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Economics literature on joint production of minerals: A survey☆

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ABSTRACT

Processes which produce more than one output jointly are common across a host of industries and play a notable role in mineral supply. Many important commodities including oil and gas, copper and gold, or iron and rare earth elements, are produced together as joint products. Despite its prevalence, joint production has received only minor explicit treatment in the literature on mineral economics. This paper surveys and categorizes the mineral economics literature to highlight notable works and gaps that deserve the attention of future researchers. A key finding of the survey is that little unifying and empirically tested theory explains the behavior of multi-product firms or markets. However, several studies have found that unimportant joint products, sometimes called by-products, tend to be more available in an economic or physical sense than conventional wisdom may hold. Finally, literature on agriculture and fishing economics are provided as an example of how mineral economics might be better integrated into the economics discipline as a whole.

1. Introduction

Recent concerns over the economic and physical availability of many minor and specialty metals, a host of which are produced as by-products of major metals, has renewed interest in the subject of mineral joint production (Nassar et al., 2015; Graedel et al., 2015; Graedel and Reck, 2015; Bauer et al., 2010). Mineral joint production allows mining a single poly-metallic ore to produce multiple metal outputs, some of which would not be profitable to extract on their own but are critical to many modern technologies. The metal gallium, for example, contributes essential properties in many electronic devices but is produced as a minor by-product of aluminum. For gallium to provide similar value to aluminum for producers its price would need to increase tenfold (Frenzel et al., 2016). The major metals such as copper, zinc, and lead and precious metals gold and silver are also frequently produced together as joint products or with by-products of their own (Petrick et al., 1973).

There is a large body of microeconomics literature on joint production where a single *technology* produces multiple outputs (Ciriacy-Wantrup, 1941; Kreps, 1930; Hall, 1973; Baumol, 1977; Willig, 1979; Chizmar and Zak, 1983; Shumway et al., 1984; Brennan and Kimmel, 1986; Kurz, 1986; Leathers, 1991; Shastitko and Shastitko, 2015), or more generally multi-product supply where a single *firm* produces multiple outputs (Teece, 1982; Hill and Hoskisson, 1987; Levy and Haber, 1986; Bailey and Friedlaender, 1982; Nichols, 1989). The related concept of economies of scope describes the unit cost savings from multi-product production (Panzar and Willig, 1981; Goldstein and Gronberg, 1984; Nichols, 1989; Klette, 1996; Wholey et al., 1996; Gimeno and Woo, 1999; Helfat and Eisenhardt, 2004). The subject of jointly produced non-renewable resources[1] has received relatively smaller treatment in the literature despite its implications for many firms in the extractive industries.

The purpose of this survey is to cite prominent past work and findings on the topic of mineral joint production and note gaps that call for further investigation. The following section describes the method and scope of the survey. In Section 3 the mineral joint production literature is discussed and a taxonomy of the surveyed papers is presented. The taxonomy includes the trends in study purposes, methodology, and materials studied. Based on the findings of the surveyed papers, the present state of knowledge regarding mineral joint production is discussed. Section 4 places the mineral economics literature in the context of the broader literature in joint production economics and describes techniques employed in these other branches of research. Section 5 addresses whether the methods from other fields might be applicable to studding mineral joint production.

The survey reveals an ad hoc history of investigation into mineral joint production, where the theoretical or empirical findings of one study are seldom incorporated or scrutinized by future work. Mineral economics, especially with a recent shift toward studies of mineral availability, has been isolated from more general past work, but is

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[1] Metallic minerals, non-metallic minerals, oil and natural gas.

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becoming more closely associated with work in geology, ecology, and materials science. Economic theory developed on the topic of joint production for general applications has been applied in only a limited number of studies. Looking to the literature on joint production in agricultural and fisheries, which readily uses such theory, the isolation of mineral economics becomes particularly stark.

Despite being a focused topic, work on jointly produced minerals is not well connected to broader topics in mineral or resource economics. For example, more current mineral availability studies provide neither criticism or extensions to the classical Hotelling model (Hotelling, 1931) of resource production, a debated but benchmark model which describes the mining firm as a long run profit maximizer constrained by a certain quantity of resources. At the same time, studies that analyze the behavior of multi-product firms using Hotelling-style models do not draw heavily from the work in geology, industrial ecology, or mining engineering. The study of mineral joint production would benefit from being more closely integrated with both mineral economics and more foundational microeconomic theory of joint production.

2. Scope and survey selection methodology

The objective of surveying the literature for particular insights into the economics of jointly produced minerals bounds the search and inclusion of research in several key ways. Most papers are drawn from the mineral economics literature, but work from industrial ecology, materials science, and mining engineering are also included to some degree. The survey does not specifically target work from these related fields as the purposes, theories, and methods found in these works are in some cases difficult to reconcile with those in economics. While the survey is designed to more comprehensively describe the state of knowledge for mineral joint production in the economics discipline,[2] it will only scratch the surface of the broader and inter-disciplinary state of knowledge in the study of jointly produced outputs generally.

