Capital Malleability, Emission Leakage and the Cost of Partial Climate Policies: General Equilibrium Analysis of the European Union Emission Trading System

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Abstract

Computable general equilibrium (CGE) models are the premier analytical platform for assessing the economic impacts of climate change mitigation. But these models tend to treat physical capital as “malleable”, capable of reallocation among sectors over the time-period for which equilibrium is solved. Because the extent to which capital adjustment costs might dampen reallocation is not well understood, there is concern that CGE assessments understate the true costs of greenhouse gas (GHG) reduction policies. This uses a multi-region, multi-sector CGE model to investigate cap-and-trade schemes such as the European Union Emission Trading System (EU ETS) which cover a subset of the economy, elucidating the effects of capital malleability on GHG abatement, the potential for emission leakage from abating to non-abating sectors, and the impacts on welfare. To simplify the complex interactions being simulated within the CGE model, the CGE analysis is complemented with constructing and parametrizing an analytical model. A partial climate policy result in negative internal carbon leakage, with emissions declining not only in capped sectors but also in non-regulated ones. This result is stronger when capital is intersectorally mobile. Interestingly, in partial climate policy settings capital malleability can amplify or attenuate welfare losses depending on the attributes of the economy.

1 Introduction

The first decade of the 21st century has seen a gradual shift away from the grand international climate architecture envisioned by the Kyoto Protocol, with the world's largest emitters of greenhouse gases (GHGs) struggling to implement their own domestic mitigation policies. In contrast to the comprehensive economy-wide cap-and-trade or GHG tax systems espoused and analyzed since the beginning of the Kyoto process, emission reduction policies in virtually all abating countries cover only subsets of their economies. This feature, even in a successful multilateral scheme such as the EU Emission Trading System (EU ETS), raises concerns about "internal" leakage of GHG emissions from constrained to unconstrained sectors in the same economy, mirroring the preoccupation of the climate policy literature with external leakage from Kyoto's Annex I to non-Annex I regions. In particular, in the advanced economies that are pursuing GHG abatement, well-developed markets are likely to facilitate intersectoral mobility of both variable inputs and polluting capital. What role such capital "malleability" might play in amplifying or attenuating internal leakage is not known, and is the topic of this paper.

GHG emission reduction policies have been the subject of extensive numerical analysis, the workhorse of which has been computable general equilibrium (CGE) models. One particular feature shared by the majority of CGE models in this arena (e.g., Klepper et al., 2003, Capros et al., 1997, Burniaux and Truong, 2002) is that physical capital inputs to production are "malleable", capable of being shifted frictionlessly among different sectors over the short to medium run so as to nullify marginal productivity differences. But it has long been known (e.g., Gapinski, 1985) that such mobility arises from capital scrappage and retrofit which proceed only slowly and in the short run can substantially dampen the elasticity of the economy's response to policy shocks, amplifying the latter's aggregate cost. A few climate-focused CGE models (e.g., MIT-EPPA— Paltsev et al., 2005) incorporate this effect through a "putty-clay" investment scheme in which new capital is malleable but extant capital is sector-specific. The latter is segmented into different vintages according to their year of investment and determines the (fixed) input proportions of production associated with each vintage. The problem that arises is that the results of any individual modeling study tends to reflect either perfect malleability or partial capital mobility, limiting our ability to infer capital mobility's impact on emission leakage and climate policy costs by necessitating comparisons among models with significant structural differences.

The crucial question is therefore how different assumptions about the degree of malleability combine with the characteristics of abating economies *within* a given model to affect the impacts of GHG abatement. Jacoby and Sue Wing (1999) and Sue Wing (2006) highlight the potential for the welfare losses from climate mitigation policies to increase substantially with the sluggishness of intersectoral capital reallocation. Given that capital is likely to be neither perfectly malleable nor perfectly immobile, but somewhere in between, implications for real-world climate policy costs turn on two key issues: the empirical question of how malleable capital is likely to be over the time-frame that emission limits are anticipated to bind, and the theoretical question of the manner in which various characteristics of abating economies influence the short-run adjustment costs to which capital rigidities give rise.

Answers to the first question are elusive because climate mitigation policies are still in their infancy. Nevertheless, despite the scant—and, at least for our purposes, inconclusive—evidence on the macroeconomic effects of price-induced capital scrappage, retrofit and second-hand capital goods market impacts,[1] the existence of aggregate capital adjustment costs (e.g., Groth, 2008) suggests that, all else equal, simulations which treat capital as perfectly mobile are likely to underestimate the costs of CO_2 emission abatement. The second question is comparatively easy to address, and is the focus of our investigation. Our approach is to bound the range of uncertainty in leakage and welfare cost by undertaking a clean comparison of the extreme cases where capital is either completely sector-specific or perfectly mobile.

Our policy application is Phase II of the EU ETS.[2] We use a multi-region, multi-sector CGE model to investigate the interactions between economies' characteristics and the intersectoral mobility of capital, focusing in particular on domestic emission leakage and welfare costs. The model distinguishes between the covered and combustion sectors under the EU ETS' jurisdiction, as well as non-trading sectors outside the scope of the program. Then, to simplify the complex in-

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[1] e.g., Dixit (1989), Goolsbee and Gross (1997), Goolsbee (1998), Ramey and Shapiro (1998, 2001), Cooper and Haltiwanger (2006), Eisfeldt and Rampini (2006).

[2] The EU ETS is a cap and trade program for limiting GHG emissions implemented in into two phases. The first, lasting from 2004-2007, was designed to allow regulators, emitters and holders of allowances to gain experience with CO_2 abatement and gain experience with emission trading—accordingly, emission limits for participating countries were set close to their expected baseline levels. In Phase II (2008-2012) the emission ceilings are tightened and all 27 EU Member States are included in the system. Although the EU ETS is the subject of a large literature (ably reviewed by Convery, 2009), most of these studies perform either prospective or retrospective analysis of Phase I.

teractions being simulated and put the mechanisms at work into sharper relief, we construct an analytical general equilibrium model of a simple one-household, two-sector economy, extending the work of Fullerton and Metcalf (2002), Fullerton and Heutel (2007), and particularly Fullerton et al. (2011). The household derives utility from clean and dirty substitute goods, both of which are produced from capital and pollution with different input intensities. The EU ETS is represented by a tax on pollution in the dirty industry. Our analysis contrasts the impacts of the tax on the equilibrium of the economy in the case where capital moves between sectors versus where it is fixed in place. Finally, we quantify the implications of our analytical results by numerically parameterizing them using the CGE model's calibration dataset, treating fossil fuel CO_2 precursors as the polluting input and the EU ETS covered and combustion sectors as the dirty industry.

We find that capital malleability results in more CO_2 abatement and in a higher negative leakage rate. When capital is sector-specific, the marginal productivity of fossil fuel commodities is generally lower and thus leads to lower equilibrium prices and demand within the EU. The welfare consequences of the climate policy depend on the malleability of capital as well as the characteristics of the economies. A decomposition analysis is used to identify the main drivers of the welfare results, which depend on the size of a negative abatement effect, a capital reallocation effect likely to exacerbate welfare losses, and a leakage effect likely to mitigate declines in utility. A numerical analysis is used to show the dependence of the CGE model results on key economic parameters in the EU ETS regions. The results indicate that the higher the share of covered industries' outputs in households expenditure, the more negative the welfare impact, while the ability to sell allowances is the key offsetting driver. This underlines the crucial importance of allowance allocation for welfare outcomes.

