Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Anna Eide Lunde

Investigating how the LFP battery demand is shaping the future of phosphorus and the role of secondary resources

A global and regional material flow analysis of phosphorus

Master's thesis in Industrial Ecology
Supervisor: Daniel Müller
Co-supervisor: Fernando Aguilar Lopez, Romain Billy, Fabrice Mathieux (JRC)
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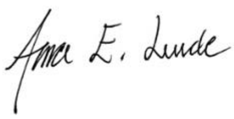
NTNU
Kunnskap for en bedre verden

Preface

This thesis is the continuation of my master project conducted fall semester 2021 and thus concludes my MSc in Industrial Ecology at the Norwegian University of Science and Technology (NTNU). I am grateful for the large amount of time and dedication both my supervisor Professor Daniel Müller and my co-supervisors at NTNU, Fernando Aguilar Lopez and Romain Billy have shown this year. Moreover, I want to give a thank you to all the external supervisors, and especially Fabrice Mathieux (JRC), who has given me valuable insights into the topic of electric vehicles.

I also want to extend gratitude to my family and friends for their support and feedback on this thesis, it has been very valued. Finally, I would like to thank my fellow students for timely coffee and lunch breaks, laughs and continuous support throughout this master degree.

Trondheim, June 20th 2022



Anna Eide Lunde

Abstract

Phosphorus (P) is one of the necessary elements for food production, with the given name ‘bottleneck of life’. The use of P as a fertilizer has increased drastically in the last decades, due to increase in population. Simultaneously, issues of resource depletion, unsustainable use of P on soil, and eutrophication of waters have been highlighted. On the other hand, P use for cathodes in electric vehicles (EVs) have increased in the last years, creating a parallel demand for P. This study aims at investigating the interactions between these parallel demands in a system perspective, to identify potential issues and barriers for P in EVs.

Using a dynamic material flow analysis and different cathode demand scenarios for P, this paper shed light on the dynamics between the cathode supply system and other uses of P in agriculture, aquaculture, and industry. Aspects such as P quality and P waste adequate to produce cathode P has been considered, both at the global and the regional level.

The results show a potential competition for P resources between EVs and food. Moreover, geographical concentrations of P production might lead to regional competition for P. Increased pressure on P resources can also influence the price of phosphate rock, consequently pushing fertilizer and food prices up, thus finding alternative sources of P is important. Steel sludge, incinerated sewage sludge ash and ferrophosphorus all show high compatibility as secondary resources for cathode P production. However, there are technological and economical barriers to using these secondary resources. Further, these secondary resources need further processing to elemental phosphorus. Elemental phosphorus manufacturing, the input material for cathodes, show high geographical concentration, high energy demand and a historically decreasing manufacturing capacity. Therefore, a high reliance on P for cathode production might be problem shifting from one cathode type to another.

Sammendrag

Fosfor (P) er et av de nødvendige elementene for matproduksjon, og har fått tilnavnet 'livets flaskehals'. Bruken av dette stoffet i gjødsel har vokst drastisk de siste tiårene, grunnet en voksende befolkning. Samtidig har problemer som ressursutarming, overbruk av P i jord og eutrofiering av vann blitt løftet fram. De siste årene har også en parallell bruk av P i batterier for elbiler oppstått, som en del av den nødvendige omstillingen av energinettverket. Dette studiet tar for seg interaksjonene mellom disse bruksområdene for P i et systemperspektiv, for å identifisere mulige problemer og barrierer for P i elbiler.

Ved bruk av dynamisk materialstrømanalyse samt ulike behovsscenarioer for P i katodebruk, får man innblikk i dynamikken mellom forskjellige bruksområder av P. Aspekter som P kvalitet og P avfallsstrømmer som kvalifiserer til P produksjon for katoder er fremhevet, både på et globalt og et regionalt nivå.

Resultatene viser at en mulig konkurranse for P ressurser kan oppstå mellom batteri- og matsektorene. Videre kan geografiske konsentrasjoner av P produksjon føre til regional konkurranse om P. Høyere etterspørsel av P kan også påvirke prisen på fosfatstein, og dermed også gjødsel- og matvareprisene. Slam fra stålproduksjon, kloakkslamaske og ferrofosfor viser alle høy kompatibilitet som sekundære ressurser for katode P produksjon. De samme sekundære materialene har imidlertid også teknologiske og økonomiske barrierer, siden de må bli prosessert til elementær fosfor før bruk i elbilbatterier. Denne produksjonsmetoden har imidlertid høy geografisk konsentrasjon, høyt energibehov, og en historisk synkende produksjonskapasitet. Disse aspektene illustrerer hvorfor en høy avhengighet av P baserte katoder kan resultere i nye problemer for batteri produksjon.

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List of abbreviations

BAU = Business as Usual

BOF-BF = Basic Oxygen Furnace – Blast Furnace

Co = Cobalt

EAF = Electric Arc Furnace

EV = Electric Vehicle

Fe = Iron

FeP = Ferrophosphorus

ISSA = Incinerated Sewage Sludge Ash

LFP = Lithium Iron Phosphate

Li = Lithium

LIB = Lithium-Ion Battery

MFA = Material Flow Analysis

Mn = Manganese

NCA = Nickel Cobalt Aluminum

Ni = Nickel

NMC = Nickel Manganese Cobalt

NPK = Nitrogen Phosphorus Potassium

P = Phosphorus

P_2O_5 = Phosphorus Pentoxide

P_4 = Elemental Phosphorus

P-acid = Phosphoric acid

PUE = Phosphorus Use Efficiency

SSS = Stratified Societies

TS = Towards Sustainability

1. Introduction

Phosphorus (P) is one of the three essential nutrients for life, being a necessary part of food production as a fertilizer component. In the last 75 years, throughout the Green Revolution, the use of P for mineral fertilizer increased tenfold (Villalba et al., 2008). Unlike nitrogen, another essential element, P is not a renewable resource and is produced from finite phosphate rock resources. While the mining of phosphate rock was barely 20 Mt/yr in the 1940s, it has enlarged to 227 Mt/yr in 2019 (Daneshgar et al., 2018). The increasing trend of fertilizer use has historically followed population growth from the 1950s, with a clear correlation between population and phosphate rock mined (Daneshgar et al., 2018). The observed dramatic increase in the production of phosphate rock is not expected to decline in the future, but rather continue its steep increase due to increasing population, growth in animal based food diets and overuse of fertilizer (Chen & Graedel, 2016). To meet the Sustainable Development Goals by 2030, a 39% increase in fertilizer production is necessary (Langhans et al., 2021), and by 2100 the amount of phosphate rock mined will have doubled compared to now (Van Vuuren et al., 2010). Therefore, the large demand in P for fertilizer has caused a great debate regarding the sustainability and availability of P for future generations. This has led to P earning the name ‘bottleneck of life’, being a restrictive factor for human food production (Jupp et al., 2021).

While the extraction of P resources is expected to intensify in the future due to food production, a more recent parallel demand has also been identified as P for Lithium Iron Phosphate (LFP) cathodes. A shift to electric vehicles (EVs) is taking place, with the global sales of electric cars tripling in the past two years (IEA, 2022). This increase is expected to continue (see Figure 1), to reduce the large emissions in the transport sector as a measure to combat climate change (de Souza et al., 2018).

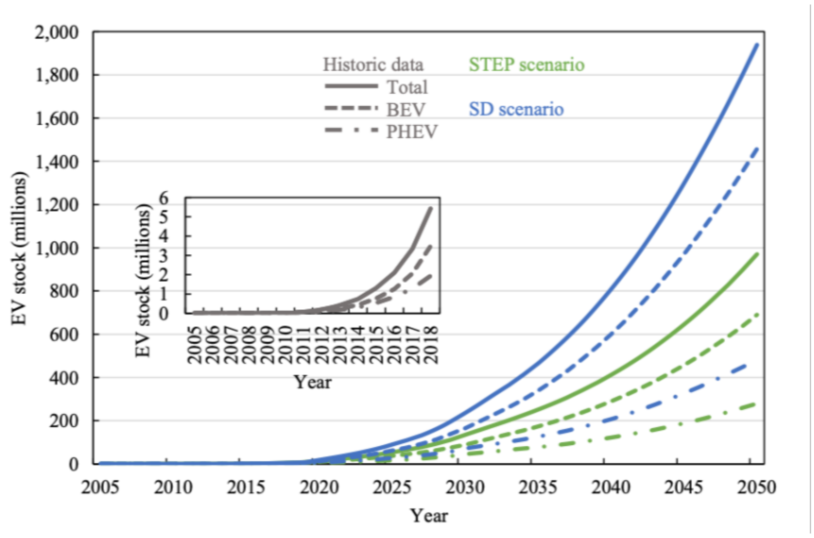

Figure 1: Expected EV increase until 2050. BEV = Battery Electric Vehicles. PHEV = Plug-in Hybrid Electric Vehicles. STEP and SD refer to two different EV penetration scenarios. Source: Xu et al. (2020)

It is widely expected that the electrification of the vehicle fleet will continue to rely on lithium-ion batteries (LIBs) in the next decades (Xu et al., 2020). LIBs are a term used to describe a wide array of different battery chemistries, which require a range of materials including P, nickel (Ni), lithium (Li), cobalt (Co) and manganese (Mn). There are widespread concerns regarding the sustainability of the continued use of Co, Ni, and Mn, in NMC and NCA batteries, due to political supply constraints (Olivetti et al., 2017), material supply criticality (Helbig et al., 2018) and availability (European Commission et al., 2020). LFP batteries on the other hand do not contain Ni, Co or Mn and are instead based on iron (Fe) and P. Indeed, authors such as Zeng et al. (2022), Olivetti et al. (2017) and Helbig et al. (2018) conclude that LFP cathodes is the better choice when looking at the supply constraints connected to other battery materials. Moreover, LFP cathodes are also considered safer, to have longer lifetimes and lower production costs (Li et al., 2018). These aspects have led to a new wave of LFP cathodes being produced, with LFP constituting 64% of all cathodes produced in China in May 2021 (Zou & Shi, 2021). This trend towards LFP batteries may put increased pressure on P demand and cause a potential competition for resources with the fertilizer industry and therefore also food production (Spears et al., 2022). Hence, the interactions between the dual demand for P, as a battery material and an input for food production, needs to be better understood to allow for food security and a cleaner energy transition in a sustainable way.

Furthermore, the predicted increase in P demand do not come without issues. The persistent use observed has also led to discussion regarding the future availability of P resources.

Material scarcity is defined to have five dimensions; physical, geopolitical, managerial, institutional and economical (Cordell & White, 2014). Global physical scarcity of P has been estimated by various authors, some believing that the P deposits will be depleted in the short-term, while others believe the economic market will ensure sufficient future supply (Cordell & White, 2014). What lies in the heart of the discussion is the uncertainty of the size of available resources, and at what speed they will be depleted (Cordell & White, 2014). Moreover, while the debate on global physical scarcity has not seen a consensus, authors agree that there will be a degree of regional physical scarcity. The resources of phosphate rock is geographically concentrated, with more than 70% of the total resources found in Morocco and West Sahara alone (USGS, 2021). This can leave regions vulnerable to changes in trade policies, limiting the availability of importing P sources. The regions with the highest population growth and subsequent demand for fertilizer for food are also the regions with the least available phosphate resources (Nedelciu et al., 2020). While physical scarcity can occur, managerial decisions also impact the timeframe of physical depletion. According to Cordell and White (2014) the poor management of P, together with skewed economic purchasing ability of P resources, further contribute to the perceived scarcity of P. As such, no clear agreement can be found on whether there is a shortage of P resources in the short term. However, an understanding can be found on the necessity to understand the whole P system to prevent overuse and unsustainable usage of P. Moreover, geopolitical dimension of P highlights the increased importance of two things; (1) Looking at how the global perspective alone can mask challenges on a regional level, meaning that investigating regional areas are important, (2) with primary resources becoming obsolete, identifying secondary resources and their potential becomes significant.

Next to issues regarding supply, issues are also tied to the use phase of P, where large amount of P on agricultural soil has led to eutrophication from water runoff, with large parts of the European and American coastlines being declared dead zones. Indeed, these large scale consequences have put use of P as one of the planetary boundaries (Cordell & White, 2014). Additionally, price spikes and phosphate rock shortages have been seen historically, with massive price fluctuations in 2007 and 2008, with a 900% increase at the peak (Heckenmüller et al., 2014). This can in turn increase the price of food, tightening the competition for food resources and potentially disproportionately affecting developing countries.

System analysis can reveal and highlight barriers and opportunities of material use through material flow analysis (MFA). Examples of substantial accumulation of P in the soil, and large waste streams, such as steel slag, along the supply chain has been revealed through this method (Cordell et al., 2009; Lun et al., 2018). Similarly opportunities of synergies between P consuming industries have been identified (Matsubae et al., 2015). MFA based studies have also been done of specific industrial sectors: agriculture (Ott & Rechberger, 2012; van Dijk et al., 2016), steel (Jeong et al., 2009) and aquaculture (Huang et al., 2019). Phosphorus MFA has also been applied at different level of analysis, national and global, identifying the challenges pertaining to geopolitics of P (Chen & Graedel, 2016; Matsubae-Yokoyama et al., 2009). However, all the above-mentioned studies exclude the use of P for battery production and have failed to extend their analysis to include the future sector of P in EVs and potential sources for secondary P availability to mitigate the increase in demand.

This paper aims at filling this gap by concluding a broader MFA looking at all sectors of P use, including LFP. To do so it will investigate the dynamics between different uses of P with a system approach. Two MFAs will be conducted, one at the global level and one at the EU level. A global level P analysis will detect potential competition and issues between the food system and LFP system, together with options for the reuse of P. The EU regional analysis will on the other hand shed light on the options and limitations for regions having limited domestic primary P resources. Thus, the objective of this paper is to identify barriers and opportunities for P use in LFP in a system perspective, both at the global and regional scale.

1.1 LFP and phosphorus

The P component in LFP production require high purity and concentration, and therefore only one production method produce the appropriate quality of phosphoric acid (P-acid) (JRC, 2020). In the Wöhler process phosphate rock is thermally treated to produce elemental phosphorus (P_4) with a purity of more than 99% (Diskowski & Hofmann, 2000). Elemental phosphorus together with phosphate rock have also been listed as two of the critical raw materials of the EU, even considered to have a substantially larger economic importance and supply risk than other battery materials such as Li and Ni (European Commission et al., 2020). Europe shut down its last P_4 production in 2012, and since then only four countries produce P_4 globally; China, US, Kazakhstan and Vietnam (Ohtake & Okano, 2015). Despite this fact together with the predicted increase in LFP production, few authors have included P_4 in their research. On a regional level a study was found including LFP in a wider systemic perspective for China. Luo et al. (2017) predicted that LFP would increase fivefold by 2025 in China, increasing the share of P-acid going to end use LFP to 5,7% compared to 2014. As this study was conducted before large investments were done by China in the LFP sector, this number could even be considered conservative. In Europe a study was conducted on the material flows of P_4, but contrary to most studies Matos et al. (2021) limited their study to P_4 and excluded other non P_4 derivatives. They found that P_4 derivatives are imported to the EU in smaller and larger quantities, and likewise end up in a range of different human uses (Matos et al., 2021).

To conclude, as Spears et al. (2022) points out in their commentary, P is hardly considered in the research and discussion on battery materials. A paradox therefore occurs where past literature has seen it as the solution to material issues in battery production, but does not investigate the challenges and issues of P. Thus, a potential problem shift can follow when production moves to LFP, if the production keeps being reliant on primary resources.

1.2 Secondary resources for LFP production

To alleviate the demand on primary resources both present and future, many authors have looked at potential secondary resources. While the primary input into the P system is phosphate rock, P is lost at many points during the production phase, use phase, and waste disposal. Authors have found that the phosphorus use efficiency (PUE) can be as low as 5% (Scholz & Wellmer, 2019). The PUE is the ratio of P that reach human consumption to P mined in phosphate rock. Recycling of secondary materials for use as fertilizer has been vastly research, with manure found appropriate as fertilizer, steel sludge as construction material and P recovered from wastewater (Ohtake & Tsuneda, 2019). Less emphasis has been on P recycling for LFP production. The focus of this study is to look at potential options for LFP P material, and thus the scope of this section is only on options pertaining to LFP.

A few secondary resources have been identified to have potential for use in LFP batteries. Ferrophosphorus (FeP), a by-product of P_4 production, has been tested at lab scale to prove adequate for manufacturing of LiFeP precursor for LFP (Ma et al., 2019). At a commercial scale incinerated sewage sludge ash (ISSA) was used as a feedstock for P_4 production in the Netherlands, before it was shut down in 2012 (Desmidt et al., 2015). Next, steel sludge has been highlighted as having the potential for recovery of P to P_4 production, as it has many of the same properties as phosphate rock. Another large waste stream, aquaculture sludge is also investigated due to the size and accessibility of the P, but no research is found on its application as LFP feedstock. Manure would likewise be a large P waste flow, but the resource has already achieved large circularity within agriculture. On the other hand, water runoff from agricultural soil and smaller waste streams from niche P_4 derivatives are considered infeasible due to access constraints.

One region where secondary materials will be important is the European Union (EU). The EU only has small domestic resources of P, and therefore the majority of the P is imported. The imports happen at all levels of the P chain, from phosphate rock, to P containing products such as food. As such, the only opportunity for the EU to become independent of P imports for LFP production is to use the P resources already existing within the region. Moreover, as the EU has a large automotive sector initating battery manufacturing projects, identifying the potential of domestic material is increasingly important (Eddy et al., 2019).

1.3 Research questions and scope

This study aims at taking a systemic approach, building on, and extending old research. It specifically builds on the project thesis, *The Role of Lithium Iron Phosphorus Batteries in the Phosphorus Cycle at the Global and EU level,* conducted fall 2021 (Lunde, 2021). The thesis project quantified the global and EU P systems for 2019, looking at both supply, production and end uses. Moreover, the thesis project identified potential problems with continued reliance on P for LFP in the supply chain of P. Additionally, it also highlighted a need for a clear systematic approach when considering the future P system, to reveal potential competition between food and LFP. Building on the work and findings made in the project thesis, this study extends it by considering future developments. Moreover, the technological potential and availability of secondary resources is also evaluated in this report, to illustrate the circular possibilities for P and LFP production. Per se the goal of this report is to increase the understanding of the P cycle, including food and LFP producing sectors, and reveal potential competition and consequences of increased production. Moreover, options of secondary uses are identified and evaluated to contribute to a circular future of P. Following this, the research questions that will be addressed are:

1. How do the global and EU phosphorus systems react to changes in the demand for LFP grade phosphorus?
2. What is the potential of secondary sources of phosphorus to alleviate demand on primary phosphorus for use in LFP?

2. Methodology

The methodology used in this study is based on Material Flow Analysis (MFA). The main principles of MFA are outlined in Brunner and Rechberger (2016). First, a system definition was established, set in time and space to understand the relevant processes in the P cycle. Second, a dynamic model was developed, to simulate the dynamics of the system and allow for changes in the system over time. The period modeled was 2019-2050, where 2019 was the base year for the quantification of the P flows. A general overview of the P system definition can be seen below in Figure 2 to provide context. A more detailed systems will be introduced later.

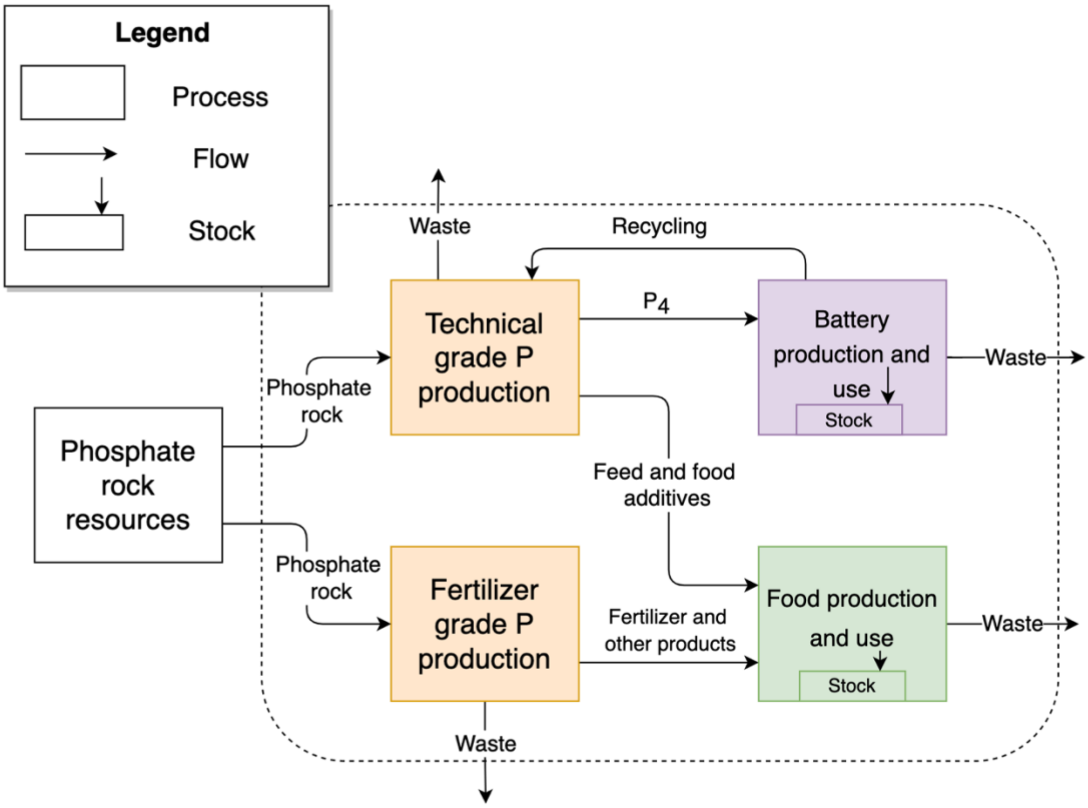

Figure 2: General P system. The white box represents the reserve of P outside the system boundary. The two yellow boxes indicate the supply system, while the green and purple box represent two separate end uses.

The P system can be in general divided into two distinct routes; (1) production route for battery use of P, and (2) production of P for food uses. For the food production, phosphate rock is mined and processed to different types of agricultural products in *Fertilizer grade P production*, where the fertilizer then enters *Food production and use*. While some of the P goes to stock in soil, P also exists the system as food waste, water runoff or to landfill. On the battery production route, phosphate rock is also mined, but enters *Technical grade P* *production*, where the P_4 can enter *Battery production and use* or *Food production and use,* as feed and food additives. Waste flows exists for all processes, as slag, sludge, or other waste.

As this report investigates two different scopes, the global and the EU, two different system definitions are created. While the latter does not contain trade flows, the former does. Consequently, the system definitions for the two models will therefore have differences. The EU model will include flows of traded P products entering and exiting the system. Moreover, the EU does not have domestic production of P_4, and therefore this is omitted from the EU system definition. First the system definitions will be displayed and discussed for both systems. Then the model development will be explored, with the model input and calibration of the drivers for the model and the model coefficients shown. Third, a short explanation of scenarios is presented and lastly the exploration of a barrier to production of P_4 is done. Next, a short discussion on the uncertainty of the model inputs and choices is conducted. Lastly, while the methodology will here be outlined in the above order, the process has been iterative, and changes have been informed by both data and literature.

2.1 Global system definition

In Figure 3, the detailed system definition of the global model is presented.

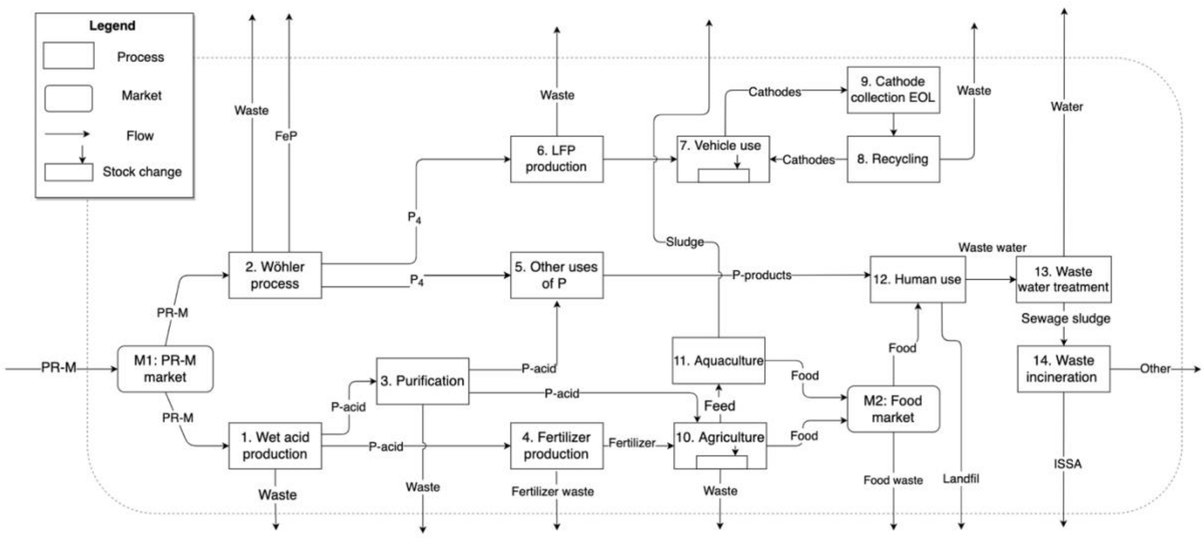

Figure 3: Global system definition of the P cycle, excluding steel production.

