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Decarbonization of the Mining Sector in the State of Minas Gerais: Evidence of Challenges

A Descarbonização do Setor de Mineração no Estado de Minas Gerais: Evidências de Desafios

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Abstract: The mining sector has historically played a central role in the economy of the State of Minas Gerais. However, it continues to face major socio-environmental challenges and recurrent disasters. Decarbonization has emerged as a strategy to address these issues, and this article examines its implications. The study discusses the socio-environmental risks of mining and the strategies to enhance its sustainability. Decarbonization may offer an opportunity for productive densification in the state, but it will require coordination among different stakeholders and careful attention to disaster prevention. This process can be strengthened by coupling Decarbonization with the adoption of digital technologies—a process the literature refers to as twin transitions.

Keywords: Mining; Decarbonization; Sustainable Development; Technological Innovation.
JEL Classification: Q01; Q53; Q55; L72; O33

Resumo: O setor de mineração é historicamente relevante para a economia do Estado de Minas Gerais. Contudo, deve lidar com desastres e impactos socioambientais. A descarbonização surge como uma estratégia para isso e o artigo examina suas implicações. A pesquisa aborda os riscos socioambientais da mineração e as estratégias para aprimorar sua sustentabilidade. A descarbonização pode ser uma oportunidade para o adensamento produtivo do estado, mas será necessária A articulação de diferentes agentes e atenção para a prevenção de desastres. Esse processo pode ser favorecido pelo "acoplamento" da descarbonização à incorporação de tecnologias digitais, processo que a literatura denomina de "transições gêmeas".

Palavras-chave: Mineração; Descarbonização; Desenvolvimento Sustentável; Inovação Tecnológica
Classificação JEL: Q01; Q53; Q55; L72; O33

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1. Introduction

In 2023, Brazil reached a historic record in export volumes. Among the main items in its export basket were products from agriculture, oil, and mining. Soybeans, crude petroleum oils, and iron ore accounted for 15.7%, 12.5%, and 9%[1] of the total export value, respectively. In addition to iron ore, Brazil is a major producer of other mineral commodities such as gold, copper, and niobium. In the same year, the mining sector's revenue amounted to R$ 248.2 billion (IBRAM, 2024), with notable participation from the states of Minas Gerais and Pará, which accounted for 41.7% and 34.4% of total revenue, respectively. Minas Gerais is Brazil's largest mining state, hosting 47 of the country's 100 largest extraction sites. In terms of its contribution to the state's gross domestic product (GDP)[2], this revenue represents just over 10% of the total GDP recorded in the same year.

The economic relevance of the mineral industry has been a defining feature throughout the history of the State of Minas Gerais. This activity began with the so-called Gold Economic Cycle (*Ciclo Econômico do Ouro*) in the seventeenth century and has remained one of the state's main economic activities ever since. Notably, from the 2000s onward, there was a strong increase in global demand for mineral products, driven mainly by Asian economies—regions that have experienced rapid economic growth and intense urbanization. This international context, favorable to the export of commodities, provided a strong incentive for the reprimarization of the economy of Minas Gerais, which today is reflected in its low level of economic diversification and exposure to external volatility (JAYME JR; CAMPOLINA; SALOMÃO, 2023).

A relevant factor to be considered is the socioeconomic and environmental consequences of mining activity. During the colonial period, mineral exploitation was marked "*by predatory actions on deposits, violent aggression against the environment, and reckless imbalances that caused shortages and, consequently, cycles of famine that afflicted the pioneers of mining*" (DA SILVA, 1995, pg.77). In more recent years, although mining has been subject to increasingly strict regulation, it has not been possible to prevent serious environmental disasters such as those in Mariana and Brumadinho. Therefore, it is essential to acknowledge the scale of its environmental and economic impacts on the state, especially given the growing environmental pressures and the need to ensure stronger social protection and safeguard the rights of workers and communities affected by mining activity.

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[1] Data from the Brazilian Trade and Investment Promotion Agency (APEXBRASIL – *Agência Brasileira de Promoção de Exportações e Investimentos*). Available at: https://apexbrasil.com.br/br/pt/conteudo/noticias/comercio-exterior-2023-recordes-historicos.html. Accessed on: May 20, 2024.

[2] The gross domestic product (GDP) of the State of Minas Gerais was recorded at R$ 1.028 trillion. Available at: https://fjp.mg.gov.br/economia-mineira-cresce-31-em-2023-e-pib-supera-r-1-trilhao-pela-primeira-vez-na-historia/. Accessed on: May 21, 2024.

The mineral-based sector—which includes the extractive industry and related segments such as metallurgy, steelmaking, and cement production— is one of the main sources of greenhouse gas (GHG) emissions worldwide, particularly steel production (IEA, 2020). One of the main obstacles to Decarbonization lies in the so-called hard-to-abate or hard-to-decarbonize industries. These sectors face technological, logistical, and economic challenges in achieving their CO_2 emission reduction targets, and the technologies and processes currently available are considered to have limited scope for mitigation (FISCHEDICK et al., 2014; IRENA, 2020). According to data from the International Renewable Energy Agency (IRENA), the industrial sector accounts for approximately 28% of total global CO_2 emissions (IRENA, 2020). However, energy-intensive heavy industries—those classified as hard-to-abate—jointly emit around 20% of global CO_2 (IEA, 2020). Iron and steel, chemicals, and cement are among the industries in this category (IRENA, 2020). In mining, although there is evidence of an accelerated pace of innovation—which brings both challenges and opportunities (OLIVEIRA, 2022)—the process of Decarbonization has become an important trend and, increasingly, a source of competitive advantage (ACCENTURE, 2022).

Brazil plays a fundamental role in the global steel industry, as it is the second-largest producer of iron ore and holds some of the world's largest reserves of high-quality iron. In addition, it is the ninth-largest steel producer in the world (IABr, 2021; World Steel Association, 2021; SIMOES and HIDALGO, 2021). Data from the Greenhouse Gas Emission and Removal Estimating System (SEEG – *Sistema de Estimativa de Emissões e Remoções de Gases de Efeito Estufa*), from Climate Observatory (*Observatório do Clima*) show that the mineral sector accounted for 14.23% of the state's emissions in 2022, in addition to other environmental externalities associated with the sector.

Minas Gerais is the third-largest economy in Brazil but ranks among the lowest in economic sophistication when compared with other states, according to a study by Salles et al. (2022). Data on the economy of Minas Gerais reveal a strong dependence on agricultural sectors[3] and those linked to the mineral-based industry (FIEMG, 2023). One of the main problems associated with this productive structure is the generation of negative externalities, such as greenhouse gas emissions. This situation may worsen due to incentives that encourage the expansion of mining, even into areas close to environmental reserves. According to Rezende (2016), this dynamic may exacerbate climate-related problems and further undermine the environmental sustainability of the state. Therefore, it is crucial to seek solutions that harmonize economic development with environmental preservation, especially in regions where mineral exploitation plays such an important role.

This study is situated precisely within this context, acknowledging that while the relevance of mining to the economy of the state of Minas Gerais is undeniable, it is essential to discuss mechanisms for the sector's adaptation and modernization to meet new socio-environmental demands. Although this scenario is challenging, it can also create windows

[3]The João Pinheiro Foundation has reported strong growth in agribusiness in the state. Available at: https://fjp.mg.gov.br/pib-do-agronegocio-de-minas-gerais-alcancou-r-205-bi-em-2022/. Accessed on: May 21, 2024.

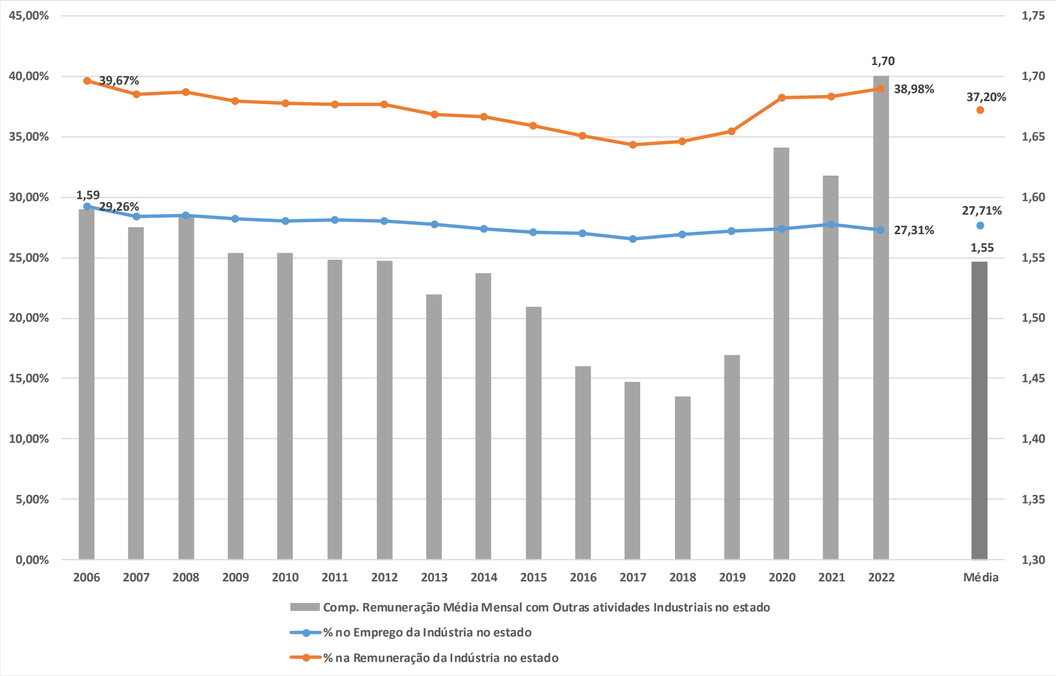
of opportunity for sectoral strengthening and diversification, innovation, and economic resilience. A decarbonization pathway for the sector has already been, at least a priori, established (KIRK; LUND, 2018). Although there are different conceptualizations regarding the characteristics of this process, as the name itself suggests, there is broad convergence on its main objective—a significant reduction in emissions within the sector and in the activities connected to it.

