway (TR) in lithium-ion batteries still poses serious risks to safety, especially as the market for electric vehicles (EVs) and energy storage systems continues to grow [50]. This hazard is observed during overheating of a battery that sets off an escalating temperature and pressure cycle of externally generated heat within the battery, which in turn can cause fires or explosions [79]. To handle this problem, researchers have recently used more favorable approaches that combine multiphysics modeling principles with machine learning (ML) algorithms to enhance the prediction and prevention of such TR incidents. The study of Goswami et al. [40] worked on bridging the gap through a unified framework of thermal, electrochemical and degradation models to test a battery in different operating conditions [41]. They have been quite innovative, using ML for the first time where a graph neural network (GNN) and Long Short-Term Memory network (LSTM) have been used for both temperature prediction and determining locations of expected hotspots, hence managing TR proactively. Demonstrating the power of ML in such studies, Goswami and others have carried out classifying TR's stages and detecting heat sources in batteries with the assistance of convolutional neural networks (CNNs) and the object detection model. Hence, this particular ability is important in making precautionary actions to avert the critical stages of TR before they escalates [41].

On the chemical front, Britala et al. [18] delve into the degradation mechanisms of NMC cathodes, particularly those with high nickel content, which are more susceptible to rapid degradation and increased TR risks. They propose several mitigation strategies, such as doping, the application of protective coatings, and microstructure engineering to enhance the safety and longevity of batteries [18]. Meanwhile, Sadeghi and Restuccia [112] introduced a pyrolysis-based modeling approach for simulating battery fires under TR conditions, offering deep insights into the thermal and chemical dynamics during such events [112]. Also, [12] have come up with models capable of predicting voltage changes, heat generation processes and temperature rises which for, TR emphasizing on the development of an advanced warning system that could modulate battery operating profiles to safer configurations to avoid TR [12]. They conducted TR safety assessments using statistical and computational modeling techniques for a range of cathodic chemistries and operating situations. They also evaluated which battery chemistries are more likely to cause thermal runaway early on. Pastor et al. [94] explored the TR characteristics aging is likely to affect concluding that older aged batteries particularly those of LFP chemistry tend to be safer because the exothermic reactions during decomposition are less pronounced [94].

During the design and use of lithium-ion batteries, thermal stability is a major consideration for safety purposes. The research by Jia et al. [56] shows that even after being subjected to extreme operational conditions, there is an unlikelihood of an LFP battery burning due to heat generated during the operational process [56]. This then makes it safe to use LFP batteries in applications where the possibility of thermal runaway, which means dangerous overheating occurs because of a system failure is high. However, NMC batteries have higher chances of experiencing thermal instability particularly under high stress or on rapid charging and discharging cycles. In order to ensure safety in this case there need to be more sophisticated cooling systems as compared to the others due to the increased risk of thermal runaway in NMC batteries. However, though the layered oxide structure provides benefit for energy density, it is less stable than olivine structure found in LFP batteries thus making NMC batteries more susceptible to heat degradation (see Table 3).

The amount of heat produced during battery operation and its ability to remove that heat are crucial factors affecting battery life and reliability. As stated by Jindal et al. [59], LFP cells generate less heat naturally which also escapes from them efficiently when required. This helps safeguard users from possible accidents caused by overheating or explosions as witnessed with other types such as NMC batteries operating under adverse conditions like long hours or elevated temperatures.

Table 3
Thermal stability of LFP and NMC.

Attribute	LFP	NMC
Chemical Composition	Lithium iron phosphate is known for its stable olivine structure [58]	Lithium nickel manganese cobalt oxide (LiNiMnCoO2), with varying ratios of nickel, manganese, and cobalt [37]
Operating Temperature Range	Typically − 20 °C to 60 °C, with high thermal stability (S.[25])	Typically − 20 °C to 55 °C, with sensitivity to high temperatures [140]
Thermal Runaway Threshold	Higher, around 270 °C, due to stable phosphate structure [15]	Lower, around 150–200 °C, due to the layered oxide structure [28]
Heat Generation and Dissipation	Lower heat generation due to stable chemistry; efficient heat dissipation [59]	Higher heat generation requires more robust cooling systems [74]
Specific Heat Capacity	Higher, which helps in absorbing heat and delaying temperature rise [125]	Lower, which can lead to quicker temperature increases under stress [10]
Thermal Management Systems	Less complex or extensive systems are needed due to inherent stability [101]	More complex and advanced systems are required to manage heat [122]
Lifecycle and Aging Effects	Less affected by thermal cycling; stable performance over time [155]	More sensitive to high temperatures, leading to faster degradation [128]
Safety Mechanisms	Inherently safer with a lower risk of thermal runaway; may have integrated BMS for temperature monitoring [101]	Often includes advanced BMS with thermal monitoring and management to prevent overheating [85]
End-use Application	Suitable for applications where safety and thermal stability are priorities, like electric vehicles and energy storage [148]	Preferred in high-energy-density applications where temperature control can be managed, like consumer electronics and electric vehicles [115]
Cost and Performance Trade-offs	Generally lower energy density but safer and more stable; often cheaper in the long term [118]	Higher energy density but at the cost of thermal stability and safety; typically more expensive due to advanced thermal management [122]

Differently, NMCs often release significant amounts of heat especially at high power discharges or fast charges. As pointed out by Lyu et al. [74], more robust cooling techniques should be used in order to avoid overheating and therefore guarantee secure operations among these types. Needless complications along with costs add up due to advanced cooling requirements imposed upon electric vehicles powered by those highly efficient batteries (see Table 3).

The safety and useful life of lithium-ion batteries, especially those exposed to high temperatures or subjected to rapid charge/discharge cycles, depend on proper thermal management. Each type has various issues when it comes to thermal management that must be addressed in the case of LFP and NMC batteries. In comparison with this, LFP with its lower heat production and ability for heat conduction have simple ways of managing the system. The control mechanism for temperature of LFP is therefore less complicated making it possible to put them into practice easily and at a low cost in different applications. Conversely, NMC requires more advanced cooling systems regarding their increased thermal generation as well as susceptibility. For example, there is need for sophisticated techniques like those recommended by Lyu et al. [74] since NMCs produce higher amounts of heat. This will lead to the application of more expensive and complex NMC batteries especially where variations in performance are expected due to maintenance of optimal internal temperature as can be seen from Fig. 6.

