**Innovations in Steelmaking Technology
and Hidden Phosphorus Flows**

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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.

Keywords: dephosphorization, steelmaking slag, phosphorus removal, technology innovation

56 1. Introduction

57

58 The increased demand for food as the global population increases must also be
59 understood as an inevitable increase in the demand for phosphorus over time (Elser
60 and Bennett, 2011; Tilman et al., 2002; Wyant et al., 2013). The strategic importance of
61 phosphorus for agriculture, food production, and the chemical industry cannot be
62 overstated. It is feasible that an alternative may be found for the applications of the
63 phosphorus currently used extensively in the semiconductor industry, in the
64 production of detergents, anti-corrosive paints, and medicine. In the case of food
65 production, however, there is and will never be an alternative for phosphorus.
66 Commercial food production is highly dependent on fertilizers, and all the positive
67 assurances that the world has the ability to feed itself in the future assume a plentiful
68 supply of phosphorus in the years to come. As such, the increase in the demand for
69 food with the growth of the global population will be accompanied by an inevitable
70 increase in the demand for phosphorus over time (Elser and Bennett, 2011; Scholz et al.,
71 2013; Vaccari, 2009).

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

79 In the steelmaking industry, on the other hand, phosphorus is simply regarded as an
80 impurity which needs to be removed, due to its detrimental effects on the mechanical
81 properties of steel (Matsubae-Yokoyama et al., 2009). Innovations in steelmaking
82 technology all require the removal of impurities, which are then considered as waste.
83 The phosphorus (P) and sulfur (S) contamination in the steelmaking process are due to
84 their concentrations in the iron ore. Thus, the conditions of resource supply, such as
85 ore grade and the form of the phosphorus and sulfur impurities in the ore, as well as
86 the market demand or high quality steel heavily impact the developments in
87 technology with regard to impurity removal, and since the removal of the impurities
88 from the molten iron is possible due to these innovations, it is possible to use low
89 quality iron resources, which are available at lower cost. It should be noted that an iron
90 ore reserves are defined as rock deposits containing sufficient iron that the production
91 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.

120

121

122 **2. The situation of phosphorus in iron ore**

123 **2.1 Sedimentary deposit**

124 According to the 1955 United Nations statistical survey(United Nations, 1955), reserves
125 in Europe alone totalled 6.413 billion t of metallic iron. Disregarding grade and scale,
126 iron ore deposits are found not just in Europe, but all over the world, and carry the
127 distinctive feature that small-scale steel manufacturers in any region can aim for local

128 production and consumption. Table 1 shows the major types of iron ore deposits
129 around the world and their respective scales (Kassner and Ozier, 1950; Parak, 1985;
130 Shimamura, 1953). The largest iron ore reserve is the Carajás iron deposit, containing
131 18 billion t of iron ore with an average iron grade greater than 67%. The excellent
132 deposit formation properties of iron set it apart from other metals, and can be
133 attributed to the specific geochemical nature of iron as an element. With each
134 dissolution, diffusion, and precipitation of iron in the earth's crust, various
135 sedimentary deposits have been formed in the seabed, rivers, lakes and marshes dating
136 back to ancient times.

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

148 There are, however, regional differences in the nature of formation. The formation of
149 European BIF-type deposits are limited to strata dating back to approximately 1.9
150 billion years ago during the Precambrian era. These reserves of BIF deposits are small,
151 at 34 million t, and even when expressed as a percentage by deposit type within
152 Europe, stand at a low 5% as indicated by (Basta, 2011). The natural distribution of
153 these resources, with fewer high-purity BIF-type deposits in Europe than in other areas
154 of the world, coupled with the fact that these deposits were limited to Northern Europe,
155 influenced the manner in which the European steelmaking industry developed. Many
156 of the other sedimentary deposits in Europe, are deposits which have accumulated
157 since hundreds of millions of years ago in geological time, of which, the so-called
158 Minette deposits are perhaps the most well-known, formed when river water dissolved
159 divalent iron and deposited trivalent iron along the coasts. Most iron ore is comprised
160 of iron oxide minerals including hematite, goethite, limonite and magnetite. Hematite
161 is mainly Fe_2O_3 and is 70% the weight of iron, goethite is FeOOH and is 63% the weight
162 of iron, limonite is a mixture of hydrated iron oxides with up to 60% the weight of iron,
163 and magnetite is Fe_3O_4 and is 72% the weight of iron.

