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Industrial policy along the mining value chain: a new taxonomy and case studies

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Abstract
The strategic importance of the mining sector has grown significantly amid the twin transitions toward digitalization and sustainability, highlighting the need for active, well-coordinated industrial policies. Yet, government institutions have often developed such policies in siloes, leading to a lack of systemic focus. As industrial policy becomes increasingly intertwined with global value chains (GVCs), with many economies targeting specific stages of mining value chains, there is a pressing need for frameworks that support more coherent industrial policy design. This paper proposes a novel taxonomy to understand and justify the design of coherent industrial policies in the mining sector. Drawing on case studies from Australia, South Africa, and Chile, we demonstrate the taxonomy's analytical value and practical relevance. Our findings reveal substantial heterogeneity in the policy instruments deployed and in the composition of industrial policy packages across the three countries. We also observe varying degrees of internal coherence and differing focal points along the mining value chain, reflecting distinct national strategies and capacities.

Keywords Industrial policy · Mining · Global value chains

Introduction

Over the last few decades, the world economy has witnessed significant changes, with new actors reshaping the existing structure of economic and industrial dynamics. The rise of China—and of Asian countries such as Indonesia, Malaysia, Thailand, and India—has been extraordinary and with no terms of comparison in the XIX and XX centuries. In contrast, Latin America, after periods of commodity booms and relative bonanzas, still faces premature de-industrialization, at much lower income levels than the now-developed countries (Brady et al., 2008; Castillo & Neto, 2016; Rodrik, 2015).

Within this context, the role of natural resources has been prominent in many regions of the world, reinforced by the discovery and utilization of new materials (e.g., lithium for Chile and Bolivia, and cobalt for the Democratic Republic of Congo) and new technologies (e.g., 4th Industrial Revolution (4IR) technologies for safer and more efficient exploration). In addition, the worldwide focus on a new energy paradigm towards sustainable models of production and consumption has also contributed to raising minerals demand, and several minerals are intensively used to produce climate change mitigation technologies (IEA, 2021)

While mining has been regarded as a low-tech enclave sector for a long time, innovation and the reshaping of production processes, as well as the growing linkages among firms, have more recently shed a positive light on resource-based development (Auty, 1994; Sachs & Warner, 1999; Bloch and Owusu, 2012). Scholarship recognizes that mining can offer new opportunities for development and value capture, yet it also identifies numerous challenges in terms of developing downstream manufacturing capacity locally (Pietrobelli et al., 2024a, b). Tapping into such opportunities requires advanced capabilities to innovate and solve

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production problems that are very mine-specific, and that involve a large amount of coordination between different public and private actors (Pietrobelli et al., 2018). The solution to these frequent and typical coordination failures, the long-term nature of mining projects, the high sunk costs of the initial exploration and exploitation phases, and a series of challenges, both internal and external to the industry, have motivated a wide range of industrial policies. While mining companies are not very keen on taking risks in the production process, hindering suppliers' entry into the market, learning, and technological upgrading mechanisms (Pietrobelli et al., 2018), also environmental and social issues are increasingly gaining consideration among private and public stakeholders (Katz & Pietrobelli, 2018). Such challenges may produce a sub-optimal level of investments by actors in the mining sectors, especially suppliers, and thus require state intervention to fix uncertainty and coordination failures.

Moreover, some "critical" minerals have become especially important to determine the vulnerability of strategic value chains, such as, for example, semiconductors or electric vehicles, and this is imposing a new perspective on GVC mining policies. For example, the negotiations for long-term concessions on the use of critical minerals from countries that enjoy clear oligopolistic power in international markets (e.g., the DRC or Indonesia) are quickly becoming a new instrument of industrial policy.

A solid and comprehensive framework to analyze industrial policies' design in the mining sector is still missing. Policies have often fallen short of a systemic focus without full consideration of the interdependencies and the necessary integration of the various dimensions and actors involved.[1] A critical dimension for most industries, including mining, is that they are nowadays embedded in global value chains (GVCs); thus, the specificities of each GVC, both in terms of structural dynamics and governance modes, should be key elements of policy design. More specifically, recent literature has stressed how the structural elements of the governance of GVCs have a critical role in defining the scope for GVC policies across tasks, linkages, and firms, and have changed the socio-economic rationale in the design of industrial policies (Pietrobelli et al., 2021). GVC-oriented policies require considering the different roles of the state (e.g., regulator, buyer, producer) and the multiple levels at which policies operate, imposing a systemic view where each element influences and is itself influenced by the others in the policy outcome (De Marchi & Alford, 2022). In this paper, we propose a new taxonomy to analyze and inform thinking on policy options, and to discuss the design and the coordination of mining policy packages in supporting industrialization. We argue that consistency and coherence between demand and supply-side policies are critical to ensuring the development of productive capabilities. Specifically, we argue that the GVC approach is crucial for identifying where industrial policy needs to be developed, and our taxonomy helps in determining how this should be done. Our taxonomy is directed at researchers and policymakers interested in supplier upgrading, a long-standing issue in a sector where suppliers face high entry barriers and uncertainty, which tend to discourage investment and learning (Pietrobelli et al., 2024a, b). We use selected evidence to apply the taxonomy and show its usefulness for Australia, South Africa, and Chile, all of which have considerably relied, in very different ways, on the mining sector for their development. Table 1 presents some evidence on the production of selected minerals, including some of the newly defined "critical" minerals, and the percentage of production carried out by the main countries during 2018–2022. The table shows that production is often highly concentrated in few countries, and that the three countries we analyze in our case studies are always among the largest producers (Table 1). Moreover, these countries appear to be targeting different segments of the mining value chains (e.g., services, capital equipment, extraction).

Against this backdrop, after short reviews of the debate on resource-based development, the GVC approach, and active industrial policies in the mining sector (Sects. "The mining sector: Exploring resources-based development and global value chains opportunities" and "The case for industrial policy in mining GVCs"), we build our taxonomy in Sect. "Active industrial policies for mining value chains: A new taxonomy", and present and discuss the empirical evidence in Sect. "Taxonomy application: Three case studies". Section "Discussion" concludes with a discussion of the results and implications.

The mining sector: Exploring resources-based development and global value chains opportunities

The role of natural resources in economic development has long been a subject of debate in economics. Although natural resource endowments have frequently been considered a 'curse' for countries, a new, more positive perspective has emerged over the past three decades. Positive examples such as Botswana's diamond processing industry and Malaysia's tin, rubber, and gas-based manufacturing industries have demonstrated how resource-based policies can accelerate development (Chang, 2010). Additionally, the surge in demand for raw materials, especially in the early 2000s, created new opportunities for local development, exploring

[1] This is what we argued in a different piece, with specific reference to local content policies (Anzolin and Pietrobelli, 2021).