Different thermal and chemical stability between LFP and NMC batteries make the need for safety mechanisms such as BMS differ. For example, high temperatures shorten the lifespan of NMC batteries without proper BMS [128]. Because NMC batteries are more prone to thermal instability and degradation, complexes or more active BMS protocols have to be employed in order to help manage temperature risks. Contrariwise, LFP batteries have a simpler built-in single unit BMS because they are inherently thermally more stable than the other types. This makes them less cumbersome, cheaper and applicable in many different industries because of the lower risk of thermal runaway. It is thus not surprising that in Table 4, LFP battery has simple and reliable safety measures that makes it ideal for stationary energy storage systems and electric vehicles.

The charging rate as well as the discharging rate influences much on how safe and durable a battery can be when used. In fact, Table 4 shows that within their initial cycle life period LFP cells can offer about three-quarters to four-fifths of their full capacity. Therefore, quick power supply delivery is realized by using these cells while at the same time protecting lives' duration or information security with such chemistry. Higher charge/discharge rates give NMC cells an added advantage of being able to charge faster than most other chemistries which make them efficient in high power output applications. Nonetheless, this feature increases hazard like poor thermal management and degradation rates among others associated with it. In any high-performance application where there must be frequent fast charging/discharging operations; this requires an efficient control over charge/discharge rates so that one can ensure safe operation of such kind especially for lithium-ion batteries made from LiNiMnCoO2 electrodes.

Cost and availability of resources

The cost of material inputs is a significant component in the production of Lithium-ion batteries. It is favorable to use less expensive and more available raw materials such as iron and phosphate in LFP battery production processes (Table 5). Because there are fewer supplies required in producing these components, they tend to have lower costs compared to NMC batteries whose raw materials entail nickel and cobalt that are relatively rare (Table 5). The presence of iron and phosphate lowers the costs for LFP batteries, making them cheaper than other kinds of batteries when budget considerations are factored into account for a wide variety of utilizes. On the contrary, NMC batteries have high production cost attributed to the usage of less abundant metals nickel and cobalt that may be politically instable with respect to their supply

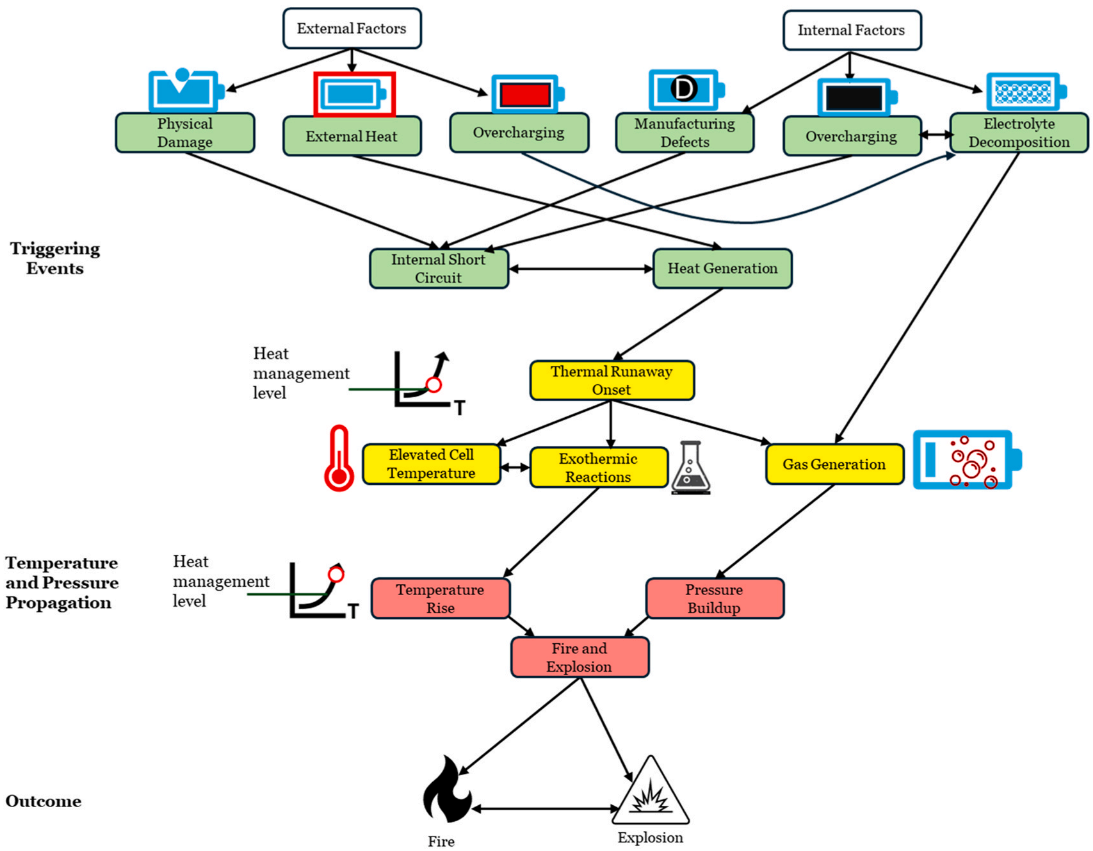

Fig. 6. Battery thermal runaway factors and their interconnected nature.

Table 4
Performance differences between LFP and NMC batteries.

Performance aspect	LFP	NMC
Energy Density	Lower energy density (~ 90–160 Wh/kg) [5]	Higher energy density (~ 150–260 Wh/kg) [47]
Cycle Life	Longer cycle life (> 2000 cycles) [51,156]	Shorter cycle life (1000–2000 cycles) [68]
Thermal Stability	Higher thermal stability, less prone to thermal runaway [138]	Lower thermal stability, more prone to thermal runaway [145]
Safety	Safer due to chemical and thermal stability [138]	Less safe due to higher susceptibility to thermal runaway [145]
Charge/ Discharge Rate	Generally lower compared to NMC [7]	Higher, suitable for rapid charging and discharging
Voltage	Lower nominal voltage (~ 3.2–3.3 V per cell) [43]	Higher nominal voltage (~ 3.6–3.7 V per cell) [46]
Operating Temperature Range	Wider, performs well under broader temperature ranges [48]	Narrower, may require additional thermal management [121]
Cost-effectiveness	Generally more cost-effective due to longer lifespan and stable materials [110]	It may be less cost-effective in the long term due to shorter lifespan and material costs [121]

Table 5
Comparing the cost aspects of LFP and NMC batteries.