164 The phosphorus content is high in the limonite ore mixed with hematite. A
165 representative example is the deposit in Lothringen in the Alsace-Lorraine region in
166 France near the German border, where the average iron content in the ore is 31% and
167 the total iron content is 6.7 billion t. The United Kingdom had the Cleveland mines,
168 which rival those of France, and Germany had Salzgitter and various other iron
169 deposits. European reserves total around 4 billion t, which, from a global perspective,
170 makes it a region rich in iron. Although smaller in scale than Minette deposits, there
171 are the sedimentary-type iron ore deposits of carbonaceous siderite formed in the
172 Carboniferous coal beds. While they can be found all over continental Europe, they
173 are especially common in the United Kingdom (with reserves of over 1 billion t). This
174 type of ore helped relieve the supply limits of conventional bog iron resources during
175 the first half of the Industrial Revolution, and supported the expansion in production.
176 BIF iron deposits are small-scale limonite deposits formed in lakes and marshes, where
177 portions become solid layers. Such deposits can be found all over Europe, and many
178 provided the primary raw material for steelmaking during the Middle Ages. Iron in
179 the exposed areas of massifs and in the gravel surrounding deposits is dissolved by
180 reductive surface water and flows into lakes and marshes where it is deposited as an
181 oxide and a phosphate: this small scale formation is said to continue even to the
182 present day. While the ore can be easily mined and reduced, the phosphorus content is
183 not always low. In Sweden, where lakes and marshes in forested areas are particularly
184 plentiful, there is an abundance of such deposits, and while the phosphorus levels vary
185 considerably, low-phosphorus iron ore deposits are more numerous than in other
186 regions, as shown in Table 1.

187

188 **2.2 Magmatic / Hydrothermal deposits**

189 Iron ore deposits from magmatic igneous activity were also formed throughout Europe,
190 but are limited to regions with past igneous activity. Igneous deposits can be classified
191 as follows: Magmatic deposits, formed when iron in magma segregate and are
192 deposited in the deep strata; contact metasomatic deposits, formed when magma rises
193 and comes into contact with limestone, etc.; hydrothermal deposits and pneumatolytic
194 deposits formed when magma rises even further to the earth's crust and the iron in
195 hydrothermal fluids is deposited. With the exception of magmatic deposits, igneous
196 deposits are usually smaller in scale than the submarine sedimentary BIF and Minette
197 deposits. The grade of ore from igneous deposits tends to be inferior with regard to
198 purity; however, while few in number, certain deposits produce high-grade ore with
199 good purity. In Europe, magmatic deposits can be found in the Kiruna district and

central regions of Sweden, and while high in phosphorus, they are high in iron ore content and are also large in scale, with reserves of 1.5 billion t. Besides these deposits, a wide variety of medium scale contact metasomatic deposits can be found in central Sweden (reserves 3.8 million t)(Shimamura, 1953). The Dannemora mine is a contact metasomatic deposit in limestone famous for its low phosphorus content. In this region, because the phosphorus content differs so dramatically from one deposit to the next, with bog iron deposits among them, it is believed that the mode of deposition changed over the ages. Compared to other areas in Northern Europe, hydrothermal deposits are formed in geologically young regions. They are the Bilbao-type deposits found by low-phosphorus hematite or siderite as a result of magmatic hot water enacting its effect in the limestone parent rock. Reserves are recorded at 400 million, and have been Europe's high grade iron source since ancient times. Well-known examples of similar deposits are Cumberland in the United Kingdom, Bilbao in Spain, and the Erzberg mine in Austria. In the United Kingdom, hematite is formed in limestone, while in continental Europe siderite ore bodies are formed when the crust is weathered by hematite-limonite; thus, while the deposit type is the same, the processes of formation are different. In addition to Bilbao-type deposits, there are small-scale deposits of ore veins primarily formed from hot water in a number of countries, most notably in Germany. The siderite deposits in Siegerland (reserves of 40 million t) are well-known, are high in manganese and were formed by the weathering of limonite near the earth's surface.