Table 1 Production of selected minerals (percent of world production in metric tons, average for 2018–2022, and ranking)

	Iron	%	Copper	%	Zinc	%	Bauxite	%	Platinum Kg.	%	Manganese	%	Titanium	%	Lithium Li20	%
1	**Australia**	36.81	**Chile**	26.73	China	31.74	**Australia**	27.57	**South Africa**	72.17	**South Africa**	31.94	China	31.71	**Australia**	50.57
2	Brazil	16.90	Peru	11.12	Peru	11.17	Guinea	21.85	Russia	11.47	Gabon	18.29	Mozambique	11.76	**Chile**	25.88
3	China	13.99	China	8.60	**Australia**	10.00	China	19.27	Zimbabwe	8.24	**Australia**	16.32	**South Africa**	11.76	China	12.57
4	India	9.32	DRC	8.30	Mexico	6.53	Brazil	8.90	Canada	3.57	China	5.41	**Australia**	8.82	Argentina	6.09
5	Russia	4.02	USA	5.86	India	6.05	India	6.07	USA	2.15	Ghana	5.26	Canada	6.34	Brazil	1.72
6	**South Africa**	2.85	Russia	4.24	USA	5.93	Indonesia	5.74	China	1.41	Brazil	4.76	Ukraine	5.52	Zimbabwe	1.03
7	Ukraine	2.72	**Australia**	4.10	Bolivia	3.81	Jamaica	2.02	Finland	0.71	India	4.33	Senegal	3.51	Canada	1.00
8	**Chile (16th)**	0.64	Zambia	3.93	**South Africa**	1.15	Russia	1.82	Colombia	0.22	Ukraine	3.06	Madagascar	3.38	USA	0.74

Source: Authors' elaboration from www.world-mining-data.info

Australia, Chile and South Africa are highlighted in the Table given that they are the case studies selected in this paper

more efficient techniques and enhancing productivity. For instance, it is estimated that the introduction and implementation of new technologies in the Australian mining industry yielded productivity growth of 130% between 1986 and 2003, four times faster than other sectors (Urzúa, 2012).

Arguably one of the most significant novelties in analyzing the mining sector is the recognition that it can be highly innovative (Aznar-Sánchez et al., 2019; Fernandez, 2020; Iizuka et al., 2022). Innovation in the sector appears to be driven by market demands, advances in science and technology, emerging market contexts such as globalization and fragmentation of production, and market volumes (Pérez et al., 2014). While such innovative potential is not always revealed by patent generation (Fernandez, 2020; Fusillo et al., 2024), recent studies have noted a remarkable increase in innovation activities in the mining sector since the 2000s, particularly in exploration activities and the utilization of new digital and environmental technologies (Daly et al., 2022; Pietrobelli et al., 2024a, b).

As with most manufacturing sectors, the fragmentation of production, characterized by extensive outsourcing beginning in the 1970s, reshaped the mining sectors and led to the emergence of GVCs, introducing a new distribution of power and opportunities (Gereffi, 1994; Pietrobelli et al., 2018). Mining value chains tend to follow a hierarchical mode of governance (Pietrobelli et al., 2018), where lead firms can leverage their power against suppliers. This is related to the high information asymmetry between lead firms and suppliers and the risk aversion and conservative attitudes of the former, which limit upgrading opportunities for suppliers. However, in some instances, the new trends in mining GVCs, where innovation also rewards proximity and in situ technology applications, open new opportunities for local competitive suppliers (Kaplinsky & Morris, 2016; Perez, 2016, Bravo-Ortega and Muñoz, 2015). In fact, although the phenomenon is still limited, sometimes local suppliers have successfully positioned themselves in specific production niches.

Figure 1 introduces a simple prototype of the main activities of a metal mining value chain; the stages of production (blue boxes) are briefly described with a series of activities (orange boxes). Linkage opportunities can stem from both capital equipment (manufactured goods required for mining operations) and mining services; these opportunities require cross-cutting sectoral policies to be fully exploited. Service inputs are required across different activities; green boxes offer some examples of service inputs along the value chain. The *servification* of the mining sector is indeed revealing a greater use of services, which are often outsourced (Korinek, 2020), and have been one of the most significant sources of value-adding in the sector. For example, Australia was particularly successful in developing backward linkages through service providers together with machinery and other

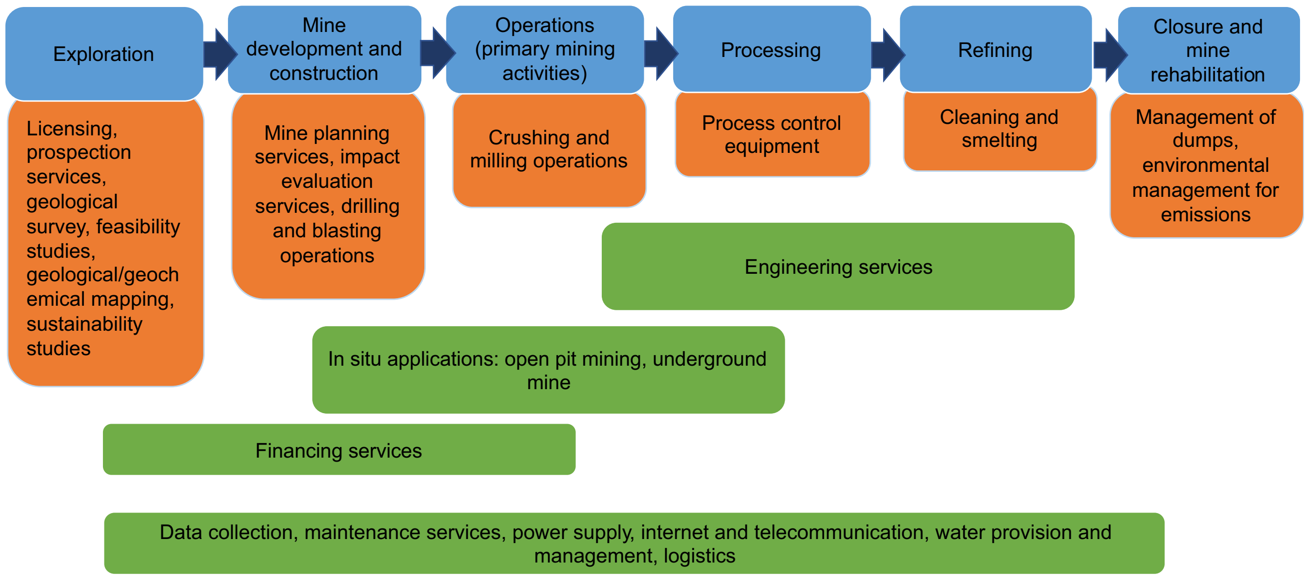

Fig. 1 Prototype of a metal mining value chain. *Source:* Authors. (Colour figure online)

equipment suppliers (Urzúa, 2012; Francis, 2015). Mining services on average constitute 23% of the value-added in exports, and most of them are produced domestically with differences across countries, e.g., in Australia 26.5%, in South Africa 20%, in Chile 21% (Korinek, 2020).[2] Mining services that offer the highest rewards are (i) exploration and mining services, and (ii) scientific electronic and other machinery equipment services (Stubrin, 2017; Korinek, 2020). Interestingly, the more sophisticated services providers are also home to top providers of mining equipment, while none of the largest mining value-added countries is among the top mining services exporters (Korinek, 2020). In mining capital equipment, South Africa managed to become highly competitive in deep-level mining and the related underground mine equipment, with a series of R&D and workforce policies (Kaplan, 2012).

The case for industrial policy in mining GVCs

The state has traditionally played an active role in the mining sector, because of the strong coordination needed to foster the required long-term business commitment, to face the remarkable risks and uncertainties, and to build the necessary productive capabilities. Considering the exploration phase, sunk costs soar considerably because of expensive capital goods investments and the long licensing process with governments. Such long-term commitment—a new mine can require more than 10 years of investments (Lundmark & Wårell, 2008)—is one of the reasons behind the consolidation trends in the mining sector, with large mergers and acquisitions.

