

SHORT REPORT

PHOSPHORUS BASED BATTERIES

Current status, opportunities,
challenges, and future
perspectives





PREFACE

Energy storage technologies are advancing rapidly, playing a crucial role in the shift toward sustainable energy solutions. Batteries, as a key component of this transition, are continuously evolving to meet the increasing demands of electric vehicles, renewable energy storage, and consumer electronics. Among these innovations, phosphorus-based batteries have gained significant attention due to their safety, environmental advantages, and cost-effectiveness. This short report explores the fundamentals and latest advancements in phosphorus-based batteries, offering a look at their development, applications, and potential for commercialization. It covers the core scientific principles, technological breakthroughs, and challenges associated with these materials, with a focus on their role in providing reliable, sustainable, and cost-effective energy storage solutions. Designed as a resource for researchers, industry experts, and policymakers, this report aims to highlight the opportunities and benefits of phosphorus-based batteries. By advancing knowledge and encouraging innovation in this field, it contributes to the broader goal of creating a cleaner and more sustainable energy future.

PHOSPHORUS-BASED BATTERIES

Unlocking a New Era
in Sustainable
Energy Storage



EXECUTIVE SUMMARY

This short report examines the potential of phosphorus-based batteries in advancing sustainable energy storage. It outlines battery fundamentals, the significance of phosphorus and its allotropes, and the role of orthophosphates, pyrophosphates, fluorophosphates, and phosphides as cathodes, anodes, and electrolytes in lithium-ion and sodium-ion batteries. These materials offer advantages such as stability, thermal resistance, and enhanced ionic conductivity. A comparative analysis with conventional batteries highlights key challenges and optimization strategies. The report also explores production processes and market trends, focusing on the growing adoption of lithium iron phosphate (LFP) and lithium manganese phosphate (LMFP) in electric vehicles (EVs) and grid storage. LFP remains dominant due to its affordability and safety, while LMFP provides higher energy density. Additionally, a statistical model assesses material reserves, production, and pricing to evaluate their impact on the phosphorus-based battery industry.

ACKNOWLEDGMENT

The realization of this book has been a collaborative endeavor, made possible by the dedication, expertise, and unwavering commitment of many individuals. We express our deepest gratitude to all those who have contributed their time, knowledge, and efforts to this work.

We extend our sincere appreciation to the contributors:

- **Dr. Zakaria CHCHIYAI**, PostDoc at **LIMSET**
- **Pr. Hanane AITOUSALEH**, Assistant professor at **LIMSET**
- **Pr. Mohamed CHAKIR**, Affiliated Professor at **LIMSET**
- **Dr. Hayat HAOUAS**, PostDoc at **LIMSET**
- **Zakaria KHARBOUCH**, PhD at **LIMSET**
- **Fadila EL KOUIHEN**, PhD at **LIMSET**
- **Houda KARIBE**, PhD at **LIMSET**

Their invaluable expertise, rigorous research, and collaborative spirit have been instrumental in shaping the content of this book.

We are particularly grateful to **Mr. Abdellah ELHOUARI**, Phosphates Expert at **Global Phosphorus Institute (GPI)**, **Morocco**, for his invaluable guidance, insightful orientation, and thorough review of this report. His expertise and support have been instrumental in shaping the direction and quality of this work.

This short report was developed as part of the **UM6P-GPI** project. We extend our sincere gratitude to **the Global Phosphorus Institute (GPI)** for their financial support and infrastructure, which made this work possible.

CONTENTS

01	I. INTRODUCTION	
01	II. BATTERY BASICS AND ELECTROCHEMICAL ENERGY STORAGE	
	II.1. WHAT IS BATTERY ?	1
	II.2. BATTERY OPERATION: RECHARGE AND DISCHARGE	2
	II.3. TYPES OF BATTERIES	3
05	III. INTRODUCTION TO PHOSPHORUS-BASED MATERIALS	
	III.1. PHOSPHORUS (P) : SOURCE AND ABUNDANCE	6
	III.2. STRUCTURE, PHYSICAL AND CHEMICAL PROPERTIES OF PHOSPHORUS ALLOTROPES	6
	III.3. OVERVIEW OF PHOSPHORUS-BASED MATERIALS	7
09	IV. PHOSPHORUS-BASED VS. CONVENTIONAL BATTERIES: COMPARATIVE ANALYSIS AND ADDRESSING CHALLENGE	
	IV.1. CATHODE BASED MATERIALS	9
	IV.2. ANODE BASED MATERIALS	11
	IV.3. OVERCOMING LIMITATIONS OF PHOSPHORUS-BASED BATTERIES: CHALLENGES AND ENHANCEMENTS	12
13	V. MANUFACTURING PROCESSES AND RAW MATERIALS OF PHOSPHORUS-BASED BATTERIES	
	V.1. RAW MATERIALS FOR P-BASED BATTERIES: ABUNDANCE, SOURCE AND MINING	13
	V.2. MANUFACTURING PROCESSES OF LITHIUM IRON PHOSPHATE BATTERY	16
	V.3. ENVIRONMENTAL AND SUSTAINABILITY ASPECTS	17
18	VI. CURRENT STATUS OF PHOSPHORUS-BASED BATTERIES: A MARKET ANALYSIS	
	VI.1. CURRENT STATUS OF LFP BATTERIES	18
	VI.2. CURRENT STATUS OF LMFP BATTERIES	22
	VI.3. BATTERY GIGAFACTORIES IN MOROCCO	23
23	VII. LFP AND LMFP BATTERY PRODUCTION AND PHOSPHORUS DEMAND ANALYSIS (2022-2030)	
	VII.1. INTRODUCTION	23
	VII.2. GLOBAL PRODUCTION TRENDS OF LFP AND LMFP BATTERIES (2030-2022)	24
	VII.3. MATHEMATICAL MODELING OF PHOSPHORUS DEMAND	27
	VII.4. PHOSPHORUS DEMAND EVOLUTION (2030-2022)	27
	VII.5. STRATEGIC IMPLICATIONS AND RECOMMENDATIONS	29
30	VIII. CONCLUSION	
31	IX. REFERENCES	

I. INTRODUCTION

Recent advancements in portable technology have substantially increased the demand for high-performance energy storage systems capable of sustaining both current and next-generation electronic devices. Addressing this demand has become a strategic imperative, fostering continuous innovation in battery technologies that are reshaping modern electronics. Despite the development of alternative energy storage methods, batteries remain the primary choice due to their versatility, scalability, and ability to meet diverse application needs.

Over the past century, batteries have demonstrated remarkable reliability as portable energy sources, solidifying their role in technological progress. Substantial investments in research and development have been dedicated to enhancing battery performance, with efforts focused on making them lighter, more compact, cost-effective, and capable of delivering higher energy densities. In parallel, advancements in intelligent charging systems aim to accelerate charging times, reduce device weight, and integrate protective mechanisms against overcharging, collectively contributing to improved efficiency, safety, and longevity.

II. BATTERY BASICS AND ELECTROCHEMICAL ENERGY STORAGE

II.1. WHAT IS A BATTERY ?

A battery is an electrochemical device that stores energy in chemical form and converts it into electrical energy through redox reactions. Batteries can be categorized as primary (non-rechargeable) or secondary (rechargeable) [1]. The essential components of a battery include (Figure 1):

- **Anode** : The negative electrode where oxidation occurs, releasing electrons.
- **Cathode** : The positive electrode where reduction takes place, accepting electrons.
- **Electrolyte** : A medium that facilitates ion movement while preventing electron flow.
- **Separator** : A membrane that prevents short-circuiting while allowing ion migration.
- **Current Collectors** : Components that facilitate electron flow to and from external circuits.

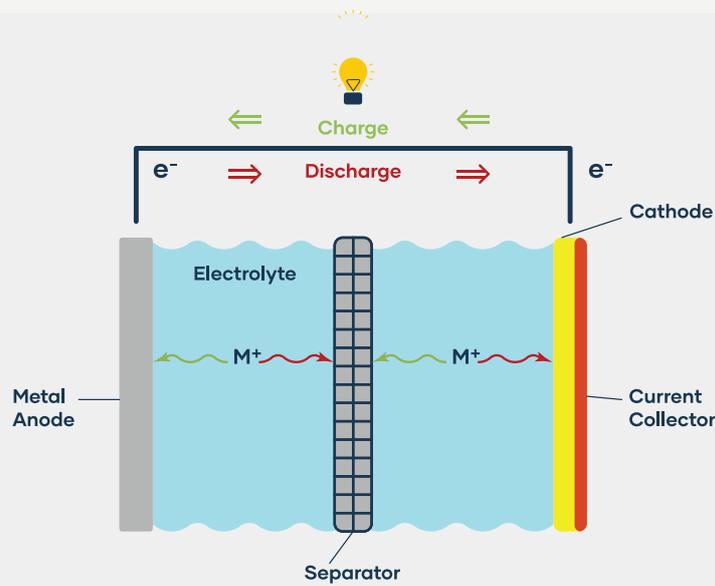


Figure 1 : A typical cell configuration is illustrated, with charging processes highlighted in green and discharging processes in red (adapted from [1]).

Batteries operate through oxidation-reduction (redox) reactions. The anode undergoes oxidation, releasing electrons that travel through an external circuit to the cathode, where reduction occurs (Figure 2). The voltage is determined by the difference in standard electrode potentials.

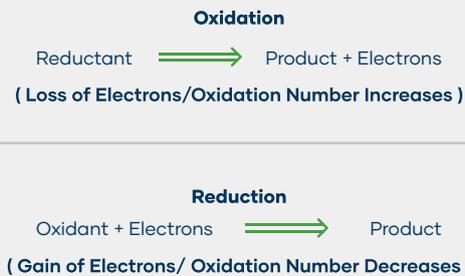


Figure 2 : Redox reaction equations.

II.2. BATTERY OPERATION: RECHARGE AND DISCHARGE

The operation of a battery is governed by the interaction of its electrode materials, electrolyte, and the movement of ions during charge and discharge processes. These interactions determine the battery's efficiency, capacity, and overall performance. To provide a clear understanding of these mechanisms, the Li-ion battery will be used as an example, illustrating how lithium ions migrate between the electrodes to store and release energy.

A Li-ion battery consists of an anode, cathode, porous separator, electrolyte, and current collectors. The cathode material defines the battery type, while the anode is typically graphite or a metal oxide. The electrolyte enables lithium-ion transport, while the separator not only prevents short circuits but also facilitates ion movement between the electrodes. During discharge, lithium ions migrate from the anode to the cathode, generating an electric current. Charging reverses this process, moving ions back to the anode for energy storage.

A typical lithium-ion battery used in commercial applications consists of multiple interconnected electrochemical cells. Each cell generally includes a graphite anode, such as mesocarbon microbeads, a cathode made of a lithium metal oxide like LiCoO_2 , and an electrolyte, such as LiPF_6 dissolved in a mixture of ethylene carbonate (EC) and dimethyl carbonate (DC), supported by a separator material. During the discharge process, lithium ions (Li^+) are released from the layered graphite anode, pass through the electrolyte, and intercalate into the layers of the LiCoO_2 cathode (LCO) (Figure 3). The electrochemical processes can be represented by the following equations [2]:

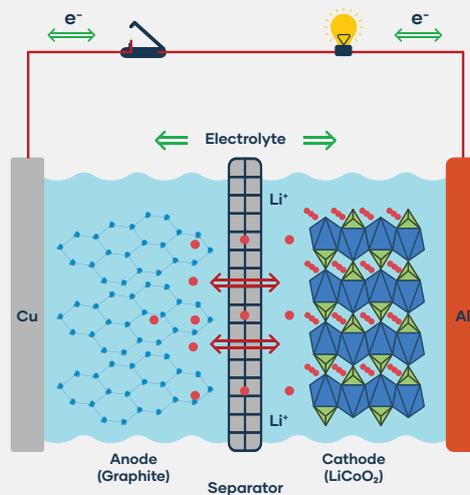
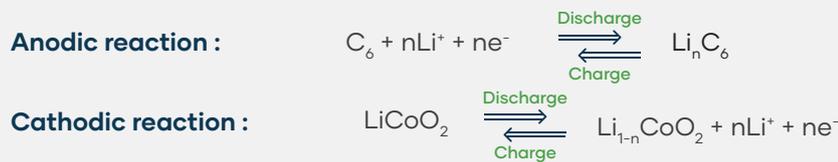


Figure 3 : Illustration depicting the working mechanism of a typical lithium-ion battery (Cathode: LCO). (Adapted from [2])

II.3. TYPES OF BATTERIES

While most batteries function based on the same fundamental principle, many have been developed by different individuals who adapted this principle to meet specific needs or project requirements. As a result, there is a wide variety of battery types (Figure 4). These differences influence factors such as materials, performance, lifespan, production methods, and costs. Selecting a particular battery involves considering all these aspects, which has driven technological advancements and expanded available options [3].

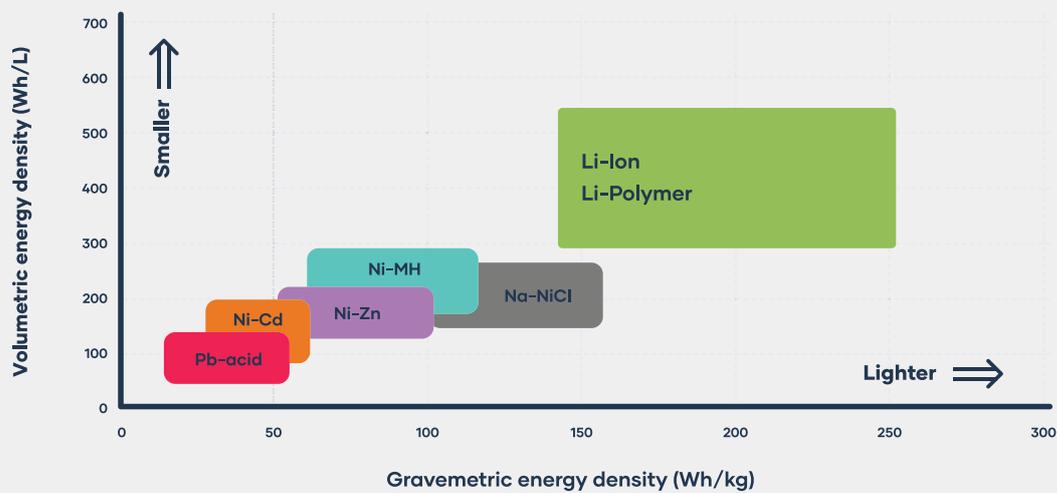


Figure 4: Comparison of volumetric and gravimetric energy density for different energy storage technologies. (Adapted from [4])

Batteries are classified based on chemistry and application. The most common types include:

- Lead-Acid Batteries:** Lead-acid batteries were the first rechargeable batteries invented and remain widely used today, especially in automotive, uninterruptible power supplies (UPS), and backup energy systems. They operate based on the electrochemical reaction between lead dioxide (PbO_2) as the positive electrode, a sponge lead (Pb) negative electrode, and sulfuric acid (H_2SO_4) as the electrolyte. Their advantages include low cost, reliability, and ability to supply high surge currents, making them ideal for starting internal combustion engines. However, they suffer from low energy density, heavy weight, and relatively short cycle life compared to modern battery technologies [5].
- Nickel-Based Batteries:** Nickel-based rechargeable batteries include Nickel-Cadmium (Ni-Cd), Nickel-Metal Hydride (Ni-MH), and Nickel-Zinc (Ni-Zn). Ni-Cd batteries are known for their durability and performance in extreme temperatures but suffer from the memory effect and cadmium toxicity. Ni-MH offers higher energy density and is more environmentally friendly, making it common in hybrid vehicles and consumer electronics. Ni-Zn provides higher voltage and energy density but has cycle life limitations [6].
- Lithium-Ion Batteries (LIBs):** Lithium-ion batteries dominate portable electronics, electric vehicles (EVs), and renewable energy storage due to their high energy density, long cycle life, and efficiency. LIBs operate through the reversible intercalation of lithium ions between the anode (usually graphite) and the cathode (various lithium metal oxides). The most common LIB types include [7-9]:
 - Lithium Cobalt Oxide (LiCoO_2 , LCO):** High energy density, widely used in smartphones and laptops, but limited by thermal instability and safety concerns.
 - Lithium Iron Phosphate (LiFePO_4 , LFP):** Offers excellent safety, long cycle life, and thermal stability, making it ideal for electric vehicles and stationary storage.
 - Lithium Nickel Manganese Cobalt Oxide (NMC):** Balances energy density, lifespan, and cost, commonly used in EVs and grid storage.