The paper is organized as follows. Section 2 outlines the CGE model and its application to the EU ETS and summarizes the results of our structural sensitivity analysis. Section 3 develops the analytical model, describes its theoretical predictions and illustrates its numerical application, and draws implications for policy and modeling practice. Section 4 concludes.

2 CGE Simulations of the EU ETS

CGE models' multi-regional, multi-sectoral architecture offers the possibility to incorporate in a consistent fashion the different interacting effects of economic activities on the baseline and counterfactual equilibria of regional economies. This makes them *the* analytical platform of choice to assess the impact of capital malleability on the macroeconomic costs of the EU ETS. However, the dark side of this all-inclusive character is the particular difficulty of disentangling the relative importance of the forces driving models' results, which sets up a tension between real-world policy assessment and clear accounting.

2.1 Model Structure

Our numerical simulations are based on the straightforward static multiregional CGE model of Harrison et al. (1997a,b), as elaborated in Rutherford (2005). As summarized in Table 1, the model divides the world into 24 regional groupings (identified by the index r), with households in each region modeled as a representative agent, and firms aggregated into 14 industry groupings (indexed by j). The output supplied by each industry in a given region satisfies sectors' domestic intermediate inputs demands (indexed by i), the representative agent's domestic final demand and other regions' demands for imports. Government is also represented, but it plays a passive role, collecting taxes and using the resulting revenues to purchases commodities which form the inputs to the production of an aggregate government good. Regional economies are linked by bilateral trade in commodities which is modeled according to the Armington (1969) specification that represents the use of each commodity as a constant elasticity of substitution (CES) composite of domestically-produced and imported varieties of that good, and models aggregate imports in turn as a constant elasticity of substitution (CES) composite of flows from individual trade partners.

The agent in each region is endowed with three factors of production: labor, capital, and energy resources (all internationally immobile), which are rented to domestic industries in return for factor remuneration. Sectors' outputs are demanded by other sectors for use as intermediate inputs and by the representative agent for the purposes of consumption and saving. Each representative agent is modeled as an expenditure-minimizing individual with Cobb-Douglas prefer-

Table 1: CGE Model Regions and Sectors

A. Regional Aggregation

EU ETS Regions (s)		Other Regions
Austria	Ireland	European Free-Trade Area (EFTA)[b]
Belgium	Italy	Rest of Europe
Czech Republic	Netherlands	North-American Free-Trade Area (NAFTA)[c]
Denmark	Poland	Russia
Finland	Portugal	Other fmr. Soviet Union
France	Spain	Rest of the World
Germany	Sweden	
Greece	UK	
Hungary	Rest of EU[a]	

[a] Cyprus, Estonia, Latvia, Lithuania, Luxembourg, Malta, Slovenia, Slovakia

[b] Norway, Switzerland and Iceland

[c] USA, Canada, Mexico

B. Sectoral Aggregation

Abating Sectors (h)		Non-Abating Sectors
EU ETS Covered Sectors (c)	Combustion Sectors (l)	
Refined petroleum/coal*	Coal Mining*	Transportation
Pulp and paper	Crude oil/gas mining*	Rest of Economy aggregate
Electric power	Gas production/distribution*	
Non-metallic mineral products	Non-ferrous metals	
Iron and steel	Chemicals, rubber & misc. plastics	
	Durable manufactures	
	Non-durable manufactures	

* CO_2 emission precursor

ences and a constant marginal propensity to save out of income, while each industry is modeled as cost-minimizing representative firm with nested CES production technology.[3]

The structure of production in the model is designed to reflect the difficulty of substituting material inputs for energy and, to a lesser extent, low-carbon energy inputs such as natural gas for carbon-intensive fuels such as coal in the short run. Although it is structurally identical across different industries, its parametrization varies with sectors' input-output coefficients. The nesting hierarchy is shown in Figure 1, with output ($Y_{j,r}$) at the top level produced from a CES aggregation of "fixed-factor" energy resource inputs ($FF_{j,r}$) and a composite of capital, labor, energy and materials (KLEM) ($YY_{j,r}$), with an elasticity of substitution σ_j^F. This portion of the hierarchy is

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[3] Although savings-investment closure rules are most critical for dynamic analysis of the effects of a contemporaneous policy shock on the capital stock and welfare in subsequent periods, they still matter for static analysis because of the interdependence between household savings and expenditure. If savings are modeled as perfectly inelastic the burden of household adjustment falls entirely on consumption, with concomitant amplification of contemporaneous welfare losses. Our formulation is a simple and transparent way of dividing the burden of CO_2 abatement-driven reductions in factor remuneration between consumption and saving.

only present in primary energy sectors which use energy resources as a non-reproducible input (coal, crude oil & gas, natural gas, electricity). In turn, we specify the KLEM composite as a CES function of value-added ($VA_{j,r}$), energy ($E_{j,r}$) and non-energy materials ($N_{j,r}$), with an elasticity of substitution σ_j^Y.

Moving down one level, value-added is a Cobb-Douglas aggregate of capital and labor inputs ($K_{j,r}$ and $L_{j,r}$) while energy and materials are modeled separately as composites of intermediate energy and materials commodities ($Q_{e,j,r}$ and $Q_{n,j,r}$, respectively, where e and n are indices of energy and non-energy goods), with the substitutability of commodities within each nest governed by the elasticities σ_j^E and σ_j^N. The lowest levels of the hierarchy represent the Armington aggregation of intermediate input. Sector j's use of the i^{th} intermediate input is a CES composite of domestically-produced and imported varieties ($q_{i,j,r}^D$ and $q_{i,j,r}^M$) whose substitutability is determined by the elasticity σ_i^{DM}. In turn, imports are a CES composite of exports of good i from regions of origin $o \neq r$ ($x_{i,j,o,r}$). These are imperfect substitutes whose demands respond to relative prices across exporting countries according to the elasticity σ_i^{MM}.

We simulate the operation of the EU ETS by requiring sectors' use of each type of fuel to be covered by emissions allowances in the amount of the fuel's CO_2 content. The key feature of the EU ETS is that it restricts emissions in a subset of regions (indexed by s) and sectors (indexed by h), across which the coverage of the program varies. The latter are made up of "covered" sectors (indexed by c in Table 1) and large combustion plants (LCPs) within "combustion" sectors (indexed by l). Producers in these sectors are therefore obliged to cover their emissions from fuel use by holding allowances $A_{e,h,s} = \varepsilon_{e,h,s}\omega_{e,h,s}Q_{e,h,s}$, where $\varepsilon_{e,j,r}$ denotes fuel- and sector-specific stoichiometric emission factors and $\omega_{e,h,s}$ is the fraction of the sector covered by the EU ETS. In covered industries $\omega_{e,c,s} = 1$, while in combustion sectors where LCPs account for less than the total quantity of energy use and emissions $\omega_{e,l,s} < 1$. The aggregate EU ETS emission cap is implemented via the constraint:

$$\sum_e \sum_h \sum_s A_{e,h,s} \leq \sum_s \mathcal{A}_s \qquad \perp \qquad \tau_{\mathrm{CO}_2}$$

where $\mathcal{A}_s$ is the quantity of allowances allocated to each region. The expression above is introduced as an additional equation in the CGE model's pseudo-excess demand correspondence, where (as indicated by the short-hand notation "$\perp$") it exhibits complementary slackness with respect to the system-wide market clearing price of allowances (τ_{CO_2}). Symmetrically, the allowance price reduces fossil fuel use by raising the consumer price of the covered amount of each fuel through a markup proportional to its CO_2 content: $\varepsilon_{e,h,s}\tau_{\mathrm{CO}_2}$.

