FOCUS ON

PHOSPHATE

FROM

ROCKS

TO

POWER

Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, & Beyond

August 2025 | V1.0

From Rocks to Power: Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, and Beyond

Focus on Phosphate

Author

Sosthène Ung, Senior Future Economy Analyst, The Transition Accelerator

Contributors

Liz Lappin, Battery Metals Association of Canada

Eric Pelletier, Battery Metals Association of Canada

Bentley Allan, The Transition Accelerator

Derek Eaton, The Transition Accelerator

About Us

BMAC Battery Metals Association of Canada

The Battery Metals Association of Canada (BMAC) is a national non-profit association of industry participants and champions from across all segments of the battery metals value chain. From mining to specialty chemical refining, manufacturing, end use and recycling, BMAC is focused on coordinating and connecting the segments of this value chain, ensuring Canada captures the economic potential of the sector and is able to attain its electrification targets. Together, our members collaborate to accelerate the development of the battery metals ecosystem in Canada.

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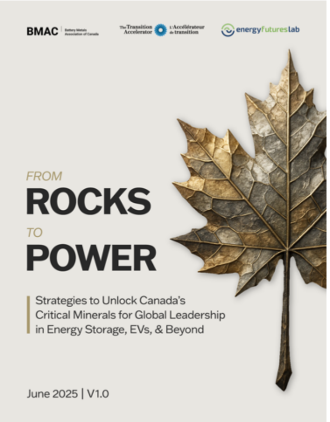
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This chapter is part of a larger report, *From Rocks to Power: Strategies to Unlock Canada's Critical Minerals for Global Leadership in Energy Storage, EVs, and Beyond*. The full report identifies clear, investable priorities in eight minerals, each of them critical to building resilient EV and energy storage value chains. By looking at specific opportunities and providing detailed justifications for its recommendations, *From Rocks to Power* offers a way out of our perpetual planning cycle and towards a new momentum for Canada's critical minerals sector—and our future economic prosperity.

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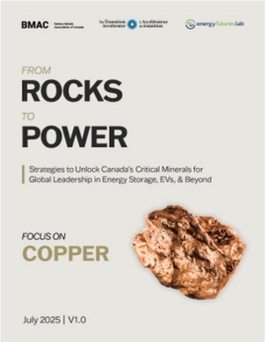
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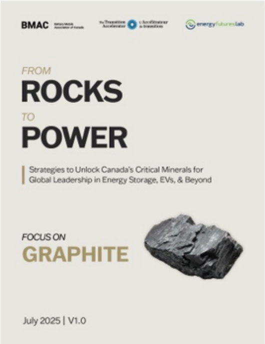
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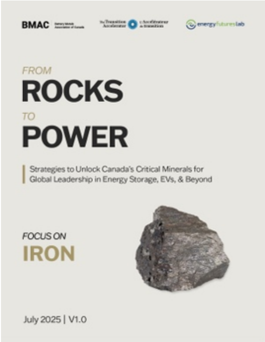
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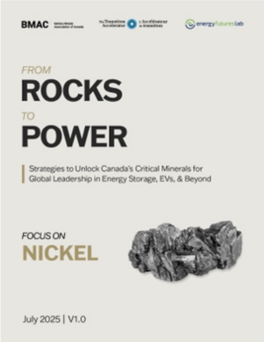
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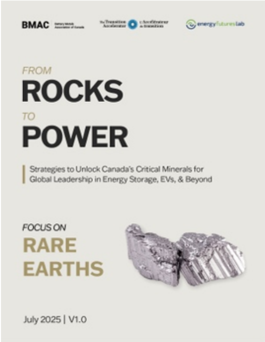
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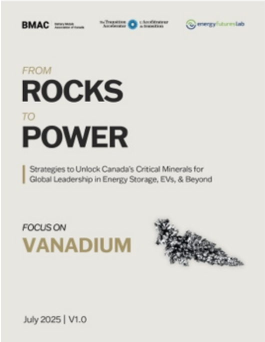
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1 The Canadian Phosphate Strategy

1.1 Phosphate in Canada

Table 1 Non-exhaustive selection of former and future phosphate extraction and processing projects in Canada

Former Phosphate Extraction Site				
Site Name	**Company**	**Province**	**Type**	**Status**
Kapuskasing	Agrium (Now Nutrien)	ON	Igneous	Closed since 2013
Selection of Future Phosphate Extraction Projects				
Project Name	**Company**	**Province**	**Type**	**Status**
Lac à Paul	Arianne Phosphate	QC	Igneous	FS 2013
Lac à l'Orignal	First Phosphate	QC	Igneous	PEA 2023
Bégin-Lamarche	First Phosphate	QC	Igneous	PEA 2024
Mine Arnaud	Investissement Québec	QC	Igneous	Paused 2017
Martison	Fox River Resources	ON	Igneous	PEA 2022
Wapiti & Fernie	Canadian Phosphate (Fertoz)	BC	Sedimentary	Exploration
*Note: most DLE brine projects are coupled with refining plants				
Selection of Future Phosphoric Acid Plants				
Project Name	**Company**	**Province**	**Product Type**	**Status**
Saguenay Plant	Arianne Phosphate	QC	MGA, PPA	PFS 2024
First Saguenay Plant	First Phosphate + Prayon Technologies	QC	MGA, PPA + LFP CAM (nearby site)	N.A.
Hearst Plant	Fox River Resources + JESA Technologies	ON	SPA/MGA	Start in 2027-2029
PPA: Purified Phosphoric Acid (battery-grade, Food, Electronics); SPA: Super Phosphoric Acid (Specialty Fertilizers); MGA: Merchant Grade Acid (Fertilizer, Animal feed, Industrial Acid)				

The only phosphate ore mine in Canada, which was previously operated by Agrium (now Nutrien), in Kapuskasing, Ontario, closed in 2013.[1–3] No phosphate rock has been produced in Canada ever since. Canada has around 0.1% of the world's phosphorus reserves,[4] so the output of prospective mines might be negligible globally. However, five extraction projects are being developed: Lac à Paul (Arianne Phosphate) and Lac à l'Orignal (First Phosphate) in Quebec, Wapiti and Fernie in British Columbia (Canadian Phosphate/Fertoz), and Martison in Ontario (Fox River Resources). Unfortunately, the federal government did not recognize the exploration priority as the Natural Resources Canada *2022 Map of Top 100 exploration projects* did not include phosphate ore deposits at the time.[5]