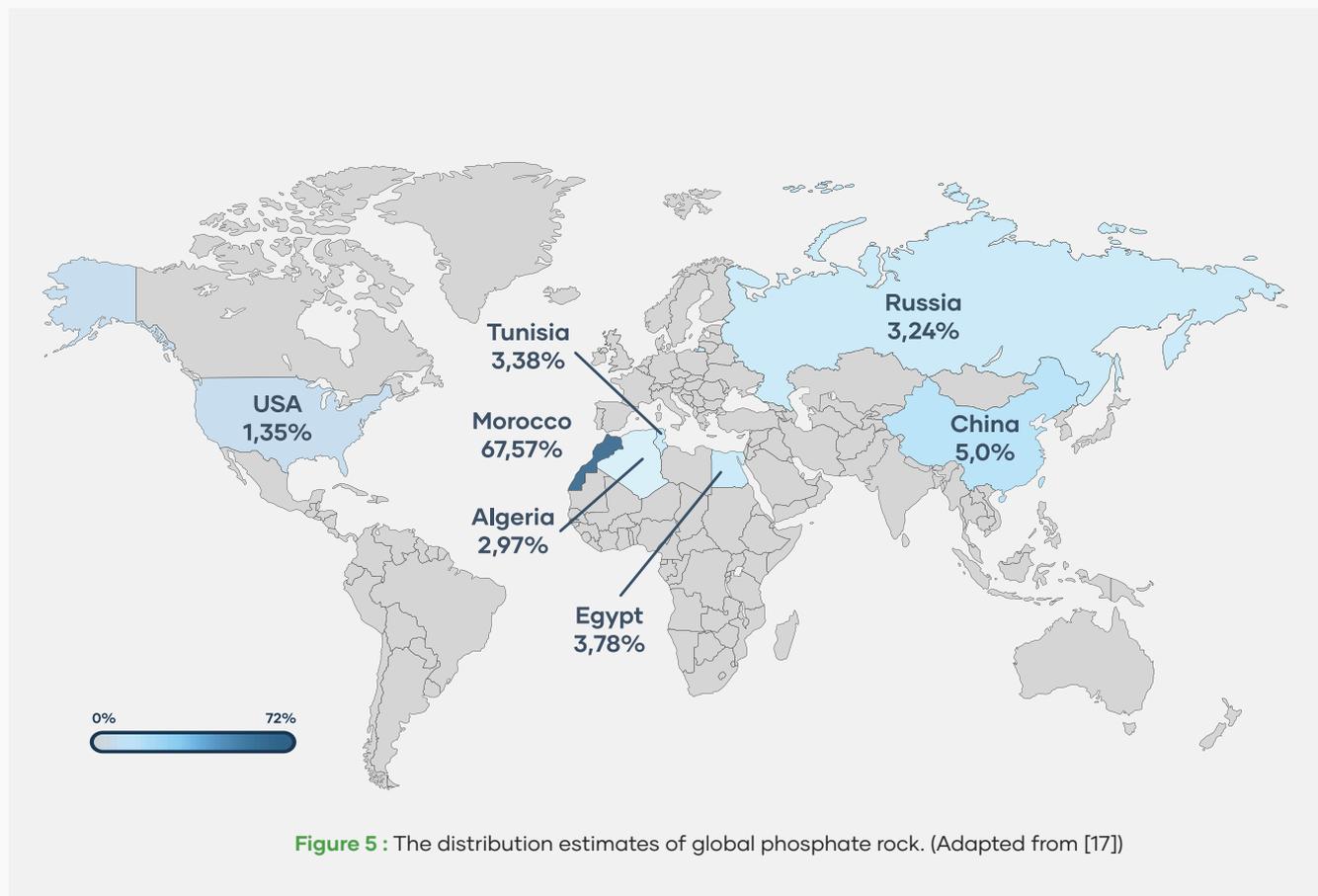
- **Sodium-Ion Batteries (NIBs):** Sodium-ion batteries have emerged as a promising alternative to LIBs, using sodium (Na^+) instead of lithium (Li^+), which reduces costs and dependence on scarce lithium resources. NIBs have similar working principles to LIBs but use sodium-based cathode materials like $\text{Na}_3\text{V}_2(\text{PO}_4)_3$. These batteries are gaining traction for grid storage and low-cost applications, but they currently suffer from lower energy density compared to LIBs [10].
- **Lithium-Sulfur Batteries (Li-S):** Lithium-sulfur batteries offer a theoretical energy density five times higher than that of LIBs, making them a strong candidate for next-generation energy storage devices. They use a lithium metal anode and a sulfur cathode. However, their commercialization is hindered by [11]:
 - ▶ Polysulfide shuttle effect, leading to rapid capacity fading.
 - ▶ Poor cycle life, due to volume expansion of sulfur during cycling.
- **All-Solid-State Batteries (ASSBs):** All-solid-state batteries replace liquid electrolytes with solid electrolytes, improving safety, energy density, and thermal stability. They prevent dendrite formation, which enhances battery lifespan. ASSBs are a major focus in EV and aerospace applications, but challenges include manufacturing complexity and high costs [12].
- **Sodium-Sulfur (NaS) Batteries:** NaS (sodium-sulfur) batteries are gaining popularity for large-scale energy storage due to their high energy density, long lifespan, and low maintenance. These cylindrical cells use molten sodium and sulfur, separated by a solid beta alumina electrolyte. During discharge, sodium ions migrate to the positive electrode, forming polysulfides, while charging reverses this process, regenerating elemental sodium [13].
- **ZEBRA Batteries:** The sodium-nickel chloride (ZEBRA) battery is a molten salt battery similar to the sodium-sulfur battery but safer, with better protection against overcharging and deep discharging. It has lower energy and power density than NaS batteries. It uses a solid nickel chloride cathode, a molten sodium anode, and a liquid sodium chloro-aluminate electrolyte for fast ion movement, separated by a solid beta alumina electrolyte. During charging, sodium ions migrate from the cathode through the electrolyte and are deposited at the anode [13].
- **Vanadium Redox Flow Batteries:** In a vanadium redox flow battery (VRFB), electrochemical energy is stored by transferring electrons between different vanadium ions. A proton exchange membrane (PEM) separates the two electrolytes. During charging, V^{3+} ions at the anode gain an electron and are converted to V^{2+} . In the discharge process, V^{2+} ions are oxidized back to V^{3+} , releasing an electron [13].

III. INTRODUCTION TO PHOSPHORUS-BASED MATERIALS

Phosphorus is a widely available and versatile element with unique properties that make it valuable for energy storage. Its different allotropes —white, red, black, and violet— each have distinct chemical and physical characteristics, making phosphorus adaptable for various applications. Phosphorus-based materials, including phosphates and phosphides, are essential in lithium-ion and sodium-ion batteries, serving as cathodes, anodes, and electrolytes. Their strong structures, thermal stability, and good conductivity help improve battery performance and sustainability. This section explores phosphorus, its properties, and its role in energy storage, highlighting its potential for advancing battery technologies.

III.1. PHOSPHORUS (P) : SOURCE AND ABUNDANCE

Phosphorus (P), element 15 on the periodic table, is vital for life and widely used in agriculture, industry, and medicine. As the 11th most abundant element in the Earth's crust [14], phosphorus is primarily found in phosphate rock, mainly in the mineral apatite ($\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{Cl}, \text{F})$) [15]. Phosphate rock is a non-renewable resource, and its distribution is uneven, with Morocco holding the largest reserves (over 60%), followed by China, Egypt, Tunisia, Russia, Algeria and the USA [16].



III.2. STRUCTURE, PHYSICAL AND CHEMICAL PROPERTIES OF PHOSPHORUS ALLOTROPES

Phosphorus is a reactive element that exists in different forms, or allotropes, each with unique properties. White phosphorus is the most reactive, flammable, highly toxic and the least stable allotrope, making it suitable for applications such as explosives and incendiary devices but posing handling risks [18]. Red phosphorus is more stable and is used in safety matches, flame retardants, and battery research, especially as an anode material in lithium-ion and sodium-ion batteries, due to its high energy capacity and cost-effectiveness [19]. Black phosphorus is the most stable allotrope and less flammable than white or red phosphorus, with a layered structure that gives it excellent electrical properties, making it promising for advanced battery applications [20].

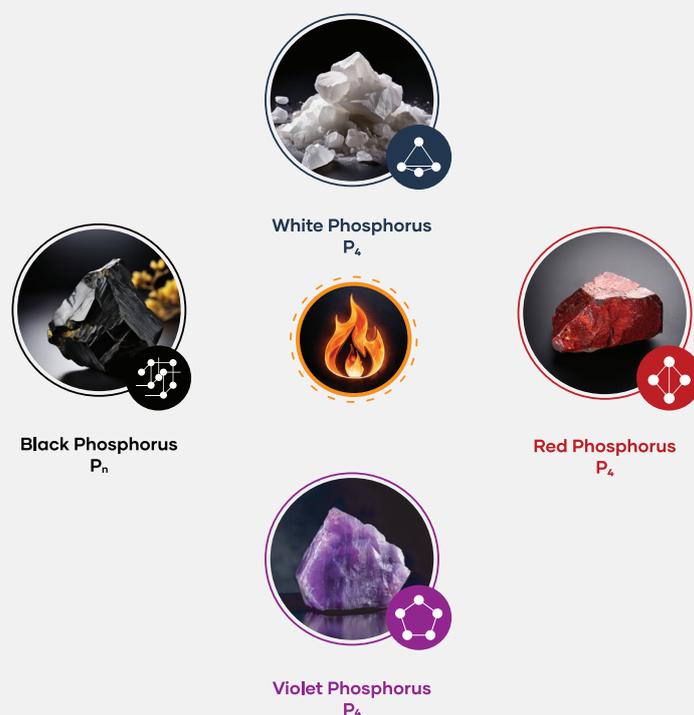


Figure 6: Allotropes for Phosphorus: White, Red, Black and Violet. (Adapted from [21])

III.3. OVERVIEW OF PHOSPHORUS-BASED MATERIALS

III.3.1. PHOSPHATE-BASED MATERIALS

Phosphate-based compounds, derived from phosphorus, are widely used in energy storage due to their excellent thermal stability, long cycle life, and suitable operating voltage [22]. These materials, including olivine, pyrophosphates, NASICON-type, and fluoride phosphates, benefit from polyanion structures that enhance their voltage performance.

- **Phosphate (olivine) materials**

Olivine phosphate materials are widely used in batteries due to their stability and efficient ion movement efficiency, making them ideal for lithium-ion and sodium-ion batteries. Iron-based phosphates like olivine type lithium iron phosphate ($LiFePO_4$, LFP) are known for safety and long lifespan [23], while sodium iron phosphate ($NaFePO_4$, NFP) offers a cost-effective and environmentally friendly alternative [24]. Manganese and cobalt-based phosphates like ($LiMnPO_4$, LMP) [25], ($NaMnPO_4$, NMP) [26], ($LiCoPO_4$, LCP) [27] and ($NaCoPO_4$, NCP) [28] provide high energy density but require further research to enhance performance.

While these phosphate materials hold promise for advancing battery technology, challenges related to stability and efficiency must still be addressed.

- **NASICON-structured materials**

NASICON materials, known for their stability, high ionic conductivity and minimal volume change during cycling [29], were originally developed for sodium-ion batteries but are now gaining attention for lithium-ion applications. Their open three-dimensional structure allows efficient ion movement, enhancing battery performance and safety [30]. Among the different types of NASICON materials, vanadium-based NASICON materials like lithium vanadium phosphate ($\text{Li}_3\text{V}_2(\text{PO}_4)_3$, LVP) [31] and sodium vanadium phosphate ($\text{Na}_3\text{V}_2(\text{PO}_4)_3$, NVP) [32] stand out for their robust structures and ability to support fast ion movement, while iron-based options such as NASICON type lithium iron phosphate ($\text{Li}_3\text{Fe}_2(\text{PO}_4)_3$) [33] and sodium iron phosphate $\text{Na}_3\text{Fe}_2(\text{PO}_4)_3$ [34] are also highly regarded for their stability, safety, and capacity to handle lithium ions effectively. Titanium-based NASICON materials, including lithium titanium phosphate ($\text{LiTi}_2(\text{PO}_4)_3$, LTP) [35] and sodium titanium phosphate $\text{NaTi}_2(\text{PO}_4)_3$ [36] add versatility, with rigid yet flexible structures, these materials enable smooth ion movement, which improves both battery performance and safety. Their blend of stability, safety, and efficiency makes them an ideal choice for building high-performance batteries that are not only powerful but also reliable and safe for everyday use.

- **Pyrophosphate materials**

Pyrophosphate materials are gaining attention for their impressive performance in battery technology [37]. While they generally have lower capacities compared to other materials, they offer excellent stability and support efficient ion movement, enhancing battery efficiency and safety [38]. Different types of pyrophosphate materials bring specific advantages. Iron-based pyrophosphates, such as $\text{Li}_2\text{FeP}_2\text{O}_7$ [39] and $\text{Na}_2\text{FeP}_2\text{O}_7$ [40], are known for their robust structures that promote efficient ion flow, providing stability and solid performance. Manganese-based pyrophosphates, such as $\text{Li}_2\text{MnP}_2\text{O}_7$ [41] and $\text{Na}_2\text{MnP}_2\text{O}_7$ [42], enable smooth ion migration which is crucial for its electrochemical performance, making them ideal for advanced batteries.

“Pyrophosphate materials could redefine energy storage thanks to their exceptional safety, structural stability, and efficiency.”

- **Fluoride phosphate (fluoro-phosphate) materials**

Fluoro-phosphate materials are attracting interest for their high capacity, stability, and efficiency in battery technologies [43]. Their unique structure enables smooth ion movement, additionally, the combination of phosphate groups and fluorine boosts their performance, offering good energy capacity and durability [44]. However, fluorine's influence can lower conductivity, posing a challenge for high-performance applications [45]. Iron-based fluoro-phosphates, such as lithium iron fluoro-phosphate (LiFePO_4F) [46] and sodium iron fluoro-phosphate ($\text{Na}_2\text{FePO}_4\text{F}$) [47], show promising potential due to their structure, which supports fast ion movement and stability. Similarly, vanadium-based fluoride phosphate materials such as sodium vanadium fluoride phosphate ($\text{Na}_3\text{V}_2(\text{PO}_4)_2\text{F}_3$) [48] and lithium vanadium fluoride phosphate (LiVPO_4F) show great promise for energy storage [49]. Their unique structure allows efficient ion movement, improving battery performance. The addition of fluorine improves stability and energy output, making these materials ideal for advanced batteries.

Fluoro-phosphate materials offer stability, high capacity, and efficiency, with research aiming to enhance their conductivity for wider use in batteries.

III.3.2. PHOSPHIDE BASED MATERIALS

Phosphide-based materials, which combine phosphorus with metals or nonmetals, are gaining attention for energy storage, especially in sodium-ion batteries [50]. These materials offer good capacity and potential for high-performance anodes but face challenges like structural changes and reduced efficiency over time [51]. Tin (e.g., Sn_4P_3) [52], nickel (e.g., Ni_2P) [53], iron (e.g., FeP) [54], and cobalt (e.g., CoP) [55] phosphides show high potential for anode materials due to their high capacity. However, they all face challenges related to structural changes or volume shifts during battery use, which can affect stability and long-term durability.

