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Abstract

Subglobal climate policies induce changes in international competitiveness and favor a relocation of carbon-emitting activities. We argue that many energy-intensive activities are also capital-intensive, so that carbon policies could affect rents rather than abatement or location. Taking copper as an example, we formulate a plant-level spatial equilibrium model of the industry, and we estimate a set of elasticities to calibrate the behavioral parameters of the model. Given 2007 market conditions, Monte Carlo simulations suggest that a \$50/tCO₂ tax in industrialized countries induces emissions reductions of less than one percent in the copper industry, with a mean emission leakage rate of 25%. Our results conform with empirical findings on the pollution haven effect but challenge projections from computable general equilibrium models.

Keywords: *Pollution haven effect, Climate policy, International environmental agreements, Carbon leakage, International trade, Copper industry.*

JEL classification: *F18; F55; H23; Q54; Q58*

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1 Introduction

The prospect of anthropogenic climate change is inducing governments to negotiate carbon abatement targets. The provision of abatement efforts is a global public good, and free-riding incentives undermine the process of international policy coordination (see e.g. Barrett, 2005). Moreover, countries holding out of a global agreement gain a comparative advantage in polluting activities (Hoel, 1991). A displacement of emissions from coalition countries to non-coalition countries, known as both the pollution haven effect¹ and emissions leakage effect, would undo environmental benefits expected by coalition members. Furthermore, specialization and investment in emission-intensive activities by non-coalition countries could increase the costs of delayed participation (Olmstead and Stavins, 2006). The prospect of emissions leakage thus magnifies international coordination problems. Policy response from countries willing to undertake unilateral abatement include regulatory exemption for trade-exposed sectors (Hoel, 1996) and trade policies based on embodied emissions of traded products (Ismer and Neuhoff, 2007). However, while leakage provides an efficiency argument for additional policy instruments, ex-ante evidence on emissions leakage is contentious, and these instruments could be used for strategic rent capture.

The impact of differentiated environmental regulation on the location of polluting activities is the subject of a large literature, mainly based on two approaches. First, ex-post econometric studies quantify the impact of local environmental regulation on trade and investment flows, and empirically test for the existence of a pollution haven effect. Recent evidence suggests a statistically and economically significant pollution haven effect (Levinson and Taylor, 2008; Kellenberg, 2009). Second, since observations on the response to a carbon policy is scarce, simulations with computable general equilibrium (CGE) models assess the impact of subglobal climate policies on the location of carbon emissions. Recent economy-wide projections of the carbon leakage rate, defined as the increase in emissions in non-coalition countries relative to

¹ Copeland and Taylor (2004) differentiate between the ‘pollution haven effect’ from the ‘pollution haven hypothesis’. The former relates to the impact of local environmental policy on the location of polluting activities, while the latter studies the link between trade liberalization and environmental degradation.

abatement in coalition countries, are between 15 and 30 percent (Babiker and Rutherford, 2005; Böhringer et al., 2010; Elliott et al., 2010). Importantly, these models are currently the main source for quantitative evidence in the climate policy debate.

While these two paradigms find that differentiated environmental policy affects the location of emissions, evidence from empirical studies suggest that projections from CGE models overestimate the response of traded energy-intensive commodities. Indeed, in CGE models carbon leakage is driven by a small number of energy-intensive sectors, namely mining and the non-ferrous metal industry, iron and steel, as well as chemical industries (Felder and Rutherford, 1993; Paltsev, 2001).² Yet these sectors are capital-intensive and involve significant sunk costs, traded products are subject to significant transportation costs, and the overhead costs of environmental regulation only represents a small portion of the value of production. In fact, the empirical literature suggests that footloose industries account for most of observed pollution haven effect, and these are typically not the most emission-intensive (Ederington et al., 2005; Kellenberg, 2009).

Based on these results, we re-examine the issue of carbon leakage both analytically and numerically. As a polar case, we focus on globally-traded homogeneous goods in a competitive partial equilibrium setting.³ We start by developing our intuition on key behavioral and technological parameters driving sectoral emissions leakage. Within a simple Marshallian model, we express the leakage rate as a function of supply and demand price elasticities, the share of production in non-coalition countries, and the relative emissions intensity in coalition and non-coalition regions. In this simple setting, supply price elasticities measure the responsiveness to relative cost differential, and sectors with low supply elasticities feature a low leakage rate.

² Existing studies focusing on energy-intensive sectors also report very high carbon leakage rates. See for example Dolf and Moriguchi (2002) for iron and steel, Fowlie (2009) for electricity, and Demaillly and Quirion (2009) for cement, all suggesting leakage rates above 50%. These models rely on engineering bottom-up cost data, and the empirical component driving economic behavior is minimal.

³ These assumptions are expected to magnify the effect of regulation on the location of activities. Homogeneity implies perfect substitution between regulated and unregulated producers, and competitive markets induces higher leakage rates (Fowlie, 2009). Further, while general equilibrium effects can have both positive and negative incidence on leakage, the largest effect occurs on the global energy markets (Burniaux and Oliveira-Martins, forthcoming). Our partial equilibrium framework accommodates exogenous changes in global energy prices, and we address this issue in the sensitivity analysis.

We then extend the analysis to a framework that accounts for the industrial geography and intra-sectoral trade in intermediate products, and we use it to assess emissions leakage in the copper industry.⁴ More specifically, we formulate a plant-level spatial equilibrium model, where plants are identified by their spatial coordinates and interact on the markets for final and intermediate copper commodities. We estimate short- and long-run regional supply and demand elasticities in a reduced-form setting, using Bayesian inference in a dynamic panel model with random coefficients. We then calibrate the parameters of the model describing the production technologies and consumer preferences to our econometric estimates, so that the response of agents in the model matches observed market behavior.

Our analysis suggests that the impact of subglobal climate policy on the copper industry is small, despite energy-intensity, product homogeneity and competitive market structure. Supply elasticities are low, and the carbon tax is mostly reflected in the returns to fixed factors rather than changes in output. For example, imposing a \$50/tCO₂ tax in highly industrialized countries under 2007 market conditions and using the statistical uncertainty on our price elasticity estimates, Monte Carlo simulations with our model suggests a long-run (steady-state) mean leakage rate of 25%.⁵ Emissions in coalition countries decline by less than 1%. Asset owners in non-coalition countries benefit from a global increase in the price of copper products through increased rents, and the location of activities remains largely unaffected.

Our framework indicates that excess demand and scarcity rents earned at copper deposits are key drivers of the industrial response. Under high copper prices, resource owners benefit from large rents, and they are less responsive to changes in the economic environment. The price of copper commodities, however, is subject to large fluctuations. For example, emissions from refined copper production per \$ value of output stood at 1.5kgCO₂/\\$ under 2002 market

⁴ High-grade copper ore is scarce, and the exploitation of low-grade deposits requires several energy-intensive transformation steps that involves both fossil fuels and electricity (Alvarado et al., 1999). On a weight basis, copper is the most energy-intensive non-ferrous metal after aluminum, and its production is also more energy-intensive than that of iron and steel, cement, paper, and most basic chemicals (Bergmann et al., 2007). The industry is competitive (Radetzki, 2009), and it is subject to large-scale international trade in refined and intermediate commodities (Radetzki, 2008).

⁵ Since we do not have information on depreciation or adjustment costs in the copper industry, we refrain from evaluating the transition path in a dynamic framework, and our long-run results approximate the steady-state outcome using comparative statics with perfect capital mobility.

conditions, but only $0.4\text{kgCO}_2/\$$ in 2007. In order to quantify the importance of commodity price fluctuations, we calibrate the model to 2002 market conditions. We find that carbon abatement in coalition regions is higher at 8%. The leakage rate remains largely unaffected by price fluctuations, and the mean derived from a Monte Carlo simulation with low copper prices is 35%. Even though the carbon price we consider is relatively high⁶, fluctuations of the market value of output dwarf abatement costs.

Our results, which conforms with findings from empirical studies, suggest two key shortcomings of multiregion, multisector CGE models used for ex-ante assessment of carbon policies. First, the representation of energy-intensive activities in these models is highly stylized. For example, a sector representing ‘non-ferrous metals’ comprises both mining and metal production activities, so that capital inputs are implicitly treated as mobile between different activities even in the short-run. The parametrization of aggregate sectoral production technologies for these sectors, which is difficult to validate empirically, implicitly define flat production possibility frontiers, and the supply response to relative price changes is large. Second, most CGE models represent international trade with the Armington model and highly aggregated regions. In the typical Armington formulations, goods are differentiated by region of origin, and changes in trade flows are proportional to the benchmark market shares, thus ignoring spatial considerations. Further, countries that do not trade with coalition members in the benchmark are in large part sheltered from changes in relative prices, which can hide geographical effects for globally traded commodities.

The rest of this paper is organized as follows. Section 2 develops a simple analytical model of emissions leakage. Section 3 overviews the main features of the copper industry and presents the estimation of price elasticities. Section 4 describes the numerical model of the copper industry and the calibration procedure. Section 5 applies this model to evaluate the impact of subglobal carbon policy in terms of abatement and emissions leakage. The final section concludes.

⁶ The 2007 average price per ton of CO_2 in the EU market was around \$25.

2 An analytical framework

In order to identify the basic drivers of emissions leakage, we develop a simple representation of differentiated emissions taxation and derive a first order approximation for emissions leakage.⁷ Consider a market for regionally produced homogeneous good in a competitive partial equilibrium setting, and denote aggregate production decisions in region $i = \{1, 2\}$ by a supply schedule $Q_i^s(P)$. At a reference equilibrium, the linear approximation of the supply response in region i is given by the first order Taylor expansion around the reference price \bar{P} and supply \bar{Q}_i :

$$\begin{aligned} Q_i^s(P) &= Q_i^s(\bar{P}) + \frac{\partial Q}{\partial P}(P - \bar{P}) \\ &= \bar{Q}_i^s + \eta_i \bar{Q}_i^s \left(\frac{P}{\bar{P}} - 1 \right), \quad \eta_i \geq 0, \end{aligned} \tag{1}$$

where η_i is the supply price elasticity at the reference equilibrium. Similarly, the linear approximation of aggregate market demand is:

$$Q^d = \bar{Q}^d - \bar{Q}^d \epsilon \left(\frac{P}{\bar{P}} - 1 \right), \quad \epsilon \geq 0, \tag{2}$$

where ϵ is the demand elasticity and $\bar{Q}^d = \sum_i \bar{Q}_i^s$ is the benchmark demand.

