

Regional Impacts of Iron Ore Production Trajectories in Minas Gerais, Brazil: Evidence from a Dynamic Interregional CGE Model

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Abstract

This paper assesses the long-run regional economic impacts of alternative iron ore production trajectories in Minas Gerais, Brazil, using a dynamic, bottom-up interregional Computable General Equilibrium (CGE) model with thirteen Intermediate Geographic Regions (RGInts) plus a Rest of Brazil block and twenty-three productive sectors. Iron ore output paths are obtained from an econometric projection that decomposes Brazilian beneficiated production into export and domestic-consumption components, the former associated with Chinese import demand and the latter with national GDP growth. The projected trajectories are introduced into the model as exogenous shocks to the activity level of iron ore extraction, and the resulting deviations from a reference path are reported for output, household consumption, employment and investment at the regional and sectoral levels. The simulations indicate that a contraction of iron ore production propagates well beyond the extractive sector, transmitted through the mineral–metallurgical chain into steel, fabricated metal products, construction and motor vehicles. Accumulated losses are concentrated in highly specialised regions such as Barbacena and in the largest producing region, Belo Horizonte, while more diversified economies absorb the shock more readily. The pattern is consistent with the regional resource-curse and economic-resilience literatures and underscores the role of productive diversification in mitigating exposure to mineral-sector shocks.

Keywords: iron ore; Minas Gerais; computable general equilibrium; regional economics; mineral dependence; economic resilience.

1. Introduction

Minas Gerais has been shaped by mining since its colonial origins, a legacy encoded in the state name and perpetuated in its contemporary economic structure. The state remains one of the central pillars of Brazil's mineral economy, particularly through iron ore extraction. Together with Pará, Minas Gerais accounted for approximately 74.5% of the value of national mineral production in 2022 (GOVERNO DE MINAS GERAIS, 2025, p. 14). Metallic minerals dominate the state's output, representing about 92.3% of the value of mineral production, of which iron ore alone corresponds to roughly 80.7% of the commercialised value (GOVERNO DE MINAS GERAIS, 2025, p. 15). Over the 2010–2022 period, iron ore represented on average 84.2% of the commercial value of the state's mineral output, with gold accounting for a further 8.8% (GOVERNO DE MINAS GERAIS, 2025, p. 14). This concentration underscores the strategic relevance of iron ore not only for the mining sector itself, but for the broader economic performance of the state.

The economic weight of iron ore extends beyond production values. In 2023, mineral products accounted for approximately 51.9% of the state's total exports, with iron ore as the dominant

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commodity and China as the main destination (GOVERNO DE MINAS GERAIS, 2025, p. 15). The sector is also a relevant source of employment: in 2021, mining and mineral-processing activities supported around 360 thousand formal jobs in the state, distributed between extractive activities (about 20%) and mineral-transformation industries (about 80%) (GOVERNO DE MINAS GERAIS, 2025, p. 15). In fiscal terms, mining royalties (Compensação Financeira pela Exploração Mineral, CFEM) reached R\$ 3.18 billion in 2023, with marked territorial concentration in mining-dependent regions (GOVERNO DE MINAS GERAIS, 2025, p. 15).

This centrality is accompanied by a high degree of structural dependence. The productive base of several regions within Minas Gerais is closely tied to iron ore extraction and to the mineral–metallurgical chain, including pig iron, steelmaking and fabricated metal products. Input–output analyses conducted for the state identify iron ore extraction and related metallurgical activities as key sectors in several Intermediate Geographic Regions (RGInts), owing to their strong backward and forward linkages (GOVERNO DE MINAS GERAIS, 2025, p. 17). These linkages amplify the short- and medium-term benefits of mining, but they also reinforce regional exposure to sector-specific shocks, particularly in territories with limited economic diversification.

The vulnerability associated with mineral dependence is not merely theoretical. The end of the international commodity supercycle in the early 2010s, and the associated decline in iron ore prices, was followed by reduced revenues, fiscal stress and employment losses in mining municipalities, a dynamic consistent with the limited economic resilience of specialised extractive territories (ENRÍQUEZ, 2007; GONÇALVES, 2013). From a broader development perspective, the literature has long emphasised that extractive-led growth, while capable of generating substantial revenues in the short run, does not automatically translate into sustained regional development in the absence of deliberate diversification strategies and sound intergenerational planning (SACHS; WARNER, 1995; AUTY, 2001).

Looking forward, the trajectory of iron ore production in Minas Gerais is subject to several structural uncertainties. A first source lies in global demand dynamics, particularly those associated with China, the world's largest iron ore importer and the main destination of the state's exports; changes in China's growth model, in steel demand and in import strategies can substantially affect international markets (GOVERNO DE MINAS GERAIS, 2025, p. 249–250). A second source stems from the low-carbon transition. Approximately 98% of mined iron ore is used in steelmaking (USGS, 2024; WORLD STEEL ASSOCIATION, 2023), and the steel industry is undergoing technological change aimed at reducing emissions, including greater use of scrap and electric arc furnaces, which tends to lower demand for primary iron ore, particularly for lower-grade ores (INTERNATIONAL ENERGY AGENCY, 2020; GOVERNO DE MINAS GERAIS, 2025, p. 251–252).

The transition is not, however, only a source of downside risk. The Plano Estadual de Mineração de Minas Gerais notes that Brazilian pig iron produced from sustainably managed charcoal, combined with an electricity matrix dominated by hydropower, confers a comparative advantage in low-carbon steel that may become a competitive differential, especially in the European market (GOVERNO DE MINAS GERAIS, 2025). Decarbonisation therefore operates simultaneously as a threat to undifferentiated primary-ore demand and as an opportunity for low-emission segments of the chain. A third source of uncertainty is geological and environmental: reserves are finite, higher-grade deposits are progressively depleted, and concentration routes such as flotation are gaining prominence as ore grades decline (GOVERNO DE MINAS GERAIS, 2025). Stricter environmental regulation, heightened scrutiny following tailings-dam failures, and climate-related risks such as increased rainfall intensity may further affect operating conditions (GOVERNO DE MINAS

GERAIS, 2025, p. 260–262). Together, these factors imply that the continuation of iron ore production at historical levels cannot be assumed over the long term.

In this context, scenario-based economic analysis is a useful tool for understanding the consequences of alternative production paths. CGE models are well suited to this purpose: unlike partial-equilibrium or reduced-form approaches, they capture economy-wide interactions, intersectoral linkages, factor-market adjustment and regional spillovers, enabling an assessment of how a change in one sector ramifies across the broader economy. The present study integrates an econometric projection of iron ore output with a dynamic interregional CGE model to examine how a slowdown in iron ore production may propagate through the economy of Minas Gerais and affect its regions unevenly. The analysis provides quantitative evidence to support discussions on economic diversification, regional development and long-term planning under increasing uncertainty surrounding the future of mining in the state.

2. Productive Structure and Regional Dependence

2.1 Spatial and economic context

Minas Gerais is located in the Southeast of Brazil and is the country's fourth largest state by area, at approximately 586.5 thousand square kilometres, and its second most populous, with around 20 million inhabitants (IBGE, 2023). Its territory encompasses the Quadrilátero Ferrífero, a mineral province in the southern portion of the São Francisco Craton that hosts one of the most significant iron ore concentrations in the world and has historically anchored the state's extractive activity (GOVERNO DE MINAS GERAIS, 2025). For analytical purposes, this study adopts the Intermediate Geographic Regions (RGInts) defined by IBGE in 2017, which group municipalities around regional urban centres and provide a consistent territorial unit for interregional analysis.

Figure 1 situates the study area. Minas Gerais comprises thirteen RGInts, ranging from the metropolitan region of Belo Horizonte to the predominantly agricultural regions of the Triângulo Mineiro and the north of the state. This territorial division organises the entire analysis that follows.



Figure 1. Intermediate Geographic Regions (RGInts) of Minas Gerais, 2017
Source: GOVERNO DE MINAS GERAIS (2025); base cartography FJP (2017) and IBGE (2017).

2.2 The role of mining in the state's productive structure

Mining and the associated metallurgical industries occupy a structural position in the economy of Minas Gerais that exceeds their direct share in output. The mineral chain links extraction to downstream transformation, notably pig iron, ferro-alloys, crude and semi-finished steel, flat-rolled products and fabricated metal goods. In 2019, the Brazilian mineral chain as a whole moved R\$ 183.3 billion, of which 43% originated in extractive mineral products and 57% in mineral-transformation products (GOVERNO DE MINAS GERAIS, 2025), an indication of the economic relevance of the segments located downstream of extraction. Minas Gerais is central to this chain: the state concentrates a substantial fraction of national production in iron ore and in several metallurgical activities.

This role is territorially uneven. Belo Horizonte is by far the dominant producing region, concentrating roughly 47.6% of national iron ore output and about 17.7% of national pig iron and ferro-alloy output. Other regions occupy specific positions in the chain: Barbacena accounts for approximately 6.1% of national iron ore production, while Uberaba combines a relevant share of national non-metallic mineral output, about 9.2%, with a notably high share of national pig iron and ferro-alloy production, about 20.6%. Patos de Minas stands out in non-ferrous metallic minerals, with around 11.3% of national output (GOVERNO DE MINAS GERAIS, 2025). These figures, summarised in Figure 3, show that the state's mineral relevance is distributed across regions with distinct specialisations rather than concentrated in a single productive profile.

The spatial footprint of extraction is itself concentrated. Figure 2 maps the municipalities that encompass the principal iron ore districts of the state, which are clustered in the central and central-southern portions of Minas Gerais, in and around the *Quadrilátero Ferrífero*. This spatial concentration foreshadows the regional unevenness of the impacts examined below.

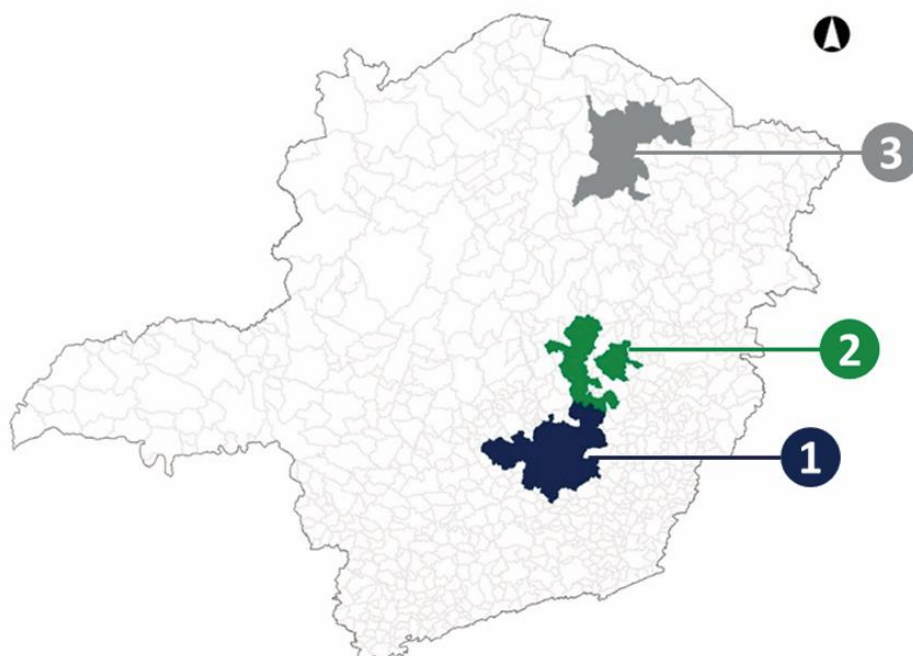


Figure 2. Spatial distribution of the municipalities encompassing the iron ore districts of Minas Gerais
Source: GOVERNO DE MINAS GERAIS (2025, p. 44).