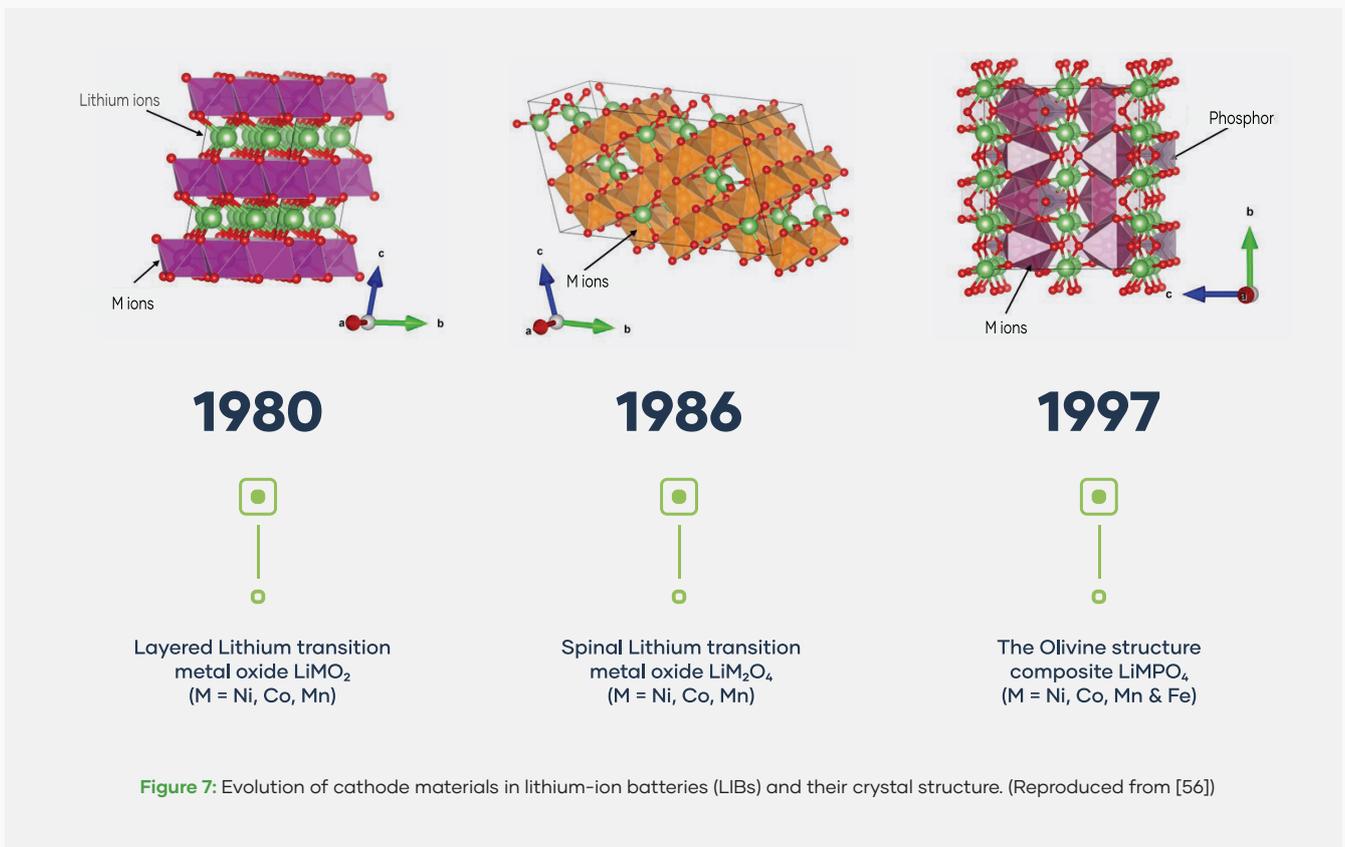
“ While phosphide-based materials hold great promise for advanced battery technologies, ongoing research aims to overcome these stability and performance challenges to make them practical for everyday applications ”

IV. PHOSPHORUS-BASED VS. CONVENTIONAL BATTERIES : COMPARATIVE ANALYSIS AND ADDRESSING CHALLENGES

Phosphorus-based batteries are a promising alternative to traditional batteries, offering improved safety, stability, and environmental benefits. Materials like lithium iron phosphate (LiFePO_4) and black phosphorus enhance stability, unlike some traditional lithium-ion batteries that use cobalt-based materials, which pose overheating risks. Phosphorus-based batteries are not only more stable but also more environmentally friendly, avoiding toxic metals like lead and cadmium. Additionally, these batteries are cost-effective and durable, making them well-suited for electric vehicles and large-scale energy storage. This section compares phosphorus-based batteries with traditional ones, focusing on their advantages and exploring ways to overcome limitations, highlighting their role in supporting cleaner energy and sustainability.

IV.1. CATHODE BASED MATERIALS

Lithium-ion battery cathode materials are generally classified into three main types: layered oxides, spinels, and olivines. While layered and spinel materials have traditionally led the market, each comes with its own set of strengths and weaknesses [56].



Among phosphorus-based cathode materials, lithium iron phosphate emerges as a leading candidate for commercial and practical applications, thanks to its exceptional blend of safety, stability, long cycle life, and cost-effectiveness. Unlike many other phosphorus-based materials that often struggle with issues such as poor electronic conductivity, capacity fading, or high production costs, LFP offers a reliable and environmentally friendly option [57].

Compared to traditional cathode materials, LFP offers significant advantages. While layered materials like lithium cobalt oxide (LiCoO_2 or LCO) and lithium nickel oxide (LiNiO_2 or LNO) have high energy density, they suffer from issues like poor thermal stability, voltage decay, cycling instability, and safety risks, leading to rapid performance degradation [58,59].

Spinel materials like lithium manganese oxide (LiMn_2O_4 or LMO) offer high energy and power density but suffer from capacity fading and manganese dissolution, limiting their use in high-performance batteries [60]. Similarly, mixed transition metal oxides like ($\text{LiNi}_x\text{Co}_y\text{Mn}_z\text{O}_2$ or NMC) have gained attention for combining the strengths of multiple materials, offering improved capacity and safety over LCO but face challenges like voltage decay and capacity loss due to structural instability and surface degradation over time [61].

In contrast, LFP offers a strong balance of performance and sustainability. Its olivine structure and phosphorus-oxygen bonds enhance safety by preventing thermal runaway, making it resistant to overheating. Additionally, the use of abundant, non-toxic elements reduces its environmental impact, supporting sustainability goals [62].

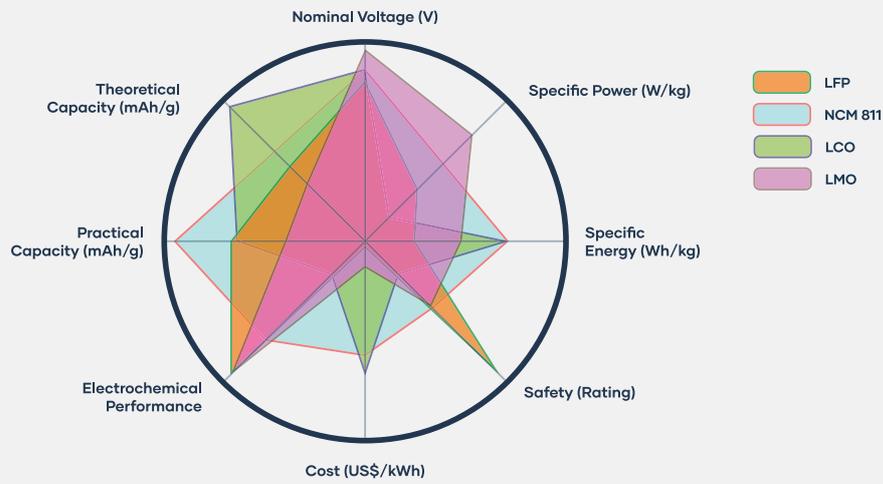


Figure 8: Comparison between different cathode materials for LIBs (Adapted from [63–67])

IV.2. ANODE BASED MATERIALS

Anode materials in lithium-ion batteries work in three different ways. The first method, called intercalation, involves storing lithium ions between layers of materials like graphite. The second method, alloying, creates alloys by combining lithium with metals like silicon, tin, or antimony. The third method, known as the conversion reaction, uses materials like oxides, sulfides, and phosphides to achieve even greater energy capacity through chemical reactions.

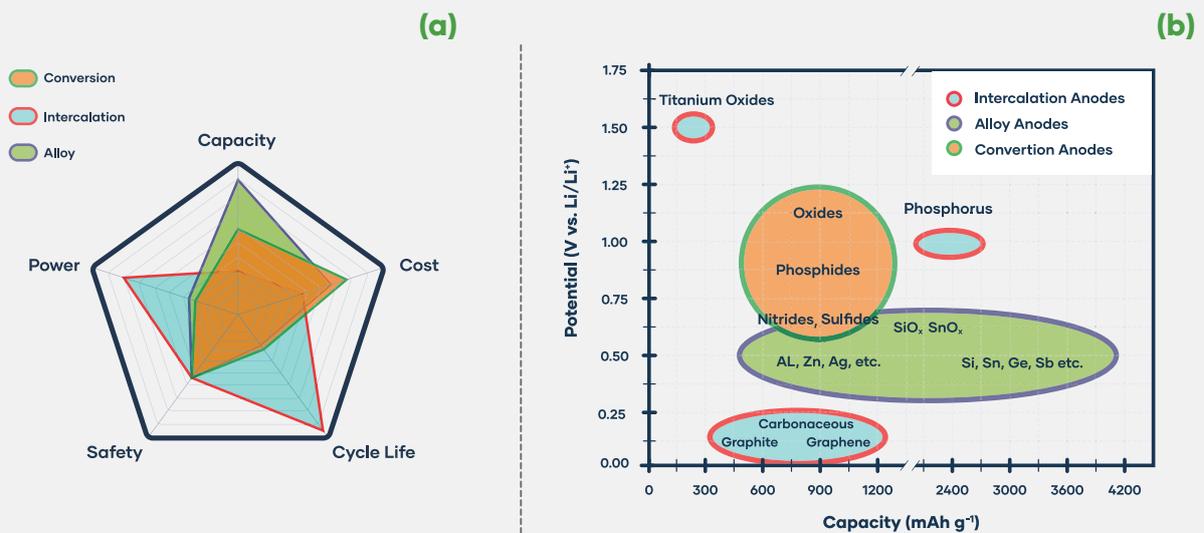


Figure 9: (a) Anode active materials comparison in terms of capacity, cost, cycle life, safety, and power. (b) Schematic illustration comparing potential vs. capacity of certain anode materials. (Adapted from [68])

Traditional materials like graphite are widely used due to their reliability, affordability, and established manufacturing processes [69]. While they provide good stability and long battery life, they don't offer the highest energy density. New materials like silicon and tin offer higher energy storage than graphite but face stability issues, and are not yet widely used in commercial batteries [70,71]. Silicon anodes expand and contract during cycling, causing breakdown over time, while tin-based anodes also offer good energy potential but face similar stability issues and manufacturing challenges. Lithium metal anodes, which were originally used in early lithium-ion batteries, offer the highest energy capacity but pose safety risks, such as short circuits and overheating. To enhance safety, modern batteries typically use carbon-based anodes like graphite, prioritizing stability over maximum energy capacity [72].

Phosphorus-based anodes are gaining attention for their high energy capacity and excellent performance in both lithium-ion and sodium-ion batteries [73]. They could provide more energy storage than traditional graphite anodes and are more stable than silicon and tin options. Although some technical and cost challenges still limit their commercial use, ongoing research could make phosphorus-based materials a key player in future battery technology [74]. These advancements could lead to better, longer lasting, and more affordable batteries, ideal for electric vehicles and renewable energy storage.

Graphite provides safety and stability, but phosphorus, silicon, and tin could unlock higher energy storage once their challenges are resolved."

IV.3. OVERCOMING LIMITATIONS OF PHOSPHORUS-BASED BATTERIES: CHALLENGES AND ENHANCEMENTS

Phosphorus-based batteries show great promise for safer, more stable, and eco-friendly energy storage. However, they face challenges that have limited their adoption compared to traditional batteries. To improve their performance and durability, researchers are exploring innovative strategies. These include materials nanostructuring to boost efficiency [75], doping with other elements to enhance conductivity [76], and combining phosphorus materials with carbon-based components like graphene [77]. These approaches help the batteries last longer and perform better, especially by reducing the material expansion and volume change during cycling. While these advanced methods may increase production costs, their benefits, such as longer battery life and higher performance, make them a valuable investment. Continued development could make them a strong, sustainable alternative for electric vehicles and renewable energy storage.

With a particular focus on lithium iron phosphate (LiFePO_4), which is known for its safety and longevity but offers lower energy compared to high-performance batteries like those with NMC cathodes. To improve performance, researchers are using strategies like nano-structuring, doping, and carbon coatings, which enhance stability, efficiency, and reduce costs [78,79]. Another promising material, lithium manganese iron phosphate (LMFP), developed by doping manganese into LiFePO_4 , combines safety with higher energy output, making it a promising material for next-generation batteries [80].

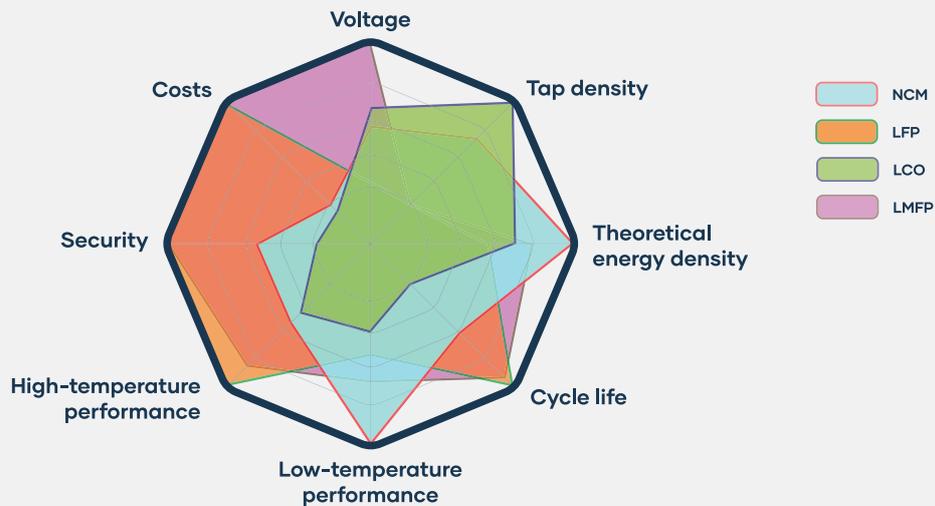


Figure 10: Comparison of comprehensive performance among LCO, LFP, NCM, and LMFP. (Adapted from [80])

V. MANUFACTURING PROCESSES AND RAW MATERIALS OF PHOSPHORUS-BASED BATTERIES

Phosphorus-based batteries, particularly LiFePO_4 , are becoming popular for their stability, safety, and affordability. They use readily available materials like phosphorus, lithium, manganese, and iron, contributing to a more reliable and sustainable supply chain. Beyond performance, phosphorus-based batteries also shine in terms of environmental impact. From the responsible sourcing of raw materials to efficient manufacturing and safe disposal, they present a greener alternative in the push for cleaner energy technologies. This section explores phosphorus-based batteries, focusing on their raw materials, manufacturing processes, steps of battery manufacturing, and environmental impact.

V.1. RAW MATERIALS FOR P-BASED BATTERIES: ABUNDANCE, SOURCE AND MINING

Phosphorus-based batteries typically use phosphorus, lithium, iron, and manganese as key raw materials. Phosphorus is a relatively abundant element found commonly in the Earth's crust. Iron is even more plentiful, making up about 5% of the crust, while manganese is less common at around 0.1%. Lithium, though not as abundant, is still widespread [81]. While these materials are generally available, the growing demand for lithium in batteries could create supply challenges in the future.

V.1.1. PHOSPHORUS

Phosphorus is an important element used in agriculture and industry, mainly sourced from phosphate rock, which contains minerals like apatite $\text{Ca}_5(\text{PO}_4)_3(\text{F,Cl,OH})$. This non-renewable resource is crucial for producing fertilizers and other phosphorus-based products.

Phosphate rock is a limited resource facing high demand, with 74 billion metric tons of reserves and 240 million tons produced in 2024 [82]. Morocco dominates the global phosphate market, holding over 60% of the world's reserves. As demand increases, production is also rising, and estimates suggest that phosphorus reserves could expand significantly with higher prices, making it economically feasible to mine lower-grade ores and access deeper deposits [83].