Regarding the surveying method, narrow keyword searches (such as "mineral by-product") in the Research Papers in Economics (RePEc) database uncover the first set of papers. More general keywords (such as "multi-product") are used to search prominent resource economics journals, particularly *Journal of Environmental Economics and Management*, *Resources and Energy Economics*, *Resources Policy*, and *Mineral Economics*. The narrow keyword searches were also conducted in the Thomson Reuters's *Web of Science* database and Google Scholar. Once an initial sample of papers was obtained, forward and backward citations of these papers are used to find other, related work. While the resulting collection of research is unlikely to be completely exhaustive, it is one of the best assemblage of research in topic to date. 53 papers or books were identified for inclusion in this survey. This literature spans the time period from 1965 to 2016 and are summarized in the Appendix table.

3. Classification of literature on mineral joint production

This section presents a classification system for grouping literature on mineral joint production. This classification is then used to discuss notable trends and gaps in past work. The classification system has three dimensions to categorize each paper: purpose, method, and materials assessed (scope). While placing studies into categories is a subjective task, it provides a useful starting place and framework to discuss the results that have been achieved in the past, the current state of knowledge, and the potential for future research.

[2] A branch of research in economics uses time series statistical approaches to study the interdependence of commodity prices, (e.g. Soytas et al., 2009 and Hammoudeh et al., 2009). These papers typically do not distinguish whether prices are linked because of supply forces (joint production) or demand forces, and are therefore only indirectly related to the topic at hand. The survey of this literature is not compressive.

3.1. Purposes

Two broad categories of purposes distinguish work on mineral joint production: *availability assessments* are designed to determine the recovery costs, potentially recoverable quantities, technical issues, and the political, environmental, and social factors related to the supply of joint products and *behavioral analysis* are designed to gain insight into the unique nature of firms and/or markets for which joint production is a key feature.

Availability studies provide insight into how easy or difficult a material is to secure. Studies may take the perspective of a particular metal (e.g., (Frenzel et al., 2015) for germanium or Mudd et al., 2013 for cobalt) and various technologies, or take the perspective of a particular technology (e.g., (Fizaine, 2013) and (Green, 2013) for the case of photovoltaic solar panels) and various metals. Studies with larger scopes may even attempt to address many metals or technologies. These studies include Petrick et al. (1973) for most commercial metals, Stamp et al. (2013) for the metals processed by a single large facility, and Peiró et al. (2013) for recycling of many minor metals, for example.

Studies on behavior of multi-product firms tend to have broader implications (in terms of material applications) than studies of availability. Insights from studies of behavior can sometimes be applied to the markets for many metals, while availability studies tend to speak just to the materials under assessment.

The purposes of behavioral studies are further distinguished by whether a paper determines optimal behavior on the part of a market or a firm, observed behavior, or both. Studies like Epple and Lave (1980), Pindyck (1982), or Wirl (1987) that focus on optimal behavior set out to determine the profit maximizing level of output of jointly producing firms. Understanding optimal behavior can help to explain why, for example, firms flare natural gas (Wirl, 1987), or help to design the storage policy for helium produced as a joint product of natural gas (Epple and Lave, 1980; Pindyck, 1982). However as Young (1991) finds, joint product firms may not behave in the real world as theoretical optimization models might predict.

Studies that focus on observed behavior describe rather than prescribe behavior of the firm or market under study. Livernois and Ryan (1989), for example, test whether oil and natural gas exhibit joint production in exploration (the alternative hypothesis is that the exploration process can be modeled separately for oil and natural gas), rather than assuming this trait characterizes the discovery process. A related idea is the degree to which substitution in supply occurs from one material to another, or the cross-price elasticity of supply, as estimated by Marsh (1983). Farrow and Krautkraemer (1989) test for a similar cross-price production behavior.

Recent focus has shifted from studies concerning behavior to those concerning material availability, as shown in Table 1. Before 2010, only seven papers were principally concerned with material availability. After 2010, fifteen papers were written to determine material availability of jointly produced minerals. The shift may be due to recent concerns over so-called "critical" materials, elements that are important to national economies or manufacturing sectors but have fragile supply chains (Eggert et al., 2008).

3.2. Analysis methods

Papers can be distinguished by what type of analysis was conducted, grouped into five broad categories:

- Analytical: Deriving a closed form solution to a theoretical model to describe behavior.
- Computational: Deriving a numeric solution to a model using simulation or programming techniques.
- Other Quantitative: Geologic accounting, discounted cash flow modeling, engineering economics or associated analysis.
- Qualitative: Analyzing descriptive statistics which are estimated by