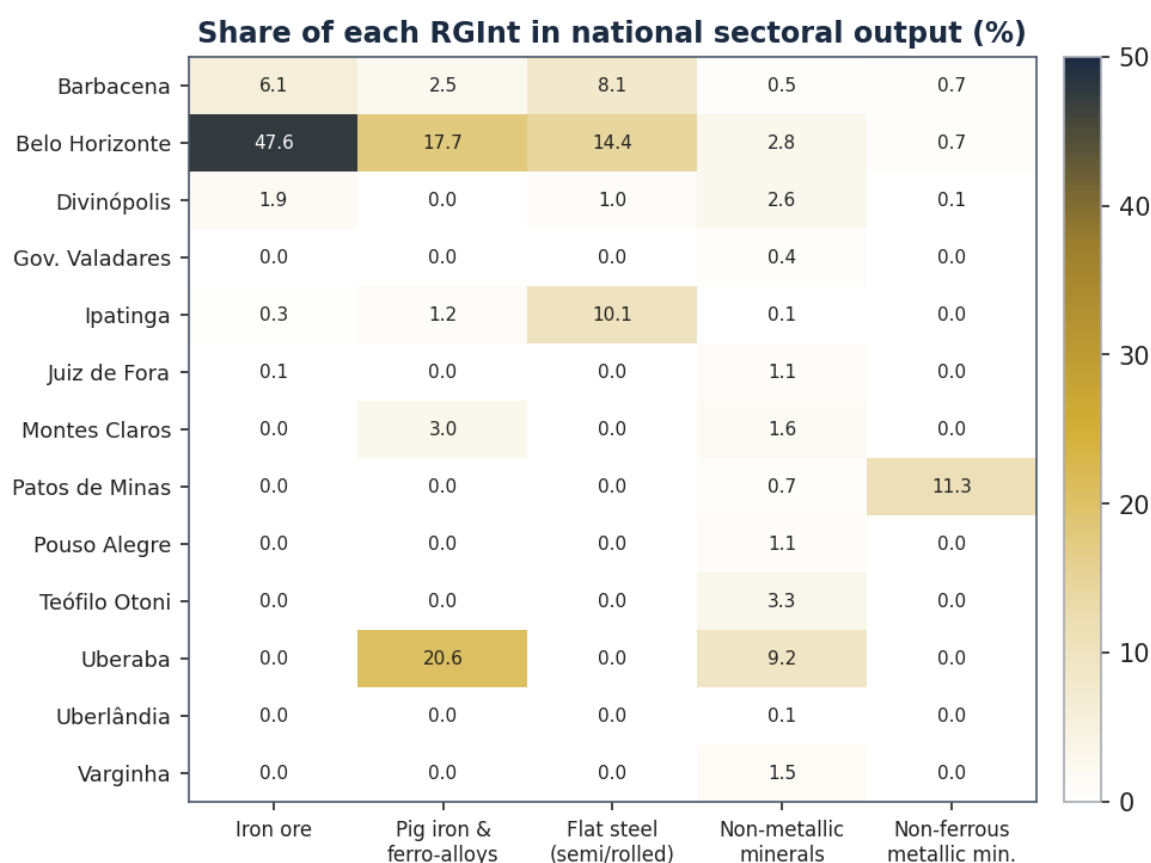


Figure 3. Share of each RGInt in national sectoral output, selected sectors (%)

Source: Prepared by the author from input–output data reported in GOVERNO DE MINAS GERAIS (2025) and FJP (2022).

2.3 Regional heterogeneity and economic specialisation

The dependence of each region on the mineral chain is better captured by the weight of these activities within the regional economy than by their share in national totals. Figure 4 reports the participation of selected sectors in the productive structure of each RGInt. The contrast is pronounced. In Barbacena, flat steel and semi-finished products represent about 25.2% of the regional economy and iron ore extraction a further 11.2%, so that the mineral–metallurgical chain alone accounts for more than a third of regional activity. In Ipatinga, semi-finished and flat steel products reach approximately 27.0% of the regional economy, reflecting the presence of integrated steelmaking. By contrast, in regions such as Uberlândia, Pouso Alegre, Montes Claros and Juiz de Fora the same activities represent only a marginal fraction of the regional product, indicating more diversified economic bases.

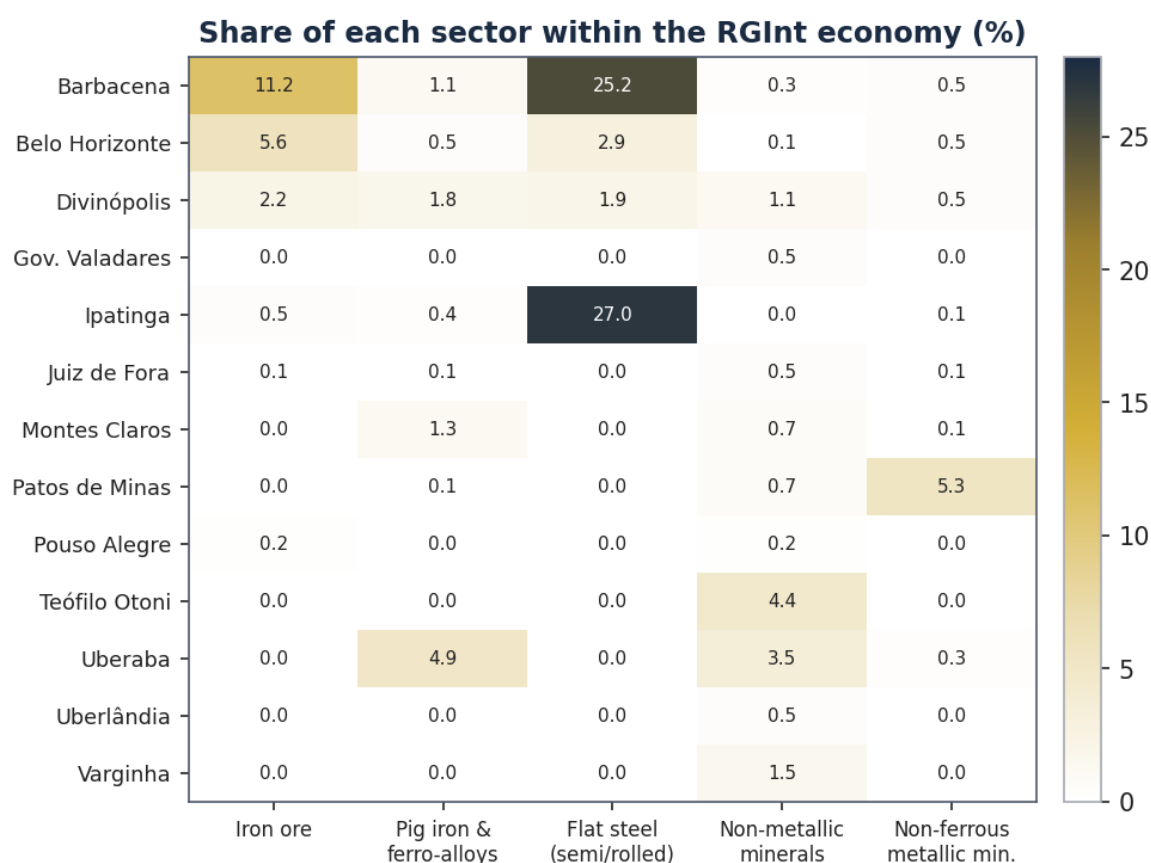


Figure 4. Share of selected sectors within each RGInt economy (%)

Source: Prepared by the author from input–output data reported in GOVERNO DE MINAS GERAIS (2025) and FJP (2022).

This heterogeneity is central to the analysis that follows. Regions in which the mineral chain represents a large share of local activity are, by construction, more exposed to fluctuations in iron ore production, whereas diversified regions possess alternative sources of income and employment that can cushion sector-specific shocks. The spatial concentration of exposure, rather than the aggregate weight of mining in the state, is what determines the regional distribution of impacts.

2.4 Sectoral integration, key sectors and economic complexity

Beyond their direct weight, mineral and metallurgical activities are embedded in dense networks of intersectoral transactions. To characterise these linkages, the state mining plan applies Rasmussen–Hirschman backward and forward linkage indices together with pure linkage indices, computed from the Minas Gerais input–output matrix (FJP, 2022). On this basis, the extractive industry is identified as a key sector, that is, a sector with simultaneously high backward and forward linkages, in three RGInts, and metallurgical activities appear as key sectors in additional regions (GOVERNO DE MINAS GERAIS, 2025, p. 17). Sectors with this profile transmit shocks with particular intensity, because a change in their activity level propagates both upstream, through demand for inputs, and downstream, through the supply of intermediate goods to other industries.

The degree of economic complexity reinforces this reading. Using the Economic Complexity Index, the state plan identifies Belo Horizonte, Divinópolis and Ipatinga as the regions with the highest complexity in Minas Gerais (GOVERNO DE MINAS GERAIS, 2025). Higher complexity is generally associated with a more diversified and sophisticated productive base, which provides greater

capacity to reallocate resources and to absorb sector-specific shocks. The coexistence, in regions such as Ipatinga, of high steel specialisation and relatively high complexity illustrates that exposure and adaptive capacity are distinct dimensions that must be assessed jointly. The interregional CGE model employed in this study operationalises precisely these linkages, allowing the propagation of an iron ore shock through the input–output structure of each region to be quantified.

Figure 5 summarises the structure through which these effects propagate. Iron ore extraction supplies, via forward linkages, the pig iron, steel and fabricated-metal segments, which in turn feed construction and capital-goods industries; the same chain generates backward linkages through the demand for inputs. It is the density of these linkages, rather than the direct size of extraction, that makes the sector a powerful transmitter of shocks in the regions where it operates as a key sector.



Figure 5. The mineral–metallurgical chain and its backward and forward linkages

Source: Prepared by the author, based on the linkage structure reported in GOVERNO DE MINAS GERAIS (2025) and FJP (2022).

3. Projecting Iron Ore Production

The economic simulations require a trajectory of iron ore production over the projection horizon. This section develops that trajectory econometrically. The approach decomposes Brazilian beneficiated iron ore production into its main uses, models the price and the volume components separately, and recombines them into an integrated projection from which the shocks applied to the CGE model are derived.

3.1 Analytical basis: the production identity

Brazilian beneficiated iron ore production is allocated between external and internal markets. Since imports are negligible, production is approximated by the accounting identity in which beneficiated production equals exports plus apparent domestic consumption. This decomposition is analytically convenient because the two components respond to different drivers: exports are governed predominantly by external demand, with China as the dominant destination, while domestic consumption is tied to the activity level of the national steel industry and, more broadly, to domestic economic growth. The historical data confirm the weight of the external market: China alone accounted for between 49.0% in 2010 and 72.6% in 2020 of the volume exported (GOVERNO DE MINAS GERAIS, 2025). The two components are therefore modelled separately and subsequently consolidated.

3.2 Price model

The reference price of iron ore is modelled following the multifactor specification proposed by Hasenclever (2015), adapted and re-estimated for the present analysis. The dependent variable is the monthly iron ore reference price, and the explanatory variables are expressed as first differences of natural logarithms (DLog) of: a commodity futures index (S&P GSCI); Chinese iron ore imports; a currency-basket index; and a market-volatility index. The model is estimated by ordinary least squares over the period from January 2008 to May 2023, comprising approximately 185 monthly observations. The functional form is:

$$D\text{Log}(\text{Price}_t) = \beta_0 + \beta_1 D\text{Log}(\text{Futures}_t) + \beta_2 D\text{Log}(\text{ChinaImp}_t) + \beta_3 D\text{Log}(\text{Currency}_t) + \beta_4 D\text{Log}(\text{Volatility}_t) + \varepsilon_t$$

To generate the price projection, each explanatory variable is first projected using a vector autoregression (VAR), and the resulting paths are then inserted into the estimated price equation. The projected reference price declines from US\$ 120.70 per tonne in 2022 to US\$ 104.58 in 2023 and US\$ 92.48 in 2024, followed by a partial recovery and long-run stabilisation in the range of US\$ 80 to US\$ 90 per tonne (Figure 6). This trajectory is consistent with the convergence of international prices towards levels below the peaks observed during the commodity supercycle, as Chinese import growth decelerates and the steel sector's technological transition advances.