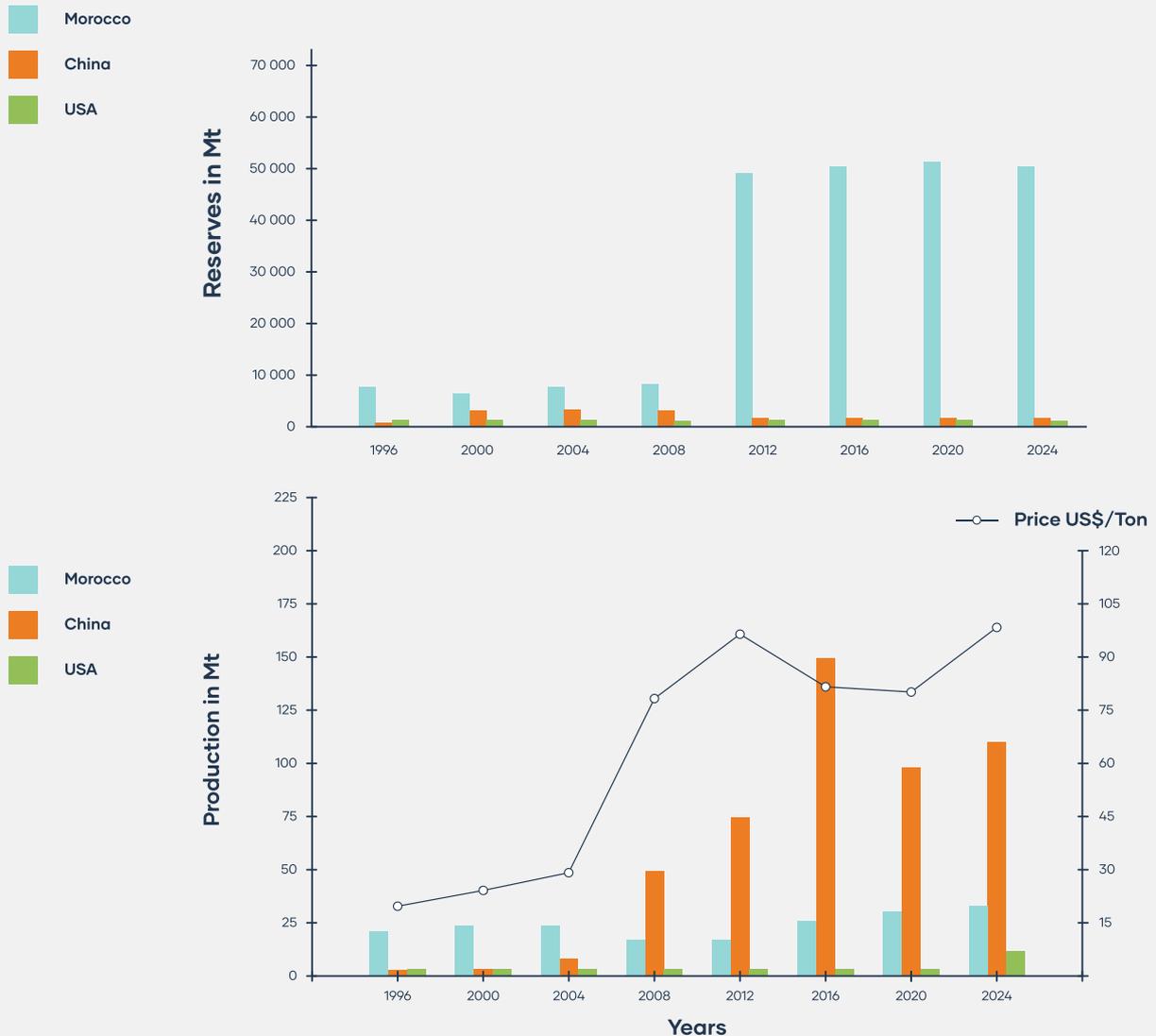


Figure 11: Global reserves, production and price of phosphate rock according to the U.S. Geological Survey USGS (2025)
(Adapted from [82])

Phosphate rock is primarily mined through open-pit methods, which are efficient for large sedimentary deposits near the surface but can cause significant environmental damage, including land disruption, dust emissions, and waste production [84]. Underground mining is also used for deeper deposits, but it's more expensive and less common [85].

Phosphorus is extracted from phosphate rock through chemical processes to produce phosphoric acid, which is widely used in agriculture and industry. The most common method (wet process) involves reacting phosphate rock with sulfuric acid to produce phosphoric acid and gypsum as a byproduct [86].

Another method (thermal process), heats phosphate rock in an electric furnace to produce elemental phosphorus (P_4) and calcium silicate slag. Though less common, it is used for industrial applications requiring pure phosphorus [87].

V.1.2. LITHIUM

Lithium is found in 48 countries and is mainly extracted from brine deposits and hard rock minerals. In brine extraction, special resins collect lithium from saltwater. The lithium is then recovered using freshwater or an acidic solution, producing a purified lithium chloride ($LiCl$) solution for further processing. Open-air evaporation ponds are used in this process to concentrate the brine before lithium recovery [88].

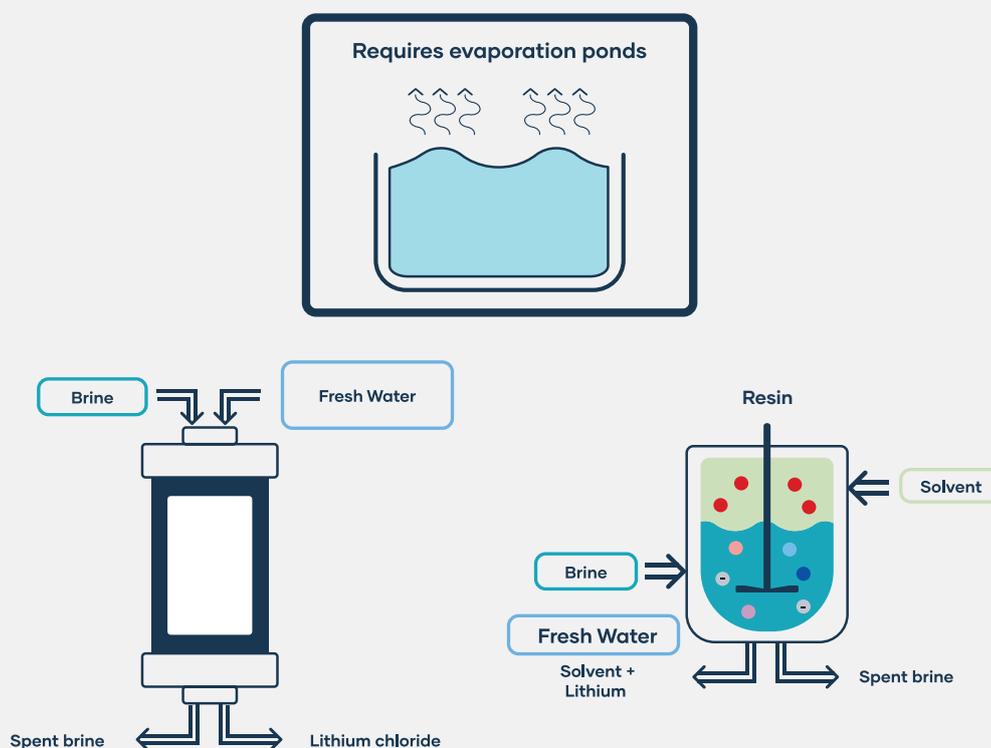


Figure 12: Direct lithium extraction from brine (Adapted from [88])

V.1.3. MANGANESE

Manganese is mainly found in minerals like pyrolusite, rhodochrosite, and braunite. As reported by the United States Geological Survey (USGS), the world's manganese reserves are estimated at 1,300 million tons, with South Africa holding the largest share, followed by Brazil, Australia, and Ukraine [90].

Most manganese is found in iron-manganese ores, and its production involves mining, crushing, magnetic separation, leaching, and refining. This process requires a lot of energy and generates waste. One key method, sulfation roasting, helps extract manganese sulfate ($MnSO_4$), in this process, Fe-Mn ores are roasted with sulfur to form sulfate compounds, then leached to efficiently extract manganese sulfate ($MnSO_4$) and sulfuric acid (H_2SO_4), allowing manganese and iron to be separated [91].

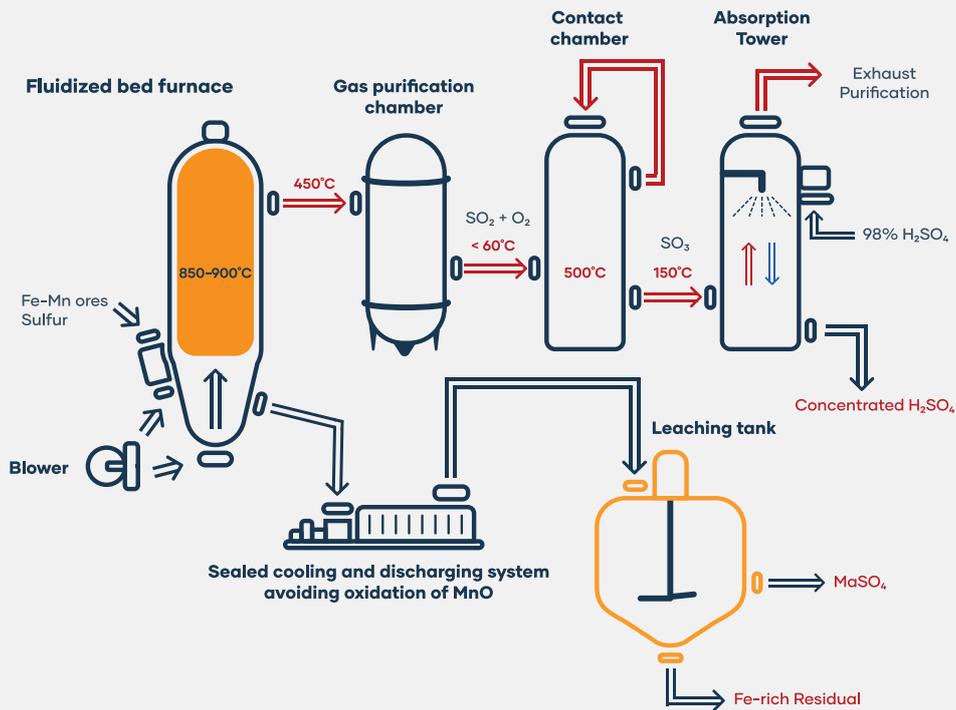


Figure 13: Industrial sulfation roasting process for Fe-Mn ores (Adapted from [91])

V.1.4. IRON

Iron ore is found worldwide, with Australia holding the largest reserves, followed by Brazil, China, India, and South Africa [88]. The main iron-rich minerals include magnetite, hematite, and goethite. Most iron is extracted through open-pit mining and processed using techniques like crushing, grinding, magnetic separation, and flotation. Newer techniques, such as bio-leaching, aim to improve efficiency and reduce environmental impact. However, traditional methods face challenges like high energy use, waste management, and increasing costs, driving the search for more sustainable solutions [92].

V.2. MANUFACTURING PROCESSES OF LITHIUM IRON PHOSPHATE BATTERY

V.2.1. SYNTHESIS METHOD OF LITHIUM IRON PHOSPHATE MATERIAL

Lithium Iron Phosphate batteries are widely used in electric vehicles and energy storage due to their affordability, safety, and environmental benefits. They are made from abundant, non-toxic materials, avoiding the need for rare metals like cobalt and nickel. There are two main ways to produce LFP battery materials: Solid-state method, the most common and cost-effective approach in industrial-scale production, where lithium, phosphate, and iron compounds are mixed and heated at high temperatures to form the crystalline LFP phase. While simple and suitable for large-scale production, this method can be energy-intensive [93].

Solution-based methods, which offer better control over material quality and battery performance but are more complex and expensive. Techniques like hydrothermal, sol-gel, and co-precipitation allow for smaller, more uniform particles, improving battery efficiency. However, they require more resources and advanced processing [94].

New technologies, such as microwave-assisted synthesis, are being explored to improve production efficiency and reduce environmental impact. Optimizing these manufacturing methods will help make LFP batteries even more competitive and widely adopted in the transition to clean energy.

V.2.2. BATTERY MANUFACTURING STEPS

Lithium-ion battery production involves several key steps to ensure performance and safety. First, the active materials, conductive agents, and binders are mixed into a slurry, which is then coated onto metal foils to form electrodes. These electrodes are dried, compressed for optimal density, and cut into precise shapes. Next, the battery is assembled by layering or rolling the electrodes with separators, filling it with electrolyte, and sealing it to prevent leaks. Finally, rigorous testing ensures the battery meets quality and safety standards. Continuous improvements in manufacturing help make these batteries more efficient and reliable for electric vehicles and energy storage [95,96,97].

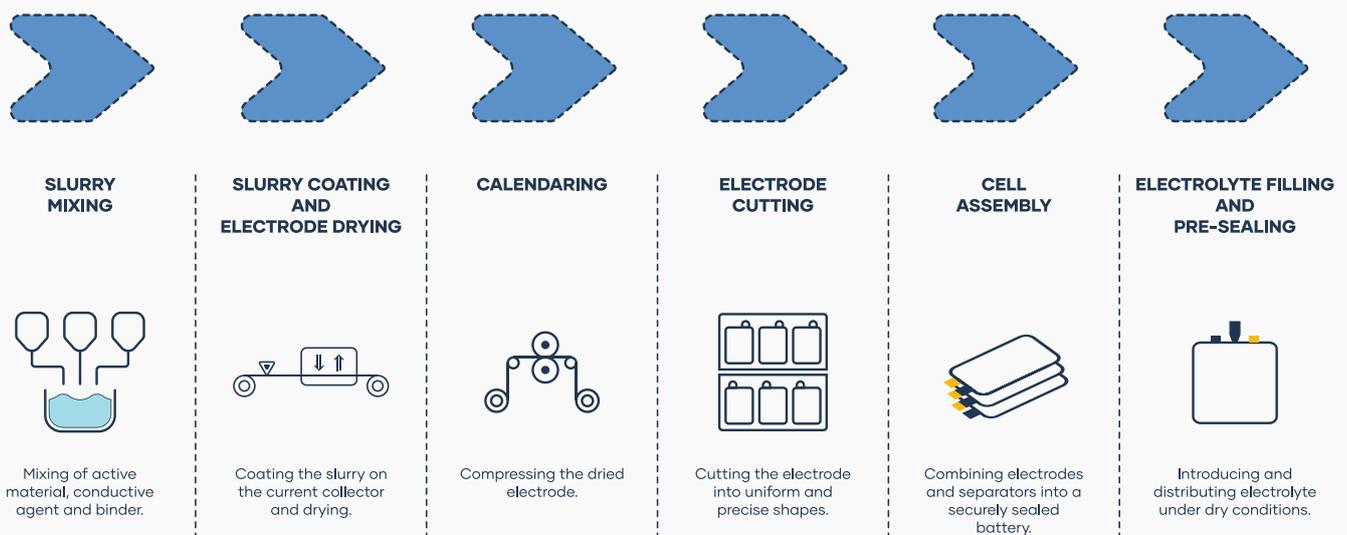


Figure 14: Li-ion battery manufacturing steps (Adapted from [98])

V.3. ENVIRONMENTAL AND SUSTAINABILITY ASPECTS

Phosphorus-based batteries, like lithium iron phosphate batteries, are considered more environmentally friendly than other lithium-ion batteries. They use abundant, non-toxic materials, reducing their overall impact.

While phosphate extraction can harm ecosystems, LFP batteries do not rely on toxic metals like cobalt and nickel, leading to lower emissions. Compared to other lithium-ion batteries, LFP batteries have the lowest carbon footprint, making them a cleaner option for energy storage and electric vehicles. Recycling and proper disposal remain key to minimizing long-term environmental effects [99].

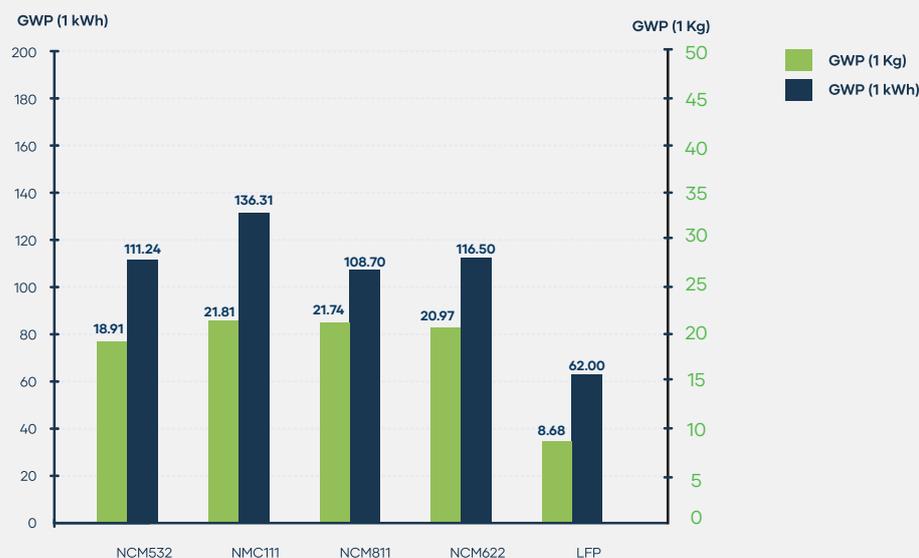


Figure 15: Carbon emissions and energy density for LFP and NCM based batteries. (Adapted from [100])

VI. CURRENT STATUS OF PHOSPHORUS-BASED BATTERIES : A MARKET ANALYSIS

As the demand for advanced and sustainable energy storage solutions grows, researchers are exploring new battery technologies that can offer better performance and lower environmental impact. Phosphorus-based batteries have emerged as a promising alternative due to their high energy density, safety features, and environmental benefits. With increasing interest in renewable energy sources and the need for efficient storage systems, phosphorus-based batteries are gaining attention as a viable option for the future of energy storage. This section examines the current status of phosphorus-based batteries, focusing on their market trends and commercialization efforts. It provides an overview of the technological advances driving the progress of these batteries, highlights key industry players.