Initially, there is no emissions restrictions, and the benchmark equilibrium is $(\bar{Q}^d, \bar{P}, \{\bar{Q}_i^s\}_{i=1,2})$.

We now consider a counterfactual equilibrium where producer $i = 1$ faces a tax t on emissions. This increases in⁴ the relative production cost, and the new equilibrium price is:

$$P = \bar{P} + t e_1 \frac{\eta_1 \bar{Q}_1^s}{\eta_1 \bar{Q}_1^s + \eta_2 \bar{Q}_2^s + \epsilon \bar{Q}^d} \tag{3}$$

where e_i denotes emissions per unit of output. As well known, the pass-through rate of the tax to the consumer depends on the relative elasticities, and in the presence of two producers, it also depends on the benchmark production levels (or market shares). The higher equilibrium

⁷ For related calculations, see Lünenbürger and Rauscher (2003).

market price induces a decline in the demand, and the corresponding supply of each region is:

$$Q_1^s = \bar{Q}_1^s - te_1 \frac{\eta_1 \bar{Q}_1^s}{\bar{P}} \left(\frac{\eta_2 \bar{Q}_2^s + \varepsilon \bar{Q}^d}{\eta_1 \bar{Q}_1^s + \eta_2 \bar{Q}_2^s + \varepsilon \bar{Q}^d} \right), \quad (4)$$

$$Q_2^s = \bar{Q}_2^s + te_1 \frac{\eta_2 \bar{Q}_2^s}{\bar{P}} \left(\frac{\eta_1 \bar{Q}_1^s}{\eta_1 \bar{Q}_1^s + \eta_2 \bar{Q}_2^s + \varepsilon \bar{Q}^d} \right). \quad (5)$$

Defining the emissions leakage rate as:

$$\ell := \frac{e_2 Q_2^s - e_2 \bar{Q}_2^s}{e_1 \bar{Q}_1^s - e_1 Q_1^s}, \quad (6)$$

simple algebra yields a first order approximation of carbon leakage for arbitrary supply and demand schedules:

$$\ell = \frac{e_2}{e_1} \frac{\vartheta_2 \eta_2}{(\varepsilon + \vartheta_2 \eta_2)}. \quad (7)$$

where ϑ_2 is the benchmark market share of the untaxed producer.

As for the pass-through rate, demand and supply elasticities have an intuitive effect on emissions leakage. First, economic activities facing an elastic demand feature a lower scope for emissions leakage. Second, the price increase induces growth in output and emissions in non-coalition regions, as a function of the price responsiveness and the benchmark market share of the untaxed producers. Intuitively, these parameters measure the importance of sunk costs and the size of the coalition. The responsiveness of the taxed producer has no impact on the leakage rate, although it affects the magnitude of emissions leakage and total abatement. Third, the rate of leakage is proportional to the relative emissions intensity of producers, and very polluting technologies in non-coalition regions could conceivably induce a leakage rate above 100%.

Some illustrative calculation follow. For regions with equal emissions intensity and market shares, similar supply and demand elasticities suggest a leakage rate of one third. If the supply elasticity of the non-coalition regions doubles, the leakage increases to 50%. Thus as time passes and capital mobility increases, the leakage rate can be expected to be higher. However, the demand also gets more elastic with time, as consumer substitute to different products, which mitigates the increase of emission leakage. We note that if the the demand elasticity increases

more rapidly than the supply elasticity, equation (7) suggests that the long-run leakage rate could decline with time.

3 The copper industry

In this section, we overview the key features of the copper industry. We first describe copper production processes, and we then provide some details about the location of production and consumption activities. Second, we report on the estimation of price elasticities for the copper industry.

3.1 Copper production, demand and carbon emissions

There exist two routes to produce refined copper from copper deposits. First, pyrometallurgical processing uses thermal treatments to recover the metal. The mined material is crushed, ground and concentrated into copper ‘concentrate’, which contains around 30% pure copper. Production of concentrate takes place near the deposit, and it is then shipped to smelters to be processed into a commodity of around 98% pure copper, henceforth referred to as copper ‘blister’. Low quality scrap copper can enter the smelting process either in addition to concentrate or in smelters dedicated to scrap. In the final production stage, refineries use electrolysis to process blister copper into 99.99% percent pure copper cathode. High quality scrap can also be refined into copper cathodes.

The second production process, commonly referred to as ‘solvent extraction - electrowinning’ (SXEW, uses hydrometallurgical methods. Copper ore is first leached into an aqueous solution, concentrated and purified before going to the electrowinning stage, an electrocatalytic process recovering the pure copper. SXEW processing takes place close to the deposit, and it produces cathodes of 99.99% pure copper.⁸

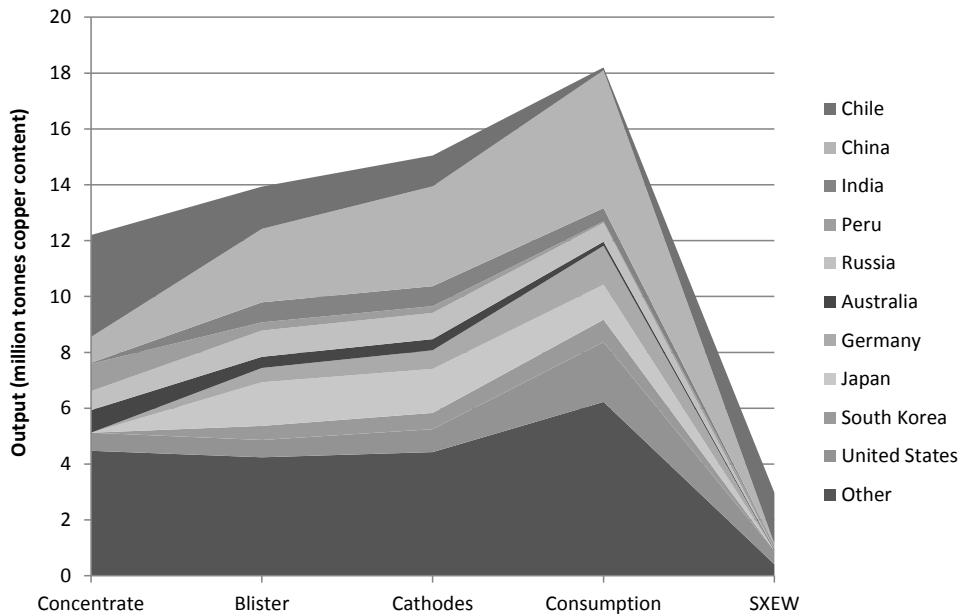
The production processes are standardized, and copper commodities produced in different

⁸ Pyrometallurgical and SXEW processes apply to different types of copper ore. Specifically, Pyrometallurgical methods recover copper from the more abundant sulfide ores deposits, while SXEW plants mostly process oxide ores.

locations are homogeneous.⁹ The average production costs of refined copper displays small variations around \$2000 per tonne of copper (CRU Analysis, 2009), but there are substantial variation in the market price. In particular, real (2007) copper prices have gone from around \$3000 per tonne at the end of the 1990's to around \$2000 per tonne during the first half of the past decade. In 2007, the price of refined copper stood at US\$7000 per tonne. Moreover, while copper commodities are costly to transport, these costs are a small fraction of the value of copper, and a global market has emerged from mid-1990's (Radetzki, 2008).

The geographical distribution of production and consumption is a key driver of emissions leakage, and we now discuss the benchmark data in some details. Figure 1 reports regional data on 2007 output, cumulated across production processes toward consumption of refined copper.¹⁰ The figure also implicitly reports the quantity produced from scrap as the difference between total production from concentrate, blister and cathodes.

FIGURE 1: OUTPUT PER PRODUCTION PROCESS, 2007 (DATA SOURCE: ICSG, 2008)



⁹ The copper content of concentrate can vary, typically between 30% and 35%, but it does not affect the smelting process.

¹⁰ Figures refer to the content of pure copper and originate from ICSG (2008).

Chile hosts major copper deposits, and it produces 3.5 million tonnes of copper concentrate, about 30% of total production. Peru, China and Australia have a market share of about 8% each. Other significant mining regions are Indonesia and Russia (both 6%), the U.S. and Canada (both 5%), and Poland (4%). International trade in copper concentrate is significant, and Chile exports almost 60% of its concentrate production. Peru, Australia and Indonesia all export more than half of their concentrate output.

China is the main producer of copper blister (2.5 million tonnes), and imports 1.1 million tonnes of concentrate for smelting. Chile and Japan both produce about 1.5 million tonnes of copper blister, but Japan produces exclusively from imports (1.3 million tonnes) and low quality scrap.¹¹ International trade flows of copper blister are smaller than those for concentrate, and Chile is by far the largest exporter with 400 million tonnes.

In 2007, total production of refined copper was more than 18 million tonnes. Production from copper blister and high quality scrap account for 80% and 5% of total production respectively. China is the largest producer in both categories (3.1 and 0.4 million tonnes respectively). Other major producers of electro-refined copper cathodes are Japan (1.5 million tonnes), Chile (1.1 million tonnes), Russia (0.9 million tonnes) and the United States (0.8 million tonnes). SXEW plants produce the remaining 15% of refined copper, as shown on the right of Figure 1. Chile produces about 60% of SXEW output, the U.S. 16%, while Zambia, Peru and Mexico make-up most of the remaining production. Note that Chile has a total market share of around 15%, and is by far the largest exporter of refined copper (2.8 million tonnes). Other major exporters are Zambia and Peru (both around 0.4 million tonnes), while Japan, Australia, Russia, Kazakhstan and Canada all export around 0.3 million tonnes.

On the demand side, construction, electronics, telecommunications and in the transportation industry are the main consumers of refined copper. China uses around 25% of total production (5 million tonnes), and the U.S. use about 12% (2 million tonnes). These two countries are also the largest importers of refined copper (1.3 and 0.5 million tonnes respectively). Germany uses

¹¹ About 10% of total blister output is produced from low quality scrap copper, mainly in China, Russia, Japan, and several European countries.

