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## Opportunities and challenges for the expansion of LFP battery supply chains

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Global markets for energy storage are growing rapidly, with some applications transitioning from traditional  $\text{LiNi}_x\text{Mn}_y\text{Co}_{1-x-y}\text{O}_2$  (NMC) toward  $\text{LiFePO}_4$  (LFP) due to cost, safety, and performance advantages. Battery growth has seeded interest in critical material supplies such as high-purity lithium precursors. In contrast, challenges in securing high-purity iron and phosphorus, historically not considered critical materials, are often overlooked. Precursors must remain inexpensive to maintain LFP's current cost advantage, which leverages the low-cost (~\$100 per t)  $\text{FeSO}_4$  byproduct from titanium dioxide manufacturing and will not be available as LFP manufacturing expands. As an alternative, iron is mined primarily for steel manufacturing, for which the existing supply chain and beneficiation process is optimized. LFP batteries require small iron volumes compared to steel (0.11%), but profit margins associated with existing low-cost iron ores and high costs (~\$27 000 per t) associated with low volume high-purity iron oxides may limit interest in manufacturing small volumes of high-purity, specialized iron battery precursors. The complementary LFP precursor, phosphoric acid ( $\text{H}_3\text{PO}_4$ ), is primarily utilized in fertilizers. Of the current phosphate ore demand for fertilizers, 4–22.8% would be required to meet projected 2045 LFP  $\text{H}_3\text{PO}_4$  demand, suggesting significant supply chain planning is needed to achieve projected demand. If only higher-grade material is considered, demand jumps to 15–77% of current world production. While lithium precursor purity requirements have been evaluated ( $\text{Li}_2\text{CO}_3$  is commonly defined as  $\geq 99.5\%$ ), “battery grade” iron and phosphorus precursors remain poorly defined, with no internationally accessible and widely adopted standard, further challenging expanding industry by creating manufacturing uncertainty and increasing potential costs.

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### Broader context

The growth of energy technologies has highlighted the need to understand and prepare supply chains for increased demand. In the case of Lithium Iron Phosphate (LFP), markets are expected to grow rapidly over the next two decades. As a critical material, lithium is well-studied, while the form and requirements for the low-cost iron and phosphorous precursors have received limited attention. This work fills this gap, identifying overlooked challenges with sourcing, purification, and qualification of non – “critical” precursors that could inhibit growth of LFP – particularly as the typical iron precursor ( $\text{FeSO}_4$ ) supply chain becomes contested and as scale-up in demand for phosphorous begins to compete with use in fertilizer. These findings indicate that further testing to identify alternative potential precursors and impurities of concern will play a key role in enabling the scale up of LFP technologies to projected scales and ultimately suggests that the “non-critical” materials can be just as inhibitory as critical materials when it comes to energy technology growth.

## Introduction: the LFP advantage

Batteries play an important role across global economies, enabling electrified transportation, reducing industrial sector costs, providing data-center backup power, stabilizing electrical grid fluctuations, and powering portable electronics.

Electric vehicle (EV) deployment is projected to increase significantly by 2030 representing the largest battery demand sector, with a total projected battery pack value of \$500 billion in 2030.<sup>1</sup>  $\text{LiNi}_x\text{Mn}_y\text{Co}_{1-x-y}\text{O}_2$  (NMC) or  $\text{LiNi}_x\text{Co}_y\text{Al}_{1-x-y}\text{O}_2$  (NCA) battery chemistries include cobalt, a critical material that frequently experiences cost and supply chain volatility due to geo-political resource concentration and human rights concerns.<sup>2</sup> NMC and NCA batteries also include nickel, which similarly experiences historical supply instabilities and price fluctuations.<sup>3</sup> In contrast, the absence of nickel and cobalt in

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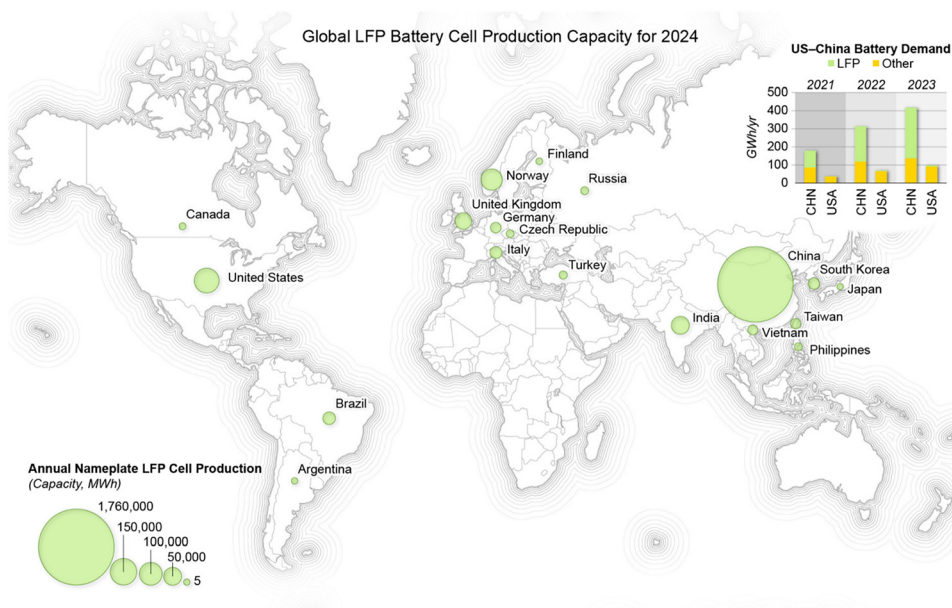


