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# Phosphate Rock Resources & Reserves

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INTERNATIONAL FERTILIZER ASSOCIATION

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**Front Cover Photo Credit** – Rotem Mine, Israel (ICL Group) by Shahar Corem.

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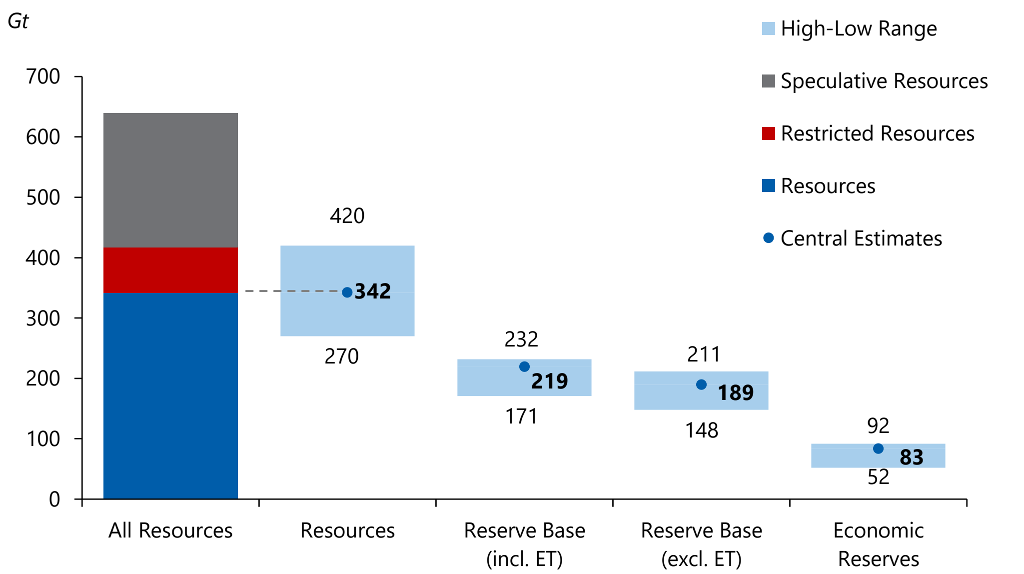
# Executive Summary

1. **Global phosphate rock resources assessed at over 300 billion tonnes**

This study estimates global phosphate rock in-situ **resources** of 342Gt (270 - 420Gt) containing 65Gt $P_2O_5$ (45 - 88Gt $P_2O_5$). We make note of restricted resources, located in areas deemed to be ecologically sensitive where mining could not take place, as well as speculative resources which account for the percentage of land area explored in those countries known to be underlain by significant phosphate deposits.

Figure 1: Current estimates of resource, reserve base and economic reserves for 2021




*ET = Emerging Technologies*
*Resources and Reserve Base shown as in-situ*
*Economic Reserves shown as run-of-mine (ROM)*

*— Argus Consulting*

Of these resources, we estimate a **reserve base** of 189Gt (148 - 211Gt) containing 36Gt $P_2O_5$ (26 - 48Gt $P_2O_5$), representing the in-situ ore volumes that are technically recoverable using current technology. Including emerging technologies, this increases the reserve base to 219Gt (171 - 232Gt), containing 39Gt $P_2O_5$ (27 - 48Gt $P_2O_5$).

**Economic reserves** are estimated at 83Gt (52 - 92Gt) run-of-mine containing 21Gt $P_2O_5$ (12 - 24Gt $P_2O_5$) and represent the portion of the resources which are both technically and economically viable at the present day and has been calculated as the sum of reported reserves by current producers, junior mining projects, geological surveys or national statistical agencies. However this metric is less useful in determining long-term supply of phosphate rock.

Where necessary legacy estimates for resources, reserve base and economic reserves have been adjusted to a 2021 base year to account for active mining. Each of these categories are inclusive of each subsequent category, for example the reserve base assessment includes the economic reserves.

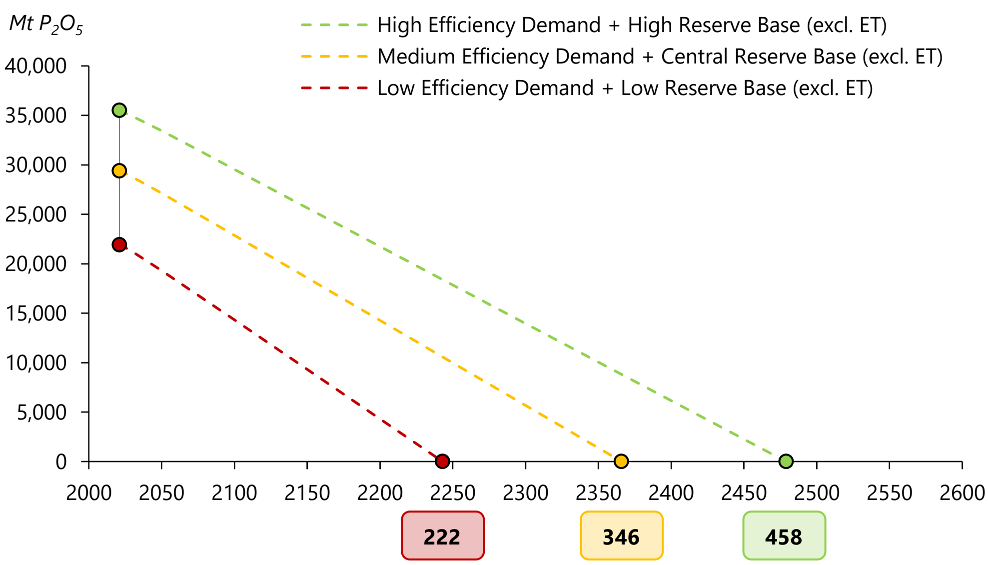
## 2. Technically recoverable phosphate expected to last more than 300 years

This study uses the concept of reserve base, which in this context refers to deposits which are technically recoverable and able to be processed into marketable or useable concentrate using current technology, but not at current prices – reflecting a better metric for long-term availability of material, given that as economic reserves become depleted, prices would incentivise production of these subeconomic deposits. Crucially, this assumes current technology and processing methods, with no speculation regarding technological advances – innovation would have the potential to increase the lifetime considerably.

These reserve base estimates have been converted into marketable or useable phosphate rock concentrate in $P_2O_5$ terms and compared to IFA's existing long-term demand projection scenarios for application to cropland to 2050. These projections have been adjusted for other fertilizer applications, industrial uses and processing losses, and the core scenarios assume a plateau in demand beyond 2050.

The central scenario uses our central estimate for reserve base compared with IFA's medium efficiency demand projection and implies a lifespan of 346 years. The low scenario uses our low estimate for reserve base compared with IFA's low efficiency (therefore higher demand) projection and implies over 200 years of phosphate availability. The high scenario uses our high estimate for reserve base compared with IFA's high efficiency (therefore lower demand) projection and implies over 400 years of phosphate availability.

Figure 2: Depletion of the reserve base (technically recoverable using current technology)




*ET = Emerging Technologies*

*— Argus Consulting, IFA*

3. **Geologic depletion should not be the only consideration**

These conclusions show that on a global level, there are sufficient accumulations of mineable and processable phosphate rock for centuries to come. However, this should not be seen as justification to discontinue sustainability trends such as improving agricultural efficiency or the recycling of nutrients to supplement mineral fertilizer usage.

In order to increase the lifespan of existing reserves and resources, and ensure long-term supply, it remains imperative to:

- Further reduce phosphate rock, acid and fertilizer processing losses
*Improvement in mining, beneficiation, phosphoric acid production and downstream processing*
- Continue to develop and increase the use of alternative sources of phosphate
*e.g. wastewater treatment, digestate from anaerobic digesters, other "waste" streams*
- Improve phosphorus use efficiency (PUE = P Outputs / P Inputs)
*Efficient use of nutrients will result in both reduced aquatic ecosystem pollution via runoff and increased lifespan of phosphate deposits*

# Terminology

| Term | Definition |
|---|---|
| Beneficiation | The ore processing stage to improve the quality of the final concentrate. |
| Concentrate | The final useable/saleable product from the beneficiation plant, converted using concentrate grade and percentage $P_2O_5$ recovery, or ore-to-product ratios.<br>*e.g.*<br>1. Beneficiation feed contains 100t ore of 20pc $P_2O_5$<br>2. Unit has 75pc $P_2O_5$ recovery (100t × 20pc $P_2O_5$ × 75pc)<br>3. Recovers 15t $P_2O_5$, equivalent to 50t of concentrate at 30pc $P_2O_5$<br>4. Can also be expressed at ore-to-product ratio of 2.0 (100t / 50t) |
| CPFIA | China Phosphate and Compound Fertilizers Industry Association |
| DAP | Diammonium phosphate (typical nutrient analysis of 18-46-0) |
| Digestate | Nutrient-rich product left over from the anaerobic digestion of organic feedstocks to produce biogas or biomethane. |
| EECA | Eastern Europe and Central Asia |
| Emerging Technologies *or* ET | Processes which can accept rock with lower $P_2O_5$ content and much higher impurities than traditional technologies. *e.g.* HCl-process or IHP |
| Geopotential *or* Geocapacity | Deposits which are currently undiscovered – the resources and reserves of the future. |
| Gt | Gigatonne = Billion metric tonnes ($1x10^9$) |
| HCl-Process | Hydrochloric acid (HCl) based process - whereby low-grade phosphate rock, hydrochloric acid and a calcium-source (e.g. calcium carbonate) are reacted to produce dicalcium phosphate (DCP), which may be further processed into phosphoric acid. *e.g. Prayon Ecophos technology* |
| IFDC | International Fertilizer Development Centre |
| Igneous | Rocks formed from the cooling and solidification of molten magma or lava. |
| In-situ | Mineralisation estimated to be within the ground or "in place"<br>*i.e. Total amount of ore without a mining recovery factor applied* |
| IHP | Improved Hard Process - whereby low-grade phosphate rock, petroleum coke and silica sand may be mixed and heated to produce phosphoric acid.<br>*e.g. Novaphos Phosphoric Acid Process, formerly JDC Phosphate IHP* |
| IPCC | Intergovernmental Panel on Climate Change |
| $K_2O$ | Potassium oxide, industry standard measurement for potash<br>(1t K = 1.2t $K_2O$; 1t $K_2O$ = 0.83t K) |
| LFP | Lithium iron phosphate batteries |
| Macronutrient | Plant nutrient required in the largest quantities |

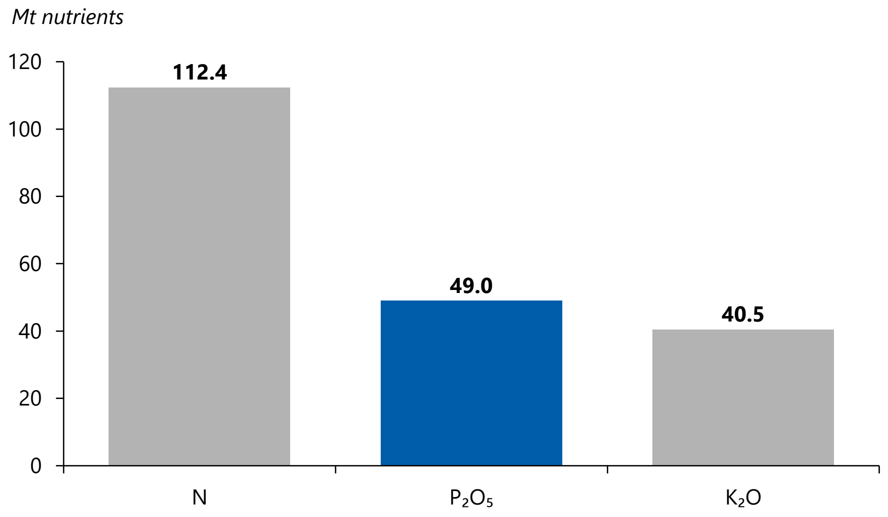
| Term | Definition |
|---|---|
| MAP | Monoammonium phosphate (typical nutrient analysis of 11-52-0) |
| Mt | Million metric tonnes ($1x10^6$) |
| NPK | Multinutrient fertilizer containing nitrogen, phosphate, and potash. |
| NUE | Nutrient Use Efficiency (NUE = Nutrient Output / Nutrient Inputs) |
| $P_2O_5$ | Phosphorus pentoxide, industry standard unit of measurement for phosphate (1t P = 2.29t $P_2O_5$; 1t $P_2O_5$ = 0.44t P) |
| pc | Percent (%) |
| PUE | Phosphorus Use Efficiency (PUE = P Output / P Inputs) |
| Reserve Base | That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices. |
| Reserves | That part of the reserve base which could be economically extracted or produced at the time of determination. |
| Resources | A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible. |
| Run-of-mine *or* ROM | Ore removed from the ground, but prior to beneficiation *i.e. Total in-situ mineralisation with a mining recovery factor applied* |
| Sedimentary | Formed by layered accumulation of minerals on the Earth's surface (incl. ocean floors). |
| TFI | The Fertilizer Institute |
| Traditional Technologies *or* TT | *e.g.* Wet Acid Process |
| TSP | Triple superphosphate (typical nutrient analysis of 0-46-0) |
| USBM | United States Bureau of Mines |
| USGS | United States Geological Survey |
| Wet Acid Process | Process where phosphate rock is reacted with sulphuric acid to produce phosphoric acid, the main intermediate chemical to produce phosphate fertilizers. |

# Section 1: Introduction to Phosphate Rock

## Chapter 1.1: Phosphorus – A Key Macronutrient

Phosphorus (P) is one of the three main macronutrients in plant nutrition, alongside nitrogen (N) and potassium (K). Global consumption of phosphorus in agriculture stood at 49Mt $P_2O_5$ in the latest available IFA assessment[1].

Figure 1-1: Global consumption of N, $P_2O_5$ and $K_2O$ in 2020




— *IFASTAT Consumption Database*

Phosphorus is a vital component in photosynthesis and plant growth; deficiency will delay plant maturity and reduce crop yields. Therefore, phosphorus is essential to maintain the high yields in modern agriculture required to sustain the global population.