The system is defined with the research aim in mind, meaning that the level of detail of the flows vary across processes. Some waste flows might contain different materials but are kept aggregated as one flow. Conversely, other waste flows are disaggregated when for example one of the waste flows are deemed adequate for recycling of P for LFP production. For example, in the *Wöhler process* (2), FeP is distinguished from other waste as literature has shown its suitability for LFP production (Ma et al., 2019). Other waste from the same process (2) occur as fly ash or is lost through air, and is therefore not recoverable (Diskowski & Hofmann, 2000). A detailed description of all the secondary resources of P identified and considered is found in Appendix I. All processes are kept within the system boundaries, with waste assumed to exit the system boundaries either as waste to water, landfill, or air.

Phosphorus enters the system as beneficiated phosphate rock (Flow 0-M1), rather than untreated mined phosphate rock, which is kept outside the system boundaries due to uncertain data on the tailings, other mining waste and concentration of the mined phosphate rock (Jupp et al., 2021). Specifically, data on beneficiated phosphate rock has the benefit of having a more homogenous concentration of P, than untreated P rock across geographical locations. The beneficiated phosphate rock enters a *phosphate rock market* (M1) which provides phosphate rock for either *Wet phosphoric acid production* (1) or the *Wöhler process* (2). Elemental phosphorus production (2) is done in a thermal process (Wöhler), where phosphate rock is heated and oxidized to produce pure P_4 (Gilmour, 2019). Technically the P_4 needs further processing to P-acid, before LFP production. However as this process have no waste flows, it is eliminated here (Chen & Graedel, 2016). Elemental phosphorus is then transported either to *LFP production* (6), or to *other uses of P* (5). *LFP production* (6) is the production of cathodes, which then go into *Vehicle use* (7). Cathodes can also be recycled, and the P can be returned to *Vehicle use* from the *Recycling process* (9).

The second outflow from *Phosphate rock market* (M1) goes to *Wet acid production* (1), which is the most common method of phosphate rock processing. Here, phosphate rock is treated with sulfuric acid, creating a quite impure and low P concentration P-acid (Gilmour, 2019). Some of this acid is further purified in *Purification* (3) to higher concentrations and purity, to be used for feed or other human uses. Most of the acid however goes to *Fertilizer production* (4). From there P enters *Agriculture* (10), which consists of a multitude of process, however here they are aggregated due to the scope of the project and data availability limitations. *Other uses of P* (5) is a process that contains a vast amount of different P_4 derivatives, such as toothpaste, medicine, and food additives and needs input from either *Wöhler process* (2) or *Purification* (3).

From *Agriculture* (10) P in the form of feed goes to *Aquaculture* (11), and in the form of food to the *Food market* (M2). From *Aquaculture* (11), P exits the system either as sludge or as food going to the *Food market* (M2). In the *Food market* (M2) there are further losses in transportation, handling, and storage. Together with food, other products containing P enters *Human use* (12). From *Human use* (12) P either goes in wastewater, through human excrete and detergents mostly, or it assumed to be lost and go to landfill. Wastewater can be treated to sewage sludge in *Wastewater treatment* (13), which can then be produced to ISSA in a *Waste incineration* (14).

Steel production system

An exception in the P cycle is the production and use of steel. Due to steel using iron ore as its primary input, rather than phosphate rock, the system definition is kept separate from the general P system. Further, little interaction can be found between the general P system and steel production, with only a small amount of FeP, a by-product from technical grade P production, entering steel production yearly (Morton & Edwards, 2005). However, as steel sludge is seen as one potential source of secondary P for LFP production, it is necessary to include steel in the model (Yu et al., 2022). The steel P system can be seen in Figure 4 below.

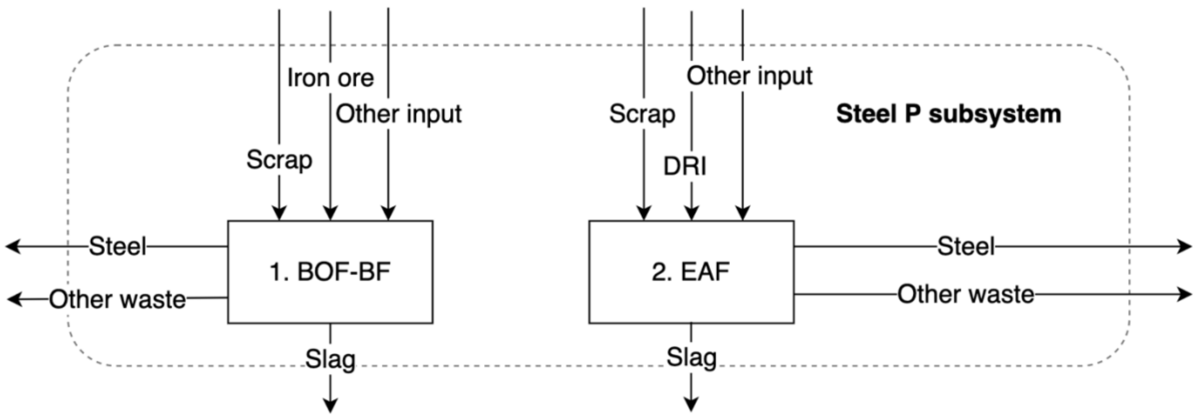

Figure 4: Steel subsystem for P, with the recovery system of P from steel slag.

Iron ore together with other inputs, coal, limestone, and steel scrap, enters either steel production through Basic-Oxygen Furnace (BOF-BF) or Electric Arc Furnace (EAF). The difference between the two pertain to the ratio of iron ore and scrap input, with the latter using substantially more steel scrap and less iron ore (World Steel, 2021a).

2.2 EU system definition

Further considerations need to be taken with the regional model of the EU, which has trade flows of P, with food, feed, animals, and miscellaneous all containing P being exported and imported to and from the region. While it is possible to calculate the complete system using trade data historically, predicting trade flows for the future would be challenging, and entail large uncertainties. One of the objectives of this study is to look at the potential of secondary resources of P in the EU, and therefore the system definition was created so that this would be possible without relying on trade flows. Consequently, the model only considers secondary resources from domestic production of material and not imported secondary resources. An overview of the EU general P system definition can be found in Figure 5. Aquaculture is omitted from the system definition as the EU do not produce substantial amounts. Moreover, LFP production is included, however the EU is not currently producing LFP cathodes domestically. This is to give a comparison to other parts of the system. Moreover, primary manufacturing of P, wet acid and fertilizer production is excluded, and the EU does not have P_4 production domestically.

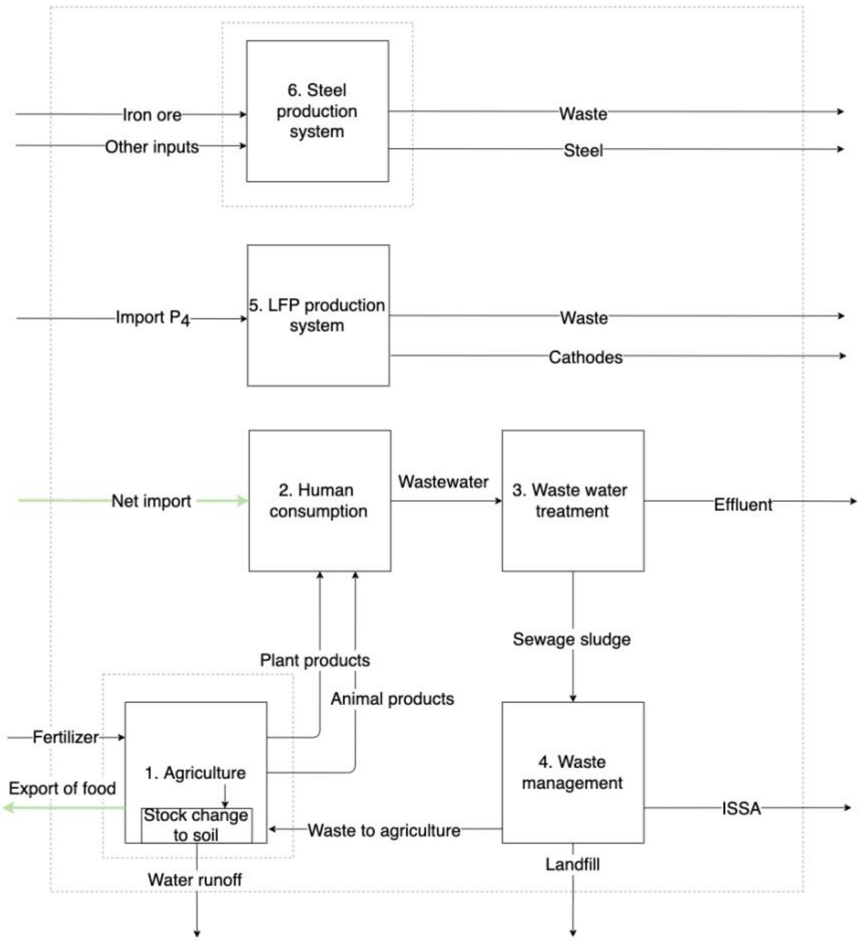

Figure 5: EU general system definition. Green flows represent necessary trade flows.

The bottom part of the system is almost identical to the global system definition, except for waste entering *Agriculture* (1) from *Waste management* (4), and trade flows. To account for food consumption that is not domestically produced, a net import of P products is included in *Human consumption* (2). This is to balance this process in terms of P. Moreover, the data used for *Agriculture* (1) designates the quantity of food produced and whether it goes to human consumption or to feed to animals. A gap between the amount produced and the products going to human consumption and animal consumption was identified, and therefore the rest was anticipated to exit the system as exports. *Wastewater treatment* (3) has an outflow of cleaned effluent, and sewage sludge which is treated wastewater. This process is important in Europe to avoid eutrophication of water (Ott & Rechberger, 2012). In *Waste management (4)* sewage sludge together with household waste is treated in numerous ways in waste management. However, here only three ways are considered. First, waste to agriculture is chemically or biologically treated sewage sludge that is used as fertilizer. Moreover, the amount of sewage sludge that is further incinerated is seen as a flow. As ISSA can be used as feedstock for thermal production of P_4, it is here kept as a separate flow. Lastly, all other treatments are aggregated in one flow here assumed to go to landfill.

Agriculture

The agricultural subsystem is seen in Figure 6, with the sector split into two separate processes. While the inflows and outflows of this system definition are the same as the inflows and outflows of agriculture in the general P system, there are internal flows. *Agricultural soil* (1a) provides plants and residues to *Animal production* (1b) as feed for husbandry. Moreover, manure produced by husbandry is returned to agricultural soil from *Animal production*. While not all manure is applied in general to agricultural soil, here it is assumed that all manure is returned to soil. This is also in line with other regional studies such as Ott and Rechberger (2012) and van Dijk et al. (2016).

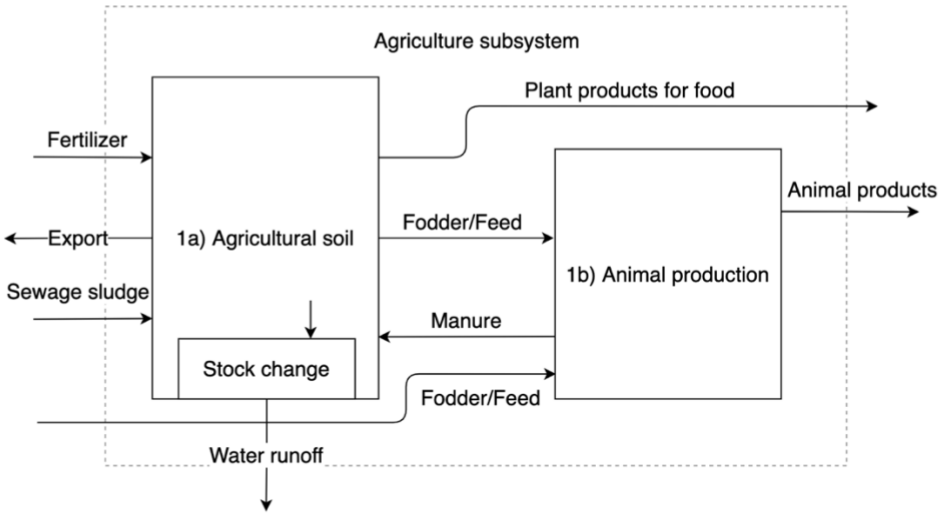

Figure 6: EU agriculture P system.

Steel

The EU steel subsystem is the same as for the global steel subsystem. See Figure 4, with the explanation of the system beneath.

2.3 Model development – Global

A dynamic substance flow analysis was conducted at the global level, both for the general P system and for the steel subsystem. The model was developed using a mix of supply and demand drivers, with seven drivers used in total. The drivers are agriculture food production, aquaculture consumption, fertilizer demand, other products containing P, wastewater produced by the population, demand for LFP cathodes and steel production. These drivers are quantified each year from statistics or forecasts. While six of the flows are given quantities, the rest of the system was calculated through transfer coefficients and mass balance. A transfer coefficient can be the efficiency of a process, yield or based on statistics, for example food waste. An overview of the flows and how they are calculated are shown in Figure 7.

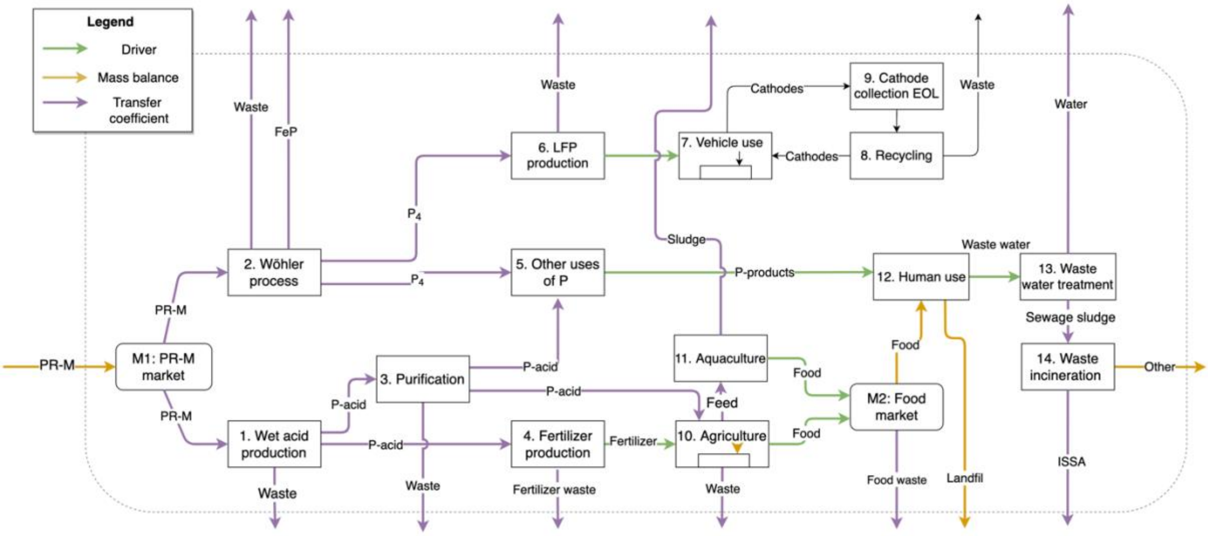

Figure 7: Graphical representation of the model data sources. Arrows without color are only considered for LFP recycling scenarios, not for the base model.

The flows downstream of the drivers are calculated as inflows driven, while the flows upstream of the drivers are calculated as outflow driven. The way these drivers inform other flows is illustrated in Figure 8. The darker shaded arrows illustrate the drivers, while the same color but lighter shade arrows show which flows are induced by the respective driver. Arrows with more than one color is induced by more than one driver.

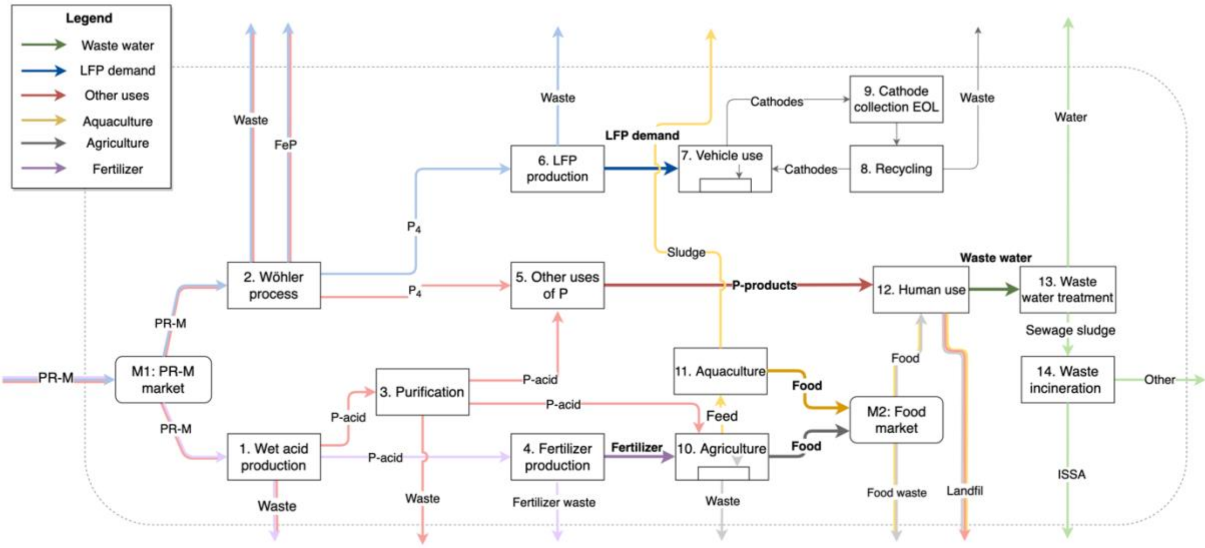

Figure 8: Visual representation of how the global dynamic model works. The darker shaded arrows represent the drivers, while the faded shades represent flows induced by these drivers. A combination of colors is used when more than one driver induced the flow. Pink = Other uses, green = Wastewater, blue = LFP demand, purple = Fertilizer demand, yellow = Aquaculture consumption, grey = Food production. The grey flows are for recycling of cathodes and are only used for some scenarios.

The above approach was taken on a year-to-year basis, where the base year 2019 was the only year quantified using historical data. Since the system has no stocks, only stock change, it was not seen as necessary to consider a large historical time frame. This is because past years do not affect the future years and the future dynamics of the model. A time period from 2012 to 2019 was therefore only used to calibrate the drivers, and not considered when running the model. Below the data input for each of the drivers are explained, both the historical data and future scenarios of production and consumption. A combination of Microsoft Excel and Python was used to quantify and run the model.

Due to the choice of aggregation of the agriculture process a more detailed explanation of this part is necessary. The agriculture process is based on the soil budget approach by Bouwman et al. (2017), which is expressed in the following equation:

$$P_{residual} = P_{fert} + P_{man} - P_{withdr} - P_{runoff}$$

The inflow to agriculture is the amount of fertilizer (P_{fert}) applied together with manure (P_{man}). The outflows are P withdrawal to harvesting of crops (P_{withdr}) and through P runoff in water (P_{runoff}). The rest is assumed to accumulate in the soil ($P_{residual}$). Atmospheric deposition is ignored in line with studies such as Bouwman et al. (2013) and Kremer (2013), as it accounts for a minor addition of P to agricultural soil. Manure is not visualized as an outflow from the system definition, as it is often reused within agriculture itself. The P that does not exit agriculture through water runoff or food products is assumed to accumulate in the soil.

2.3.1 Model input and calibration - Drivers

In Table 1 below, the overview of the drivers used in the model together with the datapoints, years, sources and calibration method are displayed. An explanation of the calibration and data collection of the drivers then follows. Stock of animals is not a driver per se; however, it is used to model the manure, and thus water runoff, and the stock change of P in agricultural soil more accurately. It is quantified yearly in a similar manner to the drivers and is therefore included in this section.

Table 1: Overview of data input for the drivers together with the sources. The dark grey font refers to input variables for the linear regression run for aquaculture. Stock of animals in italic is not a driver per se but is calibrated and therefore included in the overview.

Driver	Unit	Years	Calibration method	Historically – Source	Future - Source
Fertilizer demand	kt NPK	2012-2019, 2030, 2035, 2040, 2050	Logistic regression	FAO (2021b)	FAO (2018)
Food production	kt of products	2012-2019, 2030, 2035, 2040, 2050	Logistic regression	FAO (2021c)	FAO (2018)
Population (Wastewater)	1000 people	2012-2019, 2030, 2035, 2040, 2045, 2050	Logistic regression	UN (2021a)	UN (2021a)
Aquaculture consumption	--	2012-2019, 2030, 2035, 2040, 2050	Logistic regression	FAO (2021a)	Linear regression
GDP per cap	$ USD/cap	*2030, 2035, 2040, 2050*	--	The World Bank (2022)	FAO (2018)
Urbanization	1) % urbanized population 2) 1000 people	2030, 2035, 2040, 2050	--	UN (2021b, 2021c)	UN (2021b, 2021c)
Population	1000 people	2030, 2035, 2040, 2050	--	UN (2021a)	UN (2021a)
Steel production	kt steel	2012-2019, 2025, 2030, 2035	Logistic regression	World Steel (2021b)	Accenture (2017)
LFP demand	kt P	2019-2050	--	Aguilar Lopez (2022)	Aguilar Lopez (2022)
Other P containing products	kt P	2019	Assumed constant across time	Lunde (2021)	Lunde (2021)
Stock of animals (Manure)	*1000 heads*	*2012-2019, 2030, 2040, 2050*	*The P content of manure was calibrated rather than the stock of animals, through logistic regression.*	*FAO (2021a)*	*FAO (2018)*

Fertilizer demand

The data on future fertilizer demand was taken from the FAO (2018) report, which explored three different scenarios for food production and agriculture until 2050 (FAO, 2018) (see Figure 1 in Appendix II). The three scenarios; Business as Usual (BAU), Stratified Societies (SSS) and Towards Sustainability (TS) explored different societal paths and their effect on the food system. In this report only the BAU scenario is used, as the intention of this report is not to investigate changes to the agriculture system, but rather the interaction between it and the LFP system. Moreover, the BAU scenario was chosen as it does not assume radical change, but rather a steady development of society. The data by FAO (2018) was reported in kg of nutrient NPK[1]. FAO (2021b) reports the use of the three fertilizer nutrients separately, and while the consumption of fertilizer has gone up the share of P_2O_5 in the fertilizer has been constant at 24% in the last 7 years. Therefore, it was assumed that 24 % of the NPK applied would be phosphorus pentoxide (P_2O_5). Moreover, historical data ranging back to 2012 was likewise collected from FAO (2021b), from different fertilizer outlook reports for the period of 2012-2021. The result of the calibration is found in Figure 9 below.

Figure 9: Calibration of fertilizer demand model input.

Food production

For food calculations FAO (2018) predictions were also used, with the volume of 65 different food types reported. These 65 food types were grouped into 8 food categories provided by Liu et al. (2008), who also specified the dry matter and P content of each food group. The matching of food types to the food groups and their P content, can be found Table 1 and 3 in Appendix II. For historical data the food balances reported by FAO (2021c) was used. The same approach regarding the P content in given products described above was used. In Figure 10 below the calibration of the data is displayed in kt P.

[1] NPK = Nitrogen, phosphorus, and potassium.

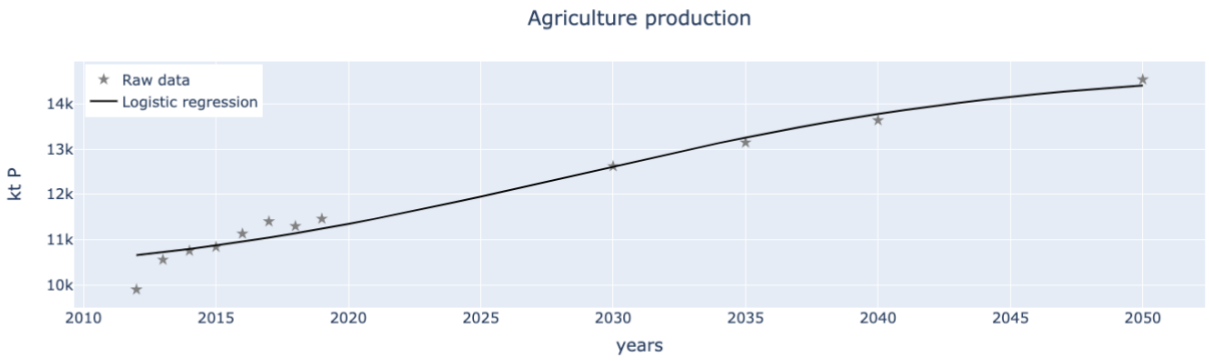

Figure 10: Calibration of food production model input.

Wastewater production

The wastewater is calculated using population predictions by the UN together with human wastewater coefficients. The UN reports a low, medium, and high scenario regarding population projections, and here the medium scenario is used. In Figure 11 the result of the calibration of the population is found.

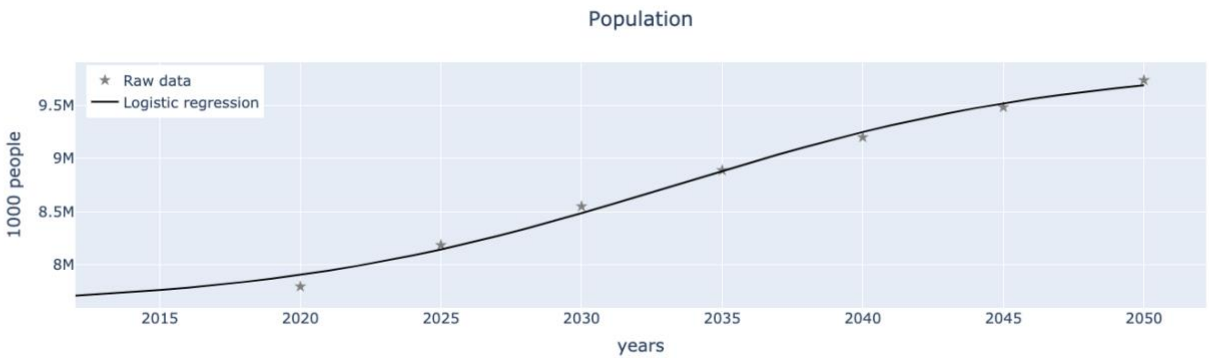

Figure 11: Calibration of population model input.