221

222 3. Steelmaking technology development and phosphorus

Iron and steelmaking processes have progressed steadily over time with advances in technology, and with increased knowledge of how to improve the properties of the product. As can be seen in Fig. 1, steelmaking can be broken into approximately six distinct stages which will be described later. The blue arrow behind the process indicates the iron/steel productivity (the potential amount of iron or steel production per unit time, such as ton/day or ton/h). The orange arrows in the process indicate the phosphorus flow for each process, with the thickness of the arrows indicating the amount of phosphorus. Phosphorous removability and ore adoptability are summarized in Table 2.

231

232 3.1 Bloomery period

In Europe during the middle-ages, direct steelmaking was the mode of production. A Renn and Stuck furnace, otherwise known as a "bloomer" was used, and various types of iron ore were utilized with no attention paid to contamination by phosphorus

(Tylecote, 1992). This suggests that no one had any concern about the existence of phosphorus in the iron ore at all. This is because the phosphorus contained in the iron ore does not thermodynamically or kinetically dissolve into the iron at the relatively lower temperatures involved in the direct steelmaking methods used at the time. Rather, the phosphorus was concentrated in the slag, as shown in Fig.1A. Interestingly, however, it would seem that people semi-empirically realized that the strength and ductility of the steel produced depended on origin of the iron ore. (Beck 1977)

243

244 **3.2 Puddling furnace period**

245 During the Industrial Revolution in the late eighteenth century blast furnaces were
246 used to produce pig iron in an effort to drastically increase the productivity of pig iron.
247 Puddling furnaces began to be employed to produce malleable wrought iron from pig
248 iron in a process referred to as indirect steelmaking (Gale, 1976; Merton C. Flemings,
249 2009; Mott R.A., 1977). It was in this period that Rinman scientifically clarified the
250 effects of phosphorus on steel (E. Rinman, *Försök Til Järnets Historia, Med*
251 *Tillämpning Frå Slögder Och Handtwerk*, 1782).

252 Since the pig iron was produced at higher temperatures (~1300 C) than those employed
253 during the bloomer period, almost all of the reduced phosphorus from the gangue was
254 first dissolved into the pig iron (0.4%), forming iron phosphate. Since the iron
255 phosphide was partially dissolved into slag and the generated slag was removed at the
256 end of the processes, the phosphorus content in the pig iron (0.4%) was reduced to
257 0.03% in the wrought iron as shown in Fig.1B (Beck, 1977). Therefore, ore with a
258 relatively higher phosphorus content, which was widely distributed throughout
259 Europe, could be used. Although the phosphorus concentration of the slag was about
260 4%, no attention was given to slag as a phosphorous source. It should be noted,
261 however, that the slag was used as a raw material in the Thomas process which
262 became the main mode of operation some years later.

263

264 **3.3 Bessemer converter period**

265 The Bessemer converter, which used acidic refractories, was invented in Britain in the
266 middle of nineteenth century. It represented a radical change in the way of steel
267 manufacturing. The key principle behind the converter is the removal of impurities
268 from the iron by oxidation, with air being blown through the molten iron without the
269 need for any further energy due to the exothermic reaction between the carbon in the
270 pig iron and the oxygen in the air. The blue arrow in Fig.1C shows a massive
271 improvement in production efficiency compared to other steelmaking processes, and

272 explains how it came to be that the United Kingdom was the world's leading steel
273 producer in the late nineteenth century(Trinder, 1996).