The changing characteristics of the mining sector described above (i.e., high fragmentation, increase of servification, local solutions for local problems approach) opened a new policy space with both opportunities and challenges. Opportunities can emerge from the demand for specific in situ applications, both for capital goods and services tailored to local needs. Challenges are related to the insufficient coordination between multinational enterprises, suppliers, and governments. Two factors exacerbate such risks. On the one hand, the strong price fluctuations in the mining sector influence companies' decisions of long-run investments, as well as the availability of government resources. On the other hand, linking up to GVCs is not enough to develop high-quality and externality-intensive linkages (Morrison et al., 2008), and the hierarchical governance prevailing in mining GVCs discourages such linkages and the related processes of capability development (Pietrobelli et al., 2018, 2024a, b). This paper focuses on the second aspect and how it calls for industrial policies in different segments of the value chain.

Government intervention can take different approaches (Horner & Alford, 2019), with government acting as a facilitator, removing market distortions, or as a regulator by restricting negative externalities (e.g., air pollution). It can also have a more active role as a producer with the state's own production activities or as a buyer through public procurement of goods and services (De Marchi & Alford,

[2] This confirms the importance and interdependence and complementarity between manufacturing and services (Park & Chan, 1989; Andreoni & Gregory, 2013) also for the mining industry.

2022; Van Assche et al., 2024). Industrial policy in mining should look 'around' the sector, in addition to 'within' the sector, since long-term economic growth is based on diversification from one sector to related sectors (Dietsche, 2018). Resource-based diversification then aims at targeting high value-adding segments (e.g., knowledge-intensive services, machinery and tools), which are more likely to have linkages with other sectors (Mancini & Paz, 2016). Recent debate on industrial policy and GVCs has been enriched by an analysis of elements that are often overlooked in standard public policy, yet very important in GVC-oriented industrial policies; they focus on tasks rather than on entire sectors, on backward and forward linkages, and on firms, both lead firms and suppliers, depending on the sector and the relative distribution of power along the value chain (Pietrobelli et al., 2021). In what follows, we briefly discuss the relevance of these elements in the mining sector.

(1) Starting from the role of firms, and especially lead firms, this is key in a sector characterized by entry barriers and related sunk costs, which make it very hard to enter and challenge the status quo. Big mining companies essentially define most of the terms and conditions of GVCs' entry for local suppliers, and are thus a key actor to consider and to actively engage with in the design of industrial policies.
(2) The risk of the mining sector to be associated with the enclave thesis has been widely documented in the literature; while the thesis has also been challenged (Bloch and Owusu, 2012), the importance to create and strengthen linkages within the mining value chain and across different sectoral value chains is critical to ensure that benefits from the mining sector spread also to the rest of the economy.
(3) As in other sectors, an analysis of the upgrading potential of specific tasks should precede industrial policy design; emerging economies aim at capturing more value with their local productions by operating *better* than their competitors. As we will see also in our real-world case studies below, industrial policies for the mining sector increasingly target specific tasks (or segments) of the value chain where upgrading can happen; such assessment is often done against existing capabilities and comparative advantages.

In sum, there are at least three main sector-specific characteristics to consider, and they all require the adoption of GVC lenses to look at the industry, and an ensuing shift of attention to the dimensions that should be targeted by industrial policy. First, the industry is characterized by long-term projects with important lumpy investments and foreign technology acquisition. The training of highly skilled personnel needs to be carried out both through education and shop floor activities (Fessehaie & Rustomjee, 2018) and, most importantly, the training needs to focus on the skills required in a future that is unknown and will depend on the technological evolution of the industry. This characteristic indeed requires long-term planning and collaboration between the industry and the education and training institutions, to direct the efforts to develop such new skills.[3]

Second, the high industry concentration and ensuing entry barriers, compounded by the hierarchical nature of the governance of the mining value chains, discourage inter-firm collaborations and do not facilitate suppliers' entry into the chain and upgrading within it. Instead, other stages, more related to in situ applications and the newest technological trends, may create a space for the development of local suppliers.

Third, as mentioned above, the recent 'rejuvenation' of the industry (Perez, 2016), characterized by high innovation-based technologies, increased the need for local applications and solutions, which call for the building up of specific capabilities. Innovation in mining differs from other industries (Fusillo et al., 2024; Andersen, 2012); new products are very rare and process and organizational innovation aims at cost reduction (Iizuka et al., 2022), and the capabilities needed to respond to such windows of opportunities are unlikely to prosper autonomously and require selective policy support in a framework very distant from perfect competition and a levelled balance of power.

Active industrial policies for mining value chains: A new taxonomy

Industrial policy has been frequent in the mining sector, but it has hardly followed a comprehensive logic or relied on a common framework. We intend to fill this gap through the development of a taxonomy of industrial policies for mining value chains that stresses the importance of consistent and integrated policies, where demand incentives are matched by the nurturing of supply capabilities and vice versa. As shown by historical experiences, the lack of complementary assets hinders innovation where it would be most needed, highlighting a remarkable "paradox" between returns from investments in innovation and the persistent lack of it (Cirera & Maloney, 2017). Upgrading in the mining sector implies higher value added in specific segments (across manufacturing and service sectors), which requires both new technologies and the adoption of foreign technologies, through substantial technological efforts and capability building

[3] Chile Foundation offers relevant examples of this approach https://fch.cl/publicacion/fuerza-laboral-de-la-gran-mineria-chilena-2017-2026/, accessed 12.02.2025.

Table 2 A taxonomy of policy instruments for coherent industrial policies for mining GVCs

	Supply side	Demand side
Market-based interventions	Tax incentives (on capital) Tax concessions (R&D) Access to venture capital and grants to overcome the 'valley of death' for small local suppliers	Demand from large firms through: (i) Local content policies (ii) Rebate policies on local production Incentives to mining exports Public procurement
Public goods		
Skills development	Training centers Specific degree programs (on mining, geology & engineering...) Skill councils	Local employment targets Local training required to mining companies
Innovation infrastructure and R&D platforms	Suppliers/business incubators Support to collaborative R&D projects	Match-making platforms to meet demand and supply (to include potential suppliers)

Source: Authors' elaboration

(Fessehaie & Rustomjee, 2018; Fu et al., 2011; Morrison et al., 2008; Pietrobelli et al., 2024a, b). Efforts on the supply side require to be matched by demand from mining companies. Our taxonomy proposes a tool to analyze the balance and coherence across different types of policies.[4]

Taxonomies are a popular tool in industrial policy, and often distinguish between horizontal and vertical tools, according to their degree of selectivity (Crespi et al., 2014). Our taxonomy follows Andreoni (2016) in the categorization of demand and supply policies and Crespi et al. (2014) and Weiss (2015) in proposing market-based interventions vs. public goods inputs. Yet none of these contributions on taxonomies offers insights into how this is combined with GVCs, and specifically which GVC considerations are critical to inform the dimensions of the taxonomy. As discussed below, we argue that a GVC understanding of the sector and the policies to develop value chain opportunities should be a precondition for a taxonomy that informs on the different types of instruments available and how to balance and coordinate them. Against this backdrop, the motivation for our taxonomy lies in the need to understand and emphasize the coherence among different measures, as well as the underlying institutional implications and the consistency in the design of policy packages (Weiss & Seric, 2021).

In the mining sector, the exclusive focus on demand or supply often causes policy failures; for example, export bans that are not matched by policies to develop the industry downstream often result in missing opportunities. In addition, mining GVCs present very high entry barriers and sunk costs (Sects. "The mining sector: exploring resources-based development and global value chains opportunities" and "The case for industrial policy in mining GVCs"). Thus, the provision of a mix of public goods and targeted market-based interventions is critical.