In light of the reflections presented above, this study seeks to understand the implications of decarbonization for the mining sector, based on a review of the existing literature on the topic. For the purpose of this analysis, the article is divided into five sections in addition to this introduction. Section 2 presents evidence of the importance of mining to the economy of Minas Gerais. Section 3 discusses the sector's environmental risks and impacts and their consequences. Section 4 examines decarbonization strategies for the sector. Section 5 analyzes the implications of decarbonization. Finally, Section 6 summarizes the study's conclusions.

2. Mining's Role in the Economy and Emissions of Minas Gerais

Mining activities play a highly significant role in the industry and economy of Minas Gerais, reflecting the state's particular endowment of natural resources and the historically relevant impact of this endowment on the dynamics of the regional economy. Recent data indicate that this importance remains significant. Data presented in Figure 1 indicate that mining and metallurgical activities, according to information from the Annual Social Information Report (RAIS – *Relação Anual de Informações Sociais*), accounted for approximately 27.1% of employment and 37.2% of total industrial wages in Minas Gerais between 2006 and 2022. During the same period, the average wage in these activities was about 55% higher than in other industrial activities. When compared with total employment captured by RAIS, the average wage in the mining and metallurgical sectors was 37% higher than the overall average wage for the same period.

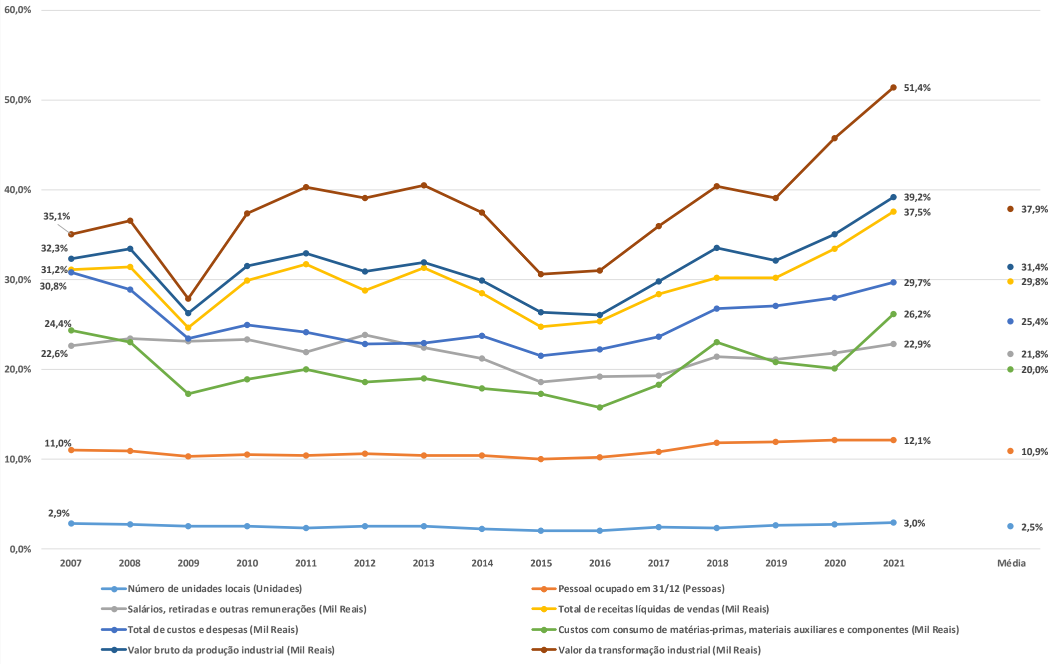
Figure 1 – Participation and Comparison of Mining and Metallurgical Activities in Minas Gerais Relative to the State Total in Terms of Employment, Total Wages, and Average Monthly Wages, 2006–2022



Source: Authors’ elaboration based on data from RAIS-Mte.

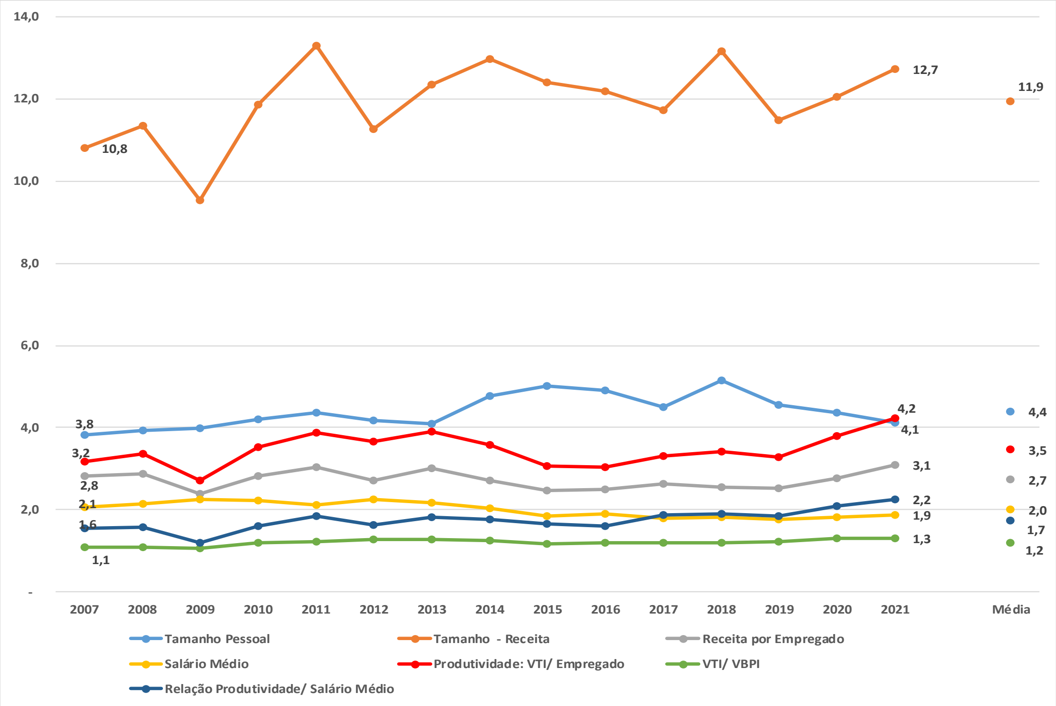
Expanding the analysis to include information on the industrial sector collected by the Annual Industrial Survey of the Brazilian Institute of Geography and Statistics (PIA-IBGE – *Pesquisa Industrial Anual do Instituto Brasileiro de Geografia e Estatística*), and considering a two-digit sectoral classification from the National Classification of Economic Activities (CNAE – *Classificação Nacional de Atividades Econômicas*), the sectors of iron ore extraction and metallurgy show the following average shares relative to the total industry of Minas Gerais for the period 2007–2021 (see Figure 2): (i) 2.5% of total local units; (ii) 10.9% of total employment; (iii) 21.8% of wages, withdrawals, and other remunerations; (iv) 29.8% of total net sales revenue; (v) 31.4% of gross value of industrial production; and (vi) 37.9% of industrial transformation value. In addition, when compared with the total industry of the state, the following trends can be observed for the indicators derived from the Annual Industrial Survey (PIA) for the average of 2007–2021 (see Figure 3): (i) 4.4 times the value observed for the state in terms of size measured by employment; (ii) 11.9 times the value observed for the state in terms of size measured by revenue; (iii) 2.7 times the value observed for the state in terms of revenue per employee; (iv) 1.9 times the value observed for the state in terms of average annual wage per employee; (v) 3.5 times the value observed for the state in terms of productivity captured by the ratio of industrial transformation value (ITV) to employment; (vi) 1.2 times the value observed for the state in terms of the ratio of ITV to gross industrial production value (GIPV); and (vii) 1.7 times the value observed for the state in terms of the ratio of productivity to average wage. Overall, these indicators have shown an upward trend since 2019, indicating an increase in the importance of these sectors within the broader industrial structure of Minas Gerais.

Figure 2 – Participation of Iron Ore Extraction and Metallurgy Activities in Minas Gerais's Industry, 2007–2021



Source: Authors' elaboration based on data from PIA-IBGE.

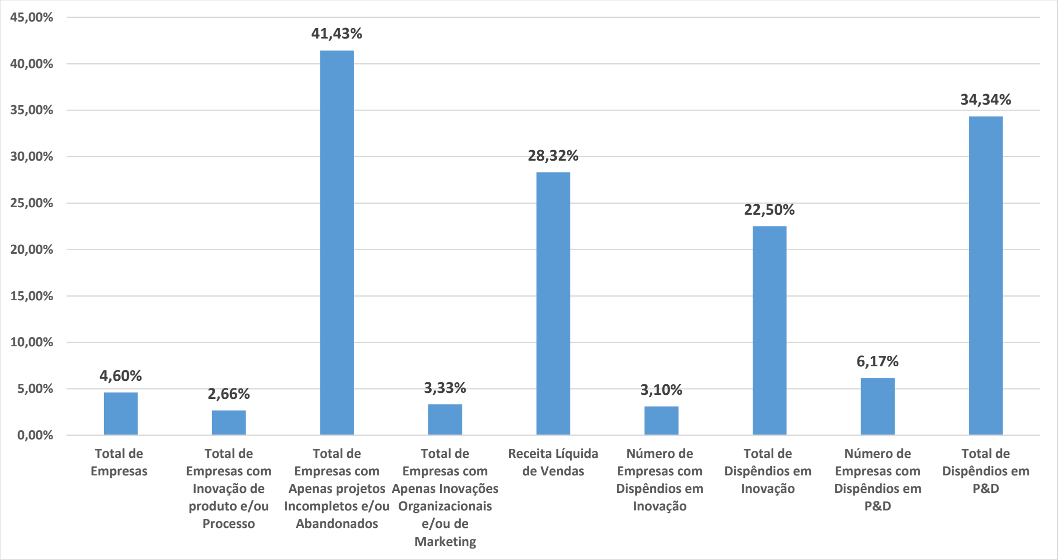
Figure 3 – Indicators Derived from PIA: Comparison Between Iron Ore Extraction and Metallurgy Activities and Minas Gerais's Total Industry, 2007–2021



Source: Authors' elaboration based on data from PIA-IBGE.