VI.1. CURRENT STATUS OF LFP BATTERIES

VI.1.1. MARKET ANALYSIS

The increasing focus on sustainability and lowering greenhouse gas emissions and the growing use of electric vehicles (EVs) is a major factor driving the demand for LFP batteries. These batteries play a vital role in renewable energy projects globally, as they offer reliable energy storage with excellent stability and a long lifespan, prompting significant government investments in such initiatives. The global market for LFP batteries was valued at USD 14.63 billion in 2023 and is expected to grow from USD 16.87 billion in 2024 to USD 72.76 billion by 2034 (Figure 16). The market is forecast to expand at a compound annual growth rate (CAGR) of 15.7% from 2024 to 2034 [101].

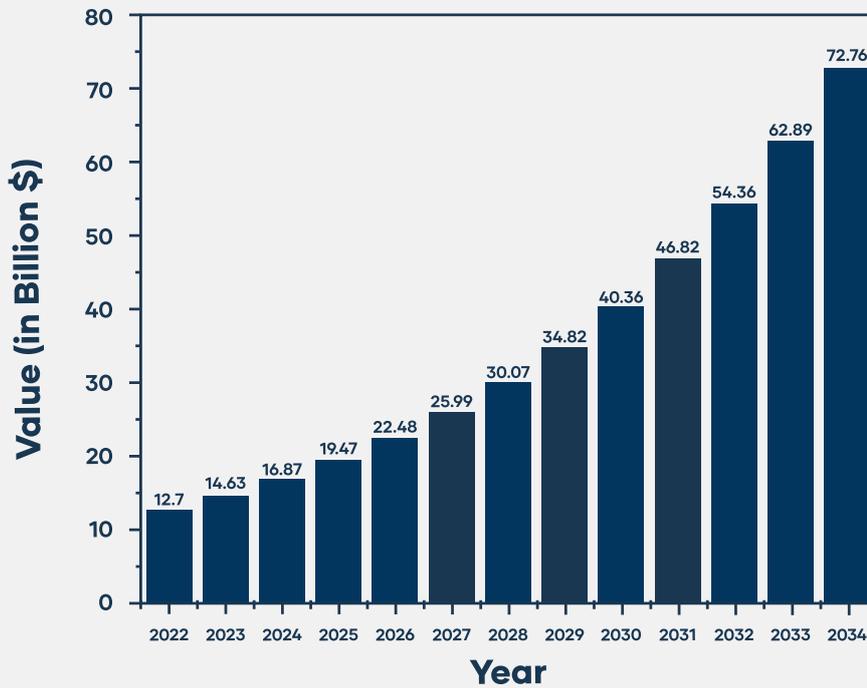


Figure 16: LFP battery market size, 2022 to 2032 (USD Billion) (Adapted from [101]).

Figure 17 illustrates the regional market share distribution for LFP batteries, highlighting Asia Pacific as the dominant region with a 34% share. Europe follows with 29%, reflecting its significant investments in clean energy technologies and electric vehicles. North America accounts for 23%, driven by rising demand for renewable energy storage and EV adoption. Latin America and the Middle East & Africa (MEA) hold smaller shares of 10% and 4%, respectively, suggesting potential for future growth in these emerging markets as global energy transitions accelerate [101].

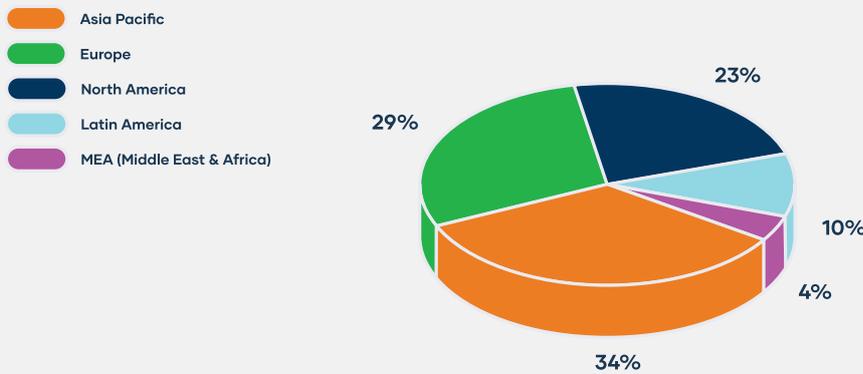


Figure 17: Regional Market Share Distribution for Lithium Iron Phosphate (LFP) Batteries (Adapted [101]).

In China, LFP batteries accounted for 30% of the global EV battery market in 2022. This once again increased demand for highly cost-effective batteries, with LFP batteries regaining significant market share. In fact, they made up 62.4% of all batteries installed in EVs in China in 2022 (see Figure 18). Approximately 30% of the batteries used in Tesla's electric vehicles are based on LFP technology, and Ford has announced plans to begin production of these batteries in the United States by 2026. This trend highlights the increasing global adoption of LFP batteries. While their market presence continues to expand, particularly in China, efforts to improve their energy density (a known limitation) are approaching the limits imposed by the material's chemical properties [102].

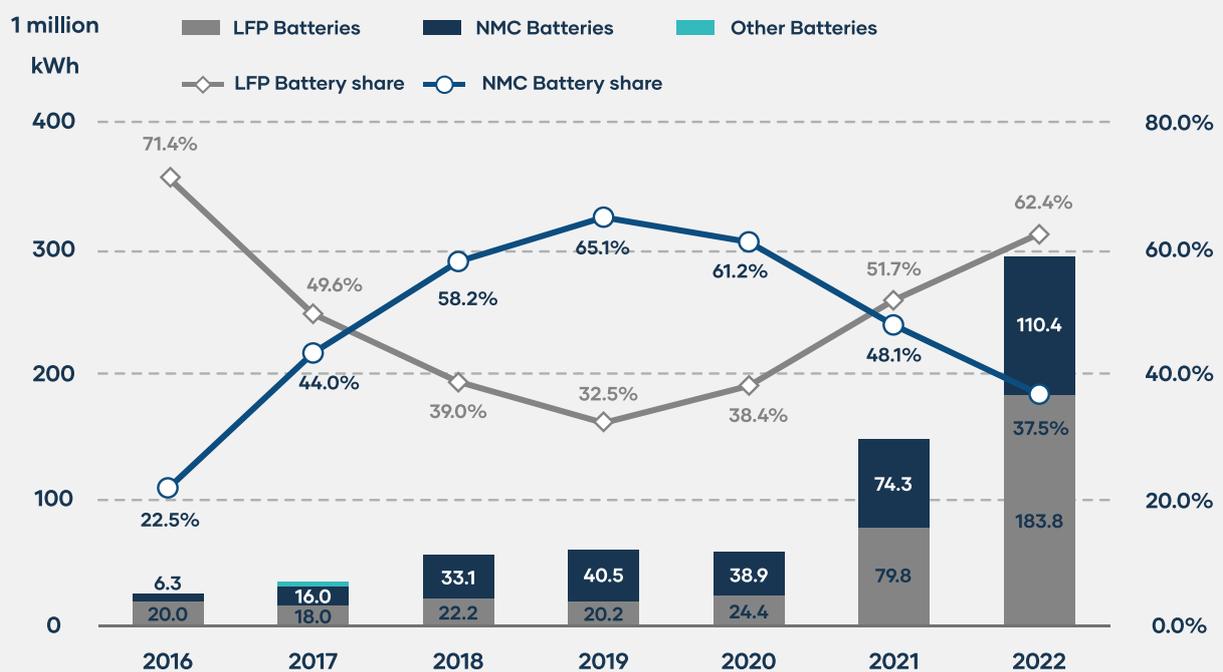


Figure 18: Trends in the installation volumes of LFP and NMC batteries in electric vehicles (EVs) in China from 2016 to 2022 [102].

By application, the 2023 market is categorized into automotive, industrial, energy storage systems, consumer electronics, and other sectors (Figure 19). The chart highlights that the largest share (33.96%) is attributed to a specific category, «Automotive,» given LFP's widespread use in these areas due to its safety, cost-effectiveness, and thermal stability. Other sectors such as «Consumer Electronics,» «Industrial,» and «Others» contribute smaller shares, reflecting diverse applications of LFP batteries in different industries. This market distribution underscores the growing demand for LFP batteries in renewable energy integration and electric vehicles, aligning with global trends toward sustainability and energy transition [103].

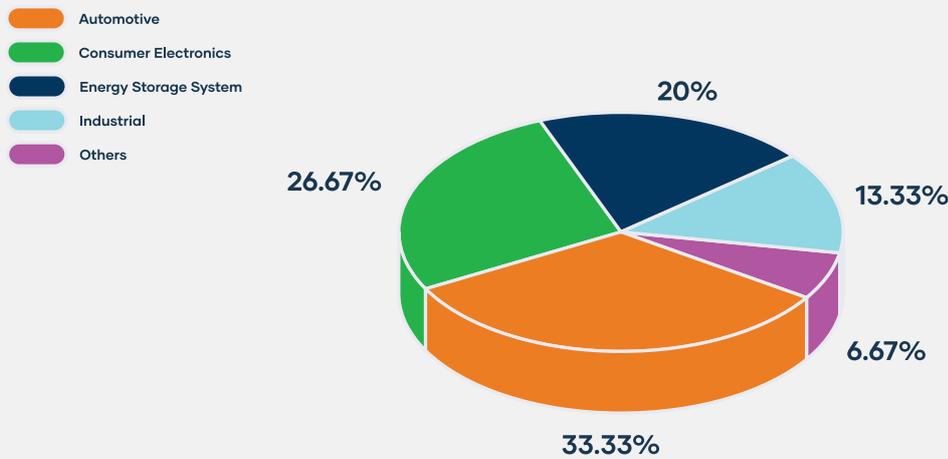


Figure 19: Global LFP market share by application, 2023 (%) (Adapted from [103]).

VI.1.2. LFP BATTERY MARKET COMPANIES

Several major carmakers, including Ford, Rivian, Volkswagen, and General Motors, are adopting LFP batteries to reduce costs and lessen dependence on Chinese materials. A significant shift occurred in October 2021 when Tesla announced its switch to LFP batteries for all standard-range models worldwide. Currently, China dominates LFP production, but efforts are underway to develop alternative supply chains [104].

BYD is a key player in the LFP battery sector, known for its innovative Blade Battery, introduced in March 2020. This battery offers a compact design, high energy density, and enhanced safety, making it a major component of BYD's EVs. The company is expanding its production, with its FAW-FinDreams joint project aiming to supply Blade Batteries for 600,000 vehicles [105-106].

CATL, another major Chinese battery manufacturer, has recently introduced significant advancements, including the Shenxing Plus battery (April 2024), which enables a driving range of over 1,000 km per charge, and the Freevoy battery (October 2024), designed for extended-range hybrid vehicles with a pure electric range of 400 km and 4C fast charging capabilities [107-108].

Shenzhen Dynanonic specializes in nano-LFP materials for EVs and energy storage, playing a key role in advancing nanotechnology for battery applications [109]. Anda Energy Technology is expanding LFP production, with a new project in Guiyang City targeting 150,000 metric tons of annual production. In 2022, China's LFP cathode material output surged by 151%, reaching 1.14 million metric tons [110].

The LFP market remains highly competitive, with major Chinese producers like BTR New Energy Materials and Pulead Technology Industry dominating production. Internationally, companies like Nano One (Canada) and ICL (North America) are investing in LFP manufacturing, reflecting the growing demand for advanced EV and energy storage batteries. The market is evolving with a focus on nano- and micro-nanostructured LFP materials tailored for improved performance [111].

VI.2. CURRENT STATUS OF LMFP BATTERIES

VI.2.1. MARKET ANALYSIS

The rising adoption of electric vehicles (EVs) is a significant factor propelling the growth of the global LMFP battery market. With governments around the world enforcing stricter emission standards and consumers increasingly prioritizing eco-friendly choices, the demand for EVs is surging. LMFP batteries are particularly advantageous for EV applications due to their superior energy density, extended cycle life, and cost-effectiveness compared to other battery technologies. Consequently, the growing popularity of EVs is fueling the demand for LMFP batteries, thereby accelerating the expansion of the global LMFP battery market.

The global market for LMFP batteries is anticipated to expand significantly, rising from \$312.65 million in 2024 to \$11,224.17 million by 2030 (Figure 20), with an impressive CAGR of 82 % during the forecast period. In the US and Canada, the LMFP market is expected to grow from \$2.76 million in 2024 to \$1,026.97 million by 2030, registering a remarkable CAGR of 168 % between 2024 and 2030. In China, where LMFP technology is rapidly gaining traction, the market is projected to increase from \$301.78 million in 2024 to \$7,682.71 million by 2030, achieving a CAGR of 72 % over the same period. The European LMFP market is forecasted to experience substantial growth, expanding from \$4.16 million in 2024 to \$941.25 million by 2030, with an extraordinary CAGR of 147 % during the forecast timeframe [112].



Figure 20: Global LMFP Battery Market Size for 2024 and 2030 (in USD Million).

VI.2.2. LMFP BATTERY MARKET COMPANIES

China leads in the production of LMFP batteries, which offer higher energy density while maintaining the cost-effectiveness and safety of LFP batteries. These features make LMFP attractive for electric vehicles (EVs) and energy storage applications. Several Chinese manufacturers have developed LMFP battery prototypes in recent years [102].

In August 2022, CALB introduced an LMFP battery with an energy density of 180 Wh/kg, followed by other manufacturers developing versions capable of supporting EV ranges between 500 km

and 1,000 km. In May 2023, Gotion High-Tech announced an LMFP battery designed for a 1,000 km range, with mass production expected in 2024. However, most LMFP prototypes are still undergoing development and testing, with large-scale production timelines yet to be confirmed. Key Chinese manufacturers, including CALB, Frasis Energy, SVOLT, REPT BATTERO, JEVE, and Gotion High-Tech, are actively working on LMFP batteries with energy densities ranging from 200 to 240 Wh/kg. These batteries come in various formats, such as rectangular, pouch, and square shapes, with some models supporting rapid charging and interchangeable battery technology [102].

On the global stage, major LMFP battery manufacturers include CATL, which has production facilities in China, Europe, and North America, and BYD, which has heavily invested in LMFP technology. BYD's vertically integrated approach and cost control strategies enhance its competitive edge in the market [112].

IV.3. BATTERY GIGAFACORIES IN MOROCCO

Morocco is becoming an important center for electric vehicle (EV) battery production. Several major companies are investing in the country to build battery material factories, strengthening Morocco's role in the global EV supply chain. LG Chem and Huayou Group [113] are constructing a LFP cathode plant and a lithium conversion facility. The cathode plant will produce 50,000 tons per year by 2026, enough for 500,000 EVs. The lithium conversion plant, starting in 2025, will produce 52,000 tons of lithium annually. This project helps LG Chem secure raw materials and benefits from Morocco's trade agreements with the U.S. Gotion High-Tech [114] is building Morocco's first EV battery gigafactory in Kenitra, with a \$1.3 billion investment. Production will begin in 2026 at 20 GWh and expand to 120 GWh. The project will create 17,000 jobs and run on renewable energy from a 500 MW wind farm and a 2,000 MWh storage system. Around 85% of the batteries will be exported. Al Mada and CNGR Advanced Material Co. [115] are developing a battery materials factory in Jorf Lasfar with a \$2 billion investment. Once operational, it will produce materials for over one million EVs per year, benefiting from Morocco's industrial infrastructure and port access. These projects position Morocco as a key player in sustainable energy and EV battery production, contributing to the global transition to clean transportation.

VII. LFP AND LMFP BATTERY PRODUCTION AND PHOSPHORUS DEMAND ANALYSIS (2022–2030)

VII.1. INTRODUCTION

The global energy transition increasingly relies on lithium-based battery technologies to achieve decarbonization objectives. Among these, LFP and Lithium Manganese Iron Phosphate (LMFP) chemistries have emerged as strategic alternatives to traditional NMC batteries due to their superior

thermal stability, extended cycle life, and cost advantages [116-117]. The absence of cobalt and nickel in these chemistries significantly reduces supply chain vulnerabilities, positioning LFP and LMFP as critical enablers for the future of battery technologies.