Cost Factor	LFP	NMC
Material Cost	Generally lower due to abundant and cheaper raw materials like iron and phosphate [153]	Higher due to the use of expensive materials like nickel and cobalt [70]
Manufacturing Expenses	Potentially lower due to simpler manufacturing processes and less stringent environmental controls [99]	Higher due to more complex manufacturing processes and the need for stricter environmental controls [143]
Energy Density vs. Cost	Lower energy density but more cost-effective for applications requiring durability and longevity [30]	Higher energy density, but this comes at a higher cost, suitable for applications needing high power and energy [142]
Market Price Trends	Decreasing costs over time due to technological improvements and scale of production [83]	Costs are fluctuating but generally increasing due to raw material price volatility [42]
Total Cost of Ownership	Lower over the battery's life cycle due to longer lifespan and stability [121]	Higher initial cost with a potentially higher total cost of ownership due to shorter lifespan and replacement needs [88]
Economies of Scale	Increasingly benefiting from economies of scale as adoption grows [83]	Well-established but may face challenges from raw material supply risks [88]

chains. Moreover, those materials' shortage makes NMC batteries more expensive while exposing them to risks emanating from the fragility inherent in global supply chain systems which subsequently impact on their availability as well as price stability. As shown in Fig. 7, NMC batteries depend on nickel and cobalt, for instance, the unit price of NMC 811 is the highest because of its high nickel content, in addition NMC batteries cost is higher especially because more electric vehicles using them will be produced leading to unsustainable prices at some point.

Manufacturing expenses vary greatly between LFP and NMC technologies used for lithium-ion battery production. The simplicity of LFP's chemistry also allows for larger scale manufacturing possibilities due to its ready availability [65]. Easy preparation as well as processing techniques make lithium iron phosphate an inexpensive material for

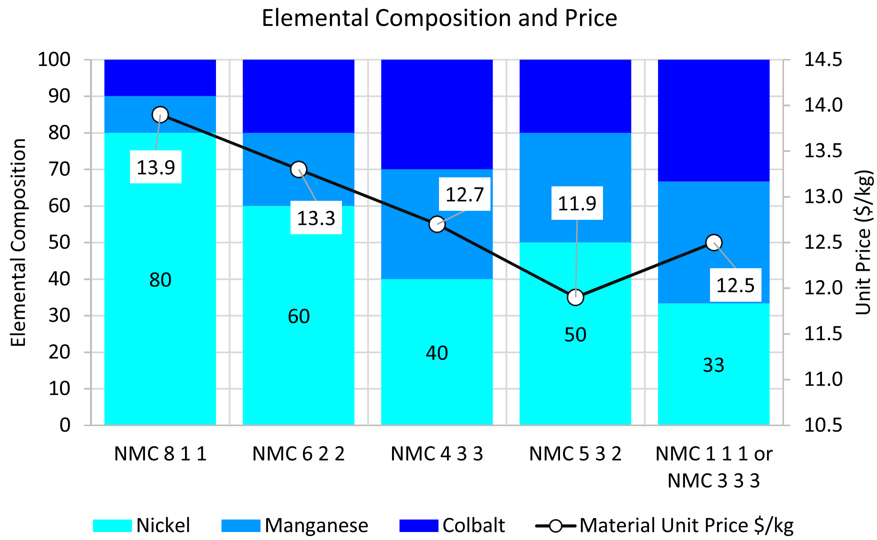

Fig. 7. Composition and price of NMC batteries [42].

large-scale applications where it has become increasingly popular in recent years due to low-cost fabrication procedures. However, this is not the case with respect to NMCs that require specific adjustment involving ratio balancing among Nickel Manganese Cobalt constituents within cathode area during manufacture. As a result, complexity means higher energy consumption related costs when dealing with NMC cells especially in terms of high energy levels needed by processing and strict control of environments that use more dangerous substances. The higher manufacturing costs of NMCs are a significant factor in their overall cost and influence their competitiveness in markets where prices are a dominant concern (see Table 6).

Another cost parameter is the energy used during the production process of Li-ion batteries. LFP battery production has lower energy requirements because of its easy chemistry and treatment [65]. On the other hand, compared to LFP batteries, more energy is consumed by NMC batteries due to the need for complex chemistry as well as material processing [127,141]. This leads to increased costs associated with producing NMC batteries and increases their carbon footprint since they are characterized by high energy consumption during manufacturing processes that result in greenhouse gas emissions. More precisely, increasing the amount of electricity required for producing such cells also results into rise in amounts involved which adds both indirectly to their manufacturing costs and directly contributes to increase in pollution caused by excessive emission of CO2 gases through them. Also seen on Table 6 is that higher power demands make NMC less attractive in relation to total expenses and environmental implications from an ecological viewpoint.

Table 6
Comparison of LFP and NMC cathode materials in lithium-ion battery manufacturing.

Aspect	LFP	NMC
Active Material	Lithium Iron Phosphate	Lithium Nickel Manganese Cobalt Oxide
Cathode Complexity	Less complex, easier to produce [26]	More complex due to the blend of nickel, manganese, and cobalt [78]
Manufacturing Process	Similar to other lithium-ion batteries but with simpler cathode material [23]	Requires precise control to balance the nickel, manganese, and cobalt ratios [78]
Energy Consumption	Generally lower due to simpler chemistry and processing [65]	Higher due to more complex chemistry and material processing [127,141]
Scalability	Relatively easier to scale due to material availability and process simplicity [26]	Can be challenging to scale due to the complexity and cost of raw materials [106]
Raw Material Availability	Iron and phosphate are more abundant and accessible [149]	Nickel and cobalt are less abundant and subject to geopolitical risks [77]
Safety in Production	Considered safer to manufacture due to the stability of materials [65]	Requires stringent safety measures due to the volatility of materials [150]
Cost Implications	Lower cost of raw materials leads to cheaper manufacturing costs [132]	Higher cost of raw materials, especially cobalt and nickel, increases manufacturing costs [42]

The overall ownership cost of a battery include not just its original price, but also the costs related to running it, keeping it in working condition and ultimately replacing it. LFP batteries have lower TCO over their life cycle because they live longer and are more stable [121]. The long cycle life and low rate of degradation of LFP batteries mean that they don't need to be replaced so often, making them more economical over time especially for uses where battery life is expected to be many years. In contrast, NMC batteries, with their shorter cycle life and higher rate of degradation, may have a higher initial cost and a potentially higher TCO due to the need for more frequent replacements [88]. For example, NMC batteries have high TCO compared to their gains in energy density if there are plans for long-term savings on power usage. Also important is the greater TCO associated with NMC batteries in certain applications where tight budgets and long-term cost-effectiveness are vital issues (see Table 6).