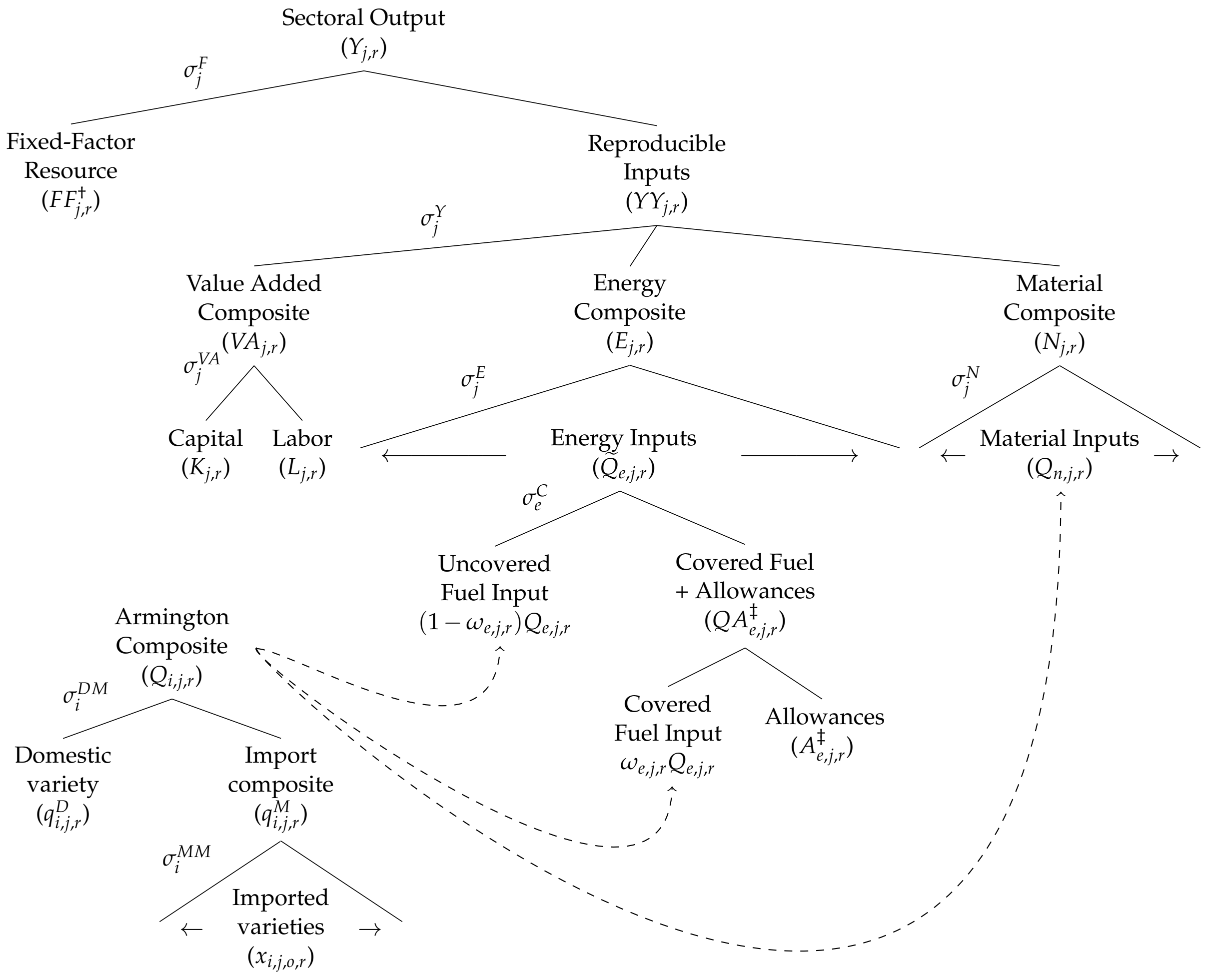
Figure 1 illustrates how this scheme is operationalized. We specify each input to the energy sub-nest ($\widetilde{Q}_{e,j,r}$) as a CES composite of uncovered physical fuel ($(1-\omega_{h,s})Q_{e,h,s}$, in combustion sectors only) and the quantity of covered fuel and associated permits ($QA_{e,h,s}$), whose constituents exhibit a fixed stoichiometric relationship with each another. Substitution of uncovered for covered fuel is determined by the elasticity σ_h^C. There is little information to guide the choice of values for this parameter. While it seems logical that uncovered fuel should easily substitute for covered fuel, it seems plausible to assume that LCPs will continue to be a necessary technology in the production of combustion sectors' outputs for the foreseeable future, with plant-level economies of scale increasing the opportunity cost of non-LCP substitutes. In an attempt to reconcile these divergent views we set $\sigma_h^C = 0.5$. Data are not available on the specific energy conversion technologies employed by covered sector firms and LCPs in non-abating industries, but it seems doubtful that many of these sources possess fuel-switching capability—with the exception of electric power generation (e.g., Soderholm, 2001). Accordingly, we set the value of the key interfuel substitution elasticity parameter (σ_j^E) to be low in non-electric industries and high in the electric power sector.

The EU ETS' short time horizon suggests that the near-term outputs of an alternative intertemporal CGE model will be fundamentally similar to the contemporaneous we present below. However, over longer policy horizons the paths of capital accumulation in the covered, combustion and non-covered sectors will likely differ markedly. In such a setting, whereas with capital malleability capital would be gradually reallocated to clean sectors, with sector-specific capital the investments in the clean sectors would take place mostly as the dirty capital becomes old and less productive.

2.2 Numerical Calibration and Parametrization

The CGE model is a numerical simulation of Arrow-Debreu equilibrium in a complementarity format. Cost minimization by industries and expenditure minimization by the representative

Figure 1: Sectoral Nesting Structure



† Primary fossil sectors (Crude Oil & Gas, Coal, Natural Gas) only, for other sectors $Y_{j,r} = YY_{j,r}$.

‡ Covered and combustion sectors only.

Elasticities of Substitution			
σ_j^F	Fixed factor vs. other inputs	0.3	(primary energy sectors)
σ_j^Y	Among energy and non-energy inputs and value added	0.4	(energy sectors)
		0.8	(non-energy sectors)
σ_j^{VA}	Capital vs. labor	1	
σ_j^E	Interfuel	1	(electric power)
		0.5	(other sectors)
σ_j^N	Among non-energy intermediate inputs	0	
σ_j^C	Between "covered" and non-covered fossil fuel inputs	0.5	
σ_j^{DM}	Armington: between domestic and imported commodities	1.9-10.6	
σ_j^{MM}	Armington: among imported commodities	3.8-32.6	
σ^U	Household elasticity of substitution among Armington goods	0.5	(not shown above)

agent in each region yield vectors of cost and expenditure functions, and commodity and factor demands. These equations are functions of domestic factor prices, domestic and international commodity prices, domestic industries' activity levels, and the income levels of the regional representative agents. They are substituted into the general equilibrium conditions of market clearance, zero profit and income balance to yield to a square system of non-linear inequalities that forms the pseudo-excess demand correspondence of the world economy (for details, see Sue Wing, 2009).

