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The mining sector: Profit-seeking strategies, innovation patterns, and commodity prices

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Abstract

This study brings together existing evidence to identify the key features of innovation in the mining sector that directly result from its profit structure, which in turn depends strongly on commodity prices. We hypothesize two innovation responses to prices which we test against existing evidence found in recent literature and available industry data. We find two different innovation responses to prices: exploration and R&D investments increase as commodity prices rise, while the use of suppliers' innovation intensifies when prices decrease.

Keywords: resource curse, mining, innovation, economic development, extractive industry

1. Introduction

The mining industry has been considered a curse to economic development due to arguments from international trade, development economics, and institutional economics literature (Prebisch, 1950; Singer, 1949; Hirschman, 1958; Sachs & Warner, 1995, 2001; Collier, 2010). However, the role of innovation in the mining sector in promoting technological upgrading and productivity has recently attracted renewed attention (Bravo-Ortega & Munoz, 2015; Kaplan, 2012; Upstill & Hall, 2006, David & Wright, 1997). Nonetheless, innovation in mining diverges from traditional conventions and many of these differences are yet to be addressed in the literature. Indeed, the interplay of several characteristics of the mining sector poses challenges in the quest to achieve higher levels of productivity and economy-wide technological upgrading.

Innovation is important for several sector-specific reasons. Firstly, it tackles the sectoral challenges encountered, including decreasing ore grades (EY, 2017a, 2017b, Hitzman, 2002), and meeting the increasing demand for mineral commodities used in renewable energy technologies such as electric vehicles (e.g. copper, nickel, aluminum, molybdenum, manganese) (Hund, Porta, Fabregas, Laing, & Drexhage, 2020). Secondly, it can stimulate the emergence of local supplier linkages to avoid the enclaveness of mining operations and create employment. Thirdly, the emerging digital technology in this sector has great potential to create lateral linkages to non-mining activities (Lorentzen, 2008). In this regard, innovation acts as a catalyst to generate broader impacts (Andersen et al., 2015; Iizuka, Pietrobelli, & Vargas, 2019; Morris, Kaplinsky, & Kaplan, 2012; Pietrobelli, Marin, & Olivari, 2018). Fourthly, the context of this sector has gone through drastic changes, impacting its innovation pattern and potential. These are the deverticalization and expansion of global mining value chains, the broader application of digital technologies, growing pressures to operate with consideration for the environmental and local communities' needs, and the rising commodity prices caused by the growing mineral demand for decarbonization technologies (i.e., electric vehicles) and the recent conflict between Russia and Ukraine.

The above emphasizes thus the importance of understanding the characteristics of innovation in this sector from a profit structure angle – which has so far been overlooked in the literature and nonetheless plays a crucial role. In particular, this study identifies innovation responses as a reaction to commodity price fluctuations. The fact that the vast majority of mining commodity prices are exogenously determined in the London Metal Exchange restricts the choice of profit-seeking strategies for the mining firms and therefore how they invest in innovation.

This paper is structured in the following manner: firstly, it briefly reviews the literature on the natural resource curse, paying special attention to instances that refer to innovation and linkages to understand sectorial idiosyncrasies. Secondly, building on the unique features of the mining sector, we propose two hypotheses on innovation - including innovations introduced via supplier linkages - as these responses to price fluctuations. Thirdly, to validate the hypothesis presented, this paper presents a compilation of evidence largely based on available secondary data sources and supplemented with empirical tests. The last section provides our conclusions, reflecting on the newly unveiled understanding of the mining sector, and exploring policy implications concerning the resource curse.

2 Literature review: Resource curse, linkages, and innovation

2.1 The resource curse: From an economic perspective

The extractive industry has often been considered a "curse" for development[1]. The most prominent argument for subpar economic performance is the Dutch disease, a phenomenon in which high commodity prices lead to the appreciation of the exchange rate, subsequently discouraging growth in other export sectors present in the country, especially in the manufacturing sector (Corden & Neary, 1982). Others have argued that the volatility of commodity prices leads to unstable macro-economic conditions, ultimately leading to poor economic performance (Deaton, 1999; Mikesell, 1997; Moradbeigi & Law, 2016; van der Ploeg & Poelhekke, 2008), especially leading to negative liquidity shocks(van der Ploeg and Poelhekke, 2008). Hence, the volatility ultimately discourages investment and hampers innovation and growth.

Furthermore, reliance on commodities for government revenue and the deteriorating terms of trade cause long-term trade imbalances, which reduce prospects for economic growth (Prebisch, 1950; Sachs & Warner, 2001; Sachs & Warner, 1995; Singer, 1949). Likewise, the mineral extractive sector tends to operate in enclaves, creating very few forward or backward productive linkages (Hirschman, 1958).

Yet, there is no conclusive evidence on the negative relationship between extractives and growth as several studies have failed to find such effects when using slightly different indicators (Brunnschweiler & Bulte, 2008; Cuddington, 1992; Ellsworth, 1956; Tilton, 2013), periods covered (Cuddington, 1992; Ellsworth, 1956), and methods of analysis (Brunnschweiler, 2008). Similarly, others argue that the provision of human capital, physical infrastructure, and institutional capability have been omitted from explanations of the link between commodity trade and growth.

The institutional mechanisms, such as sovereign wealth funds (SWF) or the Economic and Social Stabilization Fund, are effective in absorbing the volatility of commodity prices to maintain macroeconomic stability (Collier, 2010). Others have discovered that skilled human resources improve productivity, indicating that training and research enable a country to take full advantage of natural resources (Bravo-Ortega & Gregorio, 2007; Ville & Wicken, 2013). These studies point to the lack of complementary assets (human resources, financial mechanisms, institutions, etc.) as factors that hamper the effective utilization of natural resources for economic development.

To support the above claims, several case studies demonstrate that innovation in mining activities can propel the diversification of the economy and create knowledge-intensive jobs when supported by sound institutions and policy interventions (David & Wright, 1997; Upstill & Hall, 2006; Urzúa, 2012; Ville & Wicken, 2013).

2.2 Discussion on innovation and mining

Innovation contributes to development in two ways: improving productivity and diversifying activities via spillover effects, with both occurring at the firm and meso-industrial levels. The characteristics of innovation in the mining sector had been understudied until recently.

According to Pavitt's (1984) taxonomy of innovation, the mining sector can be characterized as "supplier-dominant innovation"[2]. Within this category (e.g. textile and agriculture), firms rely on suppliers as the source of innovation (Pavitt, 1984). For a supplier-dominant innovator, the goal is cost-cutting because they are price sensitive. This implies that investments in research and development (R&D) are less likely to occur because of their high cost (Hall, 2006). Furthermore, the knowledge upon which this type of innovation is based has a low level of appropriability, less likely to profit from knowledge creation and diffusion.

The mining sector-specific literature claims that exploration and development activities (E&D) share similitude with R&D in manufacturing (Hall, 2006) as this process involves 1) generating new resources for the firm's core activities, and 2) the uncertain selection process to identify the developmental pathways. Likewise, Kreuzer & Etheridge (2010) argue that having access to new deposits in the mining sector is the equivalent of developing a new "product," especially if the discovery involves better quality deposits (i.e., higher grade, easier processing, and strategic locations) that greatly improve productivity through cost reduction in processing, and allows for the expansion of production volume. This activity, moreover, entails risks of not finding one and the process that generally requires a long-term investment in scientific knowledge (e.g., geological surveys). Similarly, Baldwin et al (2009) treat the expenditures for mineral E&D the same as scientific R&D and advertisement costs in their attempt to estimate intangible investment for innovation in Canada. He claims that "exploration expenditures provide knowledge about an asset whose economic exploitation must await other events that change the economics of exploitation, such as the increase in the price of the mineral or the development of infrastructure" (Baldwin et al, 2009:19). Moreover, E&D activities are financially and legally supported in the advanced mineral resource-rich countries such as Australia and Canada, confirming its critical nature for both sustaining and developing the industry.