Fig. 1 Map displays cell production capacity by country in MWh according to Bloomberg New Energy Finance,<sup>7</sup> with the inset highlighting where those cells are being utilized, depicting annual LFP and other battery demand rates in GWh per year for China and the USA from the International Energy Agency.<sup>8</sup>

LiFePO<sub>4</sub> (LFP) cathodes theoretically enables a simpler, less volatile, and less expensive supply chain. While NMC's higher energy density was historically favored over LFP for EV batteries, renewed LFP interest is driven by superior safety, cost, cycle life, and recent pack design advances that improve system energy density competitiveness.<sup>4</sup> Fig. 1 shows increased global interest in LFP production and a surge in LFP demand (inset).<sup>5,6</sup> As LFP manufacturing expands, precursor supply chains must also grow to provide sufficient purity and adequate volume to meet demand in the coming decades. While iron and phosphorus are not commonly considered critical minerals and naively would not be expected to limit growth, this work demonstrates anticipated LFP expansion could impact existing supply chains, particularly when considering high-purity precursor requirements. Here LFP production is reviewed, specifically focusing on current and potential precursors, supply chain impacts based on future projections are explored, and suggestions are provided for industry to successfully meet future growth scenarios.

## Industrial LFP production

State-of-the-art LFP is manufactured in two steps, as shown in Fig. 2. First, iron sulfate (FeSO<sub>4</sub>) reacts with phosphoric acid (H<sub>3</sub>PO<sub>4</sub>) in solution to create iron phosphate (FePO<sub>4</sub>). Second, FeSO<sub>4</sub> is calcined in an inert atmosphere with lithium carbonate (Li<sub>2</sub>CO<sub>3</sub>) and a reducing agent (*e.g.*, glucose) to form carbon-coated LiFePO<sub>4</sub>.<sup>6,9</sup> H<sub>3</sub>PO<sub>4</sub> is utilized as an inexpensive, plentiful phosphorus precursor amenable to solution processing.<sup>6,10</sup> FeSO<sub>4</sub> is used as an iron precursor because of

its current plentiful and inexpensive supply as a titanium dioxide (TiO<sub>2</sub>) manufacturing byproduct – and its high solubility in H<sub>3</sub>PO<sub>4</sub> solutions.<sup>5,6,11</sup> Li<sub>2</sub>CO<sub>3</sub> is used in state-of-the-art LFP synthesis rather than LiOH, which has historically been more expensive and is commonly required for other battery chemistries.<sup>10</sup> Cumulatively, this produces a high performing, economically competitive battery.

As worldwide LFP demand expands, environmental and availability concerns related to the state-of-the-art method may limit growth. For example, FePO<sub>4</sub> is precipitated by raising the pH with NaOH or NH<sub>3</sub>,<sup>9</sup> which generates sulfate waste. NaOH use generates two tons of Na<sub>2</sub>SO<sub>4</sub> per ton of LFP.<sup>15</sup> While relatively nontoxic, Na<sub>2</sub>SO<sub>4</sub> waste handling and disposal can be expensive at these volumes. The NH<sub>3</sub> alternative produces (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> waste, which is restricted in many countries. Also, two factors threaten the FeSO<sub>4</sub> supply expansion needed to meet future LFP iron needs. The first is competition from its use in other applications, such as water treatment. Second, industry is moving away from manufacturing TiO<sub>2</sub> from ilmenite (FeTiO<sub>3</sub>) *via* the sulfate process (which produces FeSO<sub>4</sub> as a byproduct) for several reasons: high waste cost, low yield, environmental concerns, and most importantly that the chloride process produces a higher quality, higher yield product at lower cost.<sup>16</sup> Due to reduced FeSO<sub>4</sub> availability and waste concerns, alternative iron precursors must be considered for LFP battery growth scenarios.