This report analyzes projected production trends for LFP and LMFP batteries between 2022 and 2030 and evaluates the corresponding phosphorus demand, drawing on insights from the Fraunhofer ISI LIB Roadmap [116], IRENA's Critical Materials Report [117], and [118]

VII.2. GLOBAL PRODUCTION TRENDS OF LFP AND LMFP BATTERIES (2022-2030)

VII.2.1. LFP AND LMFP PRODUCTION DYNAMICS

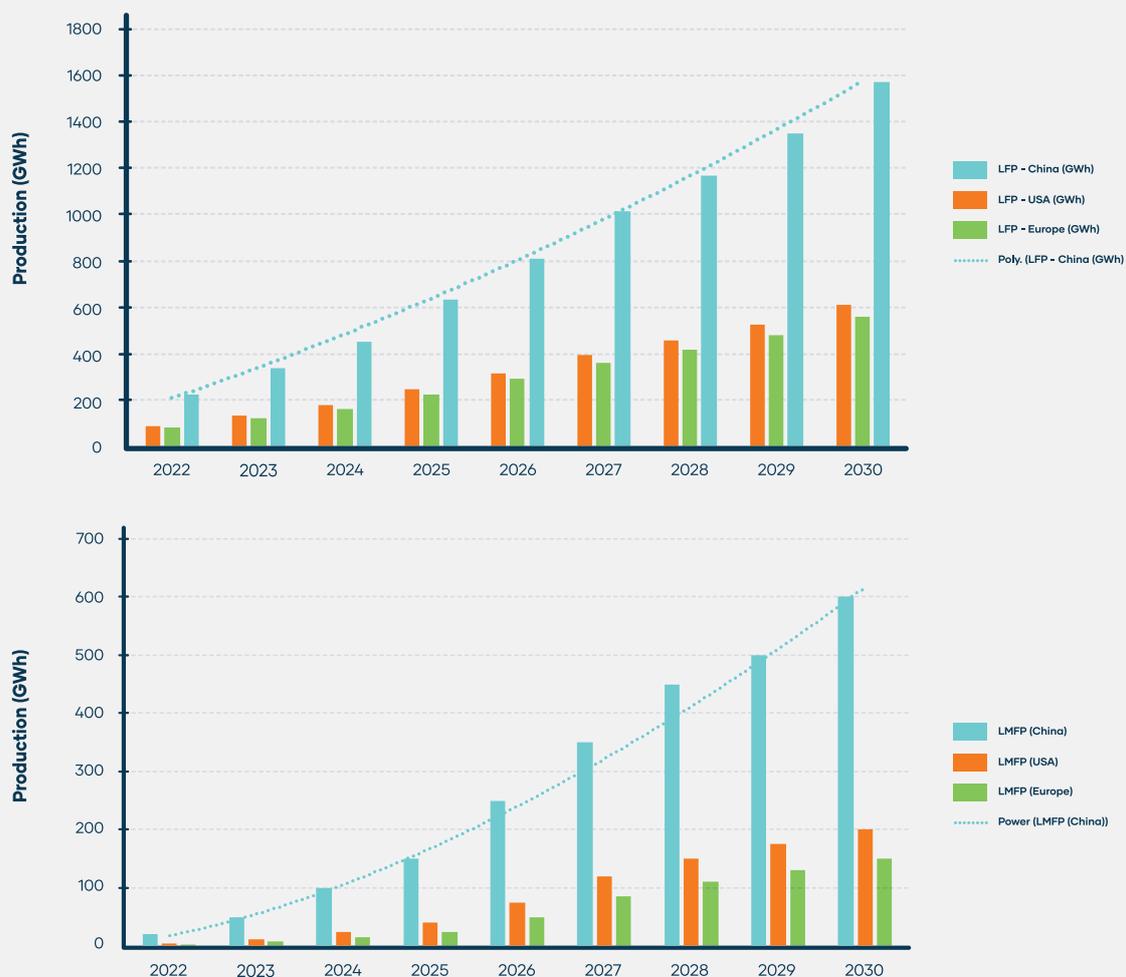


Figure 21 : Global Battery Production and LFP and LMFP Production Forecast (2022-2030). [116-118]

Based on the data presented in Figure 21, LFP production volumes are forecasted to experience continuous growth across major regions. In the USA, LFP production is set to rise from 87.5 GWh in 2022 to 612.5 GWh by 2030. Similarly, Europe is expected to increase from 80 GWh in 2022 to 560 GWh in 2030. China, already leading in LFP battery deployment, is projected to expand production from 225 GWh in 2022 to an impressive 1,575 GWh by 2030.

The regional breakdown (Figure 21) illustrates that China will maintain its dominant position, accounting for approximately 50% of global LFP production capacity in 2030, with CATL and BYD as key players. Europe and the USA will represent around 20% and 25% of total LFP production capacity respectively. Within each region, LFP is expected to account for 40% of Europe's and 35% of the USA's total battery output by 2030.

Parallely, LMFP is gaining strategic traction, with production capacity anticipated to significantly increase after 2027, led by initiatives from major manufacturers like LG Energy Solution.

LMFP batteries are gaining strategic interest for their ability to offer higher energy density than traditional LFP cells while maintaining cost and safety advantages. Leading manufacturers such as LG Energy Solution are planning large-scale LMFP deployments by 2027, particularly in Europe and South Korea [BZF, 2024].

VII.2..2. SUMMARY OF LFP PRODUCTION FORECAST (2030)

Region	Total Production (TWh)	LFP Production (TWh)
China	3.5	1.575
Europe	1.4	0.56
USA	1.75	0.6125

Table 1: Regional LFP Production Forecast for 2030. [116-118]

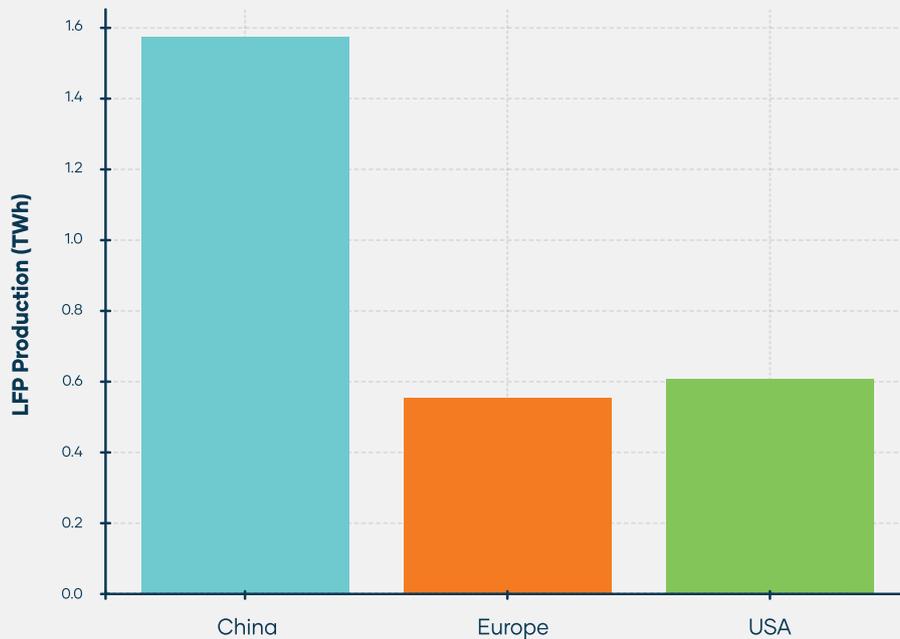


Figure 22: Regional Comparison of LFP Production in 2030.

China dominates with 3.5 TWh of annual production, representing 70% of the world's output, including 1,575 TWh of LFP batteries (45%). This high proportion is due to the massive adoption of electric vehicles and stationary storage. Europe follows with a total of 1.4 TWh, including 0.56 TWh of LFP (40%), mainly thanks to the Tesla plant in Berlin and ongoing projects by Northvolt. The US has 1.75 TWh of production, including 0.6125 TWh of LFP (35%), supported by IRA incentives and strategies from Tesla and Ford together, these three regions account for 90% of global manufacturing. China maintains its technological lead over the LFP, while Europe and the US are gradually developing their capabilities.

VII.3. MATHEMATICAL MODELING OF PHOSPHORUS DEMAND

Phosphorus is an essential component of LFP cathodes. Its demand is estimated using the following formula:

$$\text{Phosphorus Demand (tonnes)} = \text{Battery Production (GWh)} \times 425$$

where:

- 1 GWh = 1,000,000 kWh
- 1 tonne = 1,000 kg
- A typical 60 kWh LFP battery requires approximately 25.5 kg of phosphorus [117].

Example: For China's LFP production in 2030:

$$1575 \times 425 = 668,750 \text{ tonnes of phosphorus}$$

VII.4. PHOSPHORUS DEMAND EVOLUTION (2022–2030)

The evolution of phosphorus demand mirrors the projected growth in LFP battery production. The Compound Annual Growth Rate (CAGR) estimates are approximately 24% for China, 25% for Europe, and 26% for the USA over the period 2022–2030.

Region	Phosphorus Demand (tonnes)
China	668 750
Europe	238 000
USA	260 312.5

Table 2 : Phosphorus Demand Forecast by Region for 2030.

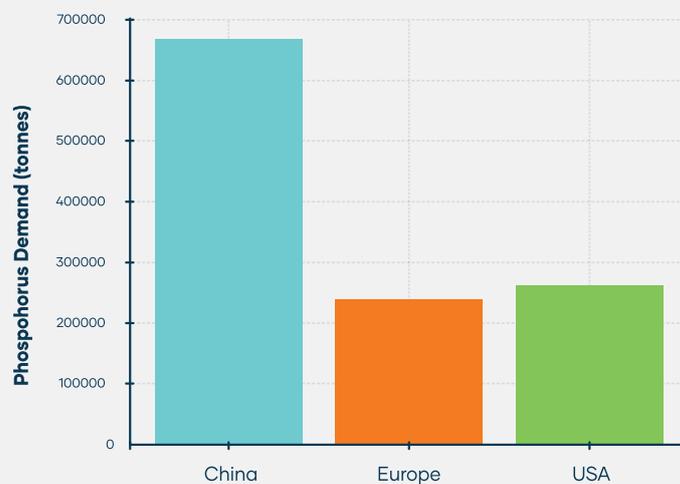


Figure 23: Regional Comparison of Phosphorus Demand in 2030.

Year	Phosphorus Demand USA (tonnes)	Phosphorus Demand Europe (tonnes)	Phosphorus Demand China (tonnes)
2022	37 188	34 000	95 625
2023	55 760	51 000	143 438
2024	74 375	68 000	191 250
2025	104 125	95 200	267 750
2026	133 875	122 400	344 250
2027	167 323	153 000	430 313
2028	193 375	176 800	497 250
2029	223 125	204 000	573 750
2030	260 313	238 000	669 375

Table 3 : Phosphorus Demand Forecast by Region for 2022 to 2030.

PHOSPHORUS DEMAND (TONNES) FOR LFP BATTERIES BY REGION (2022-2030) WITH CAGR TREND LINES

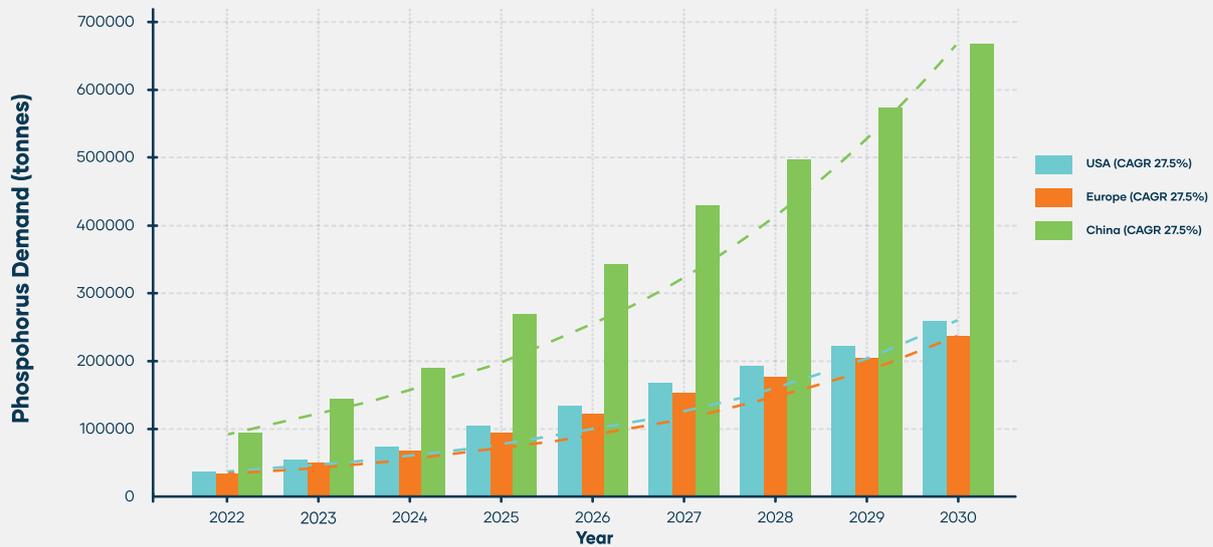


Figure 24: Evolution of Phosphorus Demand for LFP Batteries (2022–2030).

VII.5. STRATEGIC IMPLICATIONS AND RECOMMENDATIONS

Phosphorus, historically used primarily for agricultural fertilizers, is now emerging as a critical material for the clean energy transition [117]. Rapidly growing demand, if unmanaged, could create significant supply tensions as both the agricultural and battery sectors vie for resources.

Recommendations based on [116] and [117]

- **Scaling phosphorus recycling initiatives:** For example, Tesla's Gigafactory Nevada reportedly achieves recovery rates exceeding 90%.
- **Diversifying sourcing strategies:** Morocco, holding approximately 70% of global phosphorus reserves, will play a strategic role.
- **Investing in phosphorus-efficient battery chemistries:** Reducing material intensity is essential to sustain long-term supply security.

VIII. CONCLUSION

Phosphorus-based batteries offer a promising pathway for advancing energy storage, particularly in meeting the growing demands of electric vehicles, renewable energy systems, and portable electronics. LFP and LMFP are especially noteworthy for their safety, affordability, thermal stability, and environmental benefits, providing viable alternatives to conventional materials that rely on scarce and expensive elements like cobalt and nickel. As LFP and LMFP technologies gain market traction, global phosphorus demand is expected to rise significantly, with wide-reaching implications for raw material supply chains. Addressing challenges related to raw material availability, scalable production, and performance optimization is therefore critical. Proactive investment in sustainable mining practices, material synthesis, recycling infrastructure, and advanced battery chemistries will be essential to ensuring a resilient and secure clean energy transition. This underscores the need for coordinated efforts among policymakers, researchers, and industry stakeholders to manage material flows strategically, establish sustainable supply chains, and enable the long-term viability of phosphorus-based batteries. With continued innovation and collaboration, these technologies can play a vital role in supporting cleaner energy systems and a more sustainable, electrified future.