Table 2 illustrates this new taxonomy for the mining sector: on the vertical axis, we consider the scope of policy instruments, whilst on the horizontal axis we differentiate between demand-side and supply-side policies. This makes it possible to identify four policy areas, each with its specific features. The scope of instruments includes market-based interventions and public goods provision, with a further classification of the latter between skills development and innovation infrastructure and R&D platforms. We define as market-based interventions those measures that alter relative prices in favor or against given activities or specific actors. These may, of course, include various types of tax concessions and subsidies or incentives and regulations on procurement or exporting. Instead, public (and club) goods interventions include policies to provide various infrastructures, regulations, institutions, and skills.

On the horizontal axis, we differentiate between supply-side vs. demand-side policies and argue that they need to be balanced and consistent with each other. Broadly defined, supply-side policies are those that affect (i.e., improve) firms' performance by intervening to improve their supply for example through innovation and technology acquisition, by facilitating the purchase of goods and services or the provision of trained labor force, and those that affect industry/sector dynamics (tax system, capital labor markets) (Criscuolo et al., 2022). Technology infrastructure and capital access policies also represent a type of supply-side instrument because they create the conditions for firms to get access to technology and capital that otherwise a pure market mechanism would not allow. Demand-side instruments, instead, affect the demand for products and services, the rationale being the creation of demand to support scaling up and upgrading firms' efficiency and overall competitiveness. Such policies aim at generating a growing and stable

[4] A detailed discussion of the different mining concessions and fiscal regimes (e.g., royalties) is beyond the scope of this work, which remains focused on the organization of the productive structure and the micro and sectoral policies affecting it.

demand for products and services, which is essential to undertake costly capital investments and to reach economies of scale and growing productivity. These instruments also include standard forms of public procurement and product regulations.

Companies can also be favored through specific measures that give preferential access to domestic or foreign markets (Andreoni, 2015). Although in the past there has been a reluctance to favor such types of industrial policy tools, more recently, authors argued that demand-side instruments could potentially be less distortive considering the recent mission-oriented industrial policies towards sustainability and digitalization. Given the common presence of State-Owned Enterprise in the mining sector (e.g., Codelco in Chile, Coal India in India), it is worth mentioning their role as instruments that can also foster both demand- and/or supply-side policies. For example, public procurement, workforce and skill development programs, and supply chain development programs may be deployed (and enforced) through SOEs.

New and old types of policies may be combined in our taxonomy, which is informed by a GVC understanding of the sector and policies. If our taxonomy essentially provides an analysis of the *how* industrial policy is pursued (i.e., which policy instruments are used and how they are coherently packaged together and implemented), the GVC analysis and the three elements introduced above from Pietrobelli et al. (2021)—tasks, linkages and lead firms—constitute the *what* of industrial policies, i.e., the specific tasks, or GVC layer. Industrial policies target specific tasks of the mining value chain (for example, the development of the mining services for mine exploration); they would also target linkages creation both within the sector and across other sectors of the economy. This last point is particularly relevant for the mining sector given the tendency to become an enclave sector where the attraction of MNCs based on natural resources might remain completely detached from the rest of the economy. Ensuring downstream and upstream linkages as well as continuous innovation and technological inputs to and from complementary sectors of the economy is key. A slightly different aspect is related to firms, and in particular to lead firms; as already widely discussed in this and previous sections, how industrial policy manages to include the role of lead firms in the upgrading strategies is extremely important, given the power large firms exert along the value chain and their involvement in supplier development programs (see the case of Chile below).

In our taxonomy, we highlight the importance of using instruments to balance the demand and supply dimensions, otherwise bottlenecks may emerge along the process and prevent GVCs upgrading processes. For example, demand policies such as domestic market preferences for local firms may not be met due to the lack of productive capabilities. This appears to be the case in Ghana's adoption of a local content strategy imposing employment quotas that gradually increase over 10 years up until 90% of total employment (Ackah & Mohammed, 2018; Ramdoo, 2016). Very often in emerging economies, these policies act as a severe constraint for business actors, because local employment targets are difficult to achieve due to skill gaps (Anzolin & Pietrobelli, 2021; Tordo & Anouti, 2013). This mismatch needs to be balanced through education and training policies on the supply side, for example through mandatory training requirements for workforce upgrading (Korinek, 2013; Macatangay, 2016).

Taxonomy application: Three case studies

In the following section, we will apply the new taxonomy to three countries: Australia, South Africa, and Chile. Their mining sectors are widely discussed in the literature, have long histories of development, are at different stages of development and currently face different challenges. We aim to systematically analyze their policy design with our 2 × 2 matrix to analyze their main policy packages. We consider policies from the early 2000s to 2019, before the pandemic and energy crises that followed. One of the main richness of our case studies is that, besides systematically reviewing existing academic literature on the three countries, we based our analysis also on an extensive review of the grey literature from policy documents of international and sector-specific organizations, and mining and production/innovation ministerial documents of the three countries.

Australia

Background

Australia is a mature economy with remarkable success in natural resource-based development. Mining is a strategic sector for the country: it contributed to 12.2% of GDP in 2024,[5] and Australia's total earnings from resource and energy export reached US $417 billion in 2023–2024, a huge percentage of total exports.[6] In addition, Australia's Mining Equipment Technology and Services (METS) sector contributes approximately US $60 billion annually to the economy,

[5] https://www.rba.gov.au/education/resources/snapshots/economy-composition-snapshot/ accessed 15.02.205.

[6] Australian Government: Resources and energy quarterly: June 2024, https://www.industry.gov.au/publications/resources-and-energy-quarterly-june-2024 accessed 15.02.2025.

with yearly exports of around US $18 billion.[7] The intention to catch up in terms of productive and technological capabilities has led the Australian government to undertake extensive investments in R&D and engineering education for many years (Fessehaie et al., 2016). The impact of the government's action is considered a success, which placed the country among the leaders in terms of mining companies, mining capital goods, and especially METS. Between 500 and 600 such services organizations operate in Australia, and around 15 of them are public research organizations.

Industrial policy for the mining GVCs: The taxonomy

Australian policies have mainly focused on the supply side, due to the large demand from important global mining companies headquartered in Australia; in a way, demand has always been present in the country given Australia's richness in minerals and large local companies. This aspect, in addition to the presence of an already educated workforce and a solid industrialized base, was enough to induce Australia to refrain from strong demand-side policies (Heum, 2008).

Regulation of mining operations occurs at three levels: government, state, and territory. The most common forms of regulation at the sub-government level are the Mining Acts, State Agreements, and Indigenous Land Use Agreements (OECD, 2017). The country implemented a series of consistent policies to foster R&D through incentives for private-public collaboration, to tap into new segments of the mining value chain. The country's mining industry injects huge amounts of money into R&D with an average of US $2.5 billion annually (Australia Trade Commission and OECD, 2017). Continuous skill development is also ensured through the Australian system of universities and vocational training and colleges, coordinated by the Resources and Infrastructure Industry Skills Council. In addition to the federal provisions described below, each state can also prescribe further legislation. For instance, in Western Australia, the state government requires a complete description of the project, including where it will be inserted, its direct employment and skill transfer impact on regional development, and type, number and size of procurement packages, and use of competitive businesses in goods and services (GOW, 2015; IGF, 2018a).

