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Subglobal climate agreements and energy-intensive activities: An evaluation of carbon leakage in the copper industry*

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Abstract

Subglobal climate policies induce changes in international competitiveness and favor a relocation of carbon-emitting activities to non-abating regions. In this paper, we evaluate the potential for CO_2 abatement and the emissions 'leakage' effect in the copper industry, a prominent energy-intensive trade-exposed sector. We formulate a plant-level spatial equilibrium model for copper commodities in which parameters describing the behavioral response of agents are calibrated to econometric estimates of price elasticities. We find producers and consumers to be price inelastic even in the long-run, making the copper industry unresponsive to climate policies. Monte Carlo simulations with our model based on statistical uncertainty on elasticity estimates suggest that around 30% of emissions reductions in industrialized countries would be compensated by an increase of emissions in non-abating countries.

Keywords: Carbon leakage, Pollution haven effect, Climate policy, International environmental agreements, 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 dioxide (CO_2) abatement targets. As CO_2 abatement is a global public good, free-riding incentives undermine the process of international policy coordination (see e.g. Barrett, 2005). In addition, countries holding out on global agreements gain a comparative advantage in polluting activities (Hoel, 1991), and a relocation of carbon-emitting activities from coalition countries to non-coalition countries would undo the environmental benefits expected by coalition members. The potential for emissions displacement, known as both the pollution haven effect[1] and emissions leakage effect, exacerbates international coordination problems, and the scope of such an effect is a major factor in negotiations and policy design. Indeed, while unilaterally abating countries can grant regulatory exemption for trade-exposed sectors (Hoel, 1996) or impose boarder tax adjustments (Ismer and Neuhoff, 2007), these policies could conceal strategic rent capture, increasing incentives to hold out of agreements.

The impact of differentiated environmental regulation on the location of polluting activities is the subject of an extensive 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. While early studies did not find evidence supporting a pollution haven effect (see Jaffe et al., 1995), recent evidence suggests it is of statistical and economic significance (Levinson and Taylor, 2008; Kellenberg, 2009). Second, since data on the economic response to a carbon policy is scarce, the main source for quantitative evidence in the climate policy debate derived from simulations from structural economic models. In this literature, the impact of subglobal climate policies on the location of carbon emissions is typically measured through the 'carbon leakage rate', i.e. the increase of emissions in non-coalition countries relative to emissions abatement achieved in coalition countries. Recent economy-wide projections using computable general equilibrium (CGE) models typically fall between 5 and 25 percent (e.g. Böhringer et al., 2010; Elliott et al., 2010). These models suggest that emissions displacements mainly occur through a small number of energy-

[1] Copeland and Taylor (2004) differentiate between the 'pollution haven effect' and 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.

intensive sectors where leakage is very high, namely mining, non-ferrous metals production, iron and steel, as well as the chemical industry (Paltsev, 2001).

In this paper, we provide further evidence on the potential for emissions leakage at the sectoral level based on partial-equilibrium simulations. Our representation of production and trade is motivated by a number of findings from the literature. Mathiesen and Maestad (2004) study carbon leakage in the steel industry employing a model with process-specific representation of production, a feature mostly absent from CGE studies. Simulating the impact of a \$25/tCO$_2$ tax in Annex B countries of the Kyoto protocol, they find that increasing the resolution on technological details reduces the projected leakage rate from 53% to 26%. As in a wide majority of CGE models however, Mathiesen and Maestad (2004) represent trade in steel products using the Armington model (Armington, 1969), where products originating from different locations are imperfect substitute. For most basic materials, this assumption is questionable, and it was relaxed by Demailly and Quirion (2009) in the context of the cement industry. Using a detailed geographical representation, they suggest that a \$15/tCO$_2$ tax in Annex B countries would induce a 20% leakage rate in the cement industry. In our modeling framework, we use a plant-level representation of industrial geography, allowing us to compute realistic transportation costs and capture heterogeneity in the production processes and technological substitution possibilities. Furthermore, we allow for traded goods to be homogeneous, and market interactions are modeled as a spatial equilibrium (Takayama and Judge, 1971), allowing us to generate rich intra-sectoral trade patterns in intermediate and final products. Finally, we capture general equilibrium energy price effects highlighted by Felder and Rutherford (1993) and Burniaux and Oliveira-Martins (2012) through exogenous parameters in the model.

We apply our modeling framework to the copper industry, which has several interesting features. First, on a weight basis, copper is the most energy-intensive non-ferrous metal after aluminum, and a major component of the aggregate non-ferrous metal sector in CGE models. Refined copper is also more energy-intensive than iron and steel, cement, paper, and most basic chemicals (Bergmann et al., 2007). Second, within the copper industry, carbon emissions vary considerably. The production of refined copper requires several transformation steps, and there exist two competing production routes from copper deposits to refined copper. Moreover, around 15% of refined copper is produced from scrap material, bypassing the energy-intensive mining stage. Third, intermediate and final copper products are homogeneous, so that production from different plants are perfect substitutes, and refined and pre-refined copper commodities are subject to large-scale international trade (Radetzki, 2008). Finally, the industry is competitive (Radetzki, 2009), which generally induces higher emissions leakage (Fowlie, 2009).

A key contribution of this paper is to show the importance of producers' and consumers' price responsiveness for carbon leakage effects. Based on a simple Marshallian model, we show analytically that: (i) the leakage rate is higher in sectors with price inelastic demand; and (ii) sectors with relatively low supply elasticities feature a lower leakage rate. To capture these effects in our policy simulations, we develop a calibration strategy such that demand and production decisions in the numerical model approximate empirical estimates of short- and long-run price elasticities. We estimate country and process specific price elasticities and find that price responsiveness of producers and consumers in the copper industry is low. This reflects the fact that adjustments in the industry are constrained even in the long-run, notably by infrastructure requirements (such as transportation links) and institutional factors (such as environmental policies).

Our analysis suggests that the impact of subglobal climate policy on the copper industry is limited, 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 in changes of output levels. Using Monte Carlo simulations to account for the statistical uncertainty on price elasticity estimates, our model suggest that a $50/tCO$_2$ tax imposed in highly industrialized countries under 2007 market conditions would induce a long-run leakage rate of around 30%. In coalition countries, projections of emissions abatement is less than 1%. Changes in output and hence emissions are constrained even over a horizon of 10 to 20 years, and asset owners in non-coalition countries benefit from a global increase in the price of copper products through increased rents, while the location of activities remains largely unaffected. These findings are reminiscent of empirical studies by Ederington et al. (2005) and Kellenberg (2009), which suggest that most pollution-intensive sectors are also capital-intensive, constraining the relocation of activities. In the copper industry, investments are highly capital intensive and have long productive lives, making existing facilities unlikely to shut down much before their estimated life expectancies in response to a carbon tax. Furthermore, in industries with highly valuable products such as copper, the overhead costs of environmental regulation is low.

Through our analysis we also highlight the importance of baseline price assumption for the calibration of numerical models. In the copper industry, commodity prices are subject to substantial fluctuations, and CO_2 emissions from refined copper production were 1.5kgCO_2/\$ under 2002 market conditions, when refined copper prices were around \$2,000/ton, but only 0.4kgCO_2/\$ under a 2007 average price of \$7,000/ton. While the two benchmark price assumptions can be used to calibrate the model, assuming 2002 market conditions suggests carbon abatement in coalition regions is higher at 8%. The leakage *rate* remains largely unaffected however, as it is mainly determined by price elasticities, but total emissions leakage increases. While the issue of benchmark price assumption is salient for the copper industry, it applies to most basic materials traded on international commodities markets, and has major implications for policy conclusions drawn from CGE models.

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. In Section 4, we describe the model for the copper industry, calibration procedure, and estimation of price elasticities. Section 5 reports the results of counterfactual policy analysis. The final section concludes.

2 An analytical framework for emissions leakage

In this section, we develop a simple representation of differentiated emissions taxation in order to derive a first order approximation for the emissions leakage rate.[2] Consider a market for a homogeneous good produced in two regions, where production $Q_i^s(P)$ in region $i = \{1,2\}$ is a function of the market clearing price P. We can approximate the supply schedule in region i with a first order Taylor expansion around a reference equilibrium described by the benchmark price level $\overline{P}$ and production levels $\overline{Q}_i^s$:

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

[2] For related calculations, see Lünenbürger and Rauscher (2003).