Per capita wastewater P coefficients were found in the literature. Cordell et al. (2009) reports a yearly excretion rate between 0,3 and 0,6 kg P per capita per year, with a variation explained by the diverse dietary habits across the globe. While the ESPP report a wastewater coefficient between 0,7 and 0,78 kg P per capita per year (JRC, 2020). This difference is due to an inclusion of toothpaste, food wastes, soil on laundry and drinking water treatment by the ESPP in their estimate. These numbers are also consistent with the estimations by Santos et al. (2021) at 0,73 kg P per capita per year and hence is used. The two latter sources are based on European data, however as they also consider other sources of P going into the wastewater they are used as the baseline. Moreover, an assumption is that all wastewater goes to wastewater treatment. These two considerations might lead to an overestimation of the actual amount of wastewater available, however it gives an indication of the amount potentially available. However, only direct human waste is accounted for in the calculation, and no other sources such as stores, industrial or town center. Therefore, this in turn might lead to an underestimation of the P in sewage sludge.

Aquaculture demand

Data on aquaculture demand for the future is not readily available. The only global prediction for aquaculture production was found by FAO in *The state of the World Fisheries and Aquaculture 2020 (FAO, 2020).* However, the report only stated numbers for 2018 and 2030, and thus inferring the development of aquaculture prediction until 2050 would involve large uncertainties. Therefore, an alternative approach was taken to estimate the total amount of fish consumed in future years. Literature concluded that the two most important factors influencing the amount of fish consumed were income and urbanization (Béné et al., 2015; Speedy, 2003). As a proxy for income, GDP per capita (current US $) was used. Data was taken from The World Bank (2022) for past years, and FAO (2018) for future periods. For urbanization two variables were chosen; population living in urban areas as a percentage and in 1000 persons. Both variables were taken from the UN's World Urbanization Prospects for all years (UN, 2021b, 2021c). Lastly, the consumption of fish per capita reported by FAO (2021c) was used as the dependent variable. A linear regression was run on the above given variables, to predict the consumption of fish per capita in 2030, 2035, 2040 and 2050. For historical years aquaculture production per year was taken from FAO (2021a). The calibration of the data is found in Figure 12.

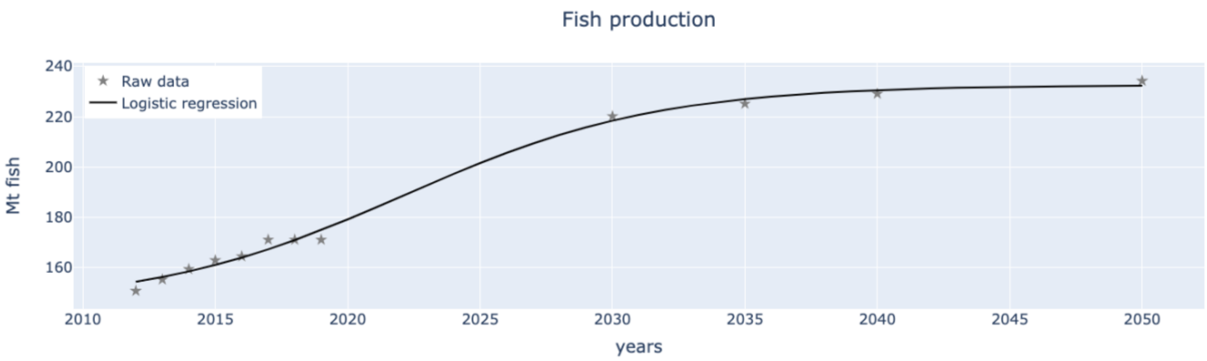

Figure 12: Calibration of fish demand model input.

Of the consumed fish globally, FAO (2020) reports that approximately 46% of produced fish originates from aquaculture production. The share of fish produced through aquaculture might change over time but is here kept constant. While aquaculture is a heterogenous sector, salmon is the most important species for international trade and is therefore used as a proxy for the P concentration (FAO, 2020). Aas et al. (2019) estimated that the P content of salmon was 0,31% of the whole fish.

Steel demand

Steel demand was derived from report by Accenture for the OECD in 2017 (Accenture, 2017). The report forecasted the steel production until 2035, together with the share of steel produced in BF-BOF and EAF. Historical data was taken from World Steel (2021b), on crude steel production in the period 2012-2018, through the different production routes The result of the calibration is shown in Figure 13. Moreover, the concentration of P in steel was taken from Morton and Edwards (2005), at 0,04%.

Figure 13: Calibration of steel production.

LFP demand

The input for LFP demand of P was based on the global vehicle stock model developed by Fernando Aguilar Lopez for his PhD thesis, not yet published at the time of this thesis. The model calculates the demand for stock by the population and vehicle per capita on a regional level, resulting in a global demand for EVs. Depending on the share of LFP cathodes in the EV stock, the P demand for LFP production was found. While this model only considers EVs, LFP cathodes will also be used for other vehicles such as plug-in hybrid, as well as stationary storage. Stationary storage has however been seen as a way to use LFP cathodes after their primary use phase is done (Ioakimidis et al., 2019). Moreover, traditionally LFP have been used for public transport, for example in China where they are used in buses. However, it is likely that if a large production of LFP will happen, EVs are the main driver. As such, only EVs will be considered in this paper.

Other uses

Phosphorus is also used in other sectors than for food production, however this use of P is highly disaggregated between different small industries (de Boer et al., 2019). P can be used for electrolytes, bleaching, leaching agents, plastic additives, and medicine to name a few. As such, calculating the demand for such products is not feasible. Moreover, the P source for the above-mentioned products can use both purified phosphoric acid and P_4 depending on the application. The ESPP shows that only a few items cannot use purified phosphoric acid, but rather has to use P_4 (JRC, 2020). Therefore, the demand for P_4 derivatives might not increase significantly in the future even if demand for the products do. As a simplification, the demand for these uses in 2019 calculated in the master project was used as a constant; 3 285 kt/yr (Lunde, 2021).

Manure

The amount of manure was calculated based on the number of livestock reported by FAO (2018), for six different animal classes[2]. Moreover, the excretion rate per animal reported by Bouwman et al. (2017) was used to estimate the total manure. While excretion rates might vary across geographical locations and within the animal class (dairy vs. non-dairy animals), this study applied a constant excretion rate per animal class. For historical data the stock of livestock was taken from FAO (2021a). The stock of each animal group for can be found below in Figures 2 and 3 in Appendix II together with the excretion rates (Table 2). A discrepancy was found between the stock of animals in 2012 for the two data sources. The historical data from FAO (2021a) used more aggregated animal groups, and disregard pigs, yet the total stock is higher than for the FAO (2018) report. The difference originate from the poultry category, with a lower stock in the FAO (2018) than in the FAO (2021a) statistics. The choice was made to use the FAO (2021a) for the 2012 numbers without further treatment. However, this data gap can indicate that the manure calculated for the future is lower than the actual amount of manure produced. The calibration of the manure data is found in Figure 14.

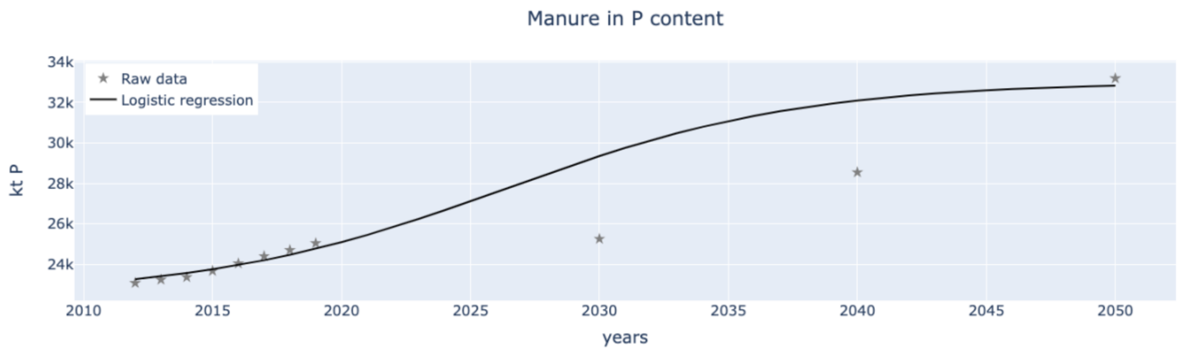

Figure 14: Calibration of manure production model input.

2.3.2 Model input - Model coefficients

In Table 2 below, an overview of the transfer coefficients and P concentrations in different products can be found, together with a quantitative evaluation of their uncertainties.

[2] Buffaloes, Cattle, Goats, Pigs, Poultry and Sheep

Table 2: Model coefficients used in this project.

Model coefficient	Range	Used value	Unit	Uncertainty	Source
Model coefficients for the drivers					
Share P of NPK	24%	24%	%	Low	FAO (2021b)
P concentrations food				Low	See Table 2 in Appendix II
P in wastewater from humans	0,7-0,78	0,78	kg P/cap	Medium	JRC (2020); Santos et al. (2021)
Salmon P concentration	0,31%	0,31%	%	Medium	Aas et al. (2019)
Share of fish produced from aquaculture	30-46%	46%	%	High	FAO (2020)
P in steel	0,005- 0,05%	0,04%	% P	High	Morton and Edwards (2005)
Manure coefficients				Medium	See Table 1 in Appendix II
Model coefficients for the rest of the system					
Fertilizer waste coefficient	0-15%	6%	%	High	Cordell et al. (2009); Matsubae-Yokoyama et al. (2009); Rittmann et al. (2011); Villalba et al. (2008)
Fertilizer yield	94-100%	94%	%	High	Cordell et al. (2009); Matsubae-Yokoyama et al. (2009); Villalba et al. (2008)
P in P_2O_5	43,7%			Low	Stoichiometric
LFP production waste coefficient	0-30%	20%	%	High	Chung et al. (2016)
Ferrophosphorus produced per ton of P produced	0,15	0,15	t/t	Low	Diskowski and Hofmann (2000)
P content in ferrophosphorus	15-30%	24%	%	Medium	Diskowski and Hofmann (2000); Gasik et al. (2020)
Ratio of phosphate to produced P_4	1,08	1,08	t/t	Low	Diskowski and Hofmann (2000)
Purification process efficiency	95-97%	96%	%	Low	Scholz et al. (2014)
Wet acid process efficiency	90-99%	95%	%	Medium	de Boer et al. (2019); Gilmour (2019)
P in effluent from wastewater	1-20%	10%	%	Medium	Cornel and Schaum (2009)
% P wastewater going to sewage sludge	80-99%	90%	%	Medium	Cornel and Schaum (2009); Meng et al. (2019)
Soil water runoff	10-30%	12,5%	%	High	Bouwman et al. (2017); Cordell et al. (2009)
Food waste	0-20%	5%	%	High	FAO (2021c)
Share of P in aquaculture feed lost to waterbodies	70%	70%	%	Medium	Wang et al. (2013)
Coal demand per steel produced – BF-BOF		0,78	t/t	Low	World Steel (2021a)
Limestone per steel – BF-BOF		0,27	t/t	Low	World Steel (2021a)
Iron ore demand per steel produced – BF-BOF		1,37	t/t steel	Low	World Steel (2021a)
Coal demand per steel produced - EAF		0,15	t/t steel	Low	World Steel (2021a)

Limestone per steel - EAF		0,088	t/t steel	Low	World Steel (2021a)
Iron ore per steel - EAF		0,586	t/t steel	Low	World Steel (2021a)
P in iron ore	0,03-0,06%	0,04%	% P	High	Jeong et al. (2009)
P in coal		0,05%	% P	Low	Jeong et al. (2009)
P in limestone		0,01%	% P	Low	Jeong et al. (2009)
Recycled steel for BF-BOF		0,125	t/t	Low	World Steel (2021a)
Recycled steel for EAF		0,710	t/t	Low	World Steel (2021a)

The efficiencies of the processes identified for 2019 were kept constant throughout the model. A dynamic change of efficiencies for the processes is likely to happen in the future, due to technological and political developments. However, the supply part of the system has already achieved quite high efficiencies, with small waste streams and high recovery coefficients. As such, it is perhaps more probable that improvements of efficiencies will happen where human action is the cause. This can be for example the use of fertilizer, food waste and dietary changes. However, predicting future consumption habits and policy changes entails large uncertainties, and is not the purpose of this study. Therefore, the efficiencies identified in 2019 are kept constant for the entire period. Below the model coefficients for each process is described.

Wet acid production

The wet acid production efficiency is reported by Gilmour (2019) as a range between 93-99% of P. However, there are three methods of wet acid production: Dihidrate process, hemidrate process and a combination of the two. The yield coefficient varies between the three; 93-97% (Gilmour, 2019), 90-94% (de Boer et al., 2019) and 98,5% (Scholz et al., 2014) respectively. With the dihidrate process being used in 90% of the cases, the yield coefficient for this process was chosen (de Boer et al., 2019). The P that does not exit the process as P-acid is assumed to go to waste. The P in waste exits the system in different forms; phosphogypsum, fly ash or other slag. Here it is treated as one flow, as the application of these wastes are not suitable for further processing to P_4.

Purification

The purification of P-acid has a P yield between 95-97%, with 96% used in this study (Scholz et al., 2014). In practice the purification of wet acid consists of several processing steps; extraction, precipitation and solvent extraction (de Boer et al., 2019). However, here they are treated as one process due to a lack of data on the efficiency of the separate steps.

Fertilizer production

There is very little data on the efficiency of fertilizer production, and great variation among the efficiency can be found in the literature. Villalba et al. (2008) and Matsubae-Yokoyama et al. (2009) both assume no P losses in the fertilizer production and distribution, while Cordell et al. (2009) assumes a 6% loss in the distribution. A potential reason for this is due to the vertical integration of fertilizer and wet acid production. In this study a 6% loss of P in the fertilizer production and handling is assumed.

Wöhler process

The P_4 production efficiency is derived from Diskowski and Hofmann (2000). Per ton of P_4 produced an inflow of 8 tons of phosphate pellets (31% P_2O_5) is necessary (Diskowski & Hofmann, 2000). This equates to 1,08 tons of P in per ton of P_4 out. Moreover, one of the byproducts is FeP. Per ton of P_4 produced 0,15t of FeP is produced. Ferrophosphorus can have different concentrations of P, with a range of 15-30% reported in literature (Diskowski & Hofmann, 2000; Gasik et al., 2020). Here 24% P in FeP is used. The P not in FeP or in P_4 goes to waste.

LFP production

The production coefficient for LFP is uncertain due to monopolistic production networks and recency, with few authors reporting coefficients in their work. Moreover, the yield coefficients will be different for each production facility, and can be regarded as an industry secret. Chung et al. (2016) use coefficients for production yields in the range of 70-90%. Moreover, the yield might also change due to experience and volume, with longer time and higher production quantities resulting in less waste. This study follows the approach taken in Chung et al. (2016) who use a constant yield, despite the abovementioned factors. Here 80% recovery of materials is used.

Agriculture

Traditionally there would be several waste flows going from agriculture; soil erosion, water runoff, manure, and waste from harvesting of crops to mention some. The three largest outflows from agriculture are soil erosion, water runoff and manure. The latter however is often used as fertilizer internally in agriculture production and is therefore not accounted as an outflow here. As such, the only notable flows from agriculture is water runoff and soil erosion (Rittmann et al., 2011). For water run off Lun et al. (2018) report that 12,5% of all P applied to soil will exit to water bodies. The amount of P in water runoff is direct result of the amount of applied fertilizer and manure, however it is also very much affected by event-specific losses such as rainstorms (Hart et al., 2004). In this study, the latter parameter is not included as this would be difficult. Manure is only used to calculate the amount of P in water runoff.

Food market

The food waste coefficient was derived from historical data from FAO (2021c) who reported the amount of food lost “between the level at which production is recorded and the household, i.e. storage and transportation”. For 2019 the food loss was 5% of produced quantities. However, this could vary across years but is here treated as a constant number.

Wastewater treatment

Cornel and Schaum (2009) and Meng et al. (2019) both report 90% efficiency of P recovery from wastewater to sewage sludge. While applying this coefficient directly to wastewater could result in an overestimation of the sewage sludge and its P content, it is meant to give an estimation of potential availability.

Aquaculture

The waste from aquaculture was for Norwegian production estimated at 70% of feed P in 2009 (Wang et al., 2012). This means that 70% of the P in feed applied in pens, are returned to water bodies through feed loss and feces in different P forms. The rest of the P is retained in the body of the fish.

Steel coefficients

Phosphorus that enters steel production through other materials than iron, limestone and coal, is also accounted for in this model, following the method of Matsubae-Yokoyama et al. (2009). The coefficients for the amounts of coal and limestone needed for the production of steel were taken from World Steel (2021a). While the P content of iron ore varies significantly across regions and deposits, a world average was taken at 0,04% P content of iron ore (Jeong et al., 2009).

2.4 Model development – EU

The model development for the EU was done in a similar method as for the global system. The largest difference between the two approaches, is that the EU system is not made dynamic, but is rather calculated for given years. The years considered are 2019, 2030, 2040 and 2050. This choice was made due to the necessary trade data that would be needed for a complete dynamic model. How the model works is displayed in Figure 15, in a similar fashion to the global system.

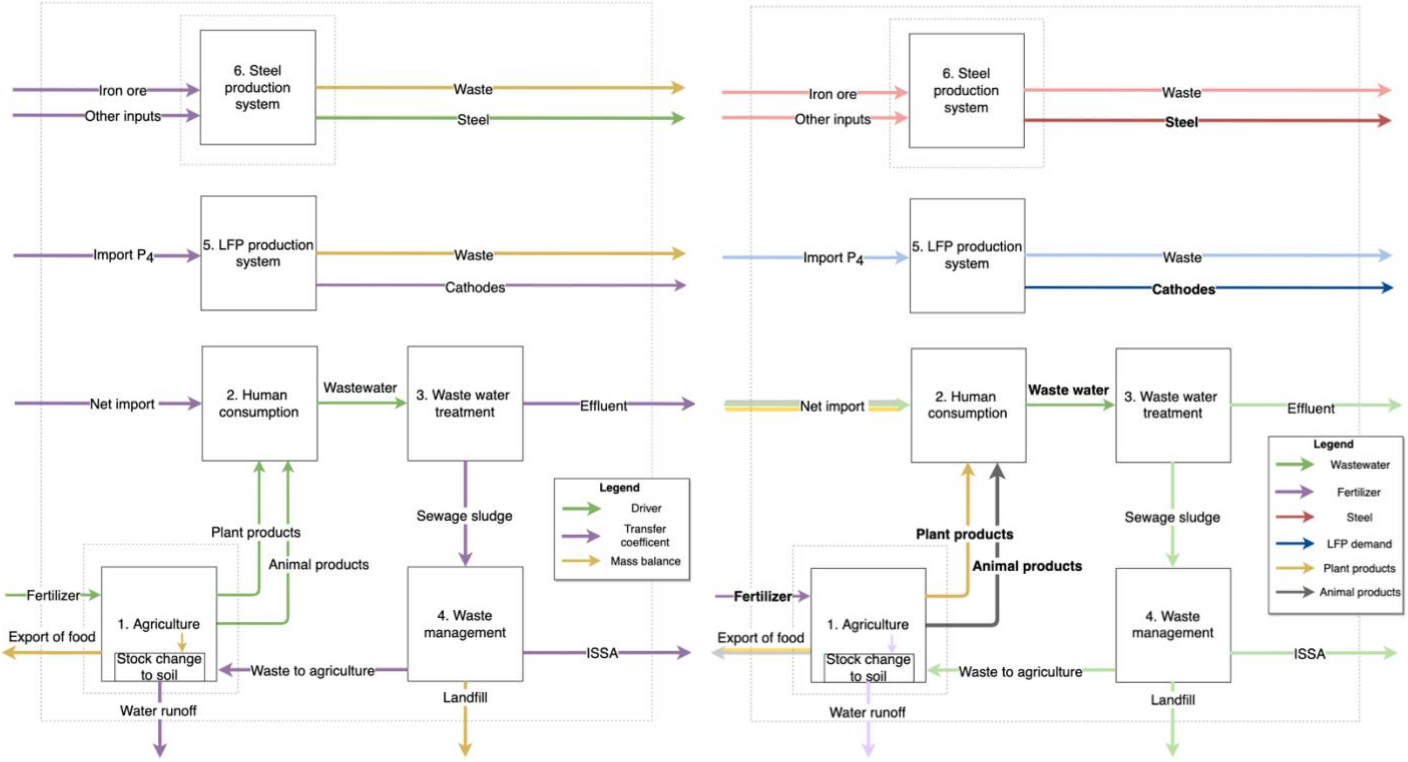

Figure 15: Left - The figure illustrates how the different flows are calculated based on quantities, transfer coefficients and mass balance. Right - Visual representation of how the EU model works. The darker shaded arrows represent the drivers, while the faded shades represent flows induced by these drivers. A combination of colors is used when more than one driver induced the flow.

Moreover, since the model is not dynamic no calibration of the drivers are conducted. Lastly, for the model coefficients only discrepancies from the global model coefficients will be explained, due to most of the model coefficients being the same.

2.4.1 Model inputs

The drivers for the EU model are the same as for the global model, with one exception. Since the EU can both produce and import food, only the domestic production of food had to be accounted for in the agriculture system. This data was however available in the outlook on agriculture model from FAO (2018), together with the proportion used for feed and for food. These data points together with the other drivers are found in Table 3.

Table 3: Drivers for the EU P system.

Driver	2019	2030	2040	2050	Unit	Source - 2019	Source - future
Fertilizer	12,36	17,26	18,19	19,05	Mt NPK	FAO (2021b)	FAO (2018)
Domestic production	1279	1377	1432	1485	kt P	FAO (2021a)	FAO (2018)
Animal feed consumption	466	599,27	604,38	606,57	kt P	FAO (2021a)	FAO (2018)
Food consumption	374	426,32	423,44	416,39	kt P	FAO (2021a)	FAO (2018)
Population	447 999	449 121	446 754	44 1220	Million people	EUROSTAT (2021a)	EUROSTAT (2021a)
Steel	150	179	188	200	Gt steel	EUROFER (2019)	EUROFER (2019)
Animal stock	1613,37	1382,71	1371,99	1370,76	Million heads	FAO (2021a)	FAO (2018)
LFP demand - NCX	7,69	4,62	14,12	13,30	Kt of P	Aguilar Lopez (2022)	Aguilar Lopez (2022)
LFP demand - BNEF	7,69	42,50	155,89	180,90	Kt of P	Aguilar Lopez (2022)	(Aguilar Lopez (2022)
LFP demand – LFP All	7,69	110,87	406,66	471,92	Kt of P	Aguilar Lopez (2022)	Aguilar Lopez (2022)

The animal stock reported by FAO (2018) for the EU was only reported in livestock units, not by type of animal group. Therefore, the historical data on animal groups from FAO (2021a) was used to determine the future split. A visualization of this approach together with the stock of animal-by-animal group can be found in Figure 4 and 5 in Appendix II.

For the model coefficients, the same ones were used for the EU system as for the global system except waste flows coefficients. It is assumed that the entire population is connected to sewer systems across Europe. EUROSTAT (2019) reports the percentage of population not connected to wastewater collecting and treatment systems with only Bulgaria showing a larger percentage than 5% not connected. The transfer coefficient for the flow of waste to agriculture was retrieved from OECD (2020) at 29% of sewage sludge produced. Moreover, an update transfer coefficient for the split between the two steel processing routes was also used, located in Accenture (2017).

2.5. Scenarios

2.5.1 LFP demand scenarios

Several LFP demand scenarios are developed to get an understanding of how the system reacts to changes in demand for P for LFP cathodes. In Table 4 below, an overview of the chosen scenarios and the parameters is given both for the EU and global system from Aguilar Lopez (2022).

Table 4: LFP demand scenarios and chosen parameters.

Name of scenario	EV penetration	Stock scenario	Chemistry scenario	Reuse scenario	Time
NCX	SD	Medium	NCX	No	2019-2050
BNEF	SD	Medium	BNEF	No	2019-2050
LFP_{60}	SD	Medium	LFP	No	2019-2050
LFP_{100}	SD	Medium	LFP_all	No	2019-2050

This study uses four different scenarios, where the only difference is the share of LFP cathodes in the vehicle stock (see Figure 6 in Appendix II). In the NCX[3] scenario, NCX cathodes are assumed to be the dominant chemistry, leaving the share of LFP cathodes at less than 3% from 2025 onwards. The next scenario, BNEF, has the share of LFP cathodes relatively stable across time. However, a small increase until 2030 can be found at 23%. The third scenario, LFP_{60}, assumes that LFP will have a breakthrough and due to issues with other cathode chemistries will dominate cathode marked by 2030 and stay the dominant chemistry throughout the period. Lastly, in the LFP_{100} scenario all cathodes entering the market from 2030-2050 will be LFP. Thus, in this scenario a complete shift will be observed from the small share of LFP cathodes today to complete reliance on LFP cathodes in the future. A visualization of the four scenarios is found in Figure 16.

[3] NCX = NCA and NMC cathodes.