Projected LFP manufacturing growth will generate demand for lithium, iron, and phosphorus. LFP synthesis routes which leverage alternative or local iron and phosphorus supplies have been demonstrated, as summarized in Fig. 2, including solid state and solution processes.<sup>14</sup> Understanding the land-



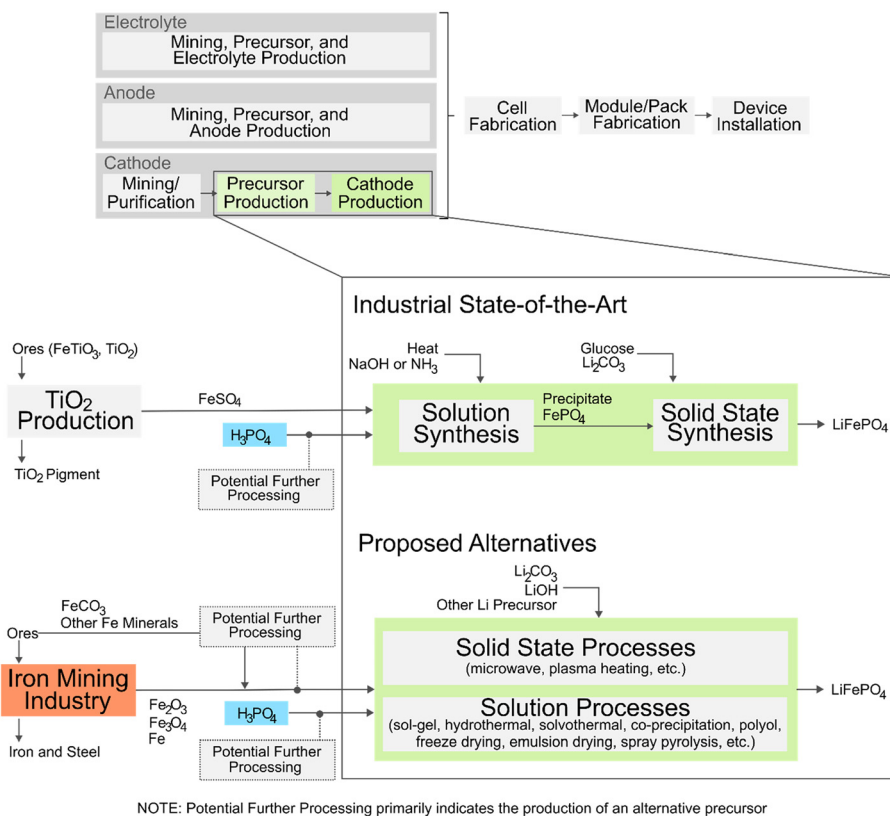


Fig. 2 LFP battery production overview comparing state-of-the-art and various alternative LFP synthesis methods.<sup>11–14</sup>

scope for sourcing and purification of precursor for both state-of-the-art and novel processes, including assessing purity requirements for synthesizing alternative precursors, is critical to identify gaps for expanding LFP manufacturing. Ensuring these materials are available at sufficient purity through diverse, distributed, and targeted supply chains is key to enabling global LFP expansion.

## Lithium: a well-studied supply chain dedicated to batteries

Globally, more than 240 kt (thousand metric tonnes, lithium content) of lithium was produced in 2024, 87% for batteries.<sup>17</sup> Lithium precursors target  $\geq 99.5\%$  purity to be considered “battery-grade”.<sup>18</sup> Permissible impurity levels are dictated by purification cost and impact to battery performance. For example, magnesium and calcium are common impurities in lithium precursors, but a minor magnesium impurity content can improve battery performance; by reducing magnesium-removal purification steps, costs may be reduced by almost 20%.<sup>19</sup>

This highlights the value of producing precursors tuned for battery applications and understanding the impacts of relevant impurities on battery performance to optimize purification techniques for cost and environmental impact. Due to the disparity between lithium, which is mined specifically for bat-

teries, and the other essential LFP elements iron and phosphorus, which are primarily mined for other major commodities, battery supply chains for iron and phosphorus require more analysis, development, and purity optimization to ensure sufficient quantities and grades are attainable and economical. Historically the lithium supply chain, due to its classification as a critical mineral, has been extensively analyzed.<sup>20,21</sup> This work focuses on supply chain considerations for iron and phosphorus and will leave lithium supply chain discussion to existing literature.

## The other LFP precursors: commodity manufacturing adaptations for battery needs

### Iron precursor origins

LFP demand is currently met using FeSO<sub>4</sub> produced as an inexpensive TiO<sub>2</sub> manufacturing byproduct.<sup>5,6</sup> Up to ~6 Mt (million metric tonnes) of FeSO<sub>4</sub> is generated annually *via* the sulfate process (12 Mt total global capacity).<sup>16</sup> The TiO<sub>2</sub> industry is moving away from the sulfate manufacturing process, so FeSO<sub>4</sub> availability will decline because its 20–30× lower value than TiO<sub>2</sub> will not likely drive production.<sup>16</sup> Further, FeSO<sub>4</sub> demand from other industries may compete with LFP requirements, including use in water treatment (which is 30% of



current market), fertilizer, animal feed, pharmaceuticals, iron fortification of foods, and pigments.<sup>22–24</sup>

While  $\text{FeSO}_4$  can be produced independently from  $\text{TiO}_2$  processing, production may be too costly to keep LFP prices low<sup>10</sup> and associated  $\text{FeSO}_4$  capture could present technical and production volume barriers.<sup>25</sup> These challenges have spurred interest in the use of alternative precursors. Understanding substitute precursor availability, including purity requirements that enable competitive performance with state-of-the-art LFP, is critical for expanding LFP manufacturing.