Supply-side policies The most comprehensive policy package was adopted in 2001, and it is the Industry Action Agenda for MTS that was endorsed by the government in 2004 with the Australian MTSAA, after consultations with major stakeholders (Austmine, 2014; Thorburn, 2005). The *Mining Technology Services Action Agenda* (*MTSAA*) is a government-led initiative to provide a collaborative framework so that government and industry come together to address the major market impediments to fostering MTS. MTSs have been the preferred segments of Australian policies in recent decades, to foster the functional specialization in high value-adding services. In fact, the MTSAA focused especially on R&D, commercialization, access to venture capital, and supply of specialized staff. As part of the Action Agenda, in 2004 the Australian government launched a US $3.5 billion package called *"Backing Australia's Ability-Building Our Future through Science and Innovation*"; although not confined to mining, also mining companies could access these programs to help SMEs scale up early-stage inventions and enhance international competitiveness. In parallel *Ausindustry,* a division of the Department of Industry, Tourism and Resources, delivered different forms of innovation grants, concessions, and investments to more than 10,000 businesses annually (OECD, 2005; Thorburn, 2005). Another measure adopted is the *InnovationXchange*, a joint program turned into a company that was formed as part of the METS Ignited's transition plan, which is a web-based data exchange designed to provide a reliable intermediary to assist businesses in gaining access to new technologies, technology transfer, financial, and other services.

The government-led R&D push has been strong in Australia for many years (Francis, 2015; Thorburn, 2005). Firms in the industry benefit from tax deductions up to 125% of R&D expenditures, a tax offset, and 175% premium tax concession. SMEs have even further tax concessions. On the supply side, CSIRO (Commonwealth Scientific and Industry Research Organisation) also plays a crucial role, being one of the largest research organizations in the country, and the most important provider of collaborative R&D projects. One of the most recent success stories of CSIRO is the creation in 2018 of the world's most advanced sensor system for large scale ore sorting to determine ore quality, a technology that NextOre—a new company that CSIRO co-founded—managed to offer to the global market (Table 3)[8].

Despite the high level of literacy in the country, the implementation of policies to ensure that the country's education system was aligned with the needs of the MTS sector was strongly supported, with various college and university programs that are sponsored to offer relevant industry skills across a wide range of disciplines. The effort to learn and adopt foreign technologies was accompanied by programs to enhance access to foreign technologies, like, for example, the EPBS (Enhanced Project by Law Scheme)—adopted in

[7] Australian Trade and Investment Commission. https://www.austrade.gov.au/australian/export/export-markets/industries/mining-equipment-technology-services.

[8] https://www.csiro.au/en/work-with-us/industries/mining-resources/Sensing/Ore-sorter accessed on 01.15.2024.

Table 3 A taxonomy of industrial policies for the mining sector in Australia

Australia	Supply side	Demand side
Market-based interventions	Tax incentives, EPBS (Enhanced Project by Law Scheme): duty-free tariff concessions to goods not available in Australia Tax concession for R&D expenditure, deduction up to 125% from taxable income + a tax offset and 175% premium tax concession Grants to overcome the valley of death, Backing Australia's Ability-Building Our Future through Science and Innovation → to help SMEs scale up Access to venture capital (AusIndustry)	Internal demand from large firms in Australia + InvestAustralia plan to attract FDI in leading segments Local content policies, Australian Jobs Act 2013 → proponent of projects > AUD 500 million for local procurement Australian Industry Participation Plan (driving local procurement) AIPNF (2001) break-up of large contracts to enable smaller suppliers to participate
Public goods		
Skills development Innovation infrastructure and R&D platforms	Universities have METS-focused and state-sponsored programs Skill Council, Industry TechLink Incubators, Innovation Xchange (joint program with government to assist business) R&D collaboration projects, CSIRO (large R&D organization with focus on MTS) AusIndustry program encompasses: (i) Commercial readiness, (ii) Commercialization of emerging technologies, (iii) Pooled development fund program, (iv) Innovation Investment Fund Program	Local employment target at state level, especially for indigenous people[a] Match-making platform to meet demand and supply, SAMP (Supplier Access to Major Projects)

Source: Authors

[a]For example, in Western Australia, all mining projects have to state their employment contribution (IGF, 2018a, b, c).

1995 and still in force—that offers duty-free concessions to goods for the mining and resource processing industries that are not available in Australia.[9]

Demand-side policies Australia passed important legislation relevant also for the demand side of our taxonomy. In 2011, the AIPNF (Australian Industry Participation National Framework) imposed on mining companies the breakdown of large contracts (so-called unbundling of contracts) into small agreements so that smaller suppliers could participate and deliver. In addition, the Australian Jobs Act implemented in 2013 imposes every proponent of major projects a minimum capital expenditure of $AUD 500 million (around US $320 million) to provide opportunities for Australian suppliers to bid for the provision of key goods and services (Australian Government, 2013; IGF, 2018a). This federal legislation is considered a key mechanism to drive local procurement, and it also introduced *The Australian Industry Participation Authority*, which oversees monitoring and enforcement of the Jobs Act. Another important measure to favor suppliers is the *Buy Australia at Home and Abroad Programme*, to foster the application to the *SAMP* (Supplier Access to Major Projects) subprogram. This programme was approved in 1997 and offered more than $AUD 18.5 million (around $US 12.7 million) to create linkages between Australian suppliers and project developers. SAMP offered funding for the industry to create a capability network and assist in the identification of competitive Australian suppliers.

South Africa

Background

South Africa has a long tradition of extractive activities, and it envisioned mining-based growth as one of the key sectors to promote socio-economic development. The local deployment of several sophisticated technologies within a proactive state framework permitted the early development of several mining technologies (Kaplan, 2012). South African companies showed a special ability to link up with GVCs in areas where the country's expertise was particularly advanced, such as deep-level mining, mainly in gold. Such abilities have also developed because of South African deposits being not especially rich and constantly requiring advanced technological knowledge to extend their life; this

[9] https://www.abf.gov.au/importing-exporting-and-manufacturing/trade-and-goods-compliance, accessed on 01.15.2024. This programme was also extended to New Zealand to facilitate regional linkages (OECD, 2017).

forced the transition of South African suppliers to specialized equipment and services.

After 1994, the government implemented a series of policies that aimed at rebalancing the socio-economic conditions of the country after the apartheid regime. On the one hand, policies were designed to support broader industrial upgrading and to empower historically disadvantaged people, e.g., Black, colored, Indians, and others. These included local content policies and upgrading policies through the formation of clusters of firms in mining equipment and services at the technological frontier (Kaplan, 2012). Despite important upgrading processes and the critical attraction of FDI in the sector, the mining industry has stagnated in the country over the past two decades: as reported by Goodman et al. (2019), between 2007 and 2017 the sector's output value declined by 4% with substantial job losses. Several reasons explain this trend, from sluggish productivity to the high volatility of prices and the South African currency (Goodman et al., 2019). However, this decline went in parallel with an upsurge in specialist services such as consulting and exploration (Kaplan, 2012).

Industrial policy for the mining sectors: The taxonomy

After the end of the apartheid regime and especially since the early 2000s, the South African government adopted a series of measures to face the decline of the sector, with a twofold aim of promoting (i) the development of mining equipment manufacturing and (ii) a collaborative and innovative R&D environment. The main segment of the value chain targeted for industrial upgrading has been mining capital equipment, a sub-sector characterized by high spillovers to the rest of the economy and to other complementary sectors, for example, specialized services (Kaplan, 2012). These measures are classified according to our taxonomy in Table 4. The mining legislation in South Africa is dense and characterized by different sources of regulation. There are three critical pieces of legislation adopted to revamp the sector's competitiveness, productivity and innovation: the *Mineral and Petroleum Resources Development Act* (2004), the *Mining Phakisa Project*, and the *Mining Charter*. The *Mineral and Petroleum Resources Development Act* (MPRDA) came into force in 2004 to establish an environment able to foster the development of the mining industry while transferring sovereignty to the state. The provision was amended in 2018 with *The Amendment Bill* to lead the country towards local beneficiation of goods.