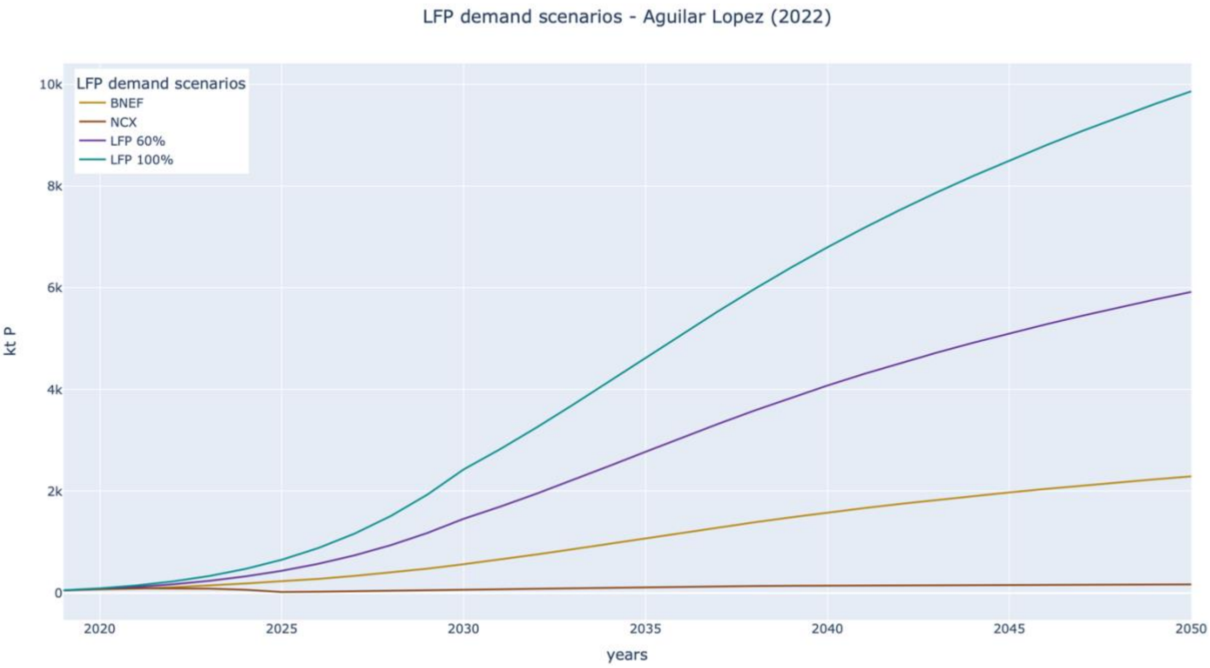

Figure 16: Illustration of the demand of kt P for LFP cathodes by scenario.

2.5.2 Recycling scenarios

Recycling of LFP cathodes has been researched extensively before, in comparison to other battery chemistries and LFP alone (Elwert et al., 2019; Forte et al., 2021; Or et al., 2020; Wang & Wu, 2017; Yang et al., 2018). However, currently the recycling of cathode material for recovery of P has not been on the agenda. Moreover, it has not been economically beneficially to recycle LFP or its materials due to the low cost of the battery (Beaudet et al., 2020). Historically, P has not been recycled using hydrometallurgical or pyrometallurgical processes, which have rather focused on the recovery of more valuable metals such as Ni and Co (Beaudet et al., 2020). However, experiments show that using a new pyrometallurgical recycling process could allow for a 64,5% recovery of P in gas (Holzer et al., 2021). In this report only direct recycling of P is considered. This is because direct recycling is considered the most appropriate for LFP cathodes, as it recovers all the active cathode material (Forte et al., 2021). Moreover, for the recycling scenarios it is assumed that all the batteries exiting the use phase are recycled (100%), and that the material recovery rate is 90%.

2.6 Additional analysis of barriers to production of P_4

To look at the consequences of the amount of P_4 produced for LFP, aspects such as large electricity demand and high production costs have been highlighted as possible challenges (Gilmour, 2019). The high demand for electricity has in the past caused challenges to production levels, and in 2021 power rationing caused a threefold increase in the price of P_4

in China (Yonglei & Bojun, 2021). The electricity use for production of P_4 is reported to be between 12,5 and 14 MWh per ton of P_4 produced (Belboom et al., 2015; Gilmour, 2019; Wu et al., 2021). Moreover, to compare a similar electricity coefficient was found to produce $LiCO_3$, which is the precursor material for the Li component of LIBs and LFP cathodes. According to Kelly et al. (2021) to produce a ton of $LiCO_3$ the electricity requirement is between 0,4 MWh and 1,8 MWh. The share of Li per LFP cathode compared to P is taken from Porzio and Scown (2021).

2.7 Uncertainty of data inputs

A clear distinction regarding uncertainty of the data sources used can be made between the historical data, and the outlook data. The statistical data used for the 2019 model is considered to have the highest certainty of the two, as it based on reported statistics. Statistical data was used for fertilizer consumed, amount of food produced, number of fish from aquaculture and steel produced. On the other hand, the future model the previous mentioned drivers had to be estimated and predicted, carrying larger uncertainties.

Model coefficients also vary in their level of certainty. The qualitative uncertainty of the different coefficients are also found in Table 2. Low uncertainty is assigned when agreement is found across literature sources, with a low range between the upper and lower bound. Next, medium uncertainty is given when there are some divergences in the literature, or a larger range between the upper and lower boundaries is observed. Last, high uncertainty is attributed when there is no coherence across literature sources, few sources are found, or the numbers vary greatly due to geographical and technological differences or due to aggregation of different products. In the latter case, with more sources, but little coherence the average value was chosen.

Some of the more technical processes, such as the Wöhler process, or the production of P-acid carry less uncertainty than the downstream processes such as human use and food waste. In general terms the uncertainty of processes efficiencies increase as one moves up the supply chain. This is due to consistent agreement across literature sources on the efficiency of the production processes, but less agreement regarding the effect of human action on flows. Additionally, at the global level aggregating regional transfer coefficients into one representative number or using a regional based transfer coefficient can yield uncertainties.

This is for example true about the water runoff from agricultural soil, which has clear regional differences (Bouwman et al., 2013).

Another uncertainty aspect are the flows calculated by mass balance. As transfer coefficients for all flows were not found, the assumption of mass balance was taken for the rest of the flows. Again, variation across processes exists, where certain processes having higher certainty than others, again increasing upstream the supply chain. The process with the highest uncertainty related to mass balance is human use. In this process all the P that is not modelled to go into wastewater is assumed to go to landfill. However, this amount is extremely large, and can contain P from food, electronics, packaging, plants, and such. All this P is assumed to exit the system however in reality some of this might also enter wastewater. Thus, and underestimation of P in wastewater might occur.

To conclude, the uncertainty of the model rise along the supply chain, with the supply system carrying the least uncertainty. A quantitative uncertainty analysis, through error propagation, would enable a more specific error estimation of the secondary resources quantities. However, as the purpose of the model is to see the interaction between the parts of the system, and give estimations on the availability of secondary resources, the model is still robust looking at the purpose and aim of the study.

3. Results

The dynamic model produced a quantified system for all years between 2019 and 2050 for the global system, and quantified systems for 2019, 2030, 2040 and 2050 for the EU model. First, the quantified global system is presented, both in Sankeys and in figures. The effect of recycling and availability of secondary resources are also illustrated in time series graphs. Third, the energy demand for P_4 production is likewise demonstrated. Lastly, the EU system is also illustrated using Sankey for discrete years, with the effect of recycling and availability of secondary materials also being exemplified.

3.1 Global P system

3.1.1 Sankey diagram of 2019 for the global P system

In Figure 17 below, the P flows for the global system in 2019 are represented in a Sankey diagram.

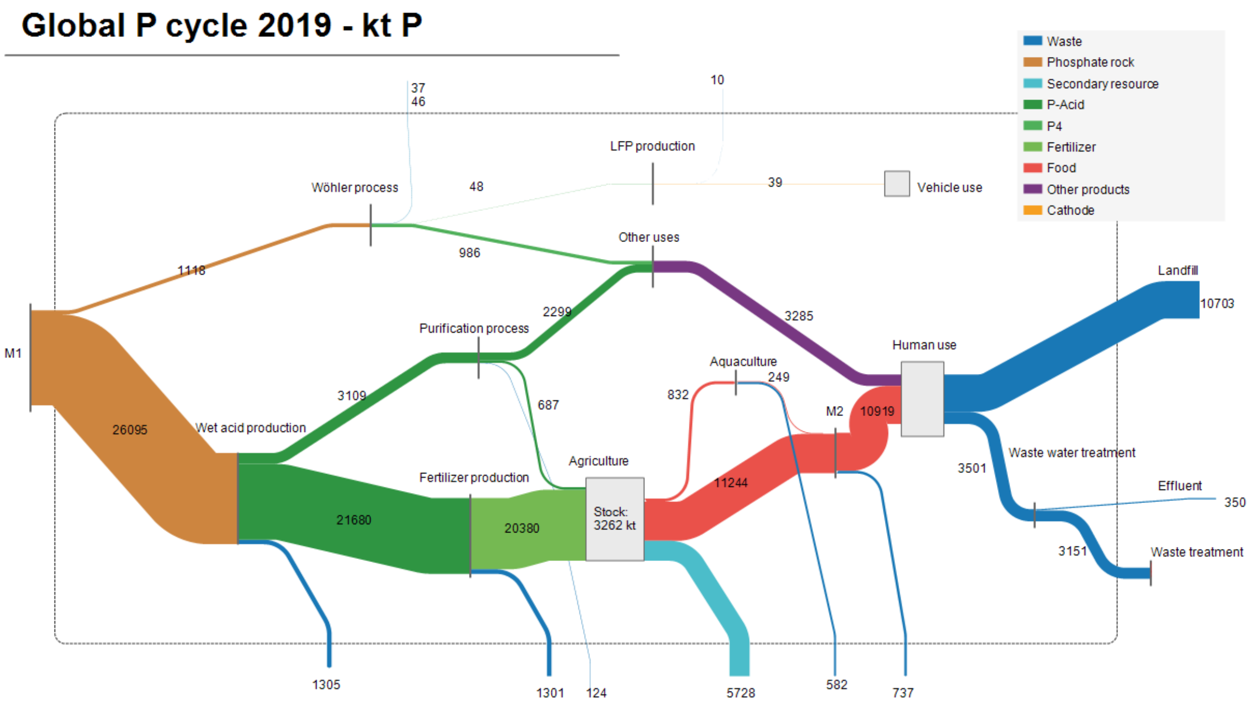

Figure 17: Global P cycle 2019 in kt P. The stock denotes the stock change.

The graph shows that <1% of global P demand is for LFP production in 2019. Most of the P mined in 2019 is used in agriculture as fertilizer. Moreover, it should also be noted the large amount of P accumulating in the soil, as well as the very low amount of P that reach human consumption. This indicates a low PUE, with most of the P being lost between mining and human consumption. Moreover, part of that is due to P accumulating in the soil, at 3308 kt in 2019. The graph also shows how few of the waste streams are reused within the system, as all waste is disposed of in water bodies and landfill. There is no flow exiting waste treatment, as the data on incineration of sewage sludge is uncertain. Therefore, the flow from wastewater treatment to waste treatment exemplifies the available sewage sludge.

3.1.2 Global LFP scenarios

In Figure 18 below, the BNEF scenario is illustrated in the global P system for the years 2019, 2030, 2040 and 2050. This is meant to show the developments of the other P sectors. Similar Sankey diagrams for the other three LFP demand scenarios can be found in Appendix III in Figures 7, 8 and 9.

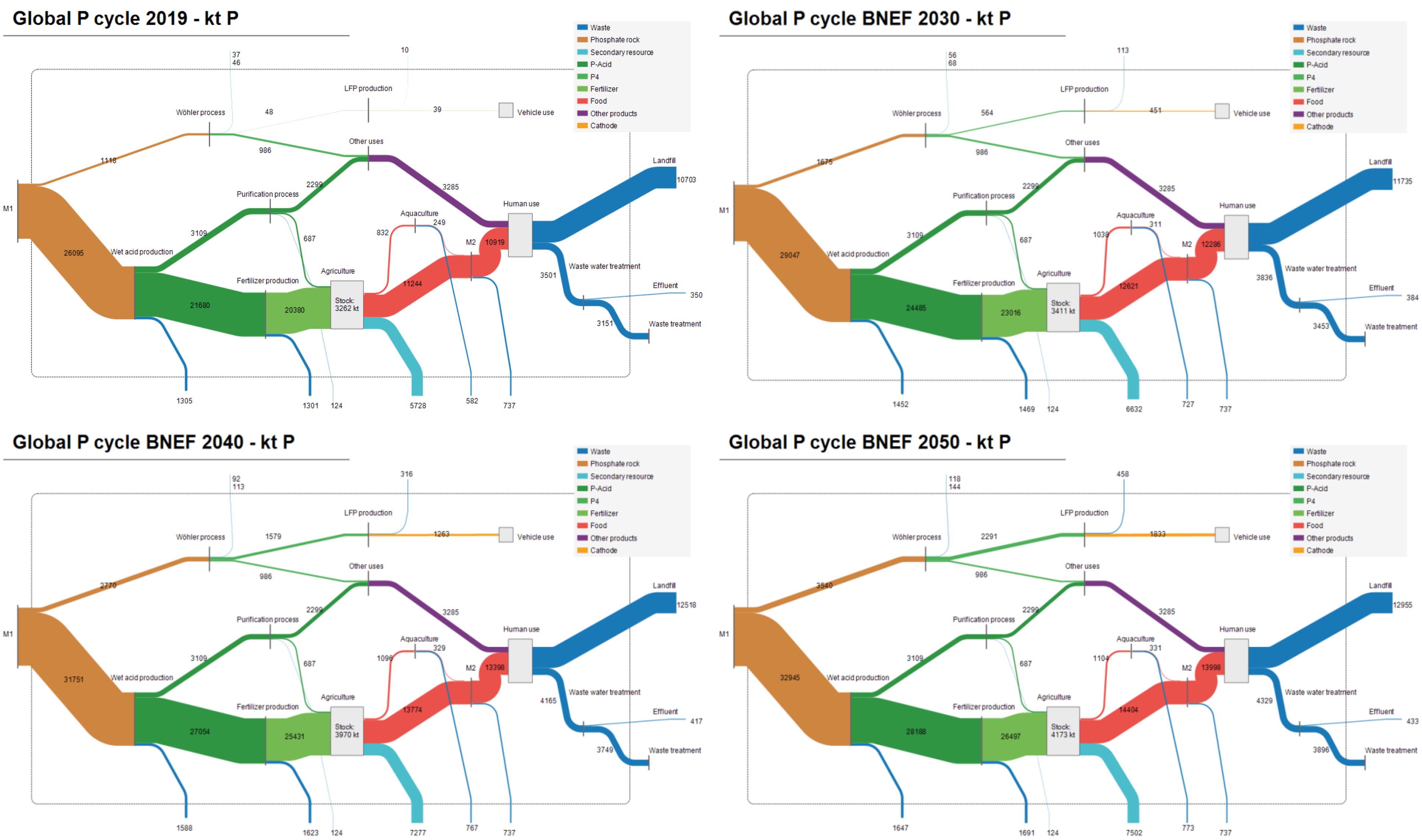

Figure 18: The global P cycle for the years of 2019, 2030, 2040 and 2050 for the BNEF scenario. The stock denotes the stock change.

The Sankey illustrate how the demand for P for LFP influences the rest of the global P system. In general, higher demand for LFP does not directly impact the other flows of P, as the supply chains for fertilizer and LFP cathodes are disconnected. Therefore, the agriculture system and other uses of P are constant across the different scenarios for the given years.

For agriculture, more and more P goes to fertilizer throughout the time period. Additionally, the amount of food reaching human consumption does not increase drastically in the later years, leaving increased amount of P in soils. Moreover, waste flows such as aquaculture sludge and wastewater also increase across time, but at a lower rate than the illustrated LFP demand scenario. On the other hand, an increase in the demand for LFP results in a larger inflow of phosphate rock to the system, waste generation and P_4 manufacturing. These aspects are illustrated in Figure 19 below.

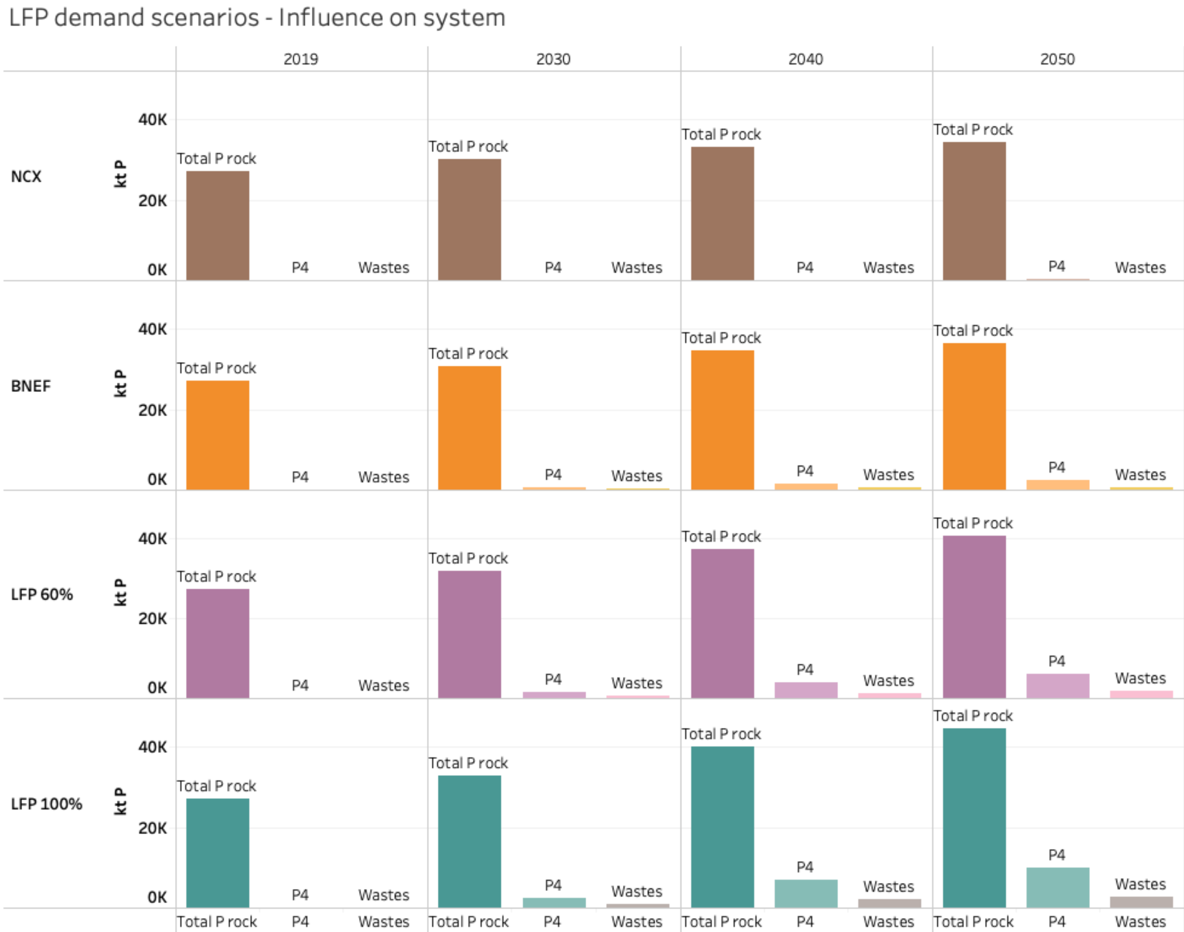

Figure 19: LFP demand scenarios in 2019, 2030, 2040 and 2050 - Total P rock into the system (Flow 0-M1), P_4 for LFP production (Flow 2-6) and wastes from P_4 production and LFP cathode production (Flows 2-0a, 2-0b and 6-0).

As seen above, the higher the demand for LFP the more waste is produced, and likewise phosphate rock mined. For the highest demand scenario 2840 kt of waste is produced, while for the NCX scenario only 125 kt of waste is generated in 2050. Similarly, P_4 production in the highest scenario is 10 848 kt, while for the lowest demand scenario it is 1 153 kt where the majority goes to other uses than LFP.

In Figure 20, on the left, a summary of the demand share of P going to batteries compared to the total input to the system is shown. There is a clear difference between the four scenarios, and the share of P going to batteries. In the NCX scenario the share of P going to LFP is negligible, not reaching 1% for the entire period. The base scenario barely reaches above 5% of the total P input into the system, while the high last scenarios reach a share of 15% and approximately 23% respectively.

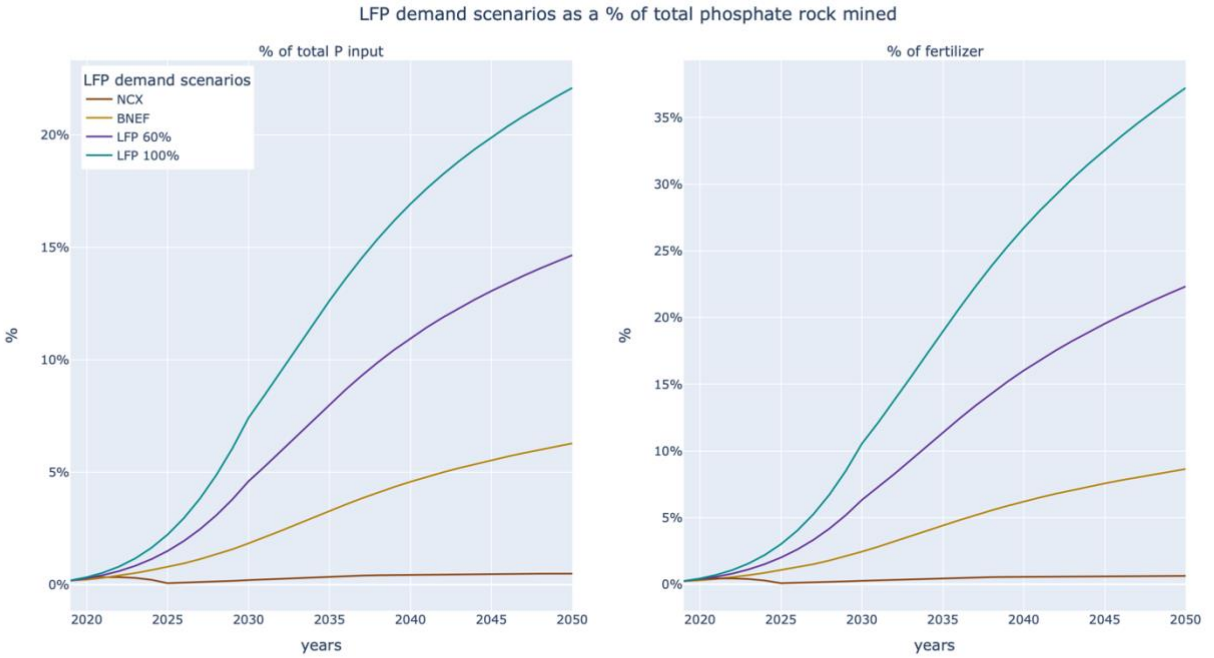

Figure 20: LFP demand scenarios of P, as a share of the total P input into the system. This means the demand for P for LFP (Flow 2-6) as a percentage of the total phosphate rock mined for all human consumption (Flow 0-M1). On the right the share of P for LFP is compared to the share of P for fertilizer (Flow 4-10).

Throughout time the share of LFP increases compared to the P going into agriculture; see graph on the right in Figure 20. This means that the P demand for LFP cathodes seem to grow faster than compared to the demand for P in agriculture. Moreover, the demand for agriculture only increases 30% from 2019 to 2050, while LFP demand increases drastically more in all scenarios. By 2050 LFP demand in the higher scenarios constitute just above 30% of the P used in fertilizer. On the flip side, in the lowest demand scenario LFP demand is barely 1% of the P used for fertilizer, not increasing much from the demand share today.

3.1.3 Global secondary resources

Recycling of batteries that have reached their end-of-life and the effect of such recycling on the P demand is illustrated in Figure 21 for the different LFP demand scenarios.

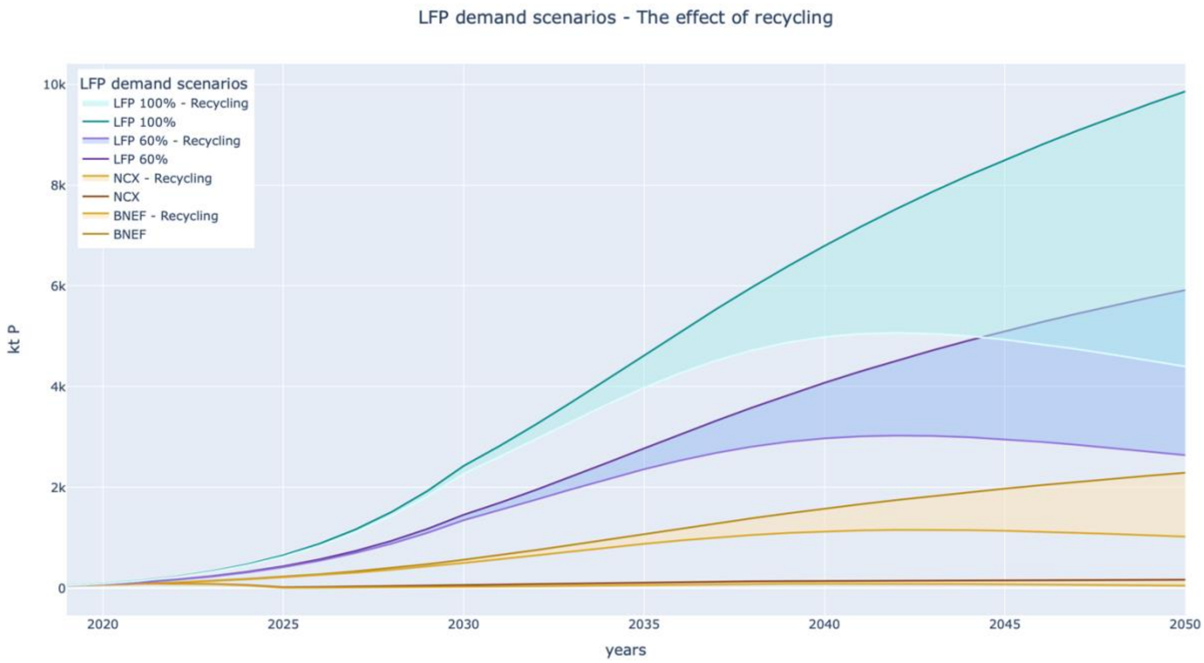

Figure 21: The effect of recycling of LFP cathodes, and the impact on the demand of primary P for batteries.