This algebraic structure is numerically calibrated using version 7 of the Global Trade Analysis Project (GTAP) database (Narayanan and Walmsley, 2008), which records data on bilateral trade flows, transport margins and tariffs in conjunction with individual country social accounting matrices for 57 industry groupings across 113 countries and world regions for the year 2004. These data are aggregated to match the regions and sectors in Table 1. The key calibration parameters are the elasticities of substitution, which are assumed to be identical across regions but vary by sector. The resulting numerical scheme is expressed as a mixed complementarity problem using the Mathematical Programming System for General Equilibrium analysis (MPSGE) (Rutherford, 1999) for the General Algebraic Modeling System (GAMS) numerical modeling language (Brooke et al., 1998), and is solved with the PATH solver (Dirske and Ferris, 1995, Ferris and Munson, 2000).

We prepared a baseline projection of economic activity in 2012 by scaling the endowments in each region according to the historical growth rates of GDP from 2004 to 2010, and forecasts of GDP growth for the period 2010-2012 from the 2011 International Monetary Fund (IMF) World Economic Outlook. To construct the corresponding baseline projection of CO_2 we calculated emission factors based on the GTAP 7 satellite database on combustion-based CO_2 emissions (Lee, 2008), following the procedures outlined in Lee (2002). We assume that these values remain constant throughout the intervening period of economic growth, which is equivalent to assuming an absence of autonomous energy efficiency improvement.

Our emission ceilings correspond the quantities of allowances established by participating countries' National Allocation Plans (NAPs).[4] To implement the EU ETS cap within the model it was necessary to estimate the shares of combustion sector CO_2 emissions attributable to LCPs.

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[4] Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community.

Relevant data that are readily available are the 2004 International energy Agency (IEA) energy statistics on countries' emissions from "unallocated producers" (generators of electricity or heat for own consumption, as opposed to for sale) whose fossil fuel use and emissions are not apportioned between industrial and non-industrial sectors. We treated unallocated producers as representative of LCP emissions across all of the combustion sectors in each country by calculating the average proportion of aggregate use of each fuel and assigning the amount of emissions from unallocated producers. While this procedure has its limitations, data constraints effectively preclude capturing sectoral heterogeneity in LCP shares.

2.3 Simulation Results

We simulate Phase II of the EU ETS, focusing on the year 2012. Our reference scenario is a no-policy business-as-usual (BAU) baseline against which we compare the economic impacts of the EU ETS cap when capital is intersectorally mobile and when it is sector-specific. Table 2 summarizes the results of the BAU scenario, while Table 3 compares outcomes of the EU ETS counterfactual scenario with and without intersectoral capital mobility. Our counterfactual 2012 emissions are quite a bit higher than the observed trend (cf Olivier et al., 2012), but our results are in line with earlier studies (e.g., Reilly and Paltsev, 2006). We find that the aggregate emission cap binds lightly on EU economies, requiring them to abate 236 $MTCO_2$, or 5% of business as usual (BAU) emissions in 2012. The net volume of interregional allowance trade is a mere 130 MT, or 6% of the cap, which suggests that Member States' allocations are fairly close to their ultimate post-abatement emissions. Italy, UK and the Netherlands are large net buyers of permits, while Germany, Belgium, Greece and the conglomeration of small Member States are large net sellers. Capital immobility has the expected effect of making abatement more costly at the margin. The CO_2 permit price is around 8% higher in the sector-specific scenario compared with the malleable scenario, 2010 €8.31 as opposed to €7.69.

Across EU ETS regions CO_2 from covered sectors declines substantially, combustion sector emissions fall by a smaller amount. Non-trading sectors emissions also exhibit very slight reductions. Emissions from non-EU regions increase significantly. This is one of the paper's key result: while external leakage from the EU ETS is substantial and positive, internal leakage is small and

Table 2: CGE Model Results: Business as Usual Scenario (MTCO$_2$)

	Covered Emiss.	Combustion Emiss.	Non-Trading Emiss.	Total Emiss.	EU ETS Caps	Warranted Abatement
EU ETS Regions						
Austria	32	7	55	95	31	9
Belgium	32	6	66	104	59	-21
Czech Rep.	85	13	30	127	87	11
Denmark	28	5	34	66	25	8
Finland	44	5	33	81	38	11
France	82	59	385	526	133	8
Germany	409	54	368	831	453	10
Greece	49	4	41	94	69	-16
Hungary	26	3	29	58	27	2
Ireland	17	5	29	51	22	0
Italy	212	44	256	513	196	61
Netherlands	91	22	102	215	86	27
Poland	234	28	91	353	209	54
Portugal	27	4	41	72	35	-4
Spain	132	30	216	379	152	10
Sweden	16	6	43	65	23	0
UK	250	72	447	768	246	75
Rest of EU	152	33	79	264	194	-9
Other regions						
EFTA	29	25	98	152	–	–
Rest of Europe	116	14	46	175	–	–
NAFTA	3561	581	2565	6706	–	–
Russia	1443	118	373	1933	–	–
Fmr. USSR	471	66	204	742	–	–
Rest of World	9566	2064	3787	15418	–	–
Total						
EU	1919	400	2345	4664	2083	236
Non-EU	15186	2868	7072	25126	–	–
World	17105	3268	9417	29790	–	–

almost without exception *negative*. Leakage rates are larger (less negative) when capital is sector-specific than when it is mobile: internally, -1.4 % versus -2.4% for the EU as a whole, and externally 31% versus 20%. Except for a handful of cases, the marginal productivity of all of the fossil fuel commodities is lower when capital is sector-specific, leading to lower equilibrium prices and demand within the EU. In particular, the prices of coal and natural gas in the major energy exporting regions of Russia and the Rest of the World region decline by much larger amounts than in the malleable capital scenario, inducing a bigger expansion in non-EU fuel use and emissions.

Our measure of the welfare impact of the EU ETS is equivalent variation, expressed as the percentage change in real expenditure of the representative agent in each region. The welfare consequences of the EU ETS are uniformly small and can be positive or negative, with both scenarios showing the largest losses in Denmark, the Netherlands and Poland and the largest gains in Belgium and the Rest of EU. When capital is sector-specific regions' impacts are almost always of the same sign (with the exception of Portugal), and are generally less negative (or more positive), except for Poland and Sweden, whose welfare losses are amplified. The magnitude of these results indicates how small the abatement burden is relative to the possibilities to substitute other inputs for fossil-fuels. The distribution of changes in welfare is significantly correlated with net sales of allowances (0.67 and 0.69 in the malleable and sector-specific scenarios, respectively), which suggests the importance of income effects associated with the initial allocation of permits under the NAPs.

Welfare outside of the EU is also adversely impacted by the emission limit, an effect which is exacerbated by capital immobility. CO_2 abatement induces movements in the terms of trade against the EU's major trade partners (see, e.g., Böhringer et al., 2010), particularly in regions that import manufactured goods from, and export fossil fuels to, Europe. A prime example is Russia, which sees the international prices of the former goods rise and those of the latter—which account for a substantial fraction of its export revenue—fall. The previously-noted exacerbating effect of sectoral capital specificity on the declines in coal and gas prices serves to amplify the contraction in Russian gas production, and the factor returns from its energy sector.