1.4 million tonnes of refined copper (importing half of it), and Japan uses 1.2 million tonnes (exporting 0.3 million tonnes).

Extraction and processing of the copper ore are energy-intensive, both in terms of electricity and fossil fuels, and energy consumption entails significant carbon emissions. We conclude this section with an overview of the carbon intensity of production, and process-specific emissions factors are reported in Table 1.¹²

TABLE 1: CO₂ EMISSIONS IN THE COPPER INDUSTRY

Country	Emission coefficients (tCO ₂ /tCU)				Emissions ('000 tCO ₂)
	Mining	Smelting	Refining	SXEW ^a	
Chile	1.7	0.6	0.2	1.4	7,766.5
China	2.5	0.7	0.2	2.0	3,914.4
India	2.4	0.7	0.2	–	692.0
Peru	1.6	0.5	0.1	1.4	1,762.5
Russia	1.7	0.5	0.1	1.5	1,537.9
Australia	2.7	0.9	0.3	2.1	2,369.7
Germany	–	0.8	0.2	–	494.6
Japan	–	0.8	0.2	–	1,421.7
South Korea	–	0.7	0.2	–	408.7
United States	2.6	0.8	0.3	2.1	3,182.5
Other countries	2.1 ^b	0.7 ^b	0.2 ^b	1.5 ^b	19,857.2
<i>Total emissions</i>					
'000 tCO ₂	21,073.9	8,294.3	2,973.6	3,299.4	35,641.2

Note: ^aSXEW figures include extraction, leaching and electrowinning.

^b Weighted average.

The production of copper concentrate is the most carbon-intensive process. The copper content at deposits currently exploited is low (between 0.5 and 1 percent), and the processing of a large volume of rocks requires a large amount of energy. Taking into account emissions from smelting and refining, pyrometallurgical processing emits more than twice as much carbon per

¹² These figures are derived using data on production technologies from Kuckshinrichs et al. (2007) and adjusted to reflect the share of electricity and diesel fuels (Pimentel, 2008), as well as the carbon content of electricity generation (IEA, 2009). These figures are consistent with bottom-up estimates of Bergmann et al. (2007). An important caveat, however, is that we cannot account for firm-level heterogeneity.

tonne of refined copper. Regional variations in carbon intensity are large, reflecting differences in electricity generation technologies. Among the main producing regions, Australia, the U.S. and China mainly use coal-fired generation and are thus more carbon-intensive than the average. In contrast, Chile and Peru are below the average because of hydroelectric resources. In terms of volume, Chile is by far the largest carbon emitter, followed by China, the U.S. and Australia.

3.2 Estimation of price elasticities

In this section we report on the estimation of country-level short- and long-run price elasticities for each production process and final demand. We use country-level data on yearly output from each production process and refined copper demand, spanning 1994 to 2007 (ICSG, 2008).¹³ The yearly average price of refined copper is also taken from ICSG (2008) and converted to PPP-adjusted international \$2007 with data from Heston et al. (2009). For the demand equation, we control for changes in regional income using real GDP figures, also from Heston et al. (2009).

In order to identify the short- and long-run price response, we use a partial adjustment, dynamic panel data model. This ad-hoc formulation captures the dynamics of the supply response stickiness and the capital-intensive nature of production of copper commodities.¹⁴ Formally, the equation we estimate is:

$$\begin{aligned} \ln Q_{r,t} &= \alpha'_r Z_t + \beta_r \ln P_{r,t} + \gamma_r \ln Q_{r,t-1} + \varepsilon_{r,t} \\ \begin{pmatrix} \beta_r \\ \gamma_r \end{pmatrix} &\sim N \left(\begin{pmatrix} \mu_\beta \\ \mu_\gamma \end{pmatrix}, \begin{pmatrix} \sigma_\beta & \sigma_{\beta\gamma} \\ \sigma_{\beta\gamma} & \sigma_\gamma \end{pmatrix} \right) \end{aligned} \quad (8)$$

where Z includes country specific quadratic time trends to control for unobserved country factors in a flexible and tractable manner, as well as GDP data for the demand equation. The short-run

¹³ While longer time series exist, we use a short panel during which the assumption of full market integration and price-taking behavior is plausible. Hence given the existence of a global commodity market with a worldwide price for copper commodities determined in a competitive environment (Radetzki, 2009), we assume that variations in the copper price adjusted by the real exchange rate are exogenous to each country's production.

¹⁴ Ideally, we would want to structurally estimate the parameters of the model formulated for the copper industry. However, the data for such an exercise is not available, and we choose instead a reduced form partial adjustment model to identify short- and long-elasticity. We then use a structural calibration procedure, choosing the free parameters describing technology and preferences to match the econometric estimates (see Section 4.2).

price response is the coefficient β , while the long-run response is $\frac{\beta}{1-\gamma}$. We model regional heterogeneity in the price responsiveness with random coefficients (see Hsiao and Pesaran, 2008), so that the estimation procedure generates evidence about the mean and variance-covariance matrix of the parameters. As customary in this setting, we model cross-sectional heterogeneity with a multi-variate normal distribution, and we use a constant elasticity (log-log) specification for each production process.

In the presence of cross-sectional heterogeneity, the inclusion of lagged outcome variable induces endogeneity of the regressors, and traditional maximum likelihood estimation produces downward biased estimates of the mean coefficients (Pesaran and Smith, 1995). As an alternative, we use a Hierarchical Bayes estimator, which has good sampling properties even for short panels (Hsiao et al., 1999). We specify a set of uninformative priors on the parameters, using Gaussian distributions with large standard deviations for the mean parameters and Wishart distribution with low degrees of freedom for the parameters of the variance-covariance matrix. Given these priors, the posterior distribution does not take a closed form, but marginal distributions are easy to draw from, and we use Gibbs sampling (Gelfand and Smith, 1990) to simulate draws from the posterior distribution. Convergence of the algorithm is typically achieved after 2000 iterations¹⁵, and we base our inference on one tenth of the following 10,000 draws to mitigate the correlation among successive draws.

Estimation results are reported in Table 2. The coefficients in the upper part of the table refer to the mean effect of the distribution of cross-sectional unit parameters, while the panel below reports estimates of the standard-deviation. Overall, we note that all the estimated coefficients have the expected sign and attain statistical significance at the conventional levels. We observe significant heterogeneity in the supply responses in different regions as measured by the standard deviation coefficients, all highly statistically significant.

Beside good frequentist properties, the Hierarchical Bayes estimator allows direct inference

¹⁵ Detection of convergence is an important issue for the implementation of sampling-based inference. To supplement visual inspection of the trace plots of the Markov Chain Monte Carlo samples, we use the method suggested by Gelman (1996). Specifically, we initialize the chain from multiple starting values and calculate the ratio of between- and within- sequence variances. The statistic typically becomes close to one after 1,000 iterations, and we discard the first 2,000 to be conservative.

TABLE 2: ESTIMATION RESULTS

Variable	Mines	Smelters	Refineries	SXEW	Demand
Average effect					
lnP _{r,t} (μ_β)	0.113 *** (0.032)	0.157 *** (0.041)	0.133 *** (0.035)	0.116 *** (0.048)	-0.067 * (0.037)
lnY _{r,t-1} (μ_γ)	0.730 *** (0.066)	0.622 *** (0.072)	0.693 *** (0.064)	0.590 *** (0.101)	0.570 *** (0.057)
lnGDP	— —	— —	— —	— —	0.400 *** (0.081)
Standard deviation					
SD(lnP _{r,t}) (σ_β)	0.087 *** (0.012)	0.118 *** (0.021)	0.104 *** (0.017)	0.138 *** (0.033)	0.087 *** (0.011)
SD(lnY _{r,t-1}) (σ_γ)	0.164 *** (0.026)	0.161 *** (0.034)	0.138 *** (0.028)	0.177 *** (0.053)	0.125 *** (0.022)
SD(lnGDP _{r,t})	— —	— —	— —	— —	0.114 *** (0.019)
Observations (N/T)	42/12	38/12	40/12	14/12	55/12
Pseudo adj. R ²	0.979	0.973	0.977	0.974	0.985

Note: Standard-error in parenthesis. ***, **, * indicates a p-value smaller than, 1%, 5%, and 10% respectively. All equations include country-specific quadratic time trends. MCMC convergence diagnostics can be obtained from the authors on request.

on country-level parameters by sampling the simulated posterior distribution.¹⁶ Similarly, we can directly sample the long-run elasticities. Short- and long-run price elasticities for countries with a significant share of copper activities are reported in Table 3.

In the short run, concentrate production at mines is price inelastic relative to other production processes, reflecting higher sunk costs, whereas long-run elasticities are comparable to those of smelters and refineries. SXEW units display a low long-run price responsiveness, which can be attributed to the lower availability of sites which can use SXEW process. Note that the long-run elasticities are all below one. Regarding regional differences, production in countries that are most active on international markets (the U.S., Chile and Japan) are generally found to be more price responsive than in other regions. Finally, the demand elasticities are low both in the short- and long-run. This reflects the difficulty to substitute to other materials, and the small

¹⁶ For each processes, estimates for a small number of countries were found to have the wrong sign (although not statistically significantly different from zero). For the parametrization of the model, we set these to zero.

TABLE 3: SUPPLY AND DEMAND PRICE ELASTICITIES

Country	Mines		Smelters		Refineries		SXEW		Demand	
	η_{st}	η_{lt}								
Chile	0.11	0.83	0.22	0.78	0.18	0.75	0.23	0.78	-0.03	-0.06
China	0.13	0.62	0.22	0.69	0.19	0.76	0.15	0.31	-0.06	-0.14
India	0.12	0.40	0.13	0.32	0.11	0.32	–	–	-0.07	-0.16
Peru	0.12	0.62	0.20	0.62	0.16	0.58	0.20	0.53	-0.06	-0.14
Russia	0.11	0.62	0.21	0.65	0.18	0.67	0.04	0.09	-0.09	-0.21
Australia	0.13	0.69	0.19	0.55	0.16	0.55	0.18	0.46	-0.05	-0.13
Germany	–	–	0.23	0.79	0.19	0.79	–	–	-0.03	-0.08
Japan	–	–	0.23	0.87	0.19	0.89	–	–	-0.05	-0.13
South Korea	–	–	0.20	0.55	0.17	0.62	–	–	-0.05	-0.13
United States	0.12	0.85	0.23	0.88	0.19	0.92	0.21	0.72	-0.05	-0.13

Note: Blank cells indicate zero output in the benchmark data.

value-share of copper in the activities using copper (e.g. buildings). Changes in the demand are mostly driven by changes in GDP. These results are in line with existing empirical studies (e.g. Pei and Tilton, 1999).