In addition, phosphorus also plays a key role in animal nutrition – maintaining the skeleton, energy regulation and cell growth. Around 10pc of global phosphate production is used to manufacture animal feed supplements – another important aspect of food security.

Approximately, 5pc of total phosphate demand derives from a wide variety of industrial uses, such as the production of detergents, food & drink additives, water treatment and toothpaste.

More recently, the shift towards electric vehicles (EVs) has prompted the development of low-cost batteries with high energy density[2]. Lithium-ion batteries are the industry standard, however within this category there are a range of competing cathode chemistries, of which lithium iron phosphate (LFP, $LiFePO_4$) is currently in the spotlight, given its long lifecycle and relative thermal stability.

# Chapter 1.2: Phosphate Rock – Important Feedstock

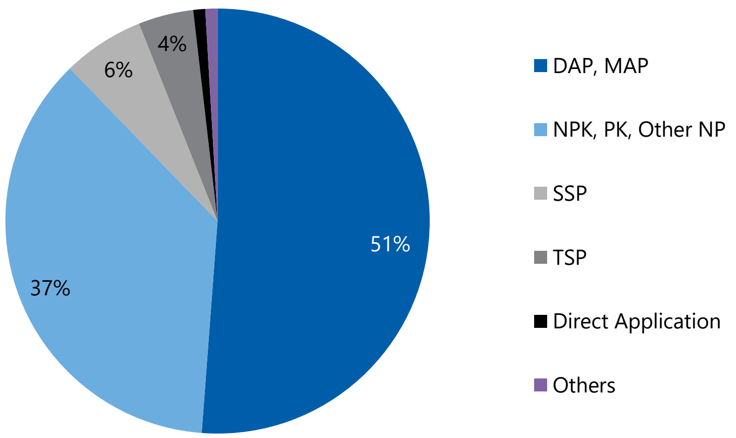
"Phosphate rock" is a generalised term for phosphate containing deposits of diverse origins, chemical concentrations and physical characteristics.

The form of phosphorus available in phosphate rock is generally seen as unsuitable for crop-nutrition – reactive grades may be suitable for direct application of phosphate rock (DAPR) to acidic soils, but this accounts for less than 1pc of global consumption[1]. Typically, the phosphate must be made plant-available. Therefore, phosphorus is applied to crops via phosphate-containing fertilizers, for which **phosphate rock is the key raw material.**

Globally, the key carriers of phosphate to the field are high-analysis phosphate fertilizers. The key products are diammonium phosphate (DAP, 18-46-0), monoammonium phosphate (MAP, 11-52-0), triple superphosphate (TSP, 0-46-0) and multinutrient compound fertilizers available in a wide range of specifications (NPKs).

Crucially, these high-P fertilizers are more nutrient dense, therefore the shipping of these forms on a per-tonne of nutrient basis, is far more economical, and facilitates the international trade between those countries with phosphate rock mining and processing operations, and countries reliant on imports for their agricultural needs.

Figure 1-2: Global consumption of $P_2O_5$ by product in 2020

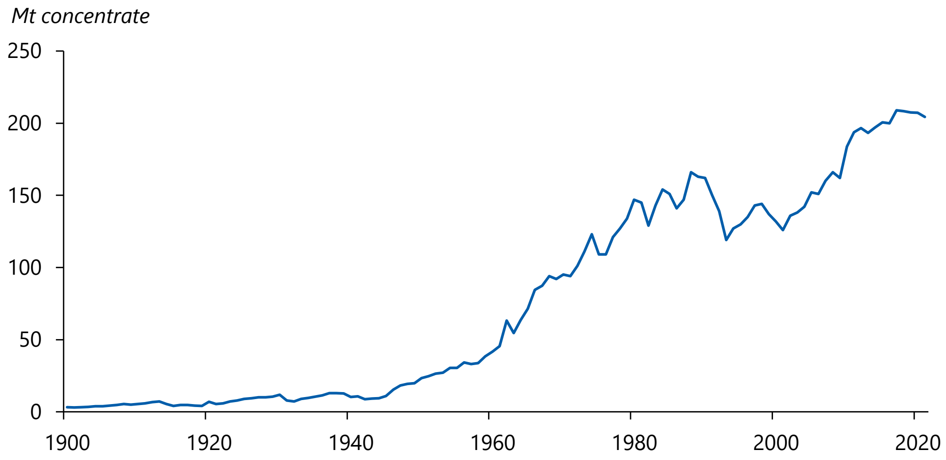



— *IFASTAT Consumption Database*

These high-analysis phosphate fertilizers are produced by reacting phosphate rock with sulphuric acid to produce phosphoric acid, the key intermediate product.

Global phosphate rock production in 2021 stood at 204Mt (63Mt $P_2O_5$) of marketable and useable concentrate[3].

Figure 1-3: World phosphate rock production, 1900-2021




— 1900-2010 USGS, 2010-2021 IFA

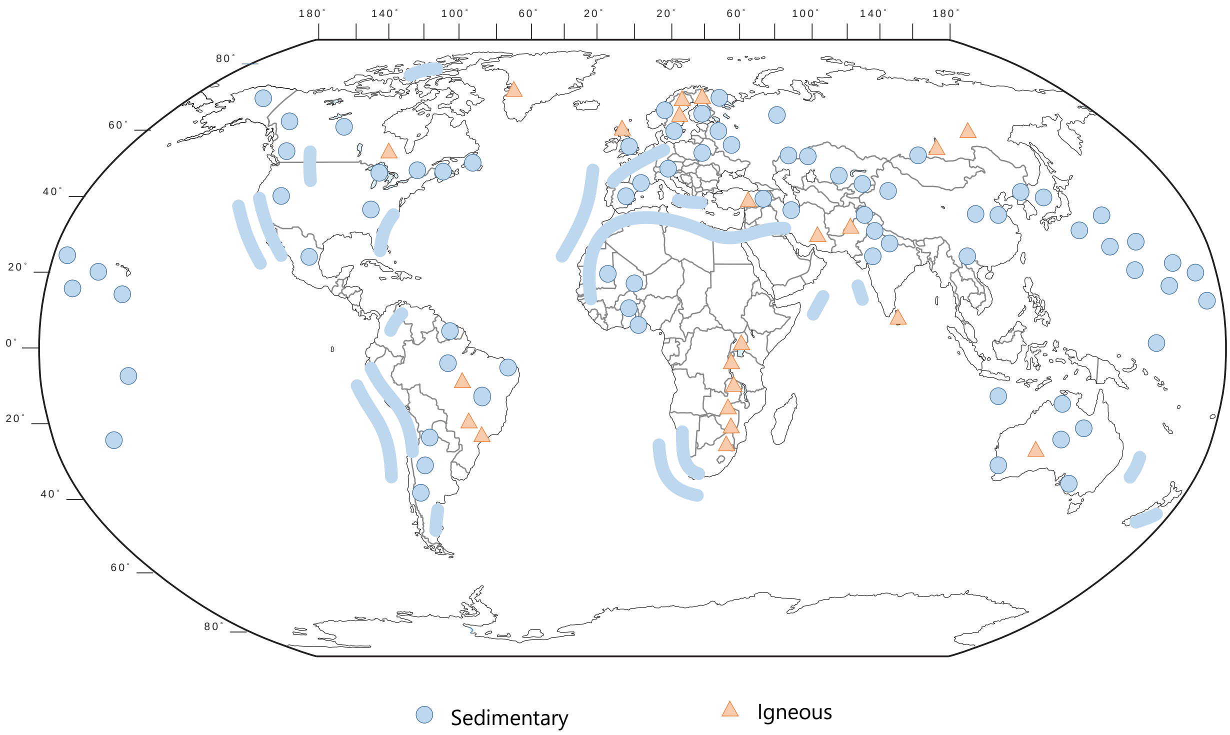
# Chapter 1.3: Phosphate Deposits

There are three main forms of phosphate deposits: sedimentary marine phosphorite, igneous apatite and guano — formed from seafowl or bat droppings. Secondary deposits form from each of these deposits by chemical and physical processes, such as weathering or leaching.

- Sedimentary phosphate deposits are generally associated with black shale and chert and account for about 75pc of phosphate rock production.
- The largest igneous deposits of phosphate are intrusions associated with carbonatite, nepheline-syenite and other alkali rocks — these account for about 23pc of phosphate rock production.
- Deposits derived from guano have largely been mined and account for negligible quantities of production today.

The grade and quality of a deposit is important to consider because it determines the suitability and costs of processing specific phosphate resources into plant-available forms.

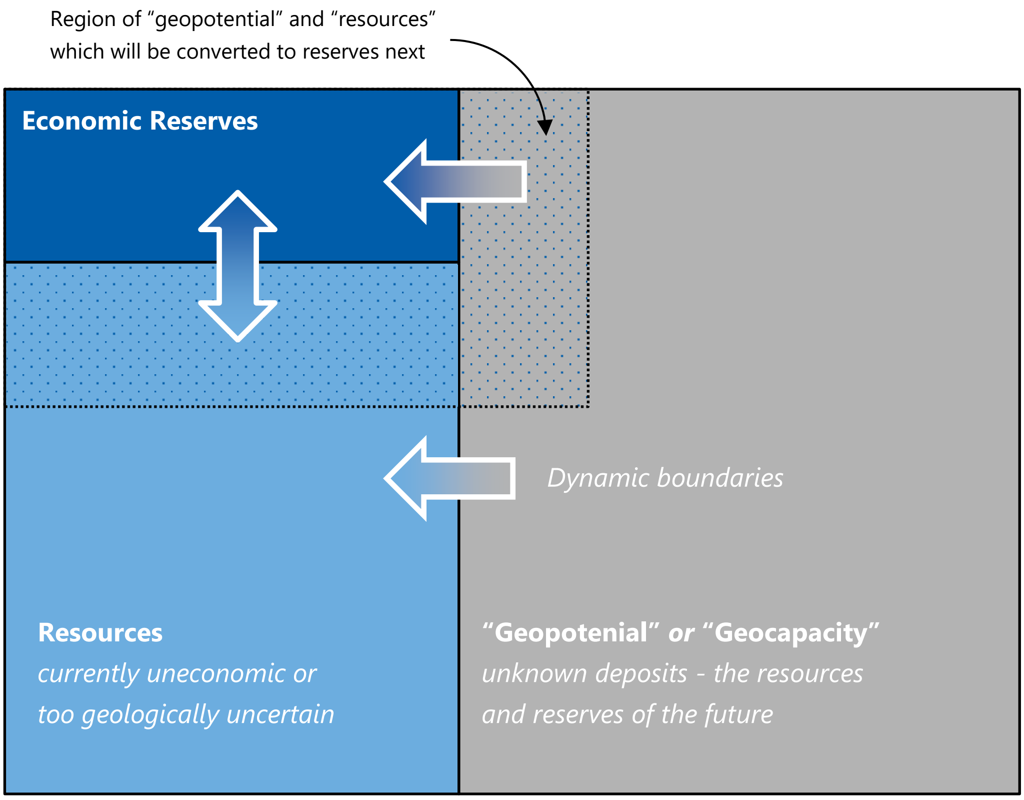
Figure 1-4: Distribution of phosphate occurrences (after Pufahl & Groat, 2017)[4]



Deposits tend to be classified on the basis of their economic potential. Generally reserves can be defined as the quantity of known and assessed phosphate rock that can be economically mined (*i.e.* at current prices, with current costs and with current technology). Resources are known deposits (with varying degrees of uncertainty), including those that are, at present, uneconomic.

Crucially, both resources and reserves are only a small portion of the "geopotential" also known as the "geocapacity" – that is, the currently undiscovered reserves and resources of the future.

Figure 1-5: The "Total Resource Box" (after Scholz & Wellmer, 2013)[5]



# Section 2: Background on Phosphate Rock Resources & Reserves

## Chapter 2.1: Previous Resource & Reserve Estimates

### 2.1.1. Resources

There have been few global studies estimating global phosphate rock resources, which are summarised chronologically below.

**De Voto and Stevens (1979)**[6] **–** This report was sponsored by the United States Department of Energy and focussed on the potential for uranium recovery from phosphate resources. The report estimated a total "Free World" phosphate resource of 1,184Gt. From this total, land not available for mining was subtracted, giving 624Gt of *"potentially mineable"* 30pc $P_2O_5$ product. This potentially mineable subtotal then had mining and beneficiation factors applied, reducing the global total to **266Gt** of *"recoverable phosphate product (~30pc $P_2O_5$)"*.

**Cathcart (1980)**[7] **–** Features in a compilation of papers entitled '*The Role of Phosphorus in Agriculture*' from a symposium on 1-3 June 1976 in Muscle Shoals, Alabama. The event was jointly sponsored by the Tennessee Valley Authority, the American Society of Agronomy, the Soil Science Society of America, and the Crop Science Society of America. Reserves and resources were expressed as product of at least 30pc $P_2O_5$. It has been noted that deposits have been converted based purely on $P_2O_5$ contents without considering mining and processing losses[8]. The paper identifies reserves of **20,557Mt** (19,705Mt sedimentary and 852Mt igneous) and resources of **90,655Mt** (87,810Mt sedimentary and 2,845Mt igneous).

**Fantel (1988)**[9] **–** The USBM, with input from Zellars-Williams Inc., Lakeland Florida and the British Sulphur Corporation, produced Information Circular 9187 titled *'Phosphate Availability and Supply'*. The study evaluated 206 deposits across 30 market economy countries (MECs), in terms of resources, costs and capacities to understand the current and future competitiveness of the US phosphate industry. The report estimated demonstrated resources of **36,595Mt** of recoverable rock product for the 1985 base year *"that can be mined and milled with current technology"*, of which MECs and centrally planned economies (CPECs) accounted for 35,055Mt and 1,541Mt respectively, but admitted that it was *"more of a reflection of a lack of data for these countries than a lack of actual resources"*. The study also notes an estimated 20Gt of inferred resources (as recoverable product) across MECs. A total for in-situ resources is not presented.