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

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

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

Initially, there are no emissions restrictions, and the benchmark equilibrium is $\left(\overline{P}, \overline{Q}^d, \{\overline{Q}_i^s\}_{i=1,2}\right)$. In a counterfactual equilibrium where producer $i = 1$ faces a tax t on emissions, the equilibrium price is:

$$P = \overline{P} + te_1 \frac{\eta_1 \overline{Q}_1^s}{\eta_1 \overline{Q}_1^s + \eta_2 \overline{Q}_2^s + \varepsilon \overline{Q}^d} \tag{3}$$

where e_i denotes emissions per unit of output for region i. The pass-through rate of the tax to the consumer depends on the relative elasticities and on benchmark production levels (or market shares). The higher equilibrium market price induces a decline in demand, and the corresponding supply in each region is:

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

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

Defining the emissions leakage rate as:

$$\ell := \frac{e_2 Q_2^s - e_2 \overline{Q}_2^s}{e_1 \overline{Q}_1^s - e_1 Q_1^s}, \tag{6}$$

an approximation of the carbon leakage rate for arbitrary supply and demand schedules is given by:

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

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

Demand and supply elasticities have an intuitive relationship with the emissions leakage rate. First, economic activities facing an elastic demand feature a lower scope for emissions leakage, since a price increase induces a greater reduction in total market size. Second, following a price increase the untaxed producer increases output, causing emissions to increase in proportion to the price elasticity of the untaxed producer and its benchmark market share. The price 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 leakage rate is proportional to the relative emissions intensity of producers, so that the leakage rate can be above 100% if there are large differences in production technologies among taxed and non-taxed producers. Finally, over a longer time horizon, capital can be reallocated, price responsiveness is higher, and the leakage rate increases. However, two effects work against an increase of the leakage rate. The demand elasticity also tends to be greater in the long-run, for example reflecting increased substitution possibilities, and the producers facing the tax can invest in abatement technologies, reducing e_1. Thus if demand elasticity increases more rapidly than supply elasticity, or if abatement technologies reduce emissions intensity, equation (7) suggests that the long-run leakage *rate* could decline over time.

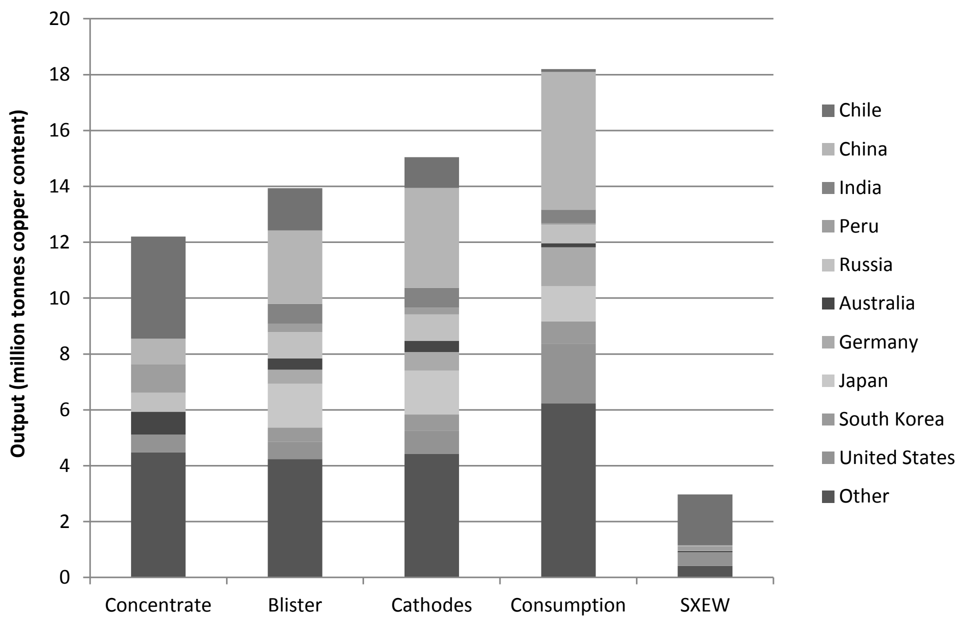
3 Copper production, demand and carbon emissions

Refined copper is produced from one of two alternative processes. In pyrometallurgical processing, the mined material is first crushed, ground and concentrated into copper 'concentrate', which contains around 30% pure copper. Copper concentrate is then shipped to smelters to be processed into copper 'blister', which contains around 98% pure copper. Low quality scrap copper can enter the smelting process either in addition to concentrate or in smelters dedicated to scrap. Blister is then processed into pure copper 'cathodes' at refineries, which can also process high quality scrap copper. The second production process is 'solvent extraction - electrowinning' (SXEW), which directly produces copper cathodes close to deposits. The pyrometallurgical process is used to recover copper from the more abundant sulfide ore deposits, while SXEW plants process mostly oxide ores and do not process scrap copper.

Copper commodities produced in different locations are homogeneous[3] and a global market for copper products has emerged since the mid-1990's (Radetzki, 2008). The copper industry features a low degree of concentration. For all copper commodities, the Herfindahl-Hirschman Indexes (HHI) at the country level is below 1,000, and no multinational firm has a market

[3] The copper content of concentrate can vary, typically between 30% and 35%, but this does not affect the smelting process.

Figure 1: Output per production process, 2007



Notes: Source: ICSG (2008b). Details of production per country is provided for the ten largest producers across all commodities. Differences between output of each commodity reflect scrap copper input.

share above 10% (Radetzki, 2009). Competition is also fostered by the possibility to produce from scrap and the existence of the two alternative production routes. Figure 1 reports regional shares of production for each copper commodity in 2007.

Despite there being no dominant producing firm in the industry, Chile is host to most of the copper deposits, and it produces around 30% of total concentrate output. Chile also produces 60% of SXEW output, but total production from SXEW plants only represents around 15% of total refined copper production. On the market for refined copper, China has the largest market share with 20%. Production from scrap, implicitly reported in Figure 1, is around 15%.

Refined- and pre-refined copper commodities are actively traded on international markets. Since trade is a major focus of our analysis, we now overview 2007 trade activities. Chile exports almost 60% of its concentrate production to be smelted abroad, while other major concentrate producers (Peru, Australia and Indonesia) export more than half of their concentrate output. China and Japan both import more than 1 million tonnes of concentrate each year for smelting. International trade flows of copper blister are smaller than those for concentrate, and Chile is by far the largest exporter (0.4 million tonnes). With almost 3 million tonnes, Chile is also the largest exporter of refined copper. Other major exporters of refined copper 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, refined copper is mainly used by the construction, electronics, telecommunications and transportation industries. Depending on its use, copper can be replaced by aluminum, plastics, or gold, but overall the substitution possibilities are limited. China uses around 25% of total refined copper 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 0.9 million tonnes respectively). Germany uses 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 is energy-intensive, both in terms electricity and fossil fuels (Alvarado et al., 1999), and energy consumption entails significant carbon emissions.[4] Table 1 reports carbon intensity of production processes. Production of copper concentrate is the most carbon-intensive process, as the copper content of exploited deposits is low (between 0.5 and 1 percent) and large volumes of ore need to be extracted. In total, pyrometallurgical processing emits more than twice as much CO_2 per tonne of refined copper. Cross-country variations mainly reflect differences in electricity generation technologies. For example, Australia, the U.S. and China mainly use coal-fired generation, whereas Chile and Peru hold large hydroelectric resources.

4 A model for the copper industry

4.1 Model description

We formulate the model at the plant-level based on a comprehensive list of copper facilities and their output for 2007 (ICSG, 2008b). The model includes two alternative production routes (see graphical representation in the Appendix). The first route starts with mines (*mn*) producing copper concentrate (*CC*). Concentrate is traded between mines and smelters (*sm*), and we represent products from different mines as perfect substitutes. Given the existence of trade costs, the producer price of copper concentrate (P^{CC}_{mn}) differs from the consumer price at smelters (P^{CC}_{sm}). Smelters then produce blister copper (*BC*), which is traded with refineries (rf) to produce re-

[4] Unlike other basic materials such as aluminum, process-related (non-energy) CO_2 emissions in copper production are negligible.