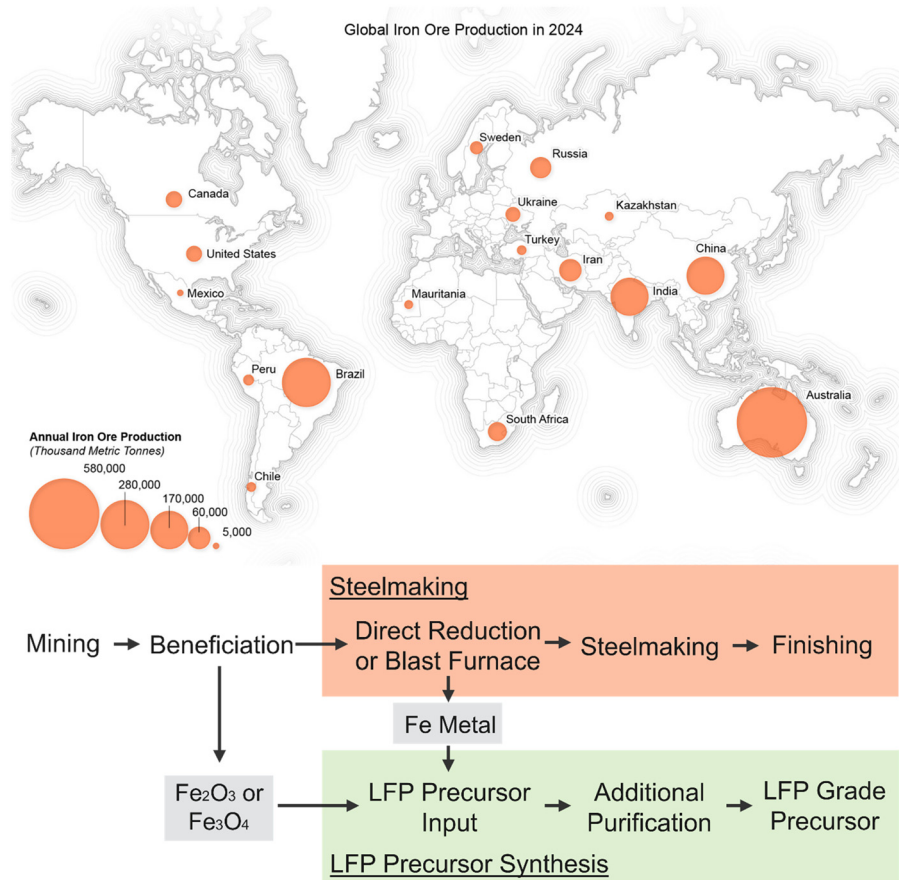
Fig. 3 shows that 98% of iron ore mined globally is historically utilized in steel production.<sup>26</sup> Iron ores are mined in many countries worldwide at scale (2500 Mt mined globally in 2023).<sup>27</sup>

The most common iron ore minerals are hematite ( $\text{Fe}_2\text{O}_3$ ) and magnetite ( $\text{Fe}_3\text{O}_4$ ), which are mined and beneficiated to produce concentrates.<sup>28,29</sup> High-grade hematite ores only require crushing and screening, whereas fine-grained magnetite ores, require additional grinding and magnetic separation. Further beneficiation is often achieved by froth flotation and/or gravity separation before the iron ore is pelletized and oxidized to  $\text{Fe}_2\text{O}_3$ . Iron precursors could be manufactured from other sources such as  $\text{FeCO}_3$  ore, lathe waste, or from mine waste, tailings, or byproducts.<sup>30,31</sup>

Iron ore pellets typically are mixed with alloying elements such as carbon or binding agents like bentonite before manufacturing into steel.<sup>29</sup> These species represent undesirable impurities for battery applications, potentially limiting the use of downstream iron-for-steel products as battery precursors. The economy of scale of iron mining is a challenge for the battery industry because the current supply chain is focused on a low-cost, high-volume product optimized for steelmaking. Interest in producing small-volume, high-purity iron battery precursors depends on profit margins, but prices for substitute precursors may be significantly constrained by the current low-cost ( $\sim \$100$  per t) of  $\text{FeSO}_4$ .

Ultimately, small fractions of  $\text{Fe}_3\text{O}_4$  or  $\text{Fe}_2\text{O}_3$  concentrates may need to be diverted to parallel processing plants for LFP precursor production before pelletization, as shown in the Fig. 3 steelmaking flow chart.<sup>29</sup> Impurity removal is tuned for steelmaking rather than battery purity requirements, both in cost and elements of concern. Battery-grade purity is poorly defined for alternative iron precursors, indicating a need to better understand the elements of concern for LFP performance optimization.

Other ultra/high-purity iron industries including pigments and dietary supplements may be suitable to leverage or expand into battery precursor production.<sup>32,33</sup> For example, pigment



**Fig. 3** Map of annual iron ore production volumes by country in thousand metric tons of iron content accompanied by a typical iron and steel process flow chart as it may integrate with battery-grade LFP precursor production.