The above arguments reflect the idiosyncrasies of the mining sector. Firstly, most of the mineral resources are fundamentally undifferentiated commodities and the price is determined by the London Metal Exchange (Filippou & King, 2011). This leaves limited room for the firm's value addition. Considering that profits are generated from the difference between the market price and production costs, the aim of innovation in this sector is strategically focused on cost-cutting to increase profits (Sanchez & Hartlieb, 2020). For instance, in the early 2000s mining firms increased the number of mergers and acquisitions, and the reliance on external suppliers for critical operational solutions while the in-house development of technological solutions declined in an attempt to boost cost-efficiency (Sanchez & Hartlieb, 2020).

Secondly, much of the innovation introduced in the mining sector is responding to contextual needs. The innovation often takes place in a specific geographical area (often in remote regions of the country), forcing mining firms to overcome location-specific challenges. Such challenges require a new combination of available physical infrastructure and technology. Other key challenges involve geological conditions such as ore grades, efficiency in the use of explosives, and equipment that can be used at varying altitudes (Bravo-Ortega & Muñoz, 2015; Kaplan, 2012). These innovations are location specific and therefore limited in scalability. Moreover, they are typically embedded through all the phases of mining operations processes (i.e., prospecting & exploration, extraction, processing, closure, and remediation) and are difficult to single out. Hence, the appropriability of knowledge is, in general, difficult. These characteristics underlies the reason for the mining firms less likely to invest in knowledge (Metcalfe, 1995; Nelson, 1959), leaving these tasks to suppliers[3].

Thirdly, the industrial characteristics of the mining sector restrict and hinder rapid and radical innovations. For instance, the mining sector requires a huge upfront investment for the exploration and construction of mines, particularly in the early phases of their life cycle (Collier, 2010). The initial investments entail infrastructure and large, specialized machinery that usually lasts over 30 years (Bartos, 2007). Such large costs for investments put mining firms under financial stress to avoid taking additional risks of introducing new technology. Instead, they are more inclined to use less innovative and already-proven one. Moreover, nowadays, large global service providers, such as engineering, procurement, and construction (EPC) companies, or engineering, procurement, construction, and management (EPCM) companies, manage the early phase of mining operations. They ultimately determine the type of equipment, technological solutions, and suppliers introduced with little or no consideration for local spillover effects (Bartos, 2007; Bramber, Fernandez-Stark, & Molina, 2019).

A crucial – yet often overlooked – consideration of innovation in the mining industry relates to productivity gains and their link to prices. This issue was particularly discussed by Tilton (2014), who explains that there are two seemingly conflicting perspectives on innovation for enhancing productivity in the mining sector. The first one puts forth that, as prices grow, so does productivity, as producers have more resources to experiment with new technologies (i.e., investment in R&D), upgrade, and expand the mine's capacity. The second, conversely, contends that, when prices are depressed, the pressure to reduce costs pushes managers and workers to be more flexible about adopting new technologies and operations and the reverse is possible. He concludes that the latter perspective on innovation is the predominant force in mining. Nonetheless, new evidence indicates that innovation activity, as proxied by mining patents, has expanded substantially in the past few decades (Valacchi et al., 2019), thereby providing some support for the former view.

The firms' decision of whether to rely on suppliers or conduct in-house R&D can be understood by differences in their intentions. Chesbrough and Schwartz, (2007) distinguished intentions for R&D collaboration into *core*, vital for the activity; *critical*, vital for competition but not core; and *contextual*, important to deal with local specific issues. By applying this classification to the extant literature on mining industry, it can be to explain that the mining firms collaborate on *critical* and *contextual* R&D with suppliers (Hall, 2006; Sanchez & Hartlieb, 2020). The investments are likely to be implemented when the commodity prices increase. For example, the introduction of digital technologies[4] in mining (Sanchez & Hartlieb, 2020; Calzada Olvera, 2021) in recent years.

2.3 Discussion on linkages and mining

For a long time, mining has been considered an enclave activity (Hirschman, 1958), having few suppliers (i.e., no backward linkages or upstream linkages), and even when suppliers are used, they are often of foreign origin, with limited local spillover effects (Dietsche, 2014). Recently, a growing body of literature illustrates several changes currently taking place concerning the backward linkages of the mining sector, particularly, in Australia (Urzúa, 2012; Scott-Kemmis, 2013; Francis, 2015). This heightens the potential to develop the local suppliers – typically small to medium enterprises which provide services, machinery, and other equipment to the mining industry[5] – to upgrade via participating in the mining global value chains (GVCs), provided that these suppliers can respond to the demands of the mining firms (Pietrobelli & Rabellotti, 2011).

The potential and challenges in materializing the above are as follows: Firstly, the wave of globalization has resulted in mining activity moving away from a high level of vertical integration of inputs and services to global outsourcing (Korinek, 2013; Urzúa, 2012). Both the increasing reliance of the mining sector on outsourcing and the specialization of mining suppliers have been widely observed in the past two decades (Urzúa, 2012; Scott-Kemmis, 2013). This was further augmented by the increase in foreign direct investment, market liberalization, and the advancement of technology that lowered the logistic costs of transporting minerals. These factors led to the building of a complex web of global value chains in the mining sector (Dietsche, 2014; Humphrey & Schmitz, 2002; Scott-Kemmis, 2013; Urzúa, 2012). International input-output data identified a substantial increase in the exchange of services along the GVCs (Kowalski et al., 2015), and the mining sector was not an exception to such global trends (OECD, 2019). While this is true, as explained in the previous section, the strong role of EPC and EPCM companies limits the participation of local suppliers and shapes the types of innovation that can be introduced in the later phases of the life cycle of mines (Bramber et al., 2019).

Moreover, a closer look at the types of mining suppliers helps differentiate the contractual relationship with mining firms. The suppliers providing large capital equipment (such as machines, trucks, grinders, etc.) are largely oligopolistic, where a few firms dominate approximately 50% of the market (Bramber et al., 2019; Comisión Nacional de Productividad, 2017). These suppliers, moreover, have critical capabilities and *majors* (or mining firms) are inclined to form collaborative relationships at the global level to minimize costs. As we explain later, mining firms take different approaches when purchasing from mining suppliers that possess contextual capabilities.

Secondly, the idiosyncrasy of the mining sector poses several challenges in forming sustainable linkages involving local suppliers (Iizuka et al., 2019; Urzua, Wood, Iizuka, Vargas, & Baumann, 2016). Mining firms have historically preferred short-term profitability over long-term productivity gains (Kuykendall & Qureshi, 2014; Roberts, 1939)[6]. In recent years, the focus on short-term profitability has grown substantially (Deloitte, 2017). For example, mining firms' procurement decisions tend to adopt incremental and ad hoc, ready-made, proven technological solutions from established local suppliers (Atienza, Lufin, & Soto, 2021; Bradley & Sharpe, 2009; Pavitt, 1984). This provides limited opportunities for local suppliers without a track record of success or established business relationships (e.g., a spin-off from the *majors)* to participate in the value chains. Moreover, the lack of experimental use or absence of a testing ground to demonstrate suppliers' prototypes is often mentioned as one reason for the limited success of local suppliers to negotiate with the *majors* (Urzua et al., 2016). The local suppliers are also often isolated, smaller in size, and suffer from power asymmetry for negotiating terms of business. The cases in Latin America demonstrate that the risks and costs of innovation are absorbed almost entirely by the local suppliers (Figueiredo & Piana, 2016, 2017; Molina, 2018). This makes collaborative innovation between users and producers difficult and leads to transactional interactions (Pietrobelli et al., 2018).