4 A model for the copper industry

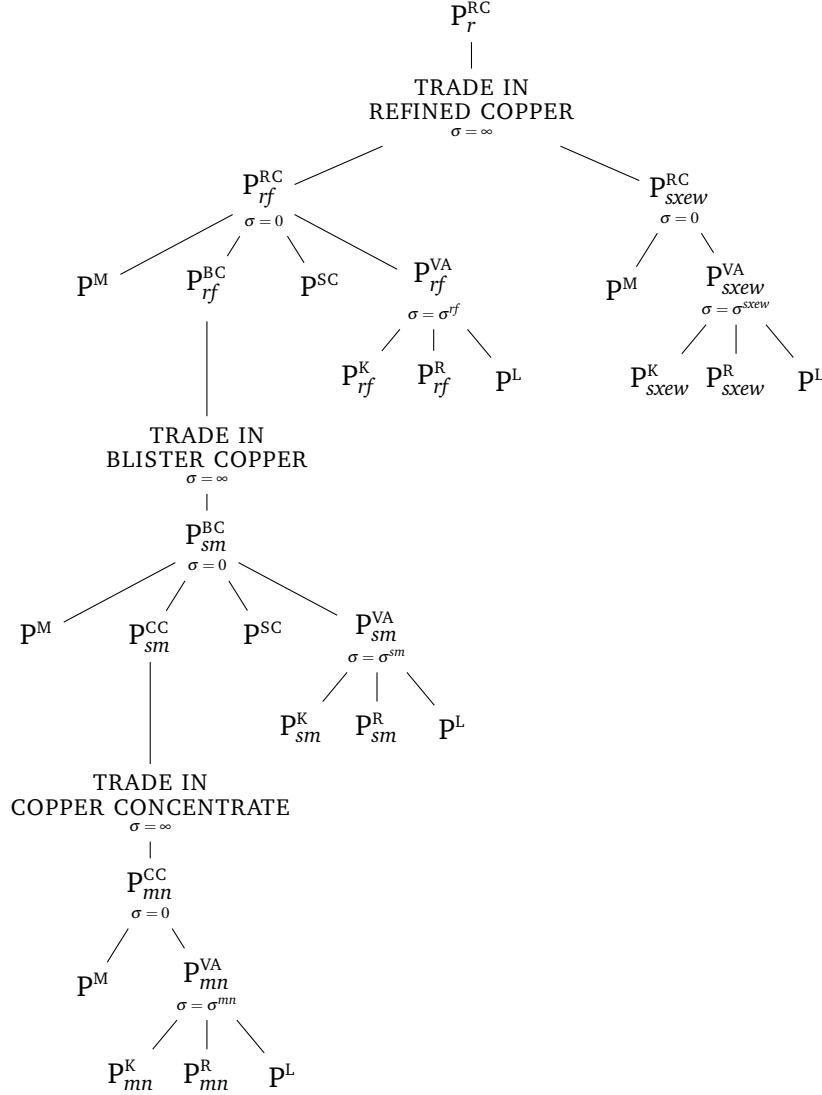
In this section, we document our economic equilibrium model of the copper industry. First, we lay out the analytical structure of the model. We then present the spatial representation of trade, calibration to the reference equilibrium, and the structural parametrization of the behavioral response to match our econometric estimates of price elasticities.

4.1 Model description

The structure of the model, represented graphically in Figure 2, is based on the two alternative copper processing routes. The first route starts with mines (mn) producing copper concentrate (CC), represented on the bottom left of Figure 2. Concentrate is traded among mines and smelters (sm), and we assume that products from different mines are perfect substitutes ($\sigma = \infty$) and subject to trade costs. Thus for example, the producer price of copper concentrate (P_{mn}^{CC}) differs from the consumer price at smelters (P_{sm}^{CC}) to reflect the shipping costs. Smelters then

produce blister copper (BC), which is traded with refineries (rf) to produce refined copper (RC). In the second production route, represented on the right of Figure 2, units using solvent-extraction/electrowinning ($sxew$) produce refined copper cathodes directly and compete with refineries to supply consumers in each region (r).

FIGURE 2: GRAPHICAL REPRESENTATION OF THE MODEL



We model production processes with two-level linearly homogeneous CES functions. The upper nest is a fixed coefficient (Leontief) technology ($\sigma = 0$), which combines ‘materials’ (M),

including chemicals, fuels and electricity inputs, with a composite input from the value-added (VA) subnest. Smelters and refineries also add a copper bearing intermediate input, namely concentrate, blister and/or scrap copper (SC). The lower-level value-added nest combines labor (L), a stock of capital (K) and a fixed resource input (R). This simple structure allows us to control the behavioral response through free parameters of the lower value-added nest. In the short term, capital and resource inputs are both plant-specific, so that the short run supply schedule is driven by the substitution possibilities with labor.¹⁷ In the long run, capital can freely adjust, but the resource input remains plant-specific. The elasticity of substitution ($\sigma^i, i = \{mn, sm, rf, sxew\}$) and the value share of the capital and resource inputs are chosen to match the short- and long-run supply elasticities (see Section 4.2).

The numerical model is formulated as a mixed complementarity problem (MCP)¹⁸ and we now lay out the algebraic conditions characterizing equilibrium on the markets for copper commodities. Assuming each producing plant is price-taker and maximizes economic profits, the zero profit conditions prevailing in equilibrium exhibit complementarity slackness with respect to the activity level Y_i :

$$-\Pi_i \geq 0 \quad \perp \quad Y_i \geq 0, \quad i = \{mn, sm, rf, sxew\} \quad (9)$$

where Π_i denotes the unit profit function for each plant, and the \perp operator indicates the complementary relationship between an equilibrium condition and the associated variable.

Unit profit functions for mines, smelters, refineries and SXEW units can be derived based on the dual cost minimization problem of individual producers. Given the structure of production technologies (and suppressing the index i for the ease of notation), unit profit functions are:

$$\Pi = P^j - \theta^{j'} P^{j'} - \theta^M - \theta^{SC} - \theta^{VA} P^{VA}, \quad j = \{CC, BC, RC\}, \quad j' = \{CC, BC\}, \quad (10)$$

¹⁷ The Leontief upper nest implies that material inputs cannot be substituted to compensate decreasing returns to labor.

¹⁸ The model is solved with the PATH solver (Dirkse and Ferris, 1993). With the functional forms we use, the model is integrable and can also be solved in its primal (surplus maximization) or dual (cost minimization) forms. We favor the MCP formulation as it seems more intuitive. The model explicitly represents the equilibrium resulting from decentralized decision-making brought together by competitive market institutions.

where P^j is the producer price of product j , $P^{j'}$ is the consumer price of the copper input j' , $\theta^{j'}$ is the demand coefficient for intermediate product j' , θ^M is the cost of material inputs, θ^{SC} is the cost of scrap copper, and θ^{VA} is the value attributed to the value-added nest.¹⁹ The cost-minimizing expression for the value-added CES price index P^{VA} is given by:

$$P^{VA} = \left(\theta^L \bar{P}^{L^{-\sigma}} + \theta^K P^{K^{1-\sigma}} + \theta^R P^{R^{1-\sigma}} \right)^{\frac{1}{1-\sigma}}, \quad (11)$$

where σ is the elasticity of substitution, P^K and P^R are price indexes for capital and the resource input respectively. Each plant is a price taker on the labor market, so that the price index of labor (\bar{P}^L) is exogenous and fixed to one.

Equilibrium interactions are further described by a set of market clearing conditions. First, each plant uses a stock of capital \bar{K} and resource input \bar{R} , with the respective rental rates determined by the demand for these inputs:

$$K = \bar{K} \frac{Y}{\bar{Y}} \left(\frac{P^{VA}}{P^K} \right)^\sigma \quad \perp \quad P^K \geq 0, \quad (12)$$

$$R = \bar{R} \frac{Y}{\bar{Y}} \left(\frac{P^{VA}}{P^R} \right)^\sigma \quad \perp \quad P^R \geq 0, \quad (13)$$

where input demands are derived by applying the envelope theorem (Shephard's Lemma).

We formulate equilibrium interactions on the market for each copper product as a spatial equilibrium (Takayama and Judge, 1971), where production and consumption sites are spatially distinct, and prices at each site differ by the trade costs on each routes:

$$P_i^j + TC_{i,i'} = P_{i'}^j \quad \perp \quad X_{i,i'} \geq 0, \quad (14)$$

where P_i^j and $P_{i'}^j$ are the price of the copper bearing commodities at plants i and i' respectively, $TC_{i,i'}$ is the bilateral trade cost, and $X_{i,i'}$ is the bilateral trade flow. In this setting, equilibrium

¹⁹ Hence if a smelter or refinery uses no scrap in the benchmark, $\theta^{j'} = 1$ and $\theta^{SC} = 0$

market clearing conditions for the supply and demand of intermediate good j are written as:

$$Y_i^j \geq \sum_{i'} X_{i,i'}^j \quad \perp \quad P_i^j \geq 0, \quad (15)$$

$$\sum_i X_{i,i'}^j \geq \theta_{i'}^j Y_{i'}^j \quad \perp \quad P_{i'}^j \geq 0, \quad (16)$$

where $\theta_{i'}^j Y_{i'}^j$ represent the demand for product j at plant i' . Finally, we close the model with a set of regional demand functions for copper cathodes characterized by a constant price elasticity (ε'):

$$Y_r^d = \bar{Y}_r^d \left(\frac{P_r^{RC}}{\bar{P}_r^{RC}} \right)^{\varepsilon_r}, \quad (17)$$

where \bar{Y}_r^d and \bar{P}_r^{RC} are respectively the benchmark demand and consumer price for refined copper.