**Notholt et al. (1989)**[10] **–** This multi-author volume represents a systematic effort to catalogue all available geologic data on every major deposit of phosphates worldwide, and remains the most comprehensive reference for phosphate resources. The publication is an accumulation of knowledge derived from Working Group 2 of Project 156 (Phosphorites) of the International Geological Correlation Programme**.** The study estimates a total resource of **163Gt** of phosphate rock of all grades and types, but caveats that *"much of the total world resources includes deposits whose commercial exploitation depends on either greatly improved or new technology or more favourable economic circumstances"*.

**IFDC (2010)**[8] - The IFDC concluded that reserves of phosphate rock suitable for the processing into phosphate derivatives, including phosphoric acid, would last hundreds of years at current production levels. The report identified **287Gt** of in-situ resources and reserves as recoverable concentrate of **60Gt.** This study did not record $P_2O_5$ content of the resources, but reserves were reported in concentrate terms. The report offers an excellent summary of the preceding studies listed above.

**USGS (2012)**[11] **-** The United States Geological Survey (USGS) started reporting that *"World resources of phosphate rock are more than 300 billion tons"* from their Mineral Commodity Summaries 2012 onwards, likely based on the prior IFDC report.

**Table 2-1: Evolution of phosphate rock resource estimates, 1975-Present** *Gt*

| | **1979** [6] | **1980** [7] | **1985** [9] | **1989** [10] | **2010** [8] | **2012** [11] |
|---|---|---|---|---|---|---|
| 30pc Product | 266 | 91 | 37 | - | - | - |
| All Grades | 1,184 | - | - | 163 | 290 | >300 |

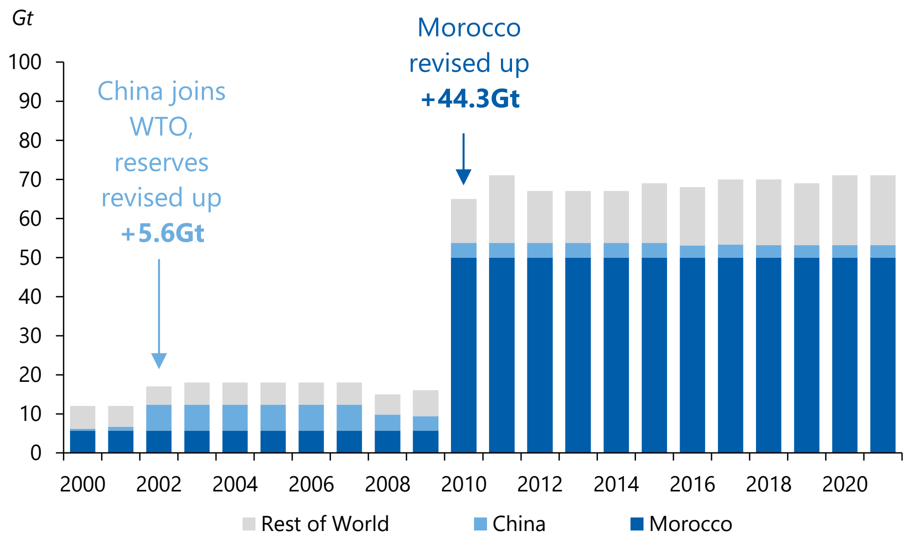
Furthermore, **Chernoff & Orris (2002)**[12] contains a list of all known occurrences and their location, providing a useful reference but contains sparce resource information. The report heavily references the very comprehensive **Mew (1980)**[13] and **Savage (1987)**[14] editions of the '*World Survey of Phosphate Deposits*' published by the British Sulphur Corporation between 1956-1987.

### 2.1.2. Reserves

Most of the literature cited above contains snapshots of reserve estimates, however, the USGS Mineral Commodity Summaries (MCS) represent the longest-running, and most consistent record of global phosphate rock reserves.

The below chart shows the timeseries of USGS phosphate rock reserves, highlighting the major historic revisions, namely in China and Morocco.

Figure 2-1: Historic major revisions of global phosphate rock reserves, 2000-21




— *USGS*

The revision of the reserves in Morocco was predominantly derived from the 2010 IFDC study, which increased the estimate from 5.7Gt to 51Gt in 2010. The report noted 28Gt at Khouribga, 22Gt at Gantour and 1Gt at Boucraa in terms of marketable concentrate[8]. While this dramatic increase did not go unquestioned[15], it was ultimately concluded that there was "*reliable evidence that at least 50Gt [of marketable phosphate rock] may be mined under the current regime*"[16].

The most recent available USGS estimate for global phosphate rock reserves is **71Gt**. This figure is often assumed by other authors to be in concentrate terms (i.e. tonnes of useable or marketable phosphate rock), however this total has been previously identified as containing both ore and concentrate added values together[15].

While this discrepancy has been shown to only have a relatively minor impact of 5-13pc[16], the limitations of the MCS data must be acknowledged. This is especially relevant as these statistics tend to be the basis of most analysis and discussion of phosphate rock geologic inventories and depletion.

# Chapter 2.2: Previous Depletion Estimates

The following chapter presents a brief history of phosphate rock scarcity in the literature, to provide a background and context to the current study.

There has long been speculation that the world may reach *'Peak Phosphorus'* or *'Peak Phosphate'*, driven by dwindling ore grades and a finite resource-base. The term was first coined by Déry and Anderson (2007)[17], in a paper applying a Hubbert curve to historical data from both Nauru and USA. One of the most influential papers arguing for the hypothesis was Cordell et al. (2009)[18]. This work fitted a Gaussian distribution to a fixed stock of reserves, based on the 2008 USGS estimates, resulting in a production peak of 29Mt P in 2033 (equivalent to 66Mt $P_2O_5$, 220Mt rock).

'Peak Resource Theory' states that when production peaks the resource becomes more difficult and expensive to extract – a 'supply-driven' peak. The application of this approach to phosphate rock production in the literature is summarised below.

**Table 2-2: Summary of phosphate rock production applying "peak resource theory"**

| Author | Peak Year | Range |
|---|---|---|
| Déry and Anderson (2007)[17] | 1989 | *N/A* |
| Cordell et al. (2009)[18] | 2033 | *N/A* |
| Cordell and White (2011)[19] | 2070 | 2051 - 2092 |
| Mohr and Evans (2013)[20] | 2027 | 2011 - 2118 |
| Walan (2013)[21] | 2084 | 2030 - 2131 |

However this approach has garnered a variety of criticisms[5,22,23]. Mew (2011)[24] argued that the Hubbert Curve only applied to substitutable commodities, such as oil (energy), whereas phosphate currently has no known substitute, thus plateaus in population and food production would lead to a corresponding plateau in phosphorus demand.

While the Hubbert Curve has the potential to hold true in phosphate in a supply-driven market with a well-defined and constrained deposit, such as the guano in Nauru, there is not enough knowledge of the magnitude of the ultimate recoverable resource (URR) nor of future technological developments to enable an estimate of a supply-driven peak[25].

**Table 2-3: Summary of phosphate rock reserves under depletion scenarios[19,26]**

| Author | Estimated lifetime of reserves | Estimated year of depletion | Assumptions |
|---|---|---|---|
| Tweeten (1989)[8] | 61 | 2050 | *Assumes 3.6pc increase in demand* |
| Herring and Fantel (1993)[27] | 40 – 169 | 2033 – 2162 | *Linear growth or exponential production growth at a rate of 1.04–3pc. Stable demand after 2025, 2050 or 2100* |
| Runge-Metzer (1995)[28] | 88 | 2083 | *Assumes 2.1pc increase* |
| Steen (1998)[29] | 60 – 130 | 2058 – 2128 | *Based on range of 2–3pc increase demand rates, plus a 'most likely' 2pc increase until 2020 and 0pc growth thereafter* |
| Smil (2000)[30] | 80 | 2080 | *At 'current rate of extraction'* |
| Fixen (2009)[31] | 93 | 2102 | *At 2007–2008 production rates* |
| Smit et al. (2009)[32] | 69 – 100 | 2078 – 2109 | *Assuming 0.7–2.0pc increase until 2050, and 0pc increase after 2050.* |
| Vacarri (2009)[33] | 90 | 2099 | *At 'current rates'* |
| Van Kauwenbergh (2010)[8] | 300 – 400 | 2310 – 2400 | *At 'current rates'* |
| Van Vuuren et al. (2010)[34] | >90 | >2100 | *50-90pc resource base remaining by 2100* |
| Cooper at al. (2011)[35] | 370 | 2381 | *Continued at constant production* |
| Rosemarin et al. (2011)[15,36] | 137 – 261 | 2148 – 2272 | *Scenarios surrounding population growth and African "green revolution"* |
| Van Enk et al. (2011)[37] | 31 – 200 | 2042 – 2211 | *Food & biofuel demand scenarios* |
| Sverdrup and Ragnarsdottir (2011)[38] | 30 – 330 | 2041 – 2341 | *S/D dynamics & price feedbacks* |
| Koppelaar and Weikard (2013)[39] | 100 – 200 | 2113 – 2213 | *S/D dynamics & price feedbacks* |

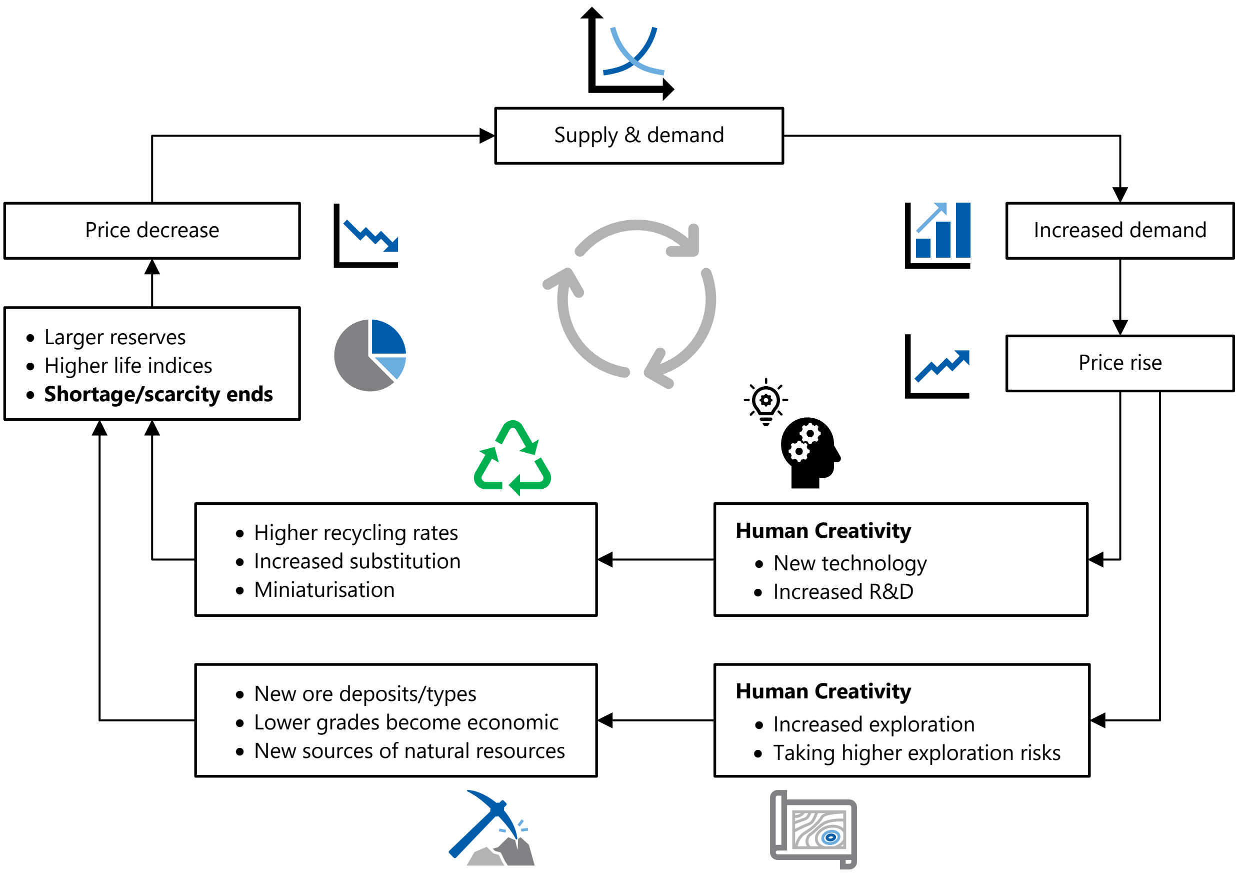
Regardless of which model is used, either "Peak Phosphorus" or "Plateau Phosphorus", it is clear they both require a **robust assessment of resources and reserves** to underpin the analysis.

However, it is worth inserting the caveat that attempts to quantify resources, reserves and depletion, while useful metrics to track, will lead to a lower estimate than the likely reality – mineral resource investigation is a dynamic process:

- A commodity is a commercial product of mining companies, and business planning horizons would typically not extend beyond 100 years. Indeed, they are often much lower[40].
    - The proving of reserves occurs mainly when planning for the mining of new blocks of land commences. It is a continual process even where mining is established.
    - Companies with significant known resources do not need to spend the capital to explore further until they are more depleted.
- Geological surveying is a continual process. The probability is that new work will result in a net addition to known resources and reserves, even accounting for areas where mining is leading to the gradual depletion of worked deposits.
- Definitions that rely on either historical or current economic realities will naturally represent an incomplete view of total potential supply and will be superseded as new processes and market realities emerge.

This is illustrated by the feedback control cycle of mineral resource management:

Figure 2-2: The feedback control cycle of mineral resource management (after Wellmer & Becker-Platen, 2002)[41]



# Chapter 2.3: This Study

The IFDC report concluded that a collaborative effort from producers, government, international organisations and academia would be required to make more detailed estimates[8]. Similarly, Scholz & Wellmer[16] suggested the *"establishment of a solidly funded, international standing committee that regularly analyzes global geopotential for assuring long-term supply security"*. Edixhoven et al.[15] state *"While there appears to be no immediate threat of PR depletion, geopolitical risks and considerations of intergenerational equity render it important to have reliable assessments of PR deposits available for extraction"*.