The shaded areas illustrate the amount of primary P that can be avoided if all batteries at the end-of-life is recycled with a 90% recycling efficiency. As seen, recycling largely affects the demand for primary P from 2040 onwards, where a decreasing trend in primary demand can be observed. In the short term however a smaller effect is seen. For all demand scenario recycling can bring down the demand for primary P by approximately 55% in 2050, compared to no recycling. Further, the largest effect is observed for the higher demand scenario, as these have a larger number of vehicles exiting the stock in future years. This delayed effect of recycling entails that large amount of P needs to be mined and processed in the next years even if recycling is done. As such, options for other secondary resources are important in the short term.

Figure 22 illustrates the number of available resources of aquaculture sludge, sewage sludge, FeP, and steel sludge over time. The estimation of secondary resources does not include waste from recovery of P and further processing to P_4.

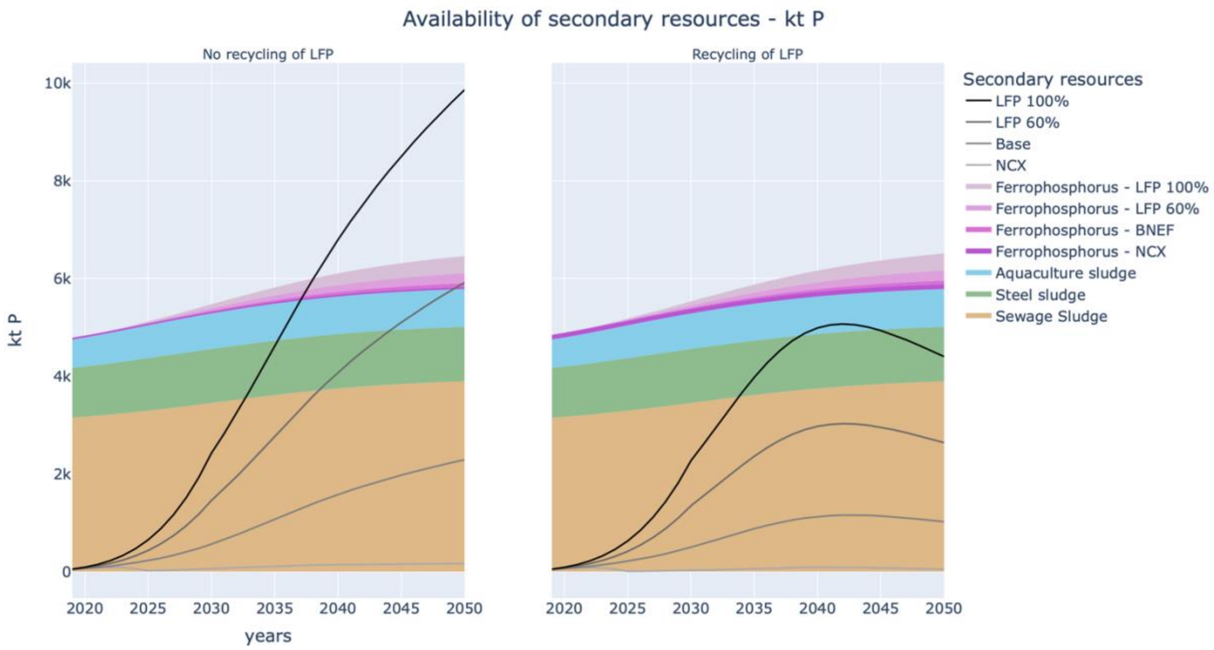

Figure 22: The availability of secondary resources at the global level in kt P.

The different shades of purple indicate the different amounts of FeP for the different LFP scenarios. Ferrophosphorus is a by-product of P_4 production, and therefore the quantity available will depend on the LFP demand scenario. For example, as more P_4 is produced for LFP during the LFP_{100} scenario, more FeP will be available compared to the NCX scenario. The left graph in Figure 22 shows the available secondary resources (stacked wedges) compared to the LFP demand (lines) with no recycling. However as seen, the secondary resources can cover a large part of the demand for the lower three scenarios but does not meet the LFP_{100} scenario. On the right-hand side in Figure 22 the same graph is shown, but here the LFP demand scenarios include recycling. This drastically alters the outcome, where now all the scenarios can be covered by secondary resources. For the complete quantification of the global steel system, see Appendix II, Figure 10.

3.1.4 Energy consumption of P_4 production for the different LFP demand scenarios.

Figure 23 shows the energy demand for production of P_4 under different LFP demand scenarios. The shaded areas illustrate the upper and lower energy demand boundaries according to literature, with the line indicating the average energy consumption across production facilities. This gives an uncertainty range of the energy consumption for P_4 production.

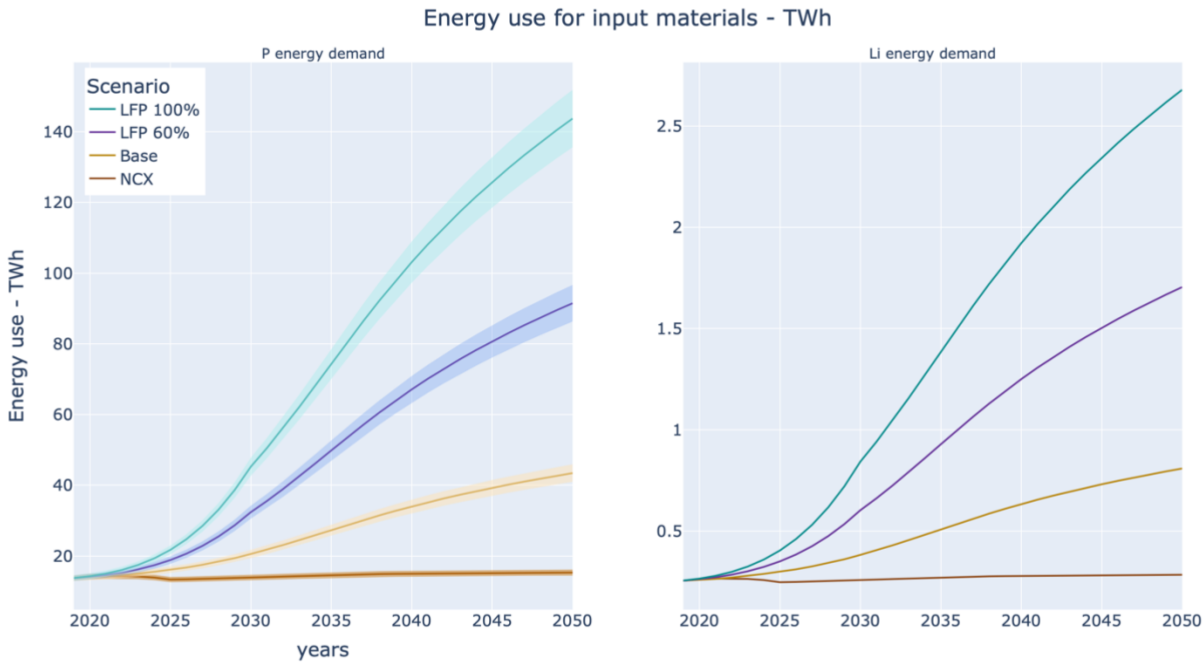

Figure 23: The energy demand to produce P_4, for LFP cathode production. The shades areas indicate the high and low estimate for the energy consumption. On the right is the energy demand for LiCO3 for the same vehicles as for P.

The right graph in Figure 23 is the energy demand for $LiCO_3$ production, for the same LFP demand scenarios (on battery volume basis). This means that the right graph shows the energy demand for production of $LiCO_3$ for the same volume of batteries, not the same volume of materials. One LFP cathode consists of approximately 19% P and 4,4% Li (Porzio & Scown, 2021). The energy consumption for P_4 production can reach almost 145 TWh for the high scenario, while the high demand for $LiCO_3$ only reach 2,7 TWh. As such, production of P_4 as precursor material for LFP cathodes demand roughly 50 times more energy than $LiCO_3$. If one ignores the $LiCO_3$ content in LFP and compare the same amount of material produced, then P_4 would need approximately 12 times the energy demand as $LiCO_3$.

3.2 EU P system

3.2.1 Sankey diagram of 2019 for the EU P system

In Figure 24 the general P system for the EU for 2019 is displayed.

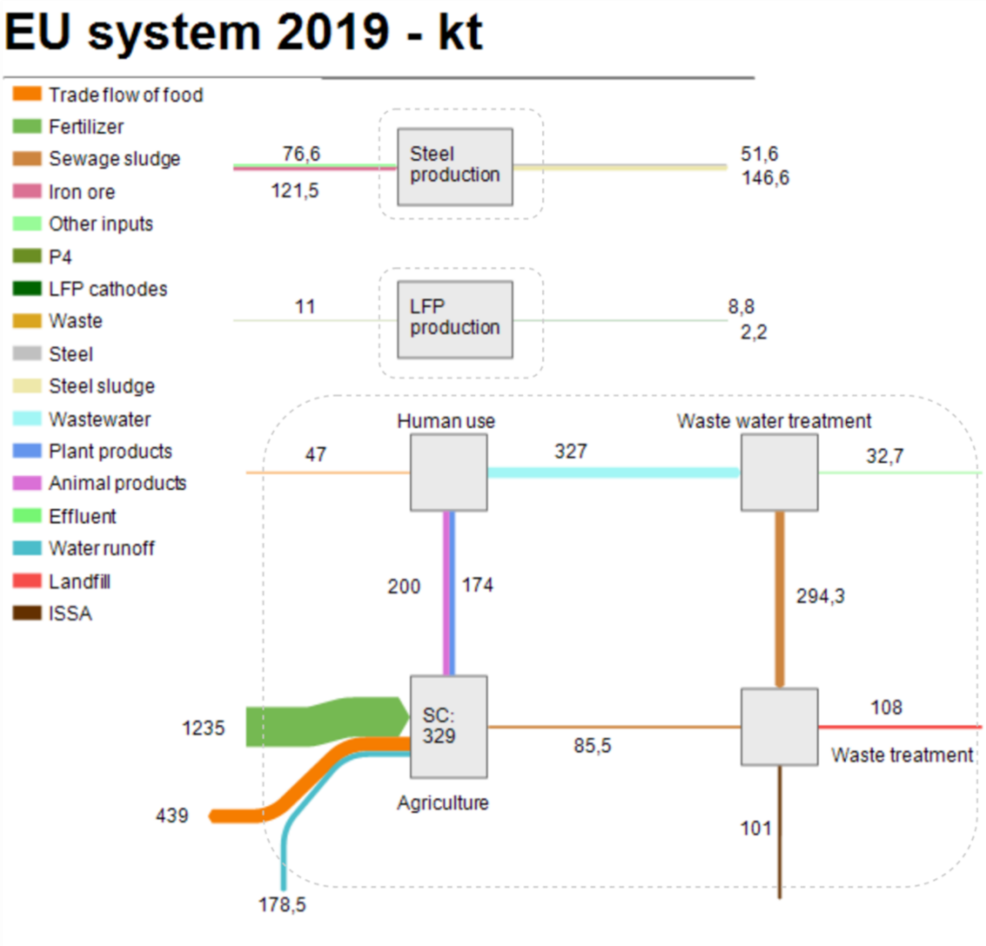

Figure 24: EU P system 2019 in kt P. SC = Stock change.

While the EU do not produce LFP cathodes domestically, the LFP production is illustrated to compare to the rest of the P system. As seen the largest flows pertain to the agriculture sector, while the LFP sector is comparatively small. Most P enters the system through fertilizer, with about 10% accumulating in the soil and a little more exiting the agriculture process through water runoff. Additionally, a relatively small amount of P enters human consumption as food, with approximately the same amount of food is exported. In this model only 47 kt is imported as food, while in reality this is substantially larger. This is due to the model set up, where the net import is only to compensate for the P in wastewater. In 2019 waste treatment generated 108 kt P of ISSA, 85,5 kt P went back to agriculture and 100,8 kt P went to landfill. Moreover, steel production is also small compared to the agriculture and waste processes but does also yield a relatively large flow of P in steel sludge.

3.2.2 EU LFP scenarios

The EU system under the BNEF scenario is illustrated in Figure 25 below, with the focus being on the developments of the other parts of the system.

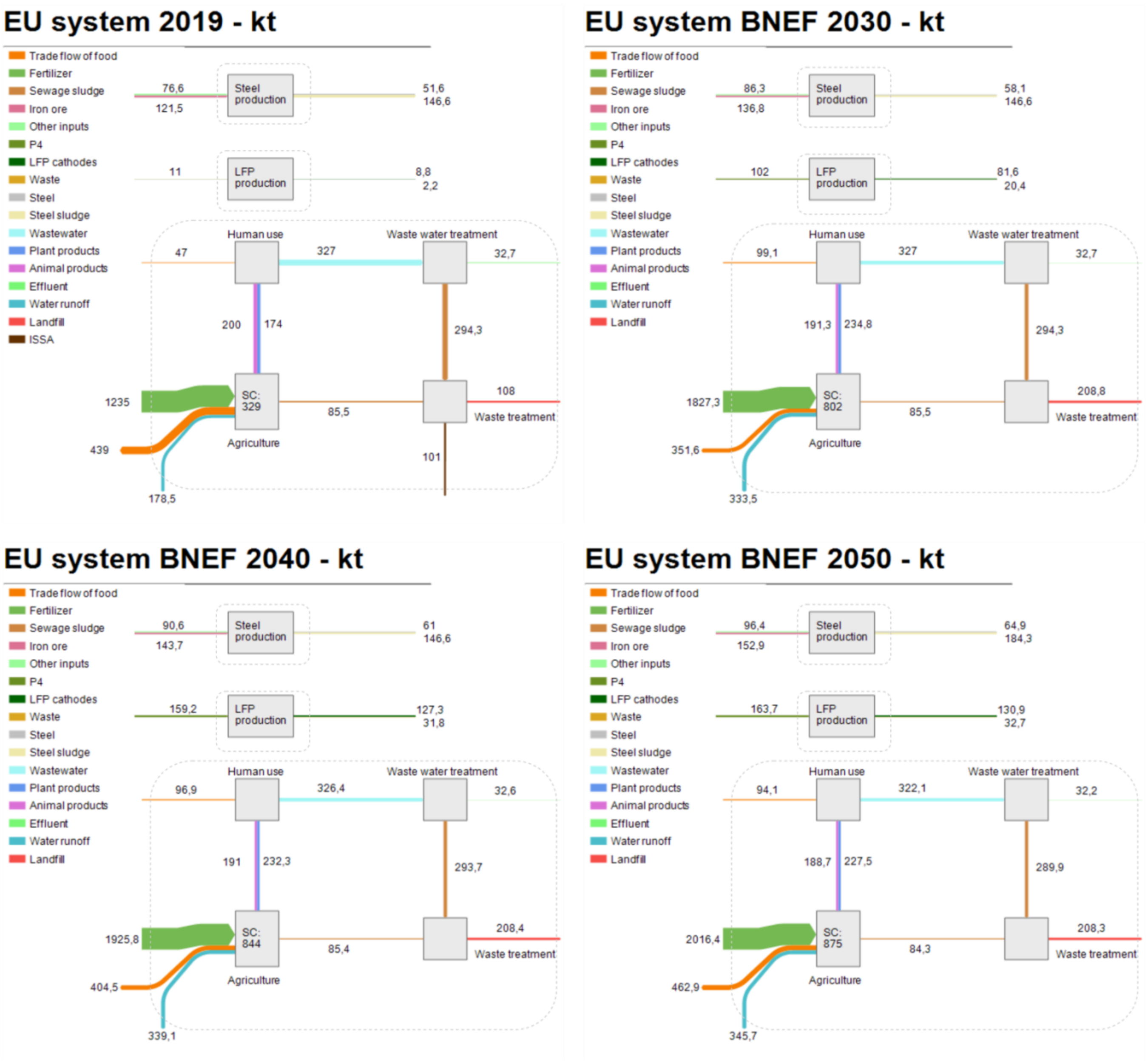

Figure 25: Quantified EU system for 2019, 2030, 2040 and 2050 for the BNEF scenario. SC= Stock change.

As seen agriculture stays the largest sector of P use throughout time. The other P using sectors stagnate, and flows connected to human use even decrease in the long term. This can be attributed to the decreasing population. The steel sector is likewise growing slowly. However, while the EU had a net import of food in 2019, this is an export for future years (flow from human use to outside system boundary). This might indicate that the EU develops larger self-sufficiency for food across time, as they now produce more food for their domestic population and for export. Moreover, ISSA is not illustrated in future years, rather it is shown how much sewage sludge is available for incineration. Due to the LFP production being completely disaggregated from the other uses and productions of P, the LFP demand scenarios are illustrated in Figure 26 with the P in cathodes, P_4 imported and waste from cathode production.

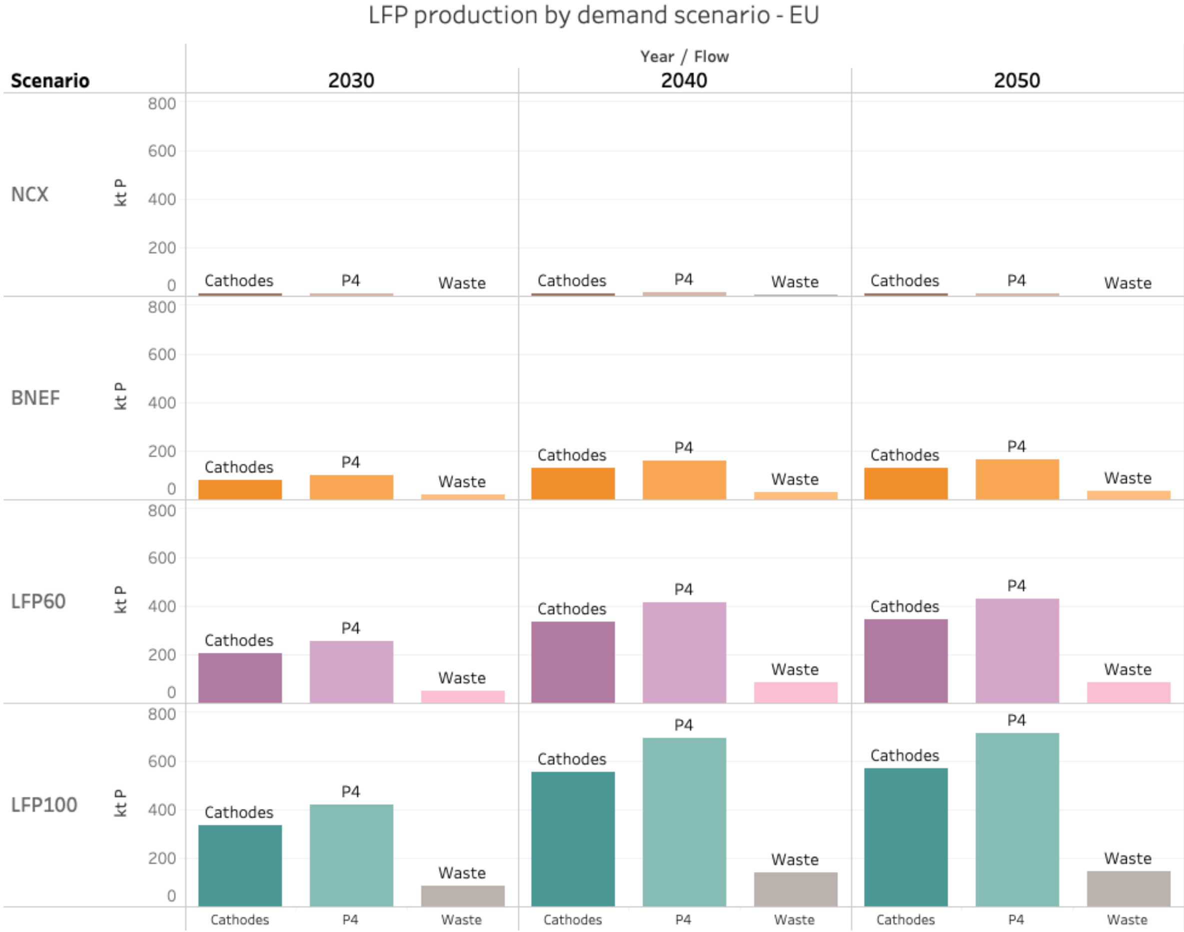

Figure 26: LFP production by demand scenario and year – EU. All flows in and out of LFP production are illustrated.

The increased demand for LFP stagnates towards the end of the century in all scenarios. For the highest LFP scenario the volume of P is a little less than half of fertilizer but is substantially larger than the volume of P in food. For the lower LFP demand scenarios the demand for P is negligible, being the smallest flow in the EU P system for all years. Similarly, if the EU produce cathodes domestically it would also depending on the demand scenario for LFP, generate waste that needs disposal.

3.2.3 EU secondary resources

The effect of the recycling the end-of-life LFP cathodes is illustrated in Figure 27. The bars are cumulative for mass not time, meaning that the in the LFP_{100} scenario the total demand for cathodes would be approximately 550 kt in 2050. Further, as seen the effect of recycling on demand is most notable in 2050 and does not seem to have any substantial impact in 2030.

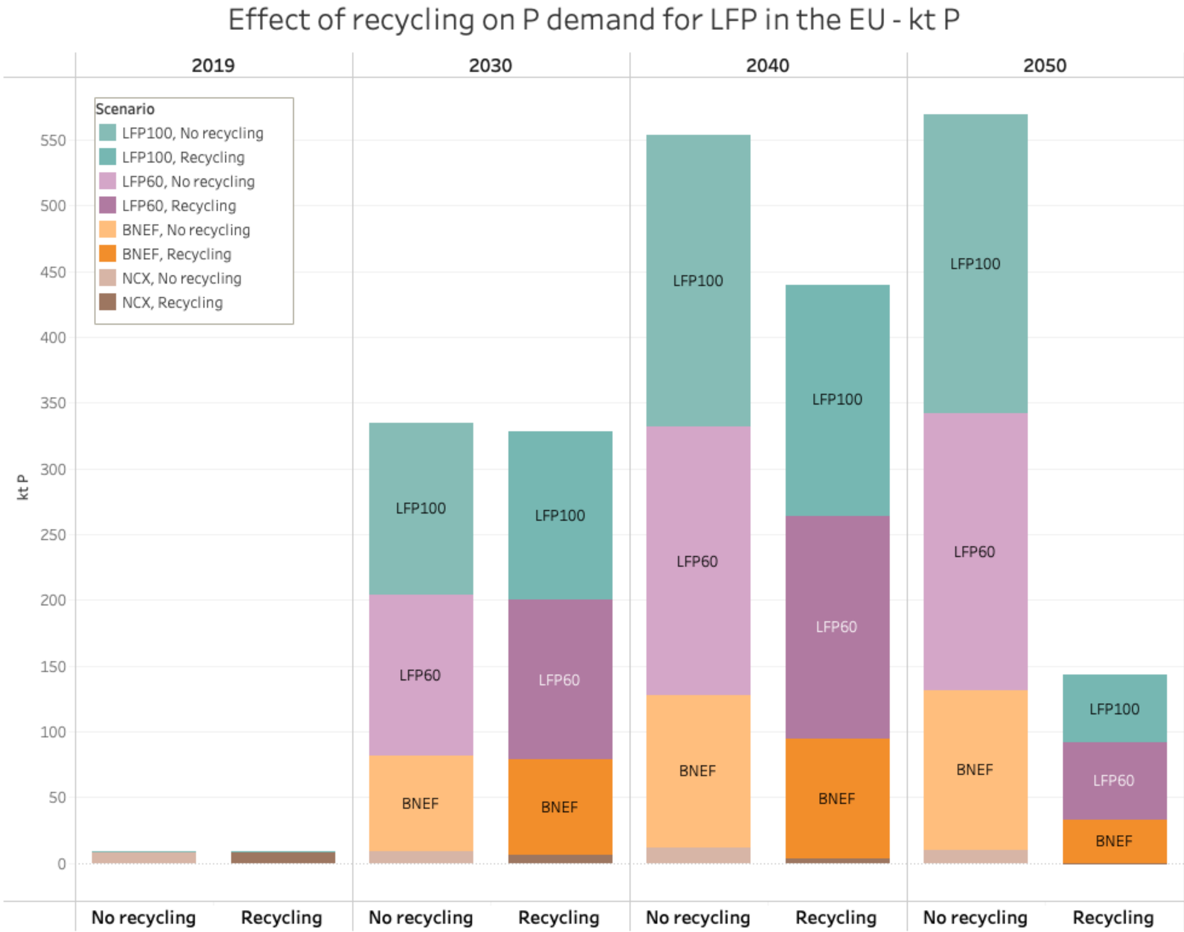

Figure 27: The effect of recycling on the demand for LFP P.

The effect of recycling in the EU includes the premise that the production of LFP is done domestically, as the graph represents the demand for primary material and not for EVs itself. Thus, the EU can import all their EVs, and not have domestic production however that entails complete import dependence. Thus, if the EU has no domestic production of LFP they would have to import a substantial amount of LFP vehicles before they could rely on domestic production of LFP through recycled resources. Like the global system, other secondary resources have therefore a significant position in the short term.

The available secondary resources for the EU are less than for the global system, as they do not produce P_4, and therefore do not have FeP domestically. Moreover, aquaculture production in the EU is minimal, and therefore does not yield substantial secondary resources. Using the same methodology as the global aquaculture production, the EU production of aquaculture sludge in 2019 would be approximately 11,5 kt as P in the sludge, based on a production of 1 114 kt fish (EUROSTAT, 2021b). Moreover, the availability of secondary resources compared to the demand for different LFP scenarios are displayed in Figure 28 with and without recycling of LFP cathodes. Manure is also included in the graph; however, it is not compatible with use in LFP cathodes, but gives scale.

