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Innovations in steelmaking technology and hidden phosphorus flows

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HIGHLIGHTS

- We outlined the historical transition in the flow of P in steelmaking technology
- The hidden P flow of the steelmaking process was 4% of the global P supply in 2013
- The steelmakers will play a vital role in ensuring better P resource governance

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ABSTRACT

This article will outline the historical transition in the flow of phosphorus in steelmaking technology, and examine the current and future phosphorus flow in steel production and the peripheral steelmaking processes. History provides many instances of innovative changes in steelmaking processes driven by various issues associated with raw materials which emerged over time, such as supply, quality and cost issues. The major steel countries with a long history, including Sweden and Japan, have shown flexibility in their ability to adapt to the changes in the value of resources and geopolitical conditions over times, and have enacted survival resource utilization measures over many centuries, leading to improvements in their respective steelmaking processes. Considering these success stories, it stands to reason that the ideal state of steelmaking is one with a clear stance with regard to resource policy.

1. Introduction

The increased demand for food as the global population increases must also be understood as an inevitable increase in the demand for phosphorus over time (Elser and Bennett, 2011; Tilman et al., 2002; Wyant et al., 2013). The strategic importance of phosphorus for agriculture, food production, and the chemical industry cannot be overstated. It is feasible that an alternative may be found for the applications of the phosphorus currently used extensively in the semiconductor industry, in the production of detergents, anti-corrosive paints, and medicine. In the case of food production, however, there is and will never be an alternative for phosphorus. Commercial food production is highly dependent on fertilizers, and all the positive assurances that the world has the ability to feed itself in the future assume a plentiful supply of phosphorus in the years to come. As such, the increase in the demand for food with the growth of the global population will be accompanied by an inevitable increase in the demand for phosphorus over time (Elser and Bennett, 2011; Scholz et al., 2013; Vaccari, 2009).

In recent years, analyses of the flow of phosphorus from the perspectives of economical use and recycling have appeared in the literature (Liu et al., 2008; Matsubae-Yokoyama et al., 2009; Neset et al., 2008). These studies have highlighted the importance of adopting industrial practices which ensure that phosphorus is recycled and that reduce phosphorus loss. Particular attention has been given to these issues in the wastewater industry, where phosphorus recovery serves to protect the aquatic environment from eutrophication as well as provide a valuable resource.

In the steelmaking industry, on the other hand, phosphorus is simply regarded as an impurity which needs to be removed, due to its detrimental effects on the mechanical properties of steel (Matsubae-Yokoyama et al., 2009). Innovations in steelmaking technology all require the removal of impurities, which are then considered as waste.

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The phosphorus (P) and sulfur (S) contamination in the steelmaking process are due to their concentrations in the iron ore. Thus, the conditions of resource supply, such as ore grade and the form of the phosphorus and sulfur impurities in the ore, as well as the market demand or high quality steel heavily impact the developments in technology with regard to impurity removal, and since the removal of the impurities from the molten iron is possible due to these innovations, it is possible to use low quality iron resources, which are available at lower cost. It should be noted that an iron ore reserves are defined as rock deposits containing sufficient iron that the production of pig iron is economically feasible in light of the iron-making technology of the given era. If pig iron cannot be economically manufactured using rock from a certain deposit, it will not be used as an iron source. It follows then that the number of economically extractable reserves changes with innovations in steelmaking technologies.

In previous studies, we clarified that a significant amount of phosphorus has flown into our society, for instance as accompanied elements of iron resources (Jeong et al., 2009; Matsubae-Yokoyama et al., 2009; Matsubae et al., 2011; Yamasue et al., 2013). Rather than being regarded as a phosphorus resource, this phosphorus tends to be regarded as impurities, and most of it is lost from our economic sphere having never been tapped, and with remarkably little attention paid to it. Here we refer to this amount of phosphorus as "hidden phosphorus".

In the event that the hidden phosphorus behind the steel production process is regarded as a secondary phosphorus resource, steelmakers will play the roles of both steel producers and concentrators of the phosphorus thinly distributed in iron resources, which can be used as an alternative to imported phosphate ore. Steelmakers will need to be convinced that the technology available is the most suitable technology for their particular circumstances, and that the costs involved in implementing that technology will be covered by the income generated by the sale of the recovered phosphorus product together with the saving which results from the lower demand for iron ore due to the recycling of the ferric residue after phosphorus separation. At present, steelmakers are not convinced that these conditions will be met.