This study has built-upon the IFDC publication, including information from literature published in the intervening years between 2010 and 2022. During this time, we saw a lot of market developments, regulatory updates and technological advancements.

In 2009, global phosphate rock production stood at 161Mt (49.5Mt $P_2O_5$); in 2021 it was reported to be 204Mt (62.9Mt $P_2O_5$)[3], which would increase an "at current production rates" assessment. Furthermore, in the 2010 report, Saudi Arabia was included in "Other Countries" as it had yet to become a key player in the global phosphate market. The Ma'aden Phosphate Company's beneficiation plant was commissioned in November 2010, and the country has now grown to be the sixth largest producer of phosphate rock in the world[3].

In 2010, there were 17,000 electric vehicles (EVs) globally[42], in 2021 there were over 16.5 million EVs on the world's roads. This exponential growth has driven a race for optimal battery chemistries, of which lithium iron phosphate (LFP) batteries are one option.

The Committee for Reserves and International Reporting Standards (CRIRSCO) published Standard Definitions to be used in company mineral resource disclosures in October 2012. Subsequently to align with these standards more closely, in October 2018, the US Securities Exchange Commission (SEC) amended the disclosure requirements for mineral reserve estimates for US registered companies – *SEC Guide 7* was replaced with a new *S-K 1300*. This change was effective from 2021 and has led to increased transparency in US-reported resource and reserve estimates.

There has been increasing attention focussed on phosphate rock processing technologies which can utilise lower-grade rock than the traditional wet acid process. There have been major acquisitions and rebrands in this area of the market in the last few years signifying a push towards commercialisation and potential adoption.

**HCl-Process:** Ecophos was founded in 1996 to research, develop and commercialise the processing of phosphate rock using the hydrochloric-acid process. The key benefit of this process is the ability to valorise low-grade phosphate rock, in terms of both $P_2O_5$ content and other impurities. In 2020, Ecophos was acquired by Prayon, a leading phosphoric acid technology provider.

**Improved Hard Process:** JDC Phosphate was founded in 2008 to develop a more efficient phosphoric acid technology. The company rebranded as Novaphos in 2019 to signify a transition from the R&D phase to commercialisation.

It is clear that the phosphate rock market landscape has changed since the last global assessment of the resources and reserves.

# Section 3: Methodology

## Chapter 3.1: Resource & Reserves Definitions

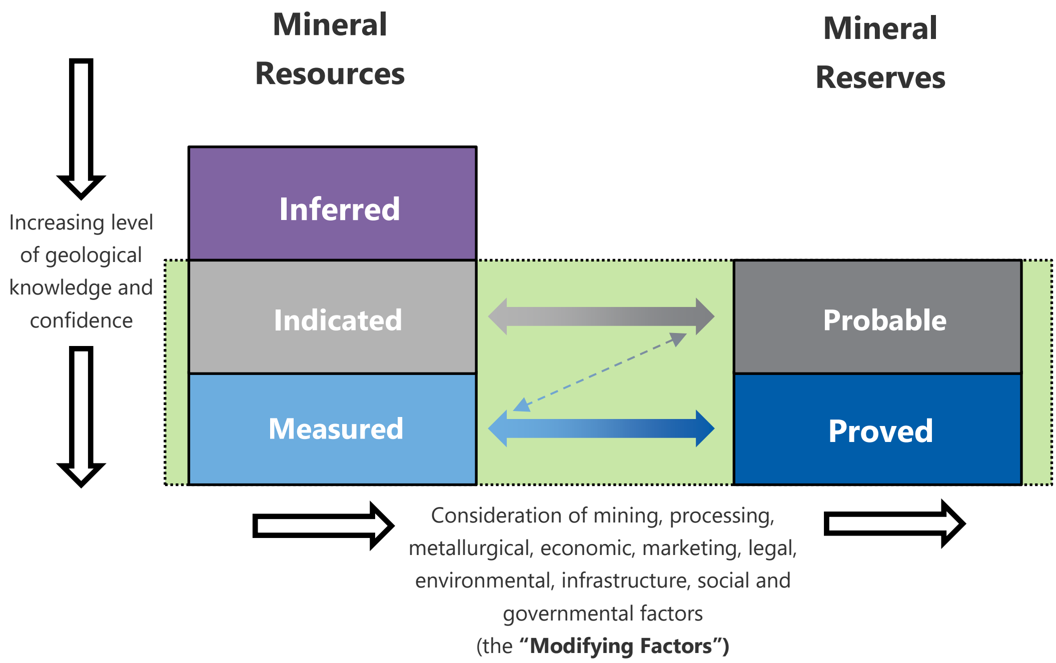
As many other authors point out, there is inconsistent application of the terms resources and reserves throughout the literature. Sometimes this is caused by differing national classification systems, but often by imprecise use of language or translation errors. Assessments are generally made on the basis of two variables: the degree of geological certainty, and the economic viability. There are two key types of resource and reserve assessments – government inventory classifications, and financial-reporting classifications[15].

### 3.1.1. Financial Reporting Classifications

Financial reporting classifications, of which the most widely known is the Australian Joint Ore Reporting Committee (JORC) Code, are focussed on ensuring investors can make informed decisions on the potential future opportunity of an investment in a mining company. Therefore, such classifications are intended to provide transparent, reliable data on a single asset or group of assets and are only focussed on typical investment timescales. Furthermore, resources may only be classified as reserves if there is an economic pre-feasibility or feasibility study in place[43].

These strict definitions currently do not appropriately capture currently sub-economic deposits (i.e. a reserve base), as their potential may not be realised within a reasonable investment timeframe, but they may be included as part of the resource if there is *"reasonable expectation"* that it will become economic. While this is vital to avoid misleading investors, it makes such classifications unsuitable for assessing long-term inventory.

Figure 3-1: General relationship between Exploration Results, Mineral Resources and Ore Reserves in financial reporting classifications (CRIRSCO, 2019)[43]



Furthermore, what is important to note, is that mineral resource estimates are also somewhat a function of economics, and don't represent a true ceiling of the quantity of mineralisation in place. Resources are typically determined from drill cores and subsequent 3D modelling of the deposit and calculated using a 'cut-off' grade to delineate the seams, which is based on economic considerations. Therefore, this leads to some phosphate being unaccounted for, which could in the future potentially become a resource or reserve. Simply put, reserves and resources increase as cut-off grades decrease[44].

### 3.1.2. Government Inventory Classifications

As stated above, financial reporting classifications do not concern themselves with the long-term availability of mineral deposits. Governments, however, are interested in the full inventory of materials within their borders for the purposes of long-term planning.

The terms and definitions used by the USGS to assess potential mineral supply are summarised below:

- The term **resource** is defined as *"a concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth's crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible"*.
- The term **reserve-base** is defined as *"that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices"*.
- The term **reserve** is defined as *"that part of the reserve base which could be economically extracted or produced at the time of determination"*.

To summarise, **resources** can be seen as a theoretical measure of whether enough potentially extractable $P_2O_5$ exists on Earth and the **reserve base** represents the subset of that resource which meets minimum requirements for current mining and beneficiation practices. **Reserves** however, include an economic component, and represent a snapshot of the feasibility of given extraction at a given time.

Therefore, to address the question of long-term scarcity, the key metrics are **resources** and **reserve base.**

The reserve base category was included in the USGS/USBM framework to provide a more stable metric. The USGS/USBM *originally* defined reserves and reserve base as phosphate rock that could be produced at less than $40/t and $100/t respectively. The IFDC study concluded that *"reserve base as used now should be discontinued unless definitive production cost criteria can be developed. The criteria of producible at less than $100/t is not appropriate"*. However, the reserve base has been considered in this study in view of emerging technologies which are able to utilise much lower grade rock than previously possible.

### 3.1.3. Study Definitions

For completeness and comparisons to existing literature, data on reserves has also been collected. However for additional clarity this report will refer to “reserves” as “economic reserves”.

This study uses the following nomenclature, where each category used within the analysis is inclusive of the subsequent category – for example resources includes the reserve base assessment, which in turn includes the economic reserves.

**All Resources**

- ✗ Speculative Resources
- ✗ Restricted Resources
- ✓ **Resources**
  - → **Reserve Base** (including Emerging Technologies)
    - → **Reserve Base** (only including Traditional Technologies)
      - → **Economic Reserves**

**Table 3-1: Resource, reserve base and economic reserve definitions used in this study**

| | |
|---|---|
| **Resources** | Total reported accumulation of phosphate where *“extraction is currently or potentially feasible”* (i.e. includes mineralisation below current technically recoverable limits, or where the degree of geological confidence is too low to qualify as reserves).<br><br>Reported in tonnes of in-situ mineralisation, typically million tonnes (Mt) or gigatonnes (Gt).<br><br>The following resources are not included in further analysis:<br>• **Restricted Resources –** Deposits located in areas deemed to be ecologically sensitive, where mining is unlikely to be able to take place (e.g. wildlife reserves, some seafloor deposits).<br>• **Speculative Resources –** Deposits speculated to exist, taking into account for the percentage of land area explored in countries known to be underlain by phosphate. |
| **Reserve Base** | That part of an identified resource that meets specified “***minimum physical and chemical criteria*** *related to current mining and production practices”* (i.e. material that is technically mineable, but may be uneconomic).<br><br>Reported in tonnes of in-situ mineralisation, and additionally converted to concentrate terms for comparison purposes.<br><br>Resources which meet the minimum specification requirements to be beneficiated into either a “useable” **(≥21pc $P_2O_5$**) or “marketable” **(≥26pc $P_2O_5$**) concentrate. Minimum sedimentary run-of-mine requirement to be processed with:<br>• **"Traditional Technologies"** (≥15pc $P_2O_5$)<br>• **"Emerging Technologies"** (≥5pc $P_2O_5$, <10pc MgO, <5pc $Al_2O_3$, <5pc $Fe_2O_3$) |
| **Economic Reserves** | *“That part of the reserve base which could be economically extracted or produced at the time of determination."*<br><br>Reported with "modifying factors" applied (e.g. mining recovery), in million tonnes of ore "as mined" at the point of delivery to the beneficiation plant. Additionally converted to concentrate terms for comparison purposes. |

# Chapter 3.2: Data Collection

## 3.2.1. Data Sources

This study updates global phosphate rock resources and reserve estimates to reflect the latest knowledge. The process included reviewing the academic literature published between 2010 to 2022; taking into account new exploration efforts from junior mining companies; updates to national statistics and conducting a survey of existing and future phosphate rock producers.

## 3.2.2. Geographic Scope

**Table 3-2: List of countries reviewed and included in this assessment**

| Country | Region | Included in IFDC 2010 | Country | Region | Included in IFDC 2010 |
|---|---|---|---|---|---|
| Algeria | Africa | ✓ | Morocco | Africa | ✓ |
| Angola | Africa | ✓ | Mozambique | Africa | - |
| Australia | Oceania | ✓ | Namibia | Africa | - |
| Belgium | West Europe | - | Nauru | Oceania | - |
| Benin | Africa | - | New Zealand | Oceania | - |
| Brazil | Latin America | ✓ | Niger | Africa | - |
| Burkina Faso | Africa | - | Nigeria | Africa | - |
| Burundi | Africa | - | Norway | West Europe | - |
| Canada | North America | ✓ | Pakistan | South Asia | - |
| Chile | Latin America | - | Peru | Latin America | ✓ |
| China | East Asia | ✓ | Poland | Central Europe | - |
| Congo | Africa | - | Portugal | West Europe | - |
| Denmark (Greenland) | West Europe | - | Romania | Central Europe | - |
| DRC | Africa | - | Russia | EECA | ✓ |
| Egypt | Africa | ✓ | Saudi Arabia | West Asia | ✓ |
| Estonia | EECA | - | Senegal | Africa | ✓ |
| Finland | West Europe | ✓ | South Africa | Africa | ✓ |
| France | West Europe | - | Spain | West Europe | - |
| Germany | West Europe | - | Sri Lanka | South Asia | - |
| Greece | West Europe | - | Sweden | West Europe | - |
| Guinea Bissau | Africa | - | Syria | West Asia | ✓ |
| India | South Asia | - | Tanzania | Africa | - |
| Iran | West Asia | - | Tajikistan | EECA | - |
| Iraq | West Asia | - | Togo | Africa | ✓ |
| Ireland | West Europe | - | Tunisia | Africa | ✓ |
| Israel | West Asia | ✓ | Turkey | West Asia | - |
| Italy | West Europe | - | Uganda | Africa | - |
| Jordan | West Asia | ✓ | UK | West Europe | - |
| Kazakhstan | EECA | - | USA | North America | ✓ |
| Malawi | Africa | - | Uzbekistan | EECA | - |
| Mali | Africa | - | Venezuela | Latin America | - |
| Malta | West Europe | - | Vietnam | East Asia | - |
| Mauritania | Africa | - | Zambia | Africa | - |
| Mexico | North Ameria | - | Zimbabwe | Africa | - |
| Mongolia | East Asia | - | | | |

### 3.2.3. Low-High Uncertainty Range

Where there are multiple estimates for a given deposit or region, we have captured the low and high estimates for both tonnage and $P_2O_5$ grade. Where necessary, legacy estimates have been adjusted to a 2021 base year to account for active mining.