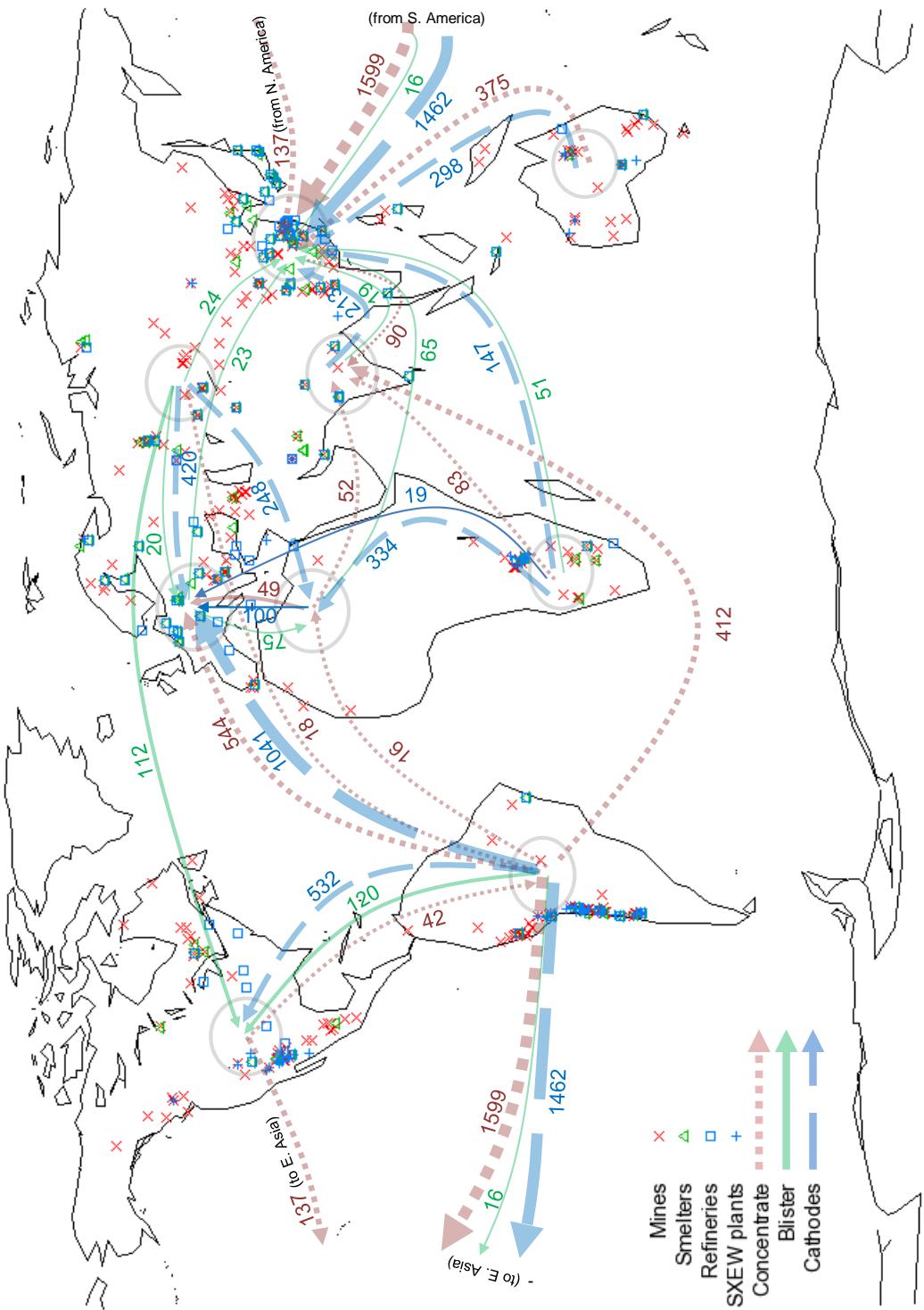
4.2 Spatial representation and model calibration

The numerical model for the copper industry is calibrated to reproduce the benchmark data on production and prices, given plant-level bilateral trade costs. Hence conditional on assumptions about technology, preferences and market institution, observed output is assumed to be an equilibrium outcome resulting from cost-minimizing behavior. We derive plant-level bilateral trade costs using a detailed geographical representation of the industry. More specifically, we use an inventory of facilities for 2007 (CRU Analysis, 2009) together with longitude-latitude coordinates for each site reported in (USGS, 2003).²⁰ The resulting spatial representation of the model is displayed in Figure 3.

Trade costs are derived as follows. Copper commodities can either be transported by rail or shipped by boat. For plants not separated by an ocean, we approximate the rail mileage be-

²⁰ Information for production sites not reported in USGS (2003) was collected online, but a small number of units could not be located and were left out of the model. These account for less than 1% of total output. Since plant-level information on the location of consumption is not available, we use country-level consumption data from ICSG (2008) and approximate the location of the demand within each country with a listing of facilities using refined copper to produce copper wire rod (IWCC, 2008), and we construct a capacity-weighted ‘average’ consumption location for each country. In other words, consumption is attributed to a fixed ‘gravity’ center in each country identified with longitude and latitude coordinates.

FIGURE 3: SPATIAL REPRESENTATION AND SIMULATED AGGREGATE TRADE FLOWS IN THE BENCHMARK ('000 TONNES OF COPPER CONTENT)



tween units through great-circle distance and apply country specific rail freight rates from The World Bank (2007). For plants separated by an ocean, we first establish a list of the major commercial ports located near the producing units. The associated geographical information (longitude/latitude and inter-ports distances) is taken from Lloyds' Maritime Atlas (Lloyd's, 2005), and the 2007 sea shipping rates for bulk (concentrate) and liner shipping (blister and refined copper) are taken from UNCTAD (2007). We then compute the transportation cost between each pair of plants as the minimum between rail freight costs (whenever possible) and the sea shipping costs, with rail freight connecting plants to their nearest port. Finally, data on tariffs levied on concentrate, blister and refined copper are from WTO (2008).

We then use bilateral trade costs and observed output to calibrate the benchmark producer and consumer prices, as well as associated trade flows. To do so, we solve an auxiliary model, selecting the benchmark bilateral trade flows $\bar{X}_{i,i'}$ to minimize total transportation costs, subject to supply and demand balance constraints:

$$\begin{aligned} \underset{\substack{\bar{X}_{i,i'}^j \geq 0}}{\text{Min}} \quad & \sum_{i,i'} X_{i,i'}^j T C_{i,i'}^j \quad \text{s.t.} \quad y_i^j \geq \sum_{i'} X_{i,i'}^j, \quad \forall i, j \\ & \sum_i X_{i,i'}^j \geq \theta_{i'}^j y_{i'}^j, \quad \forall i', j \end{aligned} \tag{18}$$

Unit-level producer and consumer prices (P_i^j and $P_{i'}^j$) are the dual variables associated with the supply and demand constraints, and represent the shadow value of the commodities at each plant and market. Trade flows simulated by solving program (18) and aggregated into nine regions are portrayed in Figure 3 (see the Appendix for the list of regions). These are consistent with trade data at the country-level, and shipment from South America to East Asia, North America and Europe make up the main trading routes. Also as expected, the volume of international trade in concentrate and refined copper is quantitatively more important than that involving blister.²¹

²¹ As a formal goodness of fit measure, we compute the coefficient of determination $R^2 = 1 - \frac{\sum_{r,r'} (X_{r,r'} - \hat{X}_{r,r'})^2}{\sum_{r,r'} (X_{r,r'} - \bar{X})^2}$, where $X_{r,r'}$ is the observed trade flow between regions r and r' , $\hat{X}_{r,r'}$ is the predicted trade flow from the model, and \bar{X} is average trade flow. The R^2 for copper concentrate is 96%, 57% for copper blister and 77% for refined copper cathodes. Our least-cost trade representation thus explains a sizable fraction of observed trade flows.

The linear homogeneity of production technologies together with the benchmark producer prices for copper products allow us to calibrate the unit cost function of each plant to match observed production decisions. Specifically, using the zero profit condition (9), together with published data on the cost of materials, energy, scrap and labor inputs (CRU Analysis, 2009; Kuckshinrichs et al., 2007), as well as the simulated price of copper commodities at each plant, we impute the share of the fixed factor as the residual value.

The choice of the remaining free parameters describing the technology (the elasticity of substitution and the allocation of the residual value share among fixed factors) is based on our econometric estimates on the regional price elasticities. In the short run, both the capital and resource inputs are fixed ($K = \bar{K}$, $R = \bar{R}$), so that a change in output is reflected in the return to the capital and resource stocks (P^K , P^R). Formally, we invert equations (12) and (13) to obtain an expression for the change in the return to the fixed factors:

$$\frac{P^K}{\bar{P}^K} = P^{VA} \left(\frac{y}{\bar{y}} \right)^{\frac{1}{\sigma}} \quad (19)$$

$$\frac{P^R}{\bar{P}^R} = P^{VA} \left(\frac{y}{\bar{y}} \right)^{\frac{1}{\sigma}} \quad (20)$$

Substituting (19) and (20) into (11), we have:

$$P^{VA} = \left(\theta^L \bar{P}^L^{1-\sigma} + (1 - \theta^L) P^{VA}^{1-\sigma} \left(\frac{y}{\bar{y}} \right)^{\frac{1-\sigma}{\sigma}} \right)^{\frac{1}{1-\sigma}} \Leftrightarrow \frac{y}{\bar{y}} = (1 - \theta^L)^{\frac{\sigma}{\sigma-1}} \left[1 - \theta^L \left(\frac{\bar{P}^L}{P^{VA}} \right)^{1-\sigma} \right]^{\frac{\sigma}{1-\sigma}} \quad (21)$$

Using this expression and setting all prices equal to unity, we can express the short term price elasticity as:

$$\eta_{st} = \frac{\partial \frac{y}{\bar{y}}}{\partial P} = \frac{\partial \frac{y}{\bar{y}}}{\partial P^{VA}} \frac{\partial P^{VA}}{\partial P} = \frac{\sigma \theta^L}{1 - \theta^L} \frac{1}{\theta^{VA}}. \quad (22)$$