Applications and use cases

Lithium-ion batteries find extensive use in electric vehicles (EVs), which also happen to face one major alternative: whether they should be powered by LFP or NMC cells in order to boost their performance without necessarily increasing their value. LFP batteries are preferred for energy storage systems that require long cycle life, stability, and safety, particularly in electric buses and low-cost EVs where these factors are more important than maximizing range (see Table 7). This means that such applications as for instance the ones involving electrical buses as well as inexpensive EV vehicles will benefit from using LFP cells which guarantee longer duration of serviceability than greater distance between two points traveled within one charge given that all things being equal. However, we could say that these concerns may not exist when considering reasons like safety, cost-effectiveness, and durability for using LFP batteries with lower energy density in these applications. In contrast, NMC batteries are more likely to be used in high-performance electric vehicles as they have higher energy densities

Table 7
Compares the market share aspects of LFP and NMC batteries.

Market Share Factor	LFP	NMC
Adoption Rate	Increasing adoption of energy storage and electric vehicles due to safety and cost benefits [136]	Historically dominant in the electric vehicle and portable electronics markets due to higher energy density [32]
Growth Drivers	Safety, cost-effectiveness, longer cycle life, and shift towards more sustainable options [98]	High energy density, performance, and established manufacturing and supply chains [147].
Geographical Presence	Strong market presence in China, expanding globally [124]	Well-established globally, with a significant presence in Asia, Europe, and North America [14]
Application Segments	Preferred in stationary storage, electric buses, and low-cost EVs [92]	Widely used in high-end electric vehicles, portable electronics, and power tools [135]
Future Prospects	Expected to gain a larger market share in the EV sector due to cost and environmental factors [147]	May face challenges from the rising costs of cobalt and nickel, but likely to remain significant in high-energy applications [88]
Supply Chain Dynamics	Concentrated supply chain in China, increasing efforts to diversify [124]	More diversified supply chain but susceptible to fluctuations in cobalt and nickel prices [24]
Regulatory Impact	Benefiting from regulations favoring environmentally friendly and safer battery technologies [88]	May be affected by regulations concerning the sourcing of raw materials like cobalt and nickel [42]

which is an important feature in such power intensive applications where space saving and high output power are vital requirements (Wang et al., 2016). In relation to critical factors like maximum vehicle range and good performance, the capacity to achieve more from less can be seen as another merit of NMC batteries due to their ability to store a lot of energy within a small size and weight. However, the initial higher price and reduced lifetime or longevity observed in NMC battery should not be ignored when the EVs requirements are considered.

NMCs are also widely used in consumer electronics because of their high energy densities and compactness that make them suitable for smartphones, laptops, tablets and many other portable devices. This is particularly helpful where space is limited, or the device needs to be light. The fast-charging rate associated with NMH batteries makes it a good fit for devices that need faster recharging rates or longer operating hours. Conversely, LFP batteries have long cycle lives and improved stability which are attractive features for certain electronic consumer goods that require greater safety levels than just maximizing on energy density (Wang et al., 2016). For instance, LFP batteries possess a low degradation rate over time hence making them quite dependable under frequent discharge-charge states as compared with NMC cells used frequently in places such as electric bicycles or power tools among others. This can serve multiple purposes by ensuring reduced need for replacing at regular intervals while enhancing reliability plus device safety overall (see Table 7).

For example, lithium-ion batteries are also commonly used in stationary energy storage systems that are utilized in renewable energy facilities and for grid stabilization. LFP-based static storage systems are becoming more common than NMC in solar and wind power related sectors within renewables industry simply because the former offers enhanced performance characteristics at diverse environmental conditions as well as having longer cycle lives satisfying the industry demands (Lombardo, 2022). Safety, long cycle life and stability make LFP batteries ideal for use in stationary energy storage, where the emphasis is on dependability instead of maximizing energy density. However, unlike LFP cells with shorter life cycles and less temperature resistant characteristics, NMC ones have higher volumetric energy densities but might not be very useful for stationary applications. The choice between LFP and NMC batteries in stationary energy storage systems depends on the specific requirements of the application, including cost, safety and expected lifespan.

Environments and sustainability factors

When looking at the overall environmental impact of lithium-ion batteries, it is important to consider their recyclability as well as end-of-life management. LFP batteries are more sustainable in the long run because they have a longer lifespan and consist of less hazardous chemistries that are easily managed and cost-effective at their end of life [35]. The recyclability of LFP batteries is superior to that of NMC batteries due to the stability of materials used such as iron and phosphate. In contrast, NMC batteries are subjected to complex disposal issues which attract high costs since the materials involved like cobalt, nickel lack stability hence presenting hazards [88]. The recycling process for NMC batteries is more complex and necessitates greater stringency in safety measures and environmental controls to address these concerns with regard to these materials. Subsequent sections will discuss the main factors behind lower recyclability and higher cost implications associated with end-of-life management for NMC batteries based on Table 8.

The availability of raw materials needed for manufacturing lithium-ion batteries determines their long-term sustainability as well as cost effectiveness. On the other hand, LFP batteries rely on abundant materials such as iron and phosphate which do not experience supply constraints or price volatility on global markets [1]. These plentiful resources contribute to the overall sustainability and affordability of LFP battery technology making them a better option in those markets where scarcity may exist in certain parts. Contrarily, NMCs depend on scarce sources like cobalt and nickel whose limitedness can be attributed to geopolitical risks as well as increased demand from an escalating electric vehicle market [116]. It is thus expected that reliance on these materials will lead to higher cost, greater adverse environmental impacts associated with NMCs while raising questions over whether their supply chains can be maintained in the longer term. These two factors significantly impact on the overall sustainability and competitiveness of NMC batteries as discussed on Table 8.

The environmental effects of lithium-ion batteries are determined by their materials, energy consumed during production, and how they are disposed at end-of-life. LFP batteries have a lesser environmental impact than NMCs because of less hazardous materials used and lower energy

Table 8
Comparing the sustainability and end-of-life aspects of LFP and NMC batteries.