In order to motivate steelmakers to take on the role of concentrators and suppliers of phosphorus, it is important to evaluate the amount of phosphorus flows behind steel production. A better understanding of the past, current and future requirement of phosphorus removal for steelmakers will serve as encouragement to engage in phosphorus recovery and recycling. This article will outline the historical transitions in the development of steelmaking technology with a particular focus on phosphorus removal, and examine the amount of hidden phosphorus behind the global steel production from a historical perspective.

2. The situation of phosphorus in iron ore

2.1. Sedimentary deposit

According to the 1955 United Nations statistical survey (United Nations, 1955), reserves in Europe alone totalled 6.413 billion t of metallic iron. Disregarding grade and scale, iron ore deposits are found not just in Europe, but all over the world, and carry the distinctive feature that small-scale steel manufacturers in any region can aim for local production and consumption. Table 1 shows the major types of iron ore deposits around the world and their respective scales (Kassner and Ozier, 1950; Parak, 1985; Shimamura, 1953). The largest iron ore reserve is the Carajás iron deposit, containing 18 billion t of iron ore with an average iron grade greater than 67%. The excellent deposit formation properties of iron set it apart from other metals, and can be attributed to the specific geochemical nature of iron as an element. With each dissolution, diffusion, and precipitation of iron in the earth's crust, various sedimentary deposits have been formed in the seabed, rivers, lakes and marshes dating back to ancient times.

Among these are large-scale deposits known as Banded Iron Formations (BIF), where iron in the alternating bands of iron oxide and silica average 35%. These accumulated in the earth's seabed from about 2.7 to 1.8 billion years ago during the Precambrian era, and are estimated to contain as much as 40 trillion t of iron ore. Some BIFs on the seabed upheaved and became dry land; others remain buried beneath the ocean floor. These deposits have undergone hydrothermal processes induced by rainwater and igneous rock. The leaching of silica and other impurities has enriched the iron, leading to high-grade iron ore deposits. The steelmaking industry in the modern world is primarily utilizing this type of ore, with 370 billion t of reserves having been proved, including 170 billion t of economically feasible ore (Japan Oil Gas and Metals National Corporation (JOGMEC), 2015).

There are, however, regional differences in the nature of formation. The formation of European BIF-type deposits are limited to strata dating back to approximately 1.9 billion years ago during the Precambrian era. These reserves of BIF deposits are small, at 34 million t, and even when expressed as a percentage by deposit type within Europe, stand at a low 5% as indicated by (Basta et al., 2011). The natural distribution of these resources, with fewer high-purity BIF-type deposits in Europe than in other areas of the world, coupled with the fact that these deposits were limited to Northern Europe, influenced the manner in which the European steelmaking industry developed. Many of the other sedimentary deposits in Europe are deposits which have accumulated since hundreds of millions of years ago in geological time, of which, the so-called Minette deposits are perhaps the most well-known, formed when river water dissolved divalent iron and deposited trivalent iron along the coasts. Most iron ore is comprised of iron oxide minerals including

Table 1
The scale of the iron ore deposit and the ore grade.

Iron ore deposit			Sedimentary deposit				Magmatic/hydrothermal deposit				Laterite deposit	Iron sand deposit
			Banded iron formation BIF	Channel iron deposits (CID)	Minette deposit	Carboniferous deposit	Orthomagmatic deposit	Skarn deposit	Iron Oxide Copper Gold Deposit (IOCG)	Hydrothermal deposit		
Represetative deposit			Hamersley, Carajas, Bailadila	Yandi, Robe River	Lorraine, Clinton	England Coal Mine	Bushveld, Panzhihua	Magnitoya	Kiruna	Bilbao	Mayari	Taharoa
			Australia	Australia	Germany, US	England	South Africa	Australia	Sweden	Spain	Cuba	New Zealand
Ore grade(%)	Finest	>66	Middle									
	High	65～63	Large	Large								
	High middle	63～58		Large				Middle		Small		
	Middle	～50～			Middle	Middle	Small		Large		Small	Small
	Low	35～25	Super large						Small			
Major iron ore			Hematite, Magnetite	Hematite, Magnetite	Siderite, Goethite	Siderite	Hematite	Hematite	Magnetite, Hematite	Magnetite, Hematite	Hematite	Hematite
Impurities					P, S	S, P	Ti, V, Cr	S, Cu	P, Cu, REE	Mn	Cr, Ni	Ti

Scale small: <0.1 G ton, middle: 0.1–1 G ton, large: 1–10 G ton, super large: >10 G ton.