Resources, Conservation and Recycling 105 (2015) 235–245

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Efficiency developments in phosphate rock mining over the last three decades

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ARTICLE INFO

Article history:
Received 17 June 2015
Received in revised form
29 September 2015
Accepted 2 October 2015
Available online 20 November 2015

Keywords:
Resource versus economic efficiency
Supply chain management
Sustainable phosphate rock mining
Global market
Innovation

ABSTRACT

This paper appraises losses and efficiency in phosphorus mining processes. The distinction between resource and economic efficiency as crucial determinants of the mining decision process is outlined in relation to the kind of agents involved. Second, we apply a system and process approach to visualize and better deal with the complexity of the phosphorus supply chain and to provide a framework of the extended phosphorus supply chain for subsequent efficiency analyses. With an emphasis on the beneficiation process, we further outline potentially conflicting priorities related to resource efficiency in contrast to economic efficiency. Based on these theoretical considerations, in our analysis, we focus on the dynamic development of efficiency between 1983 and 2013, addressing both the global and the organizational level. The core finding of this analysis suggests that, on a global scale, the ore capacity tonnage and average grade of ore mined have increased in the past 30 years, from 513 Mt at 14.3% P_2O_5 in 1983 to 661 Mt at 17.5% P_2O_5 in 2013. This counters the claims that the quality of reserves is diminishing globally, but the global averaging process masks the true trends in grade in individual countries and deposits. This analysis also exemplarily outlines how the quantities of losses and subsequently the efficiencies have changed over time, due in part to new technology-based opportunities to regain losses during the excavation and beneficiation processes. We conclude our manuscript by outlining and summarizing future challenges.

1. Introduction

The efficiency of phosphate mining is directly related to economic and physical losses and can, in more general terms, be expressed as an output–input ratio. To discuss potential methods of *performance measurement* of phosphate mining (with performance being evaluated from purely economic to sustainability implications), a *systems and process perspective* (which clearly defines the system boundaries) is advantageous with respect to both mining and the comprehensive phosphorus supply chain. The phosphate *mining process* encompasses the extraction and primary beneficiation of ore (PR-Ore) to produce marketable phosphate rock concentrates (PR-M) (with beneficiation either on-site or off-site) (Watson et al., 2014). Because phosphate rock mining represents a subsystem of a more-comprehensive phosphorus supply chain,[1] the mining phase needs to be considered as interrelated to exploration, as its pre-phase, and to processing (which is distinct from primary beneficiation), use, dissipation, and recycling as working steps in the post-mining phase (Scholz et al., 2014a). Furthermore, losses are not a static concept; what is considered a loss today, based on economic and technological feasibilities (Scholz and Wellmer, 2015a), may differ from what would be considered a loss in the future. Not only do technological innovations enable the recycling of previously abandoned low-grade portions of already-mined beds (distinct from overlooked opportunities), but they also generally enable the inclusion of lower-grade portions of the deposit. For example, in the copper industry, when the average ore-grade was around 2.5% Cu more than 100 years ago, nobody would have predicted the mining of ore grades at 0.4% Cu or even below, according to Scholz and Wellmer (2013). This calls

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[1] In the context of this paper, supply chain and value chain are synonymously used.

http://dx.doi.org/10.1016/j.resconrec.2015.10.004

for detailed investigations across the timeline, as developments (e.g., prices, technologies, political events, and crises) affect the output–input ratio (efficiency) in phosphate mining (Weber et al., 2014). Therefore, a core objective of this paper is to conduct an *efficiency analysis* of the aggregated country level (globally) in 1983, in comparison to 2013. To include the organizational level, this is extended by the analysis of two exemplary mines.

Phosphate ore deposits of industrial relevance are either of sedimentary or igneous origin, whereas guano deposits, as a minor third source of phosphate ore deposits, are of only limited importance. The vast majority of currently used phosphate rock ore, approximately 85%, is mined from sedimentary phosphate rock deposits accounting for about 90% of all known phosphate reserves worldwide (Prud'homme, 2010; Watson et al., 2014), which can be found mostly in areas of ancient marine continental shelves (van Kauwenbergh et al., 2013) and are most prominently located in Morocco,[2] the US, and China (Prud'homme, 2010; De Ridder et al., 2012; Watson et al., 2014). Currently, igneous phosphate deposits are particularly exploited in Russia, China, Brazil, and South Africa, but also – albeit in smaller fractions – in Finland and Zimbabwe (Prud'homme, 2010).

The main differences between igneous and sedimentary deposits lie in the geometry of the deposit, the mineralogy of the ore and the variability of the ore grade. The igneous deposit usually has a massive nature, with P ore sectors often being lenticular. Sedimentary deposits occur as one or more beds, separated by waste layers of varying thickness and lying under varying amounts of overburden. Grades are normally more continuous than in igneous deposits. These beds can subsequently be folded or tilted by tectonic action. The varying geometry results in a different set of parameters to define resource and reserve quantities with the consequence of different drill hole spacings. In normal cases the drill hole spacing can be wider in sedimentary deposit than in an igneous deposit.