Aspect	LFP	NMC
Raw Material Scarcity	Less scarce, more abundant materials (iron, phosphate) [1]	Uses scarcer materials like cobalt and nickel, which may face supply constraints [116]
Environmental Impact	Lower environmental impact due to less hazardous materials [137]	Higher environmental impact due to the use of cobalt and nickel, which are associated with more severe ecological and social issues [117]
Recyclability	Higher recyclability due to stable materials [65]	Lower recyclability compared to LFP, due to the complexity of materials [32]
Second-life Usage	Higher potential for second-life applications due to stability and long cycle life [137]	Lower potential for second-life use due to shorter cycle life and degradation [154]
End-of-Life Management	Easier and less costly to manage due to material stability and abundance [65]	More complex and potentially costlier to manage due to hazardous materials and less stability [88]
Sustainability	Considered more sustainable due to longer lifespan and safer chemistry [35]	Less sustainable compared to LFP, considering the total lifecycle and material sourcing issues [88]

consumption during production [137]. The usage of less harmful substances like iron and phosphate in LFP batteries is an added advantage for these types of applications where there is concern about environmental footprint. On the other hand, due to more dangerous substances like cobalt and nickel used in NMC's structure; this type has a higher impact on environment [117]. Moreover, the processes that are involved in making NMC batteries are very resource intensive making it responsible for significant environmental damage caused by carbon emission as well as resource depletion. Consequently, there is considerable rationale behind inclusion of its greater environmental impacts into criteria shaping choice of NMC battery technology applied in line with Table 8.

Market trends and future outlook

The adoption rates of LFP and NMC batteries have oscillated over time, reflecting market necessities as well as changes in the technological environment and regulatory frameworks. Fig. 8 shows that LFP type of battery is the largest when considering the overall capacity utilized in electric light-duty vehicles (LDVs), experiencing a consistent increase year after year from as low as 7 % back in 2018 to around 36 % by 2023. Such growth can be attributed to these factors which include cost, safety, and eco-friendliness among other things. Moreover, this trend reveals an ever-existing predilection for LFP chemistry throughout the EV sector on account of its reasonable prices, safe nature and environmental friendliness. The demand for EVs with LFP batteries is further shaped by efforts meant to reduce GHG emissions during battery production and usage. With a 60 % market share in 2022, NMC remained the top battery chemistry. It was followed by LFP, which made up over 30 % and nickel cobalt aluminum oxide (NCA), which made up about 8 % [53]. Consequently, compared with other types of batteries available in the market like lead acid or Li-ion, manufacturers are increasingly embracing lower priced more sustainable rechargeable lithium iron phosphate batteries such as NMC type. This is to meet changing consumer preferences due to stringent government policies on green economy development and rising costs of energy fuel sources used within their operations.

On the flip side however, NMC batteries have had significant stakes in electric vehicle and portable electronics markets since they have higher energy density thus well-established manufacturing chains globally that supply them. Nonetheless future competitiveness of NMC cells may be questioned by high cobalt & nickel raw material prices. In addition, increasing concerns about environmental impact vis-à-vis disposal practices (Table 8).

Whereas geographical locations where one finds either LFP or NMC cells reveal diverse regional market dynamics plus regulatory set ups; the Chinese market stands out regarding LFP battery deployment particularly for heavy-duty vehicles, energy storage systems, and other numerous applications. To this end, the Chinese domestic market has massively embraced LFP batteries thanks to a government that intends on having sustainable energy solutions at reduced costs. Moreover, as more areas around the world start adopting similar sustainability and cost effectiveness criteria as China does, it is expected that its strong presence there will become global in nature. However, NMC cells have already achieved considerable sales throughout Asia, Europe, and North America specifically due to their high energy density thus making them ideal for high power EVs & portable electronics that aim at maximizing energy storage while minimizing weight (Table 8).

Price convergence and market trends

As shown in Figs. 9 and 10, from 2015 to 2023, the price trends for LFP- and NMC-type batteries have fallen steadily. However, in recent times, the decline in LFP battery prices is much more significant compared to NMC batteries. The price at which LFP batteries started operations in 2015 was $600/kWh. On the other hand, the starting price of NMC batteries was nearly $200/kWh over and above the LFP price. The main reason for the big difference in prices is because extremely expensive raw materials were used in the making of these batteries, like cobalt and nickel. Since LFP's price fell more rapidly than NMC's, the difference in price between the two technologies narrowed to US$150/kWh in 2023. The wider availability of cheaper raw materials, and production scaling-in particular from China-have driven down prices of LFP, with significant volumes combined in electric vehicle and energy storage applications. While NMC's price has dropped from US$800/kWh to US$440/kWh between 2015 and 2023, supply chain bottlenecks and raw material costs have pushed the latter toward a more modest price curve. This also means that NMC remains in higher demand for high-performance applications due to its superior energy density. The resulting price convergence trend for LFP and NMC technologies is likely to render LFP increasingly competitive in price-sensitive markets.

Price convergence and market trends

Table 9 shows that there is quite sharp segmentation between the LFP and NMC battery technologies with regard to application, cost trajectory, and market adoption. LFP is used in low-to-mid-range EVs, in stationary energy storage systems, and because of its lower production cost, it therefore becomes quite attractive in price-sensitive markets and for those applications where safety and sustainability are the key issues.

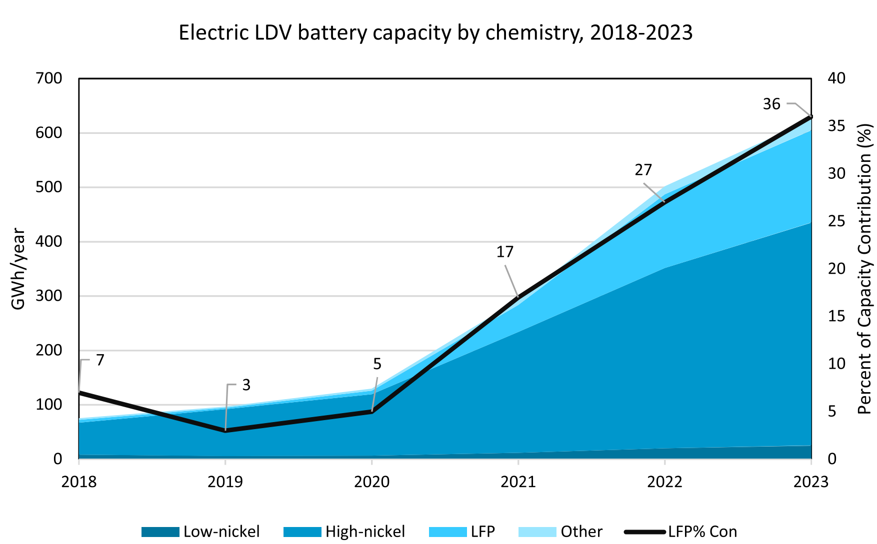

Fig. 8. Electric LDV battery capacity by chemistry, 2018–2023 [53].