A similar approach can be applied to information extracted from the Survey of Innovation of the Brazilian Institute of Geography and Statistics (PINTEC-IBGE – *Pesquisa de Inovação do Instituto Brasileiro de Geografia e Estatística*) for the year 2017, selecting, according to the sectoral breakdown available, the activities of extractive industries and steel products. In comparison with the total industry of the state, the following trends can be observed for the selected activities in 2017, based on data from PINTEC (see Figure 4): (i) 543 companies, accounting for 4.60% of the total number of companies in the state; (ii) 101 companies that implemented product and/or process innovation, equivalent to 2.66% of the state total; (iii) 105 companies with only incomplete and/or abandoned projects, equivalent to 41.43% of the state total; (iv) 127 companies with only organizational and/or marketing innovations, equivalent to 3.33% of the state total; (v) R$ 66,331 million in net sales revenue, accounting for 28.32% of the state total; (vi) 95 companies with innovative expenditures, equivalent to 3.10% of the state total; (vii) R$ 800.65 million in total innovative expenditures, accounting for 22.50% of the state total; (viii) 30 companies with Research and Development (R&D) expenditures, equivalent to 6.17% of the state total; and (ix) R$ 395.77 million in total R&D expenditures, accounting for 34.34% of the state total. When compared with the total industry of the state, the following trends can be observed for the selected activities in 2017, based on indicators derived from PINTEC-IBGE (see Table 1): (i) 18.7% for the innovation rate in these sectors, compared with 32.3% for the overall industrial sector of Minas Gerais; (ii) 23.3% for the rate of organizational innovations in these sectors, compared with 32.3% for the total industry of Minas Gerais; (iii) 17.6% for the share of firms with innovation expenditures in these sectors, compared with 26.1% for the total industry of Minas Gerais; (iv) 5.5% for the share of innovation expenditures relative to revenue in these sectors, compared with 4.1% for the total industry of Minas Gerais; (v) 1.21% for the share of firms with R&D expenditures in these sectors, compared with 1.52% for the total industry of Minas Gerais; (vi) 0.60% for the share of R&D expenditures relative to revenue in these sectors, compared with 0.49% for the total industry of Minas Gerais; (vii) R$ 8,403.7 thousand in average innovation expenditure per firm in these sectors, compared with R$ 1,156.8 thousand for the total industry of Minas Gerais; and (viii) R$ 13,187.4 thousand in average R&D expenditure per firm in the selected sectors, compared with R$ 2,368.9 thousand for the total industry of Minas Gerais. It is also worth noting that the extractive industry shows weaker performance than the manufacturing industry for all selected indicators. These findings highlight the significant weight of the selected sectors in the total innovative expenditures of the industry of Minas Gerais, as well as the comparatively higher average expenditures per firm in those sectors.

Figure 4 – Participation of Selected Activities (Extractive Industries and Steel Products) in Minas Gerais's Industry, 2017 (PINTEC Data)



Source: Authors' elaboration based on data from PINTEC-IBGE.

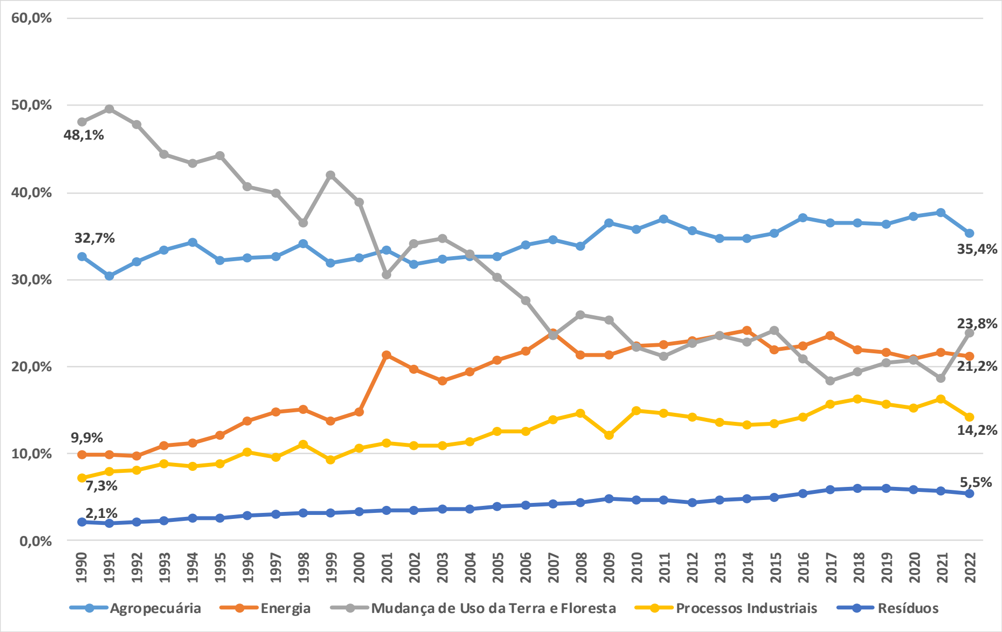
Table 1 – Indicators Derived from PINTEC for Selected Activities (Extractive Industries and Steel Products) and the Total Industry – Minas Gerais, 2017

Sectors	Innovation Rate	Rate of Organizational Innovations	Firms with Innovation Expenditures (%)	Firms with R&D Expenditures (%)	Innovation Expenditures as Share of Revenue (%)	R&D Expenditures as Share of Revenue (%)	Average Innovation Expenditure	Average R&D Expenditure
Total Industry	32,3%	32,3%	26,1%	4,1%	1,52%	0,49%	1,157	2,369
Manufacturing Industries	33,1%	32,6%	26,6%	4,2%	1,53%	0,51%	1,137	2,366
Manufacturing (excluding Steel Products)	33,0%	32,7%	26,5%	4,1%	1,64%	0,45%	925	1,658
Subtotal – Selected Activities	18,7%	23,3%	17,6%	5,5%	1,21%	0,60%	8,404	13,187
Extractive Industries	14,1%	26,1%	13,0%	1,6%	1,21%	0,17%	2,140	2,554
Steel Products	46,9%	6,2%	45,6%	30,0%	1,21%	0,68%	19,474	16,615

Source: Authors' elaboration based on data from PINTEC-IBGE.

Regarding environmental impacts, information from the Greenhouse Gas Emission and Removal Estimating System (SEEG – *Sistema de Estimativa de Emissões e Remoções de Gases de Efeito Estufa*), provided by the Climate Observatory, was considered. Data shows that in 2022, Minas Gerais accounted for 169.4 MtCO_2e of gross emissions and 24.4 MtCO_2e of removals, ranking third among Brazilian states in total emissions. Compared with Brazil as a whole, Minas Gerais shows a higher share of emissions from the agricultural sector (41.3% in the state versus 29.4% nationwide) and from industrial processes (16.6% in the state versus 5.0% nationwide—the largest discrepancy among the sectors considered), as illustrated in Figure 5. Among the emissions from industrial processes in Minas Gerais, 62.7% (15.1 MtCO_2e) originated from metal production, 37.3% (8.9 MtCO_2e) from mineral products, and 0.1% (0.12 MtCO_2e) from the chemical industry.

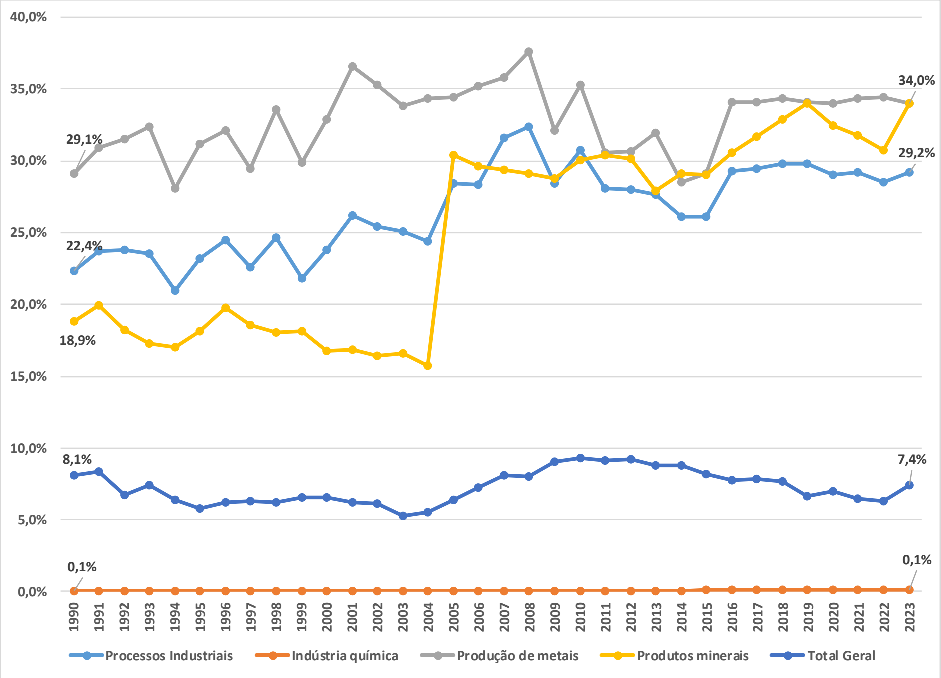
Figure 5 – Evolution of Greenhouse Gas Emission Sources in Minas Gerais, 1990–2022



Source: SEEG, Observatório do Clima.

Figure 6 presents information on the share of the state of Minas Gerais in total emissions, both for activities associated with industrial processes and for all activities combined, over the period 1990–2023. The share of Minas Gerais in total emissions linked to industrial processes increased from an average of around 24% between 1990 and 2003 to approximately 29% between 2004 and 2023. Nevertheless, the state's share in total emissions remained relatively stable, rising only from 6.6% between 1990 and 2003 to 7.7% between 2004 and 2023. Within industrial processes, the increase in Minas Gerais's share of total emissions is mainly explained by the rise in emissions from mineral products, whose share grew from around 18% between 1990 and 2003 to 30% between 2004 and 2023. An increase is also observed in the state's share of emissions from metal production, which rose from about 32% between 1990 and 2003 to approximately 33.5% between 2004 and 2023.