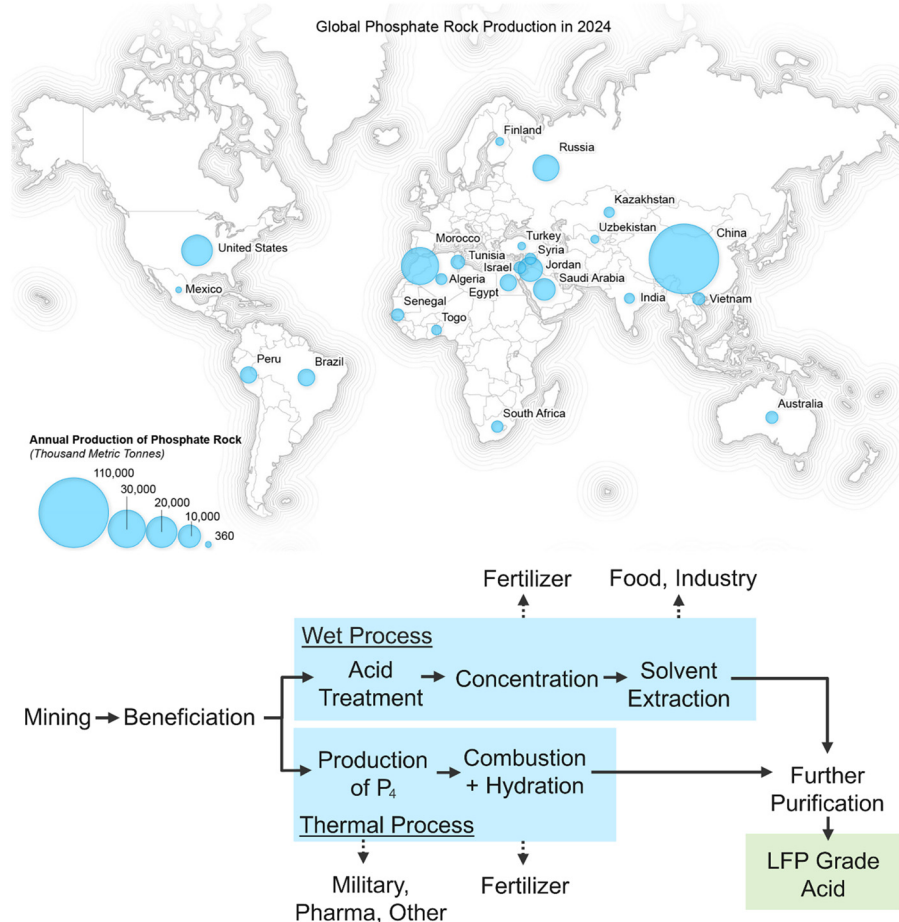
producers have announced interest in producing LFP iron precursors.<sup>34</sup> High-purity iron oxides (~\$27 000 per t) often undergo roasting, leaching, precipitation, and calcination steps after ore extraction and beneficiation;<sup>35,36</sup> however, the relevant processing steps to achieve cost, volume, purity, and scale requirements to expand these industries at low cost for use as battery precursors remain unclear and require more analysis.

Alternative iron precursors include metallic Fe, Fe<sub>2</sub>O<sub>3</sub>, and Fe<sub>3</sub>O<sub>4</sub>, which all can be produced directly from iron ore.<sup>5</sup> However, replacing FeSO<sub>4</sub> in state-of-the-art synthesis with limited solubility Fe or Fe oxides often requires significant H<sub>3</sub>PO<sub>4</sub> and/or high energy mixing, filtering, and long dissolution times, affecting the overall economic feasibility and environmental footprint of LFP production.<sup>37–39</sup> H<sub>3</sub>PO<sub>4</sub> could be substituted with alternatives; however, alternative precursors are typically synthesized from H<sub>3</sub>PO<sub>4</sub>, so their processing could introduce additional cost, safety, health, and environmental challenges.<sup>40</sup> Because H<sub>3</sub>PO<sub>4</sub> itself is globally mass produced for fertilizers and animal feed supplementation – with smaller volumes of higher quality H<sub>3</sub>PO<sub>4</sub> produced for food, beverage, or electronic industries – there is less drive to replace this precursor.<sup>41</sup>

### Phosphorus precursor origins

Phosphorus-bearing ore is distributed globally and primarily mined to produce H<sub>3</sub>PO<sub>4</sub> for fertilizers.<sup>42</sup> Phosphate rock production rates are pictured in Fig. 4.<sup>41</sup> While China is the largest phosphate rock producer, Morocco holds the majority of world reserves; minable material is distributed globally. Phosphate rock can occur in sedimentary or igneous forms, which are typically associated with lower purity and higher abundance or higher purity and lower abundance, respectively.<sup>43–45</sup> New igneous mining operations in Canada target battery-grade H<sub>3</sub>PO<sub>4</sub> as a primary product.<sup>17</sup>