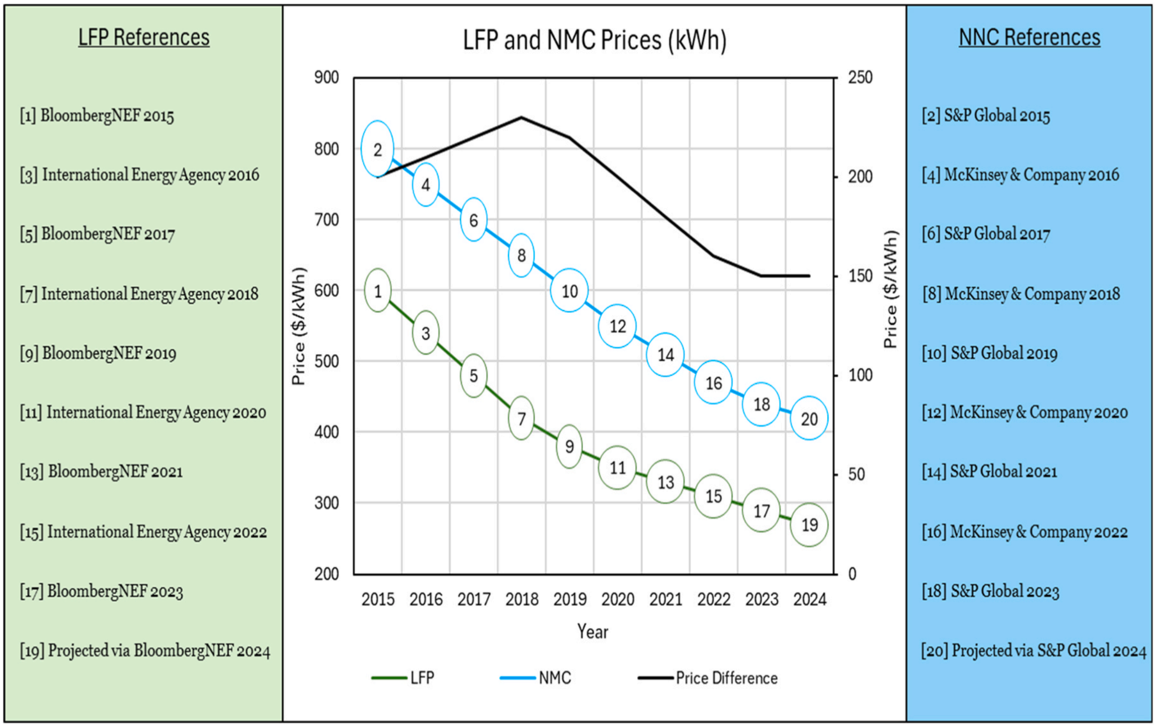

Fig. 9. LFP and NMC prices trend (Bloomberg (NEF); IEA, 2015–2023; mckinsey.com, 2015–2023; S&P Global, 2015–2023).

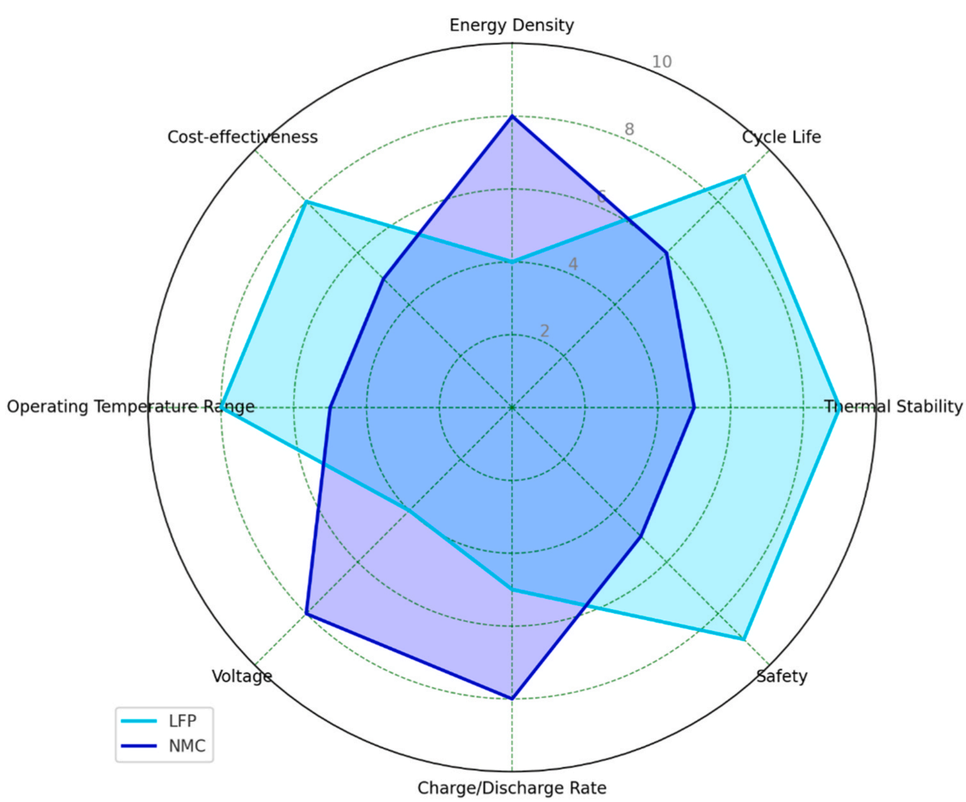

Fig. 10. Performance comparison of LFP and NMC Batteries.