Supply-side policies Since 2018, a set of legislations was fostered by the government through the *Mining Phakisa Project*, a South African initiative based on 'quick and fast result' principles, which reunited all stakeholders in the industry into a discussion table ("lab") to identify constraints and build a shared vision for long term development (Singh, 2017). This resulted in the *South African Mining Extraction Research, Development and Innovation* (SAMERDI)

Table 4 A taxonomy of industrial policies for the mining sector in South Africa

South Africa	Supply side	Demand side
Market-based interventions	Tax concession (R&D) Income Tax Act, deduction up to 150% conditional on R&D expenditure on specific areas, e.g., beneficiation	Local content policies (from the Mining Charter- BBBEE related): (i) capital goods (40%), (ii) consumables (50%), (iii) services (70%) IPAP envisages minimum beneficiation levels for ten "selected commodities" Export scheme for minerals processing
Public goods Skills development Innovation Infrastructure and R&D platforms	Mineral Councils' involvement at all levels of skills development, with technical vocational training Skill Development Act 2008 Mine Health and Safety of 1996 Specific University programs and degrees in mining, geology/engineering Collaborative R&D projects Most important mining-related R&D centers: SAMERDI, CSIR, MINTEK Mandela Mining Precinct, to bring stakeholders together in R&D act.s	Mining Charter, BBBEE* targets ownership, employment, and procurement. Mining Charter requires mining companies to invest 5% of total wages into skills development Mining Qualification Authority: supports/monitors companies Match-making platforms to meet demand and supply (e.g., potential suppliers) SACEEC, export-oriented platform

Source: Authors

**BBBEE* broad-based black economic empowerment strategy

Strategy (Singh, 2017), which was drafted before the Mining Phakisa and served as a catalyst to develop collaborative initiatives.

After the Mining Phakisa, two programmes were developed. The first one aimed at forming a collaborative R&D model with a focus on core technologies (the *Mandela Mining Precinct*), while the second was a manufacturing equipment cluster to ensure that development requirements were translated into coherent R&D programmes (MEMSA) (Singh, 2017). The *Mandela Mining Precinct* was established to facilitate stakeholders' networking and collaborations towards R&D activities (Singh, 2017). It was planned as a learning centre and house testing facilities for rock engineering, support systems, and ventilation services. The Government remarkably increased funding for this initiative over the years. While in 2015, R&D funding for mining was R750,000 (around US $50,000), in 2018 the Department of Science and Technology (DST) allocated R210 million (around US $14 million) for 3 years until 2021 for R&D in hard-rock, narrow-reef, metalliferous underground mining. The Mineral Council of South Africa pledged R33 million (around US $2 million) for 2018, which matched government funding in the 1:2 ratio (Creamer, 2018). In addition, some R&D tax incentives apply to all firms in South Africa. For example, every company which undertakes R&D qualifies for an automatic 100% income tax deduction, plus an additional 50% for R&D expenditures approved by the DST (SAG, 2012, 2018). Such activities include the development of old and new mines, logistic modelling, handling, and shipment efficiencies, as well as wireless technology at the mining sites and computer programming for real-time monitoring (Taylor, 2013).

The second focus area is MEMSA (*Mining Equipment Manufacturers of South Africa*), established in 2016, and that has a particular role in assessing technology readiness and aligning possible initiatives to the key targets identified by the Pakhisa and SAMERDI initiatives; to this aim, a Technology Availability and Readiness Atlas (TARA) was developed to map technologies and create a database. MEMSA was expected to help position the South African mining equipment as world-class through the development of an innovative cluster exporting narrow-reef hard rock mining equipment (Singh, 2017). The idea of "local solutions for local problems" is central in this initiative, since South African deposits are characterized by steep angles of orebodies and narrow width of the reef package that need important investments to understand and undertake the different challenges (James, 2018; Kaplan, 2012).[10]

A slightly separate set of policies regards skills provision, and skill development within the mining sector is ruled by the Skill Development Act of 1998. Skills have historically been a challenge for post-apartheid South Africa with substantial policy misalignments (Kaplan, 2012). Whilst education policies rightly pointed to forming skilled workers, they did not consider the demand for such skills, or the incentives firms would have to hire skilled workers. For example, South Africa has had for a long time an excess of mining engineering skills that are only partially absorbed by mining-related companies due to mismatches between the type of skills that are taught in universities and those required at the firm level (Fessehaie et al., 2016). The University of the Witwatersrand—once recognized as a leader training institution on mining and related high-level skills—and the University of Pretoria have declined (Kaplan, 2012), together with the decrease in investment and maintenance of specialist research centers.

Demand-side policies The *Mining Charter* was released in 2004 and revised in 2018. The Mining Charter reflects the effort to be comprehensive and consistent on several measures supporting South African local content policies. The core objective is to push the commitment of mining companies to offer each employee the opportunity to become functionally literate and numerate (Government Gazette, 2004; IGF, 2018b). The non-compliance with one of the above requirements can lead to the withdrawal or suspension of the permit. The scorecard contains five main criteria: Ownership participation; Employment Equity; Human Resource Development and Capacity Building; Preferential procurement and enterprise development against compliant BBBEE (Broad-Based Black Economic Empowerment) suppliers (40% for capital goods, 50% for consumables, and 70% for services); Integrated socio-economic development for host communities. Two additional requirements were introduced in 2018: beneficiation, and housing and living conditions. Such latter requirements stress a critical highly South African-specific focus for inclusive economic growth and the creation of job opportunities for a large part of the population, which was left behind during the apartheid period.

These measures were supported by export promotion programs, the most important of which is the South African Capital Equipment Export Council (SACEEC)[11], which provides a platform for capital equipment exporters, supplying information and services to promote exports (SACEEC,

[10] Overall, the technical objectives can be grouped into six main areas: 1. Longevity of current mines (high cost of electricity and cost of extraction because of the specificities of the deposits); 2. Mechanized drilling and blasting programs (to explore opportunities for mechanization); 3. Nonexplosive rock breaking; 4. Advanced orebody knowledge; 5. Real-time information management system allowing

Footnote 10 (continued)

proactive real-time decision-making; 6. Applications of technology centered on people (Mamaila, 2019).

[11] SACEEC began its mandate as a Capital Equipment Cluster in 1998 and became the first DTI Export Council in 2000 https://www.miningreview.com/interviews/presence-sa-national-pavilion-drc-min-

Table 5 A taxonomy of industrial policies for the mining sector in Chile

Chile	Supply side	Demand side
Market interventions	Access to venture capital, stronger role of CORFO in managing public funding for suppliers and start-ups	
Public goods Skills development Innovation infrastructure and R&D platforms	Skill councils, Mining Skill Council (CCM) with the aim to connect the education sector with the industry Programa de Innovacion Abierta en Mineria (Alta Ley)	World Class Supplier Programme (WCSP), then Programa de Innovacion Abierta en Mineria and later part of Alta Ley Match making platforms to meet demand and supply, Fundación Chile as part of WCSP

Source: Authors

2016), and reflecting the need to become global leaders and enter high-value segments of GVCs.