#### 3.2.3.1. Resources

Where the only available resource information is from a financial reporting classification, we have used the uncertainty categories. "Measured + Indicated" is a standard industry measure of the resources, which crucially are able to be converted to reserves, whereas the inferred category is deemed too geologically uncertain.

| | |
|---|---|
| **Low Case** | = Measured |
| **Central Estimate** | = Measured + Indicated |
| **High Case** | = Measured + Indicated + Inferred |

#### 3.2.3.2. Reserve Base

Resources were assessed as to whether they were deemed to be processable given current technology, independent of current economics. Note that reserve base is based on the in-place demonstrated (i.e. Measured + Indicated) resource, and therefore inferred resources were not included in the high case, given the high levels of geological uncertainty. Therefore, when estimating reserve base from financial reporting classifications of resources, the central estimate and the high case are identical.

| | |
|---|---|
| **Low Case** | = Measured |
| **Central Estimate** | = Measured + Indicated |
| **High Case** | = Measured + Indicated |

#### 3.2.3.3. Economic Reserves

Where economic reserves are reported by national statistics or academic studies, we have included the low and high-end of estimates. Where the economic reserve is sourced from a financial reporting classification, we have used the two uncertainty categories. Therefore, when assessing economic reserves from financial reporting classifications the central estimate and the high case are identical.

| | |
|---|---|
| **Low Case** | = Proven |
| **Central Estimate** | = Proven + Probable |
| **High Case** | = Proven + Probable |

## 3.2.4. Conversions – Mining & Processing

### 3.2.4.1. Mining

Resources have been recorded in terms of in-situ tonnage and grade. Mining recovery factors are used to convert in-situ tonnage to run-of-mine ore.

In 2009-10, IFA conducted a confidential global survey of phosphate rock mines, and found that mining recovery ranged from 45 - 98pc, with a weighted average of 82pc[45]. The default assumption in this study is that open-pit and underground methods would have mining recovery factors of 95pc and 65 - 85pc respectively[8].

### 3.2.4.2. Beneficiation

Run-of-mine ore is converted to concentrate terms using a $P_2O_5$ recovery factor. Historically the $P_2O_5$ recovery in beneficiation operations has ranged from 40.5 – 79.0pc[9]. The 2009-10 IFA survey found processing recovery range of 60 - 90pc, with a global weighted average of 84pc[45].

Generally, recovery for igneous producers is very high, whereas the inherent variability of sedimentary deposits results in a much wider range. It is noted that overall recovery has improved through time[46], and that many large sedimentary producers have expanded their flotation capacity in recent years, improving their recovery even further. This study uses a default assumption of 85pc $P_2O_5$ recovery, and where available, known $P_2O_5$ recovery factors have been used.

# Section 4: Results

## Chapter 4.1: Resources, Reserve Base & Economic Reserves

### 4.1.1. Resources

This study estimates global phosphate rock resources of 342Gt (270 - 420Gt) containing 65Gt $P_2O_5$ (45 - 88Gt $P_2O_5$). These figures are reported in-situ, representing the mass of rock in the ground, without any mining or beneficiation losses applied.

**Table 4-1: Regional breakdown of phosphate rock resources, 2021**

| Region | Resources *Mt in-situ* | | Resources *Mt $P_2O_5$ in-situ* | |
|---|---|---|---|---|
| Africa | 195,000 | (172,300 - 225,600) | 42,200 | (33,300 - 53,750) |
| North America | 59,600 | (25,800 - 76,200) | 10,650 | (2,900 - 15,300) |
| EECA | 21,900 | (20,300 - 28,800) | 2,750 | (2,300 - 3,800) |
| West Asia | 18,900 | (16,100 - 25,000) | 3,850 | (3,350 - 5,250) |
| East Asia | 16,800 | (6,800 - 30,000) | 3,300 | (1,050 - 7,250) |
| Latin America | 15,000 | (15,000 - 17,300) | 1,500 | (1,300 - 1,800) |
| West & Central Europe | 10,400 | (9,300 - 12,600) | 350 | (300 - 400) |
| Oceania | 4,000 | - | 650 | - |
| South Asia | 400 | (300 - 600) | 50 | (50 - 100) |
| **World Total** | **342,000** | **(269,900 - 420,100)** | **65,300** | **(45,200 - 88,300)** |

We also make note of restricted resources, located in areas deemed to be ecologically sensitive where mining could not take place, as well as speculative resources which account for the percentage of land area explored in those countries known to be underlain by phosphate deposits.

Included within speculative resources are the additional 100 - 200Gt in Morocco, which takes into account the incomplete exploration of the Moroccan phosphate fields[8]. These are not included in the subsequent analysis, given the low geological certainty and potential complexity in accessing these deposits if they are found to exist – portions of the Ouled Abdoun (Khouribga) field have been noted as being up to 400m deep and more structurally complex[15].

Also included within speculative resources are the estimates of 70Gt in Norway within the Bjerkreim-Sokndal intrusive complex down to 1,500m depth. However, it is worth noting the exploration target is an igneous deposit, with a likely 1-2pc $P_2O_5$ content. The more advanced exploration targets at Øygrei and Storeknuten have been included in the resource figure for this study.

Currently excluded from any of the resource categories is the deep portion of the US Western Phosphate Field. This has been estimated by other authors to contain a total of 507Gt at 28pc $P_2O_5$ (142Gt $P_2O_5$), of which 377Gt is found at depths greater than 1,500m [47]. Clearly this would not be mined for the foreseeable future, however in the long-term, these would likely become a resource in a few hundred years, albeit with potentially large losses of 50 - 65pc or greater[6,48].

## 4.1.2. Reserve Base

### 4.1.2.1. Only Traditional Technologies

Of these resources, we estimate a reserve base of 189Gt (148 - 211Gt) containing 36Gt $P_2O_5$ (26 - 48Gt $P_2O_5$), representing the in-situ ore volumes that are technically recoverable using "Traditional Technologies". This is approximately equivalent to 97Gt (70 - 116Gt) in 30pc $P_2O_5$ concentrate terms (29Gt $P_2O_5$).

These figures are reported both in-situ, representing the mass of ore in the ground, without any mining or beneficiation losses applied; and in tonnes of concentrate, which represents the useable or marketable rock, with these losses applied.

**Table 4-2: Regional breakdown of reserve base (only including traditional technologies), 2021**

| **Region** | **Reserve Base (TT)** *Mt in-situ* | | **Reserve Base (TT)** *Mt $P_2O_5$ in-situ* | |
|---|---|---|---|---|
| Africa | 95,700 | (83,900 - 106,000) | 20,400 | (16,200 - 25,000) |
| North America | 33,300 | (19,400 - 42,900) | 5,350 | (2,450 - 8,100) |
| EECA | 11,900 | (10,300 - 12,000) | 2,350 | (2,150 - 2,400) |
| West Asia | 17,700 | (15,000 - 17,900) | 3,750 | (3,250 - 3,950) |
| East Asia | 15,900 | (6,000 - 15,900) | 3,250 | (1,050 - 7,200) |
| Latin America | 4,500 | (4,000 - 4,500) | 600 | (500 - 600) |
| West & Central Europe | 8,700 | (7,600 - 10,400) | 250 | (250 - 300) |
| Oceania | 1,600 | - | 250 | - |
| South Asia | 110 | (90 - 140) | 30 | (20 - 40) |
| **World Total** | **189,410** | **(147,890 - 211,340)** | **36,230** | **(26,120 - 47,840)** |

**Table 4-3: Regional breakdown of reserve base (only incl. TT), in concentrate terms, 2021**

| **Region** | **Reserve Base (TT)** *Mt concentrate* | | **Reserve Base (TT)** *Mt $P_2O_5$ concentrate* | |
|---|---|---|---|---|
| Africa | 60,450 | (48,350 - 73,600) | 18,200 | (14,550 - 22,150) |
| North America | 12,650 | (6,250 - 14,850) | 3,900 | (2,400 - 5,050) |
| EECA | 6,250 | (5,550 - 6,450) | 1,950 | (1,750 - 2,000) |
| West Asia | 6,250 | (4,950 - 6,750) | 1,900 | (1,500 - 2,050) |
| East Asia | 8,800 | (2,750 - 11,000) | 2,650 | (850 - 3,300) |
| Latin America | 1,400 | (1,200 - 1,400) | 450 | (400 - 450) |
| West & Central Europe | 600 | (550 - 650) | 200 | (200 - 250) |
| Oceania | 750 | - | 200 | - |
| South Asia | 100 | (65 - 100) | 25 | (20 - 40) |
| **World Total** | **97,250** | **(70,415 - 115,550)** | **29,475** | **(21,870 - 35,490)** |

#### 4.1.2.2. Including Emerging Technologies

Including the emerging technologies, such as Prayon's Ecophos HCl-process or the Novaphos IHP, we estimate a reserve base of 219Gt (171 - 232Gt) containing 39Gt $P_2O_5$ (27 - 48Gt $P_2O_5$) in-situ ore. This is approximately equivalent to 103Gt (74 - 124Gt) in 30pc concentrate terms (30Gt $P_2O_5$).

These figures are reported both in situ, representing the mass of ore in the ground, without any mining or beneficiation losses applied; and in tonnes of concentrate, which represents the useable or marketable rock, with these losses applied.

**Table 4-4: Regional breakdown of reserve base (including emerging technologies), 2021**

| Region | Reserve Base (TT+ET) *Mt in-situ* | | Reserve Base (TT+ET) *Mt $P_2O_5$ in-situ* | |
|---|---|---|---|---|
| Africa | 98,400 | (86,600 - 108,700) | 20,800 | (16,500 - 25,400) |
| North America | 46,600 | (25,800 - 46,600) | 7,050 | (2,950 - 7,050) |
| EECA | 21,800 | (20,200 - 21,900) | 2,750 | (2,300 - 3,100) |
| West Asia | 18,800 | (15,900 - 19,000) | 3,850 | (3,350 - 4,100) |
| East Asia | 16,100 | (6,200 - 16,100) | 3,300 | (1,050 - 7,250) |
| Latin America | 6,100 | (5,600 - 6,100) | 750 | (650 - 750) |
| West & Central Europe | 9,500 | (8,300 - 11,200) | 300 | (300 - 400) |
| Oceania | 1,600 | - | 250 | - |
| South Asia | 300 | - | 40 | (30 - 50) |
| **World Total** | **219,200** | **(170,500 - 231,500)** | **39,090** | **(27,380 - 48,350)** |

**Table 4-5: Regional breakdown of reserve base (incl. ET), in concentrate terms, 2021**

| Region | Reserve Base (TT+ET) *Mt concentrate* | | Reserve Base (TT+ET) *Mt $P_2O_5$ concentrate* | |
|---|---|---|---|---|
| Africa | 61,300 | (49,050 - 74,550) | 18,300 | (14,600 - 22,250) |
| North America | 15,950 | (8,550 - 19,750) | 3,900 | (2,450 - 5,050) |
| EECA | 7,250 | (5,800 - 8,200) | 2,250 | (1,850 - 2,550) |
| West Asia | 6,500 | (5,200 - 7,050) | 1,950 | (1,550 - 2,150) |
| East Asia | 8,900 | (2,800 - 11,150) | 2,700 | (850 - 3,350) |
| Latin America | 1,800 | (1,600 - 1,800) | 600 | (550 - 600) |
| West & Central Europe | 750 | (600 - 850) | 250 | (200 - 300) |
| Oceania | 750 | - | 200 | - |
| South Asia | 100 | (100 - 150) | 30 | (25 - 45) |
| **World Total** | **103,300** | **(74,450 - 124,250)** | **30,180** | **(22,275 - 36,495)** |

### 4.1.3. Economic Reserves

Economic reserves are estimated at 83Gt (52 - 92Gt) containing 21Gt $P_2O_5$ (12 - 24Gt $P_2O_5$) and represent the portion of the resources which are both technically and economically viable at the present day and have been calculated as the sum of reported reserves by current producers, junior mining projects, geological surveys or national statistical agencies. This is approximately equivalent to 63Gt (36 - 71Gt) in 30pc concentrate terms (18.7Gt $P_2O_5$).

These figures are reported both as run-of-mine, representing ore "as mined" at the point of delivery to the beneficiation plant, therefore with mining losses applied; and in in tonnes of concentrate, which represents the useable or marketable rock, with beneficiation losses applied.

**Table 4-6: Regional breakdown of economic reserves, 2021**

| Region | Economic Reserves *Mt ROM* | | Economic Reserves *Mt $P_2O_5$ ROM* | |
|---|---|---|---|---|
| Africa | 63,300 | (36,100 - 68,800) | 17,550 | (9,350 - 19,900) |
| North America | 1,700 | (1,500 - 1,700) | 300 | (250 - 300) |
| EECA | 4,400 | (3,800 - 5,700) | 850 | (750 - 1,050) |
| West Asia | 7,700 | (6,400 - 7,800) | 1,550 | (1,350 - 1,600) |
| East Asia | 2,000 | (2,000 - 3,800) | 450 | (450 - 800) |
| Latin America | 1,300 | (800 - 1,300) | 150 | (100 - 150) |
| West & Central Europe | 1,600 | (300 - 1,600) | 60 | (10 - 60) |
| Oceania | 1,100 | - | 200 | - |
| South Asia | 40 | - | 10 | - |
| **World Total** | **83,140** | **(52,040 - 91,840)** | **21,120** | **(12,470 - 24,070)** |

**Table 4-7: Regional breakdown of economic reserves, in concentrate terms, 2021**

| Region | Economic Reserves *Mt concentrate* | | Economic Reserves *Mt $P_2O_5$ concentrate* | |
|---|---|---|---|---|
| Africa | 54,450 | (28,550 - 61,850) | 16,300 | (8,550 - 18,550) |
| North America | 600 | (500 - 600) | 150 | (150 - 200) |
| EECA | 3,450 | (3,050 - 3,600) | 1,050 | (950 - 1,100) |
| West Asia | 1,950 | (1,500 - 2,000) | 550 | (400 - 550) |
| East Asia | 1,150 | (1,150 - 2,250) | 350 | (350 - 700) |
| Latin America | 350 | (250 - 350) | 100 | - |
| West & Central Europe | 100 | (20 - 100) | 45 | (5 - 45) |
| Oceania | 500 | - | 150 | - |
| South Asia | 25 | (20 - 30) | 10 | (5 - 10) |
| **World Total** | **62,575** | **(35,540 - 71,280)** | **18,705** | **(10,660 - 21,405)** |

These central estimates for economic reserves in tonnes of ore (83Gt) and tonnes of concentrate (63Gt) can be compared with the USGS reserves figure of 71Gt, and further highlight the mixed units of measurement used in the Mineral Commodity Summaries.

# Chapter 4.2: Depletion

This study is focussed on providing a robust assessment of the global phosphate rock geologic inventory, rather than to provide a definitive prediction of the lifetime of the resources and reserves. However, calculating a lifespan is the most meaningful metric to provide context to the figures.