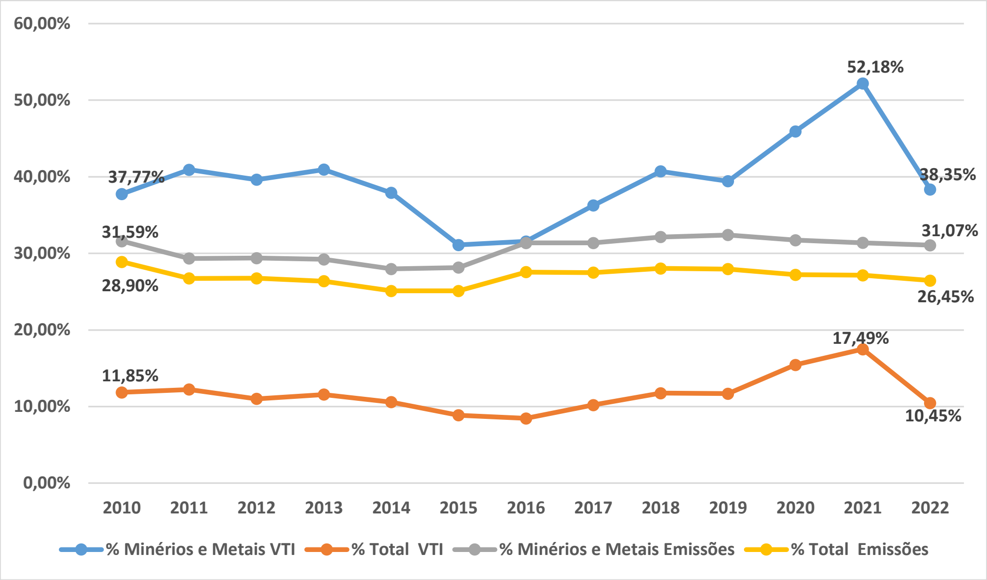
Figure 6 – Evolution of Minas Gerais's Share in Greenhouse Gas Emission Sources for Brazil as a Whole, 1990–2023



Source: SEEG, Observatório do Clima.

The analysis can be refined by examining the relationship between the volume of emissions and the monetary value of industrial transformation in the mining sector—an indicator of the sector's carbon intensity—over time, comparing the evolution of this indicator for the overall industry and between Minas Gerais and the country as a whole. Therefore, if this indicator has been decreasing over time, there would be evidence of a decarbonization process in the sector. Specifically, it is possible to assess the evolution of Minas Gerais's participation in terms of four basic indicators (see Figure 7): (i) the state's share in the total ITV of mining and metals; (ii) the state's share in total ITV; (iii) the state's share in total emissions from mining and metals; and (iv) the state's share in total emissions from industrial processes. The first two indicators come from PIA, while the latter two are based on data from SEEG. The considered period in the analysis covers 2010 to 2022. Regarding emissions, the state's share averaged 31% of total emissions from mining and metals and 27% of total emissions from industrial processes, with evidence of a slight increase in these shares starting in 2016. As for the industrial transformation value, the state's share averaged 39.4% of the ITV for mining and metals and 11.7% of total industrial ITV. These shares declined between 2010 and 2015 and rose between 2016 and 2021, although at a faster pace for mining and metals, followed by a drop in both indicators in 2022, which was also more pronounced in the mining and metals sector and likely explains the overall decrease in the industry-wide indicator.

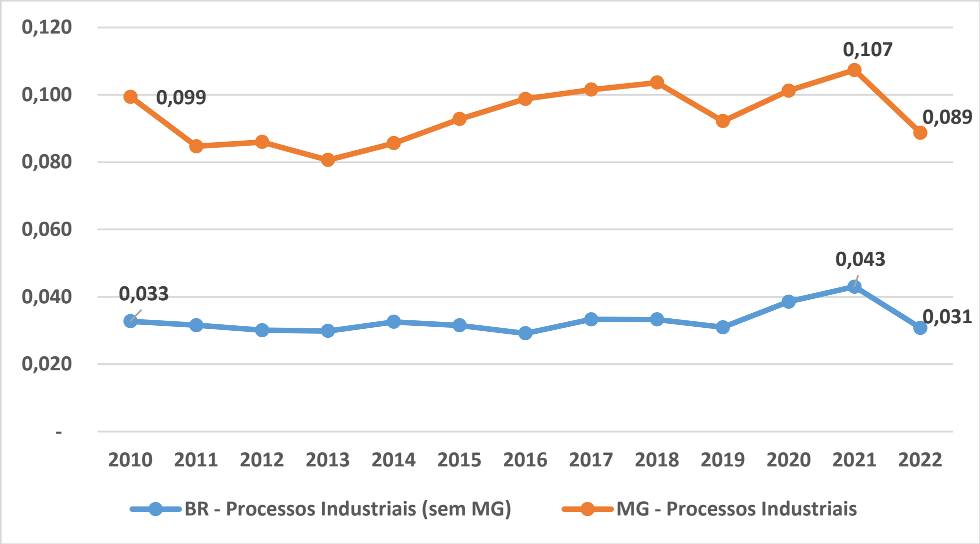
Figure 7 – Evolution of Minas Gerais's Share in Total ITV and Emissions: Mining and Metals Sector vs. Total Industry, 2010–2022



Fonte: Authors' elaboration based on data from PIA-SEEG.

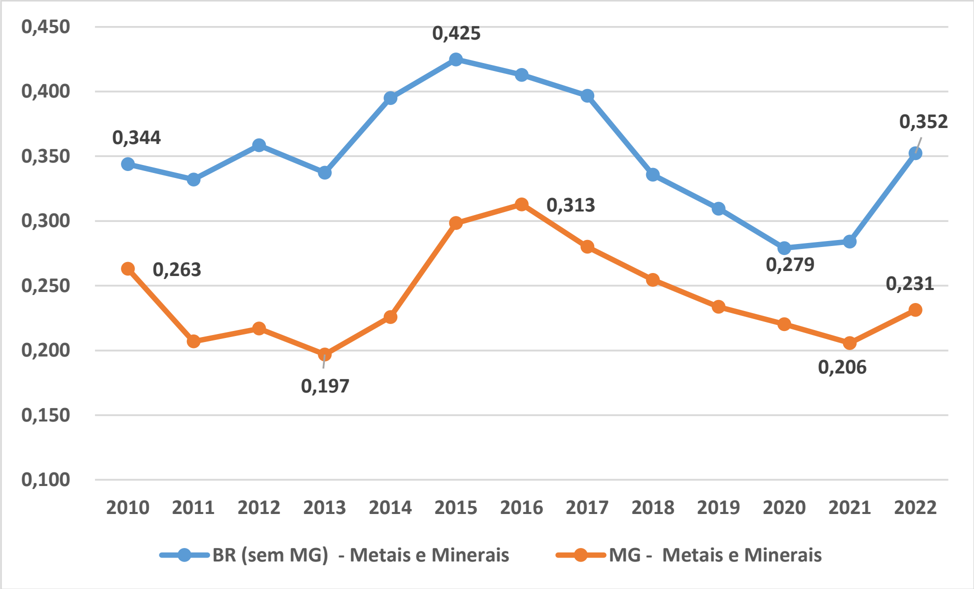
Based on the information underlying Figure 6, it is possible to analyze the evolution of a carbon intensity indicator defined by the ratio between emission volume and the monetary value of industrial transformation in the mining sector and in the total industry, for Minas Gerais and the rest of the country, as illustrated in Figures 8 and 9. When considering total industrial processes, Figure 8 shows that the average value for Minas Gerais was 186% higher than that for the rest of the country over the period 2010–2022. This difference is explained precisely by the greater relevance of mining and metallurgical activities in Minas Gerais compared with the rest of the country. Across the rest of the country, the indicator remained relatively stable between 2010 and 2019, increased from 2019 to 2021, and declined in 2022. Meanwhile, in Minas Gerais, the indicator fell between 2010 and 2013, rose between 2013 and 2018, dropped again in 2019, increased from 2020 to 2021, and declined once more in 2022. Regarding mining and metallurgical activities, Figure 9 shows that the average indicator value for 2010–2022 in Minas Gerais was 31% lower than that observed elsewhere in the country. Nationwide, after an increase from 2013 to 2015, the indicator declined by 34.3% between 2015 and 2020, then rose by 26.3% between 2020 and 2022. In Minas Gerais, after increasing 58.9% between 2013 and 2016, the indicator decreased by 34.2% between 2016 and 2021 and rose again by 12.4% from 2021 to 2022.

Figure 8 – Evolution of Carbon Intensity Indicator (Emissions to ITV Ratio) in Minas Gerais's Industry and in the Rest of Brazil, 2010–2022



Source: Authors' elaboration based on data from PIA-SEEG.

Figure 9 – Evolution of Carbon Intensity Indicator (Emissions to ITV Ratio) in the Mining and Metals Sector in Minas Gerais and in the Rest of Brazil, 2010–2022



Source: Authors' elaboration based on data from PIA-SEEG.

3. Risks and Impacts of Mining

Extractive mining activity is closely linked to territorial dynamics and the creation of externalities. In the case of Minas Gerais, this territorial component is reflected in the significant number of municipalities in the state that rank among Brazilian municipalities with the highest value of mining operations, as shown in Table 2. In fact, of the twenty municipalities with the largest mining operation values, thirteen were located in Minas Gerais. The impacts of mining unfold across different dimensions, including income, poverty, inequality, health, and the environment (DENES; DO AMARAL; DE OLIVEIRA, 2022). From an economic standpoint—particularly regarding income generation—there is a certain consensus in the literature about the gains derived from mining activity. However, the same cannot be said for other economic variables, such as inequality, for which evidence points to deterioration (LOAYZA; RIGOLINI, 2016). Beyond the analysis of macroeconomic variables, the heavy reliance of Minas Gerais's regional economy on the mining sector has contributed to a process of economic reprimarization (DE CARVALHO; DE MENDONÇA, 2019), with potential adverse effects such as declining productive complexity and lower overall productivity (JAYME JR; CAMPOLINA; SALOMÃO, 2023; OREIRO; FEIJÓ, 2010).