As shown in Table 4, negative leakage is associated with output reductions in most sectors. This result might initially appear to be consistent with the "abatement resource effect" identified by Fullerton et al. (2011), which posits that when households possess fewer substitution options than the polluting sector, the latter industry is the recipient of clean inputs released by non-abating sectors, a process which facilitates pollution reductions. However, several pieces of evidence cast doubt on this mechanism. First, Figure 1's summary of the elasticities indicates that covered sectors are less capable of substituting material and factor inputs for CO_2 precursors than households are able to substitute non-trading sectors' commodity outputs for covered and combustion sectors' CO_2-intensive products. Second, Table 4 indicates that output declines persist even when capital is immobile. Third, in the malleable scenario capital is displaced from covered and combustion sectors to non-trading sectors—not the reverse, a pattern which is also exhibited by labor inputs (which we do not show to save space). The corollary is that in the sector-specific capital scenario

Table 3: CGE Model Results: EU ETS Scenario (Change from Business as Usual Scenario)

	A. Malleable Capital							B. Sector-Specific Capital						
	Permit Sales (MT)	Covered Emiss. (%)	Comb-ustion Emiss. (%)	Non-Trading Emiss. (%)	Total Emiss. (%)	Leakage Rate (%)	Welfare Change (%)	Permit Sales (MT)	Covered Emiss. (%)	Comb-ustion Emiss. (%)	Non-Trading Emiss. (%)	Total Emiss. (%)	Leakage Rate (%)	Welfare Change (%)
EU ETS regions														
Austria	-5	-9	-6	-0.3	-4	-4.6	-0.06	-5	-9	-6	-0.1	-4	-2.0	-0.05
Belgium	23	-7	-4	-0.1	-2	-3.0	0.06	23	-7	-5	-0.1	-3	-1.5	0.07
Czech Rep.	7	-20	-13	-0.3	-14	-0.5	-0.03	7	-19	-13	0.2	-14	0.4	-0.02
Denmark	-4	-11	-24	-0.2	-6	-1.3	-0.12	-4	-11	-24	-0.1	-6	-0.6	-0.10
Finland	-6	-10	-6	-0.2	-6	-1.7	-0.05	-6	-10	-6	-0.1	-6	-0.9	-0.05
France	0	-7	-4	-0.1	-2	-2.4	-0.01	0	-8	-4	0.0	-2	-0.6	-0.01
Germany	35	-10	-5	-0.1	-5	-1.2	0.02	34	-10	-5	0.0	-5	-0.3	0.02
Greece	23	-13	-7	-0.4	-7	-2.3	0.04	22	-12	-6	-0.2	-7	-1.4	0.06
Hungary	0	-9	-5	-0.5	-5	-5.2	-0.05	0	-9	-5	-0.3	-5	-3.6	-0.04
Ireland	2	-8	-7	-0.3	-4	-5.5	0.02	2	-8	-6	-0.2	-4	-4.1	0.03
Italy	-44	-7	-4	-0.3	-3	-4.2	-0.09	-44	-7	-4	-0.2	-3	-2.9	-0.08
Netherlands	-18	-8	-5	-0.5	-4	-5.8	-0.12	-18	-8	-4	-0.4	-4	-4.6	-0.10
Poland	-9	-18	-12	-0.9	-13	-1.7	-0.18	-10	-18	-12	-0.4	-13	-0.9	-0.19
Portugal	7	-10	-4	-0.2	-4	-3.2	0.00	7	-10	-4	-0.2	-4	-2.3	0.01
Spain	3	-9	-5	-0.2	-4	-3.2	-0.01	3	-9	-5	-0.1	-4	-1.6	-0.01
Sweden	1	-6	-2	0.0	-2	0.4	-0.01	2	-6	-2	0.0	-2	1.7	-0.01
UK	-41	-9	-14	-0.3	-5	-4.2	-0.06	-41	-10	-15	-0.3	-5	-3.5	-0.05
Rest of EU	27	-10	-7	-0.2	-7	-1.0	0.05	27	-10	-7	-0.1	-7	-0.5	0.08
Other regions														
EFTA	–	0.8	0.1	0.1	0.2	–	-0.04	–	0.8	0.2	0.1	0.2	–	-0.06
Rest of Europe	–	0.9	0.2	0.0	0.6	–	-0.03	–	0.7	0.1	0.0	0.5	–	-0.01
NAFTA	–	0.1	0.2	0.1	0.1	–	0.00	–	0.2	0.2	0.1	0.2	–	0.00
Russia	–	0.5	0.6	0.1	0.4	–	-0.15	–	0.5	0.6	0.1	0.5	–	-0.17
Fmr. USSR	–	0.8	0.4	0.2	0.6	–	0.00	–	0.9	0.6	0.3	0.7	–	0.00
Rest of World	–	0.2	0.2	0.1	0.2	–	0.00	–	0.4	0.3	0.1	0.3	–	0.00
Total														
EU	–	-10.7	-7.6	-0.2	-5.2	-2.4	–	–	-10.7	-7.7	-0.1	-5.1	-1.4	–
Non-EU	–	0.3	0.2	0.1	0.2	–	–	–	0.4	0.3	0.1	0.3	–	–
World	–	-1.0	-0.8	0.0	-0.6	20.2	–	–	-0.9	-0.7	0.0	-0.6	31.1	–

Table 4: CGE Model Results: Correlates of Leakage

A. Sectoral changes in output and capital input (%)

	Output (Malleable)				Output (Sector-Specific)				Capital Input (Malleable)			
	Mean	Stdev	Max	Min	Mean	Stdev	Max	Min	Mean	Stdev	Max	Min
Covered sectors												
Refined petroleum/coal	-0.91	0.57	-0.21	-2.03	-0.75	0.47	-0.12	-1.79	-0.81	0.46	-0.19	-1.71
Pulp & paper	-0.15	0.24	0.15	-0.84	-0.16	0.15	0.03	-0.57	0.12	0.26	0.74	-0.40
Electric power	-2.90	1.97	0.31	-6.99	-2.40	1.49	-0.01	-6.22	-1.60	1.31	0.50	-4.28
Non-metallic minerals	-0.50	0.50	0.30	-1.48	-0.51	0.40	0.09	-1.30	0.16	0.33	0.77	-0.51
Iron & steel	-1.04	1.27	0.83	-3.47	-0.95	0.97	0.50	-2.76	-0.28	0.86	1.10	-1.98
Combustion sectors												
Coal mining	-9.30	3.55	-3.17	-16.21	-6.84	2.93	-1.99	-13.13	-9.71	3.55	-3.45	-15.98
Crude oil/gas mining	-0.13	0.17	-0.03	-0.77	-0.11	0.11	-0.02	-0.49	-0.03	0.11	0.17	-0.36
Gas production/distribution	-0.34	0.16	-0.07	-0.61	-0.31	0.14	-0.09	-0.58	0.18	1.20	4.67	-0.55
Non-ferrous metals	-2.41	3.71	0.25	-12.14	-1.46	1.88	0.07	-6.35	-1.79	3.33	0.53	-10.47
Chemicals/rubber/plastics	-0.69	0.94	0.36	-2.77	-0.54	0.58	0.02	-1.89	-0.30	0.68	0.53	-1.95
Durable manufactures	-0.13	0.15	0.14	-0.35	-0.14	0.07	-0.03	-0.27	0.08	0.25	0.72	-0.22
Non-durable manufactures	-0.09	0.16	0.20	-0.45	-0.13	0.06	0.00	-0.25	0.12	0.26	0.76	-0.36
Nontrading sectors												
Transportation	-0.06	0.08	0.12	-0.17	-0.07	0.05	0.02	-0.17	0.07	0.13	0.41	-0.14
Rest of Economy	-0.04	0.04	0.05	-0.12	-0.05	0.04	0.00	-0.15	0.08	0.10	0.30	-0.09