Despite the above difficulties, there are some successful local mining suppliers. Often, these require the presence of strong institutional support from the public sector, such as state-funded specialized research centers, as evidenced in the US and Australia (Calzada Olvera, 2021; OECD, 2019; Scott-Kemmis, 2013). Several countries have established a local content requirement policy (Korinek & Ramdoo, 2017).[7] Likewise, building capability (such as the institutional and systematic ability to take advantage of resource endowment) is much needed in many resource-rich emerging countries (Acemoglu & Robinson, 2012; Andersen et al., 2015; Morris, Kaplinsky, Kaplan, Farooki, & Fessehaie, 2011). Local suppliers that have managed to overcome these difficulties have focused on services and products that are highly customized and cater to local specific needs (Molina, 2018; Stubrin, 2017).

Although mining firms prefer a less risky route, new avenues are opening with emerging technologies, ranging from geo-mapping to self-driving vehicles (Bramber et al., 2019; WEF & Accenture, 2017). These employ new technologies, such as 3D printers, drones, and other digital innovations (Calzada Olvera, 2021). Under a positive commodity price environment, better provision of information and communications technology (ICT) can generate higher externalization of activities that can eventually lead to the building of new collaborative linkages between mining firms and innovative emerging suppliers (Morris et al, 2012). Environment-related innovations, such as ecologically non-invasive techniques, renewable energy, and water treatment technologies, represent another area with similar potential. For example, Vale’s tailings dam incident in 2019 generated strong incentives to develop new technologies for treating tailings, a problem now considered one of the major challenges for mining on a global scale (Global Trailings Review, n.d.). For identifying local suppliers which has solutions for contextual challenges, the *majors* often apply "open innovation" strategies, in which mining firms explore ideas outside the usual boundaries for solutions using pecuniary (e.g., patents and licences) or non-pecuniary mechanisms (e.g., boot camps, hackathons, etc.)(Chesbrough & Bogers, 2014). The new areas of activities entail lateral or horizontal linkages that allow technology to migrate between sectors (Lorentzen, 2008). For instance, innovation using ICT for better logistics, the efficient use of water, and renewable energy generation are beneficial for other sectors as well as the local community. All the above can potentially lead to the creation of broader spillover effects.

This review section concludes with three points. Firstly, contrary to conventional thinking, natural resources have the potential for development through the enhancement of productivity via innovation and for extending the production linkages of suppliers. Secondly, the innovation potential is found in mining service suppliers that employ new technologies, by responding to local specific needs that essentially reduce the costs of operation. Thirdly, although the idiosyncrasy of the industry poses challenges, linkages are essential for development, especially if suppliers can migrate or diversify into different segments beyond the mining sector. Fourthly, the mining sector, due to its peculiar characteristics in relation to productivity (i.e., price is exogenously determined), requires policy interventions that pay more tailored to its characteristics.

3. Hypotheses to understand innovation mechanisms in the mining sector

3.1 Understanding the peculiarities of the mining sector with respect to its profit structure

Over the past decades, mining firms' productivity has declined substantially (EY, 2017a, 2017b), resulting from declining ore grades and the exhaustion of productive mineral deposit sites. This makes enhancing productivity via innovation inevitable, but mining firms are known for seeking short-term profitability over long-term productivity gains and are less keen to engage in innovation processes-. To understand what triggers innovative activities, research and development (R&D) expenditures and patents are often examined, although innovation in the mining sector is said to take place without R&D (Huang, Arundel, & Hollanders, 2010)[8].

To make the peculiarity of the mining sector more explicit, the following assumptions are made. In general, mining firms, like most firms, try to increase their profits. To achieve this, a firm needs to do two things: increase revenue and minimize costs. Revenue in mining firms is determined by the unit price and the volume of minerals produced. The profit (P), is derived from revenue after subtracting the production costs, which consist of fixed (FC) and variable costs (VC(x)). Fixed costs typically include the expenditures that will not depend on the volume being produced such as initial investments for infrastructure, capital equipment, and wages of core personnel while variable costs change with the amount of mineral produced (x). These include input materials and additional wages. The above is expressed in the equation (1) below:

$$P(x)=R(x)-C(x), \text{ where } C(x)= (FC) + (VC(x)), \text{ and } R(x)=Pr \cdot (x), \qquad (1)$$

where P is profit, R is revenue, and C is cost. The commodity price, (Pr), is exogenously determined (2). Hence, revenue is largely determined by the market and a firm’s influence is limited to changing the volume of production (x).

$$P(x)=(Pr \cdot (x))-(VC(x)+FC), \qquad (2)$$

Given Pr is exogenous.

While cost-cutting is of prime importance, mining firms are willing to maintain high levels of expenditure for exploration and development (E&D) of future mining sites, as these secure future rents; however, due to the high costs involved in exploration as easily-accessible deposits are already being exploited, different strategies were taken (Schodde and Cao, 2003). It makes sense for mining firms to rely on *juniors* (firms specialized in exploration) when commodity prices are not promising. Moreover, as it is highly probable for mineral deposits to be closely located geographically, brownfield exploration, i.e., exploration around already-exploited sites, is preferred when mineral prices are uncertain. This can substantially lower the risks, compared to greenfield exploration (S&P, 2017).

To sum up, the following are the peculiarities of the mining sector with regards to productivity: 1) the price (of the mineral) is exogenously set due to its commodity nature, and 2) the relative importance of fixed cost investments (exploration and infrastructure provision) is high and more speculative than in the conventional (manufacturing) sector – as the price of commodities is exogenous and firms have no control over the price.[9] Thus, the primary means left for a firm to increase revenue are: a) to increase the volume of production (x) without increasing costs (FC and VC), b) to increase the efficiency of mineral deposits by finding more productive deposits (exploration), or c) to reduce the cost of production to a minimum by reducing fixed costs (FC(min) e.g., the introduction of new equipment or organizational changes) (3). This means that innovation should ultimately be aimed at these three objectives.

$$P(x)max=(Pr \cdot (x))\ max-(VC(x)+FC)\ min \qquad (3)$$

Optimal conditions: maximise (x), minimise VC, minimise FC

Table 1 summarizes potential areas of profit-seeking innovation in mining firms and provides specific examples to illustrate this.

Table 1. Possible areas and actors of profit-seeking innovation in mining firms

Increase revenue				Minimize costs			
Possible actions taken		Who does it?	Example	Possible actions taken		Who does it?	Example
Volume of mineral				Fixed Costs			
Find deposits with higher grade	Exploration: search for better deposits to increase efficiency and meet demands	Junior or mining firms	Remote sensors, and satellite systems; deeper exploration	**Reduce Labor Costs**	Replace labor with technology; employ the business model to reduce accidents	Collaboration with established suppliers of the sector, e.g., Komatsu with Rio Tinto in developing self-driving excavators	Self-driving large equipment, the introduction of digital devices for managing labor
Expand production volume	Increase volume of production by introducing excavation, trucks of larger quantity, drills of larger capacity and faster speed	Equipment supplier firms, service providing suppliers	Larger truck, shovels, and tires; improved drills, and explosives	**Externalize Physical Infrastructure services**	Introduced at the early phase; employ new technologies for services that can be added	EPC, EPCM, Suppliers	Tunnels, road inside the mines etc. Renewable energy, desalination plants, water treatment facilities
Enlarge the size of mines	Increase the size of mines by introducing infrastructure and equipment of larger capacity	Mines, EPC, EPCM, input suppliers and specialized companies	Infrastructure that allows larger trucks to operate, intermediate inputs such as tires, etc.	**Develop cost-reducing capital equipment**	Collaborative R&D with oligopolistic large international suppliers; alternatively, open innovation with small domestic suppliers if it is location-specific, tailor-made services	Collaboration between established large suppliers; small-scale producers responding to local needs, incorporating digital technologies	Automotive mining machines, customized building structures, use of drones for high altitude or underground
				Reduce operational services	Collaborative R&D with established suppliers, mostly large scale but can also be small scale when it is location-specific	Collaboration with established suppliers; high tech startups for customized equipment producers responding to local needs	Timely replacement (e.g., tires, grinders, etc.); customized adjustment, non-invasive inspections (e.g., pipes, pumps,), surveillance drones
				Reduce cost of logistics	Efficiency in delivery; less energy or fewer environmental impacts	Local suppliers	New truck formation for shortening loading time
				Increase use of digital platform	Introduce new management systems	Emerging suppliers (startups or large scale)	Management systems or labor, inputs
				Avoid future environmental and social cost	Organizational and technological (digital) solutions	Global suppliers for solutions that require scale, local suppliers for location-specific solutions	Global suppliers provide solutions for tailing treatment and renewable energy generation; local dispute settlement with the indigenous population

Source: Authors' elaboration

3.2 Hypotheses of innovation in mining and price fluctuation

To understand generic mechanisms of innovations in mining, the following two hypotheses on mining firm behavior are drawn from the discussions made above.