Table 1: CO_2 emissions in the copper industry

Country	Emissions coefficients (tCO_2/tCU)				Emissions
	Mining	Smelting	Refining	SXEW[a]	('000 tCO_2)
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
Total emissions '000 tCO_2	21,073.9	8,294.3	2,973.6	3,299.4	35,641.2

Notes: [a]SXEW figures include extraction, leaching and electrowinning. [b] Weighted average. *Source:* Authors' own calculations. Process related emissions are from Kuckshinrichs et al. (2007), physical electricity input is from Pimentel (2008) and carbon content of electricity generation is from IEA (2009). These figures are consistent with bottom-up estimates reported in Bergmann et al. (2007).

fined copper (*RC*). In the second production route, SXEW units (*sxew*) produce refined copper cathodes directly and compete with refineries to supply consumers in regional markets (*r*). Regional markets for refined copper are represented at the country level with copper consumption data from ICSG (2008a).

We model production processes with two-level linearly homogeneous CES functions. The main motivation for this structure is to accommodate empirical evidence on the supply price elasticities, while keeping track of the value and use of inputs. Formally, the upper nest is a fixed coefficient (Leontief) technology which combines 'materials' (*M*), including chemicals, fuels and electricity inputs, together with a composite input from a 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 is a conventional CES nest that combines labor (*L*) with two resource inputs, which we call capital (*K*) and resource (*R*). As detailed in Section 4.3, free parameters of the lower nest, namely the elasticity of substitution ($\sigma^i, i = \{mn, sm, rf, sxew\}$) and the value share of the capital and resource inputs, are calibrated to match short- and long-run supply elasticities.

The model is formulated as a mixed complementarity problem and solved with the PATH solver (Dirkse and Ferris, 1995).[5] Formally, each plant i is price-taker and maximizes profits, and the zero profit conditions prevailing in a competitive equilibrium exhibit complementarity slackness with respect to the activity levels Y_i:

$$-\Pi_i \geq 0 \quad \perp \quad Y_i \geq 0, \quad i = \{mn, sm, rf, sxew\} \tag{8}$$

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 are given by:

$$\Pi_i = P_i^j - \theta_i^{j'} P_i^{j'} - \theta_i^M - \theta_i^{SC} - \theta_i^{VA} P_i^{VA}, \quad j = \{CC, BC, RC\}, \ , j' = \{CC, BC\}, \tag{9}$$

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 and θ^{SC} are the cost of material inputs and scrap copper respectively.[6] For simplicity of exposition, the cost of the energy input is lumped together with other materials, but changes in energy costs can be assessed by breaking down the material cost shares. A tax on CO_2 emissions increases production costs in proportion to emissions coefficients (in tCO_2/ton of copper). Finally, θ^{VA} is the value attributed to lower 'value-added' nest, with CES price index P^{VA} given by:

$$P_i^{VA} = \left(\theta_i^L \overline{P^L}^{1-\sigma} + \theta_i^K P_i^{K\,1-\sigma} + \theta_i^R P_i^{R\,1-\sigma} \right)^{\frac{1}{1-\sigma}}, \tag{10}$$

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

Equilibrium is further described by a set of market clearing conditions that are complementary to a vector of prices. Market clearing equations for plant-specific capital and resource inputs

[5] Given assumptions about the functional forms, 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.

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

are given by:

$$K_i = \overline{K}_i \frac{Y_i}{\overline{Y}_i} \left(\frac{P_i^{VA}}{P_i^K} \right)^{\sigma} \quad \perp \quad P_i^K \geq 0, \tag{11}$$

$$R_i = \overline{R}_i \frac{Y_i}{\overline{Y}_i} \left(\frac{P_i^{VA}}{P_i^R} \right)^{\sigma} \quad \perp \quad P_i^R \geq 0, \tag{12}$$

where $\overline{K}$ and $\overline{R}$ are benchmark capital and resource stocks. The left-hand side of these equations represents the supply of capital and resource inputs, and the right-hand side represent the demand (derived through Shephard's Lemma).

Interactions on the markets for copper commodities are represented as a spatial equilibrium for homogeneous products (Takayama and Judge, 1971), where each plant in the model is a spatially distinct market. For producer of good j, the equilibrium market clearing condition for output Y_i^j is:

$$Y_i^j \geq \sum_{i'} X_{i,i'}^j \quad \perp \quad P_i^j \geq 0, \tag{13}$$

where P_i^j is the producer price for good j at plant i and $X_{i,i'}$ is the bilateral trade flow between plants i and i', with the sum across recipients representing the demand for output of plant i. At nodes i', where copper commodities are demanded, the market clearing condition is given by:

$$\sum_{i} X_{i,i'}^j \geq \theta_{i'}^j Y_{i'}^j \quad \perp \quad P_{i'}^j \geq 0, \tag{14}$$

where the left-hand-side supply equals the sum of incoming trade flows and $\theta_{i'}^j Y_{i'}^j$ represent the demand for product j at plant i'. The demand for refined copper in each country r is represented by isoelastic demand functions:

$$Y_r^d = \overline{Y}_r^d \left(\frac{P_r^{RC}}{\overline{P}_r^{RC}} \right)^{\varepsilon_r}, \tag{15}$$

where $\varepsilon^r < 0$ is the demand elasticity, and $\overline{Y}_r^d$ and $\overline{P}_r^{RC}$ are respectively the benchmark demand and consumer price for refined copper.

Finally, prices at spatially distinct sites i and i' differ by the bilateral trade costs TC:

$$P_i^j + TC_{i,i'} = P_{i'}^j \quad \perp \quad X_{i,i'} \geq 0. \tag{16}$$

This condition can be interpreted as a spatial arbitrage equation, and it is complementary to the trade flows between plants i and i'.

4.2 Spatial representation

All plants and markets in the model are spatially identified through their longitude-latitude coordinates. The main source for geographical information on production facilities is USGS (2003) together with a number of online resources.[7] For final demand, since consumption of refined copper is represented at the country-level, we approximate the location of consumers with capacity-weighted 'average' longitude-latitude coordinates of facilities producing copper wire rod (IWCC, 2008).

Bilateral trade costs linking plants and markets in the model are derived as follows. Copper commodities can be transported by rail and by boat. For plants not separated by an ocean the mileage between plants is approximated through great-circle distance, and the rail freight cost is based on country-specific rail rates from the World Bank (2007). Trade among plants separated by an ocean involves sea shipping. For these trade routes, we first construct a list of major commercial ports located near each plant, with geographical information (longitude/latitude and inter-ports sea distances) taken from Lloyds' Maritime Atlas (Lloyd's, 2005). We then apply 2007 sea shipping rates for bulk (concentrate) and liner shipping (blister and refined copper) from UNCTAD (2007), and add rail freight costs to link each plant to its nearest port. The bilateral transportation cost between each pair of plants is then the minimum between rail freight costs (whenever possible) and the sea shipping costs. Finally, for trade routes where the exporting and importing plants are located in different countries, we apply import and export tariffs for concentrate, blister and refined copper reported in WTO (2008).

Since we do not observe plant-level trade flows in the benchmark, we simulate them based on observed plant-level output and country-level refined copper consumption, as well as computed bilateral trade costs. To do so, we formulate an auxiliary model that selects the benchmark bilateral trade flows $\overline{X}_{i,i'}$ between units i and i' so as to minimize total transportation costs required to meet the observed output and demand at each plant and market:

$$\begin{aligned} \underset{\overline{X}^j_{i,i'}\geq 0}{Min} \quad \sum_{i,i'} \overline{X}^j_{i,i'} TC^j_{i,i'} \qquad s.t. \qquad & \overline{y}^j_i \geq \sum_{i'} \overline{X}^j_{i,i'}, \quad \forall i, j \\ & \sum_i \overline{X}^j_{i,i'} \geq \overline{d}^j_{i'}, \quad \forall i', j \end{aligned} \tag{17}$$

[7] 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.

where $\bar{y}_i^j$ is 2007 output of product j at plant i, and $d_{i'}^j$ is 2007 demand for product j at plant/market i'. The dual variables associated with the supply and demand constraints represent the shadow value of the commodities at each plant and market, and can be interpreted as the benchmark producer and consumer prices.