One phosphoric acid plant commissioned by Arianne Phosphate was previously projected in Belledune, New Brunswick,[6,7] but the project might be relocated to the Saguenay region instead. The port of Saguenay is also where First Phosphate anticipates developing a phosphoric acid plant in partnership with Prayon Technologies. The projected plan would go through a hemi-dihydrate process for MGA production and *via* a membrane filtration purification for PPA.[8] First Phosphate has found agreements with NorFalco (Glencore) for sulfuric acid supply for its PPA plant, and has moved for a vertical integration down to iron phosphate production (LFP pCAM) and even LFP CAM, projected in Saguenay-Lac-St-Jean. Collaboration with GKN Hoeganaes has been announced to license iron powder-making technology to process First Phosphate's magnetite deposits. First Phosphate also signed an MoU with U.S.-based Ultion to purchase an LFP and LFMP CAM production technology license. Fox River Resources partnered with American company JESA Technologies to achieve pilot plant production of MGA using a hemi dihydrate process earlier this year.[9] Phostech Lithium, one of the first companies to commercialize LFP since 2003, owns a cathode factory in Candiac, Quebec. Now acquired by Nano One Materials, the plant focuses on a new one-pot process for LFP cathode synthesis.

1.2 Target

Our previous report, 'Roadmap for Canada's Battery Value Chain,' established the following objectives for lithium iron phosphate battery production: reach 50 GWh per annum of LFP battery production in 2030 and 100 GWh in 2040. Aiming this target and using purified phosphoric acid (PPA, H_3PO_4 at 85 wt.%) as the required precursor for synthesizing LFP cathode active materials, the amount of PPA needed can be calculated.

Table 2 Phosphate Targets

Phosphoric Acid Mandated Benchmark (10% of 2030 North American Market)		
	2030	**2040**
Phosphoric Acid (in kt of battery-grade PPA 85 wt.%)	80	160

1.3 Scenario Outline

As the new demand for phosphoric acid purposed for LFP batteries can only be met by bringing new phosphate projects online, Canada should focus on 3–4 phosphate extraction projects. Start by exploiting igneous deposits for cathodic material before sedimentary ones. Two processing hubs capable of producing Merchant Grade Phosphoric Acid (MGA) and Purified Phosphoric Acid (PPA) should be developed, one in Quebec and one in BC.

1.3.1 Signature Projects

- Develop 3–4 major phosphate mining projects (QC, BC, ON)
- Build phosphoric acid processing hubs, one in the western provinces (BC) and one in Quebec. The igneous feeds from Quebec can be converted to PPA as a priority for pCAM and CAM projects, while sedimentary feeds can be used first in fertilizer.

1.3.2 Strategic Priorities

- **Major Mining Projects and Chemical Processing Hubs:**
    - **Focus on Key Mining Projects:** Prioritize developing 3–4 major phosphate mining projects, mainly focusing on projects in Quebec, such as Arianne Phosphate and First Phosphate. These projects are well-positioned to become leading producers in the region. Additionally, focus on the Canadian Phosphate project in British Columbia and consider the potential for the Fox River project in Ontario. These projects are strategically located to meet growing demand in North America and beyond.
    - **Establish Processing Hubs:** Construct two strategically located processing hubs—one in Quebec and another in British Columbia—designed to convert phosphate ores into phosphoric acid using the wet process. These hubs will play a crucial role in the value chain, ensuring that phosphate ore is efficiently converted into phosphoric acid for various downstream applications.
    - **Phosphoric Acid Production:** Ensure that these phosphoric acid plants have the flexibility to produce both Merchant Grade Acid (MGA) and Purified Phosphoric Acid (PPA) based on market demand and industry needs. This adaptability will allow the hubs to cater to various industries, including fertilizers, animal feed, and battery manufacturing.
    - **Collaborate with Industry Leaders:** Partner with leading companies specializing in PPA production technology, such as Nutrien, Innophos, Prayon, JESA and ICL. These collaborations will leverage existing expertise and technology, ensuring the efficient and high-quality production of phosphoric acid at the hubs.
    - **Optimize Locations:** Carefully select the locations of these hubs to optimize geographic efficiency, potentially co-locating them with significant mining sites. This will reduce transportation costs, minimize environmental impact, and enhance the overall efficiency of the operation.
    - **Integrate Gypsum Management:** Fully integrate the management of gypsum impurities generated during the wet process. This involves finding sustainable uses for gypsum byproducts, such as in construction materials, to reduce waste and create additional revenue streams.
- **Use a Mineralogy-driven Approach:**
    - **Target Battery Applications First for Batteries:** Focus on converting higher-grade igneous phosphate deposits primarily into Purified Phosphoric Acid

    (PPA), which is crucial for battery applications. Only produce Merchant Grade Acid (MGA) from these deposits, if necessary, to maximize the value of the resource.
  - **Utilize Sedimentary Deposits for Fertilizers:** Direct sedimentary phosphate deposits towards the fertilizer and animal feedstock industries by focusing on their conversion into MGA. These deposits can later supplement PPA production as demand for battery-grade materials increases.
  - **Blend Feedstock:** If necessary, consider blending sedimentary and igneous phosphate feedstocks to achieve the desired grades of MGA or PPA. This flexibility will allow for more efficient use of available resources while meeting the specific requirements of different industries.
- **Access to Energy, Chemicals, Infrastructure, and Talent:**
  - **Secure Clean Energy:** Ensure access to clean, reliable, and affordable energy sources to power the processing hubs. This is crucial for maintaining competitive production costs and minimizing the environmental footprint of operations.
  - **Obtain Essential Chemicals:** Secure a stable supply of necessary chemicals and reagents, particularly sulfuric acid, essential for the wet process used in phosphoric acid production. There is also the possibility of collocating or obtaining sulfuric acid from the metallurgy of sulfide ores such as copper, nickel, or iron. Establishing strong supply chains for these inputs will be critical to the success of the processing hubs.
  - **Develop Infrastructure:** Build the midstream hubs around existing infrastructure and transport networks, including road and rail systems. This will facilitate the efficient movement of raw materials and finished products, reducing costs and improving logistics.
  - **Attract Global Talent:** Encourage the recruitment of global talent with expertise in phosphate processing, chemical engineering, and related fields. This will ensure that the hubs are staffed with highly skilled professionals capable of driving innovation and maintaining high standards of operation.
- **Find Synergies Between Industries:**
  - **Utilize Gypsum Byproduct:** Repurpose gypsum byproducts from the wet process as building materials, particularly when processing igneous deposits or when it has low impurities. This reduces waste and creates a valuable secondary product that can be marketed to the construction industry.
  - **Repurpose Hydrofluoric Acid:** Identify uses for hydrofluoric acid byproducts, such as selling them to the graphite processing industry or hydrometallurgical plants. This approach turns a potential waste product into a valuable resource for other industries.
  - **Sell Value-added Byproducts:** Capitalize on the potential for some sedimentary deposits to contain rare earth elements (REE), niobium and vanadium, which can be recovered and sold to their respective industries. The South African company Rainbow Rare Earth has developed a process to recover rare earth from phosphogypsum stacks from phosphoric acid plant operations.