Based on the logic of profit-seeking firms, it is possible to hypothesize that the search for more productive mineral deposits (i.e., exploration activities) would increase when the price of minerals is on the rise in tandem with expansion of production volumes and the size of mines. However, latter two have certain limitation given the degrading ore grades. It is possible to assume that mining firms' investment in R&D for exploration purposes would increase with the growth of exploration activities, which are often carried out by mining firms as well as service suppliers, or *juniors*. Hence:

> H(1): Mining firms increase exploration activities to expand mineral production when the mineral price is rising so that they can expand profits. Consequently, innovation expressed as R&D investment and patents for exploration also increases when prices increase.

As already mentioned, another way to expand profits is by reducing the cost of production. This option is preferred when market demand is weak, and commodity prices are low. Under such circumstances, there are stronger incentives to reduce costs. Since variable costs diminish with reduced production, firms are especially likely to reduce fixed costs, as they incur these regardless happens especially in the critical and contextual segment of innovation. This pressure to reduce variable costs is likely to be stronger when the market is expanding (and there is a corresponding expansion of volume). However, the pressure would be substantially weaker if the increment in commodity prices is high enough to offset the current level of variable costs of production volume. The literature review reveals that this sector relies on service suppliers for cost-reducing innovation by solving local specific problems or challenges. This suggests another hypothesis: when the price of minerals decreases, cost-reducing innovations by, or with, suppliers will increase in the mining sector. This type of innovation may accompany the strengthening of linkages or the use of suppliers by the mining firms.

> H(2): When mineral prices decline, mining firms increase the linkage with suppliers (backward linkages, in terms of input and output analysis) to carry out cost-reducing innovation (customization, the introduction of digital technologies, etc.) and to increase revenue. Consequently, suppliers' innovative efforts, calculated by patenting activities, become larger than those of mining firms, and hence, innovation will increase counter-cyclically to commodity prices.

Certainly, other factors come into play when adopting new technologies. Changes in the regulatory framework – either for workers' safety or environmental reasons – represent an important driver for innovation in natural resource sectors, including mining, especially in avoiding the future costs (Perez et al., 2009).

In sum, we have derived two hypotheses concerning innovation within this industry from the existing understanding of this sector. Firstly, we assume that mining firms invest and engage directly in innovation through exploration in a pro-cyclical manner to the commodity price. Secondly, we assume that innovation is adopted mostly through third parties (suppliers) in a counter-cyclical manner to reduce costs. In the following section, we provide a compilation of evidence (i.e., aggregate sector-level data and existing empirical studies) to support our- two hypotheses on innovation patterns in the mining sector. This is then supplemented by empirically testing our hypothesis on countercyclical innovation responses.

4. Discussion of innovation particularities in mining: evidence

4.1 Procyclical innovation responses via exploration and R&D (H1)

H1 puts forth that mining firms increase innovation (as expressed in expenditure on exploration, R&D, and patents) to expand the future mineral production as the price increases.

The profit and investment of the 40 largest mining firms (by revenue) reflect this parallel trend (Figure 1). This occurs during a period of commodity price boom reflected by the profitability of its operations. Investments (which include exploration, projects and property, and other technology acquisitions) began with USD 100 billion in 2008 and ended with a figure representing roughly half of that in 2016; illustrating that, despite a mild delay, the industry is quite pro-cyclical in its investment (Bramber et al., 2019).

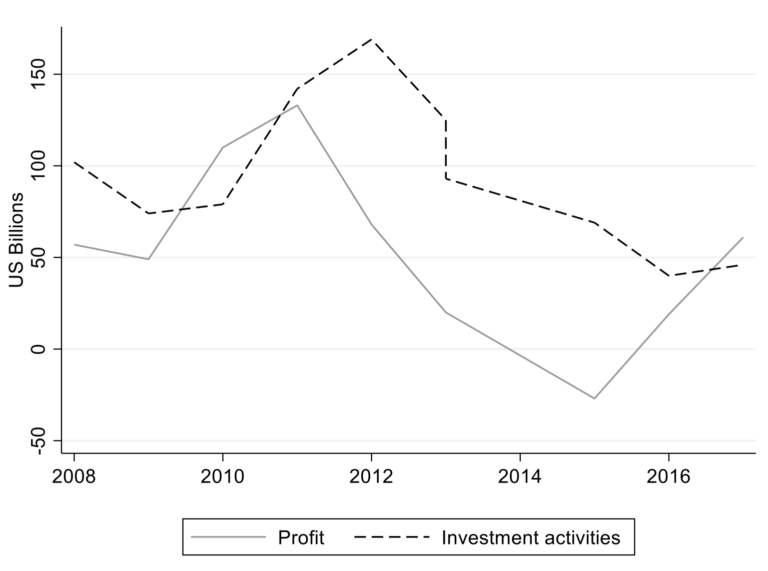

Figure 1. Aggregate profit, exploration, and capital investments for the top 40 firms. Period 2008–2017 (USD billions)

Source: Authors' elaboration with firm data from PWC reports, 2018.

Figure 2 shows the average exploration investments vis-a-vis R&D of BHP Billiton, Rio Tinto, Anglo American, and Glencore from 2003 to 2018. It is evident that exploration expenditures have increased parallel to commodity prices, and these are substantially higher than those of R&D investments. R&D has followed a similar pattern to investment activities, as shown in Figure 2, though on a lower scale, demonstrating a mild but steady growth from initial levels in 2003. This is consistent with the conclusions of Daly et al. (2019), whose data indicate that the R&D investments of mining firms show similar pro-cyclical behavior in Europe. More generally, data from OECD countries show that mining firms invested in business enterprise research and development (BERD). In aggregate terms, it also shows the increase in commodity prices occurs in a pro-cyclical manner. The degree of investment in R&D in the mining sector, however, varies greatly across countries. Norway, Chile, and Mexico, for example, have invested relatively small amounts in comparison to Canada, Australia, or the US (where BERD is generally high to start with). Among these countries, Canada has shown slight increments while the US has substantially increased its R&D investment, making it the country with the largest R&D investment in the mining sector among OECD countries. Australia, on the other hand, has dramatically reduced its investment level in the mining sector (OECD, n.d.). Even with the reduction, Australia, the US, and China still retain very high levels of investment in R&D in the mining sector (Valacchi et al., 2019). However, as can be seen in Figure 3, the lion's share of R&D investment in mining comes from China.