Table 2 – Ranking of the 20 Most Mining-Intensive Municipalities: Operation Values (OV) and Municipal GDP, 2018

Ranking	Municipality	State	OV (R$ thousand)	GDP at Current Prices (R$ thousand)	OV–GDP Ratio
1	Parauapebas	PA	20,347,431.77	15,995,450	1.27
2	Canaã dos Carajás	PA	10,032,872.24	7,106,814	1.41
3	Marabá	PA	5,967,042.54	8,780,799	0.68
4	Congonhas	MG	5,235,468.08	1,708,756	3.06
5	Itabira	MG	5,114,749.47	6,620,080	0.77
6	Nova Lima	MG	5,051,965.89	10,439,694	0.48
7	Itabirito	MG	3,760,041.34	5,010,763	0.75
8	São Gonçalo do Rio Abaixo	MG	3,337,201.36	3,648,790	0.91
9	Mariana	MG	3,136,647.34	2,753,719	1.14
10	Paracatu	MG	2,547,023.58	4,309,964	0.59
11	Brumadinho	MG	1,846,022.73	2,583,875	0.71
12	Alto Horizonte	GO	1,554,268.21	913,010	1.70
13	Sabará	MG	1,280,298.72	2,919,829	0.44
14	Ouro Preto	MG	1,204,341.16	6,831,108	0.18
15	Itatiaiuçu	MG	1,191,205.50	1,548,609	0.77
16	Conceição do Mato Dentro	MG	1,135,065.96	733,105	1.55
17	Paragominas	PA	998,937.32	2,647,150	0.38
18	Oriximiná	PA	954,324.59	1,626,709	0.59
19	Belo Vale	MG	899,292.21	152,167	5.91
20	Curionópolis	PA	807,830.21	820,223	0.98

Fonte: ANM, 2019, and IBGE, 2019, in: Atlas do Problema Mineral Brasileiro (2023).

The potential for mining activities to act as a driving force for economic and social development can be assessed by comparing indicators for the main municipalities engaged in mining (identified in Table 2) with those for the remaining municipalities of the state of Minas Gerais. To perform this comparison, it is possible to draw on secondary information sources. First, data on municipal GDP by activity made available by the IBGE can be used to compare the situation of the twelve main municipalities that operate as mining hubs in the state—identified in Table 2—with that of all other municipalities in Minas Gerais. Table 3 makes it possible to identify some important characteristics of the state's mining municipalities: (1) higher per capita GDP in mining municipalities, 3.5 times the per capita GDP calculated for all municipalities in the state in 2021 (or twice the value calculated for the average for 2002–2021); (2) higher growth rates of both GDP and per capita GDP in mining municipalities compared with the state average: 21.5% versus 10.9% for GDP growth, and 19.6% versus 10.1% for per capita GDP growth over the period 2002–2021; (3) greater weight of mining municipalities in value added by industry compared with other activities: 28.6% in industry versus 12.0% for the state's overall economy in 2021, or 15.2% in industry versus 7.2% for the state's overall economy, considering the 2002–2021 average; (4) higher growth of value added by industry in mining municipalities for the 2002–2021 average, both compared with industry in the state as a whole (30.4% versus 12.8%) and with total activities in those municipalities (30.4% versus 21.5%); and (5) a greater share of industry in relation to GDP in mining municipalities compared with the other municipalities of the state: 53.3% versus 23.7% for the 2002–2022 average.

The importance of mining hubs in the industrial dynamics of Minas Gerais can also be observed when considering information on municipal GDP. In terms of the absolute value of industrial GDP, it is verified that, in 2021, among the 20 largest municipalities in Minas Gerais, 9 were mining hubs (in order of industrial GDP): Nova Lima, Itabira, Itabirito, Conceição do Mato Dentro, Ouro Preto, São Gonçalo do Rio Abaixo, Itatiaiuçu, Mariana, and Paracatu. Regarding the share of industrial GDP in total GDP, it is verified that, in 2021, among the 20 largest municipalities in Minas Gerais, 9 were mining hubs (in order of the importance of industrial GDP in total GDP): Itatiaiuçu, Conceição do Mato Dentro, São Gonçalo do Rio Abaixo, Itabirito, Itabira, Mariana, Nova Lima, Ouro Preto, and Brumadinho. Finally, among the 20 municipalities in Minas Gerais with the highest per capita GDP, 9 were also mining hubs (in order of per capita GDP value): São Gonçalo do Rio Abaixo, Itatiaiuçu, Conceição do Mato Dentro, Itabirito, Nova Lima, Ouro Preto, Itabira, Mariana, and Brumadinho.

Table 3 – Structure of Municipal GDP by Activity, Population, and GDP per Capita – 2021 and Average Values for 2002–2022 – Mining Hub Municipalities and Other Municipalities

	Qty. of Municipalities	GVA – Agriculture	GVA – Industry	GVA – Services	GVA – Public Administration[4]	Total GVA	NTSP[5]	GDP	Population	GDP per Capita
Data for 2021 (R$ million)										
Mining Hubs	13	1,356	74,030	25,168	4,964	105,519	4,534	110,052	785,834	140,045
Other Municipalities	840	54,494	184,600	307,242	102,212	648,547	98,994	747,541	20,626,089	36,242
Total	853	55,850	258,630	332,410	107,176	754,066	103,528	857,593	21,411,923	40,052
Share of Total in 2021										
Mining Hubs	1,5%	2,4%	28,6%	7,6%	4,6%	14,0%	4,4%	12,8%	3,7%	3.50
Other Municipalities	98,5%	97,6%	71,4%	92,4%	95,4%	86,0%	95,6%	87,2%	96,3%	0.90
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	1.00
Share of Total, Average for 2002–2021										
Mining Hubs	1,5%	2,1%	15,2%	4,9%	4,3%	7,7%	3,4%	7,2%	3,6%	2.01
Other Municipalities	98,5%	97,9%	84,8%	95,1%	95,7%	92,3%	96,6%	92,8%	96,4%	0.96
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%	1.00
Average Annual Growth Rate, Nominal Values (%)										
Mining Hubs	13	14,4%	30,4%	16,4%	10,9%	22,2%	13,2%	21,5%	1,1%	20,2%
Other Municipalities	840	13,2%	10,8%	10,3%	9,6%	10,4%	9,9%	10,3%	0,8%	9,5%
Total	853	13,2%	12,8%	10,5%	9,7%	11,1%	10,0%	10,9%	0,8%	10,1%
Share of Activities in Municipal GDP										

[4] Gross value added in public administration, including defense, education, and public health.
[5] Taxes, net of subsidies, on products.

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Mining Hubs	13	1,6%	53,3%	29,4%	9,1%	93,5%	6,5%	100%		
Other Municipalities	840	5,7%	23,7%	42,9%	14,4%	86,7%	13,3%	100%		
Total	853	5,4%	26,0%	41,8%	14,0%	87,2%	12,8%	100%		

Fonte: Authors' elaboration based on data from municipal PIB (IBGE).

Secondly, information on the evolution of the Human Development Index (HDI) can be considered for the period 1990–2010, comparing the trends observed in mining municipalities with those in other municipalities of the state of Minas Gerais. Table 4 presents this evolution disaggregated by the different components of the HDI, namely: the Education HDI, based on the level of basic education among the adult population; the Longevity HDI, based on life expectancy at birth; and the Income HDI, based on average per capita income. As a general trend, higher indicators are observed for mining municipalities compared with other municipalities, although this difference has narrowed over the considered period. Among the three dimensions of the HDI, the one that continues to show the largest gap between mining and non-mining municipalities is the Education HDI, although this difference has also been decreasing. Among mining municipalities, those with the highest HDI values generally have a more diversified productive structure. Notably, five mining municipalities ranked among the fifty highest HDI values in Minas Gerais in 2010: Nova Lima (1st in the state), Itabira (31st), Congonhas (36th), Brumadinho (44th), and Paracatu (47th).

Table 4 – Evolution of HDI Components – Mining Hub Municipalities and Other Municipalities

		1991	2000	2010	Var.
Education HDI	Mining Hubs (1)	0.233	0.445	0.629	169,6%
	Other Municipalities (2)	0.177	0.373	0.556	214,1%
	Total	0.178	0.374	0.557	213,2%
	Comparison (1)/(2)	1.32	1.20	1.13	0.79
Longevity HDI	Mining Hubs (1)	0.688	0.759	0.842	22,4%
	Other Municipalities (2)	0.679	0.753	0.824	21,3%
	Total	0.679	0.753	0.824	21,3%
	Comparison (1)/(2)	1.01	1.01	1.02	1.05
Income HDI	Mining Hubs (1)	0.582	0.636	0.713	22,4%
	Other Municipalities (2)	0.522	0.592	0.651	24,6%
	Total	0.523	0.593	0.652	24,6%
	Comparison (1)/(2)	1.11	1.07	1.09	0.91
Total HDI	Mining Hubs (1)	0.450	0.597	0.722	60,5%
	Other Municipalities (2)	0.390	0.547	0.667	70,9%
	Total	0.391	0.548	0.668	70,7%
	Comparison (1)/(2)	1.15	1.09	1.08	0.85

Source: UNDP (PNUD).

Thirdly, information can be drawn from the Sustainable Development Index of Cities – Brazil (IDSC-BR – *Índice de Desenvolvimento Sustentável das Cidades – Brasil*), which monitors the progress of 5,570 Brazilian cities toward the United Nations (UN) 2030 Agenda. The IDSC-BR provides a comprehensive and integrated overview of Brazilian municipalities with respect to each of the Sustainable Development Goals (SDGs). Specifically, it is possible to compare indicators collected for mining municipalities with those for all municipalities in Minas Gerais. Therefore, the most recent information available (as systematized in the IDSC-BR 2025) can be considered with respect to two aspects: (i) the overall performance of municipalities in terms of the scores assigned to the 17 SDGs; and (ii) their performance regarding a specific set of indicators more directly related to the preservation of the natural environment.

Regarding the overall performance of municipalities in Minas Gerais in terms of the scores assigned to the 17 SDGs—which in turn reflect a particular combination of indicators—it can be observed, based on Table 5, that when the general average of indicators for mining municipalities is compared with that of the other municipalities, the former shows a higher value for nine of the seventeen composite SDG indicators. In particular, the indicator is higher for five Goals: SDG 17, Partnerships for the Goals (the score for mining municipalities is 2.42 times that observed for the other municipalities); SDG 9, Industry, Innovation, and Infrastructure (1.84 times); SDG 15, Life on Land (1.64

times); SDG 8, Decent Work and Economic Growth (1.26 times); and SDG 7, Affordable and Clean Energy (1.11 times).