    This adds another layer of value to the phosphate mining and processing operations and could synergize and connect several critical mineral flowsheets.
  - **Secure Sulfuric Acid Supply:** Collaborate with other mining industries, such as nickel sulfide, copper sulfide, or pyrite processing plants, to secure a reliable supply of sulfuric acid. In the East, sulfuric acid could be sourced from these industries, while in the West, it could be obtained as a byproduct from the oil and gas industry.
    - **Generate Power from Sulfuric Acid Production:** The conversion of sulfur to sulfuric acid releases energy, which could generate electricity through turbines for a neighbouring phosphoric acid plant if the sulfuric acid plant and phosphoric acid facilities are collocated. Excess electricity can also be sold to the local grid.
- **Pursue the Recognition of the Importance of Phosphate**
  - **Federal Recognition:** In June 2024, the federal government of Canada recognized phosphorus as a critical mineral. This new status is welcome, as it would make phosphate projects eligible for government incentives and allow them to compete for funding on an equal footing with other critical mineral projects. Pursuing this recognition to add phosphorus to provincial critical minerals lists in British Columbia and other provinces beyond Ontario and Quebec could be the next step.
    - **This Makes Phosphate Projects Eligible for Support From:**
      - The Canada Growth Fund
      - The Business Development Bank of Canada
      - Export Development Canada
      - The Canada Infrastructure Bank
      - Sustainable Development Technology Canada
      - Scientific Research and Experimental Development tax incentives
  - **Unlock Government Support:** The recent federal recognition should also help secure government support for transportation infrastructure and access to mining and processing sites, thereby lowering the capital expenditure (CAPEX) required for these projects.
  - **Raise Awareness:** Advocate for the importance of phosphate, not just for fertilizers but also for its role in the battery industry. This should involve public awareness campaigns and targeted engagement with government and industry decision-makers.
- **Regulatory Framework**
  - **Clarify Mineral Permits**: Work with provincial authorities to clarify mineral permit requirements, particularly in British Columbia, where sedimentary deposits may fall under quarrying or mining regulations. Clear guidelines will help streamline the permitting process.
  - **Streamline Mining Permits:** Push for streamlined mining permit processes, allowing timely approvals and adherence to adequate timelines. This will enable projects to move forward without unnecessary delays, ensuring that operations can commence as planned.

2 Phosphate: An Essential Compound for Life, Fertilizers but also LFP Cathodes

2.1 General Properties

Phosphate PO_4^{3-} is a commonly found ion composed of one central atom of phosphorus and four atoms of oxygen. Combined with its derivatives and conjugate acids, such as **phosphoric acid H_3PO_4**, it is Earth's most abundant form of phosphorus. Being an integral part of DNA and bone structures and responsible for biological energy storage, phosphorus is essential to all life forms, and its intake is crucial to the development of most organisms. Phosphate ions are part of a naturally occurring yet slow phosphorus cycle, migrating from plants, animals, and microscopic organisms to soil and water bodies before gradually depositing as sediments at the bottom of the ocean, giving birth to phosphate rocks after millions of years. Phosphorus is crucial for plant growth and is mainly used for **fertilizer**. However, the overuse and uncontrolled leaching of phosphates into the environment can lead to threatening toxic algae bloom, a concerning phenomenon known as eutrophication. In addition to its end application as a fertilizer, phosphate can be processed into various valuable phosphorus chemicals, such as detergents, flame retardants, pesticides, therapeutics, and ligands.[10]

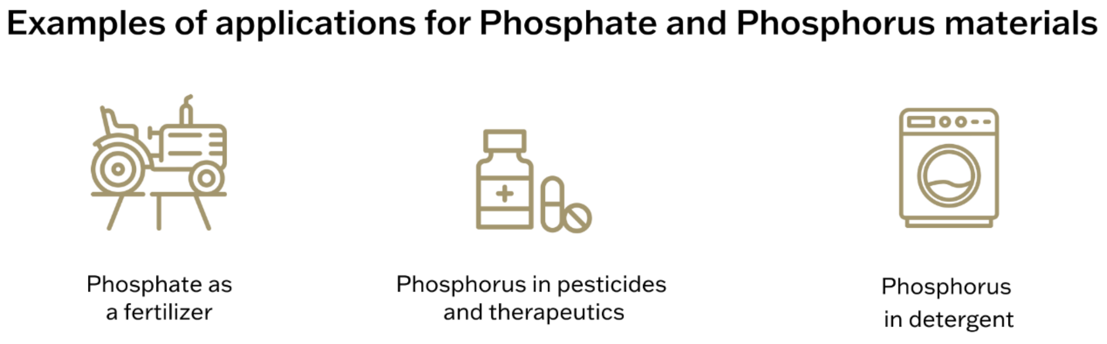


Figure 1 Examples of applications for phosphate and phosphorus materials

2.2 Role in Energy Storage

In general, using polyanionic compounds such as phosphates instead of oxides in the cathode material can reinforce the ionic bonding and, thus, increase the electrochemical potential. **Lithium iron phosphate $LiFePO_4$**, or LFP batteries, has become an attractive cathode chemistry option for lithium-ion batteries compared to other technologies like nickel-cobalt-manganese (NMC) and nickel-cobalt-aluminum (NCA). This olivine structure was discovered by Goodenough and commercialized as early as 2007.[11]

LFP has thus gained increasing appeal due to the high cost of battery metals because it uses inexpensive and abundant iron and phosphorus (90% of mineral cathode content) instead of cobalt and nickel. However, LFP remains exposed to lithium prices. Instead of using lithium hydroxide, the primary lithium intermediate in nickel-rich chemistries, LFP relies mainly on lithium carbonate, although lithium hydroxide can also be used.[12] Additionally to lithium, LFP is also made from iron phosphate, a common food additive.