Overall, the least-cost representation of trade provides a good account of observed trade flows at the country level reported in ICSG (2008a).[8] The volume of international trade in concentrate and refined copper is quantitatively much more significant than that involving blister, and shipment from South America to East Asia, North America and Europe make up the main trading routes.

4.3 Model calibration

The model 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 institutions, observed choices are assumed to be an equilibrium outcome resulting from cost-minimizing behavior. In this section, we discuss the calibration of the production technologies so that, away from the benchmark equilibrium, the associated supply schedule approximates estimates of price elasticities.

The capital intensity of copper-related activities implies that the short- and long-term response to a permanent change in price on global commodity markets are likely to differ. To calibrate the model to short-term price elasticity estimates, we treat both the capital and resource inputs as being plant-specific and fixed ($K = \overline{K}$, $R = \overline{R}$). Inverting equations (11) and (12), we obtain an expression for the change in the return to the fixed factors as a function of the change in output:

$$\frac{P^K}{\overline{P}^K} = P^{VA} \left(\frac{y}{\bar{y}} \right)^{\frac{1}{\sigma}} \tag{18}$$

$$\frac{P^R}{\overline{P}^R} = P^{VA} \left(\frac{y}{\bar{y}} \right)^{\frac{1}{\sigma}} \tag{19}$$

[8] 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 copper cathodes.

Substituting (18) and (19) into (10), we have:

$$
\begin{aligned}
P^{VA} &= \left(\theta^L \overline{P^L}^{1-\sigma} + (1-\theta^L) {P^{VA}}^{1-\sigma} \left(\frac{y}{\overline{y}} \right)^{\frac{1-\sigma}{\sigma}} \right)^{\frac{1}{1-\sigma}} \quad \Leftrightarrow \\
\frac{y}{\overline{y}} &= (1-\theta^L)^{\frac{\sigma}{\sigma-1}} \left[1 - \theta^L \left(\frac{\overline{P}^L}{P^{VA}} \right)^{1-\sigma} \right]^{\frac{\sigma}{1-\sigma}} .
\end{aligned}
\tag{20}
$$

Setting all prices equal to unity, we can express the short term price elasticity as:

$$
\eta^{st} = \frac{\partial \frac{y}{\overline{y}}}{\partial P} \frac{P}{\frac{y}{\overline{y}}} = \frac{\partial \frac{y}{\overline{y}}}{\partial P^{VA}} \frac{\partial P^{VA}}{\partial P} = \frac{\sigma \theta^L}{1-\theta^L} \frac{1}{\theta^{VA}} , \tag{21}
$$

so that the elasticity of substitution appearing in the lower-nest can be expressed as:

$$
\sigma = \hat{\eta}^{st} \theta^{VA} \frac{1-\theta^L}{\theta^L} . \tag{22}
$$

The value share of the *VA* nest is computed as the residual based on the zero profit condition (8) together with data on the cost of materials, energy, scrap copper inputs from CRU Analysis (2009), as well as the simulated price of copper commodities at each plant. Thus based on this procedure, the response of the model when both the capital and the resource inputs are held fixed approximates the estimated short-run price elasticity.

The remaining free parameters are the value shares of the capital and resource input. For the model to approximate empirical evidence about long-run price elasticities, we treat the resource input as plant-specific and fixed, whereas the capital input is freely mobile so that its rental rate is determined exogenously ($P^K = \overline{P}^K$). Equation (20) can thus be rewritten as:

$$
\frac{y}{\overline{y}} = (1-\theta^L-\theta^K)^{\frac{\sigma}{\sigma-1}} \left[1 - \theta^L \left(\frac{\overline{P}^L}{P^{VA}} \right)^{1-\sigma} - \theta^K \left(\frac{\overline{P}^K}{P^{VA}} \right)^{1-\sigma} \right]^{\frac{\sigma}{1-\sigma}} . \tag{23}
$$

With similar calculations to those described above, we find an expression for the long-run supply elasticity:

$$
\eta^{lt} = \frac{\sigma(\theta^L + \theta^K)}{(1-\theta^L-\theta^K)} \frac{1}{\theta^{VA}} \tag{24}
$$

from which we have:

$$
\theta^K = \frac{\hat{\eta}^{lt} \theta^{VA}}{\sigma + \hat{\eta}^{lt} \theta^{VA}} - \theta^L . \tag{25}
$$

Using data on the value share of labor and the elasticity of substitution derived from (22), we can thus allocate the remaining share of value-added among the capital and resource inputs for the model. The value share of the resource input is then computed as the residual $\theta^R = 1 - \theta^L - \theta^K$.

4.4 Estimation of price elasticities

Through the calibration procedure, the model perfectly fits production and price data in a given year. Following a policy shock, the behavioral response of plants in the model is determined by equations (22) and (25). Our aim in this section is to estimate short-term and long-term price elasticities so that the response of the model matches empirical evidence as to the regional price responsiveness of mines, smelters, refineries and SXEW plants. Additionally, we seek to estimate short- and long-term demand elasticities for refined copper to parametrize equation (15).

In order to ensure consistency between economic and econometric models, the ideal approach to estimation is structural. The data for such an exercise is, however, not available, as we do not have access to plant-level output over an extended period. Given data limitations, we estimate price elasticities using time series data available at the country-level. Allowing for heterogeneity among countries is important because factors influencing price responsiveness are expected to vary across producers. In the short term, access to variable input such as labor or energy depend on the characteristics of regional markets. In the long term, access to capital markets, availability of production sites and infrastructures such as transportation nodes will induce different responses. Thus on the one hand a reduced-form estimation at the country level implies some inconsistencies between the estimated elasticities and the structural model. But on the other hand, a country-level estimation allows us to capture observed changes in both output and the stock of production facilities over time as a response to price variations, so that results from the calibrated model will reflect both intensive and extensive margins.

To capture the dynamics of price responsiveness in each country over the long run, we use a partial adjustment model. This model posits that, following a change in price, the observed change in the (log of) quantities Q_r in each country r between two periods is only a fraction φ_r of the long-run response. Formally,

$$\ln Q_{r,t+1} - \ln Q_{r,t} = \varphi_r(\ln Q^*_r - \ln Q_{r,t}) \ , \quad 0 < \varphi < 1 \tag{26}$$

where Q_r^* is the optimal long-run output following a change in price, which is unobserved because of the short-run adjustment constraints. If we were to observe a permanent change in price, all other things remaining equal, the quantity would gradually converge to the long-run equilibrium Q_r^*.

Given the partial adjustment assumption, we estimate the following country-level equations for each copper commodity and for copper consumption:

$$\ln Q_{r,t} = \alpha_r' Z_{r,t} + \beta_r \ln P_t + \gamma_r \ln Q_{r,t-1} + \varepsilon_{r,t} \tag{27}$$

where $Q_{r,t}$ is output or refined copper consumption in country r and year t, P_t is refined copper prices in year t, and $Z_{r,t}$ includes quadratic time trends to control for unobserved country factors in a flexible and tractable manner. Country-level data on yearly output from mines, smelters, refineries and SXEW plants, as well as on yearly refined copper demand is taken from (ICSG, 2008a). Data on average copper prices is taken from WBMS (2008). For the demand equation, $Z_{r,t}$ includes real GDP figures from Heston et al. (2009).[9] The short-term price elasticity in country r is the coefficient β_r, while the long-run price elasticity (following full adjustments) is $\frac{\beta}{1-\gamma}$.