Table 5 – SDG Scores for Mining Hub Municipalities and for Other Municipalities

Sustainable Development Goals (SDGs)	Mining Hubs (1)	Other Municipalities (2)	Total	Comparison (1)/(2)
1. No Poverty	49.428	48.548	48.561	1.02
2. Zero Hunger	44.399	45.604	45.586	0.97
3. Good Health and Well-being	69.964	72.364	72.327	0.97
4. Quality Education	61.682	59.919	59.945	1.03
5. Gender Equality	48.631	52.193	52.139	0.93
6. Clean Water and Sanitation	61.226	61.204	61.204	1.00
7. Affordable and Clean Energy	95.100	85.708	85.851	1.11
8. Decent Work and Economic Growth	54.857	43.504	43.677	1.26
9. Industry, Innovation and Infrastructure	20.634	11.225	11.368	1.84
10. Reduced Inequalities	51.250	61.484	61.328	0.83
11. Sustainable Cities and Communities	71.210	80.596	80.453	0.88
12. Responsible Consumption and Production	64.605	74.663	74.510	0.87
13. Climate Action	69.116	67.784	67.804	1.02
14. Life Below Water	18.220	17.311	17.324	1.05
15. Life on Land	34.163	20.789	20.993	1.64
16. Peace, Justice and Strong Institutions	48.445	61.363	61.166	0.79
17. Partnerships for the Goals	48.857	20.200	20.637	2.42

Source: IDSC-BR, 2025, available at: https://idsc.cidadessustentaveis.org.br/.

In addition, a selected set of indicators related to SDGs 12, 13, 14, and 15 was also compared, as shown in Table 6: (i) indicators related to SDG 12: Household solid waste collected per capita (kg/day/inhabitant); Recovery of selectively collected urban solid waste; and Population served by selective collection (%); (ii) indicators related to SDG 13: CO_2e emissions per capita; Incidence of wildfire outbreaks; Strategies for risk management and environmental disaster prevention; Percentage of the municipality deforested; and Proportion of population living in disaster-prone areas; (iii) indicator related to SDG 14: Wastewater treated before reaching the sea, rivers, and streams; (iv) indicators related to SDG 15: Hectares of forested and natural areas per inhabitant; Protected areas for full protection and sustainable use (%); and Maturity level of environmental protection financing instruments. Across the selected indicators, mining hub municipalities, with respect to SDG 12, perform worse in “Recovery of selectively collected urban solid waste” and better in “Population served by selective collection.” Regarding SDG 13, they perform better in “CO_2e emissions per capita” and in “Strategies for risk management and environmental disaster prevention,” as well as slightly better in the "Percentage of the municipality deforested.” In contrast, mining municipalities perform worse in the “Incidence of wildfire outbreaks” and, particularly, in the “Proportion of population living in disaster-prone areas.” With respect to SDG 14, mining municipalities perform considerably better in “Wastewater treated before reaching the sea, rivers, and streams.” Finally, for SDG 15, mining municipalities perform significantly worse in “Forested and natural area per inhabitant,” while showing much better performance in “Protected areas for full protection and sustainable use” and in the “Maturity level of environmental protection financing instruments.”

Table 6 – Selected SDG Indicators Scores for Mining Hub Municipalities and for Other Municipalities

Selected Indicators	**Direction**	**Mining Hubs (1)**	**Other Municipalities (2)**	**Total**	**Comparison (1)/(2)**
SDG 12 – Household solid waste collected per capita (kg/day/inhabitant)	Descending	0.683	0.688	0.688	0.99
SDG 12 – Recovery of selectively collected urban solid waste	Ascending	6.194	10.456	10.352	0.59
SDG 12 – Population served by selective collection (%)	Ascending	76.008	67.897	68.218	1.12
SDG 13 – CO_2e emissions per capita	Descending	6.781	10.198	10.146	0.67
SDG 13 – Incidence of wildfire outbreaks	Descending	0.149	0.037	0.038	4.09
SDG 13 – Strategies for risk management and environmental disaster prevention	Ascending	51.692	15.305	15.859	3.38
SDG 13 – Percentage of the municipality deforested (%)	Descending	0.303	0.351	0.350	0.86

SDG 13 – Proportion of population living in disaster-prone areas	Descending	0.422	0.080	0.085	5.30
SDG 14 – Wastewater treated before reaching the sea, rivers, and streams (%)	Ascending	18.220	17.311	17.324	1.05
SDG 15 – Forested and natural area per inhabitant	Ascending	1.262	2.632	2.611	0.48
SDG 15 – Protected areas for full protection and sustainable use (%)	Ascending	23.267	6.288	6.547	3.70
SDG 15 – Maturity level of environmental protection financing instruments	Ascending	78.462	54.381	54.748	1.44

Source: IDSC-BR, 2025, available at: https://idsc.cidadessustentaveis.org.br/.
Note: Indicators adapted from IDSC-BR municipal database.

When analyzing the impact of mining activities on other dimensions such as health and the environment, the situation becomes even more delicate, as it is marked by strong negative externalities. Mining activity is closely related to the geophysical characteristics of the soil, and interventions during the extraction process cause significant territorial changes and require large amounts of physical resources such as water and energy. These characteristics often result in the destruction of all vegetation at the mining site and, in most cases, prevent its regeneration. In many operations, the surface layers of the soil are removed, reducing its fertility. The exposed land is then subject to erosion and to the siltation of nearby water resources (DA SILVA; ANDRADE, 2017). Part of these impacts is also associated with the need for large areas for the deposition of waste and tailings from mining , which can affect agricultural production in surrounding areas. Soil damage is evident at the extraction site itself, especially in terms of contamination, but pollution may also spread to nearby regions. The dust generated by mining not only causes air pollution but can also contaminate the soil and harm agricultural activity (BOMFIM, 2017).

Particle clouds represent a source of air pollution with significant impacts on the health of local populations. Mining activity involves the combustion of fossil fuels, blasting operations, and mineral processing, all of which contribute to greenhouse gas emissions (BOMFIM, 2017). However, according to a study by the Brazilian Development Bank (BNDES – *Banco Nacional do Desenvolvimento*) (CARVALHO et al., 2018, p. 353), "*Brazil's emissions are lower than those of other mining countries*." This is due to the relative efficiency of Brazilian mining operations in diesel consumption and to the significant share of renewables in the country's electricity mix. Nonetheless, it should be noted that mineral processing activities—such as metallurgy and steelmaking—are highly emission-intensive (CARVALHO et al., 2018, pg. 341). Overall, emissions associated with the mineral-based sector are far from negligible: in 2022, the sector accounted for nearly 15% of the state's total emissions, according to SEEG[6], and attention should also be given to the indirect emissions potentially linked to the sector, such as those from transportation and deforestation.

In terms of water impact, in addition to the potential siltation in mining regions, there are also strong possibilities of water contamination. The quality of river and reservoir water within the same basin where mining operations are located may be affected by different types of pollutants, such as fine suspended sediments, oils, grease, and heavy metals (DA SILVA; ANDRADE, 2017). The externalities affecting water resources are not limited to pollution: competition over resource use also occurs, as water consumption by mining often rivals domestic use in times of scarcity. Furthermore, pollution itself can exacerbate this situation by reducing the availability of water suitable for use (DENES; DO AMARAL; DE OLIVEIRA, 2022).

The social and environmental impacts and risks discussed so far, although inherent to mining activity, are not homogeneous and vary in intensity and scope depending on the management practices, technologies, and methods employed in the activity (BOMFIM, 2017). In particular, one cannot overlook the risk of accidents that expose the worst consequences of this activity, as tragically demonstrated by the tailings dam failures in Mariana and Brumadinho, both of which occurred in the state of Minas Gerais, Brazil.

The Mariana Dam Disaster[7] in 2015 was one of the largest environmental accidents in Brazil. The collapse of the Fundão dam, owned by the company Samarco, released more than 60 million cubic meters of mining tailings, causing a wave of mud that traveled hundreds of kilometers along the Doce River. This event devastated communities, destroyed aquatic and terrestrial habitats, and affected the health and livelihoods of thousands of people. The environmental impact was catastrophic, resulting in soil and water contamination and the irreparable loss of biodiversity. Full recovery of the affected area is still underway, and a series of ongoing legal disputes and agreements aim to compensate and rebuild the affected communities.

Less than four years later, in 2019, the Brumadinho Dam Disaster[8] occurred. The collapse of the Córrego do Feijão dam, owned by the company Vale, caused an even greater

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[6] Available at: https://seeg.eco.br/. Accessed on: June 4, 2024.

[7] Detailed information about the disaster can be found in the report Assessment of the Effects and Consequences of the Fundão Dam Collapse in Mariana, MG, prepared by the Fundão Dam Task Force, established by the Government of Minas Gerais through Decree No. 46,892/2015, and in subsequent releases by the State Department of the Environment. Available at: http://www.meioambiente.mg.gov.br/images/stories/2016/DESASTRE_MARIANA/Relat%C3%B3rios/Relatorio_final.pdf. Accessed on: June 7, 2024.

[8] Detailed information about the disaster can be found in the final report of the Parliamentary Commission of Inquiry (CPI – *Comissão Parlamentar de Inquérito*) on the Brumadinho Dam, established by the Legislative Assembly of the State of Minas Gerais. Available at: https://mediaserver.almg.gov.br/acervo/439/372/1439372.pdf. Accessed on: June 7, 2024.

human tragedy, causing over 270 fatalities. The mud released by the rupture flooded nearby areas, destroying houses and farms and severely impacting local infrastructure. Beyond the physical devastation and loss of life, the disaster had long-term effects on water and soil quality, as well as on the regional economy.

Both cases highlight the severe consequences that can result from disasters associated with mining activity. Unfortunately, the situation in the state of Minas Gerais is particularly concerning. According to the Risk Category and Potential Damage Matrix for Dams, summarized in a sectoral report by the BNDES (CARVALHO et al., 2018), Minas Gerais not only has by far the highest concentration of dams in the country but also those with the greatest potential risk of collapse and resulting damage. In addition to this adverse scenario, there is evidence that the management of these dams may present a series of deficiencies that amplify the potential risk (BOTELHO et al., 2023).