LFP battery cells were on average 32% cheaper than lithium nickel manganese cobalt oxide (NMC) cells in 2022.[13] Other than the cost of production, LFP has various advantages over other Li-ions technologies: higher safety for battery fire, good stability, a longer and more sustainable life-cycle and the advantage of not depending on socially and environmentally challenging cobalt supplies. Additionally, LFP does not require the same humidity control level during manufacturing processes as other cathode materials do.[14]

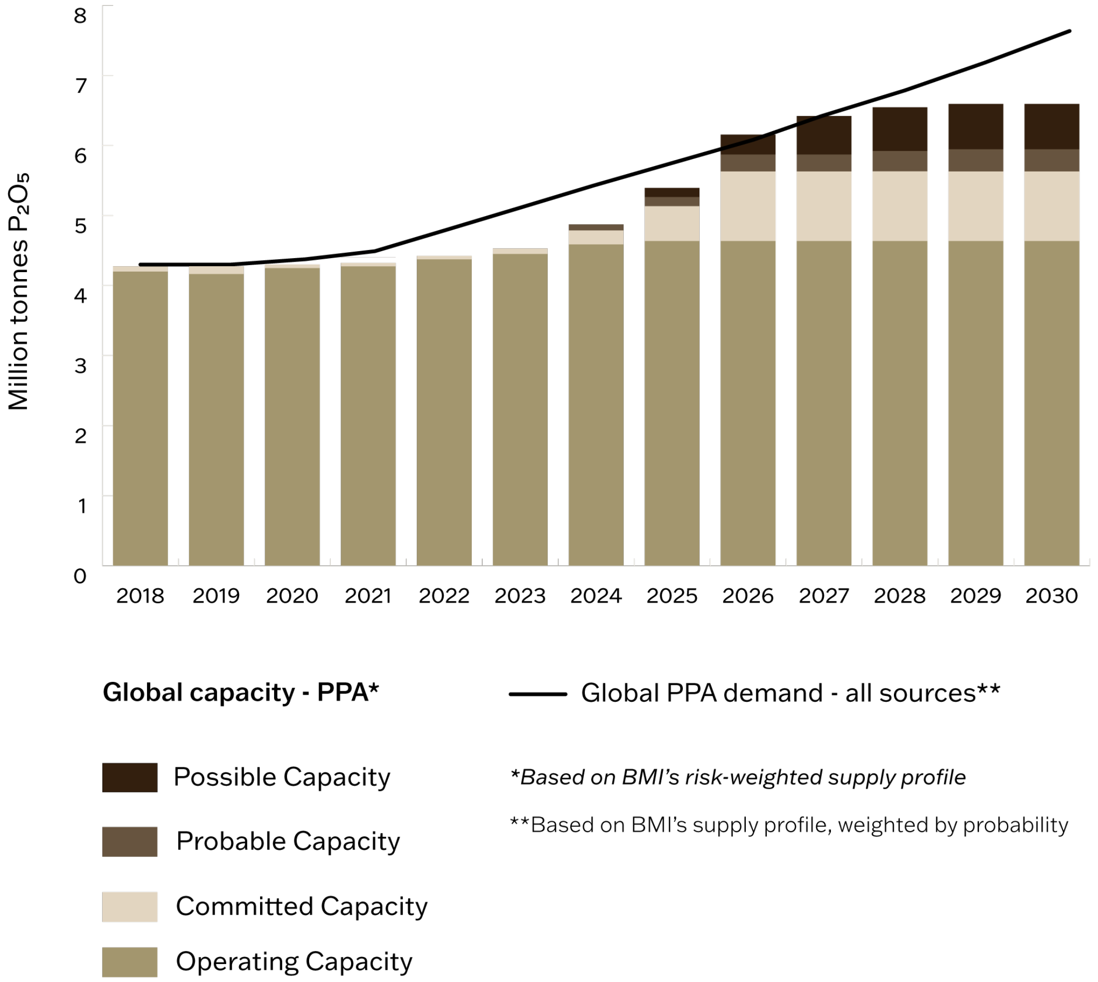
However, the LFP technology also presents important drawbacks, such as lower conductivity, energy density, and decreased efficiency at lower temperatures. However, most of those issues have been overcome due to increased research and engineering optimization (such as in coating, doping or particle size). LFP recycling is also less economically attractive than NMC recycling as only lithium recovery would be viable, unlike NMC which would have nickel, cobalt and lithium. Lithium manganese iron phosphate cathodes, or LMFP, is a next-generation iteration improvement of LFP technologies using additional manganese and could increase battery energy density while keeping a lower cost compared to high-nickel chemistries. Combined with the patent expiry in 2022, LFPs are now an attractive alternative to other Li-ion batteries. On top of usage for EV batteries and mobility, the excellent cycling capabilities of LFP make this technology particularly attractive for energy storage systems. Finally, unlike NMC cells which can follow several designs, LFP cells are usually prismatic.

Another common use for phosphorus in energy storage is in electrolytes for lithium-ion batteries. **Lithium hexafluorophosphate $LiPF_6$** is thus a common electrolyte salt, with the cation Li+ used as the charge carrier and PF_6- as a bulky counter anion. Although ubiquitous in li-ion systems, $LiPF_6$ can degrade at high temperatures and release toxic HF acid in the presence of water.[15]

2.3 Substitutes

With potassium and nitrogen, phosphorus is a limiting factor for plant development, so there is no substitute for its use as a fertilizer. For battery chemistry purposes, phosphate can be bypassed by selecting cathodes different from LFP or LMFP. NMC, NCA or newer generation batteries such as lithium-sulfur or sodium-ion technologies do not use phosphorus.

2.4 Supply and Demand



**Based on BMI's risk-weighted supply profile*

**Based on BMI's supply profile, weighted by probability

Figure 2 Purified phosphoric acid production and demand projection from Benchmark Minerals' 2023 Market Outlook[16,17]

Before the rise of LFP, the global demand for phosphate grew at a 2% yearly rate, but the Li-ion boom is drastically increasing the demand for purified phosphoric acid. Indeed, the EV sector only represented 5% of the purified phosphoric acid demand last year, but this share is likely to increase to 24% by 2030.[18] In 2023, LFP accounted for 66% of battery output in China.[19] In 2024, the American battery industry market share in GWh for LFP is still lower than 8%.[20] Although no U.S. cars were powered by LFP in 2020, BloombergNEF projected last year that the demand for LFP-powered vehicles is expected to exceed 160 GWh by the end of the decade, representing 40% of the total demand for electric vehicles in the U.S.[21] Key players in the electric vehicle industries, such as Ford, Rivian, Mercedes-Benz, and Volkswagen, have unveiled plans to use LFP in North America, and General Motors is also interested. Additionally, Tesla released its plan in October 2021 to switch to LFP batteries for all its standard-range cars.[22,23] Tesla has since confirmed that half of its vehicles produced in Q1 2022 were using LFP.[24] As such, the global LFP market is expected to grow from $10B USD in 2021 to $50B by 2028.[25]