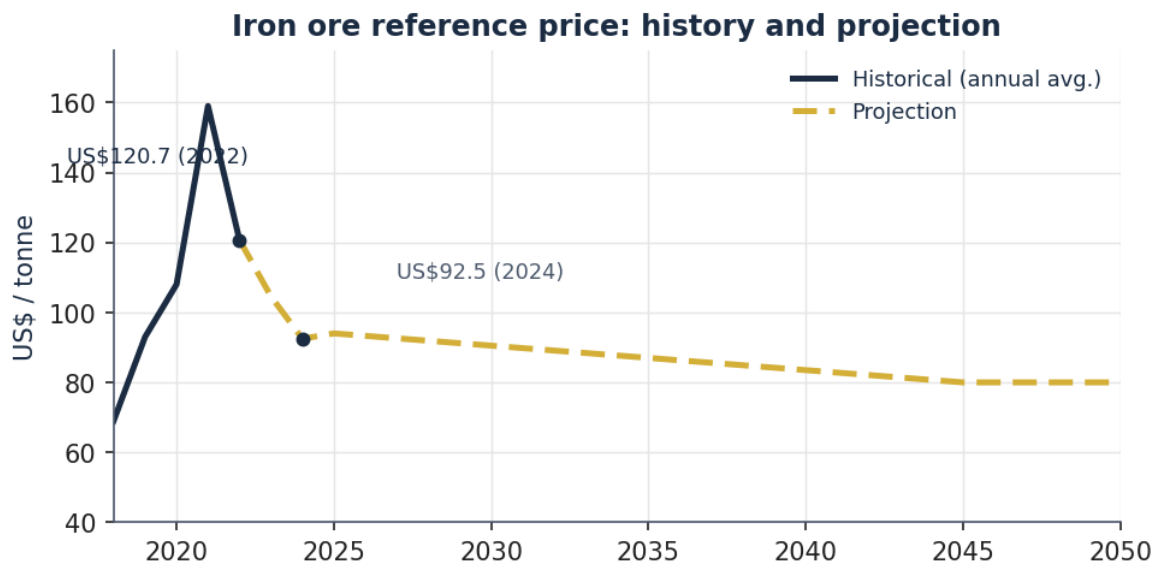


Figure 6. Iron ore reference price: history and projection (US\$/tonne)

Source: Prepared by the author. Historical series compiled from market data; projection estimated as described in the text. Anchor values from GOVERNO DE MINAS GERAIS (2025).

The price equation should be read with caution. The estimation relies on aggregate market indices, and the point estimates of the individual coefficients are sensitive to the sample period and to the treatment of structural breaks, notably the 2008 financial crisis and the 2020 pandemic shock. For this reason, the price model is used here primarily to inform the central tendency and the qualitative shape of the long-run price path, rather than to support precise point forecasts.

3.3 Volume models

The two volume components are estimated as simple log-linear regressions on annual data for the period 2010–2022 (thirteen observations). Export volume is regressed on Chinese import demand,

both in natural logarithms, yielding a positive and economically meaningful association: a 1% increase in Chinese iron ore imports is associated with an increase of approximately 0.23% in Brazilian exports. The estimated equation explains about 52% of the observed variation in exports (Figure 7). Domestic consumption is regressed on the annual rate of growth of Brazilian GDP, with the dependent variable in natural logarithms; the estimated relationship is positive, with a lower explanatory power, accounting for about 28% of the observed variation (Figure 8). The two estimated equations are reported in Table 1.

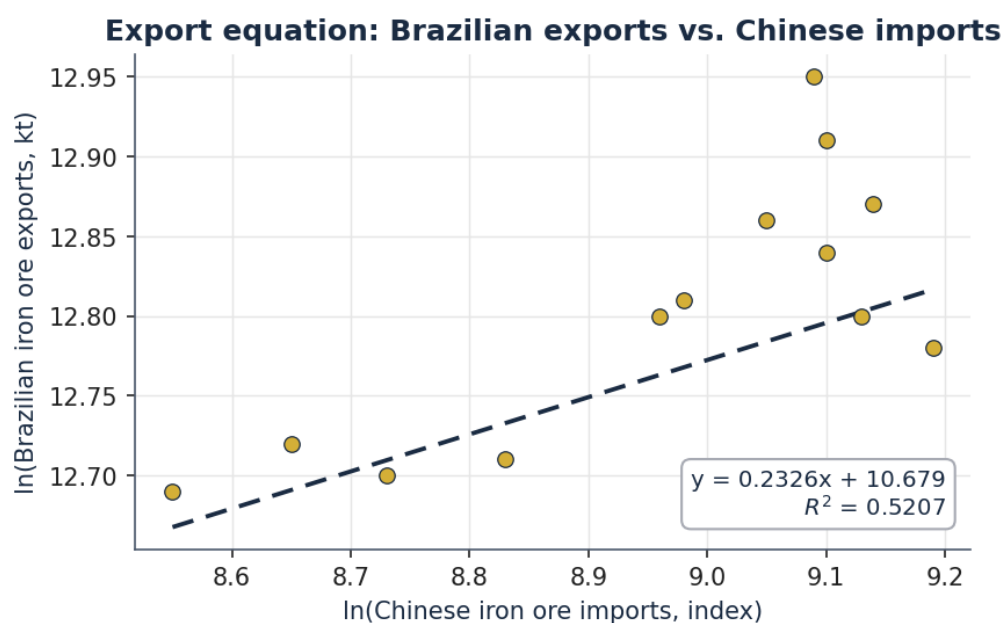


Figure 7. Export equation: Brazilian iron ore exports vs. Chinese imports (logarithms)
Source: Prepared by the author from trade data (MDIC/Comex Stat, 2023) and Chinese import statistics.

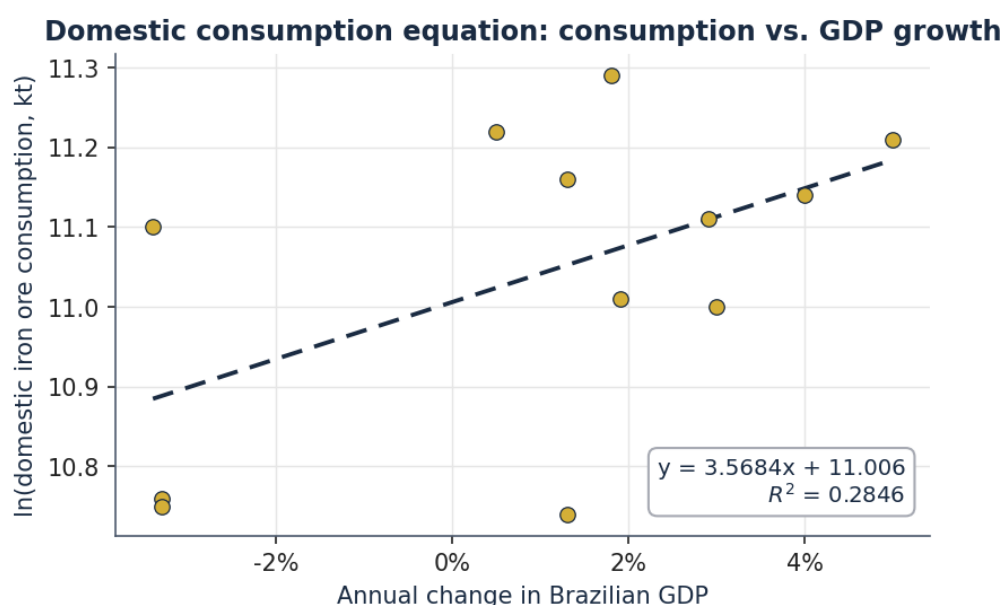


Figure 8. Domestic consumption equation: consumption vs. Brazilian GDP growth
Source: Prepared by the author from production and national accounts data.

Table 1. Estimated volume equations for Brazilian iron ore production

Equation	Specification	Slope coeff.	Intercept	R ²	Obs.	Period
Exports	ln(Exports) on ln(China imports)	0.2326	10.679	0.5207	13	2010–2022
Domestic consumption	ln(Consumption) on ΔGDP	3.5684	11.006	0.2846	13	2010–2022

Source: Estimated by the author by ordinary least squares. Standard errors are not reported owing to the small annual sample; see Section 3.6.

Once the price and the two volume components are projected, they are recombined through the production identity to obtain an integrated projection of beneficiated production in physical terms. Because the projected price stabilises below historical peaks and Chinese import growth decelerates, the consolidated projection implies that beneficiated production tends to settle below the levels observed at the end of the historical period, rather than expanding along the trajectory of the supercycle years.

3.4 Scenarios

Three integrated scenarios are constructed around the central projection. The realistic scenario adopts the baseline assumptions for GDP growth and Chinese import demand. The optimistic scenario combines a more favourable GDP path, drawn from the upper range of market expectations, with a higher trajectory for Chinese imports. The pessimistic scenario combines a GDP path two standard deviations below the baseline market expectation with a lower trajectory for Chinese imports. The scenarios share the same long-run structure and differ in the intensity of the projected adjustment, which is most pronounced at the beginning of the horizon and converges thereafter. Underlying the projections is a marked deceleration of long-run growth in the sector: the implied compound annual growth rate of the value of production falls to about 0.05% per year between 2031 and 2040 and to about 0.02% per year between 2041 and 2050 (GOVERNO DE MINAS GERAIS, 2025).

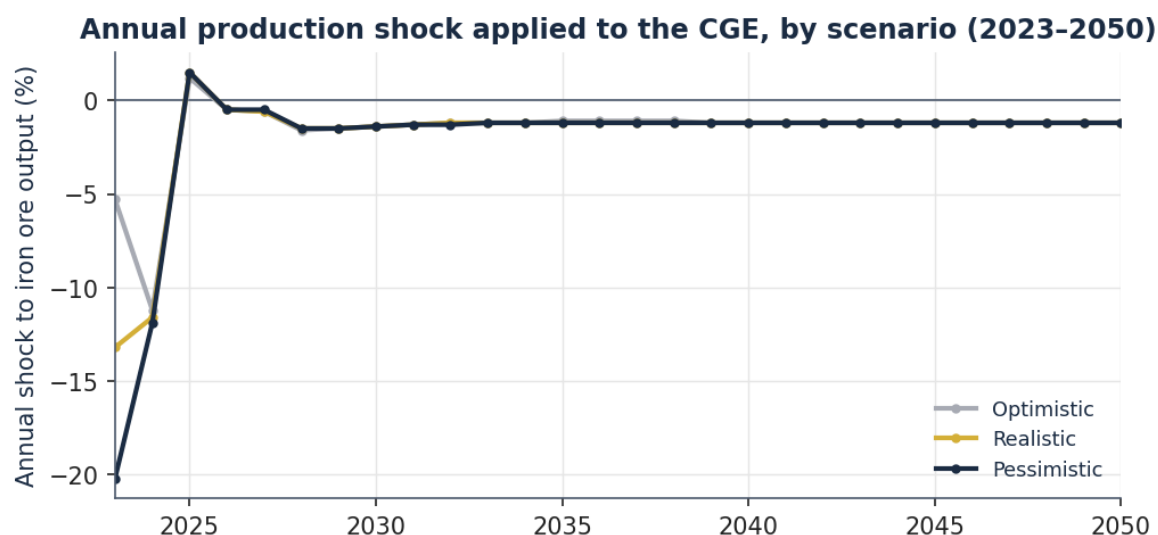
3.5 From projections to model shocks

The integrated production projection is translated into annual shocks to the activity level of iron ore extraction, which are then imposed on the CGE model. Table 2 reports the annual shocks by scenario. In all three scenarios the shock is negative over most of the horizon: production declines sharply in the first two years, relative to the reference path, and then contracts at a moderate and broadly stable rate of about 1.2% per year through to 2050. The scenarios differ chiefly in the magnitude of the initial adjustment, ranging from about -5% to about -20% in 2023, after which they converge. In level terms, beneficiated iron ore production is projected to fall from about 256 Mt in 2022 to a trough of approximately 186 Mt under the pessimistic scenario and 221 Mt under the optimistic scenario in 2024, before stabilising in the range of about 195 Mt to 233 Mt by 2050; the year-on-year variation of this trajectory is applied directly as the shock to the iron ore extraction activity. The shocks are applied uniformly to the iron ore extraction activity across producing regions; the regional differentiation of impacts arises endogenously from the distinct productive structures captured by the model.

Table 2. Annual shock to iron ore production by scenario, selected years (%)

Year	Realistic	Optimistic	Pessimistic
2023	-13.2	-5.3	-20.2
2024	-11.6	-11.2	-11.9
2025	+1.5	+1.2	+1.5
2030	-1.4	-1.4	-1.4
2040	-1.2	-1.2	-1.2
2050	-1.2	-1.2	-1.2

Source: Prepared by the author from the integrated production projection. Full annual series available on request.

**Figure 9.** Annual production shock applied to the CGE, by scenario (2023–2050)

Source: Prepared by the author.

3.6 Limitations of the projection

Several limitations should be acknowledged. First, the volume equations are estimated on short annual samples of thirteen observations, which limits statistical power and precludes a robust treatment of dynamics; the moderate coefficient of determination of the domestic-consumption equation, in particular, indicates that GDP growth alone captures only part of the variation in consumption. Second, the price model relies on aggregate indices and is sensitive to the treatment of structural breaks. Third, and most important from a long-run perspective, the projection does not explicitly model the physical depletion of reserves or the decline in ore grades. Minas Gerais faces a growing number of mines approaching the end of their economic life, and the progressive exhaustion of higher-grade reserves is shifting production towards more capital- and energy-intensive concentration routes such as flotation (GOVERNO DE MINAS GERAIS, 2025). These geological constraints could impose a steeper long-run decline than the one implied by the demand-side projection, and they represent a priority for future refinement of the analysis.