Given published data on θ^L and the imputed value for θ^{VA} , we calibrate the elasticity of substitution at each plant with estimates of the short-run price elasticity:

$$\sigma = \hat{\eta}_{st} \theta^{VA} \frac{1 - \theta^L}{\theta^L}. \quad (23)$$

In the long-term steady-state, capital is freely mobile and its rental rate determined exogenously ($P^K = \bar{P}^K$). However, the resource input remains plant-specific, and equation (21) can be rewritten as:

$$\frac{y}{\bar{y}} = (1 - \theta^L - \theta^K)^{\frac{\sigma}{\sigma-1}} \left[1 - \theta^L \left(\frac{\bar{P}^L}{\bar{P}^{VA}} \right)^{1-\sigma} - \theta^K \left(\frac{\bar{P}^K}{\bar{P}^{VA}} \right)^{1-\sigma} \right]^{\frac{\sigma}{1-\sigma}}. \quad (24)$$

With similar calculations, we have:

$$\eta_{lt} = \frac{\sigma(\theta^L + \theta^K)}{(1 - \theta^L - \theta^K)} \frac{1}{\theta^{VA}} \quad (25)$$

and we use data on the value share of labor and the elasticity of substitution derived from (23) to allocate the remaining share of value-added among the capital and resource input based on an estimate of the long-run supply price elasticity:

$$\theta^K = \frac{\hat{\eta}_{lt} \theta^{VA}}{\sigma + \hat{\eta}_{lt} \theta^{VA}} - \theta^L. \quad (26)$$

The value share of the resource input is then simply the residual $\theta^R = 1 - \theta^L - \theta^K$. Thus with this calibration procedure, economic behavior in the structural model matches our econometric estimates.

5 Results from the numerical model

In this section, we employ the numerical model of the copper industry to quantitatively investigate the drivers of carbon emissions leakage under a subglobal carbon policy. We generate comparative-statics evidence on the impact of a \$50/tCO₂ price on emissions in highly industrialized countries. These correspond to the ‘Annex B’ group of the Kyoto protocol, with the addition of the U.S. and Australia. The complete list of ‘coalition’ and ‘non-coalition’ countries

is reported in the Appendix.²²

In order to assess the effects of scarcity rents at copper deposits, we calibrate the model to two alternative benchmark equilibria. First, we use output and prices for the year 2007, during which the average price of refined copper was around \$7,000. The total production costs of refined copper were around \$2000 on average, and thus represented only a small fraction of the 2007 market price. Our calibration procedure attributes the residual scarcity rents to the fixed factors at mines. Second, we use the yearly average price for 2002, around \$2,000. In this low price environment, the residual scarcity rents are small. We retain 2007 output data for both price conditions so as to keep the comparison straightforward. Note that calibrating the model to output data for 2002 does not alter our conclusions.

We compute short- and long-term counterfactual equilibria based on alternative parametrization of the supply and demand responses. In the short-run, producers make decisions under the constraint of fixed capital and resource input. The demand response is parametrized with short-term price elasticity estimates. The long-run, we approximate the steady-state outcome by letting the capital supply be perfectly elastic, so that capital is implicitly perfectly mobile across sectors in the economy. Keeping the resource input fixed, the response of producers approximates the long-run elasticity estimates. The demand response is parametrized with long-run elasticity estimates.

5.1 Policy simulations

Table 4 provides summary results reported as percentage changes from the benchmark values. The impact of the subglobal carbon policy on the industry is moderate, even though the carbon price we consider is high. As expected, the rate of pass-through is low. Interestingly, we find the long-run price increase to be larger than in the short-run. Since the supply is significantly more elastic in the long-term, but the demand remains inelastic, the ratio of supply to demand elasticities increases, and the rate of pass-through increases (see equation 3).

²² We emphasize that our aim is not to portray a particular policy proposal. Rather, we generate evidence on changes in the industrial geography based on the detailed spatial representation and econometric estimates of the behavioral response.

TABLE 4: POLICY SIMULATION RESULTS: \$50/tCO₂ subglobal carbon tax (% change from the benchmark)

Simulation results	2007 Prices \$7066.0/t of copper		2002 Prices \$1919.1/t of copper	
	Short term	Long term	Short term	Long term
Change in refined copper price	0.29	0.36	1.18	2.30
Change in demand	-0.01	-0.06	-0.07	-0.28
Change in CO ₂ emissions	-0.04	-0.17	-0.19	-1.38
Change in output:				
<i>Mines</i>	-0.03	-0.14	-0.14	-0.99
<i>Smelters</i>	-0.03	-0.12	-0.12	-0.78
<i>Refineries</i>	-0.02	-0.07	-0.08	-0.50
<i>SXEW</i>	0.01	0.09	0.05	0.79

Under 2007 market conditions, the long-run reduction in global emissions from the copper industry achieved by the \$50 tCO₂ subglobal tax is below 0.2%. With low (2002) copper prices the industry is more responsive, and CO₂ emissions per unit of value are higher than with 2007 prices. But global abatement remains below 2%. We note that only a third of emissions get taxed, and the value-share of production of coalition countries amounts to 35%. The market shares of coalition countries for mining and SXEW processing, the most carbon-intensive activities, are only about 20% and 35% respectively, and it is around 40% for smelting and refining. Also, production in coalition countries is on average less carbon-intensive than in non-coalition countries (on average by about 10%).

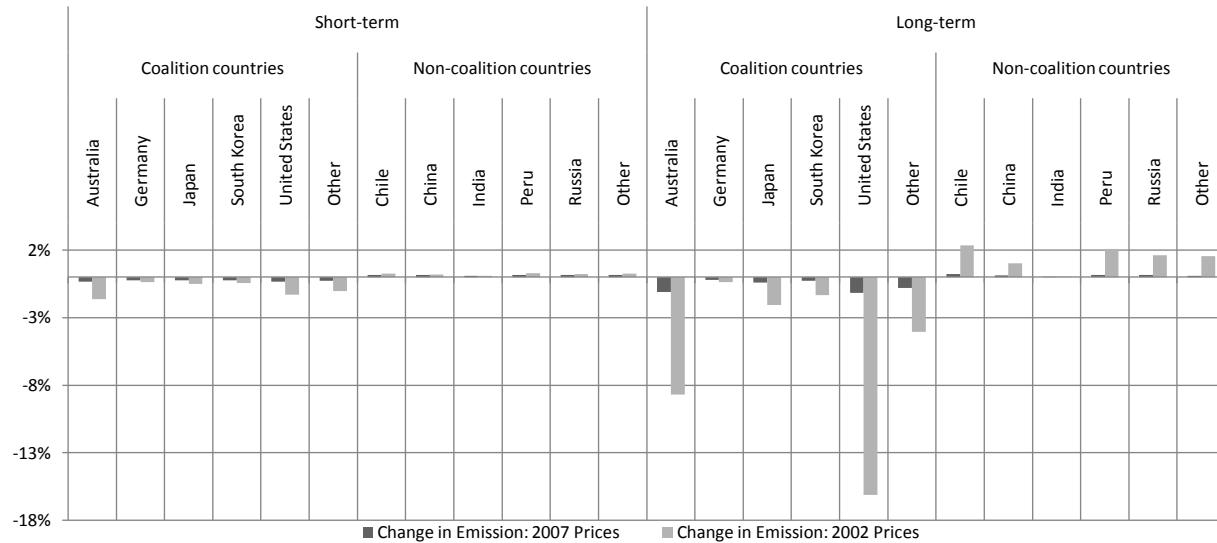
In addition to industrial geography effects discussed in detail below, the model suggests two substitution effects among production processes. First, we observe a net increase of output from SXEW units. Cathodes produced from SXEW process have a lower carbon content and, as the carbon tax raises the equilibrium price of copper concentrate and blister, refineries become less competitive as compared to SXEW plants. Second, output at mines declines more than that of smelters, signaling an increased use of scrap copper. Similarly, scrap input into refining also increases in response to a carbon tax. With the incentive to bypass the carbon-intensive mining and smelting stages, plants that use recycled copper gain a comparative advantage. As shown in Table 4, these two substitution effects are quantitatively important, highlighting the role of

process heterogeneity in the industrial response.

Regional abatement

The geographical distribution of CO₂ abatement is summarized in Figure 4. Short term results, displayed in the left panel, show the almost nonexistent response of the industry. Abatement is largest in Australia and in the U.S., the two main mining regions among coalition countries. With 2007 prices, the short-term emissions reduction is around 0.2% and, under 2002 prices, the reduction is around 1.5%. Non-coalition countries increase their emissions slightly, with the exception of India.

FIGURE 4: SIMULATED CO₂ ABATEMENT (% CHANGE FROM BENCHMARK)



The magnitude of the long-run response depends to a large extent on the benchmark prices. With 2007 prices, emissions in coalition states decline by less than one percent (around 100,000 tCO₂). Copper mining accounts for most of abatement, with the U.S., Australia, Canada and Poland contributing more than 90% of the total abatement. This contrasts with results for a copper price at \$2000, where abatement in coalition regions almost reaches one million tCO₂, or about eight percent of benchmark emissions. Here, concentrate production in coalition regions

contributes to more than 80% of total abatement, and emissions decline by around 16% in the U.S. and 9% in Australia.

In our model, the main factors driving abatement are the carbon intensity of production and the price responsiveness. In particular, production in the U.S. and Australia is carbon-intensive relative to the average, and long-run price elasticities are also large. Since production in non-coalition countries is a perfect substitute to domestic production, change in the relative production costs also induce geographical substitution among plants. Given the spatial equilibrium representation of trade, these are driven by country-specific factors, namely bilateral trade costs and interactions on markets for final and intermediate copper commodities. Given the idiosyncratic nature of changes in trade flows, we now overview changes in trade patterns for key coalition countries.