A final point to mention is South Africa's series of export permit schemes for a range of metals, all oriented to increase local content and local processing. The *Price Preference System* states that an export permit is not released unless the metal (or scrap) was previously offered for sale for domestic beneficiation. A lot of export permits are not only related to raw materials (Government Gazette, 2019): for instance, in the case of lead, the export permit scheme also refers to secondary lead raw material (ore and scrap) and selected lead-based manufacturers (Fliess et al., 2017).

Chile

Background

Since the early 1990s, Chile has been one of the fastest-growing countries in Latin America. The country has some of the largest natural resource reserves in the world, especially of copper: it produces 28% of global production, and the mining sector's contribution to the country's 2022 GDP was 13.6%, with mining exports reaching 58% of all exports. The five largest mining firms (the state-owned enterprise CODELCO, BHP-Billiton, Anglo-American, Antofagasta Minerals, and the JV Collahuasi) together produce 82% of the total copper output (Korinek, 2013). Chile highly benefited from the commodity boom at the beginning of the century, and it managed the latest commodity downturn reasonably well from a macroeconomic point of view[12]. The creation of two funds, the Economic and Social Stabilization Fund (ESSF) and the Pension Reserve Fund (PRF), established in 2006 as part of a broader fiscal responsibility law, is considered to have improved Chile's macro-economic management (Solimano & Guajardo, 2017).

Industrial policy for mining GVCs: The taxonomy

The debate on targeted industrial policies in Chile dates to several decades (Pietrobelli, 1998), and governments have often preferred a liberal, market-friendly and little interventionist approach. Interestingly, some authors note how this would be related mainly to copper, and not to other sectors (Lebdioui et al., 2020; Lebdioui, 2019a), where instead a series of vertical policies were successfully adopted to diversify its exports, economy, and capabilities.[13] However, Chile adopted far fewer industrial policies than Australia and South Africa (Table 5), with a preference of instruments based on public-private collaboration. The most important demand-side program adopted in Chile was the *World Class Supplier Programme*, started in 2008 and discussed in depth below, but with limited funding.

Demand-side policy: The World Class Supplier Programme A demonstration of the first timid move towards a more dynamic approach is the *World Class Supplier Programme* (WCSP- *Proveedores de Clase Mundial*), which started in 2008. Initiated as a private-led initiative by BHP (and rapidly followed by CODELCO), the WCSP was started by large mining companies to have reliable suppliers, and strengthen their collaboration. The program was fostered by the need of large mining companies to find market solutions to their problems (Stubrin, 2017). The WCSP also aimed at providing Chilean suppliers with opportunities to enter the Knowledge Intensive Mining Services (KIMS) segment of the industry with an open innovation approach. It has been shown that Chilean firms enter more dynamic segments of the copper value chain in two ways: (i) customized products/services that respond to specific conditions'

Footnote 11 (continued)

ing-week-positions-south-african-companies-leading-players-mining-power-sectors/ accessed on June 25, 2024.

[12] According to a survey conducted within the Chilean METS sector, only 35% of companies responded that the last downturn had impacted them negatively, see: https://aimp2.apec.org/sites/PDB/Supporting%20Docs/2886/Completion%20Report/MTF%2004%2016A%20METS%20Sector%20Final%20Report_Chile.pdf, Accessed June 25, 2024.

[13] This is especially true for the salmon industry, forestry products, and fresh fruits.

challenges (directly addressed by the WCSP); (ii) utilising new technologies as a platform to develop unique solutions to unresolved mining problems, typically by small young firms created as scientific spinoffs. In both cases, companies use their own knowledge basis as a platform to develop new market niches, and they bear all the risks (Bravo-Ortega & Muñoz, 2018; Pietrobelli et al., 2018; Stubrin, 2017).

The implementation of the WCSP program included three steps (Navarro, 2018):

1. The operational issue/problem is detected, and suppliers are informed about this. This information is transferred through formal (*Fundación Chile*), and informal channels (Molina et al., 2018). Afterwards, a pre-selection and a final matching occur.
2. The selected supplier starts a bilateral investment and innovation relationship with the mining firm.
3. The programme offers advice to suppliers to scale up their innovative solutions and try to tap into international markets.

Several public actors were involved in the program, although without extensive controlling and monitoring mechanisms. First, *Fundación Chile,* a public-private entity that acted as a sort of intermediary agency in the process between mining firms and suppliers. It disseminated mining companies' challenges and registered and preselected suppliers (the latter with the lead mining firm). Fundación Chile was requested to follow up on the programmes, but it had more of an information-provider role rather than an explicit mandate to monitor the programme and the achievement of its goals (Navarro, 2018). Second, since 2013, many universities also started to participate, acting as business accelerators and advisors. It is important also to mention the combined effort from CODELCO Tech[14], which provided further support for suppliers in understanding IPR, patent filing procedures and commercialization/scaling up strategies. Such a patent-centric approach has been highly instrumental within the WCSP to provide Chilean suppliers with the tool to upgrade from local solutions to global developers (Bravo-Ortega & Price, 2022).

One of the major obstacles to its full success was the excessive, almost exclusive, reliance on suppliers' financial resources in the second step. In most cases, there is no sharing of R&D expenditures, which limits the supplier's learning opportunities and places the entire operational risk on them. Indeed, Chile lacks R&D subsidies, different from what occurs in Australia, South Africa and other countries.[15] Moreover, the failure to create a pool of exporting suppliers led to a reconsideration of the whole programme.

A new version of the WCSP was put forward in 2017 and required a deeper commitment of mining firms to collaborate in "piloting, testing and scaling up" with a first important call for a greater involvement of the public sector. The WCSP was also reformed because large firms soon realized that the number of efforts, coordination mechanisms, and activities required went beyond the capabilities of a single actor. BHP realized they needed public goods and the participation of other mining companies to scale up within the programme, for example through access to capital, incentives, training, and testing facilities (Lebdioui, 2019b). The WCSP evolved to become the new *Programa de Innovacion Abierta en Mineria* which also became part of the 2015 bigger legislation named *Alta Ley*. Alta Ley leaves a much stronger role for public participation in these mining projects, for example, through the external funding of CORFO. These projects are in fact led by CORFO and the Ministry of Mining, and they have the objective of creating 150 local mining suppliers and exporting up to US $10 billion by 2035 (*Comisión Mineria y Desarrollo de Chile*, 2014). CORFO plays a leading role, especially when it comes to public funding for suppliers and Start Ups. Alta Ley, together with the program *Valor Minero*, also aims at promoting the sustainable development of the whole sector. The *Programa de Innovaciòn Abierta en Mineria* also importantly changed the role of Fundación Chile, assigning the role to assess the impact on providers and to improve the suppliers' development methodology.

While some case studies show that general mining capabilities are present in Chile (Arza et al., 2018; Fernandez-Stark et al., 2010), innovation capabilities are stagnant (Urzúa, 2012) and firms struggle to enter the market for two main reasons: (i) mining is an industry where there is a high degree of brand loyalty and incumbents have a clear advantage and (ii) there are important mismatches in the design and implementation of policies, and suppliers do not enjoy learning opportunities from large firms nor from coordinating public institutions. Suppliers need to take the total risk of the investment upon themselves, in a context characterized by remarkable uncertainty and information asymmetries, and with strongly hierarchical forms of governance prevailing in GVCs (Kaplinsky & Morris, 2016) that inhibit and constrain innovation and learning (Pietrobelli et al., 2018,

[14] It includes IM2 (R&D subsidiary of CODELCO, which contributed to WCSP with technical expertise and project management), BioSigma (conducts R&D on specialized bacteria and bioleaching processes that can be integrated into mining operations), and Codelco lab (facilitates collaborative projects between local startups, suppliers and other key actors).