4. Methodology: The Interregional CGE Model

The economic impacts are assessed with a dynamic, bottom-up interregional Computable General Equilibrium (CGE) model of the TERM (The Enormous Regional Model) family, calibrated for Minas Gerais. The model represents thirteen Intermediate Geographic Regions of the state together with a Rest of Brazil region, and disaggregates economic activity into twenty-three productive sectors, including iron ore extraction, non-metallic and non-ferrous mineral extraction, pig iron and ferro-alloys, semi-finished and flat steel, fabricated metal products, motor vehicles and construction, alongside agriculture, services and the remaining industries. The bottom-up specification means that regional results are computed directly rather than derived as shares of a national total, which allows the interregional propagation of shocks to be captured explicitly.

Each regional sector combines intermediate inputs and primary factors, labour, capital and land, under a nested production technology. Substitution between domestically produced and imported goods follows the Armington assumption, and trade among regions is modelled through origin–destination flows that respond to relative prices and transport margins. Household demand is represented by a linear expenditure system derived from a Stone–Geary utility function, distinguishing subsistence and supernumerary expenditure. The model is solved in the Johansen tradition, as a system of linearised equations, and adopts a small-open-economy closure in which world prices of traded goods are exogenous. The dynamic specification is recursive: each period is solved sequentially, with capital accumulation linking investment in one period to the capital stock available in the next, so that the model traces an adjustment path rather than a single comparative-static equilibrium.

Table 3 summarises the regional and sectoral dimensions of the model. The simulation strategy compares each scenario against a reference path in which iron ore extraction is not subjected to the projected shock. All results reported below are therefore deviations from this reference path, accumulated over the period 2023–2050, and should be interpreted as the economic consequences attributable to the modelled change in iron ore production, holding other drivers constant.

Table 3. Regional and sectoral dimensions of the CGE model

Dimension	Specification
Regions	13 RGInts of Minas Gerais + Rest of Brazil
Sectors	23 productive sectors
Households	One representative household per region (linear expenditure system)
Trade	Armington specification; interregional origin–destination flows
Closure	Small open economy; exogenous world prices
Dynamics	Recursive-dynamic; capital accumulation between periods
Horizon	2023–2050; results as accumulated deviation from reference

Source: Prepared by the author.

5. Results

The results are organised in three parts. Section 5.1 reports the macroeconomic impact at the level of the state as a whole; Section 5.2 examines the regional distribution of the impact across the thirteen RGInts; and Section 5.3 traces the effects through the productive structure, covering sectoral output and employment. Throughout, results are expressed as deviations from a reference path in which iron ore extraction is not subjected to the projected shock, and are reported either as annual growth rates or as deviations accumulated over the period 2023–2050. Because the

integrated projection implies a net contraction of iron ore production in all three scenarios, the deviations are predominantly negative, with the pessimistic scenario producing the largest losses and the optimistic scenario the smallest. Wherever it clarifies the interpretation, the results are read against the productive structure documented in Section 2.

5.1 Macroeconomic impacts on Minas Gerais

At the aggregate level, the contraction of iron ore production lowers the growth of the state economy, most visibly in the early years of the horizon when the production adjustment is most intense. The order of magnitude of the aggregate effect is bounded by the weight of the mineral sector documented in Section 1: iron ore represents about 84% of the commercial value of the state mineral output and mineral products about 52% of its exports, so that a sustained reduction in iron ore production is large enough to register in the state aggregates, even though mining is far from the whole of the economy. Figure 10 reports the trajectory of annual GDP growth for Minas Gerais under the reference path and the three scenarios.

Minas Gerais: GDP growth trajectory under simulated scenarios (annual %, 2023–2050)

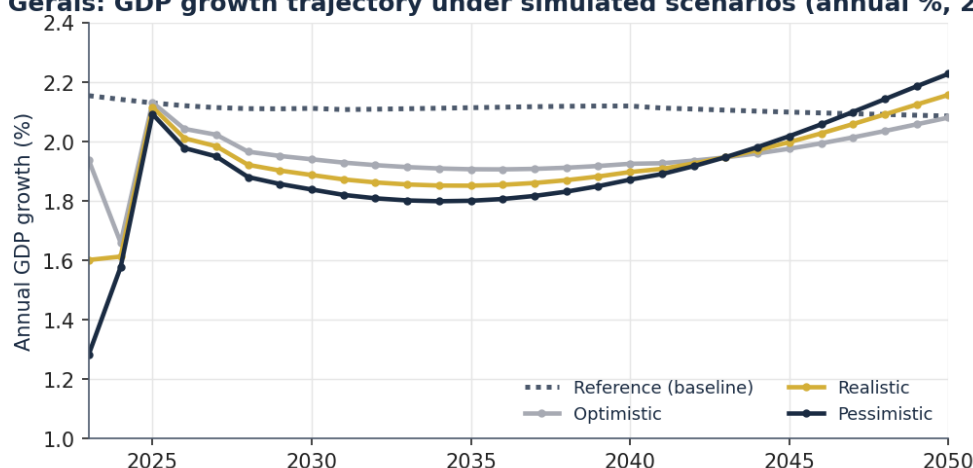


Figure 10. Minas Gerais GDP growth trajectory under simulated scenarios (annual %, 2023–2050)

Source: Prepared by the author from the CGE simulations.

In the reference path, state GDP grows at approximately 2.1% per year throughout the horizon. In 2023, the first year of the shock, growth falls to about 1.94% in the optimistic scenario, 1.60% in the realistic scenario and 1.28% in the pessimistic scenario, a gap relative to the reference of roughly 0.2, 0.6 and 0.9 percentage points respectively. This initial divergence corresponds to the sharp reduction in iron ore output documented in Section 3.5, where production contracts by between about 5% and 20% in 2023 depending on the scenario. From 2025 onward the growth rates converge back towards, and by the end of the horizon marginally exceed, the reference path, as the level of activity stabilises around the new and lower production trajectory. This reconvergence in growth rates does not undo the early losses: because output is permanently displaced downward in the first years, the accumulated level of GDP remains below the reference throughout the period. The pattern, an abrupt initial divergence followed by a gradual reconvergence in rates, is characteristic of the recursive-dynamic structure of the model, in which the shock is concentrated at the start of the horizon and the economy adjusts thereafter along a lower path. Table 4 summarises the trajectory at selected years.

Table 4. Minas Gerais GDP growth by scenario, selected years (annual %)

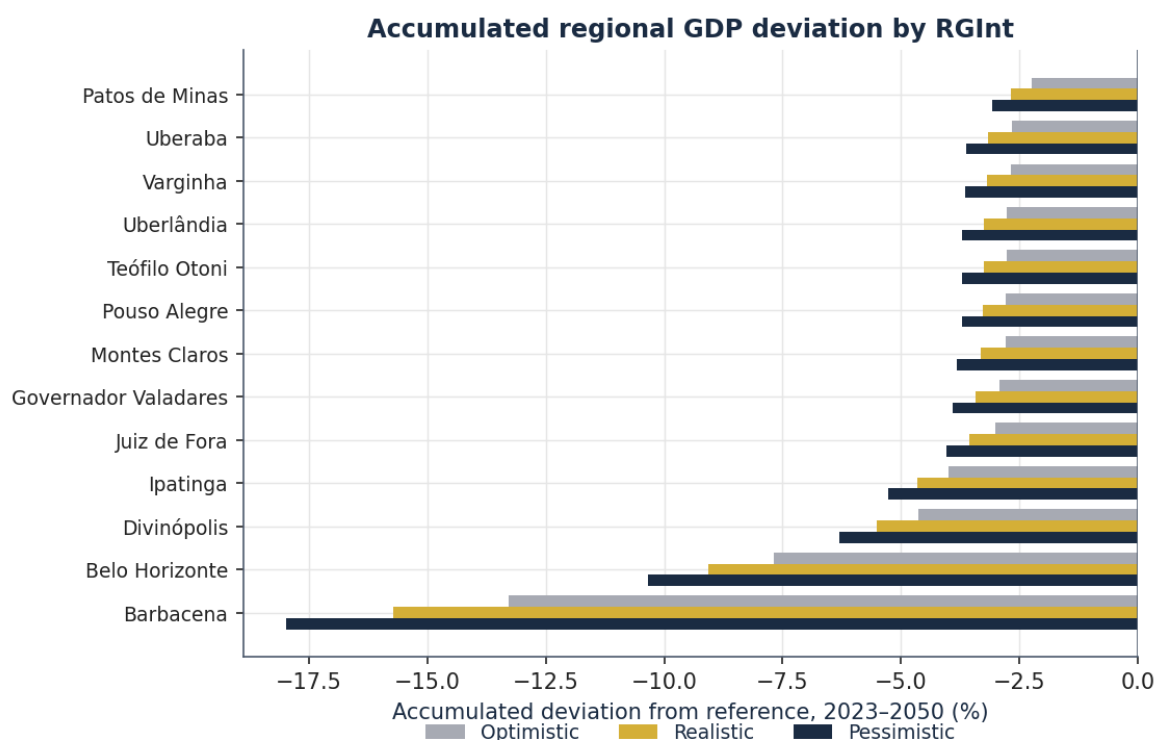
Scenario	2023	2030	2040	2050
Reference (baseline)	2.15	2.11	2.12	2.09
Optimistic	1.94	1.94	1.93	2.08
Realistic	1.60	1.89	1.90	2.16
Pessimistic	1.28	1.84	1.87	2.23

Source: Prepared by the author from the CGE simulations.

The aggregate effect, although moderate at the level of the state, conceals pronounced regional and sectoral heterogeneity. As Section 2 documents, iron ore extraction and the metallurgical chain are concentrated in a small number of regions, so that the state-level figures average together territories in which the mineral chain commands more than a third of local activity and territories in which it is marginal. The following sections disaggregate the impact accordingly.

5.2 Regional impacts

Figure 11 reports the accumulated deviation of regional output over 2023–2050, and Table 5 gives the full set of values for the thirteen RGInts. The losses are markedly heterogeneous, and their ordering follows the degree of mineral specialisation documented in Section 2.3 rather than the absolute size of the regional economy.

**Figure 11.** Accumulated regional GDP deviation by RGInt and scenario (%)

Source: Prepared by the author from the CGE simulations.

Table 5. Accumulated regional GDP deviation by RGInt and scenario (% , 2023–2050)

RGInt	Optimistic	Realistic	Pessimistic
Barbacena	-13.3	-15.7	-18.0
Belo Horizonte	-7.7	-9.1	-10.3
Divinópolis	-4.6	-5.5	-6.3
Governador Valadares	-2.9	-3.4	-3.9
Ipatinga	-4.0	-4.7	-5.3
Juiz de Fora	-3.0	-3.6	-4.0
Montes Claros	-2.8	-3.3	-3.8
Patos de Minas	-2.2	-2.7	-3.1
Pouso Alegre	-2.8	-3.3	-3.7
Teófilo Otoni	-2.8	-3.3	-3.7
Uberaba	-2.7	-3.2	-3.6
Uberlândia	-2.8	-3.3	-3.7
Varginha	-2.7	-3.2	-3.6
Rest of Brazil	-2.8	-3.3	-3.7

Source: Prepared by the author from the CGE simulations. Columns: optimistic, realistic and pessimistic scenarios.

Barbacena records the deepest contraction, from about -13.3% in the optimistic scenario to about -18.0% in the pessimistic scenario. This is consistent with its productive structure: as documented in Section 2.3, flat steel and semi-finished products account for about 25% of the Barbacena economy and iron ore extraction for a further 11%, so that the mineral–metallurgical chain alone commands more than a third of regional activity, leaving little capacity to absorb a sector-specific shock. Belo Horizonte follows, with deviations between about -7.7% and -10.3%. The contrast with Barbacena is instructive. Belo Horizonte is by far the largest producer in absolute terms, concentrating roughly 48% of national iron ore output and 18% of national pig iron and ferro-alloy output (Section 2.2), yet its relative GDP loss is smaller, because its economy is more diversified and, on the economic-complexity evidence of Section 2.4, among the most complex in the state. Absolute production weight and relative vulnerability are therefore distinct: the region that produces the most is not the region that loses the most in relative terms. Divinópolis and Ipatinga occupy intermediate positions, consistent with their steel specialisation, which in Ipatinga reaches about 27% of the regional economy (Section 2.3). At the opposite end, the diversified economies of Uberaba, Uberlândia, Patos de Minas and Pouso Alegre register accumulated deviations of only about -2% to -4%. Uberaba is a clear illustration of the same distinction in reverse: although it accounts for about 21% of national pig iron and ferro-alloy production (Section 2.2), these activities represent a small share of its own diversified economy, so that its aggregate loss is modest.