Considering the U.S. and Australia, both are net exporters of concentrate in the benchmark (mainly to Mexico and China respectively). With 2007 prices, the subglobal tax does not substantially change relative production costs, and trade impacts are negligible. With 2002 prices, the magnitude of the tax is much larger, and U.S. exports of concentrate decline by 80%. Moreover, smelters located in the U.S. start importing concentrate from Chile and Peru, and imports of refined copper from SXEW plants in Chile and Peru also increase, so that all activities decline. In Australia, exports of concentrate to China decline, but the domestic demand from smelters remains stable.²³ Indeed, smelters and refineries in Australia continue to use intermediate copper inputs produced in Australia (both have a low elasticity), and exports of refined copper to China decline only slightly. Thus to a large extent, producers in Australia buffer changes in the production costs, and the demand for exports of refined copper mitigates the change in output along the production chain.

The situation is very different in coalition countries that do not exploit copper deposits. In Japan for example, concentrate is imported from Chile for smelting and refining, and part of the refined copper production is exported to China. Given China also imports concentrate from

²³ As an aside, we note that China compensates the reduction of concentrate imports from Australia by increasing both its domestic concentrate production and its imports from Indonesia. This trade diversion effect induces a drastic reduction of smelting activities in Indonesia, even though these producers do not face a carbon tax.

Chile for smelting, there is a strong incentive to bypass the smelting and refining stages in Japan, and the loss of competitiveness induces a decline in Japan's production and emissions. Moreover, even though there is no copper mines in Japan, lower mining rents induces a larger abatement. This is due to the proportionally larger impact of the tax with low (2002) copper prices, which induces a larger demand response. In turn, the demand reduction at refineries in Japan (from both Japan and China) is more pronounced with low copper prices.

As a final example, Germany also has no copper deposits, but it produces a significant amount of copper commodities using scrap. As facilities processing scrap gain a comparative advantage, it mitigates abatement. Moreover, Germany imports a large share of refined copper from neighboring countries that are also subject to the carbon tax but do not use scrap (mainly Poland and Scandinavian countries). Thus in Germany, the substitution towards scrap leads to an increase in the demand for copper products, and a relatively small emissions reduction.

To sum up, abatement in coalition countries depends to a large extent on the presence of scarcity rents at mines, on the composition of output in each country, as well as trade opportunities with neighboring countries. Moreover, changes in trade flows reveal complicated substitution patterns, and accounting for trade in intermediate commodities and substitution among production processes generates plausible evidence on industrial geography effects.

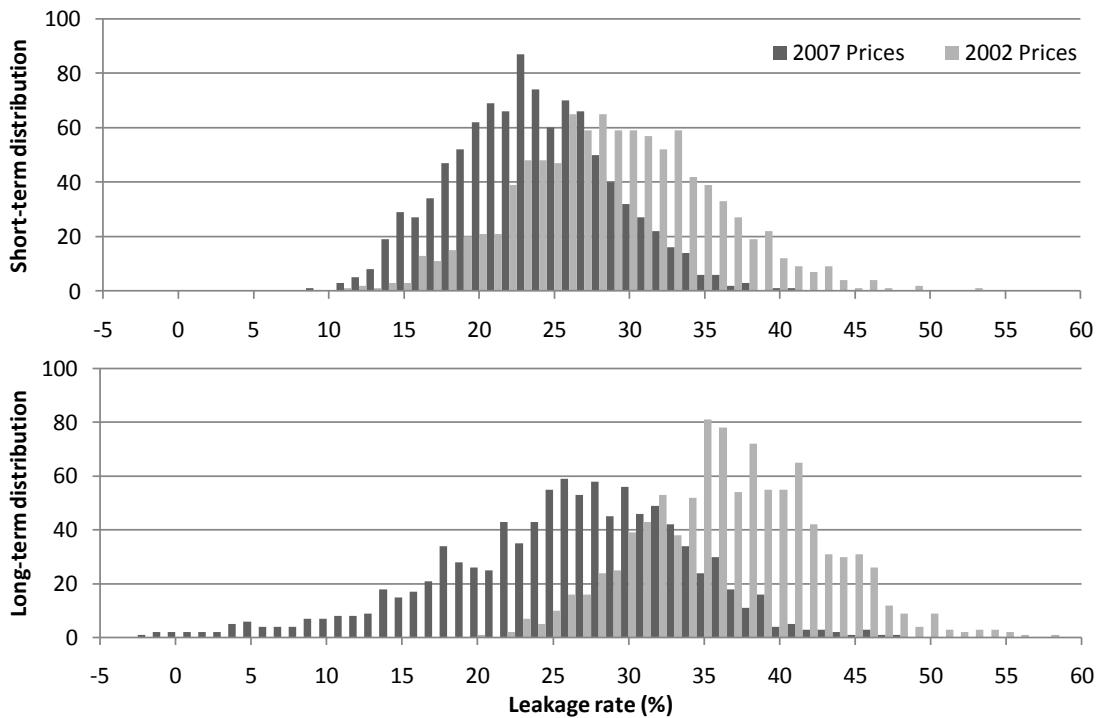
Carbon leakage: Monte Carlo simulations

Competitiveness effects tend to decrease the demand for production in coalition countries, and increase the demand from non-coalition countries through trade.²⁴ Given carbon leakage rate projections is the focus of a large literature, we explicitly account for the statistical uncertainty on our estimates and carry-out a probabilistic assessment of emissions leakage. Specifically, we undertake Monte Carlo simulations based on the estimated standard-errors of the regional price elasticities, drawing from the respective estimates' distribution to successively re-parametrize the supply and demand response before solving for the policy counterfactual.

²⁴ As trade flows both increase and decrease depending on the trade route considered, the net change in emissions associated with transportation is small. For long-run results based on 2002 prices, where we observe the largest change in trade flows, increase in transport CO₂ emissions is less than one percent.

Figure 5 reports the distribution of leakage rates derived from 1000 model run. The short-run distributions, reported in the upper part of Figure 5, suggests a similar range of values for the leakage rate under 2007 and 2002 prices, with a mean of 24% and 29% respectively. The dispersion of the short-term leakage projections is small; lower and upper quartiles are 20–27 for 2007 prices and 25–33 for 2002 prices. The long-run distribution suggests a slightly higher leakage rate. With 2007 prices, the mean leakage rate is 25%, 35% with 2002 prices. However, the support of the long-run distribution is wider, reflecting the larger statistical uncertainty on the long-run price response. The respective lower and upper quartiles are 21–30 and 33–41.

FIGURE 5: SIMULATED EMISSIONS LEAKAGE RATE (NUMBER OF MODEL RUNS)



Our results suggest that emissions leakage might not significantly increase with time. As for the pass-through rate, this reflects changes in the ratio of supply to demand elasticities. On the one hand, the capital stock adjusts to reflect changes in the rental rate, which leads to a greater output response and in turn to a higher leakage rate. On the other hand, the demand is also more elastic, which mitigates leakage regardless of the supply-side response. The empirical

magnitude of these effect implies that, on average, leakage rate increases by about 10% to 20% depending on the copper price.²⁵

The magnitude of leakage is primarily driven by a shift of concentrate production to non-coalition countries. This accounts for around 70% of total long-run leakage. Emissions from concentrate production increase significantly in Chile, which contributes to about 25% of total emissions leakage. Other major contributors to the relocation of concentrate production include non-coalition countries that increase exports of concentrate to smelters in coalition countries (Peru, Russia and Indonesia) and smelters in non-coalition countries that divert imports of concentrate from coalition states to mines in non-coalition states (China and Mexico).

Smelters and SXEW plants each account for about 15% of the remaining emissions leakage. Specifically, China increases its smelting output significantly as it gains market shares over Japan and South Korea, while Chile and Peru account for most of increased emissions at SXEW plants, mainly supplying refined copper to the U.S. Further, simulations suggest no significant leakage from refineries. An important exception is China, which is the only country with a large increase of emissions from refineries, as it reduces its imports of refined copper from Japan. However, in most non-coalition countries emissions from refineries decline. There are two main reasons for this. First, production costs at refineries in both coalition and non-coalition countries increase due to higher equilibrium price of copper blister, making the loss of competitiveness relatively small. Second, the equilibrium price increase of refined copper induces a decline in demand, so that refineries supplying in non-coalition regions also reduce output.

We also observe that scarcity rents mitigate leakage, an effect primarily driven by the response at mines and SXEW units, since the loss of competitiveness is proportionally larger. In fact, the long-run distribution with 2007 prices features a number of model runs with very low leakage rate, where the response of mines is low. Given that copper commodities are homogeneous, this can appear surprising. However, the equilibrium price increase in intermediate products affect all producers in the industry, and the global increase of copper prices lead to a

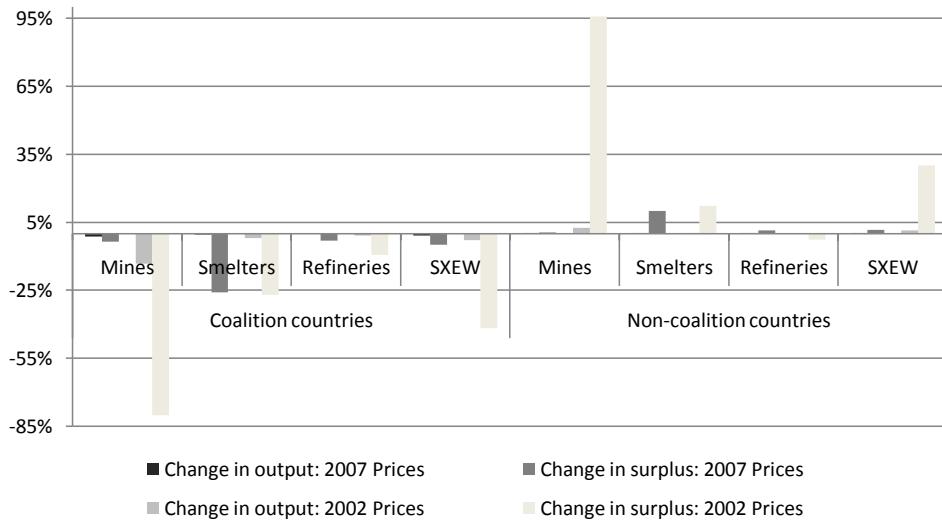
²⁵ Interestingly, using average short-term and long-term elasticity estimates, the linear approximation (equation 7) suggests an increase of leakage by 15%.

decline in the demand in both coalition and non-coalition countries. This leads to a net decline of emissions in a number of non-coalition countries, mitigating the sectoral leakage. Moreover, producers are not responsive to price changes and the cost differential is small, so that the tax is mainly reflected in the return to the fixed factors rather than changes in output.