Two different primary processes, thermal and wet, are used to convert phosphate-bearing ore to H<sub>3</sub>PO<sub>4</sub> (Fig. 4). The thermal process involves a reaction between ore, silica, and coke in an electric furnace to produce P<sub>4</sub>, which is combusted in air to form P<sub>2</sub>O<sub>5</sub> vapor and hydrated into H<sub>3</sub>PO<sub>4</sub>. The wet process treats rock with acid (typically sulfuric) to form phosphogypsum (Ca<sub>2</sub>SO<sub>4</sub>) and impure, dilute H<sub>3</sub>PO<sub>4</sub>, which can be concentrated and/or purified.<sup>43</sup> The more common wet process primarily produces fertilizer-grade H<sub>3</sub>PO<sub>4</sub> (82.5% of market) at low cost.<sup>42</sup> The thermal process is more tolerant to



**Fig. 4** Map of annual phosphate rock production volumes by country in thousand metric tons of iron content accompanied by a typical H<sub>3</sub>PO<sub>4</sub> production process flow chart as it may integrate with battery-grade LFP precursor production.



impurities in lower quality ores and produces an industrial-grade product, historically utilized for high-purity applications;<sup>43</sup> however, acid produced by the wet process can be processed by solvent extraction, crystallization, and membrane separation to meet requirements for high-purity applications.<sup>43,46</sup> The prominence of one production method over another can be highly dependent on regional regulations related to environment and permitting. Some sources claim high-grade igneous ores must be utilized for the wet process to achieve acceptable purities and volumes.<sup>44</sup> While the thermal process faces the risk of environmental impacts associated with coke and natural gas use, the wet process produces large volumes of phosphogypsum waste (5 tonnes per tonne of  $P_2O_5$ ), which may contain radioactive byproducts originating from phosphate minerals, leading to limited material reuse (~15%) in other applications.<sup>43,47</sup> Similar challenges exist from  $P_4$  production waste, but these concerns are poorly described in the literature due to the reduced thermal process prevalence.<sup>48</sup>

Every ton of  $P_2O_5$  in wet-processed  $H_3PO_4$  requires 2.79 tons of  $H_2SO_4$ , presenting an additional supply chain concern.<sup>43</sup> Up to 80% of global sulfuric acid supply is obtained as elemental sulfur *via* petroleum and natural gas de-sulfurization, implemented in many countries to combat acid rain.<sup>49</sup> When petroleum and natural gas de-sulfurization became prevalent, traditional mining operations declined. Even without considering  $H_3PO_4$  for batteries, the reduction in  $H_2SO_4$  generation from declining fossil fuel consumption could threaten  $H_3PO_4$  production. Re-establishing sulfur supplies independent of fossil fuels may become key for maintaining adequate supplies.<sup>49</sup>

Beyond supply and waste constraints,  $H_3PO_4$  products lack defined purity standards. When comparing commercial  $H_3PO_4$  datasheets, “battery-grade”  $H_3PO_4$  had lower iron and fluorine contents compared to technical and food grade  $H_3PO_4$ ; however, most impurities on battery-grade datasheets are not specified in the other acid grades, preventing identification of which elements are removed as purity increases, as seen in Table S5. Specific impurities may be associated with ore type (sedimentary *vs.* igneous) and production method (wet *vs.* thermal), suggesting additional research and analysis is required to understand conditions that optimize  $H_3PO_4$  cost and purity for battery applications. The ore type, production method, and purity requirements are all critical to understand, because, as discussed in the next section, these details have profound impact on  $H_3PO_4$  demand scenarios for LFP batteries.

## New demand for global supplies

In 2045, annual EV demand is projected to reach 6.2 TWh, with LFP expected to provide 37% of EV storage or 2.3 TWh.<sup>50,51</sup> 4.7 Mt of LFP would be required to meet 2045 projected demand. The corresponding lithium, iron, and phosphorus precursor requirements are listed in Table 1, compared to 2025 demand values.<sup>52</sup>

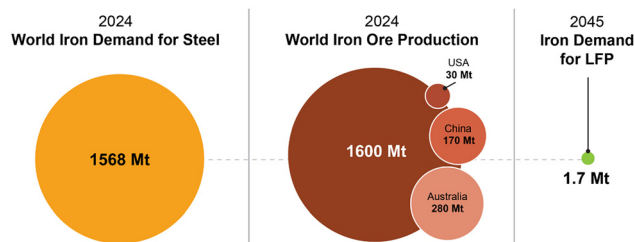
**Table 1** 2045 precursor requirements – each precursor source shows 2025 worldwide production numbers and 2045 project usage for LFP production assuming all production uses stoichiometric precursor ratios with 100% yield

Precursor		Material demand (Mt)	
		2025	2045 projection
Lithium	LiOH·H <sub>2</sub> O	0.26	1.25
	Li <sub>2</sub> CO <sub>3</sub>	0.23	1.10
Iron	FeSO <sub>4</sub>	0.94	4.54
	Fe <sub>2</sub> O <sub>3</sub>	0.49	2.39
	Fe <sub>3</sub> O <sub>4</sub>	0.48	2.31
	Metallic Fe	0.34	1.67
Phosphorus	H <sub>3</sub> PO <sub>4</sub>	0.61	2.93

These numbers represent minimum requirements to meet projected demand, assuming 100% precursor to LFP synthesis yield. Calculation details and additional calculations with varied assumptions are discussed in SI sections 1–4.