IX. REFERENCES

- [1] R. Borah, F.R. Hughson, J. Johnston, T. Nann, On battery materials and methods, *Mater Today Adv* 6 (2020) 100046. <https://doi.org/10.1016/j.mtadv.2019.100046>.
- [2] C. Liu, Z.G. Neale, G. Cao, Understanding electrochemical potentials of cathode materials in rechargeable batteries, *Biochem Pharmacol* 19 (2016) 109–123. <https://doi.org/10.1016/j.mattod.2015.10.009>.
- [3] V. Anoopkumar, B. John, M. Td, Potassium ion batteries: Key to future large scale energy storage ?, *ACS Appl Energy Mater* 3 (2020) 9478–9492. <https://doi.org/10.1021/acsaem.0c01574>.
- [4] J. Kepler, Increasing Electric Vehicle Range with a Recommendation App providing Context-Specific Trip Rankings *Computer Science*, 2016. www.jku.at.
- [5] P. Ros Bosch, J. Pla Aldabo, *Battery Technology: A review*, 2020.
- [6] C. Jeyaseelan, A. Jain, P. Khurana, D. Kumar, Ni-Cd Batteries, *Rechargeable Batteries: History, Progress, and Applications* (2020) 177–194.
- [7] C. Liu, Z.G. Neale, G. Cao, Understanding electrochemical potentials of cathode materials in rechargeable batteries, *Biochem Pharmacol* 19 (2016) 109–123. <https://doi.org/10.1016/j.mattod.2015.10.009>.
- [8] X. Wu, Investigations of LiCoPO₄ as a cathode material for high-voltage lithium-ion batteries, 2019.
- [9] M.-K. Tran, A. DaCosta, A. Mevawalla, S. Panchal, M. Fowler, M. Fowler, Comparative Study of Equivalent Circuit Models Performance in Four Common Lithium-Ion Batteries: LFP, NMC, LMO, NCA, MDPI: *Batteries* 7 (2021) 1–15. <https://doi.org/10.3390/batteries7030051>.
- [10] N. Yabuuchi, K. Kubota, M. Dahbi, S. Komaba, Research Development on Sodium-Ion Batteries, *Chem Rev* 114 (2014) 11636–11682. <https://doi.org/10.1021/cr500192f>.
- [11] A. Manthiram, Y. Fu, S. Chung, C. Zu, Y. Su, Rechargeable Lithium-Sulfur Batteries, *Chem Rev* 114 (2014) 11751–11787. <https://doi.org/10.1021/cr500062v>.
- [12] A. Sakuda, Favorable composite electrodes for all-solid-state batteries, *Journal of the Ceramic Society of Japan* 9 (2018) 675–683. <https://doi.org/10.2109/jcersj2.18114>.
- [13] M. Kanwal, M. Raza, M. Shahbaz, U. Farooq, M. Usman, Recent advancement in energy storage technologies and their applications, *J Energy Storage* 92 (2024) 112112. <https://doi.org/10.1016/j.est.2024.112112>.
- [14] K. Song, Y. Ling, B. Lin, Developing abundant rare-earth iron perovskite electrodes for high-performance and low-cost solid oxide fuel cells, *iScience* 27 (2024) 109982. <https://doi.org/10.1016/j.isci.2024.109982>.
- [15] E. Macia, E. Macia, The role of phosphorus in chemical evolution, *Chem Soc Rev* 34 (2005) 691–701. <https://doi.org/10.1039/b416855k>.
- [16] U.S. Geological Survey, Mineral commodity summaries 2020, 2020. <https://doi.org/https://doi.org/10.3133/mcs2020>.
- [17] H. Liu, G. Hu, I.A. Basar, J. Li, N. Lyczko, A. Nzihou, C. Eskicioglu, Phosphorus recovery from municipal sludge-derived ash and hydrochar through wet-chemical technology: A review towards sustainable waste management, *Chemical Engineering Journal* 417 (2021) 129300. <https://doi.org/10.1016/j.cej.2021.129300>.
- [18] M. Oguz, E. Alkan, M. Mahmut, D. Kuruahmet, Phosphorus carbon based hybrid electrodes for sodium ion batteries, *Diam Relat Mater* 146 (2024) 111170. <https://doi.org/10.1016/j.diamond.2024.111170>.
- [19] D. Yang, D. Xiong, L. Chen, Z. Feng, K. Wen, Red phosphorus confined in porous structures formed by PVDF-Derived carbon as superior anode material for sodium-ion batteries, *Journal of Electroanalytical Chemistry* 957 (2024) 118122. <https://doi.org/10.1016/j.jelechem.2024.118122>.

- [20] Y. Yan, Z. Zhou, P. Wu, B. Tang, J. Tang, X. Zhang, Transition metal enhanced black phosphorus for early thermal runaway gas detection of lithium-ion batteries: A theoretical study, *Chem Phys Lett* 857 (2024) 141675. <https://doi.org/10.1016/j.cplett.2024.141675>.
- [21] R. Herbst-Irmer, X. Wang, L. Haberkorn, I. Kohne, R. Oswald, J. Behler, D. Stalke, A new polymorph of white phosphorus at ambient conditions, *International Union of Crystallography Journal* 10 (2023) 766–771. <https://doi.org/10.1107/S2052252523009247>.
- [22] S. Ranjan, V. Gadore, V. Chavda, S. Panda, Black phosphorene: A versatile allotrope revolutionizing environmental, energy, and biomedical applications, *Coord Chem Rev* 524 (2025) 216345. <https://doi.org/10.1016/j.ccr.2024.216345>.
- [23] Y. Bi, D. Wang, Revisiting Olivine Phosphate and Blend Cathodes in Lithium Ion Batteries for Electric Vehicles, in: *New Perspectives on Electric Vehicles*; IntechOpen, 2022. <https://doi.org/http://dx.doi.org/10.5772/intechopen.95662>.
- [24] S. Oh, S. Myung, J. Hassoun, B. Scrosati, Y. Sun, Reversible NaFePO₄ electrode for sodium secondary batteries, *Electrochem Commun* 22 (2012) 149–152. <https://doi.org/10.1016/j.elecom.2012.06.014>.
- [25] I. Bezza, H. Aziam, I. Saadoune, On the LiFe_{1-x}Mn_xPO₄ (x = 0, 0.4, 0.6, 0.65, 1) olivine-type cathode materials for lithium ion batteries, *Mater Today Proc* 51 (2022) 1913–1917. <https://doi.org/10.1016/j.matpr.2021.02.648>.
- [26] G. Hautier, A. Jain, S.P. Ong, B. Kang, C. Moore, R. Doe, G. Ceder, Phosphates as Lithium-Ion Battery Cathodes: An Evaluation Based on High-Throughput ab Initio Calculations, *Chemistry of Materials* 23 (2011) 3495–3508. <https://doi.org/10.1021/cm200949v>.
- [27] Y.H. Ikuhara, X. Gao, C.A.J. Fisher, A. Kuwabara, H. Moriwake, K. Kohama, H. Iba, Y. Ikuhara, Atomic Level Changes during Capacity Fade in Highly Oriented Thin Films of Cathode Material LiCoPO₄, *J Mater Chem A Mater* 5 (2017) 9329–9338. <https://doi.org/10.1039/C6TA10084H>.
- [28] A. Gutierrez, S. Kim, T.T. Fister, C.S. Johnson, Microwave-Assisted Synthesis of NaCoPO₄ Red-Phase and Initial Characterization as High Voltage Cathode for Sodium-Ion Batteries, *ACS Appl Mater Interfaces* 9 (2017) 4391–4396. <https://doi.org/10.1021/acsami.6b14341>.
- [29] Y. Liu, J. Li, Q. Shen, J. Zhang, P. He, X. Qu, Y. Liu, Advanced characterizations and measurements for sodium-ion batteries with NASICON-type cathode materials, *EScience* 2 (2022) 10–31. <https://doi.org/10.1016/j.esci.2021.12.008>.
- [30] S. Rizvi, I. Aladhyani, Y. Ding, Q. Zhang, Recent advances in doping Na₃Zr₂Si₂PO₁₂ (NASICON) solid-state electrolyte for sodium-ion batteries, *Nano Energy* 129 (2024) 110009. <https://doi.org/10.1016/j.nanoen.2024.110009>.
- [31] M. Amou, B. Larhrib, N. Sabi, M. Srout, A.H. Assen, M. Mansori, O. Dolotko, N. Ouedna, H. Martinez, I. Saadoune, Novel NASICON-typed porous Ni_{1.5}V₂(PO₄)₃/C and Mn_{1.5}V₂(PO₄)₃/C as anode materials for lithium-ion batteries: Crystal structure and electrochemical lithiation/delithiation reaction mechanism, *J Energy Storage* 70 (2023) 107889. <https://doi.org/10.1016/j.est.2023.107889>.
- [32] S. Liu, Z. Xu, L. Ren, W. Xu, Y. Liu, X. Fan, M. Luo, J. Li, J. Tong, Fe-modified NASICON-type Na₃V₂(PO₄)₃ as a cathode material for sodium ion batteries, *RSC Adv* 14 (2024) 4835–4843. <https://doi.org/10.1039/d3ra08714j>.
- [33] M. Sato, S. Tajimi, H. Okawa, K. Uematsu, K. Toda, Preparation of iron phosphate cathode material of Li₃Fe₂(PO₄)₃ by hydrothermal reaction and thermal decomposition processes, *Solid State Ion* 152–153 (2002) 247–251. [https://doi.org/10.1016/S0167-2738\(02\)00306-5](https://doi.org/10.1016/S0167-2738(02)00306-5).
- [34] Y. Cao, Y. Liu, T. Chen, X. Xia, L.C. Zhang, J. Zhang, Y. Xia, Sol-gel synthesis of porous Na₃Fe₂(PO₄)₃ with enhanced sodium-ion storage capability, *Ionics (Kiel)* 25 (2019) 1083–1090. <https://doi.org/10.1007/s11581-018-2804-z>.
- [35] Z. Guo, X. Qin, Y. Xie, C. Lei, T. Wei, Y. Zhang, Advanced NASICON-type LiTi₂(PO₄)₃ as electrode materials for lithium-ion batteries, *Chem Phys Lett* 806 (2022) 140010. <https://doi.org/10.1016/j.cplett.2022.140010>.
- [36] M. Wu, W. Ni, J. Hu, J. Ma, NASICON-Structured NaTi₂(PO₄)₃ for Sustainable Energy Storage, Springer Singapore, 2019. <https://doi.org/10.1007/s40820-019-0273-1>.
- [37] Y. Niu, Y. Zhang, M. Xu, A review on pyrophosphate framework cathode materials for sodium-ion batteries, *J Mater Chem A Mater* 7 (2019) 15006–15025. <https://doi.org/10.1039/c9ta04274a>.
- [38] J. Li, R. Wang, W. Zhao, X. Hou, E. Paillard, D. Ning, C. Li, J. Wang, Y. Xiao, M. Winter, J. Li, A high-voltage symmetric sodium

ion battery using sodium vanadium pyrophosphate with superior power density and long lifespan, *J Power Sources* 507 (2021) 230183. <https://doi.org/10.1016/j.jpowsour.2021.230183>.

- [39] M. Tamaru, S.C. Chung, D. Shimizu, S.I. Nishimura, A. Yamada, Pyrophosphate chemistry toward safe rechargeable batteries, *Chemistry of Materials* 25 (2013) 2538–2543. <https://doi.org/10.1021/cm4010739>.
- [40] M. Priyadarshini, K. Preeti, K.P. Kirubakaran, L. Kumaresan, K. Vediappan, Electrochemical studies on Na₂FeP₂O₇ pyrophosphate enhanced with SWCNT as intercalation compounds for Na-ion batteries: An insight into sensitive mode operations, *Mater Lett* 284 (2021) 128949. <https://doi.org/10.1016/j.matlet.2020.128949>.
- [41] L. Adam, A. Guesdon, B. Raveau, A new lithium manganese phosphate with an original tunnel structure in the A₂MP₂O₇ family, *J Solid State Chem* 181 (2008) 3110–3115. <https://doi.org/10.1016/j.jssc.2008.07.039>.
- [42] M. Tanabe, T. Honma, T. Komatsu, Unique crystallization behavior of sodium manganese pyrophosphate Na₂MnP₂O₇ glass and its electrochemical properties, *Journal of Asian Ceramic Societies* 5 (2017) 209–215. <https://doi.org/10.1016/j.jascer.2017.04.009>.
- [43] X. Ge, X. Li, Z. Wang, H. Guo, G. Yan, Facile synthesis of NaVPO₄F/C cathode with enhanced interfacial conductivity towards long-cycle and high-rate sodium-ion batteries, *Chemical Engineering Journal* 357 (2019) 458–462. <https://doi.org/10.1016/j.cej.2018.09.099>.
- [44] S.T. Dacek, W.D. Richards, D.A. Kitchaev, G. Ceder, Structure and Dynamics of Fluorophosphate Na-Ion Battery Cathodes, *Chemistry of Materials* 28 (2016) 5450–5460. <https://doi.org/10.1021/acs.chemmater.6b01989>.
- [45] M. He, S. Liu, J. Wu, J. Zhu, Review of cathode materials for sodium-ion batteries, *Progress in Solid State Chemistry* 74 (2024) 100452. <https://doi.org/10.1016/j.progsolidstchem.2024.100452>.
- [46] P.V. Shinde, D.P. Dutta, An insight into the electrochemical properties of sodium/vanadium co-doped LiFePO₄F cathodes for application in lithium-ion batteries, n.d. <https://ssrn.com/abstract=4455237>.
- [47] B.L. Ellis, W.R.M. Makahnouk, Y. Makimura, K. Toghill, L.F. Nazar, A multifunctional 3.5 V iron-based phosphate cathode for rechargeable batteries, *Nat Mater* 6 (2007) 749–753. <https://doi.org/10.1038/nmat2007>.
- [48] Y. Li, X. Liang, G. Chen, W. Zhong, Q. Deng, F. Zheng, C. Yang, M. Liu, J. Hu, In-situ constructing Na₃V₂(PO₄)₂F₃/carbon nanocubes for fast ion diffusion with high-performance Na⁺-storage, *Chemical Engineering Journal* 387 (2020) 123952. <https://doi.org/10.1016/j.cej.2019.123952>.
- [49] J. Wang, Z. Wang, X. Li, H. Guo, X. Wu, X. Zhang, W. Xiao, XLi₃V₂(PO₄)₃-LiVPO₄F/C composite cathode materials for lithium ion batteries, *Electrochim Acta* 87 (2013) 224–229. <https://doi.org/10.1016/j.electacta.2012.09.014>.
- [50] T. Sharmin, N. Hossain, F.T. Mohsin, M.A. Haque, M.M. Mashfy, T.A. Alvy, M. Nasim, Advancements in Cutting-edge Materials for Sodium-ion Battery Anodes: A Comprehensive Review, *Mater Today Chem* 42 (2024) 102407. <https://doi.org/https://doi.org/10.1016/j.mtchem.2024.102407>.
- [51] Z.H. Luo, D. Zhang, J.X. Guo, F. Jiang, N.L. Shen, Y.F. Du, Z.J. Jiang, T. Wang, X. Liu, X.B. Cheng, Y. Wu, Recent progress on the materials design towards thermally safe sodium-ion batteries, *Journal of Energy Chemistry* 102 (2025) 555–575. <https://doi.org/10.1016/j.jechem.2024.11.014>.
- [52] Z. Li, J. Ding, D. Mitlin, Tin and Tin Compounds for Sodium Ion Battery Anodes: Phase Transformations and Performance, *Acc Chem Res* 48 (2015) 1657–1665. <https://doi.org/10.1021/acs.accounts.5b00114>.
- [53] Q. He, Y. Li, D. Wang, J. Xie, Facile synthesis of a novel P-doped carbon coated nickel phosphides nanorods as sodium storage anode materials, *Journal of Materiomics* 10 (2024) 408–415. <https://doi.org/10.1016/j.jmat.2023.04.015>.
- [54] Y. Yang, W. Fu, D.C. Lee, C. Bell, M. Drexler, Z.F. Ma, A. Magasinski, G. Yushin, F.M. Alamgir, Porous FeP/C composite nano fibers as high-performance anodes for Li-ion/Na-ion batteries, *Mater Today Energy* 16 (2020) 100410. <https://doi.org/10.1016/j.mtener.2020.100410>.
- [55] Y. Du, H. Li, Construction of 3D nanoarchitectural porous carbon supported carbon nanotubes@CoP with enhanced lithium

ions storage performance, *Chem Phys Lett* 732 (2019) 136633. <https://doi.org/10.1016/j.cplett.2019.136633>.

[56] S. Kaushik, T. Mehta, P. Chand, S. Sharma, G. Kumar, Recent advancements in cathode materials for high-performance Li-ion batteries: Progress and prospects, *J. Energy Storage*. 97 (2024) 112818. <https://doi.org/10.1016/j.est.2024.112818>.

[57] Y. Liu, W. Qin, D. Zhang, L. Feng, L. Wu, Effect of Na⁺ in situ doping on LiFePO₄/C cathode material for lithium-ion batteries, *Prog. Nat. Sci. Mater. Int.* 31 (2021) 14–18. <https://doi.org/10.1016/j.pnsc.2020.10.006>.

[58] Z. Chen, J.R. Dahn, Methods to obtain excellent capacity retention in LiCoO₂ cycled to 4.5 V, *Electrochim. Acta*. 49 (2004) 1079–1090. <https://doi.org/10.1016/j.electacta.2003.10.019>.

[59] H.H. Sun, U.H. Kim, J.H. Park, S.W. Park, D.H. Seo, A. Heller, C.B. Mullins, C.S. Yoon, Y.K. Sun, Transition metal-doped Ni-rich layered cathode materials for durable Li-ion batteries, *Nat. Commun.* 12 (2021) 1–11. <https://doi.org/10.1038/s41467-021-26815-6>.

[60] Y. Huang, Y. Dong, S. Li, J. Lee, C. Wang, Z. Zhu, W. Xue, Y. Li, J. Li, Lithium Manganese Spinel Cathodes for Lithium-Ion Batteries, *Adv. Energy Mater.* 11 (2021) 1–21. <https://doi.org/10.1002/aenm.202000997>.

[61] X. Li, J. Liu, M.N. Banis, A. Lushington, R. Li, M. Cai, X. Sun, Atomic layer deposition of solid-state electrolyte coated cathode materials with superior high-voltage cycling behavior for lithium ion battery application, *Energy Environ. Sci.* 7 (2014) 768–778. <https://doi.org/10.1039/c3ee42704h>.