Benchmark Minerals Intelligence reported earlier this year that a global supply gap of 0.8 Mt of purified phosphoric acid (PPA) is expected by 2030 due to growing demand and underinvestment in this value chain.[26,27]

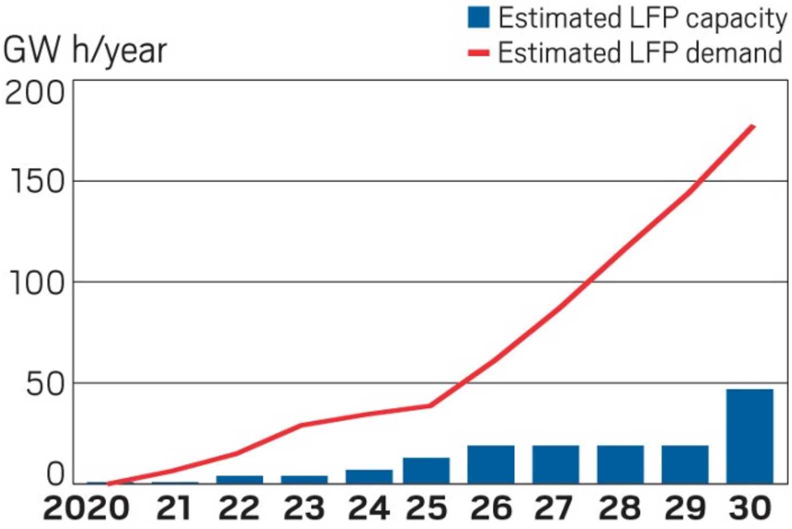


Figure 3 U.S. demand for lithium iron phosphate (LFP) batteries in passenger electric vehicles is expected to continue outstripping local production capacity. (Source: BloombergNEF)[28]

3 The Phosphate Flowsheet: From Rocks to Phosphoric Acid

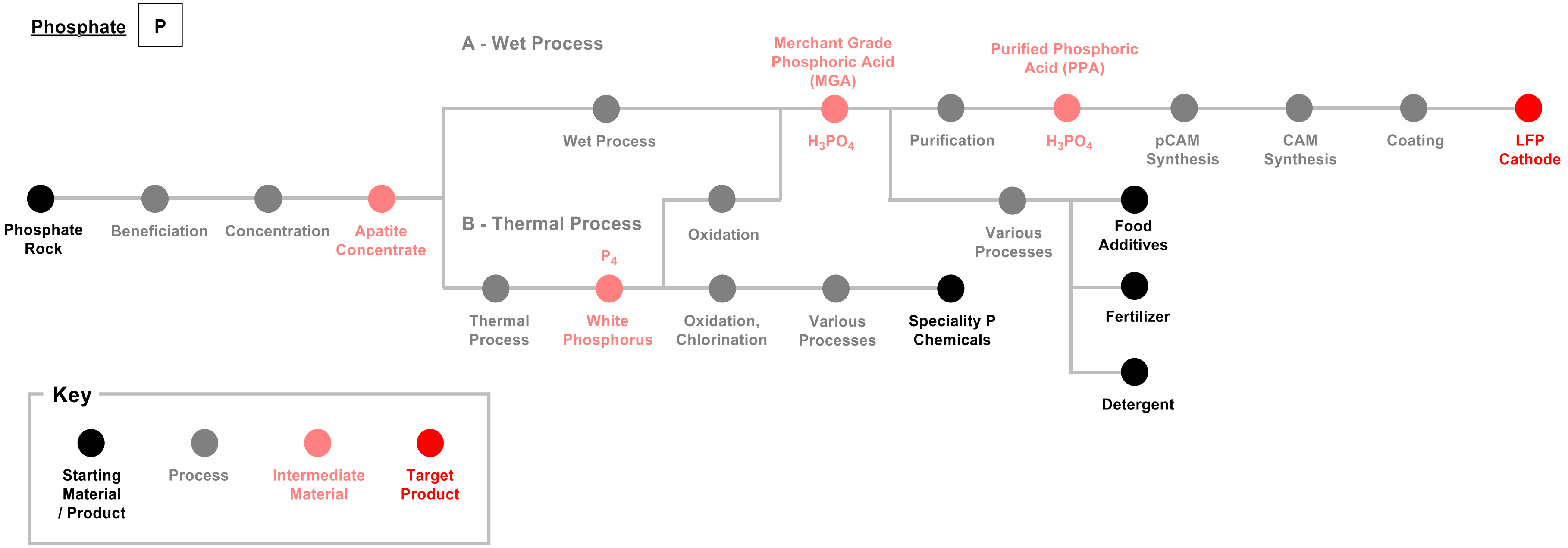


Figure 4 Simplified flowsheet of phosphate and phosphorus products

3.1 Ores & Reserves

Phosphorus is not a rare element on the surface of the Earth. It is thought to make up between 1,000 to 1,300 ppm by mass of the Earth's continental crust, and as such, it is more abundant than chlorine, sulfur, or even carbon.[29–32] It is Earth's crust's 11th most abundant element. However, most exploitable phosphorus sources reside in sedimentary phosphate rocks, typically **fluorapatite $Ca_5(PO_4)_3F$** or **hydroxyapatite $Ca_5(PO_4)_3OH$**. The availability of those phosphate rocks is finite, and various estimates of the longevity of the world's reserve vary between complete depletion within the next 70 to 400 years.[33] The continuously changing assessment of this controversial issue can be explained by relying on limited but ever-changing new information and considering the future economic and technological dynamics of exploitation and evaluation.[34] The exact magnitude of the scarcity of phosphorus is still far from settled. However, a concept known as peak phosphorus, the point in time when the maximum production rate of phosphorus will be reached, has emerged as an analogy to the concept of peak oil.[35] However, It is reasonably accepted that there is no imminent shortage of phosphate resources.[36]

86% of the commercial reserves of phosphate rocks are split between only six countries, and 67% of the reserves lie solely within Morocco/Western Sahara. At the same time, China, Egypt, Tunisia, Russia and Algeria hold smaller but relevant deposits. Russia is also the only supplier of high-purity phosphate rocks. An extensive deposit in Norway made the news in the summer of 2023 as it could potentially store as much phosphate as the currently proven global reserves.[37] Canada held an estimated **76×10^6 tonnes of phosphate rock in 2016**,[4] approximately 0.1% of the global phosphate reserves at the time; the U.S. Geological Survey did not update this data since no ore was mined. Providing that this number did not change drastically, and compared to the current reserve estimates, this would rank **Canada as the 18th country with the largest phosphate rock reserves**.