Projected LFP growth would require only 0.11% of current iron produced globally for steel, as visualized in Fig. 5; as a result, diverting iron ore for LFP manufacturing is unlikely to impact steel supply chains.<sup>17</sup> Interest in developing low-volume, high-purity iron precursors for LFP likely hinges on profit margins, which are constrained by existing low-cost LFP precursor supply and manufacturing, presenting unique challenges for material procurement. Specialized beneficiation and purification processes or alternative sourcing may prove cost effective for generating battery-grade iron precursors, depending on regional availability, like China's efficient reuse of FeSO<sub>4</sub> from TiO<sub>2</sub> waste in LFP synthesis. Specialty markets like ultrapure 4N+ iron could be disrupted if leveraged by the LFP industry, as production is currently limited to 1100 metric tons per year – 1500 times lower than projected 2045 metallic Fe demand for LFP.<sup>53</sup>

Projected 2045  $H_3PO_4$  demand for LFP requires 4–22% of the current annual world mine production of phosphate rock for fertilizer, depending on ore type and production method (thermal or wet, respectively). When compared to present higher purity  $H_3PO_4$  production, including food and technical grade acids, this range increases to 15–77%.<sup>54</sup> The higher end of this range relates to producing high-purity  $H_3PO_4$  from low-grade ore by the wet process and is largely due to inefficient



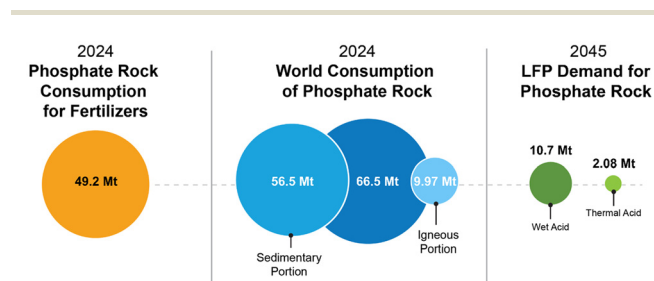
**Fig. 5** Material demand comparison for battery-grade iron precursor production compared to existing orebodies and current world production rates.



conversion; the impact of poor conversion is reduced if phosphorus intermediates could be efficiently recycled back into lower grade  $\text{H}_3\text{PO}_4$  products.<sup>55</sup> Some sources indicate only high-grade resources are suitable for battery-grade  $\text{H}_3\text{PO}_4$  with the wet process because they offer more efficient ore conversion.<sup>44</sup> High-grade resources, such as igneous anorthosite phosphate rock, are only 1% of known phosphate reserves and represent only a small fraction of igneous ore production shown in Fig. 6. Global LFP supply chain expansion may be constrained if efficient wet process conversion depends on a specific ore with limited availability. Lack of global high- and ultrahigh-purity  $\text{H}_3\text{PO}_4$  production data obscures analysis of further purification pathways, hindering supply chain planning for the expansion of LFP manufacturing.

While primary iron and phosphorus resources are plentiful and geographically diverse, battery-grade precursor quality remains poorly defined. There are no international, widely available standards for “battery-grade” precursors from regulating bodies like exist for other industries (*e.g.*, semiconductors); despite this, “battery-grade”  $\text{Li}_2\text{CO}_3$  is commonly defined as  $\geq 99.5\%$ .<sup>18</sup> In contrast, “battery-grade” iron and phosphorus precursors differ significantly in advertised purity. This further exemplifies the difference in securing supply chains for lithium, which is mined primarily for batteries, and the other LFP precursors which must adapt from supply chains focused on alternative primary commodities. Recycling, which could be one strategy for increasing available supplies, faces economic viability challenges for LFP and will not be able to meet exponential material demand from this sector during growth phases. Design-for-recycling concepts could be implemented now to facilitate recycling in the future.

While precursor impurities and their impacts on LFP battery performance are poorly defined, this investigation highlights the need for future work to understand impurity impacts on LFP from a variety of precursor ore sources. The precursor purity requirements coupled with projected demand means there are far-reaching consequences on the entirety of the supply chain, making the aforementioned tasks critical for facilitating diverse and secure battery supply chains on a global scale.



**Fig. 6** Comparison of current consumption of phosphate rock, in total as well as by ore type, to current demand for fertilizers and potential demand for battery-grade  $\text{H}_3\text{PO}_4$  production *via* different production methods, with independent values for production of acid *via* the wet process or the thermal process.

## Impacts and conclusions

LFP battery manufacturing growth over the past few years has been driven by its promise of high performance at low cost.