Market integration and competitive price setting is a key requirement for the estimation to be valid, and we only use observations from 1994 to 2007. Over this period, there is a single price for copper products which is determined on global commodity markets by interactions of aggregate supply and demand. Price variations are thus endogenous to variations in aggregate demand and supply, but assumed to be exogenous to variations in country-level output and demand. This 'small country' or price-taking assumption is justified by the relatively small share of individual countries on global markets for copper products, also reflected in the low value of concentration indexes (see Section 3). In this setting, the simultaneity bias is likely to be

[9] We experimented with a number of expanded specifications. In particular, coefficients on energy (oil) prices in the supply equations and aluminum prices in the demand equation were statistically insignificant at the country-level (although statistically significant at the aggregate level). The inclusion of spatial lags based on the inverse of bilateral trade costs computed from the model were also rejected based on conditional LM tests in (static) random effect panel data models (Baltagi and Liu, 2008).

small.[10]

Given the short length of country-level time series, robust estimation country-by-country was problematic. As an alternative, we impose a parametric structure on country-level heterogeneity to exploit both time-series and cross-sectional variations. Specifically, we use a random coefficient assumption (Hsiao and Pesaran, 2008) where cross-sectional heterogeneity on price responsiveness is modeled with a multi-variate normal distribution:

$$\begin{pmatrix} \beta_r \\ \gamma_r \end{pmatrix} \sim N\left(\begin{pmatrix} \mu_\beta \\ \mu_\gamma \end{pmatrix}, \begin{pmatrix} \sigma_\beta & \sigma_{\beta\gamma} \\ \sigma_{\beta\gamma} & \sigma_\gamma \end{pmatrix} \right). \tag{28}$$

In this setting, the estimation provides evidence about the mean (μ) and standard-deviation (σ) of the distribution of elasticities, which considerably reduce the number of parameters to be estimated. We use a Hierarchical Bayes approach to estimation, which has been shown to have good 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 distributions 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 2,000 iterations, and we base our inference on one tenth of the following 10,000 draws to mitigate the correlation among successive draws.[11]

Estimation results are reported in Table 2. The upper part of the table refers to the mean of the distribution of cross-sectional estimates. All estimates have the expected sign and attain statistical significance at the conventional levels. Given distributional assumptions on parameters, standard-deviation estimates reported in the lower panel measure cross-sectional heterogeneity,

[10] We have assessed the validity of this assumption for concentrate production in Chile and refined copper demand in China, two countries with the largest market share on the respective markets. Specifically, we have instrumented price variations with global GDP as an aggregate demand shifter and oil prices as an aggregate supply shifter. We find price elasticities to be stable across specifications, providing further support for exogeneity of price variations at the country-level.

[11] 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					
$\ln P_t$ (μ_β)	0.131 ***	0.170 ***	0.144 ***	0.125 ***	-0.080 *
	(0.035)	(0.040)	(0.036)	(0.053)	(0.050)
$\ln Q_{r,t-1}$ (μ_γ)	0.711 ***	0.614 ***	0.684 ***	0.587 ***	0.567 ***
	(0.069)	(0.065)	(0.061)	(0.100)	(0.057)
lnGDP	–	–	–	–	0.412 ***
	–	–	–	–	(0.079)
Standard deviation					
SD($\ln P_t$) (σ_β)	0.090 ***	0.121 ***	0.109 ***	0.143 ***	0.093 ***
	(0.013)	(0.021)	(0.018)	(0.032)	(0.012)
SD($\ln Q_{r,t-1}$) (σ_γ)	0.162 ***	0.154 ***	0.135 ***	0.182 ***	0.127 ***
	(0.025)	(0.032)	(0.026)	(0.053)	(0.022)
SD($\ln GDP_{r,t}$)	–	–	–	–	0.109 ***
	–	–	–	–	(0.021)
Observations (N/T)	42/12	38/12	40/12	14/12	55/12
Pseudo adj. R^2	0.979	0.973	0.977	0.976	0.984

Notes: Standard-errors in parenthesis. Stat. significance***$p < 0.01$; **$p < 0.05$; *$p < 0.1$. respectively. All equations include country-specific quadratic time trends.

and we find these to be both statistically and quantitatively significant. Since price responsiveness is a key determinant of carbon leakage, empirical evidence about country-level heterogeneity in price elasticities is an important feature of carbon leakage projections derived from the calibrated model.

The magnitude of the coefficients for the price variable implies that around 15% of the distribution has a sign that is not consistent with optimizing behavior. In our sample, this translates into a small number of countries having the 'wrong' sign for each estimated equation.[12] However, none of these are major producers, and for all these countries elasticity estimates are not statistically significantly different from zero. Given that the activities we consider are capital intensive, a short term output response around zero is not implausible, and for the calibration of the numerical model we set these to zero.

Short- and long-run elasticities for major producing countries are reported in Table 3. In the short run, concentrate production at mines is price inelastic relative to other production

[12] These are: mining in Tanzania; smelting in Armenia, Columbia, Indonesia, Pakistan and Thailand; refining in Congo, Indonesia and Ukraine; SXEW activities in Iran and Myanmar; and consumption in Serbia, Slovakia, and Zimbabwe.

TABLE 3: SUPPLY AND DEMAND PRICE ELASTICITIES FOR SELECTED COUNTRIES

Country	Mines		Smelters		Refineries		SXEW		Demand	
	η^{st}	η^{lt}	η^{st}	η^{lt}	η^{st}	η^{lt}	η^{st}	η^{lt}	η^{st}	η^{lt}
Chile	0.12	0.65	0.24	0.74	0.20	0.37	0.25	1.11	-0.04	-0.22
China	0.15	0.76	0.24	1.09	0.21	0.66	0.17	0.36	-0.08	-0.24
India	0.14	0.44	0.15	0.38	0.12	0.39	–	–	-0.09	-0.14
Peru	0.13	0.88	0.21	0.68	0.18	0.62	0.21	0.41	-0.08	-0.23
Russia	0.12	0.65	0.23	0.57	0.19	0.66	0.04	0.09	-0.12	-0.35
Australia	0.16	0.66	0.19	0.51	0.17	0.51	0.18	0.49	-0.06	-0.19
Germany	–	–	0.24	0.83	0.20	0.76	–	–	-0.04	-0.06
Japan	–	–	0.24	0.86	0.20	0.83	–	–	-0.06	-0.16
South Korea	–	–	0.21	0.56	0.17	0.60	–	–	-0.06	-0.20
United States	0.14	0.82	0.25	0.91	0.20	0.92	0.22	0.82	-0.06	-0.23

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

processes. Regarding long-run elasticities, sampling-based estimation also allows direct inference on country-level parameters by sampling the simulated posterior distribution for the ratio $\eta_r^{lt} = \frac{\beta_r}{1-\gamma_r}$. Long-run elasticities are comparable across mines, smelters and refining activities, while SXEW units generally display a lower long-run price responsiveness, which can be attributed to the lower availability of sites where SXEW processing can be applied. These results are in line with estimates of aggregate short- and long-run supply price elasticities reported in Vial (2004).

A striking feature of these results is that long-run elasticities are low. On the supply side, this confirms the existence of significant constraints to the creation of new facilities (in terms of infrastructures or because of institutional features). The demand elasticities are low both in the short- and long-run, which confirms the limited substitution possibilities with other materials, but also reflects the small value-share of refined copper components in activities using copper (e.g. cars, electronic equipment, and buildings). Changes in demand are mostly driven by changes in GDP, which corroborates findings on demand price elasticity for refined copper reported in Pei and Tilton (1999).

5 Results from the numerical model

We employ the numerical model of the copper industry to quantify the potential for carbon leakage under a subglobal carbon policy. We simulate short- and long-term evidence about the impact of a \$50/tCO_2 price on emissions in highly industrialized countries, which correspond to the 'Annex B' group of the Kyoto protocol.[13] In the short-run, both the capital and resource inputs are fixed, so that the supply schedule reflects the short term supply price elasticity estimates, while regional demand functions are parametrized with short-term price elasticity estimates. In the long-run, only the resource input remains plant-specific, so that the response of producers approximates the long-run elasticity estimates, and the demand response is parametrized with long-run elasticity estimates.

While the model is formulated at the plant-level, we emphasize that results from policy simulations should be interpreted at the country-level. Indeed, data on production costs, carbon emissions intensity, and estimated price elasticities, all refer to country-level. Hence although the location of plants in the model is held fixed over time, variations of output at the country level will reflect both intensive and extensive margins. We also emphasize that our aim is not to portray a particular policy proposal. Rather, the main objective of the simulations is to assess the international trade response to a subglobal carbon price based on a detailed representation of trade costs and empirically-based price responsiveness.