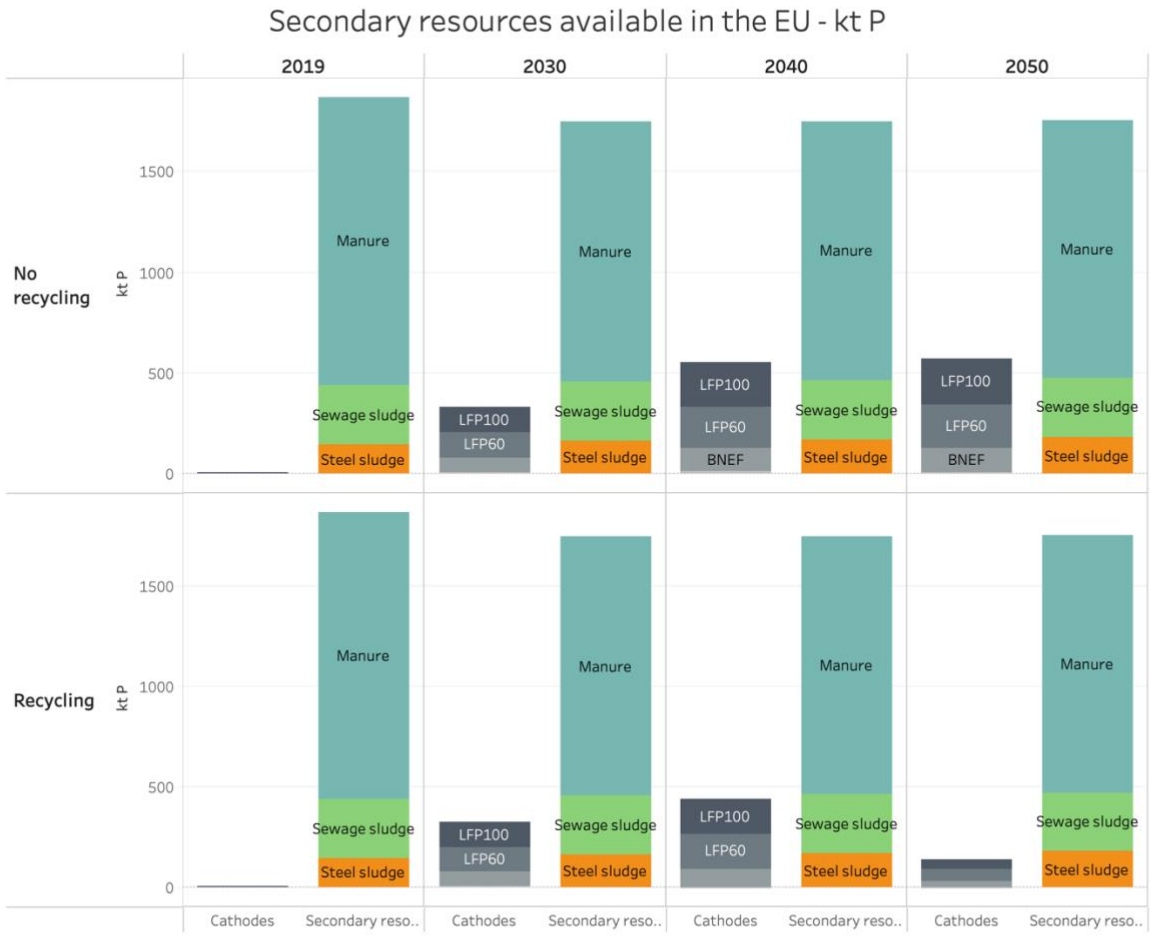

Figure 28: Secondary resources available in the EU, compared to different demands for LFP P.

As seen on the graph, almost all the LFP demand can be covered by sewage sludge and steel sludge alone even for the high scenarios. If one factors in recycling of LFP cathodes, the demand can easily be met by secondary resources for all years, even solely by steel sludge in the long term.

4. Discussion

The results show that a clear increase in the demand for P can be expected, both from food and LFP cathodes. Moreover, the results show there is not a direct competition for P manufacturing capacity between the two uses at the global level, but rather a competition for phosphate rock as an input material. The intensity of this competition depends on the level of reliance on LFP in the future, as the demand for phosphate rock is directly correlated with the amount of LFP cathodes. On a regional basis, the consequences of LFP demand for the EU will manifest in various way depending on the ambition to produce these cathodes domestically or whether they are imported in EVs. Either way, as the EU does not produce phosphate rock or P_4 domestically, the EU is dependent on imports all along the P supply chain. This is true for both LFP production, but also P for agriculture and other uses.

First, the consequences of an increase in the demand of LFP will be discussed. Scaling up the demand of LFP production has also revealed some barriers to the P system, but also enables opportunities in terms of secondary materials available for LFP production. Then issues and barriers related to P_4 production will be discussed. Lastly, a commentary on the model robustness and considerations will be done.

4.1 Competition between P sectors for P resources

The results showed that the demand for phosphate rock is highly affected by the demand for LFP cathodes and can in the high scenario have a share at almost 20% of the total P demand globally. While this scenario depends on high penetration of LFP cathodes, and a 100% LFP reliance for future production, it gives an insight into the effect this use has on the system. The share of P going to LFP production in contrast to agriculture is small, however even this small share can have consequences for food production in terms of dependency on imports, higher prices, and adverse access across the globe.

One challenge to intensified production of P is the disaggregated location of P resources, production of P for agriculture uses, the production of P_4 and the consumption of fertilizer. This geographical scattering is shown visually in Figure 29 below.

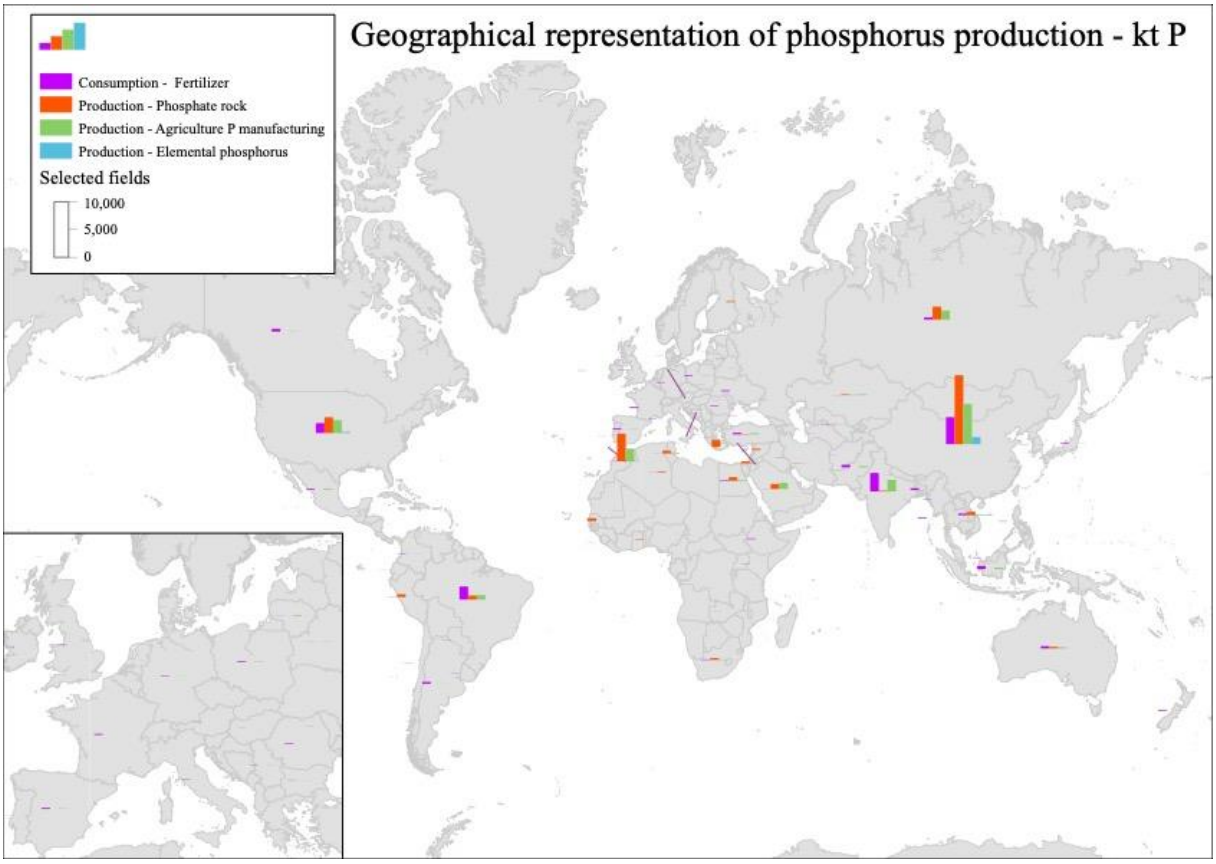

Figure 29: Geographical representation of phosphorus production for different uses, as well as the consumption of fertilizer. In kt P (de Boer et al., 2019; IFASTAT, n.d.).

As seen, there is not a clear correlation between the demand of P as fertilizer and the production of phosphate rock. This leaves regions vulnerable to changes in trade policies of countries having phosphate rock reserves. For example, the current largest producer of phosphate rock and fertilizer, China, completely stopped their export of fertilizer between 2021 and June 2022, due to concerns regarding domestic food security (Baffes & Koh, 2021). Following China's example, Russia similarly imposed restrictions on phosphate fertilizer for the first half of 2022 (Baffes & Koh, 2021). This is especially concerning as Russia is the largest exporter of fertilizer globally (Caprile, 2022). Access vulnerability also pertains to the EU as the domestic production of phosphate rock is minimal, with only one mine in Finland (Kontinen et al., 2016). This limited access to fertilizer is seen as acute according to the European Parliament in light of the war on Ukraine and thus trade restrictions with Russia, together with increasingly limited energy supply (Caprile, 2022). As competition for resources intensify regional dependencies on imports of P for food production will deepen, but this competition can likewise occur for P for LFP production.

Increased demand for phosphate rock together with the geographically limited supply can also increase the price of the commodity, which has materialized in the past. Phosphate rock noted large price spikes occurring both during the financial crisis in 2008 and Covid-19 in 2020 (Baffes & Koh, 2021). Several factors contributed to this; increase in demand and energy prices, and restrictive trade policies (Spears et al., 2022). China put a 135% tariff on phosphate rock, contributing the massive price spike in 2008 (Cordell & White, 2014). As there are few other supplier of phosphate rock, and an expected time lag of ramping up production capacity of at least 5 years, the supply in the following years were tightened (Ashley et al., 2009). Thus, a small increase in demand had large effects. This can be exemplified by biofuels. Biofuels were a concern for P demand in the past, with several authors acknowledging that the demand for P fertilizer for these crops pushed the prices of fertilizer and food upwards (IFA, 2011). However, considering that fertilizer for bioenergy only constituted 3,6% of the total fertilizer consumption in 2011, a 20% demand for LFP production could similarly influence the price of phosphate rock (IFA, 2011).

Moreover, the geographical location of the consumer can also influence the price of fertilizer, with landlocked countries such as Mali having substantially higher costs of fertilizer than coastal countries due to the additional cost of transportation and handling (IFA, 2011). Therefore, increase in demand for phosphate rock, import dependence and restrictive trade policies leading to decreased access, can have massive consequences for food security both globally and maybe more so regionally. Depending on the geographical location the consequences will appear adversely across the globe. This will then have large adverse effects on the parts of the population with lower purchasing power, and import dependent regions.

An increase in the price of phosphate rock might also affect LFP production, with an increase in production costs. Moreover, if restrictive trade policies are put in place on the input material for LFP production, it can create difficulties for regions such as the EU being dependent on import of these materials. However, as seen in the results there are some options to lighten the pressure on phosphate rock looking at the LFP side.

4.2 Alternatives to primary demand for LFP P

4.2.1 Recycling of LFP batteries

Specifically, for LFP P, recycling of cathodes would make P available to the regions with EVs containing LFP cathodes. However, there are some concerns regarding the feasibility and likelihood of LFP recycling of P. First, recycling of LFP does not have a large effect near term but can have substantial effect in the long term (see Figure 21 and Figure 27). This outcome is however contingent on the number of batteries produced, as the larger the current production is, the larger number of batteries are available in the future. Moreover, this also entails that the P being recycled in the future still must be produced and does not currently exist in EVs, but rather is still located in the ground. As the EU is dependent on imports for P materials, they are also reliant on not exporting the end-of-life vehicles. The historical trend showed that the EU exported approximately 7,6 million used light duty vehicles to other countries in the period between 2015 and 2018 (UNEP, 2020). While the share of EVs in the exported cars is small, it has grown from year to year (UNEP, 2020). If the export trend of used vehicles continues the EU might ship their secondary resources abroad.

Second, the most feasible option for recycling of LFP is direct recycling, which is the technology assumed in this model. Direct recycling can however bring some challenges, such as technological lock in. As direct recycling recycles all the cathode active material, it does not allow for changes to the technology used. As such, if LFP cathodes are recycled in the future, they must use the same technology as today’s battery. Therefore, it can obstruct future growth in technology. Moreover, if only appropriate technology for P recycling is direct recycling, it also hinders the use of P for other applications. This is not to say that material recovery of P from LFP will not occur in the future, but for that to happen technological development and especially economic barriers will need to be overcome. Currently, it is not economically, and sometimes environmentally beneficial, to extract the P for recycling from LFP cathodes (Forte et al., 2021). On the flip side if the price of LFP cathodes or the primary material for production rise, it might become a good business case to recycle LFP cathodes both directly and for P itself.

4.2.2 Secondary resources for LFP

The second option for alleviating the pressure on P from a LFP point of view, is to look at secondary materials as feedstock for LFP production. The EU can access P for LFP cathodes in several parts of the supply chain. First, they can import or use their domestically produced phosphate rock to produce P_4 based acid, which in turn can be used as a cathode feed stock. Currently, the EU only produce minimal amounts of phosphate rock, which also is only used for agriculture purposes. Second, they can also import the P-acid. Third, importing the cathode active material is further possible, and lastly importing cathodes or EVs with LFP cathodes is an option. As such, waste streams of P produced domestically in the EU are options to secure domestic supply.

The results show that the EU do not have a large range of secondary resources being appropriate for LFP use, but they do have access to steel sludge and sewage sludge, with especially sewage sludge showing the furthest technological development. However, steel and sewage sludge cannot cover the total demand for LFP material for the LFP_{100} scenario from 2030 onwards, but it can almost cover the LFP_{60} scenario for all periods of time. Globally the secondary resources do not meet the demand for LFP P for the highest scenarios, but sewage sludge alone can cover the demand for the lower scenarios throughout the period. However, that does not consider the additional losses in the recovery processes of the P from the two waste streams, therefore the results can be seen as optimistic quantitatively.

Sewage sludge

Sewage sludge has been used as fertilizer historically in the EU, however this has been increasingly banned (Ohtake & Tsuneda, 2019). This has led to investments of incinerators for sewage sludge to ISSA. ISSA has benefits of having low water content, centralized and large scale production, and a high P content. Therefore, to prevent accumulation of P in landfilled sewage sludge, a new application as LFP input could be beneficial. Depending on the precipitation method used to extract P to sewage sludge, a drawback of ISSA is the potential high content of Al and Fe. Producing P_4 from ISSA can happen in the same equipment as P_4 produced from phosphate rock (Wöhler process). However, this treatment of ISSA to P_4 can have large amount of FeP forming if the iron content is high (Ohtake & Tsuneda, 2019). While no study has looked at whether FeP produced from sewage sludge is adequate for LFP production, this could potentially be the case. Next to technological challenges, a practical barrier is the availability of the resource. While the model investigated the potential availability, the actual quantity is dependent on the number of people connected to sewage systems, and the capacity of incinerating the sewage sludge produced. These barriers are not pressing for the EU, where most of the population are connected to sewage systems and there is an increase in the investment for incinerators. On the global scale, the access to P from wastewater can expect to increase as the population become urbanized. It will therefore mostly depend on the capacity of incineration.

Steel sludge

Like sewage sludge, steel sludge also has some barriers to the recovery of P. While sewage sludge recovery of P has been commercialized, P recovery from steel sludge is still being researched and no commercially available technology is out on the market yet. Literature shows however technological potential of treating steel sludge to P_4 through pyro treatment (Yu et al., 2022). Moreover, the sludge has low contamination of other elements, but faces even larger issues of FeP forming as a byproduct in thermal based processing (Yu et al., 2022). While the technological and economic aspect of recovery are clear barriers, steel sludge does have the advantage of having concentrated and high volume supply (Yu et al., 2022).

Ferrophosphorus (FeP)

FeP is largely a byproduct of other processes, the amount available is therefore dependent on the capacity of production of these materials. Traditionally the production of P_4 from phosphate rock is the largest contributor to FeP. Ferrophosphorus has the advantage of not needing further treatment to P_4 before entering LiFeP precursor production (Ma et al., 2019). However, in the precipitation method by Ma et al. (2019) some input of P-acid was necessary, therefore not creating complete independence from primary material. A barrier is that this waste material is located at the same location as the primary material, therefore not contributing to better accessibility for many regions. Moreover, little specification regarding the quality of the FeP was specified, and therefore it is not known whether P_4 production from steel sludge or sewage sludge would yield the appropriate FeP for cathode precursor production.

Use of secondary resource barriers and opportunities

Combing the use of secondary resources and recycling of LFP cathodes show the greatest potential when it comes to alleviating pressure on primary resources, at both the global and EU levels. In fact, secondary resources could cover the demand for P for all years and all demand scenarios, when recycling was considered. However, as seen recycling of LFP cathodes have issues connected to technological and economic feasibility. Similar barriers are true for the use of secondary resources. Historically the relatively low price of phosphate rock has hindered the development and market emergence of recycling and recovery technology for P in general (Ohtake & Tsuneda, 2019). Moreover, the undeveloped and small-scale market for P_4 for LFP is reflected in the scarce literature and technology development of recovering and recycling P for industrial uses. Thus, an increased understanding of P chemistry of waste streams is important. Increasing the understanding of P components in waste streams might create beneficial synergies between P recycling for LFP and for agriculture. As some waste streams have P adequate for growing crops, while others have P suitable for other uses. Manure is for example already highly recirculated within agriculture, because the P can be taken up by plants. Other waste streams such as FeP or sewage sludge might not be appropriate for use on agricultural soil, and therefore be better used for LFP production. Such considerations should be taken in further research to facilitate efficient and sustainable use of P resources.

Next, a clear barrier in the transformation from P recovered to P adequate for battery materials, is the processing of the waste material to P_4. As the P for battery grade materials require high purity, removal of other elements and trace material is necessary. ISSA has been processed to P_4 previously, however it was processed using the same technology as from phosphate rock. While P from steel slag has not yet been commercially recovered as P_4, Yu et al. (2022) found in their literature review that pyro treatment of steel slag showed the greatest recovery rate of P_4. Therefore, while secondary resources can help alleviate a material competition for primary material, it still faces certain obstacles.

4.3 Issues and barriers with P_4 production.

For batteries, Figure 29 also illustrate the narrow supply of P_4. China is by far the largest producer of P_4; however, the product is almost exclusively used domestically. The same is true for the US, which also only produce P_4 for domestic production of glyphosate (Ohtake & Tsuneda, 2019). The only two other countries Kazakhstan and Vietnam, however, produce mostly for exporting and are the sole providers for P_4 for the EU. Again, with only a few producers available, changes to supply from these actors have large effects on the global supply. In 2019 the global production capacity for P_4 was estimated at 2 145 kt/yr, with much less being produced annually (de Boer et al., 2019). Of this China’s capacity alone is 1 900 kt/yr, meaning that the export-oriented countries have very low share of capacity. Compared to the high scenario of LFP_{100}, demand in 2050 could be 9 862 kt, thus increase in production capacity is necessary.

There are no clear objections to why other countries cannot adapt P_4 production capacity, however there are some barriers to why it is not widely attractive. First, the production yields hazardous waste of heavy metals and radioactive materials in the fly ash which needs to be disposed properly (Gilmour, 2019). Secondly, the production of P_4 is more costly than purifying wet acid. The largest applications of P requiring higher purity can normally use purified P-acid, and do not require a 99% purified acid from P_4 (JRC, 2020). Therefore, the demand for P_4 has in the last decade decreased, as the market has shifted towards purified P-acid. Third, the price of P-acid derived from P_4 is twice as expensive as purified acid when holding the P content, labor cost and overhead rates equal (Gilmour, 2019). Low variable costs are therefore necessary to have a business case. The most influential costs for P_4 production has historically been labor costs and electricity price which have an increasing price trends (Gilmour, 2019). Indeed, almost 50% of the cost of producing P_4 is from the cost of electricity (Gilmour, 2019). Energy shortages also led Japan to cease their production of P_4 completely in the 1970s (Ohtake & Tsuneda, 2019). Furthermore, when electricity prices rose, the production in Europe and the Americas decreased.

The results show that production of P_4 is a highly electricity intensive industry. For the LFP_{100} scenario, the electricity demand peaks at approximately 160 TWh in 2050. In comparison Vietnam, a producer of P_4, consumed 223 TWh in total in 2019 (IEA, 2020). Moreover, compared to the production of $LiCO_3$, another battery material, the demand for electricity for P_4 manufacturing is very large. A large increase in the demand for LFP would therefore entail a need for more infrastructure on electricity, not just to produce the input material but also for production of the battery and the charging of the cars. Electricity can be the inhabiting factor for production due to availability. Historically, the producers in China, which is the largest producer, has older and smaller factories. This led to a sharp decrease in the production quantity of P_4 in China in 2021, due to shortages of electricity. Factories working below the best available technologies had to restrict their production to 10% of capacity (Yonglei & Bojun, 2021). Consequently, the price also increases almost 200% in only a few months (Yonglei & Bojun, 2021). This is also visible in their import of P_4, which in 2021 set a record high (see Figure 19 in the Appendix IV). To meet future increase in demand, a secure supply of electricity is therefore needed to meet this demand in quantity for LFP. Additionally, whether the precursor material is produced from renewable based electricity or from nonrenewable sources will impact the environmental footprint of the cathodes. Renewable resources are necessary for the shift to batteries to be as sustainable as possible.

Technological improvements

While the conventional process for production of P_4 has the above-mentioned issues, there has been some technological breakthrough in the industry. The P_4 for batteries have to further processed to P-acid, which is the fate for about 70% of the produced P_4 (de Boer et al., 2019; Scholz et al., 2014). A Chinese developed technology: kiln phosphoric acid (KPA) has shown potential to alleviate some of the issue regarding P_4 production. Traditionally the P_4 and the thermal acid is produced in two separate facilities, while for the kiln process the thermal acid is produced straight from phosphate rock. Moreover, the process can produce the same quality and low impurity acid as the thermal process, however it is better both economically and environmentally (Wu et al., 2022). The former is due to the drastically reduced demand for energy. The heat released from the oxidation of P is reused inside the equipment, reducing the energy demand by 70% (Wu et al., 2022). On the environmental side, as the main discharge from KPA production is in the form of pellets which can be used for concrete products. An additional benefit is the ability to use low grade phosphate rock (Wu et al., 2022). This is especially beneficial as the amount of high and medium grade phosphate rock ores are diminishing over time (de Boer et al., 2019). Moreover, as the P-acid production for food requires high and medium grade phosphate ores, building a P industry with the ability to use low phosphate rock could prevent competition for the same phosphate rock resources.

4.4 Model robustness

There are no studies looking at the future demand of LFP P, and therefore validating the LFP results of the model is difficult. A comparison however, can be made in terms of the P extracted as phosphate rock for future years, giving an indication of whether the model predicts in a feasible range. Van Vuuren et al. (2010) explore four different scenarios for P rock demanded until 2100, and report a range between 25 and 45 Mt P in 2050. Moreover, Cordell and White (2014) found a larger range between 10 and 50 Mt P. This model estimated a supply of phosphate rock between 33 and 44 Mt P. The range from the model by Van Vuuren et al. (2010) is derived from different population expectations, GDP and agriculture scenarios, while the range in this model is solely due to the change in LFP demand. While the range from Cordell and White (2014) originates from different P efficiency and reuse scenarios. Additionally, LFP is not included in either of the above models and can partly explain why this model has a higher estimate than the mentioned studies. However, it can be concluded that this model is within the range predicted by other studies on the future consumption of P.

One way to investigate the dynamics of the model is to perform a sensitivity analysis, which was not conducted in this study. As the results reveal that LFP demand only affect the inflow of phosphate rock and P_4 produced, a 10% change in the demand would likewise only cause a 10% increase in the inflow of phosphate rock and P_4 produced. As such, a sensitivity analysis could be seen through the different LFP demand scenarios. A similar analysis was however not done for the other parts of the system, as this was not the subject of investigation.
Lastly, an increase in demand of LFP P could have adverse effects on agricultural use of P by increased prices, and tightened access to phosphate rock. Therefore, additional economic analysis; such as price elasticity of demand, and social-environmental analysis; such as environmental impact from increased mining should be done. As these aspects where only briefly touched upon in this study, these analyses could potentially strengthen the findings of this report.

4.5 Implications and future research

One of the findings of this study was the geographical complexity of the P supply and consumption network. Phosphorus is produced, manufactured, and consumed across the world; however, certain parts of the supply chain is highly geographically concentrated. This implicates that a regional disaggregated analysis of the supply chain is needed, to further unravel potential regional scarcities and opportunities of P circularity. This study of the EU P supply chain underpins this necessity. While regional assessment of P depletion (Van Vuuren et al., 2010), fertilizer demand (Tenkorang & Lowenberg-DeBoer, 2009) and P soil balances (Bouwman et al., 2013) have been conducted, none include the regional disaggregation of the supply system of P in general and for LFP. Therefore, a more comprehensive study of P on a regional basis is needed.