274 While production efficiency was dramatically improved, the phosphorus flowed not to
275 the slag, but to the final steel product, as shown in Fig 1C. Because this process
276 involved higher smelting temperatures (1600-1800 C) than the puddling process (1300
277 C), the phosphorus oxide in the acidic slag was reduced into elemental phosphorus,
278 resulting in its dissociation into the molten steel(Emi, 2015). To avoid this, the
279 Bessemer process required the utilization of low-phosphorus pig iron, which was
280 known as Bessemer pig iron. This pig iron could only be produced from the use of low
281 phosphorus iron ore such as Dannemora ore in Sweden (Beck, 1977). This was a very
282 limiting constraint. There were few reserves in Europe which met the necessary
283 requirements. Although the United Kingdom used not only domestic ore but imported
284 Swedish and Spanish ores, the supply of low phosphorus iron ore in Europe was still
285 inadequate. As such, the development of a dephosphorizing refinery process became a
286 matter of great urgency. The answer eventually came with the invention of the Thomas
287 converter in the United Kingdom in 1878.

288

289 **3.4 Thomas converter period**

290 **3.4.1 Thomas converter**

291 The bottom-blown design of the Thomas converter was almost the same as that of the
292 Bessemer converter, but it employed a basic refractory, resulting in the efficient
293 removal of the phosphorus, as can be seen in Fig. 1D. This development led to further
294 increases in the amounts of steel being produced and changes in the methods of
295 steelmaking from country to country. Because the United Kingdom continued using
296 the Bessemer converter due to cost issues and was relatively slow to change its mode of
297 steel production, it was not able to keep pace with Germany, which rather quickly
298 adopted the new technology. The United Kingdom gradually shifted to a process using
299 an open-hearth furnace that was suitable for molten pig iron with a medium
300 phosphorus content in the twentieth century. On the other hand, Germany made
301 significant progress by introducing the Thomas converter with Minette ore. Another
302 factor that helped Germany gain ground on the United Kingdom at the end of the
303 nineteenth century was that the converter slag, with its high phosphorus content, was
304 used as fertilizer. This reduced the county's dependence on imported fertilizer and
305 led to significant gains in agricultural productivity.

306 Although the annual production of pig iron in Germany was one seventh that of the
307 United Kingdom in 1860, Germany had overtaken the UK by the beginning of the

twentieth century. Another factor that helped Germany gain ground on the United Kingdom at the end of the nineteenth century was that the converter slag, with its high phosphorus content, was used as fertilizer. This reduced the country's dependence on imported fertilizer and led to significant gains in agricultural productivity (Beck, 1977).

3.4.2 Appearance of basic open hearth furnace

The United States faced a different situation to that in Europe. In the middle of the nineteenth century, a large-scale ore deposit with a low phosphorus content was found in the area around the Great Lakes, such that, using the Bessemer process, the USA was able to gain competitiveness and surpass the United Kingdom. At the end of the nineteenth century, reserves of minable ore with a phosphorus content of less than 0.08% began to be exhausted, leading to the gradual replacement of the Bessemer converters with basic open-hearth furnaces which were able to utilize scrap steel. As a result, at the beginning of the twentieth century, the USA captured the title of the world's leading steel producer from the United Kingdom. At that time, low-phosphorus ore was used for the Bessemer process. Ore with a higher phosphorus content of 1.7% to 2% was used in the Thomas process, while ore with a medium phosphorus content was used with the basic open-hearth furnaces. The production efficiency and the flow of phosphorus for this process are indicated in Fig.1E. While the production efficiency of this process was somewhat less than the Bessemer and Thomas converter processes, the distinct advantage was the ability to recycle scrap together with iron ore with a medium phosphorus content.

3.4.3 Thomas process in Japan

Between 1935 and 1955, Nippon Kokan (NKK) produced both steel and phosphorus fertilizer using Thomas converters by mixing ordinary iron ore and phosphate ore (Inazumi, 2009; Nakamura, 2007). This process helped to reduce the total cost by 3% to 5%. However, with the development of the LD converter (named after the Austrian towns of Linz and Donawitz), the use of the Thomas process in Japan came to an end.