Since most of the parameters of the model are calibrated to a single year of data, a secondary objective of our simulations is to illustrate the importance of alternative assumptions about benchmark data used for calibration. To do so, we compare results under two alternative benchmark data. First, we use output and prices for the year 2007, during which the average price of refined copper was around \$7,000/tonne. Second, we use the yearly average price for 2002, at around \$2,000/tonne. Given our calibration procedure, the rents to the fixed factors are relatively low under low copper prices, and much higher under high prices. We retain 2007 output data for both price conditions so as to keep the comparison transparent, although using output data for 2002 does not alter our conclusions.

5.1 Policy simulations

Table 4 provides industry-wide results for refined copper prices and consumption, CO_2 emissions, and process-specific output 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

[13] The complete list of 'coalition' and 'non-coalition' countries is reported in the Appendix.

TABLE 4: POLICY SIMULATION RESULTS: \$50/tCO_2 subglobal carbon tax (% change from the benchmark)

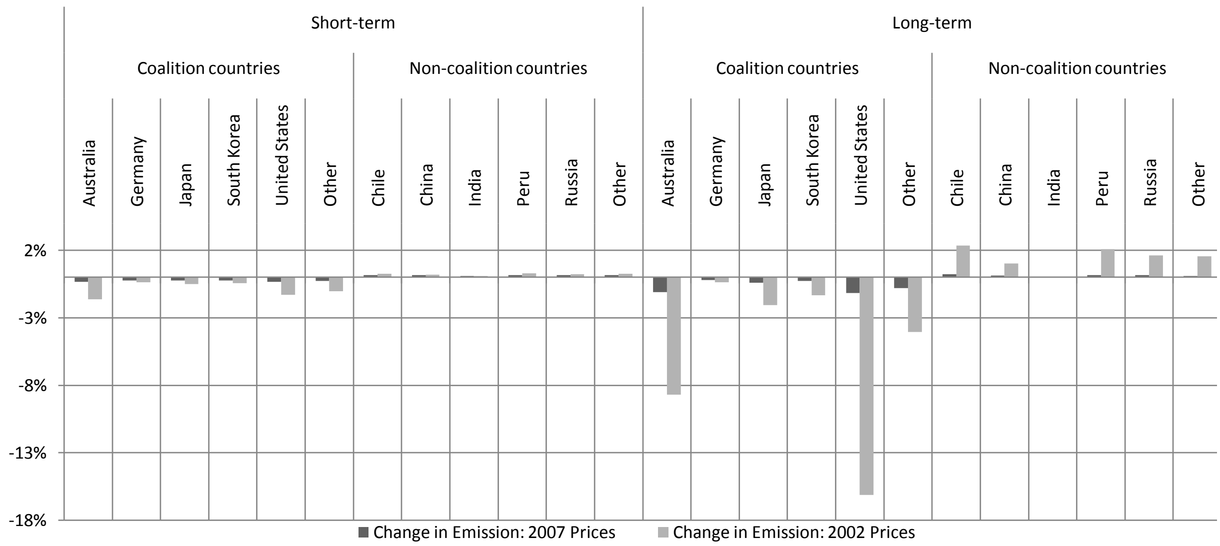
Simulation results	2007 Prices \$7066.0/t of copper Short term	Long term	2002 Prices \$1919.1/t of copper Short term	Long term
Change in refined copper price	0.29	0.36	1.18	2.30
Change in demand	-0.01	-0.06	-0.07	-0.28
Change in CO_2 emissions	-0.04	-0.17	-0.19	-1.38
Change in output:				
Mines	-0.03	-0.14	-0.14	-0.99
Smelters	-0.03	-0.12	-0.12	-0.78
Refineries	-0.02	-0.07	-0.08	-0.50
SXEW	0.01	0.09	0.05	0.79

we consider is high. The rate of pass-through is low, and the copper price increase is larger in the long-run than in the short-run, reflecting an increase of the ratio of supply to demand elasticities.

Under 2007 market conditions, the long-run reduction in CO_2 emissions from the copper industry achieved by the \$50/tCO_2 subglobal tax is below 0.2%. Under low (2002) copper prices, global abatement remains below 2%. We note that the market shares of coalition countries for mining and SXEW processing, the most carbon-intensive activities, are only 20% and 35% respectively, while this comes to 40% for smelting and refining. Also, production in coalition countries is on average less carbon-intensive than in non-coalition countries (on average by 10%).

Regarding output from each production process, the model suggests two substitution effects. First, we observe a net increase of output from SXEW units, as cathodes produced from SXEW plants have a lower carbon content. This substitution effect mitigates carbon leakage by reducing the demand for concentrate in non-abating countries. Second, output at mines declines more than that of smelters and refineries, signaling an increased use of scrap copper for smelting and refining. As shown in Table 4, these two substitution effects are quantitatively important, illustrating the importance of process heterogeneity highlighted by Mathiesen and Maestad (2004).

FIGURE 2: SIMULATED CO_2 ABATEMENT (% CHANGE FROM BENCHMARK)



Regional abatement

The geographical distribution of CO_2 abatement is summarized in Figure 2. Short term results, displayed in the left panel, show an almost inexistent response of the industry. Coalition countries reduce emissions by 0.2% under 2007 prices and 1.5% under 2002 prices. The long-run response depends to a large extent on the choice of the benchmark prices/year. Under 2007 prices, emissions in coalition states decline by less than one percent, or around 100,000 tCO_2. Under 2002 prices, abatement in coalition regions almost reaches one million tCO_2, or about eight percent of benchmark emissions in coalition countries. In both price regimes, copper mining accounts for most of emissions reduction, and over 80% of total abatement takes place in coalition countries producing copper concentrate (the U.S., Australia, Canada and Poland).

Production in non-coalition countries is a prefect substitute to production in coalition countries. As a subglobal tax changes the relative production costs, it induces geographical substitutions among plants. In the model, trade flows are determined by the spatial equilibrium representation, and changes in trade patterns are driven by country-specific factors, namely regional characteristics, interactions on markets for final and intermediate copper commodities, and bilateral trade costs. Given the idiosyncratic nature of these factors, 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. In the U.S., exports of concentrate decline by 80%, and smelters located in the U.S. start importing concentrate from Chile and Peru instead of processing production from local mines. Imports of refined copper from Chile and Peru also increase, so that all copper activities in the U.S. decline. In Australia, exports of concentrate to China decline, but the domestic demand from smelters remains stable.[14] Indeed, smelters and refineries in Australia continue to use intermediate copper inputs produced in Australia, 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.

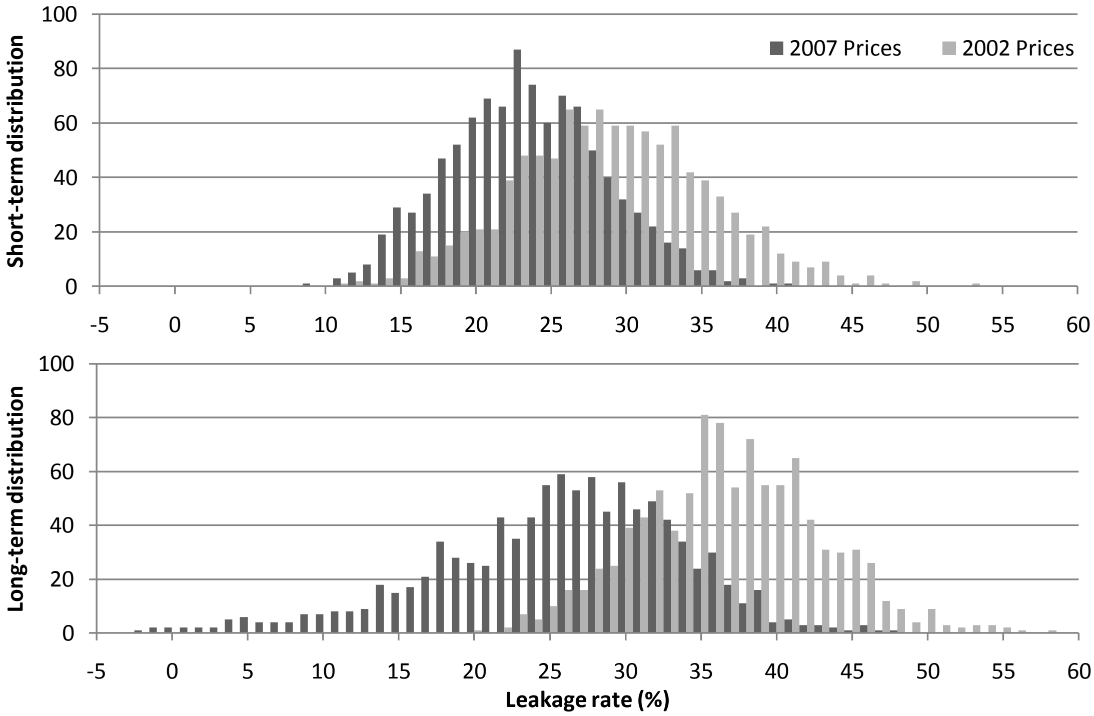
The situation is very different in coalition countries with no copper deposits, such as Japan and Germany. In Japan, concentrate is imported from Chile for smelting and refining, and part of the refined copper production is exported to China. Given that China also imports concentrate from Chile for smelting, there is a strong incentive to bypass the smelting and refining stages in Japan, and the loss of competitiveness leads to a decline in Japan's production and emissions. In Germany, a significant amount of copper commodities are produced from scrap, and large quantities of refined copper are imported from neighboring countries that are also subject to the carbon tax but do not use scrap (mainly Poland and Scandinavian countries). Thus the use of scrap leads to an increase in the demand for copper refined in Germany, and a relatively small emissions reduction.