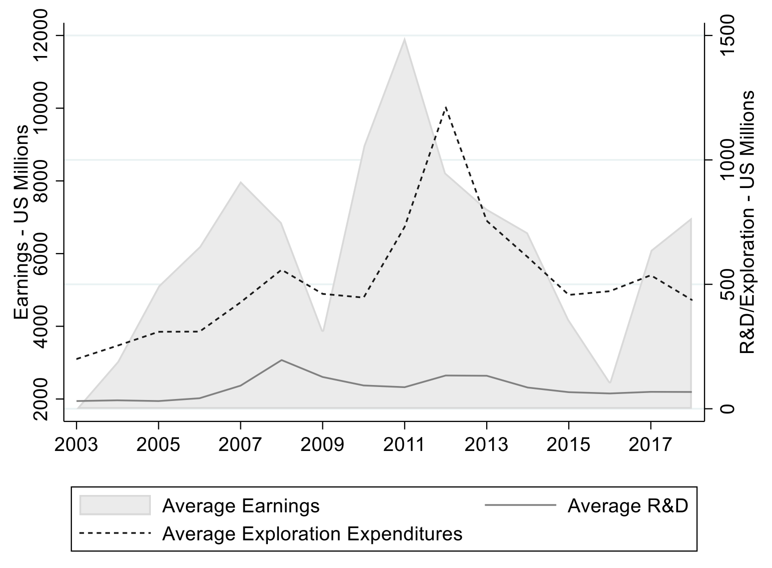

Figure 2. Average R&D (solid line) and exploration investments (short-dash line) for the largest mining firms: BHP Billiton, Rio Tinto, Anglo American, and Glencore from 2003 to 2018 (USD millions)

Source: Authors' elaboration with data from firms' reports

As can be seen in Figure 3, the BERD levels have increased in the last two decades. Recent empirical data shows further details about the mining R&D efforts, such as the fact that they are largely concentrated around exploration and carried out utilizing mining equipment, technology, and services (METS: mining equipment, technology, and services) (Valacchi et al., 2019).

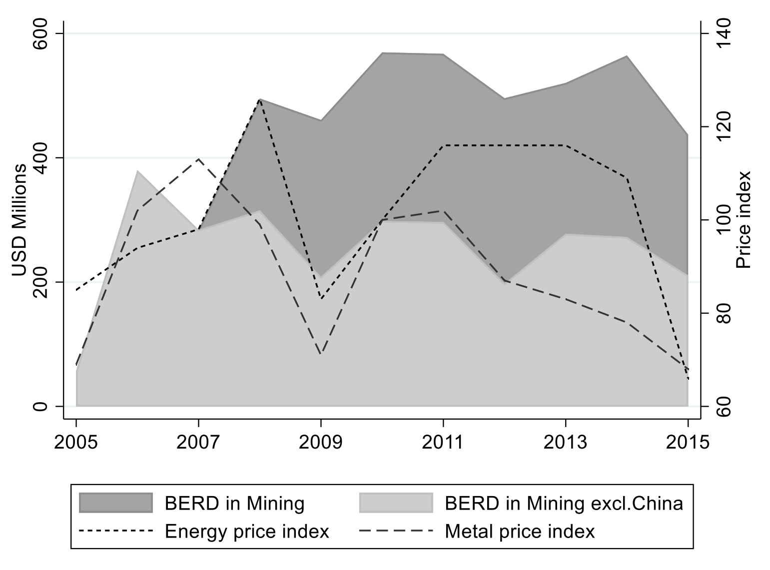

Figure 3. Business R&D figures for the mining sector (USD millions)

Source: Authors' elaboration with OECD and World Bank Pink Sheet data on annual price indices for energy and metals.

Note: BERD: Business Research and Development. Energy price added to reflect coal.

Consistent with our expectation, Figure 4 illustrates the number of patents from suppliers and mining firms for exploration. This figure suggests that the increase in the number of patents (one of the indicators of innovation) is closely related to the increase in the price of metals. Finally, Valacchi et al., (2019) using time-series and the same dataset for patents found that, on average, mining patents – including exploration patents – respond strongly and positively to commodity price increments. Namely, it finds that a one-percent increment in mining prices increases global mining patenting activity by 0.35% after a year (Valacchi et al., 2019), which is in line with the high pro-cyclicality features pointed out earlier.

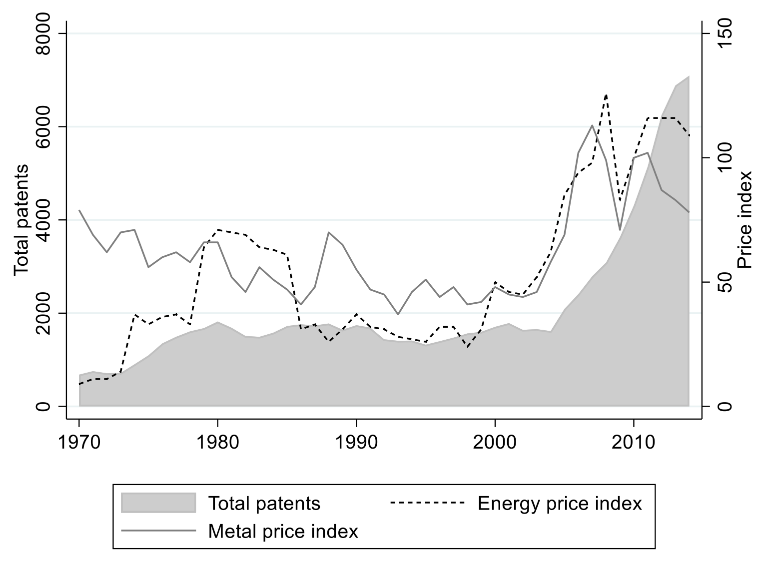

Figure 4. Exploration patents (by family application ID) by METS, mining firms, and mineral commodity price indices (2010 = 100)

Source: Authors' elaboration with OECD data and the World Bank Pink Sheet data on annual price indices for energy and metals.

Note: Energy price index is added to reflect METS working for oil, coal, and gas industry

The evidence above supports our arguments presented in H(1): mining firms increase exploration activity to expand mineral production when mineral prices are rising, as they hope to increase their profits.

4.2 Relationship (linkages) with suppliers and its countercyclicality

H(2) investigates mining firms' investment behavior to increase productivity through cost reductions, namely by externalizing cost-cutting innovations to suppliers; we support this argument by discussing METS patent activity in subsection 4.2.1. Based on the profit-seeking logic of the firm expressed in equation (1) and given the limitations of the mining sector, H(2) was drawn from the mining firm's behavior in relation to commodity price fluctuations.

4.2.1 Suppliers (METS) patenting activity

The evidence on patenting illustrates an important trend that concerns mining firms' changing relationship with METS concerning innovation. This trend is characterized by strategic decentralization (open innovation[10]) and enhancing collaboration in some specific sectors (i.e., large-scale capital equipment) that are critical and fit local needs. Table 2 presents patenting trends in mining with additional disaggregated data by type of firm based on data from the World Intellectual Property Organization (WIPO). Firstly, the patent data were divided into two periods: 1970 to 1995 and 1996 to 2015[11]. Looking at the absolute number of patents, specialized suppliers, or METS, acquired more patents than mining firms. During the 1996 to 2015 period, almost 70% of patenting activities in mining firms were concentrated in the exploration sub-sector. This share is double that of the 1970 to 1995 period. While METS have also increased exploration (from 17% to 25%), their patenting remains less concentrated on exploration activities and is spread across the mining sub-sectors. The number of patents is significantly higher in METS than in mining firms in both periods except for the sub-categories of exploration and blasting, which also concerns the exploration phase.