B. Regional changes in capital input and rental rates by sectoral groupings (%)

	Capital Input (Malleable)			Avg. Rental Rates (Sector-Specific)		
	Covered	Combustion	Nontrading	Covered	Combustion	Nontrading
Austria	-0.19	-0.01	0.02	0.18	-0.02	-0.00361
Belgium	-0.09	-0.06	0.03	0.10	0.00023	0.00126
Czech Rep.	-1.86	0.09	0.32	-0.39	-0.14	-0.11
Denmark	-0.92	0.10	0.05	-0.26	-0.11	-0.02
Finland	-0.46	0.09	0.06	-2.64	-0.72	-0.25
France	0.13	-0.03	0.00	-1.28	-0.16	-0.12
Germany	-0.34	-0.17	0.05	-0.68	-0.21	-0.16
Greece	-1.99	-0.39	0.12	-0.00001	-0.11	-0.07
Hungary	-0.87	0.01	0.08	-0.57	-0.37	-0.06
Ireland	-0.52	0.12	-0.09	-2.30	-0.52	0.01
Italy	-0.55	0.05	0.02	-1.31	-0.26	-0.15
Netherlands	-0.43	-0.22	0.08	-0.63	0.02	-0.06
Poland	-1.18	-0.24	0.25	-0.96	-0.17	-0.20
Portugal	-0.50	-0.07	0.08	-0.94	-0.49	-0.18
Spain	-0.43	-0.08	0.05	-2.33	-1.22	-0.52
Sweden	0.19	0.01	-0.03	-0.89	-0.24	-0.08
UK	-0.62	-0.09	0.05	-0.82	-0.22	-0.09
Rest of EU	-1.25	-0.14	0.25	0.15	-0.05	-0.07

the capital rental rate experiences the largest declines in covered industries, suggesting that, if mobile, their capital will be displaced to unconstrained sectors. As well, under this scenario mobile factors such as labor continue to exhibit a similar pattern of displacement.

To explore these issues further we reverse the sectoral pattern of values of the elasticities of substitution at the top level of our production hierarchy in Figure 1, setting $\sigma^Y = 0.8$ in energy sectors and $\sigma^Y = 0.4$ in non-energy sectors. In this sensitivity test the pattern of elasticities renders energy supply sectors' demands for fossil fuels more elastic than those of households, which seems less plausible than our base case. Nevertheless, the relative magnitudes of these parameters remain a key uncertainty which can only be resolved by careful empirical analysis.

As summarized in Tables 5 and 6, our reparameterization generates a striking reversal in the foregoing results. The EU's net abatement is less than two-thirds of the CO_2 reduced in our base case. The reason is that internal leakage rates are now large and positive, averaging 27% across EU ETS regions and exceeding 100 % in Belgium, France and Sweden, an effect that is driven by an increase in emissions in non-trading sectors. Internationally, the magnitude of leakage increases as well, but does not flip sign, exceeding 200%, with the result that EU ETS' emission reductions are swamped by the expansion of CO_2 emitted by non-abating regions (especially EFTA and Russia). Positive internal and external leakage are both lower when capital is sector-specific.

There is evidence of the abatement resource effect, whose occurrence is predestined by the relative magnitudes of the household and abating sector substitution elasticities. Factor inputs to combustion sectors and the rest-of-economy aggregate decline as a consequence of displacement of capital (and labor) to covered industries, which is now accompanied by an *increase* in the output of unconstrained sectors as fossil-fuel precursor intermediate goods substitute for factors. As before, the magnitude of this phenomenon is also reduced by capital immobility. The welfare impacts of abatement continue to be small, with regions evenly split between gains and losses. We see a reversal of the pattern of incidence from our base-case results: changes in welfare are less negative in regions where losses were formerly concentrated, while regions which experienced gains (Belgium, Czech Republic, Greece, Portugal, Spain and Rest of EU) tend to be less well off. With the exception of Denmark, Ireland and the UK, capital immobility results in increased welfare losses or reduced welfare gains.

This sensitivity analysis underlines the crucial role of the characteristics of the economies, as

Table 5: CGE Model Results: EU ETS Scenario with Flipped Elasticities of Substitution (Change from Business as Usual Scenario)

	A. Malleable Capital							B. Sector-Specific Capital						
	Permit Sales (MT)	Covered Emiss. (%)	Comb-ustion Emiss. (%)	Non-Trading Emiss. (%)	Total Emiss. (%)	Leakage Rate (%)	Welfare Change (%)	Permit Sales (MT)	Covered Emiss. (%)	Comb-ustion Emiss. (%)	Non-Trading Emiss. (%)	Total Emiss. (%)	Leakage Rate (%)	Welfare Change (%)
EU ETS regions														
Austria	-5	-10	-2	3.7	-1	60.6	-0.01	-5	-10	-2	3	-2	47.6	-0.06
Belgium	23	-7	-1	3.8	0	105.5	0.03	23	-8	-2	3	0	79.9	-0.05
Czech Rep.	8	-21	-8	4.4	-14	6.9	-0.08	8	-21	-8	4	-14	6.3	-0.16
Denmark	-3	-13	-24	2.9	-6	20.8	0.04	-3	-13	-24	2	-6	14.8	0.05
Finland	-6	-12	-2	3.4	-5	20.7	-0.03	-6	-12	-3	3	-6	16.5	-0.09
France	-4	-6	1	3.2	2	304.2	0.01	-4	-6	0	2	1	199.4	-0.06
Germany	38	-11	-1	3.1	-4	24.1	0.04	36	-11	-2	2	-4	19.5	-0.03
Greece	22	-13	-2	4.1	-5	26.6	0.00	22	-12	-2	3	-5	23.3	-0.05
Hungary	0	-11	-1	3.3	-3	33.0	-0.03	0	-11	-1	3	-4	26.3	-0.13
Ireland	2	-10	-3	2.2	-2	36.4	0.17	2	-10	-2	2	-3	26.9	0.14
Italy	-46	-7	0	3.0	-1	52.7	-0.05	-45	-7	-1	2	-2	37.8	-0.15
Netherlands	-18	-9	-2	3.0	-3	35.5	0.00	-18	-9	-2	2	-3	27.6	-0.05
Poland	-8	-19	-5	4.8	-12	9.5	-0.17	-9	-19	-5	4	-12	8.7	-0.28
Portugal	7	-11	0	2.9	-2	40.5	-0.04	7	-11	-1	2	-3	29.8	-0.14
Spain	1	-8	0	4.0	-1	77.6	-0.03	1	-9	0	3	-1	60.2	-0.10
Sweden	1	-5	1	3.5	1	185.9	0.04	1	-6	0	3	0	125.4	-0.04
UK	-40	-11	-11	3.1	-3	39.7	0.04	-40	-11	-11	2	-3	30.8	0.02
Rest of EU	28	-12	-3	4.7	-6	19.6	-0.06	28	-12	-3	4	-6	17.0	-0.13
Other regions														
EFTA	–	2.1	-2.0	3.2	2.1	–	0.30	–	2.0	-2.2	2.6	1.7	–	0.45
Rest of Europe	–	-2.9	2.0	3.6	-0.8	–	-0.30	–	-2.9	1.7	3.1	-1.0	–	-0.44
NAFTA	–	-0.5	1.9	3.9	1.4	–	0.00	–	-0.4	1.7	3.3	1.2	–	-0.03
Russia	–	0.6	0.0	6.2	1.6	–	0.42	–	0.8	-0.4	5.9	1.7	–	0.72
Fmr. USSR	–	-2.2	1.3	8.6	1.1	–	0.15	–	-2.5	0.2	8.5	0.8	–	0.18
Rest of World	–	-0.2	2.5	5.1	1.5	–	0.06	–	-0.1	2.2	4.3	1.3	–	0.04
Total														
EU	–	-11.6	-3.4	3.4	-3.4	33.6	–	–	-11.5	-3.8	2.7	-3.7	26.8	–
Non-EU	–	-0.3	2.2	4.8	1.4	–	–	–	-0.2	1.9	4.1	1.3	–	–
World	–	-1.5	1.5	4.4	0.7	229.2	–	–	-1.4	1.2	3.8	0.5	186.5	–