Table 3 Estimated mining production of marketable phosphate rocks in 2022 by country in thousands of tonnes

Country	**Production of P-rocks in 2022**[a] (tonnes x 10^3)	**Country**	**Production of P-rocks in 2022**[a] (tonnes x 10^3)
Mexico	442	Australia	2,500
Other Countries	750	Senegal	2,600
Turkey	900	Tunisia	3,560
Uzbekistan	900	Peru	4,200
Finland	923	Egypt	5,000
Syria	1,100	Brazil	6,200
Kazakhstan	1,500	Saudi Arabia	9,000
Togo	1,500	Jordan	11,300
India	1,740	Russia	14,000
Algeria	1,800	United States	19,800
South Africa	1,990	Morroco	39,000
Vietnam	2,000	China	93,000
Israel	2,170	**World Total (rounded)**	**228,000**

[a] Data in thousands of tonnes of marketable phosphate rock, from the 2024 U.S. Geological Survey.[36]

Table 4 Estimated reserves of marketable phosphate rocks in 2024 by country in thousands of tonnes

Country	**Reserves of P-rocks in 2024**[a] (tonnes x 10^3)	**Country**	**Reserves of P-rocks in 2024**[a] (tonnes x 10^3)
Mexico	30,000	Finland	1,000,000
Togo	30,000	Jordan	1,000,000
Vietnam	30,000	Australia	1,100,000
India	31,000	Saudi Arabia	1,400,000
Senegal	50,000	South Africa	1,500,000
Israel	60,000	Brazil	1,600,000
Turkey	71,000	Algeria	2,200,000
Canada[b]	**76,000**[b]	Russia	2,400,000
Uzbekistan	100,000	Tunisia	2,500,000
Peru	210,000	Egypt	2,800,000
Syria	250,000	China	3,800,000
Kazakhstan	260,000	Morroco	50,000,000
Other Countries	800,000	**World Total (rounded)**	**74,000,000**
United States	1,000,000		

[a] Data in thousands of tonnes of marketable phosphate rock, from the 2024 U.S. Geological Survey.[36]
[b] Data from the 2016 U.S. Geological Survey.

In 2022, the global extraction capacity of phosphate rocks reached 228 x 10^6 tons, with significant players in phosphate mining such as China (41% of 2022 global production), Morocco (17%), the U.S. (9%), Russia (6%) and Jordan (5%).[36]

Even though most global phosphorus resources are sedimentary ores, under 10% of global phosphate is **igneous,** meaning it originates from phosphate dissolved in magmatic rocks and not directly from sedimentary ores. Significant igneous occurrences are found in Brazil, Canada, Finland, Russia, and South Africa. Although igneous phosphate rocks have a lower P_2O_5 content than sedimentary ones on average (8.1 wt.% *vs.* 21.3 wt.%), the concentrated ores obtained after beneficiation, also called **marketable phosphate** concentrates, are of higher grades for igneous rock sources (36.9% wt. % *vs.* 29.6 wt.% for sedimentary).[38] igneous phosphate also bears the advantage of less potential contamination of radioactive heavy metals (cadmium, thorium, uranium, *etc.*), more efficient processing, and a higher phosphorus content after concentration.[7] This is why igneous phosphate ores could be prioritized as feedstock for cathode production.

3.2 Processing

The effect of such concentrate grades means that, contrarily to other minerals and metals, it is not very economically viable to transport marketable phosphate concentrates to process them elsewhere; this is why most conversion from concentrates to phosphoric acid is conducted domestically.[18] In 2022, almost two-thirds of the global capacity for phosphate rock refining into purified phosphoric acid (PPA) was in China, representing a market share of 42%. Moreover, the Chinese share of PPA supply is expected to increase to 73% of the total capacity by 2030.[27] In 2023, only 3% of the global supply of phosphate products with the proper grade was actually usable for cathode active materials.

3.3 Beneficiation

The typical process of phosphate mining involves extracting a mixture of phosphate rock, clay, and sand matrix from the ground by a dragline. The phosphate is separated from the sand and clay through beneficiation to obtain the concentrated phosphate product. The beneficiation steps require screening, washing, and flotation: the phosphate rock ores are first crushed before having high-pressure water guns create a slurry. Calcium phosphate compounds are easily separated from the sand impurities through froth flotation and using fatty acids.[39,40] The obtained concentrates, or marketable phosphate rocks, can be sent to produce **wet-process phosphoric acid** (WPA) or smelted through the thermal process to obtain **elemental white phosphorus** P_4. Those phosphate concentrates have P_2O_5 contents of at least 28%, but most marketable rocks have content above 30%.

3.3.1 The Wet process: Direct to Phosphoric Acid

It has been estimated that over 90% of the phosphate rock exploited is converted to phosphoric acid according to the 'wet process' (**Figure 5**). The method consists of the digestion of fluorapatite minerals by concentrated sulfuric acid. **Calcium sulfate,** also called **gypsum** or **phosphogypsum,** which is yielded as a by-product (about 4–6 tonnes produced per tonne of phosphoric acid), is later precipitated and filtered out, and the wet phosphoric acid obtained is purified and concentrated.[41] The process usually starts with the milling and sizing of phosphate concentrate feed before adding sulfuric acid to the processed concentrate inside a reactor at atmospheric pressure at 70–80°C.[42]

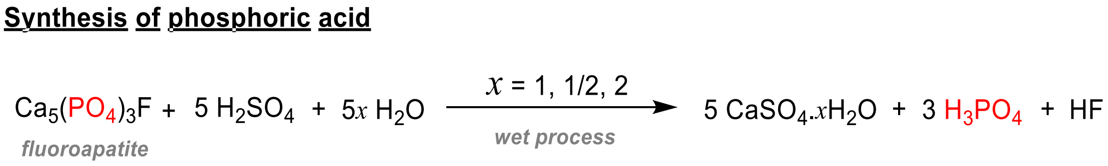


Figure 5 Conversion of phosphate rock to orthophosphoric acid through the wet process

The gypsum formed during the reaction is consistently separated through a filter from the phosphoric acid produced. This calcium sulfate filter cake is then washed several times to optimize phosphoric acid recovery. The filtered weak acid usually has a 42–54% P_2O_5 content, which is still too low for specific applications such as battery cathode. Still, after concentration reaches around 54% P_2O_5 content, the acid can be commercialized as **merchant grade acid** (MGA), which is eligible for fertilizers and animal feed products.