Table 2. Category, number, and percentage of patent filings according to firm type (1970–2015)

	Automation	Blasting	Environment	Exploration	Metallurgy	Mining	Processing	Refining	Transport	Total
1970–1995										
METS	19	55	1,966	3,406	329	**6,125**	433	5,803	1,526	19,662
	0.1%	0.3%	10.0%	17.3%	1.7%	**31.2%**	2.2%	29.5%	7.8%	100.0%
Mining	3	73	1,368	**3,729**	116	1,126	559	3,720	159	10,853
	0.0%	0.7%	12.6%	**34.4%**	1.1%	10.4%	5.2%	34.3%	1.5%	100.0%
Total	22	128	3,334	7,135	445	7,251	992	9,523	1,685	30,515
	0.1%	0.4%	10.9%	23.4%	1.5%	23.8%	3.3%	31.2%	5.5%	100.0%
1996–2015										
METS	62	452	5,616	13,316	334	**14,845**	1,910	10,075	6,124	52,734
	0.1%	0.9%	10.7%	25.3%	0.6%	**28.2%**	3.6%	19.1%	11.6%	100.0%
Mining	17	482	3,716	**28,254**	70	4,174	773	4,443	467	42,396
	0.0%	1.1%	8.8%	**66.6%**	0.2%	9.9%	1.8%	10.5%	1.1%	100.0%
Total	79	934	9,332	41,570	404	19,019	2,683	14,518	6,591	95,130
	0.1%	1.0%	9.8%	43.7%	0.4%	20.0%	2.8%	15.3%	6.9%	100.0%

Source: Authors' elaboration with WIPO data

The patent data demonstrates that there is a concentration of mining firms in the exploration sub-sector, confirming the arguments presented in H(1). This finding is consistent with conclusions presented in Valacchi et al. (2019). The flipside of this implies the reliance of mining firms on METS for innovation in other subsectors. This partially confirms our arguments in H(2).

4.2.1. Innovation by suppliers (METS) and its countercyclicality

According to Pavitt's (1984) taxonomy of innovation, the mining sector closely resembles the supplier-dominated innovation category. This means that mining firms are the users of innovation provided by the suppliers. To measure the degree of third-party innovation adopted by the mining industry (i.e., the contribution of innovation by suppliers to the mining industry), this study analyzed supplier linkages, formally referred to as *backward linkages*; it does so by providing an overview of existing empirical evidence which is supplemented by an econometric test. Backward linkages reflect the share of purchases that originate from other sectors, making it possible to trace sector-specific contributions to the value generated in the final product – for instance, the share of purchases that are necessary from sector *i* to satisfy the demand of sector *j*. In other words, backward linkages include how much of sector *i* is necessary to produce an additional unit of sector *j* (unless specified otherwise)[12].

Empirical studies at the country level have shown a decrease (in various degrees) in backward linkages to supplier industries in major mining exporters, such as Australia, Chile, Canada, Brazil, and Russia (Calzada Olvera & Foster-McGregor, 2018). Moreover, these results echo other studies that emphasize the weak supplier development in mining countries such as Brazil (Figueiredo & Piana, 2017) and Canada (Stanford, 2020).

Furthermore, a negative relationship between prices and linkage formation has been found in empirical studies conducted both in cross-country and within-country set-ups. Calzada Olvera and Foster-McGregor (2019) find that commodity prices have a highly significant negative effect on backward linkage formation based on a time-series analysis using data for more than 120 countries during the 1975–2015 period. The analysis shows that the price-linkage relationship remains negative even after controlling for relevant variables, such as government effectiveness, human capital proxies, and macroeconomic variables. Namely, the estimations suggest that a 10% price increment translates into a reduction of backward linkages equivalent to 1.8% after one year (Calzada Olvera & Foster-McGregor, 2019). Castaño, Lufin, and Atienza, (2019) present the case of Chile as an insightful example of the counter-cyclical reaction of suppliers' services and products to the commodity price. Based on input-output methods and structural path analysis, their study concludes that there was a significant reduction in mining linkages, especially during higher commodity prices. Specifically, it shows that when commodity prices were high during the 2003-2011 period, the Chilean mining sector not only reduced the number of suppliers, but also supplier-induced innovations in key sectors (such as transport, commerce, R&D, and financial services). Moreover, they explain that during this period, energy, labor, and capital were used excessively to support production expansion to take advantage of the commodity boom. This trend, however, was reversed when the mineral commodity prices fell. The World-Class Suppliers Program in Chile, which aimed at fostering innovative suppliers along the value chain, was launched in 2009, right after the sharp decline in copper prices following the global financial crisis in 2008. The imminent need to maintain profits (or reduce losses, at least) by reducing production costs pushed mining firms to seek for innovative suppliers (Castaño, Lufin, & Atienza, 2019).

The aforementioned studies refer to backward linkages measuring the supplier transactions from all sectors to the mining sector - potentially including non-innovative suppliers. This distortion is, however, expected to be relatively minor as the bulk of suppliers come from (typically) modern service sectors and the acquisition of new inputs. Nonetheless, to supplement those conclusions and to provide a perspective that is more specific to innovation-related sectors, we test empirically the relationship between METS linkages and price increments using a panel approach. We define METS linkages as those linkages stemming from equipment and machinery sectors (ISIC Rev. 4, Sectors 26 to 33) as well as knowledge-intensive services, i.e., professional, scientific, and technical activities (ISIC Rev. 4. Sectors 69 to 75) to the mining and quarrying, non-energy sector (ISIC Rev. 4, Sector 07 and 08). The data used for backward linkages are taken from the OECD IOTS database 2021 edition which includes 66 economies and covers the 1995-2015 period. A country-specific price index based on Deaton and Miller, (1995) is constructed with data from World Bank's Pink Sheet and Thibault Fally. The index is weighted based on each country's mining output contribution to GDP. The log of tons of mining production and logs of GDP per capita are also introduced to control for changes in physical mining production (volume) and level of development of each country, using World Development Indicators and Thibault Fally's commodity data. All variables are calculated excluding energy products. Further details on the data sources and variables are available in Appendix 1.

Table 3 presents summary statistics for the regression. The table highlights that, on average, for every 1 USD of mining output there is 0.09 USD worth of equipment and machinery and 0.06 of knowledge-intensive services. Standard deviation values suggest a high level of heterogeneity for the mining price index and controls.

Table 3. Summary statistics

Variable	Obs	Mean	SD	Min	Max
Equipment suppliers	1026	0.089	0.053	0.004	0.324
Knowledge-intensive services suppliers	1026	0.055	0.038	0.001	0.187
Log of mining price index (Weighted by mining % in GDP)	1026	0.376	0.883	0.000	6.304
Log of GDP per capita (constant 2015 US$)	1026	12.880	2.784	-2.976	18.550
Log of yearly mining production in tons by country	1026	9.398	1.201	5.473	11.327

Table 4. Results – METS linkages and mining prices

	1	2	3	4	5	6	7	8
	Δ Log of equipment supplier linkages				Δ Log of knowledge-intensive services linkages			
Δ Log of mining price index	-0.132***	-0.143***	-0.140***	-0.141***	-0.107**	-0.108*	-0.137***	-0.132***
	(-0.042)	(-0.045)	(-0.04)	(-0.042)	(-0.053)	(-0.056)	(-0.051)	(-0.05)
Δ Log of mining production in tons		0.000		0.001		0.001		-0.009
		(-0.018)		(-0.017)		(-0.015)		(-0.018)
Log of GDP per capita		0.003		-0.004		0.066		0.003
		-0.061		-0.004		-0.071		-0.004
N	1238	1027	1238	1027	1240	1027	1240	1027
R-sq	0.038	0.043			0.041	0.047		
adj. R-sq	0.022	0.023			0.025	0.027		
Time and country effects	Yes	Yes	Yes	Yes	No	No	No	No
Random effects	No	No	No	No	Yes	Yes	Yes	Yes

Robust and clustered standard errors are reported in parentheses; * p<0.10, ** p<0.05, *** p<0.01.

Table 4 shows that METS supplier linkages are negatively related to the mining price index; these indicate that there is negative price elasticity equivalent to 0.13-0.14 with equipment and machinery suppliers (Models 1-4) and 0.11-0.13 in the case of knowledge-intensive services (Models 5-8). The results remain significant at the 95% and 99% levels regardless of the panel specification taken (i.e., fixed, or random effects). None of the controls are statistically significant, indicating that volume may not necessarily play a role in the higher adoption of third-party innovations nor does the level of development of each country. This econometric test confirms previous empirical analyses highlighting the negative effect of prices on supplier innovation (Calzada Olvera & Foster-McGregor, 2019; Castaño, Lufin, & Atienza, 2019). Results of additional regressions accounting for other factors, e.g., the size of the mining sector, or the response in non-innovative sectors, further corroborate results (see Appendix 2).