This study only considered P demand for the cathode material in LFP but did not include the P demand for the electrolyte or the P used for treatment of steel for the EVs. Both of these mentioned applications of P are dependent on P_4 as the input material (JRC, 2020; Ohtake & Tsuneda, 2019). Consequently, the demand for P in the EV sector is higher than the estimation here, and therefore future studies should investigate the additional impact of P demand by electrolytes and steel treatment. Especially the latter has historically accounted for a large part of the traded P_4 between Vietnam and India (Ohtake & Tsuneda, 2019). These factors have led to this study potentially underestimating the demand of P for EVs in the future, however this just contributes to the robustness of the discussion in this study. If the demand for P in EVs are higher than this estimation the consequences of this demand could potentially be larger.

5. Conclusion

The global and regional P systems are plagued by concerns and issues of supply constraints coupled together with increased demand of P. Past literature has concerns regarding the sustainability of the P system but has neglected to include the increased demand of P for batteries. This study has tried to rectify this by taking a wide system approach looking at both uses of P, revealing the resilience and down falls of the system by also looking at potential future developments.

The results have revealed that there is no quick fix to a sustainable P management, neither for battery use or the system as a whole. While the focus in this system has been on potential improvements to the battery supply system, there is a clear need for improvements of all sectors of P. Technological and economic barriers to recycling of LFP cathodes and the use of secondary P resources are currently both present. However, as the P battery system is just starting to develop there is golden opportunity for policy makers and governments to create a clear strategy and influence the future of the P battery system, also considering secondary resources and recycling technologies.

Another option to alleviate pressure on primary P, not explored here, and consequently also alleviate pressure on resources for food production, is a low demand of P for batteries. This can be achieved in different ways. First, while an option is to completely avoid the production of LFP batteries, numerous research has shown that a complete reliance on batteries consuming Ni and Mn have issues on their own. Thus, relying on only one battery chemistry can cause issues regardless of the chemistry selected. As such, there are several options. One would be to disperse the demand for batteries on different chemistries, alleviating the demand for only one type of material creating a resilient battery industry. Secondly, new technologies are being developed, and is foreseen to emerge in the future, which can alleviate the demand on primary materials and hinder a problem shift from one cathode type to another. Concludingly, policies and political action will be influential in affecting the demand on P in the future.

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Appendix

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Appendix I – Secondary resources literature review

Ferrophosphorus

Ma et al. (2019) looked at the use of ferrophosphorus, which is a by-product of P_4 production for LFP production. It emerges as the iron present in the phosphate rock ore binds with some of the P in the rock during the thermal treatment of the phosphate. Currently this waste material is used as an input material for the steel industry (Morton & Edwards, 2005), but was proven by Ma et al. (2019) to be adequate as an input material for $LiFePO_4$ precursor. Whether FeP formed during thermal production of P_4, using steel sludge or ISSA as feedstock, is appropriate for LFP precursor production remains unclear in the literature.

Steel

While the majority of the P waste originates from phosphate rock input, the steel sector is the exception, using iron ore as feedstock. Iron ore in itself does not contain a great amount of P, between 0,02 to 1%, however with the large quantities of steel produced input of P to steel production can be vast (Morton & Edwards, 2005). Morton and Edwards (2005) estimate that in 2005, the amount of P found in steel was 5% of the world total P going to fertilizer. Phosphorus can be a harmful substance in steel production, and can form brittle iron phosphide networks and is therefore removed when necessary (Morton & Edwards, 2005). Consequently the steel and iron waste have a significant P content, and can be considered a large waste flow where P could be recovered (Jupp et al., 2021). While previous literature focused on internal use of the steel slag, Yu et al. (2022) conclude that steel making slag has many of the same properties as phosphate rock; a high P content, large available quantities and similar thermochemical characteristics, and can work as an input material for P_4 production. However, there is yet to be developed an economically viable P recovery process from steel slag, with most processes currently being too costly (Yu et al., 2022).

Human waste

Sewage sludge P recovery is the most advanced recovery for P_4 production historically. It has both been used as a feed material for wet acid producton in Japan (Ohtake & Okano, 2015), as well as for P_4 production in the Netherlands from 2007 to 2012 (Desmidt et al., 2015). However, unlike steel slag, sewage sludge has to undergo further treatment before recovery of P can take place. Incinirating sewage sludge can reduce the volume of the feedstock by 90%, and simulatnously increase the P content per volume to 11% (Jupp et al., 2021). That goes as long as the iron content of the feed material is sufficiently low, as ferrophosphorus will be produced if iron is present (Jupp et al., 2021). In areas where a large part of the population is connected to waste water systems, the availability of sewage sludge is high. A barrier for the use of ISSA in P_4 production is the competition for sewage sludge. Sewage sludge has already been seen as an input for fertilizer production, and with a hightened focus on secondary sources of P this might lead to a competition for sewage sludge. While sewage sludge can have large traces of heavy metals and low bioavailability of P, new technolgoies have shown promising results that this will change allowing for better compatibility as fertilizer (Herzel et al., 2016).

Other secondary sources

The most prevalent secondary source of P is manure from cattle. Every year about 127 Mt of manure is produced, of which most is returned to grassland and pasture as fertilizer (FAO, 2021b). As the manure as a secondary resource is already heavily recycled, it is here not investigated any further. A competition for manure between battery production and food production would not yield beneficial outcomes, as this could lead to economic barriers for farmers today reliant on free access to manure as fertilizer. Likewise, no research on manure as a feedstock to P_4 or LFP precursor production was found.

Another source of P is sludge from aquaculture production, which has seen a dramatic increase in production in the last years (Huang et al., 2019). Aquaculture produces sludge, which is the excess feed and the feces produced from the fish that enters waterbodies. Like agriculture the PUE[1] for aquaculture is low, meaning that input of P to the process is high compared to what is retained in the fish. As such, large quantities of P in sludge are available in the locations where aquaculture is produced. Moreover, this availability is expected to increase with heightened aquaculture production in the future. However, similarly to manure literature on the recycling of P in sludge for industrial uses was not located.

[1] Here defined as "ratio of harvested to input of P" Huang, C.-L., Gao, B., Xu, S., Huang, Y., Yan, X., & Cui, S. (2019). Changing phosphorus metabolism of a global aquaculture city. *Journal of Cleaner Production*, *225*, 1118-1133. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.03.298 .

Appendix II – Model inputs

Global model inputs

Fertilizer demand

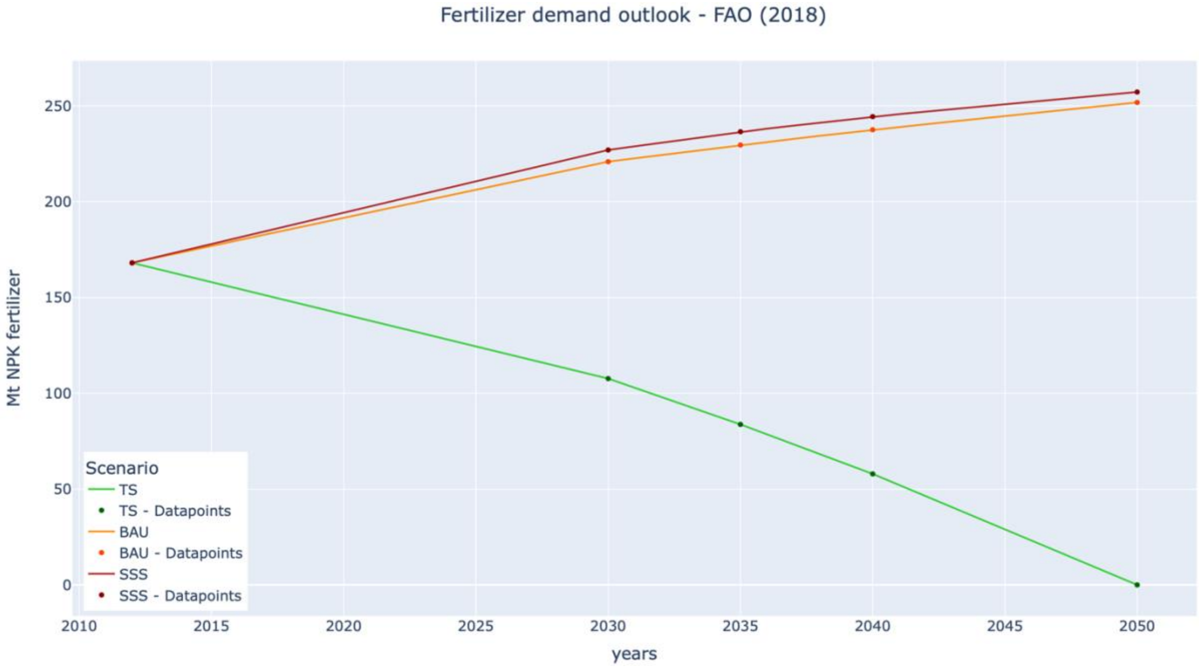


Figure 1: Future fertilizer demand outlook - (FAO, 2018)

Stock of animals (Manure)

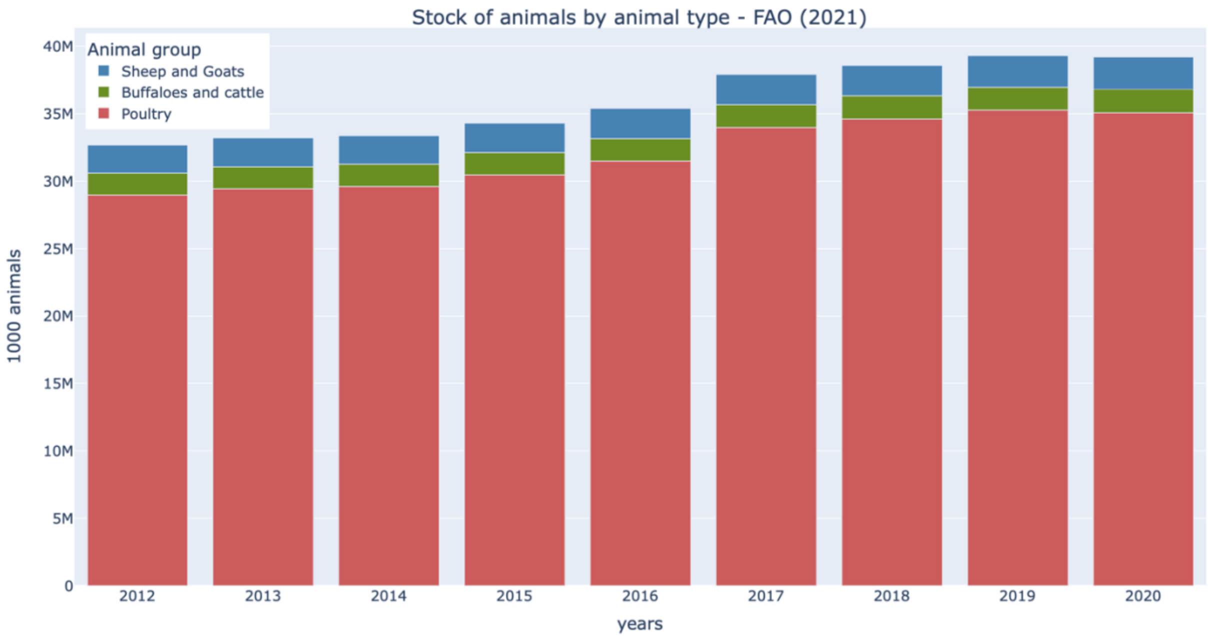


Figure 2: Stock of animals by animal type for historical years 2012-2020 - (FAO, 2021a)

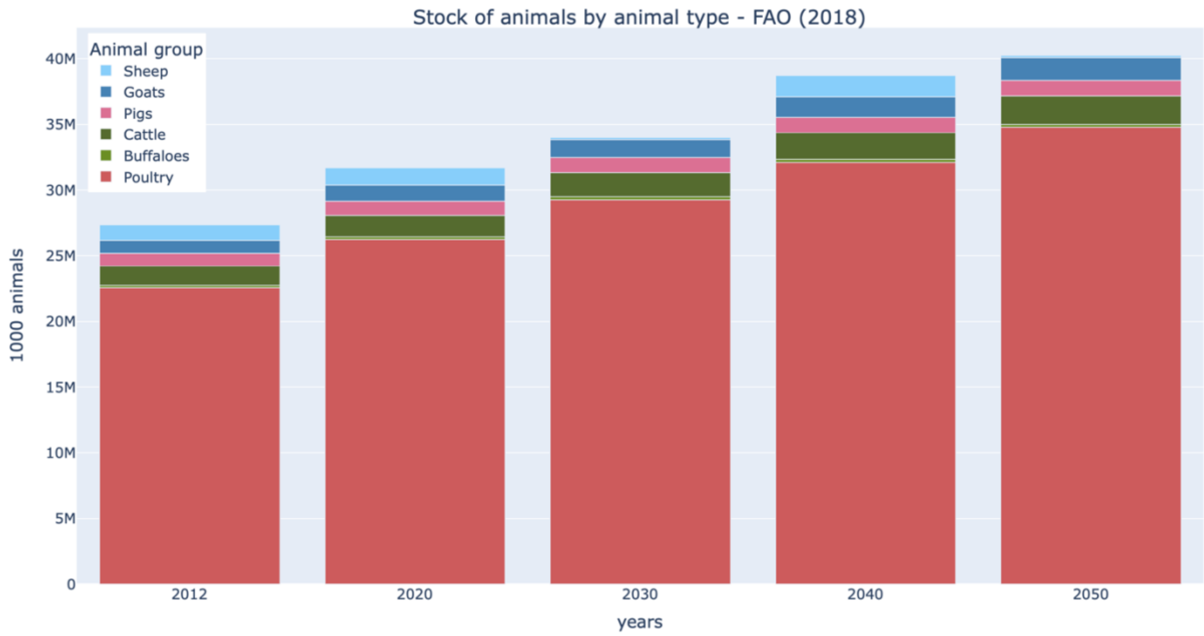


Figure 3: Stock of animals by animal type for future outlook - (FAO, 2018)

Phosphorus content of plant products

Table 1: Phosphorus content of different plant food categories.

Crop	Dry matter/fresh weight	P in grains/dry matter
Cereals	0,879	0,003
Sugar crops	0,310	0,001
Roots and tubers	0,201	0,001
Vegetables	0,100	0,001
Fruit	0,150	0,001
Pulses	0,951	0,005
Oil crops	0,734	0,001
Other	0,800	0,001
Forages	only dry weight	0,002

Source: Liu et al. (2008)

Manure coefficients

Table 2: Manure coefficients

Animal category	Excretion in kg P head^{-1} year $^{-1}$
Cattle	10,5
Buffaloes	7,9
Pigs	1,8
Poultry	0,1
Sheep and goats	1,5
Horses	6,5

Matching of food items to P concentrations food groups

*Table 3: Matching of food groups by **FAO (2018)** and the P concentration by **Liu et al. (2008)**.*

Aggregated group (Liu et al., 2008)	Food item (FAO, 2018)
Fruits	Bananas
	Citrus Fruits
	Other fruits
	Cocoa beans
	Coconut
	Coffee, green
Pulses	Dried pulses
Other	Copra cake
	Milled rice
	Other crops
	Other fiber crops
	Tea
	Tobacco
	Natural rubber
Cereal	Grain maize
	Millet
	Other cereals
	Paddy rice
	Barley
	Sorghum
	Wheat
Oil crops	Oilcrops, nes, cake
	Oilcrops, nes, oil
	Olive oil
	Olives
	Other oilseeds
	Rapeseed and mustard seed
	Rapeseed cake
	Rapeseed oil
	Cotton lint

	Cottonseed cake
	Cottonseed oil
	Palm kernel cake
	Palm kernel oil
	Coconut oil
	Sesame seed cake
	Sesame seed oil
	Soya cake
	Soya oil
	Soybeans
	Sunflower seed
	Sunflower seed cake
	Sunflower seed oil
	Groundnut cake
	Groundnut oil
	Groundnuts
Roots and tubers	Other roots and tubers
	Potatoes
	Sweet potato and yams
	Cassava
Vegetables	Other vegetables
	Sugar beet
Sugar crops	Processed sugar
	Sugar cane

EU model inputs

Manure methodology

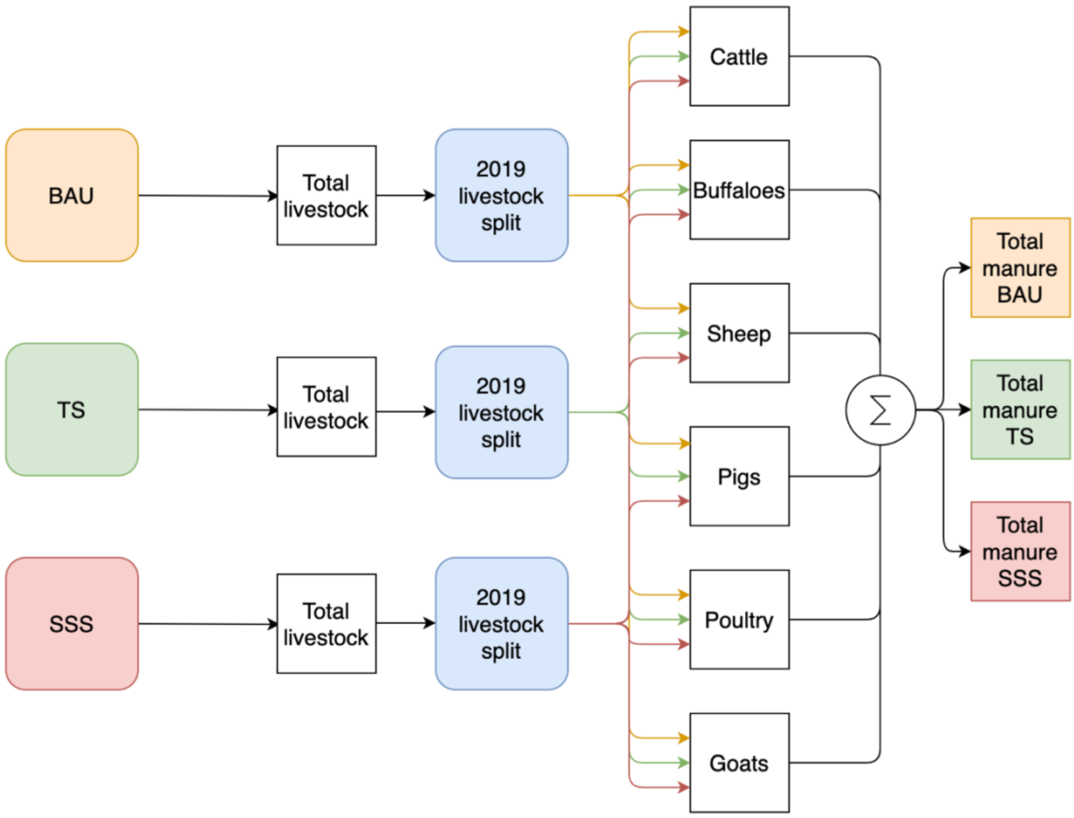


Figure 4: Calculation of manure in the EU system.

Stock of animals (Manure)

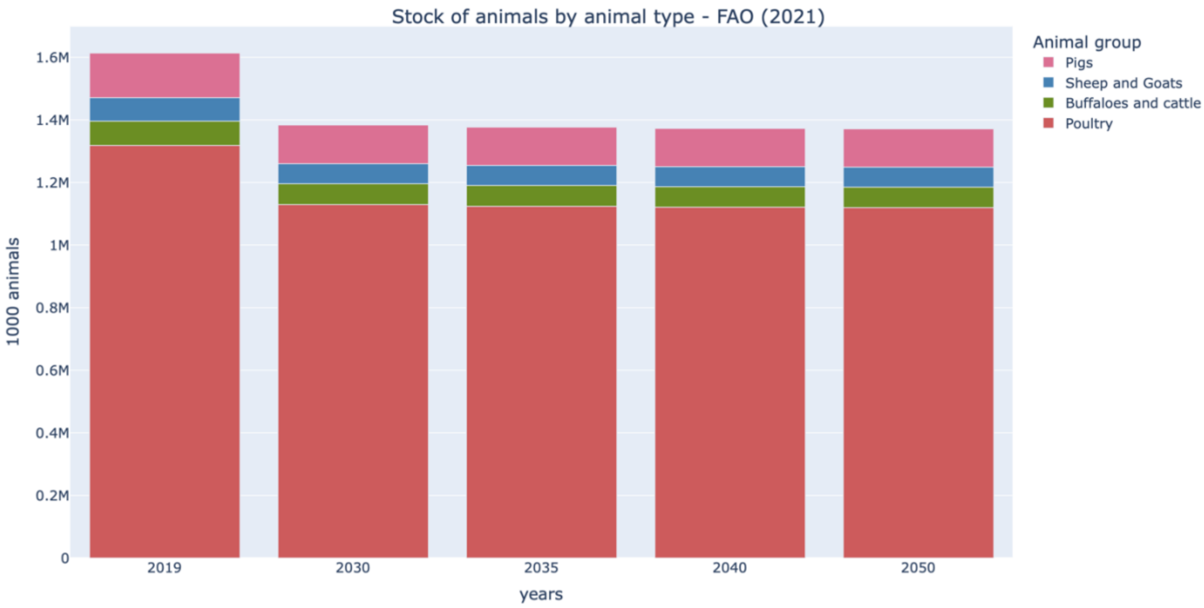


Figure 5: Stock of animals by year for the EU system.

Scenarios

Chemistry share of the vehicle stock by scenario

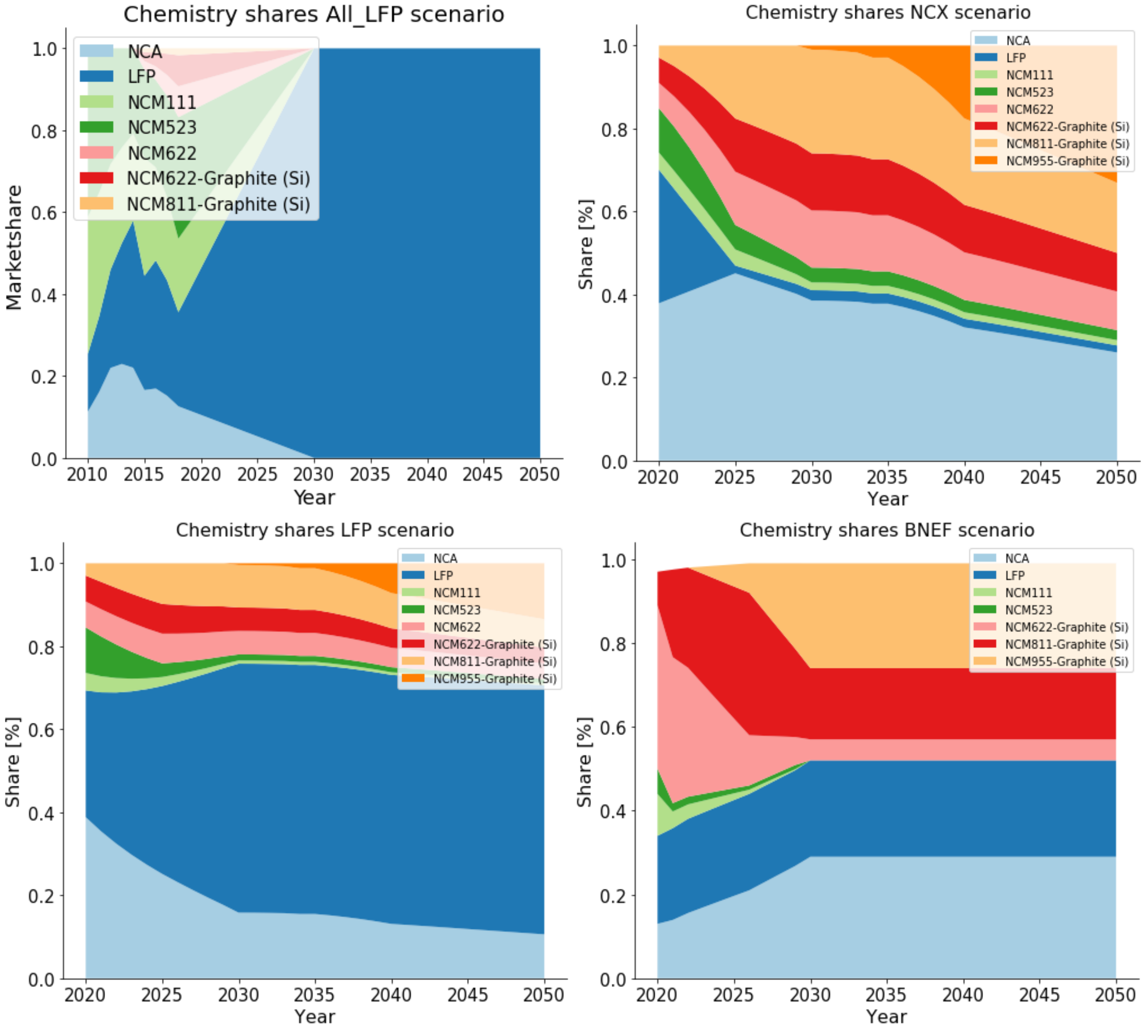


Figure 6: Chemistry compositions of the vehicle stock by scenario. (Top left is LFP_60 and bottom left is LFP_100).