Carbon leakage: Monte Carlo simulations

Since emissions leakage is primarily driven by elasticity estimates, we explicitly account for the statistical uncertainty by undertaking Monte Carlo simulations based on the estimated standard-errors of the regional price elasticities. Figure 3 reports the distribution of leakage rates derived from 1000 model runs, each time drawing from the respective estimates' distribution to calibrate

[14] 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.

FIGURE 3: SIMULATED EMISSIONS LEAKAGE RATE (NUMBER OF MODEL RUNS)



the supply and demand schedule before solving for the policy counterfactual.

The short-run distributions, reported in the upper part of Figure 3, suggest a similar range of values for the leakage rate under 2007 and 2002 prices, with a mean of 24% and 29% respectively. In the long-run the leakage is slightly higher. With 2007 prices, the mean leakage rate is 25%, 35% with 2002 prices. The support of the long-run distribution is wider than that for the short term, reflecting greater statistical uncertainty on the long-run price response. Lower and upper quartiles are 21–30 for 2007 prices and 33–41 for 2002 prices.

Our results suggest that the emissions leakage rate 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 effects implies that, on average, the leakage rate increases by about 10% to 20% depending on the copper price. Nevertheless the total emissions leakage increases.

Around 70% of total long-run leakage is explained by an increase in concentrate production in non-coalition countries. Emissions from concentrate production increase significantly in Chile, which contributes to about 25% of total emissions leakage. Peru, Russia and Indonesia increase their concentrate supply to smelters in coalition countries, while China and Mexico divert imports of concentrate from coalition countries to mines in non-coalition countries.

Smelters and SXEW plants each account for about 15% of emissions leakage. 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 North-American markets. Simulations suggest no significant leakage from refineries, except in China where refineries increase output to compensate for a reduction in imports from Japan. But in other non-coalition countries, emissions from refineries decline. Indeed, the higher equilibrium price for copper blister increases production costs of refineries in both coalition and non-coalition countries, and the ensuing increase in the equilibrium price of refined copper causes a decline in demand in all local markets. Hence a large fraction of refineries supplying in non-coalition regions also reduce output.

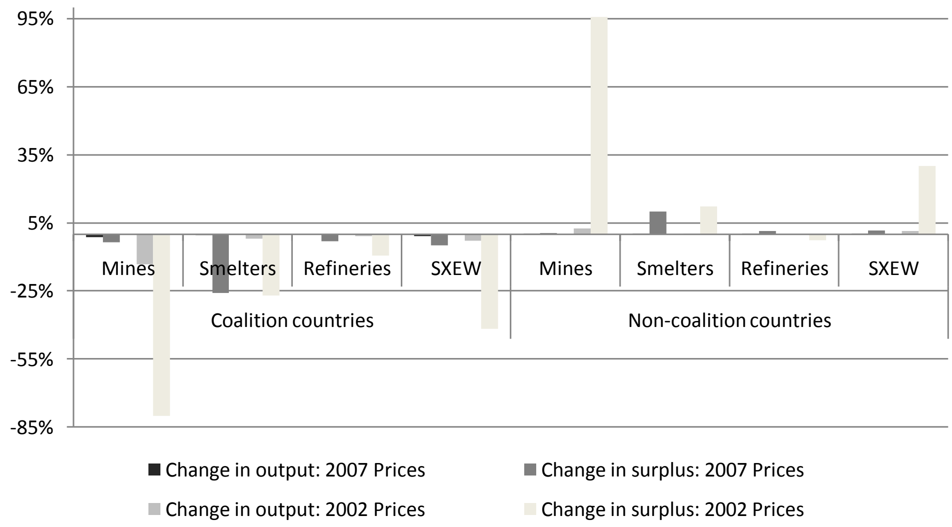
Production and welfare

We now assess the impact of the subglobal tax on the rents of producers, as measured by changes of the rental rate of the fixed resource input. Changes in the return to fixed input mitigate cost differentials, and thus contain the emissions leakage effect. As the demand for output of producers in coalition countries declines, rents to the fixed factors declines. Conversely, producers in non-coalition countries increase their rents rather than expanding output.[15] Figure 4 reports long-run changes in rents for each production process and compares these to changes in output. As expected, changes in output are small, while changes in the value of productive assets are much larger.

The percentage change in rents under 2007 prices is much smaller than under 2002 prices (the absolute changes in the level of rents are relatively similar). Indeed, at 2007 prices, rents in the benchmark are high and the industry's response in terms of production is modest. With 2002 prices, rents at mines in coalition countries are driven down almost entirely, while the rents at mines in non-coalition regions almost double. In turn, the output response is larger. We also

[15] Importantly, the magnitude of these adjustments is driven by our econometric estimates of price elasticities.

Figure 4: Change in output and producer surplus (% change from the benchmark)



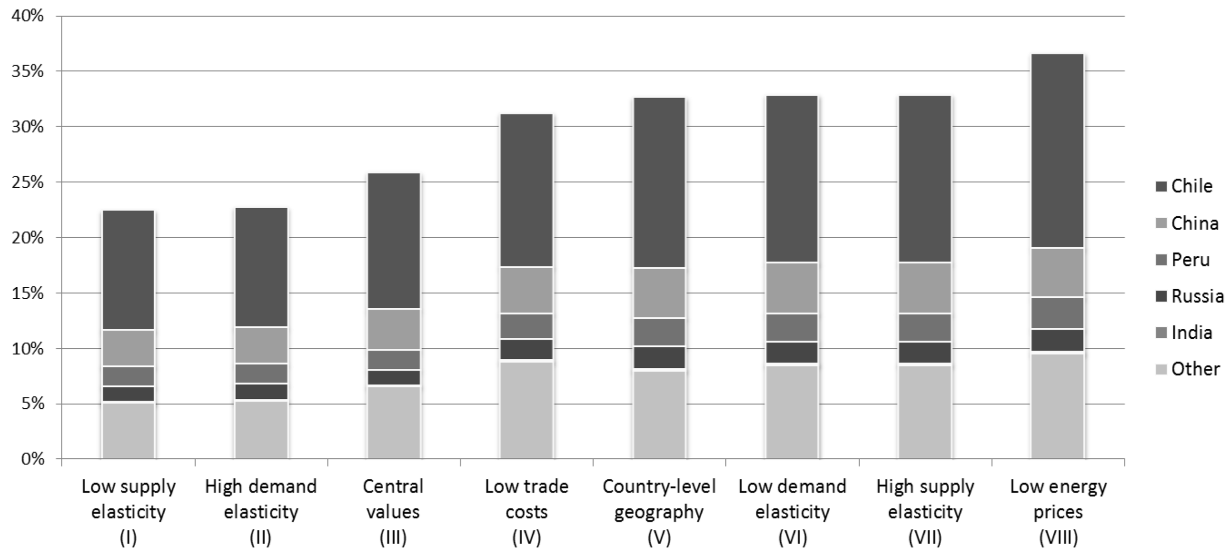
note that rents at refineries in non-coalition countries decline, reflecting the global reduction in the demand for refined copper.