Household consumption (Figure 12) follows the same regional ordering but with a markedly compressed amplitude, ranging from about -3% to -5%. The compression is consistent with the partial insulation that interregional trade provides: a household located in a mining region continues to purchase goods produced elsewhere, so that part of the income loss generated in the most exposed regions is shared with the rest of the state and the country. Consumption is therefore less spatially concentrated than production.

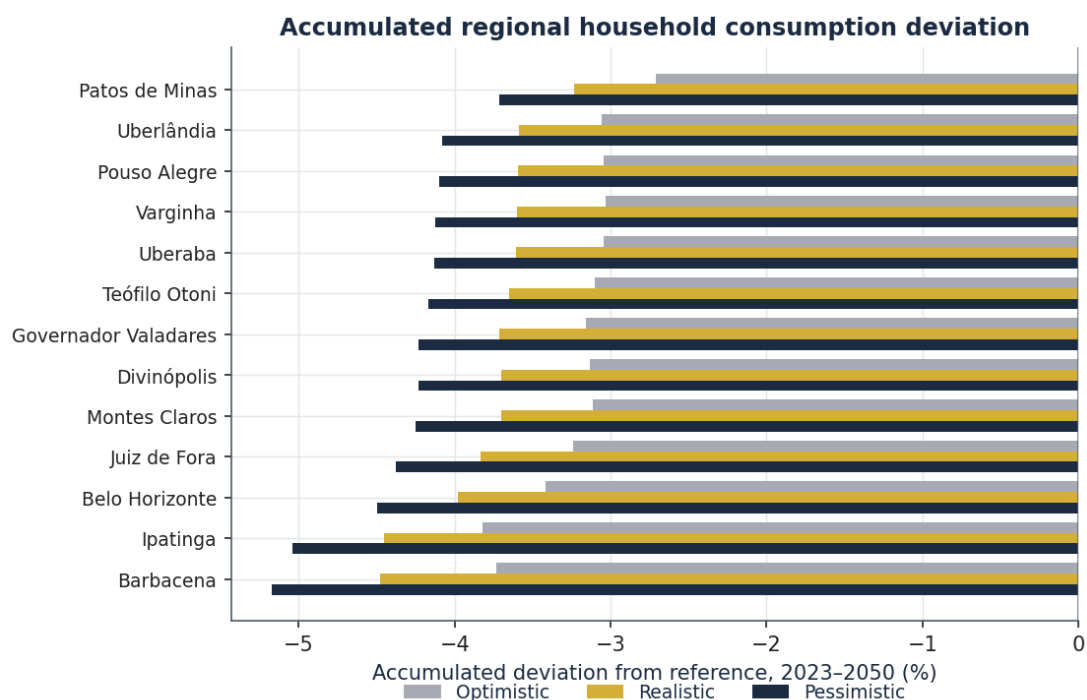


Figure 12. Accumulated regional household consumption deviation (%)
Source: Prepared by the author from the CGE simulations.

Employment (Figure 13) tracks the output ranking closely, with the largest contractions in Barbacena, Belo Horizonte, Divinópolis and Ipatinga, the regions most specialised in the steel and metallurgical segments. This concentration is material in light of the employment structure documented in Section 1, where mining and mineral transformation together support some 360 thousand formal jobs in the state, about four fifths of them in the transformation industries that the present results identify as the most affected.

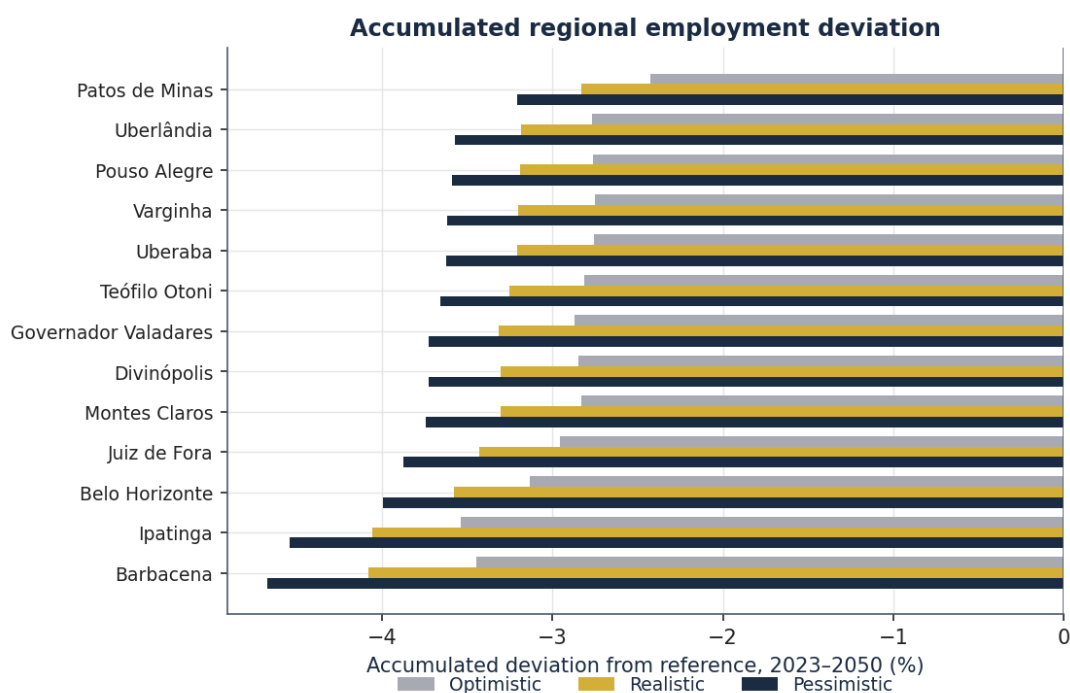


Figure 13. Accumulated regional employment deviation (%)
Source: Prepared by the author from the CGE simulations.

Investment (Figure 14) is comparatively uniform across regions and, in several cases, more pronounced in the optimistic than in the pessimistic scenario. This pattern is consistent with the forward-looking nature of investment in the recursive-dynamic specification, in which the timing of the production adjustment, and not only its terminal magnitude, shapes the capital-accumulation path; an alternative explanation, namely differences in regional capital intensity, is also compatible with the observed pattern and cannot be separated from it with the present results.

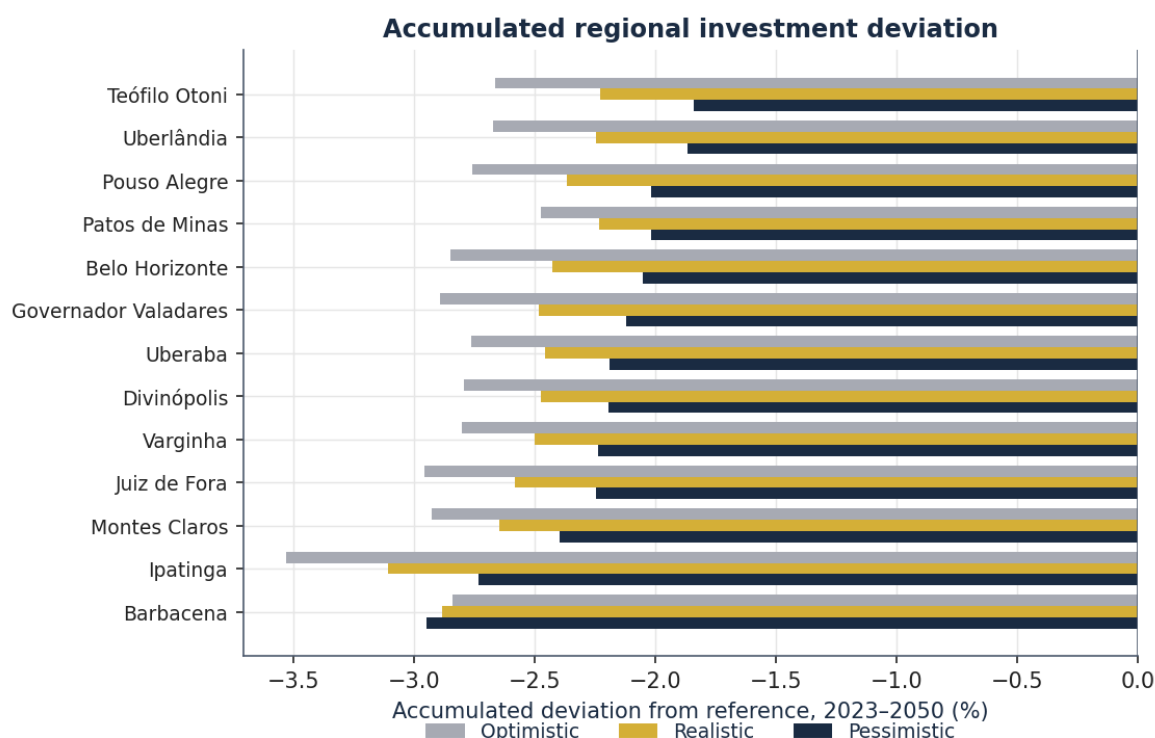


Figure 14. Accumulated regional investment deviation (%)
Source: Prepared by the author from the CGE simulations.

Taken together, the regional results indicate that the burden of a mineral-sector slowdown would fall disproportionately on a small number of highly specialised territories. This concentration has a direct fiscal dimension: as noted in Section 1, mining royalties (Compensação Financeira pela Exploração Mineral), which reached about R\$ 3.2 billion in the state in 2023, are themselves territorially concentrated in the same regions, so that the territories most exposed to the production decline are also those most reliant on mining-related public revenue.

5.3 Sectoral results and employment variation

The sectoral analysis focuses on six activities selected because of their direct and indirect linkages to mining. Two of them, flat steel and semi-finished products and fabricated metal products, constitute the metallurgical transformation of iron ore and are linked to extraction through strong forward linkages. Two others, motor vehicles and construction, are the principal steel-using industries and are connected to mining indirectly, through their demand for steel and metal products. The remaining two, the extraction of non-metallic minerals and of non-ferrous metallic minerals, are extractive activities exposed to the same regional and macroeconomic conditions as iron ore mining. These are precisely the linkages that the input–output analysis of Section 2.4 captures, where iron ore extraction and metallurgy appear as key sectors, in the Rasmussen–Hirschman sense, in several RGInts. Reporting these six sectors therefore traces both the direct

metallurgical chain and the indirect demand- and factor-market channels through which an iron ore shock propagates. The results correspond to the same three integrated scenarios used at the aggregate and regional levels, expressed as accumulated deviations from the reference path over 2023–2050.

5.3.1 Sectoral output

Figures 15 to 20 report the accumulated output deviation of the six sectors by region. The metallurgical core of the chain is the most affected. Flat steel and semi-finished products (Figure 15) contract, on average across the RGIInts, by about 5.5% under the optimistic scenario, 6.6% under the realistic scenario and 7.6% under the pessimistic scenario, reaching about 9.0% in Barbacena. This regional gradient maps directly onto the structural shares of Section 2.3: the deepest sectoral losses occur in Barbacena and Ipatinga, where flat steel represents about 25% and 27% of the regional economy respectively, followed by Belo Horizonte and Divinópolis. Fabricated metal products (Figure 16) decline by roughly 3.2% to 4.0% and motor vehicles (Figure 17) by about 3.0% to 3.6%; these are the indirect, steel-using activities, affected through their demand for metal inputs rather than through a direct tie to extraction. Among the extractive activities, the extraction of non-metallic minerals (Figure 19) contracts by about 2.7% to 3.3% and of non-ferrous metallic minerals (Figure 20) by about 1.6% to 2.8%, the latter most pronounced in the regions identified in Section 2.2 as nationally relevant in these segments, notably Uberaba in non-metallic minerals and Patos de Minas in non-ferrous minerals. In each of these sectors the scenarios are ordered as expected, with the pessimistic scenario producing the largest losses and the optimistic scenario the smallest, and the regional gradient places Barbacena, Belo Horizonte, Divinópolis and Ipatinga among the most exposed.