In terms of mineralogy, within the beneficiation process, the separation of the P minerals in both cases is achieved using flotation, where the different mineral densities are exploited. In the case of the generally simple mineralogy of igneous ores, this process can be very efficient and effective, but less so with the more-complex mineralogy of sedimentary ores. Both ore types require a sizing step (grinding, etc.), with the sedimentary ores also often requiring a desliming step (washing to remove sub-sized particles of clays, etc.). In the past, many sedimentary ores (other than those in the Southeast US) did not require flotation, relying on washing and sizing to concentrate the phosphate minerals to a sufficient level. However, most producers from sedimentary ores have now introduced flotation schemes to treat lower-grade ores, some of which were not mined in the past because they were considered too low grade.

The *grade of phosphate rock concentrate* (i.e., the percentage P_2O_5, PR-M) mined and beneficiated from sedimentary deposits usually lies between 28% and 36%, whereas beneficiated igneous ore (i.e., PR-M) tends to contain higher grades of 39–40% (van Kauwenbergh, 2010). Both sedimentary and igneous phosphate ore are mined principally using *surface methods* and, less often, *underground mining methods* (van Kauwenbergh, 2010; Watson et al., 2014). Other techniques such as marine dredging have also been tested but have not become prevalent in phosphate mining thus far (Midgley, 2012). Marine dredging has raised major environmental concerns as a result of the Sandpiper Project, which has recently been put on hold (Benkenstein, 2014), located offshore from the coast of Namibia. Hence, as phosphate mines vary in size, mechanization, and ownership (e.g., state-owned or publicly quoted), the mining method to be applied depends largely on the geological setting (e.g., the type, size, depth of the phosphate matrix below the surface) and economics (van Kauwenbergh, 2010).

Potential single dimensions to measure the *performance of the phosphate mining industry* include economic, ecological, and social dimensions and, additionally, effects on the health and safety of the workforce as well as on the local community (Laurence, 2011), which, in their interplay, may be interpreted as sustainability-oriented industrial activities. However, some sustainability scholars have questioned whether the extraction of a *non-renewable* resource could indeed be part of *sustainable resource management* (e.g., by focusing on the strategic outline of the original report of the World Commission on Environment and Development, 1987). Yet various investigations do point out that sustainability considerations have a high impact on the strategic concerns of the mining industry, as they may affect both economic return and stakeholders' acceptance (e.g., MMSD, 2002; Botin and Palacios, 2010). The subject of stakeholder acceptance, in particular, has emerged in the recent past through the social license to operate (in this case, the social license to mine) in order to address the growing divergence of stakeholders' expectations and, consequently, the need to reconceptualize the relationship between companies and stakeholders toward more dialog, reflection, and collaboration (Freeman, 1984; Steiner, 2008; Owen and Kemp, 2013; Parsons and Moffat, 2014). Furthermore, as we argue in this paper, there are two main concerns that support why phosphate mining – despite the fact that it is a finite resource – should still be seen in the context of a sustainability orientation. First, phosphorus (P) is one of three macronutrient elements for which there is no substitute (for agricultural applications such as fertilizers); P resources are finite, in contrast to nitrogen (N) and potassium (K), which can be considered as infinite (Wellmer and Scholz, 2015); hence, this poses a natural restriction that must also be considered from the perspectives of those who depend heavily on increased agricultural productivity, i.e., as a determinant of social sustainability. Second, because PR-mining is a high-impact extraction process, taking jointly into account the social, economic, and ecological effects can be beneficial when aiming for comprehensive mining performance as part of a sustainability-oriented mining policy. Following these arguments, we consider efficient PR-mining processes as a crucial foundation for extended sustainability considerations.

In the theoretical part of this paper, we first discuss how losses and efficiencies in mining and beneficiation processes have changed over time. Second, we outline and visualize a comprehensive picture of the extended mining process (i.e., the phosphorus supply chain with its pre-mining, mining, and post-mining phases) and discuss phase-specific losses and efficiencies. Based on these theoretical considerations, in our analysis, we focus on the dynamic development of efficiency at the global level between 1983 and 2013 and at the organizational level between 1968 and 2009. On the global level (1), we analyze losses and efficiencies in the mining industry using beneficiation rates, defined as the ratio of PR-M volumes (in product tons or P_2O_5 tons) to PR-Ore volumes (in the same product tons or P_2O_5 tons) (using data from Fertecon/CRU/Zellars-Williams/SRI International) and discuss external factors that trigger these developments (e.g., technological, economic, and legislative factors). On the company level (2), we exemplarily investigate organizational implications by taking the case of the Canadian company Potash Corporation of Saskatchewan Inc. (PCS), which mines PR in the Southeastern US.

2. Losses and efficiencies in the phosphate mining sector

Losses occur along the entire mining process, which encompasses excavation (consisting of planning and mining) and primary

[2] Including the disputed territory of the Western Sahara (in the following, referred to only as Morocco).