The above evidence supports the argument that we put forward in H(2). Mining firms increase their linkage with suppliers when mineral prices decline because it aims to expand profit via cost-reducing innovations, such as customization and the introduction of digital technologies, relying upon suppliers. However, this perspective may not be applicable across all countries. For instance, linkage formation in several Asian countries in recent years does not point to a clear counter-cyclical response, as is the case in Latin American countries (Calzada Olvera & Foster-McGregor, 2018). There are reasons to believe that more advanced economies such as Australia, Canada, or the US are more prone to developing mining innovations due to the provision of sector-specific interventions and educational &technical institutions. This does not mean that mining firms in developed nations are free from decreasing productivity because productivity and linkages have dwindled by various degrees during the super commodity cycle, indicating that corporate behavior in the mining sector (which is largely determined by the profit structure) is faced with inherent challenges. These aspects are discussed but had been overlooked by policymakers when seeking to foster linkages in the mining sector. Moreover, the importance of the supply chain had increased due to the energy crisis caused by recent political conflicts.

The empirical study on the cyclicality of prices on patents by Valacchi et al. (2019) finds no evidence of counter-cyclical innovation. Nevertheless, the study does not rule out the possibility of counter-cyclical innovations happening at the same time as pro-cyclical innovations. Hence, what Valacchi et al. (2019) suggest does not necessarily contradict our conclusion regarding innovation. This is because we focus on supplier-induced innovations, which refers to technological adoption and is not necessarily linked to patenting activities

5. Conclusion

Emerging literature in this field has claimed that natural resource-based activities, including those within the extractive industry, are no longer a curse. The literature states that the mining sector can be innovative and stimulate innovation in other sectors through the emergence and development of specialized suppliers via case studies. However, current innovation policies and initiatives may not be sufficient to spur innovation to the breadth and depth needed to tackle current challenges in the industry, such as degrading ore grades, and more importantly, to reap economy-wide benefits through the development of a strong base of innovative suppliers making full use of digital technologies. Furthermore, empirical evidence is needed to support the policy making process in this sector.

This study outlined general features of innovation for the mining sector – largely shaped by conflicting forces stemming from the role that prices play – and illustrated innovation potential and challenges for development to illustrate the importance of understanding sector-specific characteristics for effective policy formulation using and testing the existing empirical evidence. The study demonstrates that commodity prices strongly influence the innovation processes and supplier development (linkages) within the mining sector. Firstly, it illustrates that investment in this sector is pro-cyclical to commodity prices, which are set exogenously by market forces. Secondly, it identifies that a large proportion of investment is dedicated to exploration, which functions as R&D in the mining sector. Moreover, the R&D investment, though modest in quantity, also shifts in a pro-cyclical manner to commodity prices. Thirdly, patent data revealed that METS innovate more than the mining firms, (partially) confirming that the mining sector follows supplier-dominant innovation (Pavitt, 1984).

Fourthly, the distribution in patent areas along the mining value chain shows that mining firms concentrate in exploration as they consider it a strategic choice, the *core*, yet they rely on METS for other *critical* and *contextual* activities. Consequently, this implies an enhanced but selective collaboration between mining companies and METS. Concerning when such collaborations are likely to happen, this paper demonstrates this is linked to commodity price fluctuations. The reliance of the mining firms on METS was confirmed by input-output data which shows a counter-cyclical reaction to commodity prices, suggesting that backward linkages extend further when commodity prices decline. The above evidence rejects the long-standing notion of the mining sector operating as an enclave without much innovation, showing instead that the sector embodies complex linkages owing to sectoral characteristics. This means that the mining sector can play a critical role in development if local suppliers are effectively involved in the productive process.

Nevertheless, the opportunities for suppliers may not be evenly spread across the board. Most patenting in this sector is currently happening in just a few countries, and the upgrading of technological capability still poses a great challenge in some resource-rich countries in developmental stage. Even if suppliers manage to provide innovative solutions to the mining industry, the adoption of these solutions is tainted by the profit-seeking behavior of the *majors*, whereby high commodity prices delay the adoption of technological solutions and other good practices. This has been more pronounced in developing regions like Latin America than in advanced economies. However, even in advanced countries such as the US, a leader in mining-related innovation, productivity in mining sectors has consistently dropped as prices have grown. This suggests that innovation in the mining industry occurs not just on the supply side but also on the demand side. Smoothening demand effects for local innovative suppliers may be key for their long-term survival and development and the sector-specific policy interventions much called for.

From our findings on the innovation process in the mining sector, we raise the following policy implications. From an industrial development perspective, there is a need to rectify the ad hoc approach towards innovation by mining firms where short-term gains are prioritized. Moreover, applying digital technology would generate lateral linkages to bring about industrial transformation. Furthermore, addressing societal challenges such as environmental issues by involving local and regional suppliers in global value chains is critical to gaining a social license to operate and enable sustainable mining operations. From a development economics perspective, it became clear that the fluctuations in mineral commodity prices influence not only economic stability at the macro-level but also industrial activities at the micro-level, such as the innovation process and linkage formation involving suppliers. Another crucial area for policy-making discussions is how to diversify and smooth out the demand for mining suppliers' products and services as commodity prices change.

This paper brought together existing evidence to illustrate the generic characteristics of innovation processes in the mining sector, a sector often misunderstood in development economics and understudied from an innovation perspective. There are some limitations regarding how well this picture can be applied to the diverse realities of resource-rich countries. Firstly, this paper could not deal with granular differences in diverse mineral-rich countries. The existing disparity in technological and institutional capability creates differences in how the sector evolves, particularly in the adoption of new technologies. Secondly, the analysis in this paper relied on R&D and patenting data to evaluate the innovation process in the mining sector. Although these indicators are commonly used to understand innovation process, these may not be pertinent for the mining sector. Thirdly, due to limitations of comparable data, this paper used available data in an eclectic manner at distinctive levels of country, firm, and industry, to capture the innovation activities in the mining sector. Further and more fine-tuned analysis can be done with comparable firm-level data when it becomes available.

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[1] In discussing the context in which resources are used, there are valuable contributions from political and economic literature that explain the negative consequences of natural resources on the governance of a country, stemming from the control of its access to these natural resources. These studies explain the contextual differences from a historical, social, and political perspective to understand the differences and similarities of the developmental outcomes of resource abundance. Though this is certainly a valuable question, our study focuses on understanding the sectorial contributions to development stemming from innovation mechanisms. In the case of mining, these are highly connected to productive linkages, such as suppliers and other mechanisms of an economic nature. For a thorough discussion of economic and political mechanisms that explain the resource curse, see Badeeb, Lean, & Clark (2017) and Frankel (2010).

[2] One of the early studies that can be linked to extractive industries with innovation is Pavitt (1984). This study, based on UK data from 1945 to 1979, classified “agriculture, traditional manufacturing industries, and housing” activities as “supplier-dominant innovation” (these industries depend on suppliers to generate innovation for cost-cutting, as they have limited means to gather appropriate knowledge). This category does not specifically mention the mining sector. However, the basic characteristics of the mining sector are more closely associated with the “agriculture, traditional manufacturing industries, and housing” sector than the other sectors listed below.