Table 6: CGE Model Results: Correlates of Leakage with Flipped Elasticities of Substitution

A. Sectoral changes in output and capital input (%)

	Output (Malleable)				Output (Sector-Specific)				Capital Input (Malleable)			
	Mean	Stdev	Max	Min	Mean	Stdev	Max	Min	Mean	Stdev	Max	Min
Covered sectors												
Refined petroleum/coal	1.00	0.57	1.66	-0.13	0.44	0.58	1.40	-0.56	9.28	1.41	12.40	6.33
Pulp/paper	0.12	0.56	1.51	-0.76	0.11	0.38	1.09	-0.43	-0.07	0.41	0.99	-0.81
Electric power	-0.21	1.57	1.88	-3.62	-0.85	1.40	1.68	-3.77	3.44	0.91	5.05	1.62
Non-metallic minerals	-0.25	0.80	1.05	-2.14	-0.18	0.58	0.78	-1.40	-0.55	0.73	0.50	-2.10
Iron & steel	-0.56	0.99	0.67	-2.92	-0.50	0.90	0.66	-2.82	-0.90	1.24	0.72	-3.33
Combustion sectors												
Coal mining	-9.47	3.69	-2.13	-15.08	-7.17	3.56	-1.15	-15.56	-9.37	3.65	-2.07	-14.74
Crude oil/gas mining	0.71	0.31	1.26	0.29	0.62	0.24	0.95	0.01	1.50	0.68	3.04	-0.04
Gas production/distribution	0.00	0.19	0.20	-0.40	-0.05	0.28	0.22	-0.61	2.98	3.36	10.97	-0.79
Non-ferrous metals	-1.77	4.19	0.95	-14.17	-1.00	2.29	0.75	-7.07	-1.95	4.11	0.73	-14.29
Chemicals/rubber/plastics	-0.29	1.21	0.69	-4.47	-0.21	0.80	0.46	-3.02	-0.93	1.61	0.82	-5.88
Durable manufactures	0.08	0.56	1.41	-1.08	0.06	0.43	1.10	-0.67	-0.04	0.29	0.53	-0.57
Non-durable manufactures	0.04	0.50	0.96	-1.11	0.01	0.39	0.82	-0.77	-0.10	0.30	0.33	-0.86
Nontrading sectors												
Transportation	-0.02	0.38	0.61	-0.86	-0.02	0.40	0.71	-0.84	-1.07	0.46	-0.09	-1.95
Rest of Economy	0.09	0.22	0.53	-0.44	0.08	0.20	0.50	-0.36	-0.04	0.09	0.07	-0.30

B. Regional changes in capital input and rental rates by sectoral groupings (%)

	Capital Input (Malleable)			Avg. Rental Rates (Sector-Specific)		
	Covered	Combustion	Nontrading	Covered	Combustion	Nontrading
Austria	1.22	-0.08	-0.09	3.89	0.15	-0.44
Belgium	1.76	-0.25	-0.10	2.83	0.11	-0.34
Czech Rep.	1.33	-0.42	-0.07	1.39	-0.33	-0.38
Denmark	0.87	0.34	-0.18	2.18	-0.60	-0.42
Finland	0.27	0.03	-0.06	1.26	-1.42	-0.99
France	1.34	-0.03	-0.06	1.64	1.03	-0.08
Germany	1.22	-0.36	-0.01	0.35	-0.37	-0.37
Greece	1.68	-0.45	0.00	1.65	-0.31	-0.38
Hungary	1.66	-0.09	-0.13	1.49	-0.67	-0.29
Ireland	0.27	0.32	-0.34	2.35	-0.70	-0.29
Italy	1.73	0.02	-0.10	2.02	-0.60	-0.66
Netherlands	2.07	-0.61	-0.05	1.15	0.48	-0.11
Poland	1.72	-0.44	-0.09	1.91	-0.42	-0.64
Portugal	1.48	-0.19	-0.14	2.35	-1.04	-0.53
Spain	1.80	-0.24	-0.10	1.06	-1.73	-1.36
Sweden	1.06	-0.10	-0.15	1.72	-0.76	-0.70
UK	1.75	0.04	-0.10	2.15	-0.74	-0.61
Rest of EU	2.53	-0.50	-0.21	1.41	-0.33	-0.37

reflected in their elasticities and share parameters, in determining the results of the EU ETS. The results show that negative leakage can occur without an abatement resource effect while positive leakage can occur in presence of an abatement resource effect. The complexity of the interactions being simulated by the CGE model makes it difficult to characterize a clear explanation of what yields this result. To develop the necessary insights we need an analytical model, to which we now turn.

3 Analytical GE Modeling: Capital Malleability and Partial Emission Taxation

Analytical general equilibrium models are used to specify production functions and consumer behaviours into equations that can be converted into a simple linear system. The advantage of these models is that, once the linear system is solved, they can clearly illustrate the impacts of a tax on prices and quantities. Thus, while analytical models cannot realistically reproduce an emissions trading scheme, they can be used to identify the key effects behind a tax-induced relative price increase.

3.1 The Model

Our analytical test-bed is a two-sector tax incidence model in which capital is the only factor of production. There are two industries, the dirty sector (D) which represents energy-intensive industries and the clean sector (C) which proxies for the Rest of the economy aggregate, indexed by $j = \{C, D\}$. Each industry produces a single good from inputs of capital (K_j) and pollution (Z_j), which represents the composite of fossil fuel CO_2 emission precursors. Sectors' outputs (X_j) are sold at a competitively-determined market prices (P_j) to a representative household, who derives utility (U) from consuming them and suffers disutility from exposure to aggregate pollution generated by producers' activity ($Z = Z_C + Z_D$). Apart from this externality, pollution is subject to a competitively-determined aggregate opportunity cost, P_Z, which we model through an upward-sloping supply schedule.[5] The household is endowed with a stock of capital (K), which she rents

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[5] An example might be expenditure on smokestacks to limit pollution's adverse effects on production—but not the larger environment.

out to the sectors at competitively-determined market rates (ρ_j).