[62] K. Zaghib, J. Dubé, A. Dallaire, K. Galoustov, A. Guerfi, M. Ramanathan, A. Benmayza, J. Prakash, A. Mauger, C.M. Julien, Enhanced thermal safety and high power performance of carbon-coated LiFePO₄ olivine cathode for Li-ion batteries, *J. Power Sources*. 219 (2012) 36–44. <https://doi.org/10.1016/j.jpowsour.2012.05.018>.

[63] K. Amiri Kasvayee, Synthesis of Li-ion battery cathode materials via freeze granulation, 2011.

[64] E. Laakso, S. Efimova, M. Colalongo, P. Kauranen, K. Lahtinen, E. Napolitano, V. Ruiz, J. Moškon, M. Gaberšček, J. Park, S. Seitz, T. Kallio, Aging mechanisms of NMC811/Si-Graphite Li-ion batteries, *J. Power Sources*. 599 (2024). <https://doi.org/10.1016/j.jpowsour.2024.234159>.

[65] C. Mao, R.E. Ruther, J. Li, Z. Du, I. Belharouak, Identifying the limiting electrode in lithium ion batteries for extreme fast charging, *Electrochem. Commun.* 97 (2018) 37–41. <https://doi.org/10.1016/j.elecom.2018.10.007>.

[66] D. Versaci, R. Colombo, G. Montinaro, M. Buga, N. Cortes Felix, G. Evans, F. Bella, J. Amici, C. Francia, S. Bodoardo, Tailoring cathode materials: A comprehensive study on LNMO/LFP blending for next generation lithium-ion batteries, *J. Power Sources*. 613 (2024) 234955. <https://doi.org/10.1016/j.jpowsour.2024.234955>.

[67] Y. Surace, M. Jahn, D.M. Cupid, The Rate Capability Performance of High-Areal-Capacity Water-Based NMC811 Electrodes: The Role of Binders and Current Collectors, *Batteries*. 10 (2024). <https://doi.org/10.3390/batteries10030100>.

[68] M. Abdollahifar, P. Molaiyan, M. Perovic, A. Kwade, Insights into Enhancing Electrochemical Performance of Li-Ion Battery Anodes via Polymer Coating, *Energies*. 15 (2022). <https://doi.org/10.3390/en15238791>.

[69] Q. Cheng, D. Sun, X. Yu, Metal hydrides for lithium-ion battery application: A review, *J. Alloys Compd.* 769 (2018) 167–185. <https://doi.org/10.1016/j.jallcom.2018.07.320>.

[70] V. Pavitra, U.R. Harini, R.V.B.M. Praveen, Sonochemical synthesis of SnO₂ – CuO nanocomposite : diverse applications on Li-ion battery , electrochemical sensing and photocatalytic activity, *J. Mater. Sci. Mater. Electron.* (2020). <https://doi.org/10.1007/s10854-020-03408-5>.

[71] L. Zhang, C. Chen, Electrode materials for lithium ion battery, *Prog. Chem.* 23 (2011) 275–283. <https://doi.org/10.1016/j.mset.2018.08.001>.

[72] M. Stanley Whittingham, Electrical Energy Storage and Intercalation Chemistry, *Science* (80-.). 192 (1976) 1126–1127. <https://doi.org/https://doi.org/10.1126/science.192.4244.1126>.

[73] I. Capone, J. Aspinall, E. Darnbrough, Y. Zhao, T.U. Wi, H.W. Lee, M. Pasta, Electrochemo-Mechanical Properties of Red Phosphorus Anodes in Lithium, Sodium, and Potassium Ion Batteries, *Matter*. 3 (2020) 2012–2028. <https://doi.org/10.1016/j.matt.2020.09.017>.

- [74] B. Peng, Y. Xu, K. Liu, X. Wang, F.M. Mulder, High-Performance and Low-Cost Sodium-Ion Anode Based on a Facile Black Phosphorus-Carbon Nanocomposite, *ChemElectroChem*. 4 (2017) 2140–2144. <https://doi.org/10.1002/celec.201700345>.
- [75] T. Zhao, H. Mahandra, R. Marthi, X. Ji, W. Zhao, S. Chae, M. Traversy, W. Li, F. Yu, L. Li, Y. Choi, A. Ghahreman, Z. Zhao, C. Zhang, Y. Kang, Y. Lei, Y. Song, An overview on the life cycle of lithium iron phosphate: synthesis, modification, application, and recycling, *Chem. Eng. J.* 485 (2024) 149923. <https://doi.org/10.1016/j.cej.2024.149923>.
- [76] A.K. Koech, G. Mwandila, F. Mulolani, P. Mwaanga, Lithium-ion battery fundamentals and exploration of cathode materials: A review, *South African J. Chem. Eng.* 50 (2024) 321–339. <https://doi.org/10.1016/j.sajce.2024.09.008>.
- [77] M. Cai, C. Sun, D. hao Le, P. yao Li, Y. de Huang, H.Z. Chen, X. hui Zhang, J. chao Zheng, Recent advances in synthesis and modification of phosphate-based cathode materials, *J. Energy Storage*. 95 (2024) 112511. <https://doi.org/10.1016/j.est.2024.112511>.
- [78] X. Jiang, Y. Xin, B. He, F. Zhang, H. Tian, Effect of Heteroatom Doping on Electrochemical Properties of Olivine LiFePO₄ Cathodes for High-Performance Lithium-Ion Batteries, *Materials (Basel)*. 17 (2024). <https://doi.org/10.3390/ma17061299>.
- [79] B. Lung-Hao Hu, F.Y. Wu, C. Te Lin, A.N. Khlobystov, L.J. Li, Graphene-modified LiFePO₄ cathode for lithium ion battery beyond theoretical capacity, *Nat. Commun.* 4 (2013) 1–7. <https://doi.org/10.1038/ncomms2705>.
- [80] B. Zhang, X. Wang, S. Wang, Y. Li, L. Chen, H. Jiao, Z. Yu, J. Tu, High-energy-density lithium manganese iron phosphate for lithium-ion batteries: Progresses, challenges, and prospects, *J. Energy Chem.* 100 (2025) 1–17. <https://doi.org/10.1016/j.jechem.2024.08.011>.
- [81] W. Liu, H. Zhi, X. Yu, Recent progress in phosphorus based anode materials for lithium/sodium ion batteries, *Energy Storage Mater.* 16 (2019) 290–322. <https://doi.org/10.1016/j.ensm.2018.05.020>.
- [82] U.S. Geological Survey, 2025, Mineral commodity summaries 2025 (ver. 1.2, March 2025): U.S. Geological Survey, 212 p. <https://doi.org/10.3133/mcs202>
- [83] R.W. Scholz et al., The dynamics of increasing mineral resources and improving resource efficiency: Prospects for mid- and long-term security of phosphorus supply, *Resources, Conservation & Recycling* 213 (2025) 107993.
- [84] M. Elmeknassi, A. Elghali, A. Laamrani, M. Benzaazoua, Circular economy strategies in sedimentary phosphate mine reclamation: Development of technosol from phosphate waste rock, *J. Environ. Manage.* 370 (2024) 122674. <https://doi.org/10.1016/j.jenvman.2024.122674>.
- [85] H. Amar, M. Benzaazoua, A. Elghali, Y. Taha, M. El Ghorfi, A. Krause, R. Hakkou, Mine waste rock reprocessing using sensor-based sorting (SBS): Novel approach toward circular economy in phosphate mining, *Miner. Eng.* 204 (2023) 108415. <https://doi.org/10.1016/j.mineng.2023.108415>.
- [86] U. Ryszko, P. Rusek, D. Kołodźńska, Quality of Phosphate Rocks from Various Deposits Used in Wet Phosphoric Acid and P-Fertilizer Production, *Materials (Basel)*. 16 (2023). <https://doi.org/10.3390/ma16020793>.
- [87] S. Xie, J. Yang, R. Huang, X. Lv, X. Li, X. He, A novel process for the separation and recovery of phosphorus and rare earth elements from associated rare earth phosphate ores, *Sep. Purif. Technol.* 340 (2024) 126687. <https://doi.org/10.1016/j.seppur.2024.126687>.
- [88] A. Nekahi, A. Kumar M.R., Xia, S. Deng, K. Zaghbi, Sustainable LiFePO₄ and LiM_xFe_{1-x}PO₄ (x=0.1–1) cathode materials for lithium-ion batteries: A systematic review from mine to chassis, *Mater. Sci. Eng. R Reports*. 159 (2024). <https://doi.org/10.1016/j.mser.2024.100797>.
- [89] E. Petavratzi, P. Josso, Global material flows of lithium for the lithium-ion and lithium iron phosphate battery markets. British Geological Survey Open Report, OR/21/055, 2021.
- [90] S. El Aggadi, M. Ennouhi, A. Boutakiout, A. El Hourch, Progress towards efficient phosphate-based materials for sodium-ion batteries in electrochemical energy storage, *Ionics (Kiel)*. 29 (2023) 2099–2113. <https://doi.org/10.1007/s11581-023-04936-w>.
- [91] B. Liu, Y. Zhang, M. Lu, Z. Su, G. Li, T. Jiang, Extraction and separation of manganese and iron from ferruginous manganese ores: A review, *Miner. Eng.* 131 (2019) 286–303. <https://doi.org/10.1016/j.mineng.2018.11.016>.

- [92] F. Gitau, O.O. Alabi, F.O. Aramide, K.H. Talabi, M.N. Ondiaka, Towards a Sustainable and Enhanced Iron Ore Recovery: Bio-beneficiation Review, *Mining, Metall. Explor.* 41 (2024) 1069–1078. <https://doi.org/10.1007/s42461-024-00950-2>.
- [93] Y. Lu, T. Zhu, Status and prospects of lithium iron phosphate manufacturing in the lithium battery industry, *MRS Commun.* 14 (2024) 888–899. <https://doi.org/10.1557/s43579-024-00644-2>.
- [94] B. Chacko, M. W, A comprehensive investigation on the electrochemical performance, synthesis, modification, and recycling methods of LiFePO₄ for sustainable future, *J. Energy Storage.* 98 (2024) 112851. <https://doi.org/10.1016/j.est.2024.112851>.
- [95] P.K. Dammala, K.B. Dermenci, A.R. Kathribail, P. Yadav, J. Van Mierlo, M. Bercibar, A critical review of future aspects of digitalization next generation Li-ion batteries manufacturing process, *J. Energy Storage.* 74 (2023) 109209. <https://doi.org/10.1016/j.est.2023.109209>.
- [96] S. Wolf, N. Schwenzer, T. Tratz, V. Göken, M. Börner, D. Neb, H. Heimes, M. Winter, A. Kampker, Optimized LiFePO₄-Based Cathode Production for Lithium-Ion Batteries through Laser- and Convection-Based Hybrid Drying Process, *World Electr. Veh. J.* 14 (2023). <https://doi.org/10.3390/wevj14100281>.
- [97] L. Qi, Y. Wang, L. Kong, M. Yi, J. Song, D. Hao, X. Zhou, Z. Zhang, J. Yan, Manufacturing processes and recycling technology of automotive lithium-ion battery: A review, *J. Energy Storage.* 67 (2023) 107533. <https://doi.org/10.1016/j.est.2023.107533>.
- [98] Y. Gao, Z. Pan, J. Sun, Z. Liu, J. Wang, High-Energy Batteries: Beyond Lithium-Ion and Their Long Road to Commercialisation, Springer Singapore, 2022. <https://doi.org/10.1007/s40820-022-00844-2>.
- [99] M. Shan, C. Dang, K. Meng, Y. Cao, X. Zhu, J. Zhang, G. Xu, M. Zhu, Recycling of LiFePO₄ cathode materials: From laboratory scale to industrial production, *Mater. Today.* 73 (2024) 130–150. <https://doi.org/10.1016/j.mattod.2023.12.012>.
- [100] X. Lai, J. Chen, Q. Chen, X. Han, L. Lu, H. Dai, Y. Zheng, Comprehensive assessment of carbon emissions and environmental impacts of sodium-ion batteries and lithium-ion batteries at the manufacturing stage, *J. Clean. Prod.* 423 (2023) 138674. <https://doi.org/10.1016/j.jclepro.2023.138674>.
- [101] Lithium Iron Phosphate Battery Market Size, Share, and Trends 2024 to 2034, <https://www.precedenceresearch.com/lithium-iron-phosphate-battery-market>. Accessed 14 January 2025., (n.d.).
- [102] J. Zhao, LITHIUM MANGANESE IRON PHOSPHATE (LMFP) BATTERIES RECEIVING RENEWED ATTENTION IN CHINA-EXPECTED TO BE INSTALLED MAINLY IN MIDDLE-CLASS EVS, n.d. <https://www.batterydesign.net/lithium-ion/>.
- [103] Lithium Iron Phosphate Battery Market Size, Share & Industry Analysis, By Type (Portable Battery, Stationary Battery), By Application (Automotive, Industrial, Energy Storage System, Consumer Electronics, and Others), and Regional Forecast, 2024-2032, <https://www.fortunebusinessinsights.com/lithium-ion-li-ion-phosphate-batteries-market-102152>. Accessed 14 January 2025., (n.d.).
- [104] M. Blois, Lithium iron phosphate comes to America, *Chemical&Engineering News*, <https://cen.acs.org/energy/energy-storage/Lithium-iron-phosphate-comes-to-America/101/i4> Accessed 13 Jan 2025., (n.d.).
- [105] BYD says it will launch new generation of blade batteries next year, https://www.reuters.com/business/autos-transportation/byd-says-it-will-launch-new-generation-blade-batteries-next-year-2024-11-25/?utm_source=chatgpt.com, Accessed 14 January 2025., (n.d.).
- [106] BYD and FAW's joint battery project goes into production https://cnevpost.com/2024/02/02/byd-faw-battery-project-goes-into-production/?utm_source=chatgpt.com, Accessed 14 January 2025., (n.d.).
- [107] CATL Unveils Shenxing PLUS, Enabling 1,000-km Range and 4C Superfast Charging, https://www.prnewswire.com/news-releases/catl-unveils-shenxing-plus-enabling-1-000-km-range-and-4c-superfast-charging-302127578.html?utm_source=chatgpt.com. Accessed 14 January 2025., (n.d.).
- [108] CATL launches Freevoy battery for hybrid cars that can offer over 400 km range, https://cnevpost.com/2024/10/24/catl-launches-freevoy-battery-for-hybrids/?utm_source=chatgpt.com. Accessed 14 January 2025., (n.d.).
- [109] Shenzhen Dynanonic Co., Ltd. <https://www.dynanonic.com/en/about.aspx>, (n.d.).

- [110] Anda Energy Technology Launches a 60,000 mt/year LFP Project, Anda Energy Technology Launches a 60,000 mt/year LFP Project | SMM (metal.com), Accessed 14 January 2025, (n.d).
- [111] Y. Lu, T. Zhu, Status and prospects of lithium iron phosphate manufacturing in the lithium battery industry, MRS Commun (2024). <https://doi.org/10.1557/s43579-024-00644-2>.
- [112] Lithium Iron Phosphate Battery Market Size, Share & Industry Analysis, By Type (Portable Battery, Stationary Battery), By Application (Automotive, Industrial, Energy Storage System, Consumer Electronics, and Others), and Regional Forecast, 2024-2032, <https://www.fortunebusinessinsights.com/lithium-ion-li-ion-phosphate-batteries-market-102152>. Accessed 14 January 2025., (n.d).
- [113] LG Chem et Huayou Group s'associent pour construire une usine de cathodes LFP au Maroc, <https://snrtnews.com/fr/article/lg-chem-et-huayou-group-sassocient-pour-construire-une-usine-de-cathodes-lfp-au-maroc-84184>. Accessed 14 January 2025., (n.d).
- [114] Kénitra : le chinois Gotion démarrera la production des batteries pour véhicules électriques en juin 2026, https://fr.le360.ma/economie/le-groupe-chinois-gotion-demarrera-la-production-des-batteries-pour-vehicules-electriques-en-juin_THUN7W35V5H5RET4GXPJRDKMDI/. Accessed 14 January 2025., (n.d).
- [115] Batteries électriques : L'accord entre Al Mada et le chinois CNGR acté, l'usine de Jorf Lasfar opérationnelle en 2025. <https://www.lepatron.ma/news/business/batteries-electriques-l-accord-entre-al-mada-et-le-chinois-cngr-acte-l-usine-de-jorf-lasfar-operationnelle-en-2025/5146>. Accessed 14 January 2025., (n.d).
- [116] Fraunhofer ISI, "LIB Roadmap 2030+," 2023.
- [117] IRENA, "Critical Materials for the Energy Transition: Batteries for EVs," 2024.
- [118] BZF, "Market Analysis Q2," 2024.



University
Mohammed VI
Polytechnic