3.5 LD converter period

After the end of World War II, the LD converter, which uses pure blown oxygen, was developed. As shown in Fig.1F, this process was characterized by high production efficiency and the production of two different slags, with the phosphorus concentrated in one of them. (Emi, 2015; Inazumi, 2009; Wolf, 1997). Unlike the Bessemer converter, where air is blown into the process, the LD converter process creates a large

exothermic reaction, allowing the use of pig iron with fewer exothermic elements such as phosphorus and silicon. In addition, the process is capable of using pig iron with relatively higher phosphorus content. Further oxygen blowing also reduces the nitrogen content in the steel that is produced. This process was developed to suit the particular circumstances in Australia at the time: the country had insufficient scrap steel but was self-sufficient in pig iron. Japan also had insufficient scrap, making the LD converter process more appropriate than the basic open-hearth furnace. By making use of very large ore carriers, Japan was able to import high-quality iron ore low in phosphorus mined from BIF deposits in India, Australia, Brazil, etc. Once stable converter operation was established, the world's first continuous casting process was devised, followed by a secondary refining process, whereby a rolling line was directly connected to a continuous caster, a continuous annealing processing line (CAPL), or a thermo-mechanical control process (TMCP), among other processes. The adoption of Japan's new LD converter process in Europe and North America resulted in a 50% reduction in exports of iron ore from Sweden, and the closing of the Minette mines. The mining of iron ore with a higher phosphorus content came to a virtual standstill.

4. Hidden P flows behind steel production

4.1 Method and data

The material flow of phosphorus for each commodity and country was estimated. A total of 231 countries are set in BACI (Base pour l'Analyse du Commerce International) and 286 commodities were extracted from the HS code. In order to evaluate the hidden phosphorus flows behind the steelmaking process over time, it is necessary to make some assumptions. It was assumed for the purpose of consistency that the amount of steelmaking slag produced was 15% the total production of pig iron, and the slag contained 0.75% of P (Matsubae-Yokoyama et al., 2009). Statistics is provided by the World Steel Association (World Steel Association) include historical iron production data.

4.2 Estimation

The estimated amount of phosphorus contained in the various steelmaking slags since 1980 is indicated in Fig.2. The regional classification follows the UN statistics. The 1649 million tons of crude steel produced in 2013 was more than twice that produced in 1980. Behind the scenes, the production of this huge amount of steel has been accompanied by the production of a significant amount of hidden phosphorus. This phosphorus has been accumulated into steelmaking slag and has ended up lost or

380 dissipated in our subeconomic field, where it is economically difficult to mine.
381 According to the USGS, the global production of phosphate ore was 135,000 kt and
382 228,000 kt in 1980 and 2013 in the world, respectively(USGS, 2014). If we suppose that
383 that phosphorus rock has a P_2O_5 of 30%, the hidden phosphorus flow from the
384 steelmaking process was equivalent to 2% of the global phosphorus supply in 1980 and
385 4% in 2013. It is worth noting that the hidden phosphorus flow in China was more than
386 500 kt-P, more than 10 times the amount of phosphate rock exported by China in
387 2013(BACI, 2013; Webeck, 2014a).

388

389 **4.3 Uncertainties and Limitations**

390 The estimated values are calculated under some very strong assumptions, including
391 that the phosphorus content of all the mined iron ore is the same. While this is clearly
392 not the case, an average value was chosen. There is, however, a difference between the
393 minimum and maximum value of the phosphorus content in the ores in various
394 deposits around the world(Pumpelly, 1886) (Jeong et al., 2009). Considering this
395 uncertainty, which is due to the geological and historical difference in the phosphorus
396 content of mined iron ore, the difference between the minimum and maximum value
397 of the estimated results in 2014 would be 15% in 2014. This fluctuation equals 0.03% of
398 the global phosphorus demand. While there are clear limitations of making estimates
399 using broad assumptions, the estimates are evidence that the steelmakers are one of the
400 most important stakeholders in the utilization of the very significant amount of
401 untapped phosphorus resources which flow into steelmaking slag. The steelmakers
402 will play a vital role in ensuring better future phosphorus resource governance.