[15] According to OECD data 2019 Chile is placed among the lower tier of OECD economies in terms of government support for business R&D, equivalent to 0.03% of GDP. https://www.oecd.org/sti/rd-tax-stats-chile.pdf.

2024a, b). Thus, large companies are very resistant to being the first movers and devote resources to testing or offering testing facilities (Arza et al., 2018).

Supply-side policies Skilled human capital shortage is one of the most important factors inhibiting the participation and innovation potential of suppliers; training measures internal to the firms are normally taken, but no university offers specific human capital formation (Korinek, 2013; Lebdioui, 2019b). In 2012 the *Consejo Minero*—the trade association that brings together the large-scale mining companies operating in Chile to promote the competitive and sustainable development of Chilean mining—made an effort in this sense and founded Chile's Mining Skills Council (CCM) to connect the education sector with the industry, through a sort of labour-matching platform between demand and supply (IGF, 2018c). Based on successful experiences from other countries, this sort of platform would also offer specific qualifications and standard requirement certifications (Villarino, 2016) and provide the same information to demand and supply stakeholders. CCM collects data from mining companies, education institutions, and training suppliers to identify skills shortages and forecast. Despite this policy measure, recent case studies highlighted the need for skills and tax incentives as two of the most important bottlenecks encountered by suppliers (Bravo-Ortega & Muñoz, 2018).

Discussion

In this paper, we propose a taxonomy to study the use of different policy instruments in the mining sector. Our taxonomy shows that the analysis of policies based on their supply and demand sides and considering market-based and public goods instruments offers a tool to map different policy packages and clarify their consistency (Olabisi & Wei, 2025). While such a tool does not provide insights into the functioning, the implementation and the effectiveness of policies, it may help policymakers in the policy design phase, to anticipate the necessary matching efforts between different policies, and the institutional requirements of each. The main novelty of our taxonomy is related to the demand and supply elements and its application to the mining sector (we extend the sectoral application proposed by Weiss and Seric, 2021); in this sense, we built on Andreoni (2016), yet taking a sectoral perspective and extending it further, including considerations on the availability of market tools and public good tools that might influence demand and supply policies. In addition, our work points to the interrelation between GVCs considerations on *what* to target (which segments, linkages creation, and actors) and which instruments to adopt to reach a policy outcome. For example, if a GVC analysis of the mining sector in a specific country points to the opportunity to develop capital equipment for underground mining, which can then have linkages to capital equipment for other sectors, the taxonomy then provides indications about the types of instruments to use and their consistency across demand and supply.

We applied our taxonomy to Australia, Chile, and South Africa. Australia emerges as an interventionist country in mining, especially given the strong emphasis on supporting R&D (on the supply side), and on the mechanisms to help SMEs and service providers reach large mining customers and fulfil certain local sourcing criteria (on the demand side). South Africa also reflects an interventionist policy approach, yet with a combination of both industrial development and socio-economic goals in its policy agenda. South Africa became a global leader in several mining capital goods and services, and the high local content required in mining inputs sourcing contributed to strengthening backward linkages. However, despite an increase in capabilities, the country still faces remarkable challenges in terms of private actors' responses to policy incentives (Ramdoo, 2015). Chile, in contrast, followed a much softer approach to mining industrial policy. For example, the demand-side approach adopted by the WCSP to help develop suppliers did not include any support for their risky investments in innovation and technology development. Although Chilean policies traditionally maintained a horizontal approach, without targeting specific activities or segments of the value chain, recent developments (i.e., the *Alta Ley 2050*) indicate that the government has begun to acknowledge the importance of industrial policy to promote value-adding activities.

A further contribution of our study is the connection between different types of industrial policy instruments and the value chain segments targeted, which can vary from services along the mining process to manufacturing and/or skills inputs (Fig. 1). For example, South Africa targeted the development of machinery inputs, especially for exploration and mine construction, while also promoting engineering services for later stages of the process. In Australia, the recent focus has been on mining services and equipment along different segments of the value chain. Insofar as a scenario of international production fragmentation continues, despite the recent tendencies towards backshoring and nearshoring (Pietrobelli & Seri, 2023), countries will be bound to target specific segments of the value chain. The selected targets will be those where they have higher opportunities for value creation and value capture (Pietrobelli et al., 2021), in line with the initial rationale of the Chilean WCSP. Therefore, a comprehensive understanding of the value chain(s) and the countries' trajectories for technological upgrading is critical to designing effective policies.

In addition, besides a different emphasis on supply and demand policies, our taxonomy reveals the countries' focus on different segments of the value chain. Australia focused mostly on the development and exploitation of mining services (MTS) while guaranteeing that MNCs would provide a stable demand for such services. South Africa focused on capital goods, promoting both R&D and internal demand related to specific equipment, and it managed to develop a global leadership position in capital goods where the country's comparative advantage had been deepened with local content policies (Kaplan, 2012; Pogue, 2008). These included spirals for washing coal, pumping up water, hydropower, tracked mining, underground locomotives, ventilation, and other activities where local content policies allowed leveraging local constraints to acquire high technology capabilities. Chile, traditionally less inclined to promote government intervention, remained focused on extraction and more recently slowly moved to mining services. Although it is not part of the period considered in our paper, the changes in Chile are reflected by the Chilean government targeting lithium in a more vertical way, through the creation of a state-owned lithium company and a national strategy to support local value creation and capture.

Most of the policies in our three countries aimed at reinforcing suppliers' capabilities to enter the industry, whether they were suppliers in the provision of knowledge-intensive mining services or simply suppliers of specific capital goods. A GVC approach is intertwined with the selection of the policy tools, and the choice of GVC segments to target needs to be consistent with the choice of policy tools and the country's institutional capabilities.

Conclusions and future studies

Our study introduces a new taxonomy for industrial policies in the mining sector, which characterises policies based on their demand or supply side (horizontal axis) and on market intervention and public goods (vertical axis). Based on this paper, we expect that the integration and coherence between demand- and supply-side policies are needed for a balanced and sustained mining development. The specific features of the mining industry, particularly the high sunk cost, the remarkable information, and technology asymmetries and risk aversion, are all arguments in favor of selective government interventions. The taxonomy we have proposed may help provide a framework to design policies, analyze their consistency, and draw international comparisons, as well as offer a method to study the evolution of policy packages across countries and over time.

Our study has several limitations. First, we apply our taxonomy to three specific countries in a specific time frame, yet more work needs to be done to prove the applicability to other countries and across different periods. Second, our analysis looks at the type of policies, without including an analysis of whether such policies worked or not; this requires an analysis of historical and institutional factors that are beyond the scope of this paper but could be an interesting direction for future work.

To conclude, and in addition to this last aspect, different research avenues have been opened by this paper. First, using the taxonomy we studied the objectives of the policies, which GVCs elements were in fact targeted, and how countries positioned their activities in mining GVCs; this would complement our analysis including both the *what* and the *how* of industrial policies in mining for our three countries; extending the analysis to other mining GVCs' policies would add to the comparability of the different packages adopted. Second, GVC analyses of additional countries and the policy packages implemented for the different GVC segments would be useful. Finally, given that some "critical" minerals often determine the vulnerability of strategic value chains, such as, for example, semiconductors or electric vehicles, a new perspective on GVC mining policies will need to be considered. Thus, the negotiations for long-term concessions on the use of critical minerals from selected countries are quickly becoming a new instrument of industrial policy, and this will require new research.

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Data availability The data that support the findings of this study are openly available from the authors upon request.

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