Construction (Figure 18) is the exception to this ordering: its output contracts by about 2.8% under the optimistic scenario and 2.2% under the pessimistic scenario, that is, slightly more in the milder scenario. The pattern coincides with the behaviour of investment noted in Section 5.2 and is consistent with a general-equilibrium reallocation in which resources released from the contracting mining and metallurgical sectors are absorbed more strongly by non-tradable activities such as construction in the deeper downturn. The same qualification applies to a small number of other non-tradable segments where inter-scenario differences are minor. Table 6 reports the sectoral output deviations for Barbacena, the most exposed region, allowing the six sectors and three scenarios to be compared directly.

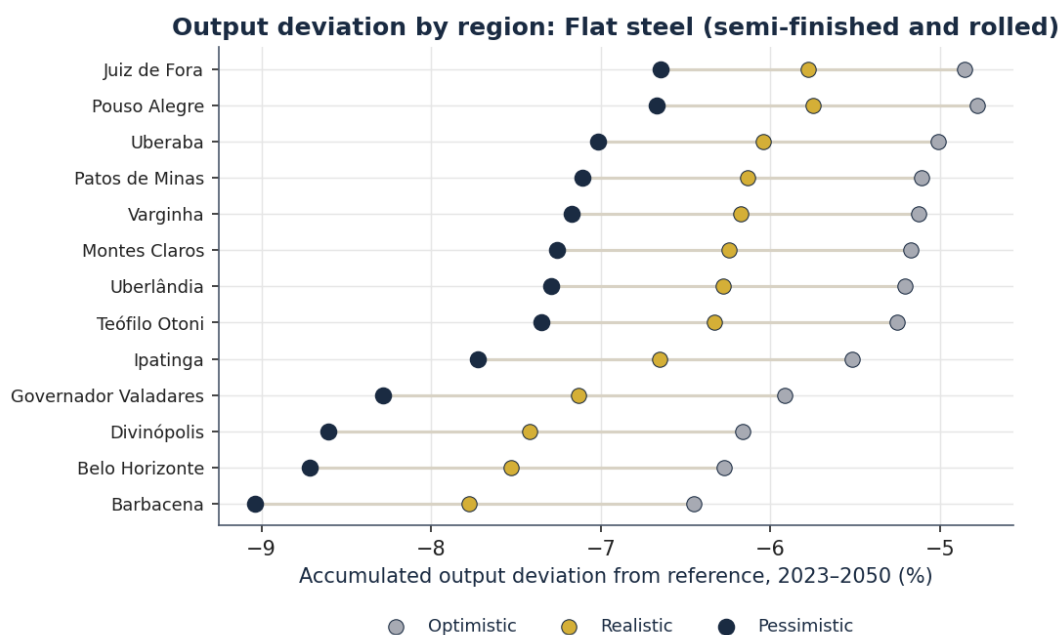


Figure 15. Accumulated output deviation by region: flat steel, semi-finished and rolled (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

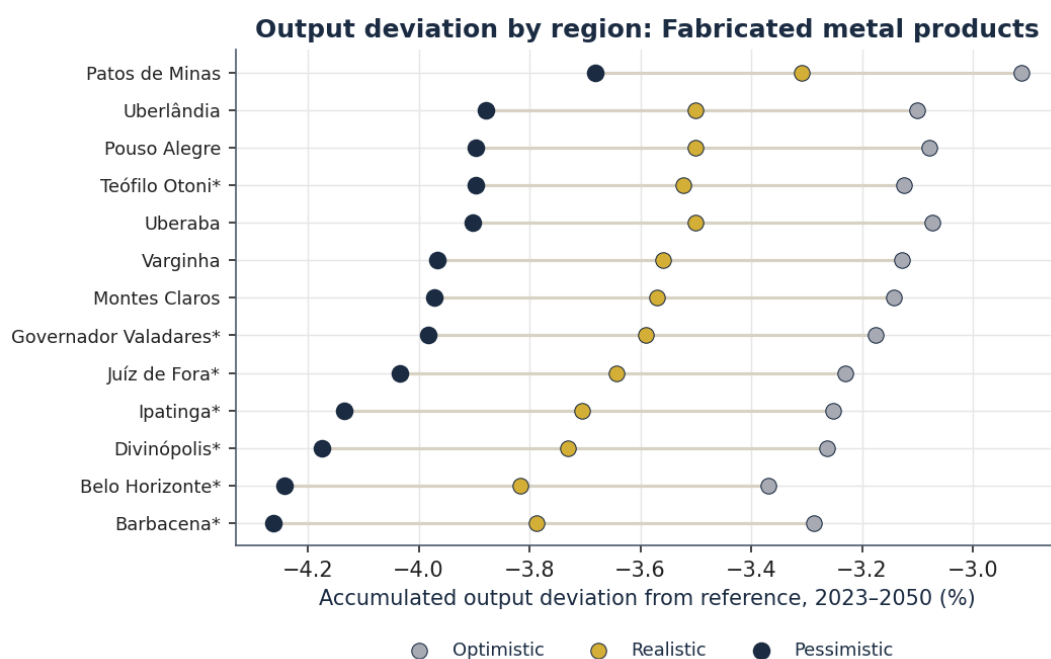


Figure 16. Accumulated output deviation by region: fabricated metal products (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

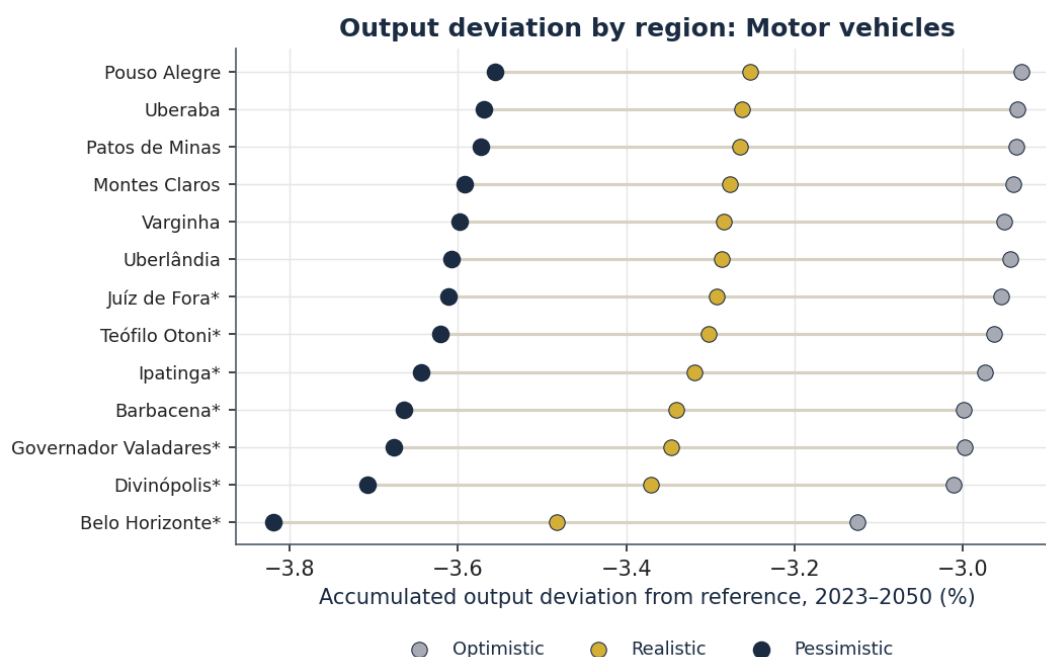


Figure 17. Accumulated output deviation by region: motor vehicles (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

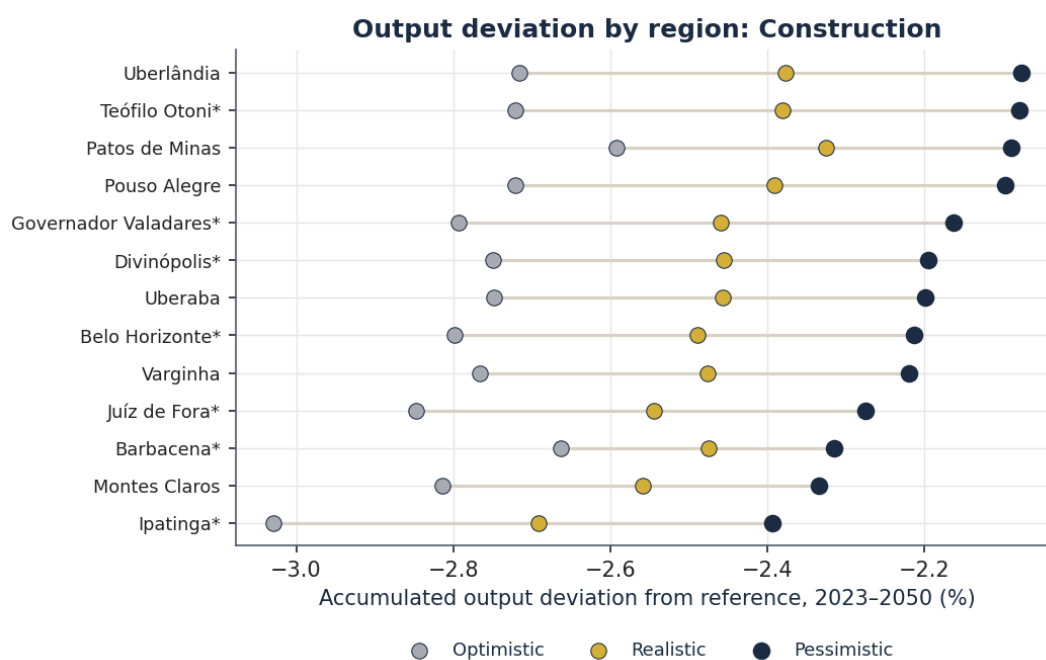


Figure 18. Accumulated output deviation by region: construction (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

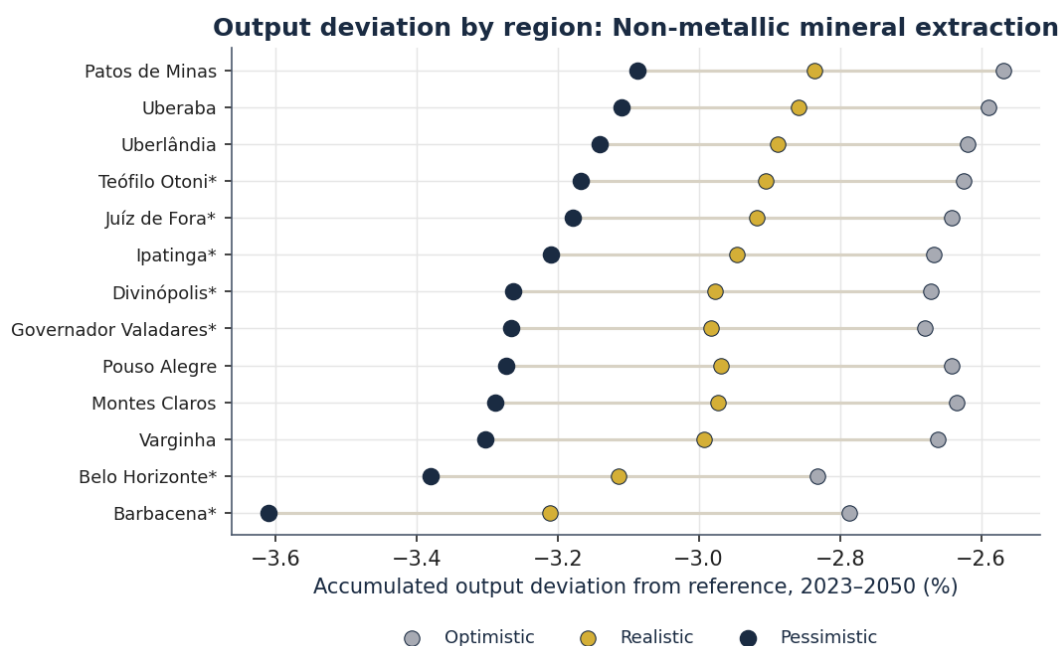


Figure 19. Accumulated output deviation by region: non-metallic mineral extraction (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