The subglobal tax implies substantial changes in revenues for coalition countries, as owners of the fixed resource buffer cost differentials. This mitigates competitiveness effects, as output price variations are capitalized in earnings of the fixed resource. In addition, as the equilibrium price of refined copper increases world-wide, consumer surplus declines in all countries. Thus on the one hand, major copper producing countries such as Chile and Peru still make substantial gains by holding out on global 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

The long-run leakage rate for 2007 copper prices and eight alternative parametrizations are reported in Figure 5. First, we assess the impact of supply and demand elasticities in a systematic manner. Columns (I), (II), (VI) and (VII) report the leakage rate simulated by independently increasing and decreasing long-run 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 demand elasticities have a negative impact on leakage.

FIGURE 5: SENSITIVITY ANALYSIS: EMISSIONS LEAKAGE RATE



We next examine two features of our trade representation. First, we consider the impact of trade costs, and the leakage rate under a reduction of trade costs by half is reported in Column IV. In this case, the number of new trade routes increases, but overall leakage is contained by the low price elasticities at these new producers. Second, we assess the impact of the plant-level representation, and column (V) reports the leakage rate in a model where each country has only one representative plant. As expected, the leakage rate is higher at 33%, showing the importance of aggregation in the representation of carbon leakage effects highlighted by Demailly and Quirion (2009).

Finally, we look at the issue of energy prices. First, a tax on CO_2 can be difficult to administer, and can be substituted by an increase in energy prices. We determine that a tax raising energy prices by 15% would yield the same abatement in coalition countries and would induce the same long-run leakage rate. Second, we quantify the impact of a reduction in global energy prices on the leakage rate. This is a key general equilibrium effect of climate policies, since a decline in the demand for energy in coalition countries would depress world fossil fuel prices, leading to an increase in fossil energy use 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.

6 Conclusions

In this paper, we have examined the magnitude of carbon abatement and emissions leakage in the copper industry, which features energy-intensive production processes and large scale international trade in final and intermediate commodities. Our analysis is based on a partial equilibrium model for homogeneous commodities with a plant-level representation to generate realistic trade costs and where the behavioral response of agents is calibrated to empirical estimates of price elasticities. Simulations with the model suggest that the copper industry is unresponsive to subglobal climate policies, which is consistent with empirical studies on local environmental policies that find little geographical impact in industries that are both highly pollution- and capital-intensive (Ederington et al., 2005; Kellenberg, 2009).

Our work has several implications for ex-ante assessment of carbon abatement measures and associated trade policies. First, infrastructures and institutional factors constrain the industrial response, and in turn leakage, even though these basic materials are homogeneous products. Abatement costs 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.

Second, our modeling framework suggests complex changes in trade patterns, reflecting trade costs, regional heterogeneity in carbon intensity, and interactions on markets for intermediate and final products. This provides a much richer setting as compared to the Armington trade model used in most CGE analysis, where an aggregate regional analysis only provides a crude approximation of industrial relocation effects. In turn, the use of aggregate models for the assessment of subglobal carbon policies and border measures will most probably overlook major trade effects in intermediate product markets.

Third, because the price of copper fluctuates from year to year, the choice of the benchmark year to calibrate the model has a significant impact on simulations and policy conclusions. Since substantial price fluctuations are observed for most basic materials traded on the commodity markets, policy conclusions derived from CGE models will hinge upon the choice (or availability) of a benchmark dataset.

We close by emphasizing two caveats of our simulations. First, while the calibration of production technologies to estimates of price elasticities is an improvement over existing studies, assumptions underlying the estimation are not fully consistent with the model for the copper industry. Second, our findings highlight the importance of commodity prices on abatement potential, but also raise the question as to which price level appropriately reflects a long-run equilibrium. Indeed high prices might reflect a short-run disequilibrium where prices would be driven down by the entry of new plants. However, for non-renewable resources such as copper, high prices might also reflect expectations relating to the depletion of the richest deposits. Given their effect on prices, such expectations are likely to significantly influence the response to climate policies, and should thus be borne in mind when interpreting our results.

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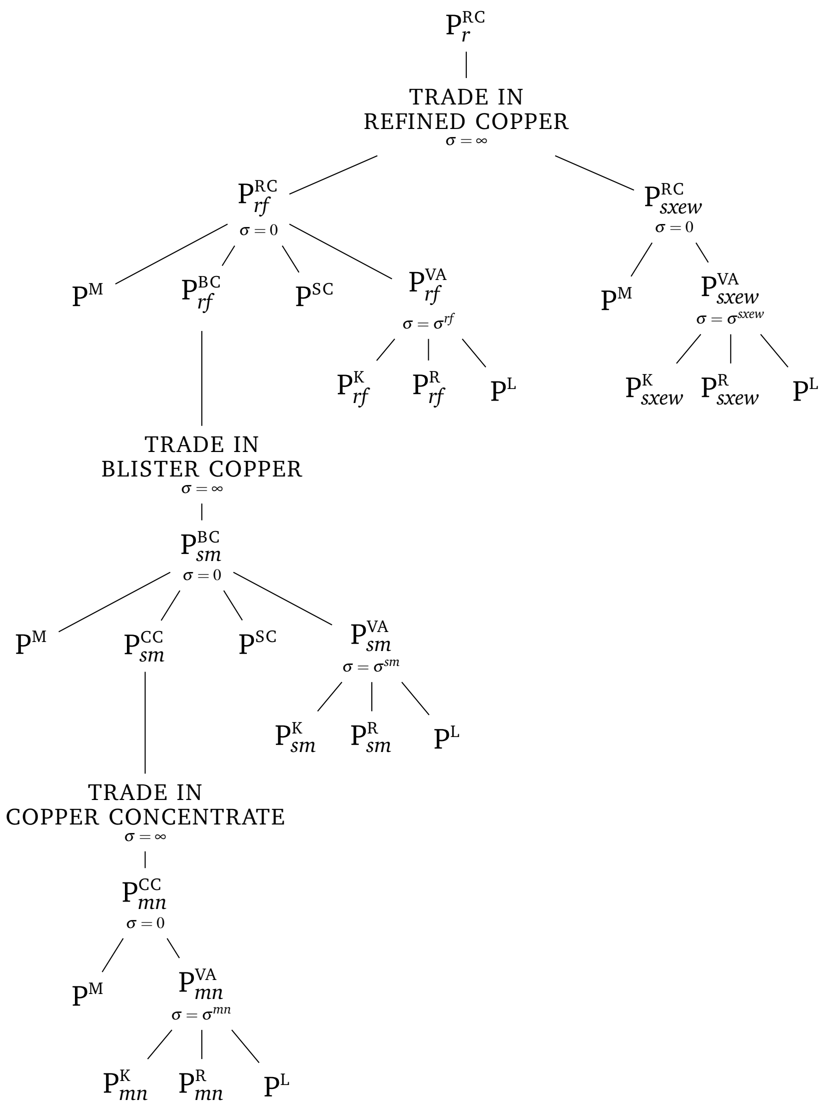
Appendix: Graphical representation of the model

FIGURE 6: GRAPHICAL REPRESENTATION OF THE MODEL



Appendix: List of regions

Africa	*Europe*	*Central Asia*
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
North Africa and	Germany*	*East Asia*
Middle East	Greece*	China
Egypt	Hungary	Indonesia
Iran	Italy*	Japan*
Mauritania	Netherlands*	Korean Republic*
Morocco	Poland*	Malaysia
Oman	Portugal*	Mongolia
Saudi Arabia	Romania	Myanmar
Turkey	Scandinavia*	North Korea
Latin America	Serbia	Papua New Guinea
Argentina	Slovakia	Philippines
Brazil	Spain*	Taipei
Chile	United Kingdom*	Thailand
Colombia	*North America*	Vietnam
Ecuador	Canada*	*South Asia*
Mexico	United States*	India
Peru	*Oceania*	Pakistan
Venezuela	Australia*	

Note: * Coalition countries

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