The process of regressive specialization in the economy of Minas Gerais has led to an increasing pursuit of mineral resources. The growing global demand for minerals in the context of the energy transition—including high-value rare minerals—may result in the expansion of mining areas (SONTER et al., 2023; MARÍN; GOYA, 2021). The trend, therefore, is that mining operations will move increasingly closer to the state's Conservation Units (REZENDE, 2016). This situation, combined with the lack of public-sector planning, the inadequate use of technical procedures in mine development, inefficiency in regulatory control, and the absence of proper environmental recovery measures, has been generating significant social, environmental, and economic conflicts (REZENDE, 2016).

The Mariana (2015) and Brumadinho (2019) disasters—both caused by the collapse of mining tailings dams—led to a series of significant developments in the regulatory framework for mining in Minas Gerais, with impacts at both the state and federal levels. At the federal level, notable changes were introduced to the National Dam Safety Policy (PNSB – *Política Nacional de Segurança de Barragens*) through Law No. 14,066/2020. The main changes include the prohibition of new upstream dams, with existing structures of this type required to be decommissioned by 2027, as well as the introduction of stricter risk classification criteria, more rigorous safety protocols, and stronger penalties for companies that fail to comply with safety standards. Also at the federal level, the establishment of the National Mining Agency (ANM – *Agência Nacional de Mineração*)—which replaced the former National Department of Mineral Production (DNPM – *Departamento Nacional de Produção Mineral*)—expanded the agency's functions to more effectively oversee mining activities in Brazil.

In Minas Gerais, environmental protection is guaranteed by the State Constitution of Minas Gerais, in accordance with the Federal Constitution. The State Secretariat for the Environment and Sustainable Development (SEMAD – *Secretaria de Estado de Meio Ambiente e Desenvolvimento Sustentável*) is responsible for coordinating the State System for the Environment and Water Resources (SISEMA – *Sistema Estadual de Meio Ambiente e Recursos Hídricos*), and mining enterprises seeking environmental licensing must consult this Secretariat. In 2002, COPAM Directive No. 62 established "criteria for classifying containment dams for tailings, waste, and water reservoirs in industrial and mining enterprises in the State of Minas Gerais" (COPAM, 2002). This directive was amended and supplemented by COPAM Directive No. 87 (COPAM, 2005) and later by COPAM Directive No. 124 (COPAM, 2008). In 2006, COPAM Directive No. 94 determined that entrepreneurs engaged in activities with significant environmental impact must comply with the guidelines and procedures established in that directive concerning environmental compensation (COPAM, 2006). IEF Ordinance No. 30/2015 established the procedures related to environmental compensation arising from the removal (cutting or clearing) of native vegetation in the Atlantic Forest biome (IEF, 2015). In 2016, Decree No. 46,993 (Minas Gerais, 2016c) established the Extraordinary Technical Audit for Dam Safety. Joint Resolution SEMAD/FEAM No. 2,372/2016 set forth guidelines for conducting the Extraordinary Technical Audit of Tailings Dam Safety. In 2018, COPAM Directive No. 220 "established guidelines and procedures for the temporary suspension of mining activity and for mine closure; defined criteria for the preparation and submission of the Mining Activity Suspension Report, the Degraded Area Recovery Plan (PRAD – *Plano de Recuperação de Áreas Degradadas*), and the Mine Closure Environmental Plan (PAFEM – *Plano Ambiental de Fechamento de Mina*); and provided other related measures" (COPAM, 2018b).

At the state level, a more recent milestone was the enactment of State Law No. 23,291/2019—known as the "Mar de Lama Nunca Mais" ("Sea of Mud Never Again") Law—which prohibits upstream dams in the state, requires the decommissioning of existing upstream structures by 2023, and expands safety criteria by mandating Emergency Action Plans (PAEs – *Planos de Ação de Emergência*) for all mining dams classified as high risk. There have also been significant changes in the environmental licensing process in Minas Gerais, making it more stringent through the classification of dams by environmental risk and the adoption of more restrictive licensing procedures for new mining projects. Oversight has been expanded, with mandatory continuous monitoring of dams using technologies such as drones, radars, and satellites, along with the requirement for independent technical audits. Social responsibility has been reinforced through the creation of a Watershed Recovery and Rehabilitation Fund, which supports environmental and social recovery actions in affected areas, including compensation for victims and the reconstruction of degraded infrastructure and ecosystems. Mining companies operating in Minas Gerais have also faced growing international pressure from investors and markets to adopt more responsible and transparent practices, with environmental and safety certifications becoming increasingly strict prerequisites for participation in the global mining market.

This context raises a complex question about how to reconcile mining development with sustainability—ensuring both the future supply of minerals and the preservation of the environment—while simultaneously strengthening the economy of the state of Minas Gerais with gains in complexity and resilience. Therefore, the strategy most widely debated is perhaps the decarbonization of the sector, making it essential to discuss the potential pathways of this process and its possible implications.

4. Decarbonization of the Mining Sector

The Mariana and Brumadinho disasters not only underscore the inherent challenges of mining but also serve as a warning of the need for structural changes in the sector. The pursuit of more sustainable and safer models of mineral extraction is critical to preventing similar events in the future and to protecting communities and the environment from irreversible harm. The main strategy that has emerged is decarbonization. Although it unequivocally points toward a significant reduction in sectoral emissions, there are multiple possible pathways related to this strategy, including the incorporation of other sustainability objectives. In general terms, the decarbonization process in the sector will involve three key elements: the use of new energy sources, more efficient processes, and technological innovations (KIRK; LUND, 2018; CASAS et al., 2022; GOVIER et al., 2022; HEBEDA et al., 2023; OLVEDA, 2022). Naturally, these elements are interrelated: the adoption of technological standards is closely tied to the type and availability of energy used and directly affects the production processes employed in the industry.

Energy use is part of the broader context of the high energy intensity involved in mining operations and in the downstream stages of mineral processing, such as metallurgy and steelmaking. The energy used in these operations is generally fossil-based—coal and diesel oil (IGOGO et al., 2020). Some proposals place greater emphasis on the electrification of operations (KIRK; LUND, 2018), usually through the adaptation of machinery and the implementation of renewable energy sources such as solar panels near mining sites. Other approaches are more flexible and advocate for better use of new resources, such as biomass (HEBEDA et al., 2023) and hydrogen (SILVA, 2021). In the Brazilian case, charcoal—considered a form of biomass—has already been used, representing a distinctive feature of the sector in this country.

In the study *Pathways for Deep Decarbonization of the Brazilian Iron and Steel Industry* (HEBEDA et al., 2023), a model was proposed that minimizes mitigation costs by considering a set of measures—such as energy efficiency technologies and innovative production routes—conditioned by the availability of raw materials and the diffusion of new technologies. Moreover, the model stands out for incorporating crucial elements of a circular bioeconomy strategy, including the supply of scrap and biomass, as well as biomass-based production technologies. This type of approach a priori presents synergies with another key sector of the economy of Minas Gerais, notably agriculture, which is a major generator of residues and biomass. However, this strategy alone does not ensure the mitigation of several other mining externalities, such as water contamination.

As mentioned above, energy use is closely linked to the technology and processes adopted in production. Therefore, improvements in energy efficiency and the promotion of innovations aimed at reducing emissions and environmental impacts are of utmost importance. One technology that appears promising for decarbonizing the industry is hydrogen-based Direct Reduction (H-DR) (Fan and Friedmann, 2021; GRIFFITHS et al., 2021; KIM et al., 2022; REN et al., 2021). Vogl et al. (2018) investigated the potential and costs of emission reduction in steel manufacturing using hydrogen. According to their study, this technology could become competitive relative to traditional production, but its viability would depend on the implementation of a carbon market. Thus, several studies emphasize the importance of developing a carbon market as part of the transition process (Vogl et al., 2018; GROTTERA et al., 2022; HARPPRECHT et al., 2022; HEBEDA et al., 2023).

The stance of consulting firms such as Accenture (GOVIER et al., 2022; JACOBS; KEENAN; CRANMER, 2022), McKinsey (DELEVINGNE, 2020), and Deloitte (2020) already positions the decarbonization process as an opportunity for companies in the sector. Financial incentives resulting from market pressures play a crucial role in shifting mining companies' perspectives toward decarbonization. These companies view this transition as an opportunity to diversify their revenue sources: first, by extracting and selling raw materials essential to the energy transition, such as copper, lithium, cobalt, and nickel, taking advantage of the growing demand for sustainable technologies such as batteries; second, by charging premiums for low-carbon products, thereby gaining a competitive advantage; and third, by enhancing corporate value through improved brand reputation and public image. In any case, consulting firms acknowledge that the success of the decarbonization process depends on several key conditions, such as the incorporation of new technologies and the establishment of a regulatory environment conducive to change.

One of the central technologies in the decarbonization debate is digital-based technology. This category includes artificial intelligence, the Internet of Things, cloud computing, blockchain, and other tools that can be used to optimize processes, reduce energy consumption, and promote the adoption of renewable energy sources. The combination of the transition to a green economy with the incorporation of digital-based technologies—also known as Industry 4.0—has come to be referred to as the "twin transition" (BIANCHINI; DAMIOLI; GHISETTI, 2023). However, the adoption of these technologies in the mining sector remains low, despite the growing interest among companies (SÁNCHEZ; HARTLIEB, 2020).

A recent report by UNCTAD (2023), which examines options for developing countries in terms of greening and digitalization, points out that mining can pose a challenge for advanced digital technologies, as it is a sector where implementing and developing tools such as IoT is relatively difficult due to environmental conditions involving dust, high humidity, and often remote locations with limited connectivity. However, this does not prevent the onset of a profound digital transformation that is already underway in the mining industry.