Appendix III – Results

Global LFP demand scenario

Figure 7: Global P system – LFP 60%

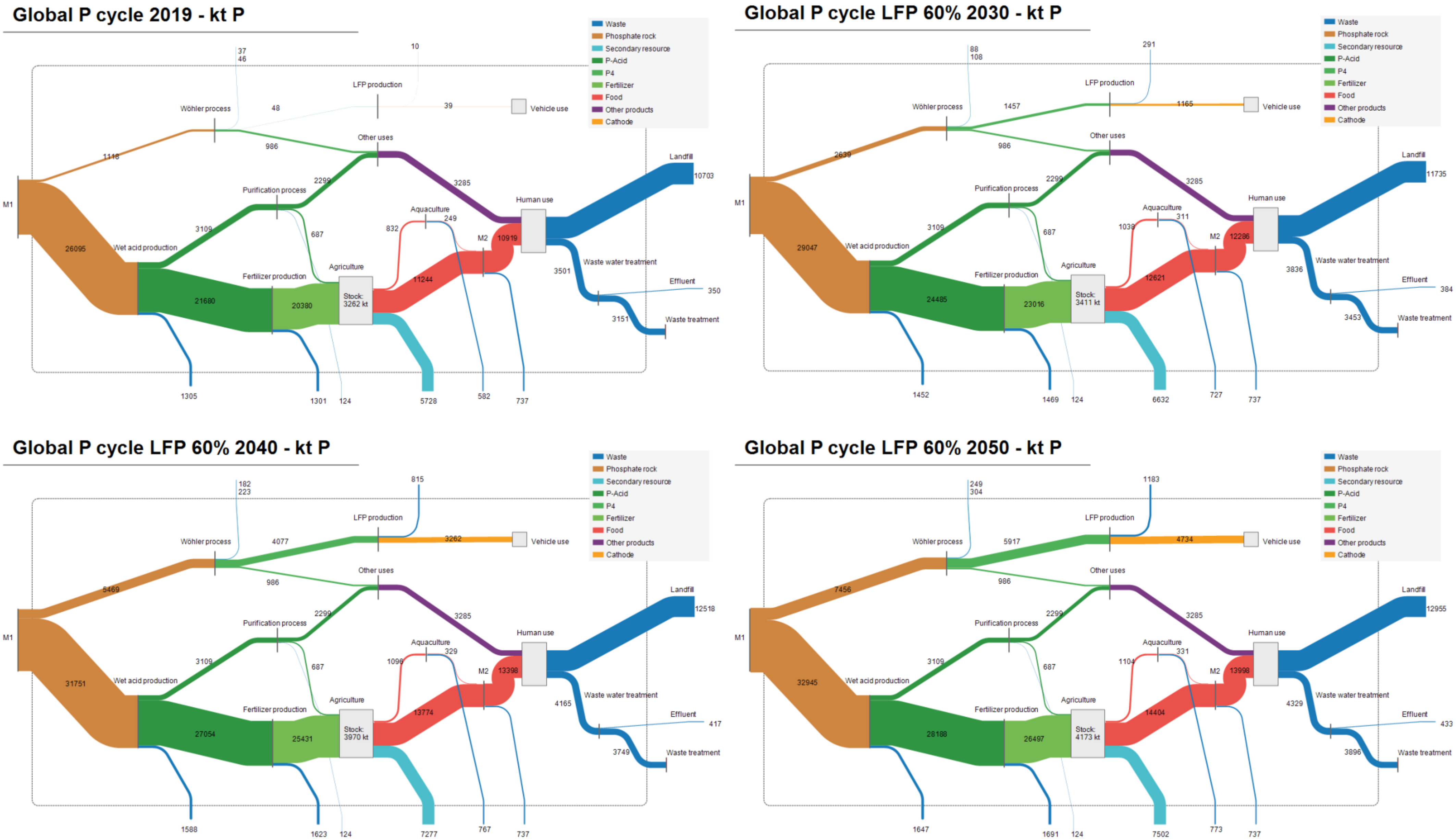


Figure 8: Global P system – LPF 100%

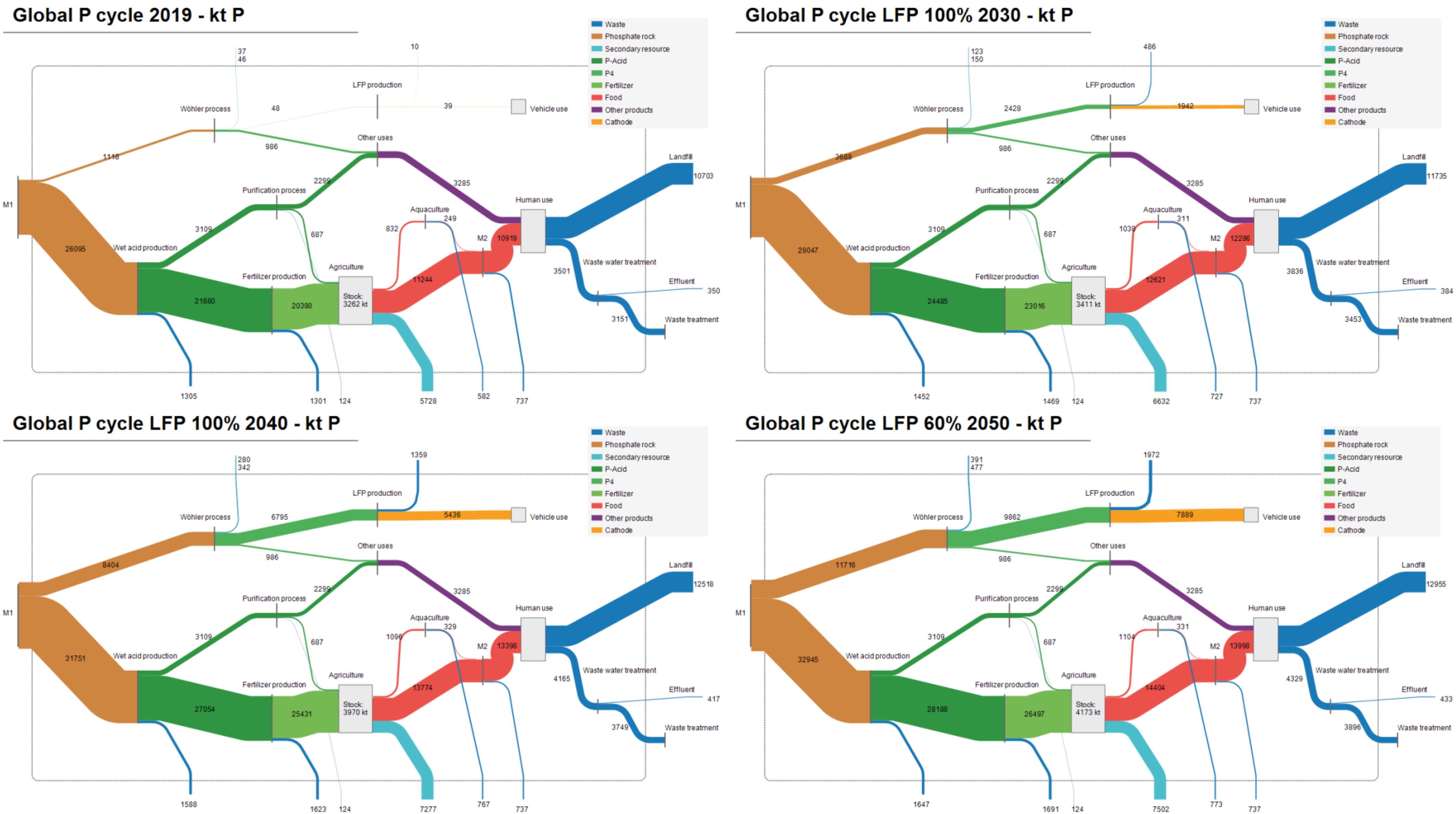
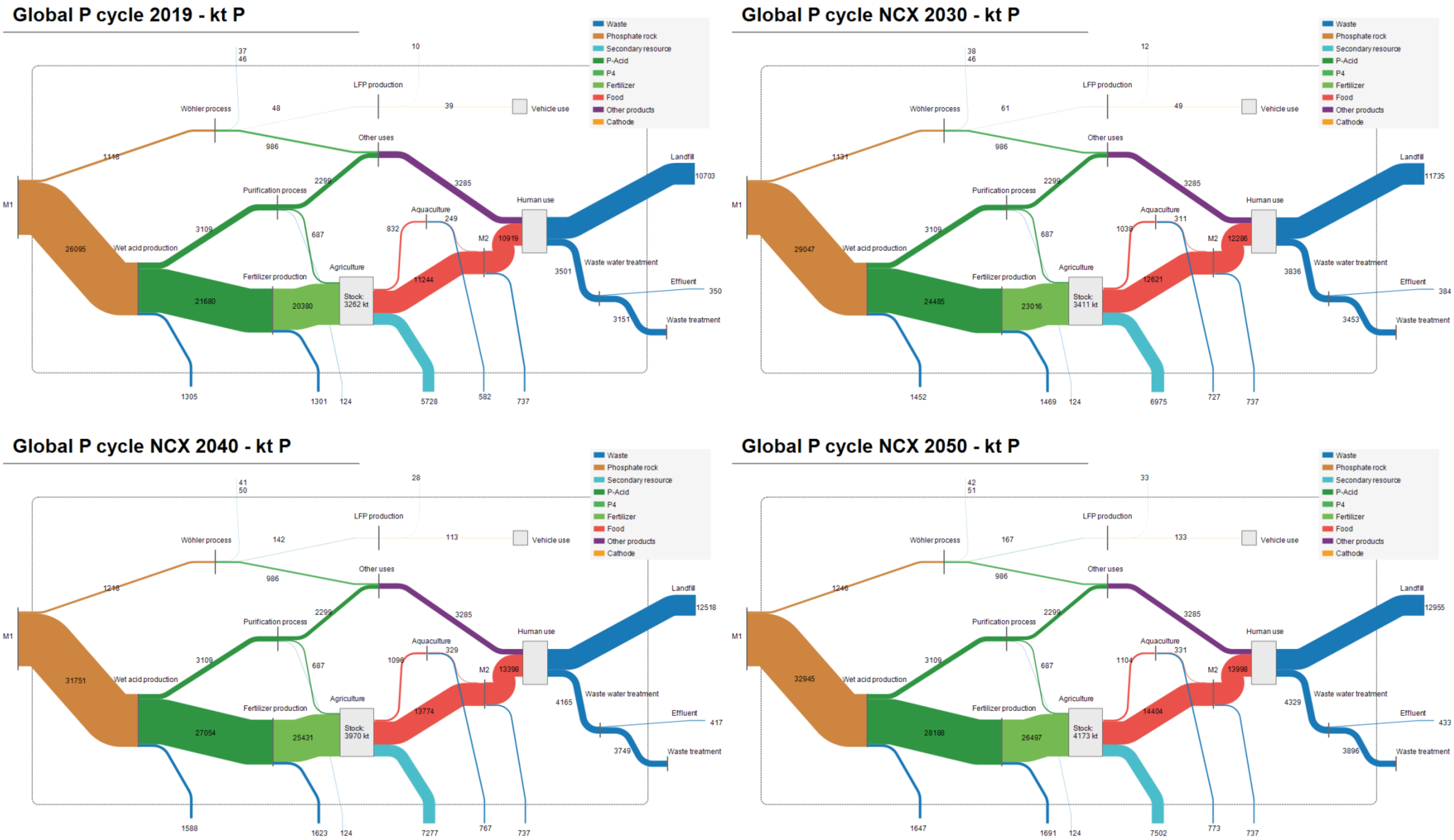


Figure 9: Global P system - NCX



Global steel production

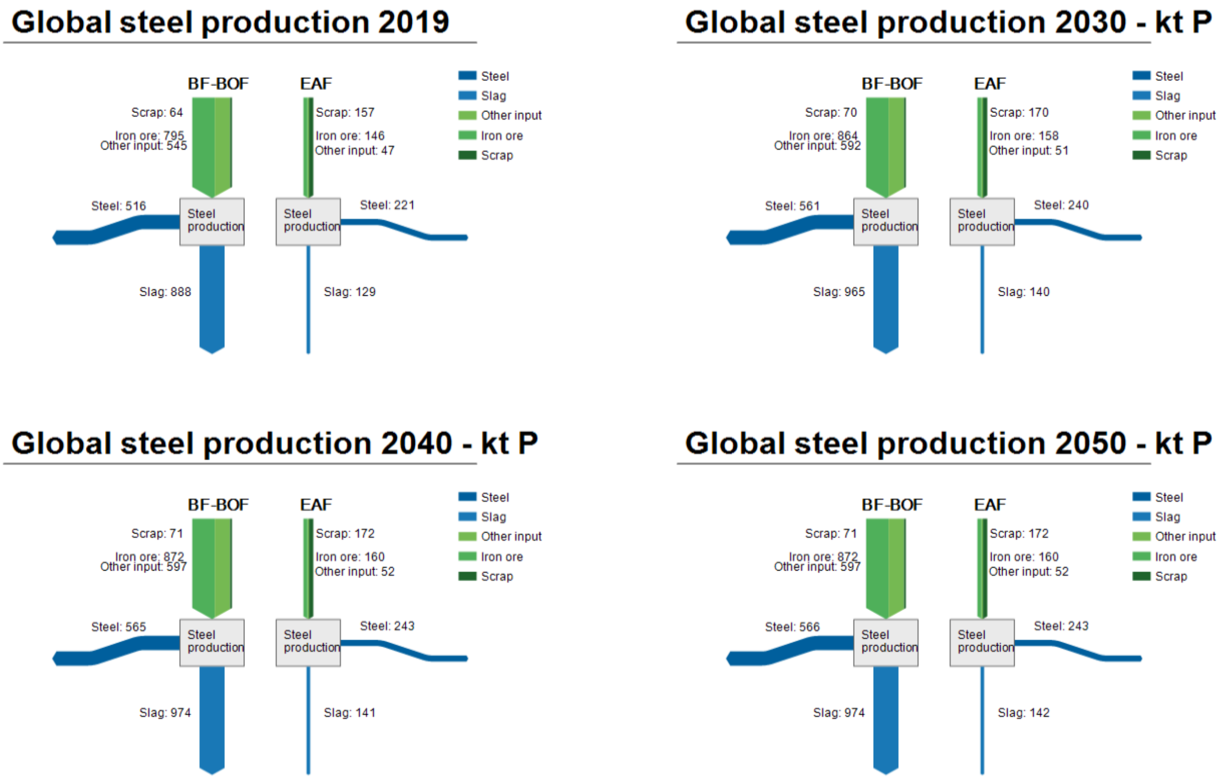


Figure 10: Global steel production for 2019, 2030, 2040 and 2050.

EU results

NCX

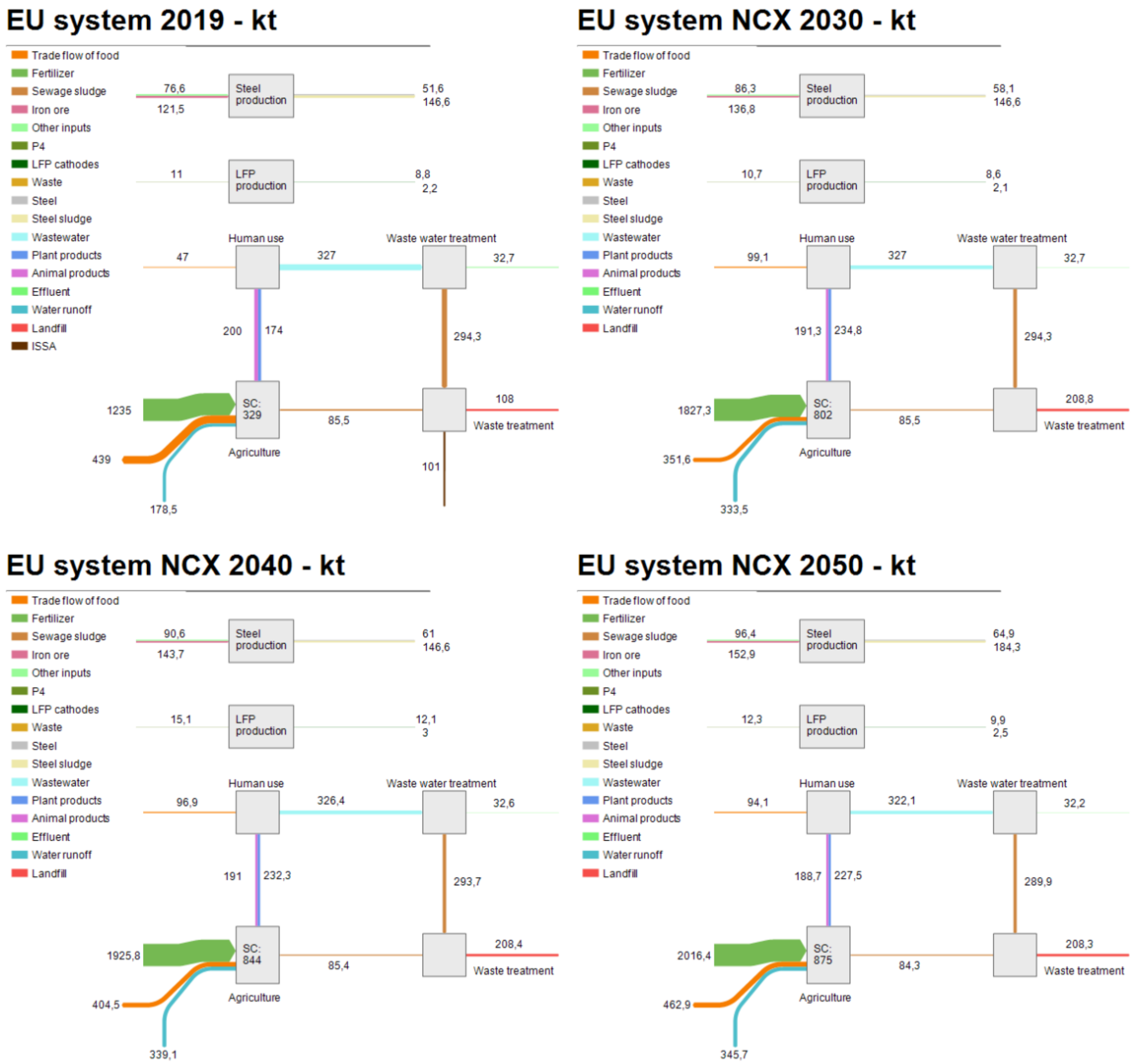


Figure 11: EU system – NCX scenario. SC = stock change.

LFP 100%

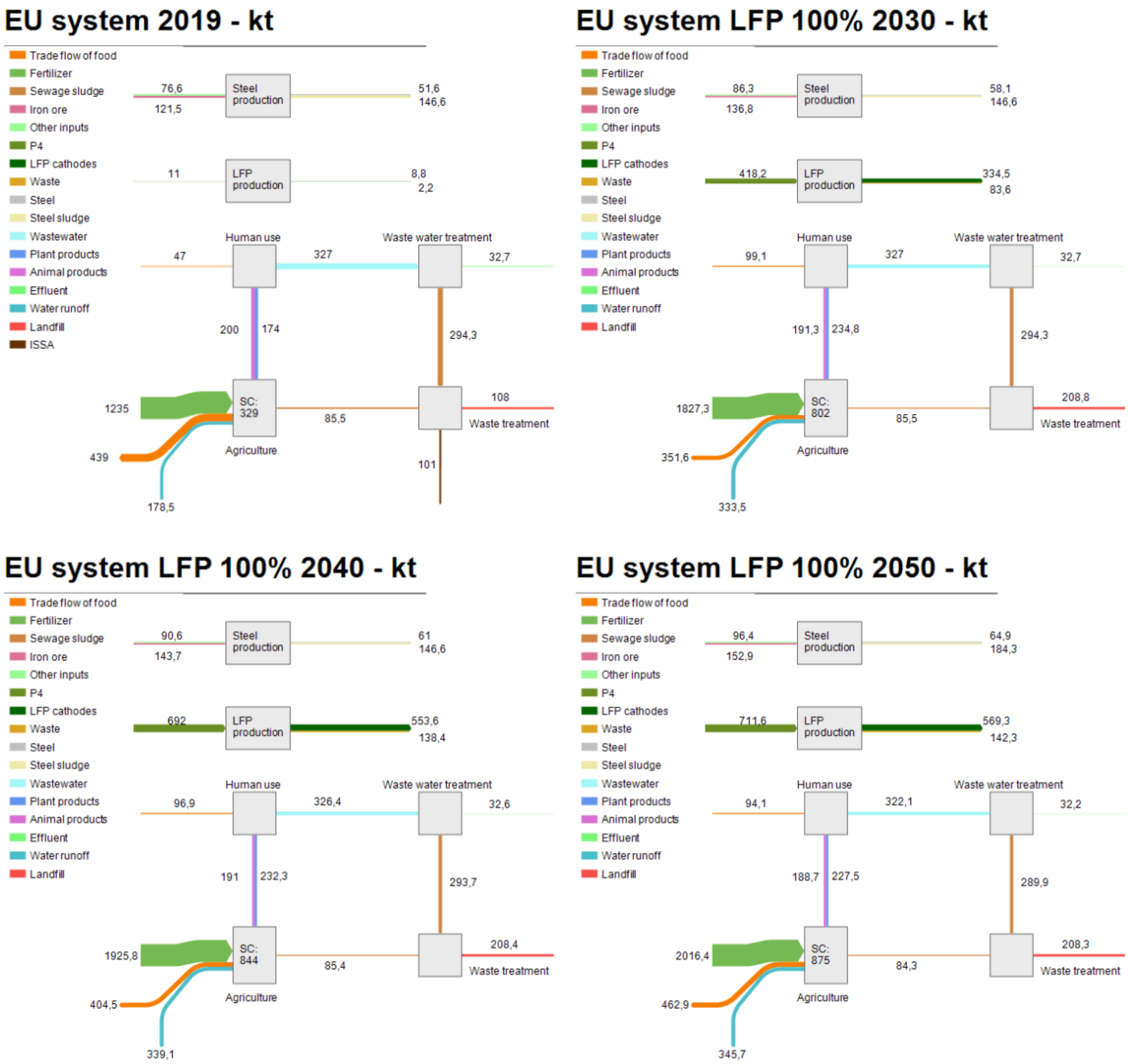


Figure 12: EU system - LFP 100% scenario. SC = stock change.

LFP 60%

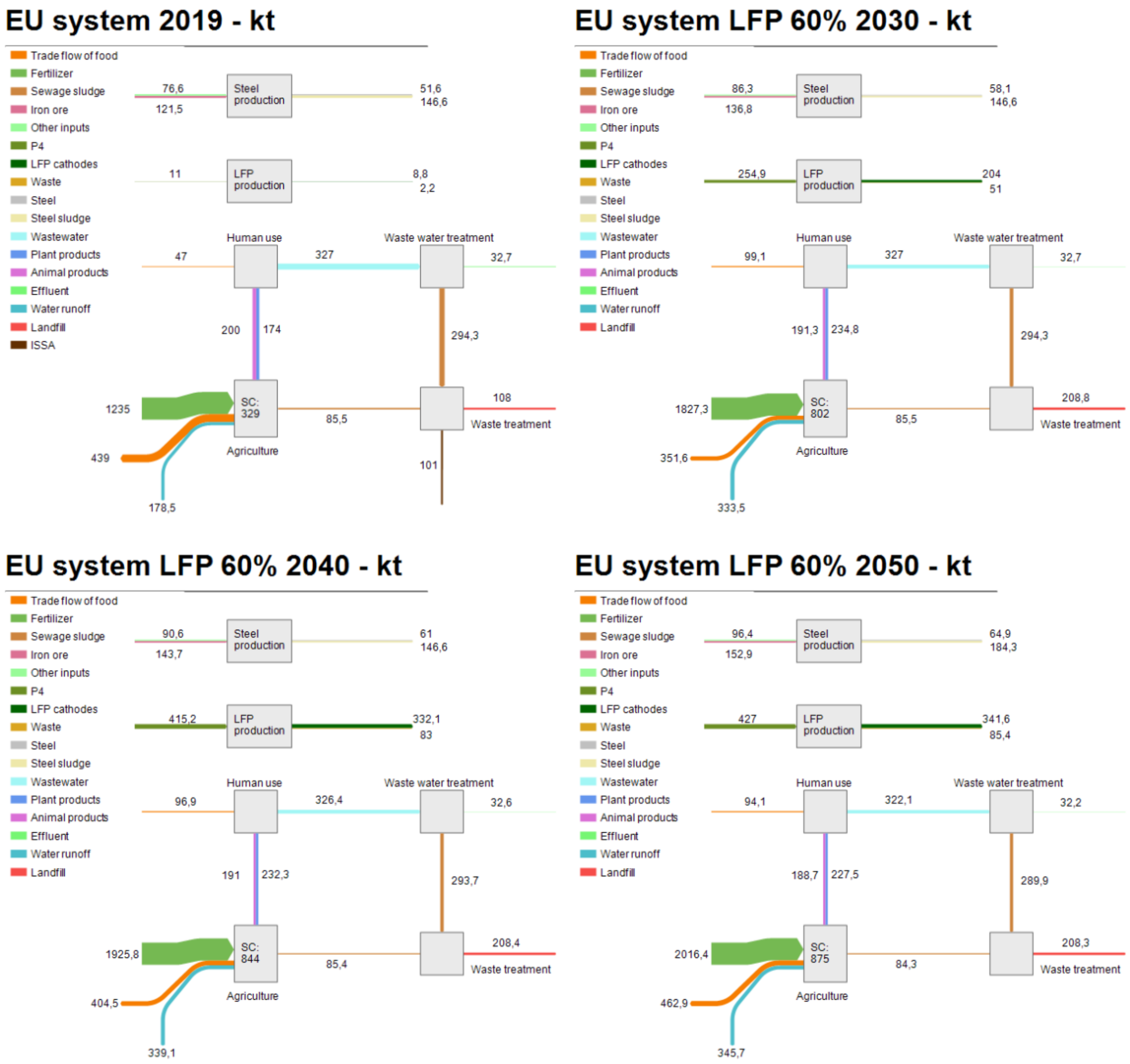


Figure 13: EU system - LFP 60% scenario. SC = stock change.

Appendix IV - Discussion

Figure 14: P4 export and import for China from 1992 to 2021 (UN Statistics Division, 2021).

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