To account for price elasticity, we can deplete the reserve base (technically recoverable reserves), as a shortage of phosphate rock supply will increase the price and incentivise further production. It is deemed to be too speculative to account for innovation, but there will likely be further improvements in mining techniques and beneficiation technology.

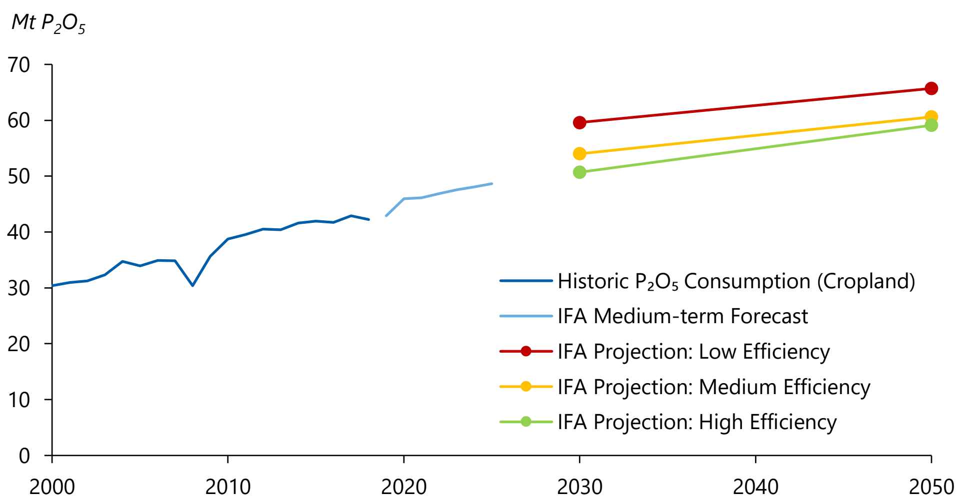
## 4.2.1. Phosphate Demand Outlook

IFA produces data on phosphate fertilizer consumption in $P_2O_5$ terms, with the period 1961-2020 freely available on IFASTAT[1]. The Association also produces Medium-Term Outlooks of how demand will evolve over the next five years.

In 2021, IFA produced a series of long-term projections for how fertilizer demand for cropland could evolve under different scenarios[49]. These projections excluded fertilizer application to grassland, forestry, ornamentals, or turf, as well as feed or industrial uses.

The projections were based on the FAO's business as usual (BAU) agriculture projections (±10pc) alongside an outlook for future nutrient management in a BAU case, medium ambition and high-ambition, accounting for an improvement towards optimal nutrient use efficiency (NUE) and an increase in nutrient recycling. For phosphorus specifically, a P soil fixing factor was applied for countries where prevalence of P-fixing soils is high, and legacy of previous phosphate applications was taken into account if soil retention was deemed low-moderate (history of surpluses or deficits).

Figure 4-1: Cropland $P_2O_5$ demand projections to 2050



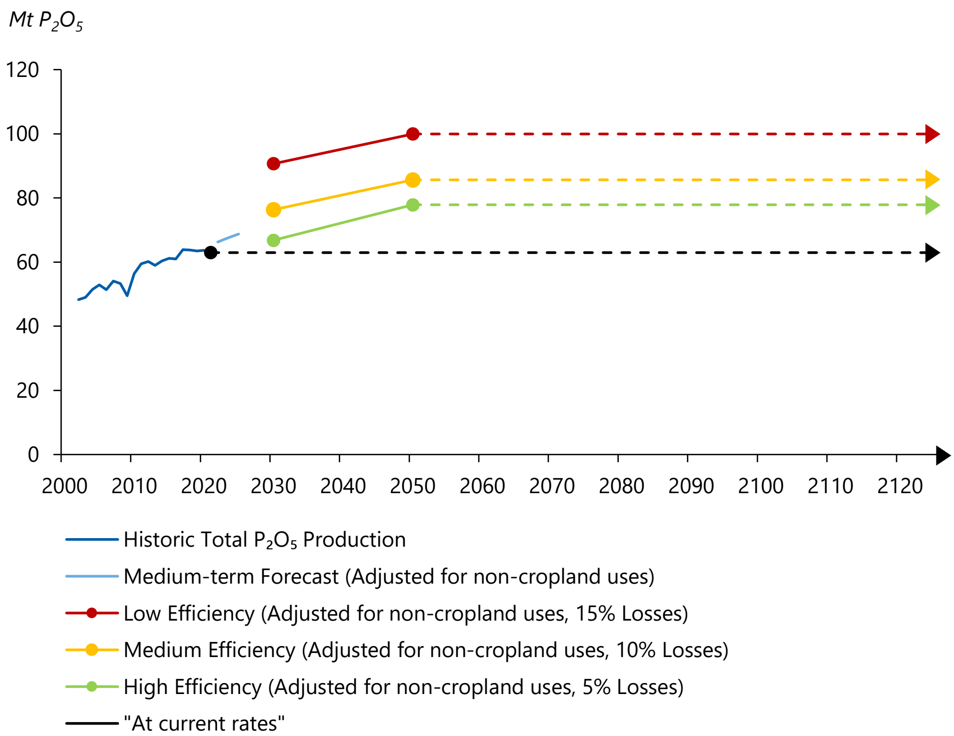

— *IFA*

As stated, these projections do not capture other fertilizer applications, such as those to grassland, nor do they account for feed and industrial uses. Based on the historical difference between the IFASTAT demand and the cropland projections, the grassland portion accounts for approximately 7.5pc, which is the central adjustment used in the medium-efficiency projection, with the low and high scenarios using 6pc and 9pc respectively (7.5pc ± 1.5pp).

To account for non-fertilizer demand, it is assumed this adjusted total fertilizer consumption accounts for 85pc of total $P_2O_5$ demand. Battery uses are handled in a separate scenario in the next section.

Phosphate fertilizer production processes tend to have relatively low losses – with the wet acid process achieving over 90pc $P_2O_5$ recovery (10pc loss), and downstream phosphate fertilizer production having around 95pc recovery (5pc loss)[50]. According to IFASTAT, global phosphate rock production in 2021 stood at 204Mt (63Mt $P_2O_5$) of marketable and useable concentrate, compared with an estimated 58.7Mt $P_2O_5$ of total demand. Therefore the total demand projections have been further adjusted to account for a total of 10pc (5-15pc) losses during the processing stages. These scenarios result in a production of 86Mt (78 - 100Mt) by 2050, which is assumed to plateau.

Figure 4-2: Total $P_2O_5$ production projections to 2050 and beyond



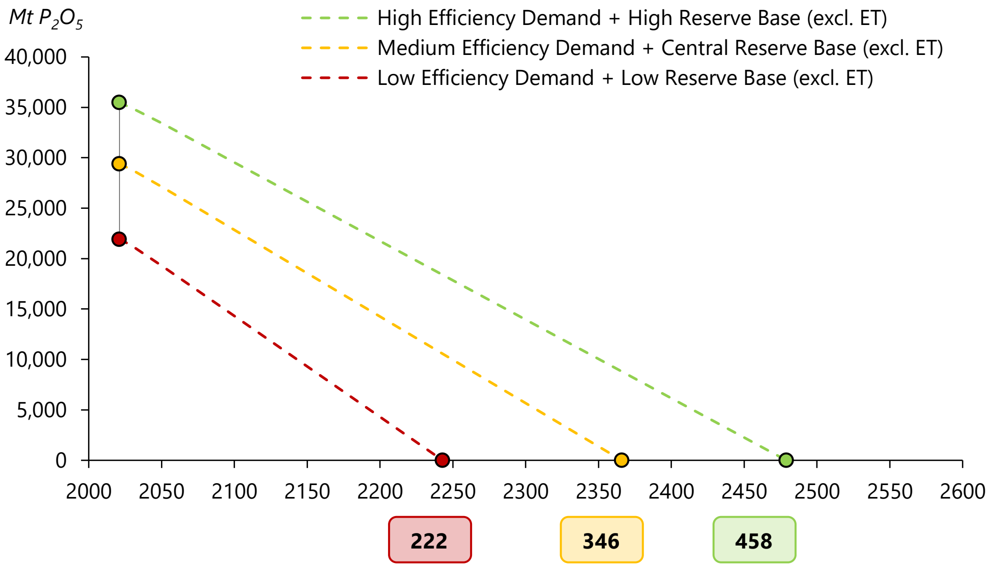

*— Argus Consulting, IFA*

**Table 4-8: Demand and production scenario configuration in 2050** *Mt $P_2O_5$*

| **Efficiency:** | **High** | **Medium** | **Low** |
|---|---|---|---|
| Cropland | 59 | 61 | 66 |
| Grassland | 4 | 5 | 6 |
| **$P_2O_5$ Consumption Subtotal (Fertilizer Uses)** | **63** | **66** | **72** |
| Industrial Uses | 11 | 12 | 13 |
| **Total $P_2O_5$ Consumption (incl. Industrial Uses)** | **74** | **77** | **85** |
| Processing Losses | 4 | 9 | 15 |
| **$P_2O_5$ Production Requirement (incl. Losses)** | **78** | **86** | **100** |

By applying these production scenarios to our upper, central and lower estimates for reserve base, years until depletion may be estimated. If only traditional phosphate rock processing techniques are included, the phosphate rock reserve base is estimated to have a lifespan of 346 years (222 - 458).

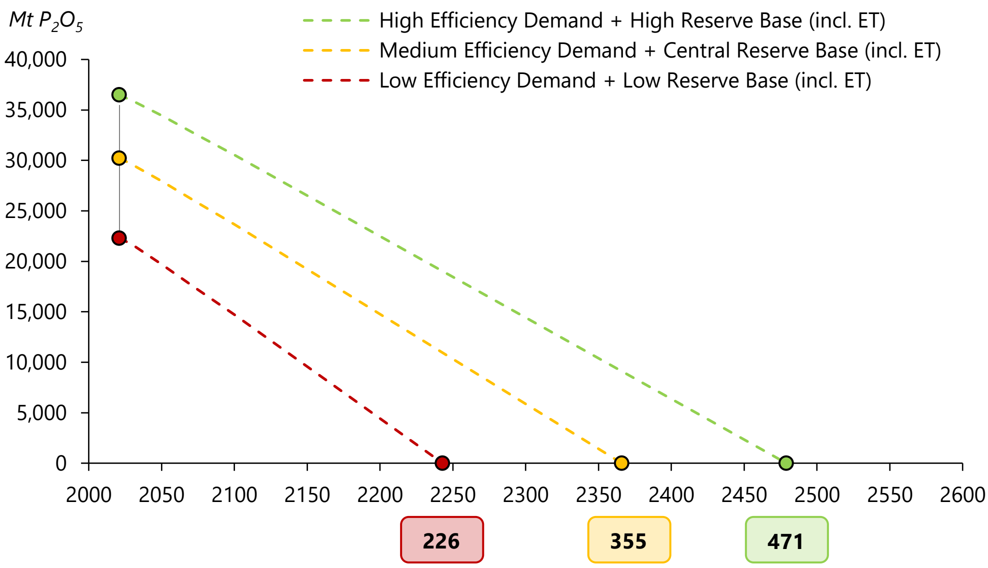
Figure 4-3: Depletion profile of the Reserve Base (only incl. Traditional Technologies)




— *Argus Consulting, IFA*

By including material that is technically recoverable with emerging technologies, i.e. those that currently exist but are yet to be widely adopted, that allow lower grade of phosphate ore to be processed, this lifespan increases by nine years (4 - 13).

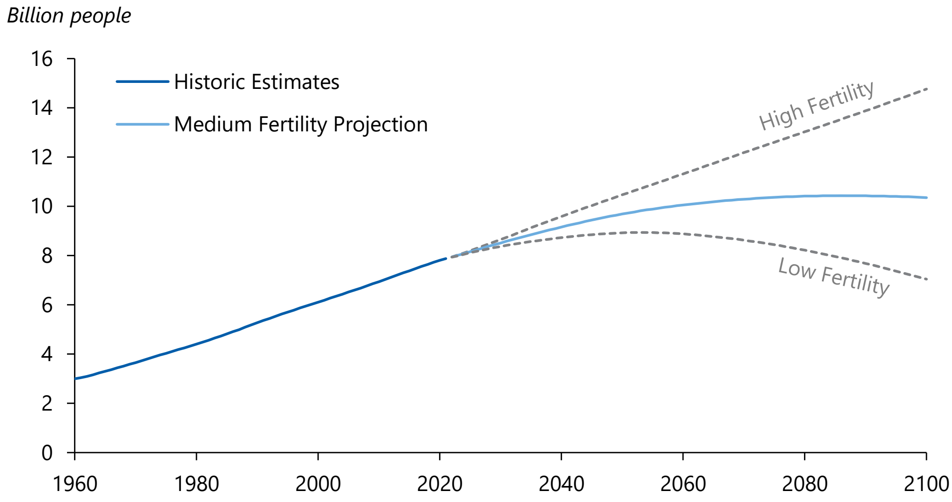
Figure 4-4: Depletion profile of the Reserve Base (incl. Emerging Technologies)




— *Argus Consulting, IFA*

Based on the latest population projections from the UN[51], which forecast a likely decline in human population, this plateau from 2050 approach appears justified given the long-term likelihood of diets shifting from meat-centric towards plant-based, as well as increasing nutrient use efficiency at the farm level. Furthermore, given the decline in birth rate over the past few years, accelerated by the Covid-19 pandemic, some authors note that the current birth trend could result in a peak much sooner than the UN projections, potentially in the late 2040s[52].