It requires costly raw material inputs, hence making it more expensive to manufacture, while NMC is favored in higher value applications like premium EVs and consumer electronics. However, unstable pricing for its raw materials threatens the long-term cost stability of NMC. The market trend indicates a continually increasing adoption of LFP in emerging markets, largely due to its affordability, while NMC remains predominant in premium sectors, though it may be confronted with the challenges of volatility in supply chains in the future.

Table 9
Applications, key adopters, and trends.

Category	LFP	Ref.	NMC	Ref.
Applications	Utilized in low to mid-range electric vehicles (EVs)	[109]	Preferred for high-performance electric vehicles (EVs)	[139]
	Employed in stationary energy storage systems (e.g., solar, wind energy)	[104]	Used in consumer electronics (e.g., smartphones, laptops)	[21]
Key Adopters	Tesla (Standard Range Model 3, Model Y)	[136]	General Motors, BMW, Hyundai, Apple, Samsung	[29]
	BYD (major Chinese automaker)	[136]	High-end EV manufacturers	[49]
Cost Trajectory	Lower production cost due to absence of cobalt and nickel	[137]	Higher production cost driven by cobalt and nickel content	[137]
	Consistent price reduction driven by large-scale manufacturing	[136]	Price volatility linked to raw material supply fluctuations	[84]
Manufacturers	CATL, BYD, EVE Energy	[39]	LG Chem, Samsung SDI, SK Innovation	[49]
Notable Products	Tesla (low-range models), BYD electric vehicles	[136]	GM (Chevy Bolt, Hummer EV), BMW i-Series, Hyundai Ioniq	[4, 54]
	Stationary storage systems (solar, wind)	[120]	Consumer electronics (smartphones, laptops)	[111]
Automotive Integrators	Tesla, BYD, and other Chinese automakers	[136]	General Motors, BMW, Hyundai	[75]

Discussion

Considering different aspects of LFP and NMC battery technologies including chemistries, performance, safety, environmental impact and lifecycle management of lithium-ion batteries (LIBs), this study finds that in terms of performance and safety LFP is more preferable than NMC due to its chemical stability as well as low risk of thermal runaway. This has been supported by research like [113] where they have experimentally compared the performance and degradation of LFP cells against NMC under different conditions which showed higher stability but lower degradation rate for LFPs. On the other hand, while NMCs are known to have higher energy densities which are vital for applications such as electric vehicles where weight and space are at premium; these also pose greater safety hazards because they react more with heat according to some investigations like [114]. The radar chart shown in Fig. 9, compares LFP and NMC batteries in five key areas: Energy Density, Cycle Life, Safety, Cost Efficiency, and Environmental Impact. LFP scores higher in these areas, while NMC excels in energy density, making it suitable for compact applications.

Our analysis also indicates that when it comes to raw materials cost per unit capacity produced there is a significant gap between these two types especially in mass production scenarios. Similarly, another study done by Cheng et al. [24] discovered supply risks coupled with cobalt-nickel based cathode materials used by NMCs being much higher than those associated with iron-phosphate based ones employed by LFP. Additionally, recycling is becoming increasingly important due material recovery economics regulations can be achieved through better designed recycling methods thus stabilizing material costs if adopted together with improved collection rates or regulations enforcement. The importance of these elements cannot be overemphasized especially now that battery-market continues growing towards energy systems efficiency sustainability transport sector development where according to Ali et al. [9] recycling could help alleviate some cost concerns through providing secondary critical minerals though current technologies for recycling are not yet environmentally friendly [9].

The findings from our study clearly indicate that both types play crucial roles in grid stability improvement renewable energy integration enhancement as indicated by Knibbe et al. [64]. Practical application of LFP in heavy haul rail decarbonization scenarios showed adaptability of LFP batteries on various energy demand platforms. Recent works such as that conducted by Ferrando et al. [66] reveal new possibilities in NMC technology advancement with respect to intermittent challenges posed by renewable sources and grid balancing through optimization EMS operational strategy for longer battery life as well better economic returns. EMS allows precise control over charge discharge cycles thus managing trade-off between longevity and profitability. According to the study, implementing this system can extend SoH mark by four years thereby reducing replacement costs significantly delaying degradation of NMC batteries up to 80 % and enhancing sustainability of energy storage investments.

Future perspectives in battery technology development

Our findings underscore the distinct advantages and limitations of LFP and NMC lithium-ion batteries guiding the trajectory for future research and technological advancements. Material science should continue to advance continuously toward better performance and sustainability in battery technologies. This narrative is supported by Qi et al.'s work on decay mechanisms for LFP batteries as well as recent developments in their recycling techniques [100]. Further research should therefore focus on developing cathodes and anodes with a wider scope of applications so that NMC batteries do not rely heavily on valuable metals like cobalt or nickel. In an attempt to enhance EV battery performance, researchers have introduced novel elements like titanium niobium oxide and molybdenum disulfide. Layered oxide substances could in fact be used in sodium-ion batteries instead of lithium-ion batteries according to Azambou et al. thus leading to improvement of structural stability and electrochemical performance [11]. Alemu et al.'s work presents transition metal-based air batteries that would replace the conventional lithium systems through another method [8]. We need to leverage these research and development in order to fine-tune these technologies and surmount existing limitations of LFP and NMC so that they can address current demands for modern energy storage applications.

Future research programs should concentrate on increasing energy density, safety, and environmental friendliness of LFP and NMC batteries hence expanding horizons by looking at innovative materials while finding more cost-effective recycling processes may lead to improved system performance/safety levels. Moreover, better recycling methods for increased environmental sustainability starting from designing processes could reduce negative impacts associated with adoption of sustainable life-cycle management models within these specific areas. Importantly, the integration of advanced renewable energy systems with advanced battery technologies offers a potential avenue for future studies. Battery research should focus on understanding their role in dynamic energy systems including smart grids applications or large-scale renewables integration. LFP batteries could get a boost from green battery policies, while NMC technology could see significant innovations due to the desire for better performance. Researchers should continue working on new battery technologies that would ensure all batteries are safe for the environment through increasing productivity as well as combining all these inventions. More cross-study collaborative efforts are needed, the transformative power of structured partnerships in the photovoltaic sector [50], could serves as a model for battery technology, particularly LFP and NMC batteries. By leveraging collective strengths and addressing shared limitations, these strategies can enhance energy storage technology development, driving innovation and speeding up technological advancements.