Production and welfare

We now assess the impact of the policy on the rents of producers, as measured by changes of the rental rate of the fixed resource input. As the tax raises production costs in coalition countries, the demand for output at these plants declines, and so is the value of the fixed factors. In turn, revenues of resource owners decline, which mitigates the cost differential. Conversely, producers in non-coalition countries increase their rents rather than expanding output.²⁶ Figure 6 reports long-run changes in rents for each production process and compares these to the change in output. As expected, changes in output are small, while changes in the value of productive assets are much larger.

FIGURE 6: CHANGE IN OUTPUT AND PRODUCER SURPLUS (% CHANGE FROM THE BENCHMARK)



²⁶ Importantly, the magnitude of these adjustments are driven by our econometric estimates of price elasticities.

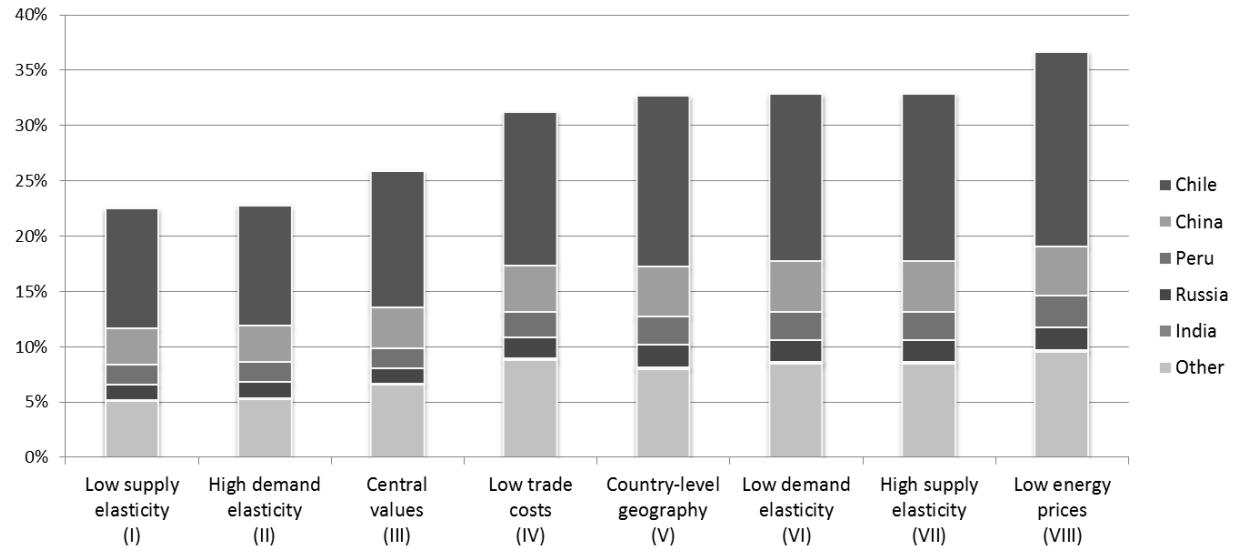
We observe that the percentage change in rents is much smaller with 2007 prices (the absolute changes in the level of rents are relatively similar). Indeed, at 2007 prices, rents in the benchmark are large and the response of the industry in terms of production and rents is modest. With 2002 prices, the equilibrium adjustments in rents is a larger share of benchmark rents, and the output response is larger. In coalition countries, rents at mines are driven down almost entirely, while the rents at mines in non-coalition regions almost double. We also note that rents at refineries in non-coalition countries decline, reflecting the global reduction in the demand for refined copper, and the substitution operating in favor of SXEW plants.

The subglobal tax implies substantial change in revenues for coalition countries, as owners of the fixed resource buffer cost differentials. This change in rents mitigates competitiveness effects, and output price variations are capitalized in earnings of the fixed resource. Over the whole industry, increased producer rents in non-coalition countries do not compensate losses in coalition countries. In addition, increase in the equilibrium price of refined copper leads to a world-wide decline in consumer surplus. Thus on the one hand, major copper producing countries such as Chile and Peru still make substantial gains by holding out of the climate policy. On the other hand, China is both a large producer and the largest market for refined copper, and the total loss of consumer surplus is larger than the total increase in producer surplus.

5.2 Sensitivity analysis

This section focuses on the sensitivity of the leakage results with respect to exogenous parameters of the model. The long-run leakage rate for eight alternative parametrization and 2007 copper prices are reported in Figure 7. First, we assess the impact of supply and demand elasticities in a systematic manner. Columns (I), (II), (VI) and (VII) report the leakage rate, independently increasing and decreasing supply and demand elasticities by 50%. Compared to the mean leakage rate reported in column (III), supply elasticities have a positive impact on carbon leakage and the demand elasticity has a negative impact on leakage. The change in leakage is of the same magnitude for similar changes in the demand and supply elasticities, which is in line with equation (7).

FIGURE 7: SENSITIVITY ANALYSIS: EMISSIONS LEAKAGE RATE



We next examine two features of our trade model. First, we consider the impact of trade costs, which are also subject to variations depending on the global demand for international shipping. In particular, shipping rates were relatively high in 2007, and column IV reports the leakage rate lowering the trade costs by 50%. We find the leakage rate increases to 31%, suggesting that the high value of copper makes trade costs relatively unimportant. Second, we assess the impact of the plant-level representation, and column (V) reports the leakage rate in a model where each country only has one representative plant. As expected, the leakage rate is higher at 33%, showing the importance of aggregation in the representation of carbon leakage effects.

Finally, we look at the impact of global energy prices. Indeed, beside competitiveness effects, the literature finds that general equilibrium effects through energy prices can create substantial emissions leakage (e.g. Felder and Rutherford, 1993; Burniaux and Oliveira-Martins, forthcoming). A decline in the demand for energy in coalition countries may depress the world prices and lead to an increase in the demand for energy in non-coalition countries. Column (VIII) reports the leakage rate with world energy prices lower by 2%. At 36%, we find the increase of

the leakage rate to be significant. Our results thus confirm that spillovers through global energy markets have an important impact on the industrial geography, and that the effectiveness of subglobal climate policies in great part depend on the energy market.

6 Conclusions

This paper has employed analytical and numerical models to study the link between subglobal climate policies and trade in homogeneous, energy-intensive commodities. Qualitative predictions on emissions leakage from the numerical model align with those from a simple analytical representation of differentiated taxation. Our numerical model allows quantifying the scope of leakage based on econometric estimates of price elasticities, and it includes a detailed representation of industrial geography. We examine the magnitude of carbon abatement and emissions leakage in the copper industry, which features energy-intensive production processes, large scale international trade in final and intermediate commodities, as well as significant fluctuations in commodity prices. Simulations suggest that the existence of sunk costs and scarcity rents make the copper industry unresponsive to subglobal climate policy. This finding is in line with the empirical literature on pollution haven effect, which finds that differentiated environmental policy has little impact on the location of capital-intensive activities, even when these are the most polluting.

Our work has several implications for ex-ante assessment of carbon abatement measures and associated trade policies. First, substantial sunk costs in the sector constrain the industrial response, and in turn leakage, even though these basic materials are homogeneous products. In the presence of scarcity rents, abatement cost are almost entirely capitalized into the value of sector- and process-specific assets but have relatively little impact on the location of production. This means that over the time frame of 10 to 20 years, carbon emissions in the copper industry are insensitive to carbon policy. More generally, the supply curve for abatement from heavy industries is likely to be much steeper than would be suggested in a conventional CGE models, and abatement will need to be undertaken in other activities.

Second, geographical effects and emission leakage obviously depend on the representation

of trade. Our framework suggests complex changes in the trade patterns, reflecting trade costs, regional heterogeneity in carbon intensity, and interactions on markets for intermediate and final products. It follows that the Armington trade model and regional aggregation used in standard CGE analysis are likely to provide a crude approximation of industrial relocation effects. The use of such models for the assessment of subglobal carbon policies and border measures in will likely overlook important geographical effects taking place on intermediate product markets.

Third, if the leakage rate for copper, one of the more energy-intensive products in the world, is only around 30%, economy-wide leakage rates due to competitiveness effects are modest. We note that assumption about product homogeneity and perfectly competitive market tend to make our projection an upper bound to what can be expected in reality. In turn, the use of additional policy tools, in particular border measures, is likely to be unnecessary, and developments on global energy markets are likely to be more important for the effectiveness of subglobal climate policies.

We close by emphasizing that our simulations should not be interpreted too literally as they do not incorporate a number of potentially important features. In particular, fluctuations in commodities prices have a large impact on abatement potential of industrial sectors, and the response of producers will include expectations about the future evolution of these prices. Further, in the case of copper, increasing resource scarcity will induce structural changes in the production costs, which will be reflected in forward-looking investment decisions. These considerations are absent of our static deterministic framework. Our qualitative insights are, however, robust to these considerations.

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Appendix: List of regions

<i>Africa</i>	<i>Europe</i>	<i>Central Asia</i>
Botswana	Austria*	Armenia
Congo	Bulgaria	Georgia
Namibia	Belgium*	Kazakhstan
South Africa	Cyprus	Russia
Tanzania	Czech Republic	Ukraine
Zambia	Denmark*	United Arab Emirates
Zimbabwe	France*	Uzbekistan
<i>North Africa and Middle East</i>	<i>Germany*</i>	<i>East Asia</i>
Egypt	Hungary	China
Iran	Italy*	Indonesia
Mauritania	Netherlands*	Japan*
Morocco	Poland*	Korean Republic*
Oman	Portugal*	Malaysia
Saudi Arabia	Romania	Mongolia
Turkey	Scandinavia*	Myanmar
<i>Latin America</i>	Serbia	North Korea
Argentina	Slovakia	Papua New Guinea
Brazil	Spain*	Philippines
Chile	United Kingdom*	Taipei
Colombia	<i>North America</i>	Thailand
Ecuador	Canada*	Vietnam
Mexico	United States*	<i>South Asia</i>
Peru	<i>Oceania</i>	India
Venezuela	Australia*	Pakistan

Note: * Coalition countries