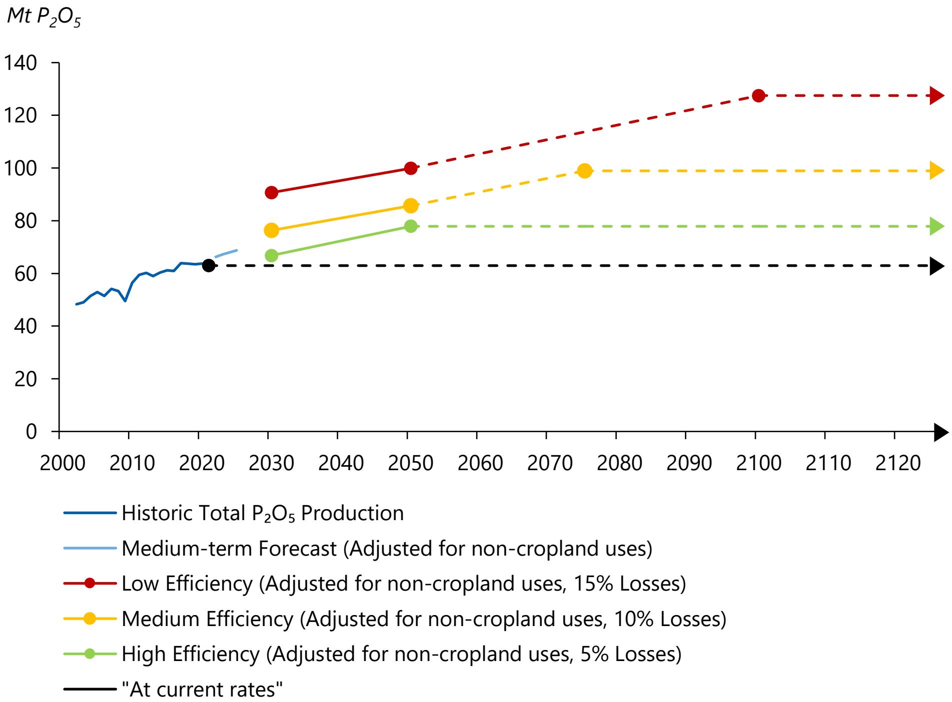
Figure 4-5: Global population growth forecasts to 2100




— *UN World Population Prospects 2022*

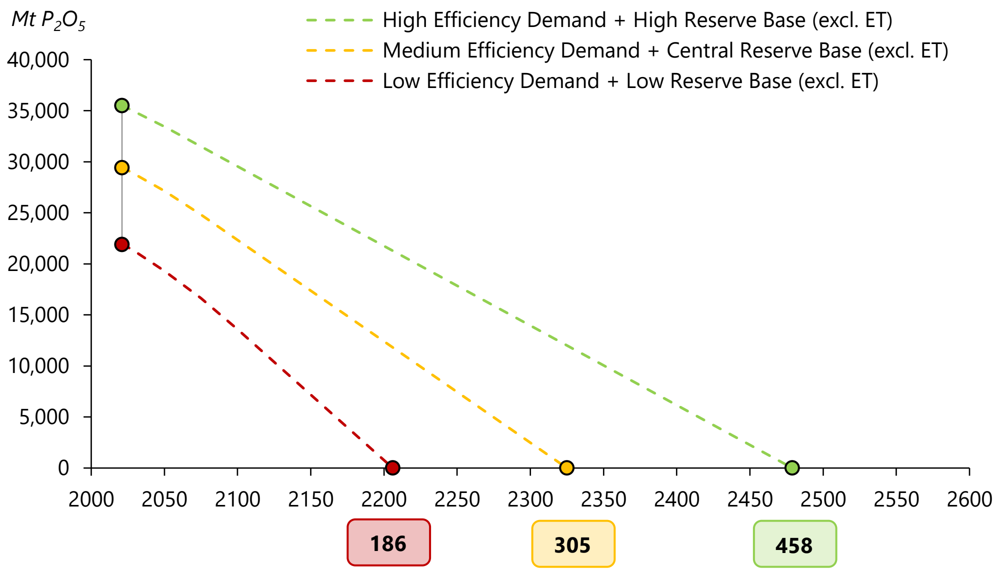
However, an "Extra High" demand scenario, with plateaus from 2050, 2075 and 2100 has been calculated, based on the high-low fertility assumptions in the UN projections. These scenarios result terminal production of 78Mt, 99Mt and 127Mt.

Figure 4-6: "Extra High" production scenario, based on 2050, 2075, 2100 plateaus




— *Argus Consulting, IFA*

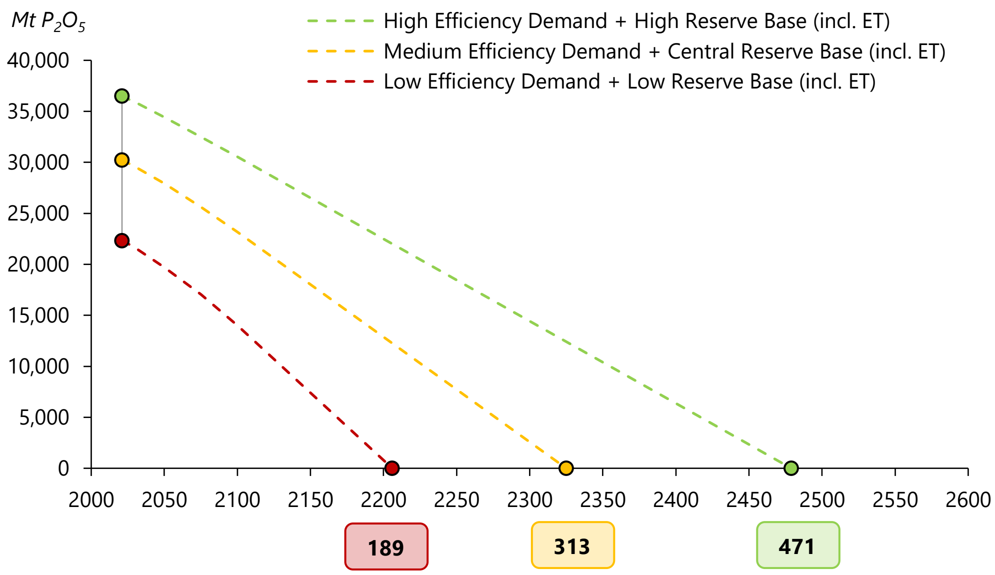
Figure 4-7: "Extra High" depletion profile of the Reserve Base (excl. Emerging Technologies)




— *Argus Consulting, IFA*

If only include traditional phosphate rock processing techniques are included, the phosphate rock reserve base is estimated to have a lifespan of 305 years (186 - 458). Including the emerging technologies, this increases the lifespan by eight years (3 - 13).

Figure 4-8: "Extra High" depletion profile of the Reserve Base (incl. Emerging Technologies)




— *Argus Consulting, IFA*

### 4.2.2. Batteries

To mitigate against climate change, there is a global shift towards replacing internal combustion engine (ICE) vehicles with electric vehicles (EVs), with many developed economies set to ban the sale of ICE vehicles in the coming decades and most manufacturers adding EVs into their product portfolio. Furthermore, in looking to replace fossil fuels in power generation, intermittent power generation methods, such as solar and wind, also face the challenge of large-scale energy storage infrastructure.

The exponential growth of the EV sector has led to rapid development of battery technology. Currently lithium-ion batteries (LIBs) are the dominant type used in EVs, however since their commercialisation there has been significant research to increase their energy density, lifespan and safety, as well as reduce the cost per unit[53]. Current typical cathode chemistries are lithium nickel cobalt oxide (NCM), lithium nickel cobalt aluminium oxide (NCA) and lithium iron phosphate (LFP)[54]. According to *Argus* data, in 2021 LFP batteries were estimated to consume just 170,000t $P_2O_5$.

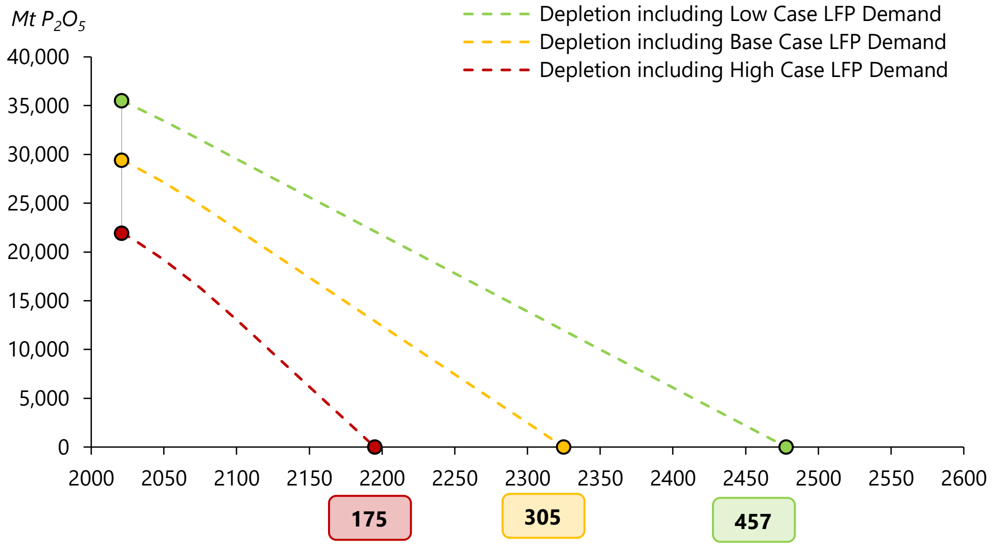
While LFP batteries have a lower energy density than nickel-based chemistries, the lack of exposure to elevated pricing of battery materials such as nickel and cobalt currently makes them an attractive choice for entry-level car models, with Tesla and Volkswagen opting for the technology.[55]

Based on the sustainable development with LFP scenario from Xu et al.[54], and subsequent calculations by Spears et al.[56], phosphate demand for LFP batteries could reach 6.9Mt $P_2O_5$ by 2050. This figure, added to the total phosphate demand from this study, represents 7.5pc (6.7 - 7.8pc). While not insignificant, agricultural uses are projected to remain the primary driver of phosphate demand within this century.

Given the rapid rate of advancement of battery technology, our core depletion estimates do not include the impact of speculative LFP battery demand - especially given the potential impact of novel battery chemistries such as lithium-sulphur (Li-S) and lithium-air (Li-Air), or as yet undiscovered combinations.

For completeness however, this study has included additional depletion profiles based on figures from Xu et al[54]. The paper includes projections based on the International Energy Agency (IEA) Stated Policies scenario (STEP), which includes existing government policies, and Sustainable Development (SD) scenario, which addresses the climate targets of the Paris Agreement. In all these additional depletion projections, the more ambitious SD scenarios are used. The base case demand scenario uses the "most likely" NCX scenario, assuming a continuation of widespread use of NCA and NCM batteries, and results in a 1.7pc market share of LFP batteries in 2050. The high case demand scenario assumes linear growth in LFP market share until a plateau of 60pc in the period 2030-50. The low case demand scenario assumes a commercial breakthrough in the development of Li-S and Li-Air, resulting in a 0.6pc market share of LFP batteries by 2050. Finally, the total demand from all battery scenarios is assumed to plateau from 2050.

Figure 4-9: "Extra High" depletion of the Reserve Base (excl. ET) with LFP battery scenarios




— *Argus Consulting, IFA*

What is harder to predict will be the use of batteries in energy storage infrastructure. LFP batteries are ideally suited to battery energy stationary storage (BESS) applications owing to their cost-competitiveness and long discharge periods. However, in the longer-term other technologies such as sodium-ion and vanadium redox flow are likely to emerge as potential alternatives.

Governments and markets should ensure that legislation and investments do not favour the use of LFP batteries over phosphate for crop-nutrition, analogous to the food vs. fuel debates surrounding first generation biofuels. Furthermore, the recovery of phosphorus from batteries should be encouraged.

### 4.2.3. Resources

Purely as a hypothetical exercise, the total quantity of $P_2O_5$ contained within all identified resources, is currently 65Gt $P_2O_5$ (45 - 88Gt $P_2O_5$). If we were able to assume advancement in technology and all the in-situ phosphate were able to be accessed (i.e. 100pc mining recovery, 100pc beneficiation recovery), we would expect a lifetime of 765 years (455-1,138). It is worth noting that even the high estimate of 1,138 does not account for the unexplored areas within Morocco, the speculative portion of the Norwegian Bjerkreim-Sokndal intrusive complex, the extensive deep portion of the US Western Phosphate Field or the currently unknowable geopotential.

### 4.2.4. Sensitivity & Summary

Each of the core scenarios presented account for both the geological uncertainty of the phosphate inventory, as well as the different projections of the future of phosphate demand. Therefore the high and low depletion estimates presented represent the plausible boundaries, with the majority of combinations resulting in our central scenario of approximately 350 years. The sensitivity to these assumptions is presented below, with the core assessment range highlighted.

**Table 4-9: Summary of years until depletion estimates** *years*

| | | Resources (at 100pc) | | | Reserve Base (incl. ET) | | | Reserve Base (excl. ET) | | | Economic Reserves | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Growth Profile** | **Plateau** | **L** | **M** | **H** | **L** | **M** | **H** | **L** | **M** | **H** | **L** | **M** | **H** |
| "At Current Rates" | 2021 | 719 | 1,038 | 1,405 | 355 | 481 | 581 | 349 | 468 | 565 | 171 | 300 | 341 |
| Low Efficiency | 2050 | 455 | 657 | 888 | **226** | **305** | **368** | **222** | **297** | **358** | 110 | 191 | 217 |
| Medium Efficiency | 2050 | 530 | 765 | 1,035 | **263** | **355** | **429** | **258** | **346** | **417** | 128 | 222 | 252 |
| High Efficiency | 2050 | 583 | 841 | 1,138 | **289** | **390** | **471** | **284** | **380** | **458** | 140 | 244 | 277 |
| Low Efficiency | 2100 | 369 | 526 | 707 | 189 | 251 | 300 | 186 | 245 | 292 | 98 | 161 | 182 |
| Medium Efficiency | 2075 | 465 | 668 | 901 | 233 | 313 | 377 | 229 | 305 | 367 | 116 | 198 | 224 |
| Low Efficiency+LFP | 2100 | 346 | 493 | 663 | 178 | 236 | 282 | 175 | 230 | 275 | 93 | 152 | 171 |
| Medium Efficiency+NCX | 2075 | 464 | 667 | 901 | 233 | 313 | 376 | 229 | 305 | 366 | 116 | 198 | 224 |
| High Efficiency + Li-S/Air | 2050 | 582 | 839 | 1,135 | 288 | 389 | 470 | 283 | 379 | 457 | 140 | 243 | 277 |

*ET = Emerging Technologies*

## Chapter 4.3: Global vs. National

These results show that on a *global level*, there are sufficient accumulations of mineable and processable phosphate rock for centuries to come. However, as with any naturally occurring resource, given the geologic processes involved, phosphate deposits are unevenly distributed across the globe – while some countries may have plenty of sizeable mineable deposits, others may have limited deposits, or even none.