Conclusion

This research focused on the characteristics of LFP and NMC batteries, including their performance, safety, cost, environmental effect, and market presence. LFP batteries are known for being safe to use, advantageous in terms of cost, durability, as well as becoming more prevalent in energy storage and electric vehicle domains. Large presence especially in China and global emerging influence together with rising interest in low-priced electric cars and stationary energy storage systems have made these elements become a reliable long-term solution. On the other hand, NMC batteries have been recognized for having high power density and outstanding performance. However, they encounter problems emanating from variable prices as well as limited availability of key components such as cobalt and nickel, among others. They play a significant role in industries that require high amounts of energy like luxury electric cars or portable electronic devices. Therefore, there is a need to manage NMC batteries cautiously considering logistical issues and environmental concerns associated with battery component recycling.

The anticipated increment in LFP's market share signifies the deliberate shift towards batteries that are environmentally friendly, dependable and economically viable. This has been driven by technological advancements plus governmental support for sustainable technologies. Currently, NMC batteries' position on the market is under scrutiny because of their cost along with logistical weaknesses. This requires careful exploitation of their advantages regarding energy density. A comprehensive evaluation will determine whether LFP or NMC technology suits unique applications based on specific needs, environmental impact as well as budgetary considerations. The study provides a comprehensive handbook to guide decision makers towards making choices that promote resilient sustainable energy storage systems due to growing global demand for efficient affordable energy storage.

It helps make urgent decisions but also lays down groundwork for future improvements in efficiency, safety, cost-effectiveness relating to battery technologies. Moreover, the growth in sustainability orientation coupled with an increasing adoption rate of green energies could be driving factors for LFP battery market. Nevertheless, NMC batteries will always be needed for demanding applications. The overall review conducted in this study would be a significant resource for policymakers' conducting insight on strategic battery options aligned with emerging energy and environmental trends. LFP batteries are preferred primarily due to their longer life span and resistance to temperature changes while NMC batteries are selected mainly because of their remarkably high energy density in energy intensive applications. Which one to choose depends on the specific energy requirements at an exact place of operation.

For LFP batteries, thermal risk is a common characteristic for which they have good thermal stability and safety. On the other hand, high-energy-density NMC batteries require precise temperature control to prevent accidents. Economically speaking, LFPs have advantages in terms of cost reduction that can arise from economies of scale as compared to NMCs having financial and supply chain problems caused by higher costs arising from materials prices. However, despite their growing popularity because of their safety features and cost effectiveness as well as environmental benefits, NMC batteries will still be needed for applications with a high energy demand. The future developments in battery technology will provide more clarity on the roles of LFP and NMC batteries in the energy sector. This will be on the basis of sustainability, efficiency and cost-effectiveness that usually aid in advancement and selection of battery technologies.

Research implications contributions

The results of this study on comparative analysis on LFP and NMC cells present useful insights in terms of research for energy storage and battery development.

Theoretical implications enhancement of battery chemistry understanding

1. This research provides a good understanding of electrochemical properties and thermal responses of LFP and NMC batteries by analyzing all factors which affect their efficiency, safety and life span in detail. This research improves the theoretical knowledge base on battery chemistry concerning ionic versus covalent interactions and how they influence battery stability performance.
2. In the course of studying LFP vs NMC batteries under operating conditions different from those experienced during tests conducted within this investigation, new indicators might be found for use in more accurate models explaining today's battery characteristics.
3. The work contributes to the theoretical discussion on sustainable battery technologies by assessing the environmental effects and end-of-life management of LFP and NMC batteries. The study evaluates the sustainability of battery systems by considering criteria such as the availability of materials, the capacity to recycle them, and the emissions produced during their lifespan.

Practical contributions

1. The study's results provide a useful reference for stakeholders in industries such as automotive, renewable energy, and portable electronics. It assists them in selecting the most suitable battery technology according to specific application needs, such as energy density, safety, cost, and environmental impact.
2. By conducting a comprehensive analysis of LFP and NMC batteries, experts in the field may make informed judgments about incorporating energy storage solutions into the power grid, electric cars, and several other applications. This encompasses the strategic planning for the acquisition of batteries, the development of system design, and the implementation of lifecycle management practices to maximize performance and achieve cost-effectiveness.
3. The research emphasizes that NMC batteries are vulnerable due to dependence on unstable raw materials like cobalt and nickel; this may help organizations develop mitigation measures like diversifying supply sources or investing resources into recycling technology or switching over more robust chemistries such as LFP.
4. Gaining knowledge about different types of batteries' environmental properties as well as safety aspects could provide government with useful insights when making policy decisions that are informed by scientific facts only. Governments can use findings from this study to inform legislation requirements that will encourage adoption of safer environmentally sustainable battery technologies at lower costs.
5. A detailed evaluation considering pros/cons' relationship between LFP & NMC batteries can inspire creativity and progress in the battery industry. Manufacturers and researchers are therefore advised to research novel materials, developments in design as well as technical breakthroughs aligned to the restrictions presented herein hence enabling future development of sophisticated battery technologies.
6. This work enhances the scholarly literature on battery technologies by providing a thorough comprehension of their chemistry, performance, and sustainability attributes, thereby contributing to the theoretical implications in this area. It offers practical and useful information for different people or organizations involved in energy sector. Such data is vital when making informed choices about policies through strategic planning for instance and promoting innovation in battery technology field.

List of abbreviations

BESS: Battery Energy Storage Systems
BMS: Battery Management Systems
CAES: Compressed Air Energy Storage
CNN: Convolutional Neural Network
DoD: Depth of Discharge

EIS: Electrochemical Impedance Spectroscopy
EMS: Energy Management System
ESS: Energy Storage Systems
EVs: Electric Vehicles
GHG: Greenhouse Gas
GNN: Graph Neural Network
LDVs: Light-Duty Vehicles
LFP: Lithium Iron Phosphate
LIBs: Lithium-Ion Batteries
LSTM: Long Short-Term Memory
NCA: Nickel Cobalt Aluminum Oxide
NMC: Nickel Manganese Cobalt
PHS: Pumped Hydroelectric Storage
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SoC: State of Charge
SoH: State of Health
TES: Thermal Energy Storages
TR: Thermal Runaway
TWh: Terawatt-hour

CRediT authorship contribution statement

Solomon Evro: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Abdurahman Ajumobi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Darrell Mayon:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Olusegun Stanley Tomomewo:** Writing – review & editing, Validation, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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