Much of LFP's success is linked to the use of cheap materials, such as the byproduct  $\text{FeSO}_4$ . To leverage the current process, new  $\text{FeSO}_4$  supply chains would have to be established, which would increase manufacturing deployment time and potentially increase precursor costs. Thus, expansion may require different precursors to maintain LFP's cost advantage. The most critical factors that must be considered for neoteric supply chains are material availability (volume), material purity, and cost. Identifying risks to supply chain security not only hinges on the availability of “critical” materials, but also the potential scarcity of the correct purity of “non-critical” materials.

For iron, the obvious low-cost alternative would leverage the iron and steel supply chain, targeting metallic iron,  $\text{Fe}_2\text{O}_3$ , and/or  $\text{Fe}_3\text{O}_4$ . Volumetrically, iron supply chains are some of the world's largest, such that iron sourcing for LFP would not be hindered by ore supply; instead, the small LFP market size and cost constraints imposed by current LFP processes may limit meaningful profits and interest for industrial producers. Similarly, scaling the current high-purity market 1500 $\times$ , while requiring a low price point, could prove prohibitive.

In contrast, LFP demand in 2045 may require 4–22% of total current  $\text{H}_3\text{PO}_4$  production, which is dominated by low-purity fertilizer applications. This  $\text{H}_3\text{PO}_4$  demand for LFP rises to 15–77% of high-purity, industrial-grade markets. These estimates are intended to be conservative such that demand increases with varied assumptions.

$\text{H}_3\text{PO}_4$  demand for LFP could be more than double the value discussed throughout this work. The 2.93 Mt of  $\text{H}_3\text{PO}_4$  demand listed in Table 1 could rise to as much as 6.55 Mt when including industrial factory inefficiencies, projected growth of stationary storage, and phosphorus demand of  $\text{LiPF}_6$  electrolyte (further detail on additional scenarios in SI sections 2–4). Other factors could lower demand, such as improved high-purity  $\text{H}_3\text{PO}_4$  production efficiency and sending inefficiently converted material back into acid processing. Without greater understanding of the battery-grade  $\text{H}_3\text{PO}_4$  purity needs, supply chains may struggle to meet LFP demand cost effectively.

Beyond raw material availability concerns for battery manufacturing, battery precursor purity requirements remain underdefined in the open literature. Unlike the semiconductor industry, the battery industry has not yet internationally and publicly defined “battery-grade” quality, particularly for iron and phosphate precursors. Current precursors undergo rigorous evaluation by LFP manufacturers for impurities of concern; however, this information is often proprietary. In turn, lack of public, international purity standards further obfuscates potential synergies between alternative, local supply chains and the rapidly growing



battery industry. This leads to uncertainty about how existing, low-cost material streams could be leveraged for the LFP industry.

The iron supply chain in particular requires these standards because optimizing the processing step where material is diverted from current production pathways is key to reducing subsequent purification costs. Purity standard opacity also hinders H<sub>3</sub>PO<sub>4</sub> supply chain growth. Even though H<sub>3</sub>PO<sub>4</sub> will likely remain an important precursor, each production method results in a different impurity profile and differing cost to achieve battery-grade purity, thus ultimately impacting availability for the LFP industry.

Impurity characterization in sources and impurity tolerance studies to understand the impurity impacts could inform public, international standards for battery-grade precursors, following precedents set by other industries. This could take the form of extensive performance testing with varied impurities to help define these cost-performance tradeoffs and minimize purification costs by selectively targeting problematic impurities. Evolution in purity standard reporting – distinguishing both “purity level” and type of impurity in a precursor – could expedite manufacturing growth and innovation in the LFP industry. Compared to lithium, iron and phosphorus are less consistently designated critical materials; however, securing their supply chains to produce high-purity precursors that expand LFP battery manufacturing is non-trivial. Impurity research will play a key role in increasing supply chain security and decreased costs for LFP manufacturing expansion.

In summary, while the economics of precursor production remain unclear, perhaps the highest priority is to identify an alternative Fe precursor amenable to LFP cathode production followed by identifying which impurities must be removed to enable it to qualify as “battery-grade”. The next highest priority is to understand the industrial implications of scaling “battery grade” phosphorus sources. These priorities are followed by a series of additional concerns such as regional concentration of processing capacity and environmental burdens. This all comes under an overarching need to set standards defining “battery-grade”.

## Author contributions

Conceptualization: K. H., S. R., H. W.; methodology: H. W., S. R., K. H.; validation: R. B., T. M., C. S., R. T. B; investigation: H. W., K. R., K. H., S. R., M. R.; writing – original draft: H. W.; writing – review and editing: K. R., A. B., E. D., R. B., T. M., H. W., K. H., S. R., R. B., M. R.; visualization: H. W.; supervision: S. R., K. H., H. W.; project administration: K. H.; funding acquisition: A. B., E. D.

## Conflicts of interest

There are no conflicts to declare.

## Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: <https://doi.org/10.1039/d6eb00078a>.

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