403

404 **5. Discussion and conclusion**

405 Due to manufacturing expansion in China, supplies of low-phosphorus, high-grade
406 iron ore, for which Japan had previously been the largest consumer, became scarce and
407 the price of ore soared as the three major providers formed an oligopoly. This could
408 well be interpreted as a sign that it is time to make steps toward a transition to the next
409 generation of ore utilization. As with all mineral products, iron ore deposits are
410 gradually becoming depleted as the ore is mined and consumed, and the ore is
411 non-renewable. As such, it will become necessary to switch to as-yet-unutilized mineral
412 types once deposits of the mineral types currently being consumed are exhausted.
413 Assuming that history will indeed repeat itself, the next steelmaking innovation
414 enabling the utilization of currently unused mineral types will come in the near future.
415 When this occurs, the trends of steelmaking developments suggest the move will be

416 towards a larger scale process and the utilization of ores of mineral types that can be
417 stably supplied. From this standpoint, there is a clear abundance of remaining iron ore
418 resources with as-yet untapped mineral types (Inazumi, 2009). The utilization of these
419 resources will very likely prove difficult: these types of iron ore reserves have not been
420 regarded as economically feasible.

421 The currently mined BIF-type high-grade ore reserves are limited and will ultimately
422 be depleted, but huge quantities of parent rock from which the BIF is extracted are left
423 behind. However, while the phosphorus content of this parent rock is generally low,
424 mineral processing becomes necessary as the iron content is also low. Additionally,
425 while BIF-type ore has a high iron content, because it is also high in phosphorus,
426 reserves of untapped ore remain in various regions. Rapitan-type iron formations, a
427 type of BIF deposit formed about 600 million years ago, are usually high in phosphorus
428 and have yet to be extracted (Inazumi, 2009). Igneous deposits, which contain iron
429 oxide copper gold (IOCG) deposits, are large in scale, and since they include
430 non-ferrous metals and phosphorus, almost none of these have yet to be developed
431 (Inazumi, 2009).

432 History has shown many instances of innovative changes in the steelmaking process,
433 driven by problems associated with raw materials. Historically, major steel-producing
434 countries like Sweden and Japan have adapted flexibly to changing resource values
435 and the geopolitical challenges that have been encountered over time. The enacting of
436 survival resource utilization measures in both countries over many centuries has been
437 one of the factors underpinning their success.

438 In line with the practices being carried out at present, the recycling of steelmaking
439 slags tends to be understood to mean that this slag should be used as a material for
440 civil engineering applications. This practice only results in the loss of a valuable
441 resource from our economic sphere. Recovering phosphorus from steel-making slag
442 simply makes good resource-management sense. Utilizing all untapped phosphorus
443 reserves to ensure the better global use of this strategic resource will help make it
444 possible to feed burgeoning populations over the coming decades. In the future, when
445 considering the ideal state of steelmaking, it will be necessary to adopt a stance based
446 on resource policy (Tayeb et al., 2014). As the reserves of high grade iron ore become
447 depleted, the amount of phosphorus in the iron ore used in the steel industry will
448 gradually rise, which will equate to higher amounts of phosphorus with the potential
449 to be recovered and utilized in the domestic market. It is no exaggeration to claim that
450 as the demand for steel in developing countries rises and BOF furnaces are built to
451 produce the steel to meet that demand, a new source of phosphorus is borne. The

452 steelmakers have two options in the marketing of recovered phosphorus. One is to
453 market it directly to the fertilizer or chemical industry. The other is to produce a
454 value-added product, a phosphate fertilizer, for the market. The first option will
455 require the fertilizer industry and the chemical industry to accept the recycled
456 phosphorus, which is likely to be more expensive than phosphate ore until the prices of
457 phosphate ore rise, for use in their fertilizer product. The second option will require
458 steelmakers to either acquire the knowledge required to make phosphate fertilizers, or
459 to acquire existing phosphate fertilizer producing companies. Since both of these
460 options represent a significant step in a completely new direction for the steelmaking
461 industry, confidence in the existence of a strong market for the product will be vital
462 before the industry agrees to embark on the task of recovering phosphorus from the
463 steelmaking slag and marketing it.

464

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