- Supplier-dominated: mostly includes firms from traditional manufacturing sectors (textiles and agriculture, which rely on sources of innovation external to the firm, such as suppliers. Users of these products are price sensitive (as with commodities), and the goal of innovation is cost-cutting.
- Scale-intensive: mainly characterized by large firms producing basic materials and consumer durables (such as the automotive sector). Sources of innovation may be both internal and external to the firm with a medium level of appropriability. Users are price sensitive. The goal of innovation is cutting costs and product design.
- Specialized suppliers: smaller, more specialized firms producing technology to be sold to other firms (specialized machinery production and high-tech instruments). There is a high level of appropriability due to the tacit nature of the knowledge required, and

so the use of patents becomes prevalent. Users are performance sensitive. The sources of technologies are customers and are developed in-house. The goal of innovation here is product design.

- Science-based: high-tech firms that rely on research and development (R&D) from both in-house sources and university research, including industries such as pharmaceuticals and electronics. Firms in this sector develop new products or processes and have a high degree of appropriability from patents, secrecy, and tacit know-how. The sources of technologies and the goals of innovation are mixed, but the bulk of innovation is supplied in-house.

[3] Notwithstanding the above characteristics, in some cases, innovation has created breakthrough to improve productivity. Some notable examples are listed below:

- Drilling technology for deep-sea oil in Norway (Upstill & Hall, 2006);
- Liquefy oil to allow long-distance transportation in Australia (Ville & Wicken, 2013);
- Advanced coal-washing technology in South Africa (Morris et al., 2012; Pogue, 2008)
- Open-pit mining technology to overcome the poor quality of deposits/ores in the United States (US) (Urzúa, 2012; Wright & Czelusta, 2004)
- Solvent extraction electrowinning (SX-EW) technology in copper to overcome degrading ore quality (Bartos, 2002)

[4] The typical examples are autonomous vehicles collaboration with earth moving equipment manufacturers, the use of drones for geological surveys, among others. However, the adaption rate is still not very high (Sanchez & Hartlieb, 2020)

[5] An important distinction here is that suppliers do not encompass firms engaged in the core business of mining but rather provide specialized inputs: from chemicals to maintenance and environmental services. A complete description of the services provided by these firms can be found in Urzúa (2012).

[6] In 1949, for example, productivity and coal prices in the US coal industry showed an almost-perfect negative correlation (Kuykendall & Qureshi, 2014). In 1904, it was stated that the best practice for the mining industry was to withhold investments in new equipment as far as possible, as "the patchwork character of additions to […] equipment will make up for the inefficiencies of the operation" (Roberts, 1939, p. 22).

[7] Despite generating local employment, the extent of the effectiveness of local content policies in development is highly debatable (Korinek & Ramdoo, 2017). These tend to focus on low-hanging activities and not on knowledge-intensive activities that concern productivity upgrading.

[8] In a later section, this study utilizes R&D expenditure and patents to illustrate some trends. This is strictly due to the availability of certain indicators. Authors are fully aware that this is not all the knowledge employed in the mining industry.

[9] In the case of the manufacturing sector, firms invest in R&D to differentiate between products, because the price is decided by the market because of competition. The characteristics of innovation in the mining sector are distinct from those of the manufacturing sector. In the mining sector, innovation is not related to the conventional "value addition" in terms of increasing the perceived value of the product, having a distinguishing feature from similar products (differentiation), or augmenting the implicit quality appreciated by consumers (i.e., brand image). These aspects do exist in minerals (e.g., certifications and international standards concerning environmental and labor conditions), but they only add marginal value to mineral commodities because the end-use of minerals is currently inconspicuous. This means that incentives for innovation and the appropriation of knowledge are substantially lower in the mining sector. These conditions, however, differ in the case of mining suppliers, as the quality of inputs and services are important to continue as part of the GVC and gain business from big miners.

[10] Open innovation uses externally generated ideas, often by startups, to solve problems associated with the productivity of firms instead of traditional in-house R&D.

[11] The split 1970-1995 period refers to the pre-boom period while the latter captures the 2000s commodity boom, as well as the second half of the 1990s when prices began to rise (see Figure 4).

[12] Please note that the backward linkage measure we refer to is the column-sum of the mining sector in the Input-Output framework. However, since it considers third-party inputs, it excludes the on-diagonal elements which refer to the inputs that the mining sector obtains from itself.

Appendix 1. Notes on data and sources

1. Sectors considered in each sector category (from OECD IOTs 2021):
    a. *Equipment and machinery*: Machinery and equipment (D26T28); Transport equipment (D29T30); and furniture; other manufacturing; repair and installation of machinery and equipment (D31T33).
    b. *Knowledge-intensive services*: Legal and accounting activities; activities of head offices; management consultancy activities; architecture and engineering activities(D69T71); Scientific research and development (D72); Advertising and market research; other professional, scientific and technical activities; veterinary activities (D73T75).
2. Country-specific mining price index:
    a. The approach followed in our calculation considers exclusively the prices of aluminum, iron ore, copper, lead, tin, nickel, zinc, gold, platinum, and silver, using World Bank data. Weights to calculate the index employ commodity trade data from Thibault Fally.
    b. Index calculations are based on the measure developed by Deaton and Miller (1995) with commodity-specific weights following the calculations described in Calzada Olvera & Foster-McGregor (2019).

Appendix 2. Additional regressions

a. We ran an additional panel estimation to estimate differences in the price effects on supplier linkages in countries with relatively low vis-a-vis high mining production. To account for the former, countries whose average mining commodities production stood at or below the 50% percentile were given a value of 1, and 0 otherwise. We interacted the binary variable with the log of the mining price index (*log of mining price index*low*). The same is done for the control variable (GDP per capita). The interaction terms allow seeing if there are any differences between the two groups. The net effect for the countries with relatively higher mining output (the group with a value of 0 in the binary variable) is taken directly from the non-interacted term (Log of mining price index). The net effect for the group of relatively lower mining output (the group with a value of 1 in the binary variable) is given by adding up the non-interacted term and the interaction term. Results in Table 5 indicate that while effects do differ (i.e., the group with a relatively larger mining production output has a considerably bigger effect), the 'net effects' for both groups remain negative and significant.

Table 5. Estimation with interaction terms

	(1)	(2)	(3)	(4)
	Δ Log of equipment supplier linkages		Δ Log of knowledge-intensive services linkages	
Δ Log of mining price index	-0.182***	-0.184***	-0.186***	-0.186***
	(0.022)	(0.022)	(0.037)	(0.037)
Δ *Log of mining price index*low*	0.142***	0.143***	0.168***	0.168***
	(0.035)	(0.035)	(0.053)	(0.052)
Log of GDP per capita		-0.003		0.003
		(0.003)		(0.003)
Log of GDP per capita*low		-0.001		-0.000
		(0.001)		(0.001)
N	1238	1236	1240	1238

Robust standard errors are reported in parentheses; * p<0.10, ** p<0.05, *** p<0.01. All models reported are random effects.

b. We estimated the effect of mining prices on the link between general mining services and the mining sector (non-energy) to have a comparison with the results presented in Table 4. In Table 6 thus the dependent variable is the change in backward linkages for the “Mining support service activities” (ISIC Rev. 09) from the OECD IOTs 2021. This classification includes general operation services (including but not limited to sampling, drilling, draining, and pumping activities). The coefficients of prices are not statistically significant, as seen in Table 6. This suggests that whereas commodity prices affect negatively linkages associated with third-party innovations, this is not necessarily the case for those aimed at general operations support.

Table 6. Estimations for general support services

	(1)	(2)	(3)	(4)
	Δ Log of general support services linkages			
Δ Log of mining price index	-0.087	-0.109	-0.099	-0.102
	(0.094)	(0.094)	(0.086)	(0.087)
Δ Log of mining production in tons		-0.020		-0.028
		(0.016)		(0.017)
Log of GDP per capita		0.050		0.005
		(0.097)		(0.006)
N	1168	969	1168	969
R-sq	0.048	0.050		
adj. R-sq	0.032	0.028		
Time and country effects	Yes	Yes	No	No
Random effects	No	No	Yes	Yes

Robust and clustered standard errors are reported in parentheses; * p<0.10, ** p<0.05, *** p<0.01