Both the temperature of the wet process and the P_2O_5 concentration in the reactor affect the type of gypsum hydrate produced: dihydrate $CaSO_4 \cdot 2H_2O$ is formed at lower temperatures, while hemihydrate $CaSO_4 \cdot ½H_2O$ is made at 80–90°C. Depending on the hydrate byproduct obtained, the corrosion, precipitation, filtration, and, ultimately, the purity of the phosphoric acid can differ. That's why wet-process plant designs vary according to the hydrate byproduct, either going through dihydrate, hemihydrate, or both.[42]

Depending on the plant location, byproduct content and regulations, the gypsum produced is either pumped to the sea or local river, stockpiled, or used in the gypsum industry. Phosphogypsum can notably be used as an additive to Portland cement, road pavements, soil conditioners, or artificial reefs. However, depending on the phosphate rock source, the gypsum produced can be slightly radioactive due to the presence of uranium, thorium, radium, radon and polonium. As such, discarding or stockpiling those dangerous phosphogypsum slags can pose a double environmental threat, with weak radioactivity from the toxic heavy metal contaminants and a high potential for toxic algae bloom eutrophication due to remaining phosphate. Igneous phosphate sources have the advantage of producing gypsum with fewer contaminants and are suitable for their sales and use in the construction, cement and agriculture industries.[43,44]

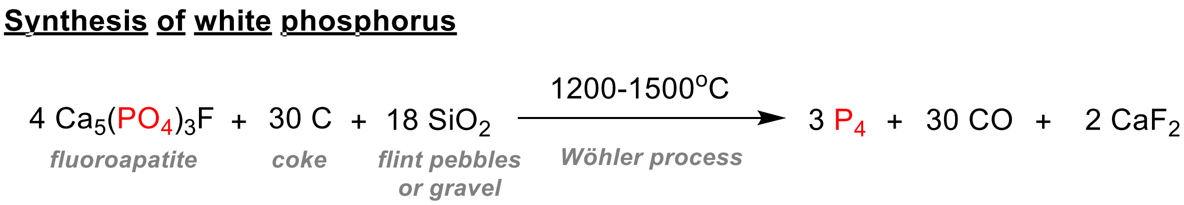
The fluorine-containing byproducts, labelled HF or **hydrogen fluoride** gas in the reaction scheme above, can be recovered by passing the gas through a water scrubber to produce **hydrofluoric acid**. Fluorine can also be retrieved as silica tetrafluoride SiF_4 using clay or activated silica. After conversion, **fluorosilicic acid** H_2SiF_6 or sodium fluorosilicate can be sold as a byproduct. Fluorosilicic acid has numerous applications, such as wood preservatives, rust removers, and concrete additives. However, it is mainly used to produce AlF_3 or cryolite, necessary additives for aluminum production.

As MGA grade is unsuitable for many applications, further phosphoric purification is necessary to obtain **purified phosphoric acid,** or PPA (62% P_2O_5 content and above), and even more for battery-grade PPA. Several technologies can be used for purification, such as solvent extraction, neutralization and precipitation, or crystallization. Precipitation was previously widespread for synthesizing sodium triphosphate, a standard detergent, but it has mostly been supplanted by solvent extraction, which is more flexible and efficient. This method preferentially extracts phosphoric acid *via* a mixture of organic solvents while cationic impurities are separated. Anionic impurities are separated through precipitation and evaporation to remove sulfate, fluoride and heavy metals. After extraction, the purified acid is recovered from the organic phase using countercurrent water or aqueous alkali stream. The depleted phosphoric acid solution, or raffinate, is obtained as a byproduct and can be sold to manufacture triple superphosphate fertilizer. Using additional sulfuric acid during extraction or to treat the raffinate can improve recovery effectiveness. Alternatively, or on top of the solvent extraction method, the crystallization purification process yields very high-purity phosphoric acid, suitable for battery and electronic markets. It uses PPA as a feedstock, which is cooled down to 8–12°C to slowly crystallize as hemihydrate compounds before being filtered, washed and melted.[42] Finally, novel methods such as nanofiltration using specialty membranes are emerging.

It is estimated that the wet process accounts for more than half of the global sulfur supply, taking the form of sulfuric acid, thus showing how tightly the phosphorus and sulfur industries are interdependent.[45] The quantity of sulfuric acid used during the wet process can vary according to the content of the phosphate rock concentrates: a concentrate containing more alkaline rocks, such as calcium oxide CaO, will need more acid to be treated.[8] The colocation of a sulfuric acid production plant near a phosphoric acid processing facility can also be beneficial: the exothermic conversion of sulfur to sulfuric acid could generate energy for both sites.[44] Generally, most phosphoric acid produced is used for the fertilizer industry. The remaining part of phosphate rocks can be converted to molecular phosphorus P_4 through the thermal process for subsequent reactions.

3.3.2 The Thermal Process: An Energy-Intensive Route

Historically, phosphoric acid was also synthesized by oxidizing the white phosphorus obtained to afford phosphorus pentoxide, the anhydride version of phosphoric acid. However, because the reaction is strongly endothermic, this thermal process requires electric furnaces, which are highly energy intensive. These issues caused the development of the wet process, which circumvented the need to go through a white phosphorus intermediate to obtain phosphoric acid. Nevertheless, this **thermal process** (the Wöhler process) remains the most efficient pathway to produce pure molecular phosphorus. An electric furnace heating around 1450°C is fed the three raw materials: Phosphate rocks that are either sintered or pelletized, dried metallurgical coke for the carbon source, and silica deposits such as pebbles, gravel, or coarse sand (**Figure 6**).[46]



Synthesis of white phosphorus

$$4\,Ca_5(PO_4)_3F + 30\,C + 18\,SiO_2 \xrightarrow{1200\text{-}1500^{o}C} 3\,P_4 + 30\,CO + 2\,CaF_2$$

Figure 6 Conversion of phosphate rocks to white phosphorus through the Wöhler process

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The P-gas produced are then condensed and washed with water. The white phosphorus afforded is then stored underwater to prevent it from self-ignition. Even though the wet process mostly supplanted the thermal pathway, around 83% of the P_4 obtained is still converted to phosphoric acid through combustion.[46] This phosphoric acid is purer than obtained through the wet process and can be used accordingly for more sensitive applications. Only about 12% of the white P_4 produced is converted into fine chemicals and heavy phosphorus compounds, including PCl_3, PCl_5, and P_4S_{10}, with the remaining being used for all other industrial phosphorus species.[47] Most P_4 produced in the U.S. in 2022 was primarily used to synthesize glyphosate herbicide.[36,48] PCl_5 is notably used for producing $LiPF_6$ **electrolyte salt**, and the Canadian company Targray is a world leader in its synthesis.