Considering a fully automated mine model, it would employ a fiber-optic network designed to control and monitor surface-level operations, incorporating an automated transportation system, automated handling stages, and digitalization. This is expected to reduce costs by around 30 percent and improve efficiency and productivity, as machines can operate 22 hours a day without downtime for shift changes. According to Sánchez and Hartlieb (2020), new digital technologies have the potential to bring about operational changes across the entire mining value chain. For instance, smart operation centers are being implemented for both extraction and processing activities. Likewise, augmented and virtual reality, coupled with digital twin technology, are tools that will improve the design and construction of mining projects as well as extraction and processing operations.

Although the concept of "digital mine" may vary across companies and organizations, it is possible to define a set of core technologies that represent the pillars of digitalization in the mining industry: 1) Automation, Robotics, and Remote Operation: the use of robots in critical activities and remote operation centers (ROCs) improves safety and reduces the number of operators required in hazardous locations; 2) Internet of Things (IoT) and Smart Sensors/Real-Time Data Capture: the establishment of low-cost networks enables real-time data collection from machines and equipment across the entire operation; 3) Artificial Intelligence (AI) and Machine Learning (ML): the use of vast amounts of available data on production, processes, and equipment performance allows for better activity planning and supports fast and effective decision-making processes for operations, in addition to predictive models that improve equipment maintenance and the use of AI/ML methods for mineral prospecting; 4) Digital Twins: the construction of digital models of physical operations using geological and engineering information from the site, along with real-time data generated by connected sensors during operation.

Approaches based on the twin transition framework emphasize that the implementation of these technologies can serve three main objectives: increasing profitability; reducing emissions, notably through efficiency gains; and potentially mitigating other externalities and accident risks. The latter could be achieved by enhancing the precision of mining and industrial operations (SÁNCHEZ; HARTLIEB, 2020; OLVERA, 2022). It is also possible to envision the development of more sophisticated technologies through sectoral synergies, such as nanotechnology and biotechnology for waste-processing management, or the use of big data and artificial intelligence for accident prediction (SÁNCHEZ; HARTLIEB, 2020; OLVERA, 2022). However, questions remain as to whether the increased use of electricity and rare materials driven by digitalization will be offset by efficiency gains and sustainable behaviors promoted by these innovations (ANDERSEN et al., 2021), and what social and sustainability risks may arise from the incorporation of such technologies depending on how they are developed and implemented (MÄKITIE et al., 2023).

The emission process does not occur exclusively during the extraction and processing of minerals but is also closely linked to the energy used in commercial logistics and to the waste generated by operations (GOVIER et al., 2022). In fact, influencing the structure of the mining sector and its relationship with other stages in the chain is fundamental to reducing emissions in the sector, as low-emission mining is useless if it is associated with highly polluting or fossil fuel-powered processing industries. The decarbonization process cannot be viewed as limited exclusively to the industry itself, as it requires the engagement of other sectors, such as energy and transportation. There is no real benefit in achieving energy efficiency gains and electrifying a significant share of industrial processes and machinery if the energy matrix is not clean. Similarly, there is no point in having a “clean” mine if logistics and downstream operations are not decarbonized as well.

Regarding the mining sector in Brazil—particularly in Minas Gerais—the growing demand for sustainable social and environmental practices, the spread of innovative technologies, and structural interventions are highlighted as the main drivers of change in the industry (CARVALHO et al., 2018). In terms of efficiency gains, there are currently opportunities to improve productivity in electricity use, even though the industry is already relatively efficient in its use of diesel oil. The incorporation of new technologies will be a critical factor in achieving significant decarbonization gains, as will investments in infrastructure and logistics (HEBEDA et al., 2023).

Other externalities of mining activity—such as waste management and the recovery of degraded areas—also deserve special attention. Although this debate has already been the subject of several reports and proposals concerning decarbonization (KIRK; LUND, 2018; IGOGO et al., 2020), there is still a lack of focus on how these problems can be addressed at the local level, considering that the environmental impacts of mining activities also affect public health, particularly that of surrounding populations (REIS; MOROZESK, 2022; DE FREITAS MUNIZ; OLIVEIRA-FILHO, 2006).

The state of Minas Gerais is characterized by an extensive presence of extraction areas (REZENDE, 2016). Thus, decarbonizing the sector through technologically advanced, energy-efficient mines powered by clean energy—although representing major progress—must also include effective local strategies for risk management, waste handling, and the recovery of degraded areas.

5. Implications of Decarbonization

The implications of decarbonization for mining activities in Minas Gerais are broad and complex, encompassing economic, environmental, social, and technological dimensions. The main implication of decarbonization is the reduction of carbon emissions. This can be achieved through the electrification of operations, the use of renewable energy sources, the adoption of hydrogen, and the implementation of digital-based technologies. In the short term, adopting more efficient processes and minimizing the use of fossil fuels such as coal and diesel oil can already lead to reductions in emission levels. Naturally, a broader transition process will require the coordination of multiple actors (OLVERA, 2022) and a favorable environment for the reorganization of these operations (GOVIER et al., 2022; HEBEDA et al., 2023).

Depending on how the mineral-based value chains are restructured in pursuit of greater sustainability, the state of Minas Gerais may benefit to varying degrees from the incorporation of new production paradigms. The state could evolve from its traditional position as a technology importer and mineral producer and exporter toward the local development of part of the technology employed, thereby generating greater productive density and diversification. Although in both cases it is possible to envision production with a smaller carbon footprint, in the latter scenario the state could reap broader economic benefits—such as increased job and income generation—while also leveraging local synergies, such as the development of biotechnology-related value chains, to further promote sustainable development.

The adoption of renewable energy sources such as solar and wind power is already available to companies, and there is room for their implementation in the case of Minas Gerais, since a significant share of the energy used still comes from diesel oil (FIGUEIREDO; DA SILVA; ORTIZ, 2023). There are also indications of potential use of alternative sources such as biomass (HEBEDA et al., 2023) and hydrogen (SILVA, 2021; FIGUEIREDO; DA SILVA; ORTIZ, 2023), although further studies are needed for their implementation. In any case, improving the sector's energy efficiency is essential—through the optimization of industrial processes, the use of more efficient machinery, and the implementation of technologies that reduce energy waste (KIRK; LUND, 2018; CASAS et al., 2022; GOVIER et al., 2022). Achieving these goals will, to a greater or lesser extent, require the incorporation of new technologies into the production process, including machinery adaptation, the development of new extraction methods, and the adoption of digital-based technologies.

If the decarbonization process becomes more ambitious and targets downstream sectors of the value chain—such as steelmaking—the state of Minas Gerais could achieve significant emission reductions. It is worth noting that, according to data from the Brazil Steel Institute (Instituto Aço Brasil, 2024), Minas Gerais was the leading producer of the country's three main steel products: pig iron, crude steel, and semi-finished rolled products. Strengthening the value chain and seeking to add value to production could yield advantageous outcomes in terms of economic value per unit of emissions. Moreover, by targeting downstream sectors such as steelmaking, Minas Gerais could position itself as a leader in sustainable mining practices (GOVIER et al., 2022; HEBEDA et al., 2023). However, coordination between public and private actors will be necessary to develop new technologies and invest in infrastructure. The logistics process is also an important component of sectoral decarbonization (GOEDHALS-GERBER; FREIBOTH; HAVENGA, 2018) and must be aligned with the intended destination of the product.

It is also important, when exploring the opportunities associated with decarbonization, to consider the possibility of linking this process to the incorporation of digital-based innovations in mining—what the literature refers to as a "twin transition." A recent report by Accenture (2023) identifies several potential impacts of digitalization on the mining sector: operational optimization, particularly in reducing truck loading queue times; the use of advanced analytical solutions for planning and dispatch to improve operational efficiency and reduce energy consumption inefficiencies; the use of AI and telemetry to monitor road and equipment conditions and generate real-time, large-scale operational recommendations; and automation and control systems capable of detecting and responding to idle equipment, such as conveyor belts. Moreover, advanced digital technologies—such as data analytics, artificial intelligence (AI), and blockchain—will also be essential for achieving and monitoring decarbonization performance. This includes the deployment of solutions such as green hydrogen, through the adoption of hydrogen fuel cell technology to power machinery and transportation, as well as the use of alternative fuels in pelletizing. However, leveraging the opportunities offered by advanced digital technologies requires coordinated political efforts and targeted investments in infrastructure to support mine digitalization, along with education and training programs to mitigate the impact on low-skilled labor. Therefore, policies and regulations play a crucial role in fostering innovation in the sector, for example, by creating pressure through stricter environmental standards.

Finally, there is a need for more active engagement by public authorities at different levels in the regulation and oversight of the sector's activities. The role of the state is essential in managing the externalities and risks arising from mining. Efforts must continue to be directed toward the prevention of disasters such as those of Mariana and Brumadinho. Efforts must continue to be directed toward the prevention of disasters such as those of Mariana and Brumadinho. Under no circumstances can the sector's decarbonization process accommodate the possibility of such accidents, whose impacts are irreversible—especially in the case of Minas Gerais, where the highest-risk dams are located. In other words, all actors directly or indirectly involved in production must exercise the highest level of precaution.

6. Conclusion

Decarbonization must be accompanied by effective waste management and actions aimed at the recovery of degraded areas. As discussed in Section 2—Risks and Impacts of Mining—the populations and ecosystems surrounding mining sites are particularly vulnerable to the externalities arising from mining activities. The waste and environmental risks inherent to mining can cause significant impacts in nearby regions, with serious consequences for the environment and public health, in addition to harming other economic activities that are important for the state, such as agriculture and livestock production.

Therefore, mitigating these risks and externalities must be a priority for the sector. This involves not only the adoption of more sustainable technologies and practices but also a serious commitment to the safety and integrity of mining operations. The severity of disasters such as those of Mariana and Brumadinho underscores the need for stricter oversight frameworks and proper governance, both on the part of companies and public authorities.

The decarbonization of the sector involves research, development, and the implementation of new technologies—including digital-based ones—as well as the utilization of existing technologies that remain underused in the industry. This scenario can be seen as a window of opportunity for the economy of Minas Gerais, provided that the region develops potential players in technological innovation for the sector. Such developments could greatly benefit the state's economy and generate greater productive density in an activity that has historically demonstrated a competitive advantage.

If a productive structure capable of meeting the sector's decarbonization demands is effectively developed, this technological base could later be adapted to other value chains, leveraging synergies with existing local activities and fostering the growth of additional local suppliers.

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