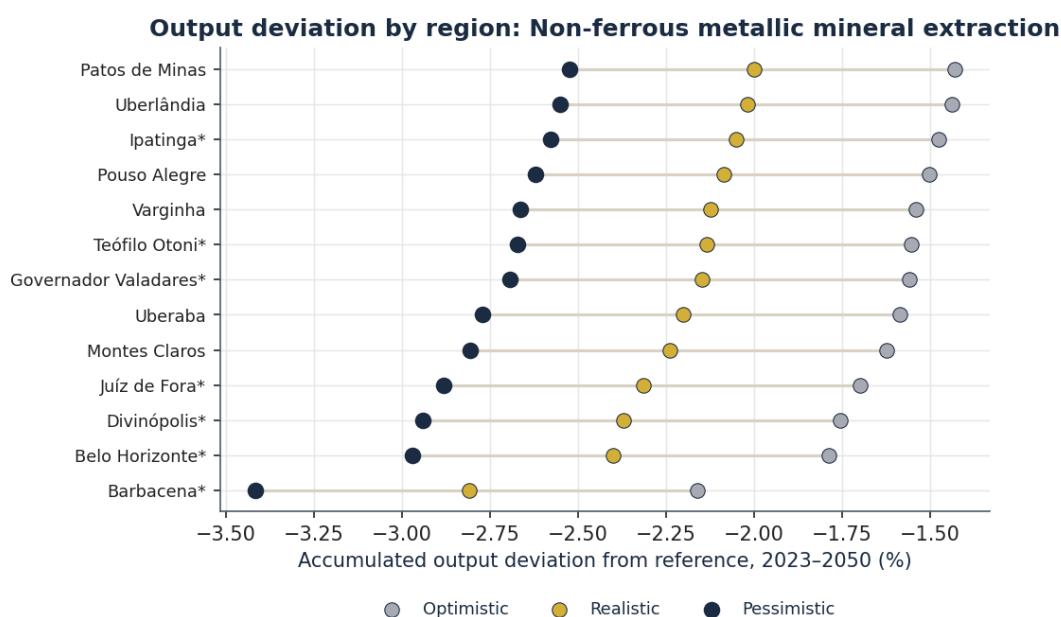


Figure 20. Accumulated output deviation by region: non-ferrous metallic mineral extraction (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

Table 6. Accumulated output deviation by sector, Barbacena, by scenario (% , 2023–2050)

Sector	Optimistic	Realistic	Pessimistic
Flat steel (semi-finished and rolled)	-6.45	-7.78	-9.04
Fabricated metal products	-3.29	-3.79	-4.26
Motor vehicles	-3.00	-3.34	-3.66
Construction	-2.66	-2.47	-2.31
Non-metallic mineral extraction	-2.79	-3.21	-3.61
Non-ferrous metallic mineral extraction	-2.16	-2.81	-3.42

Source: Prepared by the author from the CGE simulations. Columns: optimistic, realistic and pessimistic scenarios.

5.3.2 Employment variation

Figures 21 to 26 report the accumulated employment deviation of the same six sectors. The employment results broadly mirror the output results, but with a distinctive feature. Employment in the extraction of non-metallic minerals records the largest contraction, on average about 5.5% under the optimistic scenario and 7.5% under the pessimistic scenario, and about 8.9% in Barbacena (Figure 25), exceeding even the steel employment loss. This reflects the relatively high labour intensity of that activity, so that a given reduction in output sheds proportionally more labour. Employment in flat steel and semi-finished products (Figure 21) contracts by about 3.0% to 3.6%, in non-ferrous mineral extraction (Figure 26) by about 3.1% to 3.7%, and in motor vehicles (Figure 23) by about 2.4% to 2.7%. Construction employment (Figure 24) declines by about 1.7% to 2.8%, ordered as expected across scenarios. Employment in fabricated metal products (Figure 22) contracts by about 1.2% to 2.3% and, as with construction output, is marginally larger in the milder scenario, consistent with the reallocation dynamics noted above. The largest employment losses are concentrated in the same regions identified for output, namely Barbacena, Belo Horizonte, Divinópolis and Ipatinga.

Read together with the regional aggregate employment results of Section 5.2 and the employment structure documented in Section 1, where about four fifths of the roughly 360 thousand mineral-chain jobs are located in transformation industries, the sectoral evidence indicates that the labour-market consequences of an iron ore slowdown would be concentrated both territorially, in the most specialised regions, and sectorally, in the metallurgical and extractive segments, so that a relatively contained aggregate effect at the level of the state corresponds to pronounced losses in specific labour markets.

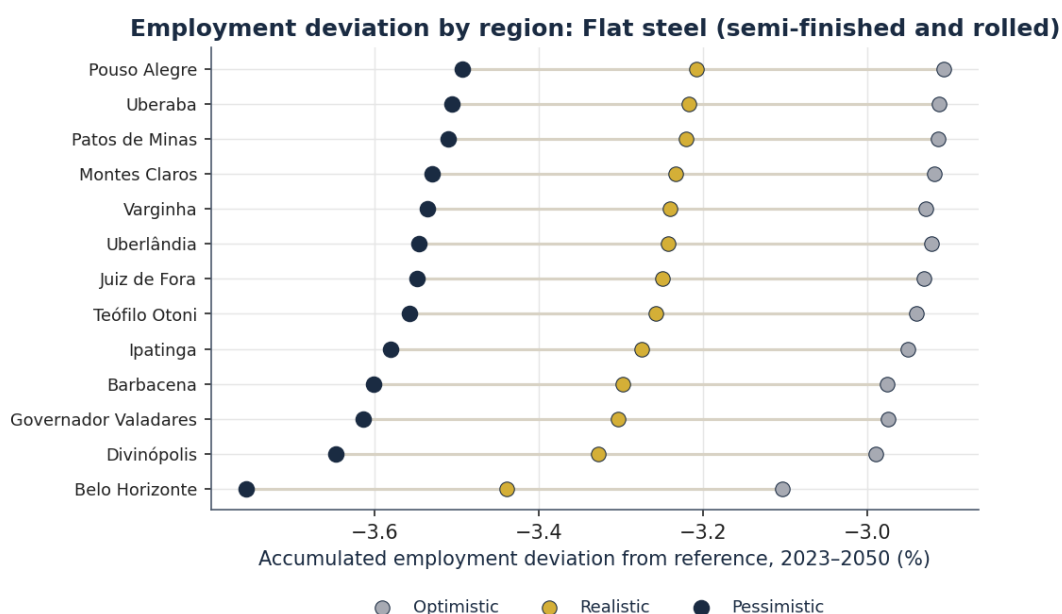


Figure 21. Accumulated employment deviation by region: flat steel, semi-finished and rolled (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

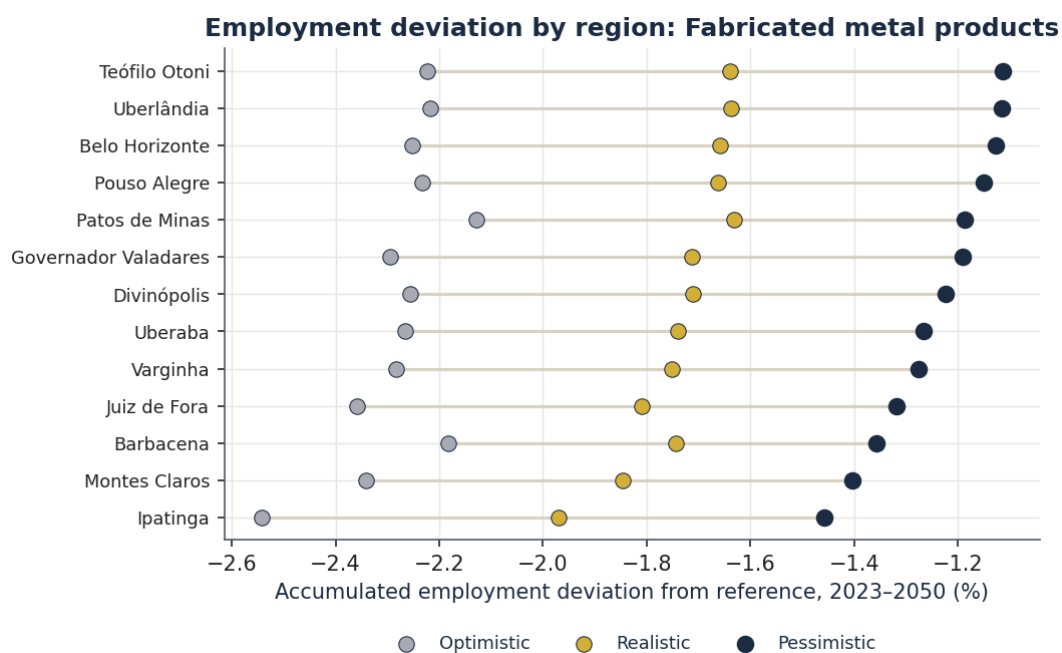


Figure 22. Accumulated employment deviation by region: fabricated metal products (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

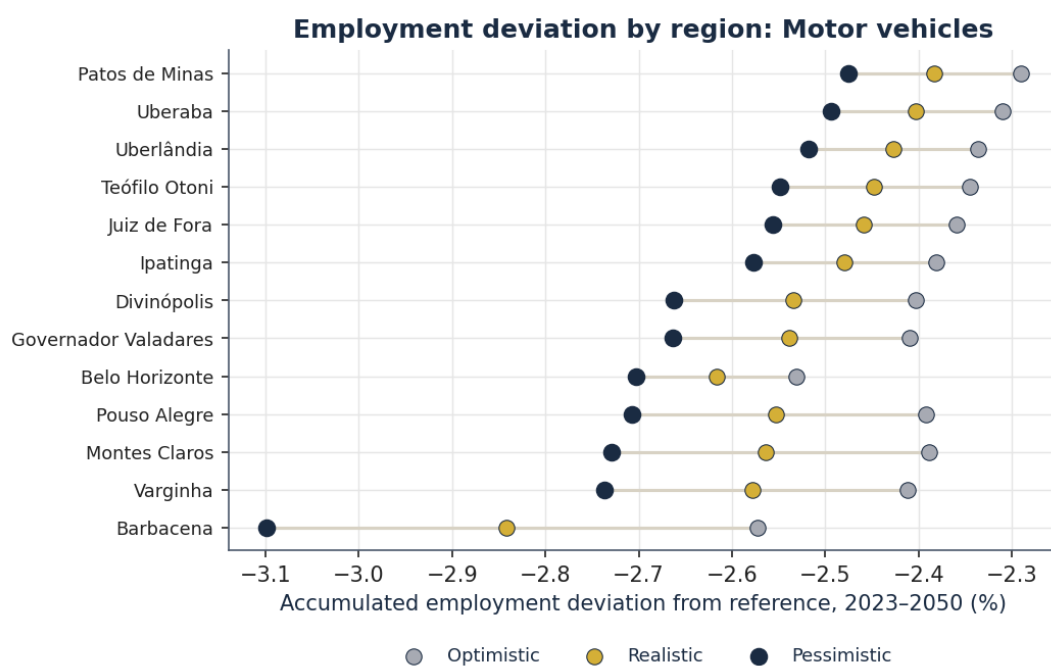


Figure 23. Accumulated employment deviation by region: motor vehicles (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

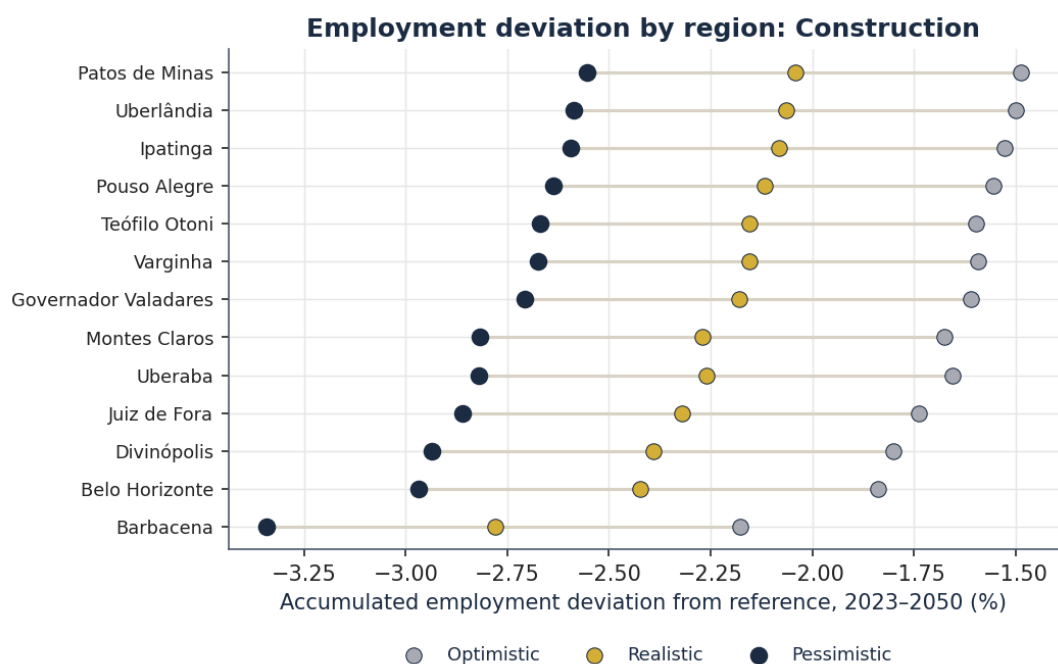


Figure 24. Accumulated employment deviation by region: construction (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