3.3.3 Synthesis of LFP Cathode

Several methods for producing LFP,[49] include freeze-drying, hydrothermal, microwave heating, polyol process, supercritical water, co-precipitation, solid-state reaction, calcination, solvothermal, sol-gel, rheological, and combustion. The most used methods remain the hydrothermal process (**Figure 7**),[50,51] and the solid-state (**Figure 8**). The majority of LFP factories in China use the latter. This process starts with the reaction of iron sulfate $FeSO_4$ and phosphoric acid to produce iron(III) phosphate $FePO_4$. The iron phosphate powder is mixed with lithium carbonate and a carbon source to form the conductive coating. The mixture is then heated to temperatures of 700-800 °C to form the olivine structure that allows it to function as a cathode.[21] One-pot processes, such as the method used by Nano One, are also emerging. More details on the different processes can be found in reviews from the literature.[50,52]

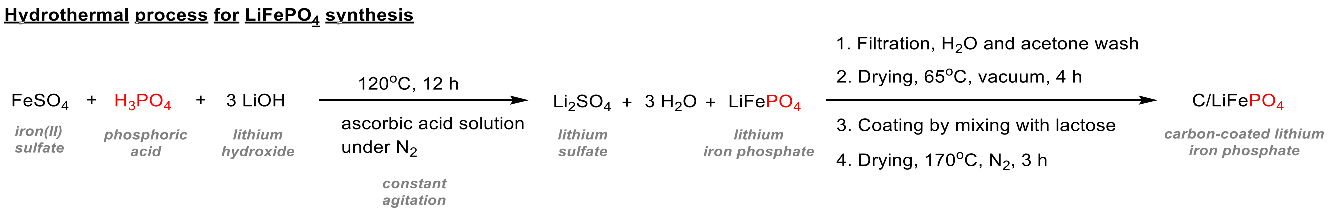

Figure 7 Example of LiFePO₄ synthesis through a hydrothermal process

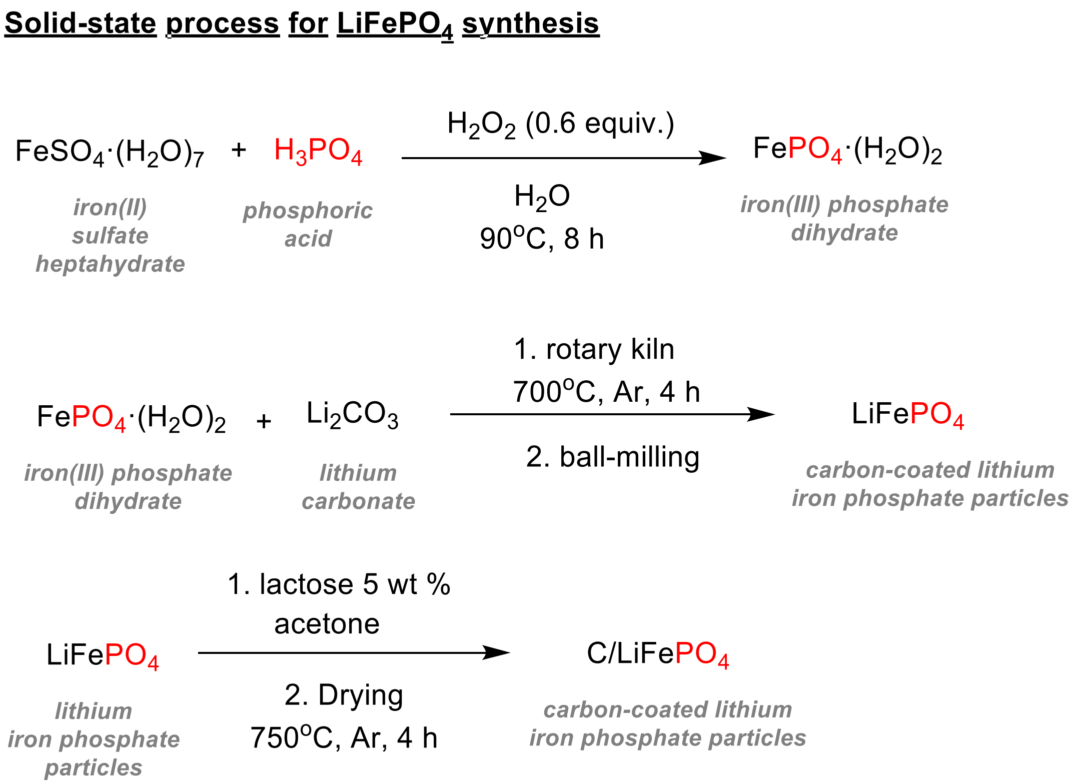

Figure 8 Example of LiFePO₄ synthesis through a solid-state methodology

The solid-state reaction is most adapted for manufacturing as it is inexpensive and creates an ordered crystal structure. However, it requires high temperatures and long sintering times and does not necessarily yield the best results. In comparison, the hydrothermal process creates a more complex and ideal carbon coating, allowing for better conductivity and performance. The main drawback of this solution-based methodology is its difficulty scaling on a production site.

Phostech Lithium was one of the first companies to commercialize LFP, receiving the first license to manufacture LFP commercially in 2003. After that, the company graduated to more massive LFP factories, culminating in a 2,400 t per year plant near Montreal in 2012.

However, progress was slow due to cautious investors, and the company struggled financially until the German chemical company Süd-Chemie bought a majority stake in 2005. Süd-Chemie financed pilot facilities and the Montréal plant, but the company's hydrothermal process was more expensive than Phostech's solid-state method. Clariant acquired Süd-Chemie in 2012 and promptly sold the LFP business to Johnson Matthey. Now acquired by Nano One Materials, the Montreal factory is the only facility in North America that can produce meaningful quantities of LFP.

Today, there is growing interest in producing LFP cathode materials outside China. In October 2022, the Israeli chemical maker ICL Group announced plans to build a 30,000 t per year LFP cathode powder factory in Missouri with a $200 million US Department of Energy grant. The Norwegian start-up Freyr Battery and Utah-based American Battery Factory also plan to make LFP cathode material in the US for their battery factories in Georgia and Arizona, respectively. In addition, China's Gotion High-Tech hopes to establish LFP cathode material production in Michigan.

One potential difference between ICL's Missouri plant and Chinese factories is the starting materials. ICL is evaluating using iron oxide rather than iron sulfate, which can be difficult to procure outside China. Iron oxide is more expensive, but the process produces higher-quality LFP. ICL plans to use technology from Aleees, a Taiwanese LFP maker with nearly two decades of experience, to produce high-quality LFP.

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