This introduces the possibility of phosphate scarcity on a national scale – or rather, a reliance on imported material. This reliance could take the form of the raw material - phosphate rock, or the intermediate product - phosphoric acid. Alternatively, the production process may be moved offshore entirely, with countries choosing to import finished fertilizers such as DAP/MAP/TSP/NPKs. This dependence on globalisation increases the vulnerability of a country to unexpected price or supply shocks. When prices are high, the reprioritisation of the domestic agriculture industry becomes a factor, as seen in the elevated price levels across the entire suite of N, P, K crop nutrients since the beginning of the Covid pandemic and the Russia-Ukraine conflict.

To maintain national security of supply (and therefore domestic food security), countries or economic unions with untapped deposits could plan to harness their resources. Those without could increase long-term planning to secure some of their phosphate requirement from alternative production sources, especially via recovery from industrial, municipal and agricultural waste streams.

# Section 5: Sustainability Considerations

The results of this study should not be seen as justification to overlook sustainability practices such as improving agricultural efficiency or the recovery and recycling of nutrients to supplement mineral fertilizer usage. Furthermore, encouraging diets with lower nutrient requirements (lower intake of food of animal origin), and therefore lower environmental impacts, would see the lifespan of phosphate deposits increase even further.

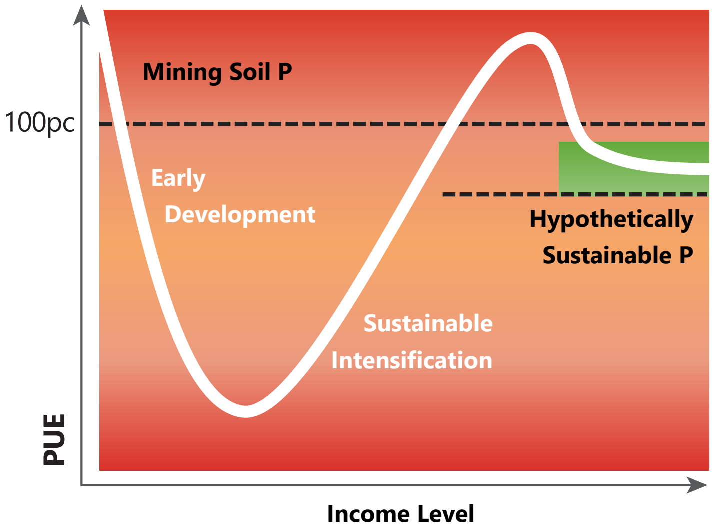
### 5.1.1. Nutrient Use Efficiency

Phosphorus use efficiency (PUE), in its simplest form, can be defined as a partial nutrient balance - the ratio of P removed from a field during harvesting, versus the sum of the inputs applied to the field (removal-to-use ratio[57]).

$$PUE = \frac{P_{output}}{P_{inputs}} = \frac{P_{harvest}}{P_{fertilizers} + P_{manure}}$$

This metric is a useful long-term indicator of nutrient management trends[31], and in November 2022 the FAO and IFA jointly launched a cropland nutrient budget database[58]. PUE of greater than 100pc indicates the soil is being mined of nutrients and is typical of the developing stages of agriculture. PUE of less than 100pc indicates that either surplus P remains in the soil or indicates losses to the environment.

Figure 5-1: Illustration of the relationship between PUE and national income level[59]




Overapplication of phosphate inputs in crop production has the potential to cause leaching into nearby water systems. Phosphorus is regarded as a key source of eutrophication of water systems[60], whereby bacteria reduce the available oxygen supply as they consume algal blooms, a direct result of rapid growth in response to the increased nutrients available. Global agriculture has been identified as the cause of 38-47pc of anthropogenic phosphorus inputs (from mineral and organic fertilizers) into freshwater[61], therefore it remains imperative to ensure that proper nutrient stewardship is applied at the farm level, using the 4Rs principle – right source, right rate, right time, right place.

In 2009, researchers identified nine planetary boundaries (PB), one of which was biogeochemical flows – represented by the global nitrogen and phosphorus cycles[62]. The concept was designed to define a *safe operating space* for humanity, to avoid crossing thresholds whereby the anthropogenic forces would rapidly destabilise the earth system. The phosphorus threshold was originally estimated at ten times (10x) of the natural background rate of ~2.3Mt/yr $P_2O_5$, in order to avoid a major ocean anoxic event, with a high degree of uncertainty.

Current estimates place the planetary boundary of phosphate applied in agriculture to be 13.7-27.5Mt/yr $P_2O_5$[63]. A better metric to track environmental stress is the surplus phosphorus which either accumulates in the soil or is lost to the environment[64,65]. The planetary boundary for surplus phosphorus is estimated at 10.3-20.6Mt $P_2O_5$/yr[59].

In order to not exceed these planetary boundaries, PUE in global crop production should tend to 68-81pc[59]. At the time of those calculations the five-year (2015-19) average of PUE stood at 65pc. Revised figures, place the same time period average at 78pc, with the estimate for PUE in 2020 at 75pc[58]. It is still deemed that PUE will need to increase slightly to be within safe operating bounds. Note that the IFA long-term demand projections do consider increasing of PUE under the medium and high efficiency scenarios.

There is a high degree of uncertainty with regards to both the measurement of the P surplus (especially the manure-P component), but also the global phosphorus planetary boundary. While on the global level PUE should remain within planetary bounds, there should still be consideration given to regional-level impacts and consumption of phosphate fertilizer needs to move from areas of overapplication (surplus) to underapplication (deficit). More developed agricultural economies should move towards precision agriculture, and those which are less developed require improved agricultural extension services to educate and inform on the importance of nutrient stewardship (4Rs).

### 5.1.2. Alternative Phosphate Sources

As discussed throughout the report, phosphorus is a key component of a wide variety of biological and industrial processes – this presents the opportunity to harness the recycling potential. Circular economy principles should be applied to phosphorus, with appropriate value applied to P-rich waste streams. Two of these alternative sources – biogas and rare-earth elements - also represent significant synergies with decarbonisation of energy systems.

#### 5.1.2.1. Biogas & Digestate

As the world transitions away from fossil fuels, there has been great interest in the production of biogas from organic matter. Installed capacity of biogas increased from 13.1MW in 2012 to 21.4MW in 2021, with Europe accounting for two thirds of this capacity[66].

The process typically uses food waste, livestock manure, crop residues, dedicated crops or sewage within an anaerobic digestor, and the collected biogas may be used on-site or upgraded to biomethane (renewable natural gas) and injected into the grid. A co-product of this process is the remaining left over organic material, called digestate, which still contains a portion of the nutrients of the feedstocks, including phosphate.

This digestate can either be used locally in whole (raw), fibre (solid) or liquor (liquid) form. In the case of local surplus, solid product can be dried and pelletised or granulated to move greater distances from the production site – therefore production and consumption do not necessarily need to be co-located.

#### 5.1.2.2. Rare Earth Elements & Tailings Recovery

Rare earth elements (REEs) are not only used for high-tech consumer goods and as catalysts in industrial processes, but are also vital for ensuring the energy transition, through use in the high-performance magnets often used in wind turbines.

The iron-ore producer, LKAB, currently mines iron-apatite at two sites in Sweden – Kiruna and Gällivare. The company plans to use magnetic separation and flotation to recover apatite concentrate from their tailings, which will be processed into phosphoric acid (for MAP production) and extract the REEs. LKAB estimates a total mineral resource of 2,319Mt @ 1.6pc $P_2O_5$, and expects the ReeMAP project to be commissioned in 2027.

Anglesey Mining have also floated the possibility of apatite recovery for their Grangesberg (Sweden) project, as have Marula Mining at Nkombwa Hill (Zambia).

The exploration for REEs will no-doubt increase the likelihood of comineralised phosphate discoveries, and the desire to extract them will make the economic extraction of the phosphate component more feasible.

#### 5.1.2.3. Industrial Recycling

Industrial uses of phosphorus, despite only being a small proportion of total demand, also represent an opportunity to recover nutrients.

One such example is fire extinguishers; half of these contain a dry chemical powder primarily composed of monoammonium phosphate. Once they reach their safe use-by date, they should be replaced. Over the past five years, technology has been developed by PhosCycle to recycle this expired powder to produce phosphate fertilizer[67]. While this may only represent a small contribution to the recovery of nutrients, it adds welcome circularity to another end-use.

#### 5.1.2.4. Manure, Biosolids & Struvite

Finally, livestock manure or human excreta offer a recyclable source of phosphorus, with notable examples of high incidence of suitability – a function of import dependence and co-location of supply and cropland – being found within India, China, southeast Asia, Europe and Africa[68]. Manure was estimated to account for 15.1Mt $P_2O_5$, or 24pc, of total cropland application in 2020[58].

Wastewater (sewage) treatment plants remove contaminants so that water may be reused. One such contaminant is phosphorus, which is removed from the solid fraction as biosolids, also known as sewage sludge, and can be precipitated out of the liquid fraction as the mineral struvite ($NH_4MgPO_4{\cdot}6H_2O$)[69].

The EU is currently looking to amend the Urban Waste Water Treatment Directive (UWWTD 91/271) to add more stringent phosphorus discharge limits and ensure improved recovery rates of both nitrogen and phosphorus from sewage works[70].

### 5.1.3. Phosphogypsum

The traditional Wet Acid Process produces approximately 5t phosphogypsum (PG) per 1t $P_2O_5$ of phosphoric acid. Currently an estimated 60Mt (30pc) of annual production is reused[71]. Further efforts are being made to safely utilise this co-product, and reach 100pc PG use, to ensure sustainable production of phosphate fertilizers in the long term[72].

PG is composed primarily of calcium sulphate, and therefore provides two important secondary crop nutrients. It may be used either directly as a soil amendment or as an additional feedstock in fertilizer production.

- It may be used to treat saline or sodic soils, as well as neutralise acidic subsoils to a depth greater than traditional lime.
- PG can be used in large quantities as a substrate for fast-growing trees. An "anthrosol" composed of soil and 80-90pc PG has been shown to produce greater plant biomass over soil alone. This application shows promise for land reclamation and carbon sequestration, with trials showing 30t $CO_2$ equivalent per hectare per year[72].
- Paradeep Phosphates in India, developed a high-sulphur granular fertilizer marketed as Zypmite, containing both PG and dolomite. Furthermore, there has been research in the production of urea calcium-sulphate (UCS) fertilizers based on PG[73,74], with SABIC trialling commercial production of UCS at their Ibn Al-Baytar plant in 2019[75].

PG may also be used in the construction industry, substituting mined gypsum in the production of cement, the production of plasterboard, bricks, and other building materials and used as bedding in road construction[72].

### 5.1.4. Reducing Processing Losses

The $P_2O_5$ recovery in phosphoric acid production is high – at approximately 95pc and 93pc for the dehydrate and hemihydrate processes respectively. A move towards technologies with higher efficiency, such as the Nissan-H or Prayon DA-HF[76], would reduce losses, and further increase the lifespan of known deposits.

### 5.1.5. Carbon Emissions

The mining of phosphate rock and processing into phosphoric acid accounts the majority of the carbon emissions from phosphate fertilizers[77]. Given the calculated lifespan of phosphate rock inventories, the global focus must shift from concerns about potential scarcity, to the decarbonisation and ongoing sustainability of phosphate rock mining, processing and use.

# Section 6: Conclusions

This study re-iterates that on the global level there are sufficient accumulations of mineable and processable phosphate rock for approximately 350 years.

Given that these numbers assume no advancement in mining and processing technology from the present day, they can be seen as a lower estimate. If we consider the total available global resources of 342Gt (65Gt $P_2O_5$), we could expect an upper limit of the known lifespan in excess of 1,000 years. This doesn't account for the unexplored areas within Morocco, the speculative portion of the Norwegian Bjerkreim-Sokndal intrusive complex, the extensive deep portion of the US Western Phosphate Field or the global "geopotential" or "geocapacity" – deposits which have yet to be found or even been speculated to exist.

However, this should not be seen as justification to discontinue sustainability practices such as improving agricultural efficiency or the recycling of nutrients to supplement mineral fertilizer usage.

Given the uneven geological distribution of phosphate deposits across the world, we are likely to face the challenge of scarcity on the national scale. This would result in a reliance on imported product or greater production of phosphate fertilizers from other production routes.

Therefore, it remains imperative to:

- Continue to mine and process phosphate rock into synthetic fertilizers in a sustainable manner, increasing recovery while producing as few carbon emissions as possible.
- Continue to develop and increase the recovery and recycling of phosphorus from various waste streams.
- Improve phosphorus use efficiency at the farm level.

Efficient use of nutrients will result in improved crop yields and farm economics, reduced aquatic ecosystem pollution via runoff and increased lifespan of currently known phosphate deposits.

As discussed in the background to the concept of global scarcity, the notion of a 'supply-driven' peak, on the basis of production constraints, is highly unlikely. However, given population projections and the environmental considerations, using alternative sources of phosphate and improving PUE, it is likely that there may eventually be a demand-driven peak as attempts are made to close the anthropogenic phosphorus cycle[25].

There is no imminent threat to the global supply of phosphorus for plant-nutrition; in fact, under all scenarios presented here, there should be good availability for abstract lengths of time. Furthermore, given the findings of the IPCC (Intergovernmental Panel on Climate Change), and the increasing sense of urgency surrounding the COP Climate Summits, attention should be focussed on the decarbonisation of the sector, rather than any perception of global phosphate scarcity.

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