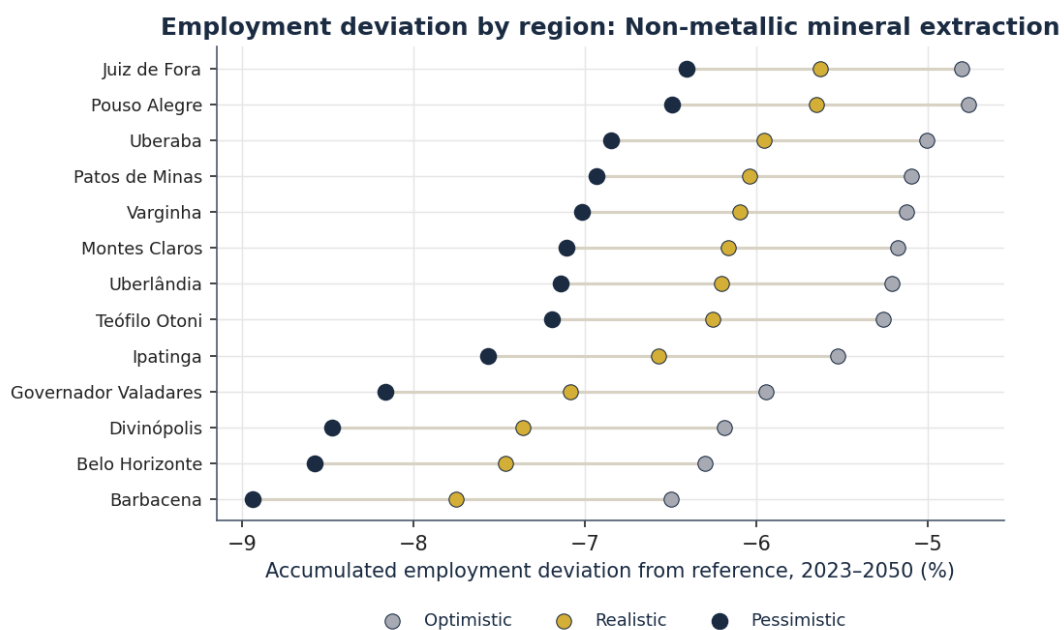


Figure 25. Accumulated employment deviation by region: non-metallic mineral extraction (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

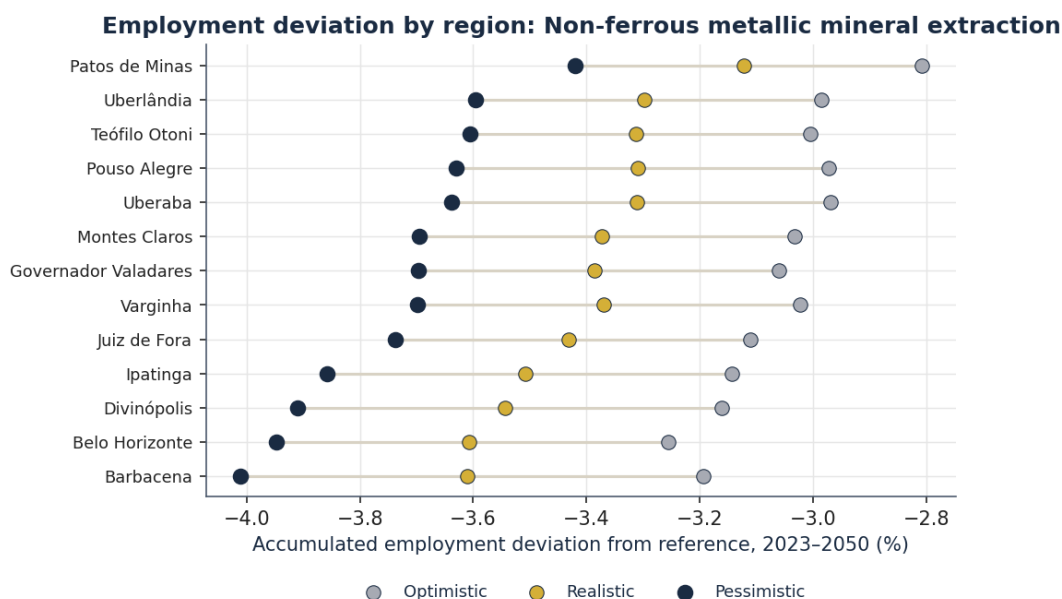


Figure 26. Accumulated employment deviation by region: non-ferrous metallic mineral extraction (% , 2023–2050)
Source: Prepared by the author from the CGE simulations.

6. Discussion

6.1 Transmission through the mineral–metallurgical chain

The simulations describe a clear transmission mechanism. A contraction in iron ore extraction reduces the supply of intermediate inputs to the metallurgical chain and the income generated within it, which in turn lowers demand for steel-intensive goods, construction and, through household income, local consumption. The sectoral results make the mechanism concrete: the largest losses occur not in extraction itself but in the flat steel and metal-transformation segments that depend on it, together with the labour-intensive extraction of non-metallic minerals, and the employment effects track these segments closely. Because iron ore extraction and metallurgy operate as key sectors, in the Rasmussen–Hirschman sense, in several regions of the state, the shock propagates with particular intensity where these activities are concentrated. The regional pattern of impacts is thus consistent with the linkage structure documented in Section 2: the most exposed regions are those in which the mineral chain commands a large share of local activity, exceeding a third of the regional economy in Barbacena and reaching about a quarter in Ipatinga on the structural shares reported in Section 2.3, and functions as a key sector, not necessarily those with the largest economies.

6.2 Regional vulnerability and economic resilience

This reading aligns with the regional economics literature on mineral dependence. Highly specialised extractive territories tend to organise their productive structure around a single chain, which raises short-run productivity but reduces the capacity to absorb sector-specific shocks, a configuration associated with limited economic resilience and, in the longer run, with the regional manifestations of the resource curse (SACHS; WARNER, 1995; AUTY, 2001; GONÇALVES, 2013). The contrast between Barbacena, where the mineral–metallurgical chain commands more than a third of the regional economy (Section 2.3) and losses are large and concentrated, and the diversified southern and western regions, where the chain is marginal and losses are modest, is consistent with this interpretation. The evidence on economic complexity reinforces the point: the

regions identified as most complex, Belo Horizonte, Divinópolis and Ipatinga, possess more diversified productive bases that, in principle, offer greater scope for reallocating resources away from a declining sector, even where, as in Ipatinga, steel specialisation remains high. The same logic accounts for the position of Belo Horizonte, which concentrates close to half of national iron ore output (Section 2.2) yet records a smaller relative GDP loss than Barbacena, because its more diversified and more complex economy absorbs the shock more readily. The observed association between specialisation and vulnerability does not establish a causal relationship; it is also compatible with alternative explanations, such as differences in labour-market flexibility, in access to credit or in the mobility of capital across regions, which the present model does not isolate. What the simulations do establish is that, conditional on the modelled structure, the regions most specialised in the mineral chain are those in which a given production shock translates into the largest economic loss.

6.3 The low-carbon transition: threat and opportunity

The findings should be read in light of the structural transitions facing the sector. On the demand side, the decarbonisation of steelmaking, through greater use of scrap and electric arc furnaces, tends to reduce demand for primary iron ore, particularly for lower grades, reinforcing the downward pressure embedded in the projections (INTERNATIONAL ENERGY AGENCY, 2020). This channel acts in the same direction as the modelled shock and could deepen the long-run contraction beyond what the demand-side projection implies. At the same time, the comparative advantage of Minas Gerais in low-carbon pig iron, based on sustainably managed charcoal and a hydropower-dominated electricity matrix, suggests that part of the chain could reposition itself towards low-emission steel for markets such as the European Union, where carbon-border adjustment mechanisms increasingly reward low-emission production (GOVERNO DE MINAS GERAIS, 2025). The net regional outcome will depend on whether the state captures this higher-value segment or remains specialised in undifferentiated primary ore. The sectoral results suggest that such a repositioning would matter most precisely in the regions identified as most exposed, since flat steel and the metal-transformation segments are those that concentrate the largest sectoral losses.

6.4 Supply-side risks: reserve depletion and environmental constraints

The projection developed in Section 3 is driven by demand and does not model the physical evolution of supply. Yet several supply-side factors point in the same direction. Minas Gerais faces a growing number of mines approaching the end of their economic life, and the progressive exhaustion of higher-grade reserves is shifting production towards more capital- and energy-intensive concentration routes such as flotation (GOVERNO DE MINAS GERAIS, 2025). Stricter environmental regulation, heightened scrutiny following tailings-dam failures, and climate-related risks such as increased rainfall intensity and water stress may further constrain operating conditions (GOVERNO DE MINAS GERAIS, 2025). To the extent that these constraints bind, the realised production path could lie below even the pessimistic scenario considered here, so that the regional impacts estimated in this study are best interpreted as a lower bound on the potential long-run adjustment rather than as a worst case.

6.5 Policy implications

From a policy standpoint, the results lend quantitative support to the diversification agenda emphasised in the state mining plan. The concentration of output and employment losses in a

small number of highly specialised regions indicates that the costs of a mineral-sector slowdown would fall disproportionately on specific territories, with attendant fiscal consequences given the territorial concentration of mining royalties. Three implications follow. First, policies that broaden the productive base of the most exposed regions, particularly Barbacena and the steel-specialised regions, would reduce their exposure to the structural decline of primary iron ore. Second, support for the higher-value and lower-carbon segments of the metallurgical chain could convert part of the decarbonisation threat into an opportunity, retaining activity in the regions that would otherwise bear the largest losses. Third, the fiscal adjustment associated with declining royalty revenues should be anticipated, since the regions most affected by the production decline are also those most dependent on mining-related public revenue. On the basis of this analysis, productive diversification of the most exposed regions is the most direct lever for mitigating the structural vulnerability of the Minas Gerais economy.

7. Conclusion

This study integrated an econometric projection of iron ore production with a dynamic interregional CGE model to assess the regional economic impacts of alternative production trajectories in Minas Gerais. The projection, which decomposes beneficiated production into export and domestic-consumption components, implies a net contraction of output relative to the levels of the supercycle period, driven by the deceleration of Chinese import demand and by the stabilisation of international prices below historical peaks.

The simulations show that this contraction would propagate well beyond the extractive sector. Through the mineral–metallurgical chain, the shock reaches flat steel, fabricated metal products, motor vehicles, construction, and the extraction of non-metallic and non-ferrous minerals, and its regional incidence is highly uneven. Accumulated output losses are concentrated in Barbacena, where the mineral–metallurgical chain represents more than a third of the regional economy (Section 2.3), and in the principal producing region, Belo Horizonte, and more generally in the steel-specialised regions of Ipatinga and Divinópolis, while diversified economies absorb the shock with comparatively minor effects. Household consumption, employment and investment follow the same regional ordering with attenuated amplitude. The sectoral results confirm that the impact is concentrated in the flat steel and metal-transformation segments and in the most labour-intensive extractive activities, which sustain the largest output and employment losses in the most exposed regions, while the downstream and remaining extractive activities are affected more modestly.

The analysis is subject to the limitations set out in Section 3.6, notably the short estimation samples of the volume equations, the sensitivity of the price model, and the absence of an explicit treatment of reserve depletion and ore-grade decline. These limitations point to a clear research agenda: incorporating geological constraints into the production projection, extending the sample and the dynamic specification of the econometric models, and modelling the low-carbon repositioning of the steel chain as an explicit scenario rather than as a contextual factor. Subject to these qualifications, the results provide quantitative evidence that the principal vulnerability of the Minas Gerais economy to a mineral-sector slowdown is structural and territorial, and that productive diversification of the most exposed regions is the most direct lever for mitigating it.

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