The centerpiece of the model is a structural sensitivity analysis of the capital market. In the case of malleable capital, the capital stock is capable of being reallocated between industries according to the market clearing condition $K = K_C + K_D$ in order to equalize sectoral rates of return ($\rho_C = \rho_D = \rho$). In the polar opposite case of perfectly immobile capital, industries' inputs of capital are fixed but their rates of return are free to diverge. For each case we examine the effects of an exogenous ad valorem tax (τ) on the input of pollution to the dirty industry, which captures the effect of the price of allowances on producers in the EU ETS covered sectors.

3.1.1 Households

The representative agent's utility is increasing in consumption and decreasing in pollution, and can be written as $U = U(X_C, X_D, Z)$, with $U_{X_C}, U_{X_D} > 0$ and $U_Z < 0$. The impact of the tax on households' welfare operates through two channels: the market effects of changes in goods consumption and the non-market effect of mitigating the disutility of pollution, which, following convention, we treat as separable (e.g., Bovenberg and de Mooij, 1994). We assume that pollution negatively affects utility through damage to an environmental amenity, $\mathcal{E}$, where $\mathcal{E}_Z < 0$. Letting M denote aggregate income, the agent's utility maximization problem is

$$\max_{X_C, X_D} \left\{ U(X_C, X_D, \mathcal{E}(Z)) \,|P_C X_C + P_D X_D \leq M \right\}.$$

The first order conditions equate the two goods' appropriately deflated marginal utilities of consumption to the Lagrange multiplier (μ), whose natural interpretation is the marginal utility of income: $\mu = U_{X_C}/P_C = U_{X_D}/P_D$. Using this result, the total differential of U is

$$dU = [\mu P_C dX_C + \mu P_D dX_D] + U_{\mathcal{E}} \mathcal{E}_Z dZ,$$

where the term in square braces is the market-mediated incidence of the pollution tax and the last term is the environmental benefit. Dividing both sides by income in utility-equivalents yields the utility differential in percentage terms:

$$\frac{dU}{\mu M} = \left[\frac{P_C X_C}{M} \frac{dX_C}{X_C} + \frac{P_D X_D}{M} \frac{dX_D}{X_D} \right] - \delta \frac{Z}{M} \frac{dZ}{Z}$$

This expression is recast as eq. (1) in Table 7, in which a "hat" ($\wedge$) over a variable indicates its logarithmic differential (e.g., $\hat{z} = d \log z = dz/z$, Fullerton and Metcalf, 2002). The left-hand side is a dimensionless index of the total welfare effect of the tax. On the right-hand side, ϕ is the benchmark no-policy expenditure share of the dirty good, $\zeta = Z/M$ is the initial pollution intensity of GDP, and $\delta > 0$ is the marginal disutility of environmental damage. In this simple model the marginal utility of consumption is the reciprocal of the unit expenditure index (the income necessary to generate one unit of utility). Optimum aggregate expenditure is therefore $U/\mu = P_C X_C + P_D X_D$, which yields the logarithmic change in expenditure given by eq. (2). Lastly, we assume that the substitutability between inputs to consumption are determined by elasticity of substitution in the utility function, σ_U, which yields the log-differential relationship between the prices and quantities of clean and dirty goods given by eq. (3).

3.1.2 Producers

Turning to the supply side of the economy, each good is produced according to a homogeneous-of-degree-one technology, $X_j = f_j(K_j, Z_j)$.[6] Free entry and competitive markets for inputs and output require that each sectoral producer exhausts its revenue on input expenditures. We express this using the zero-profit conditions $P_C X_C = \rho_C K_C + P_Z Z_C$ and $P_D X_D = \rho_D K_D + (1+\tau) P_Z Z_D$. Log-differentiating the production functions and zero-profit conditions yields eqs. (4), (5), (6) and (7), in which $\theta_C = P_Z Z_C / (P_C X_C)$ and $\theta_D = (1+\tau) P_Z Z_D / (P_D X_D)$ indicate the shares of pollution in the cost of clean and dirty production, with $\theta_C \ll \theta_D$. Explicit tracking of pollution inputs to both sectors facilitates analysis of the extent to which abatement of polluting inputs in the sector subject to the tax (D) induces increased pollution in the untaxed sector (C). This effect is measured by the leakage rate, $\Lambda = -dZ_C/dZ_D$, given in log-differential form by eq. (8). Lastly, we assume that the substitutability between inputs to production are determined by elasticities of substitution σ_j, yielding the log-differential relationships in eqs. (9) and (10).

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[6] We assume the standard concavity properties, $f_K, f_Z > 0$, $f_{KK}, f_{ZZ} < 0$.

Table 7: Equations of the Analytical General Equilibrium Model

	Household behavior:	
Utility	$\hat{U} = [(1-\phi)\hat{X}_C + \phi\hat{X}_D] - \delta\zeta\hat{Z}$	(1)
Expenditure	$\hat{\mu} + \hat{U} = (1-\phi)(\hat{P}_C + \hat{X}_C) + \phi(\hat{P}_D + \hat{X}_D)$	(2)
Substitution in consumption	$\hat{X}_C - \hat{X}_D = \sigma_U(\hat{P}_D - \hat{P}_C)$	(3)
	Producer behavior:	
Clean production	$\hat{X}_C = \theta_C\hat{Z}_C + (1-\theta_C)\hat{K}_C$	(4)
Dirty production	$\hat{X}_D = \theta_D\hat{Z}_D + (1-\theta_D)\hat{K}_D$	(5)
Clean production cost	$\hat{P}_C + \hat{X}_C = \theta_C(\hat{P}_Z + \hat{Z}_C) + (1-\theta_C)(\hat{\rho}_C + \hat{K}_C)$	(6)
Dirty production cost	$\hat{P}_D + \hat{X}_D = \theta_D(\hat{\tau} + \hat{P}_Z + \hat{Z}_D) + (1-\theta_D)(\hat{\rho}_D + \hat{K}_D)$	(7)
Emission leakage	$\Lambda = \left(\frac{\gamma-1}{\gamma}\right)\frac{\hat{Z}_C}{\hat{Z}_D}$	(8)
Substitution in clean production	$\hat{K}_C - \hat{Z}_C = \sigma_C(\hat{P}_Z - \hat{\rho}_C)$	(9)
Substitution in dirty production	$\hat{K}_D - \hat{Z}_D = \sigma_D(\hat{\tau} + \hat{P}_Z - \hat{\rho}_D)$	(10)
	Factor market closure:	
Emissions supply	$\hat{Z} = \eta\hat{P}_Z$	(11)
Emissions	$\hat{Z} = \gamma\hat{Z}_D + (1-\gamma)\hat{Z}_C$	(12)
Capital supply-demand balance	$0 = \lambda\hat{K}_D + (1-\lambda)\hat{K}_C$	(13)

Variables: $\hat{X}_C$, $\hat{X}_D$ output of the clean and dirty good; $\hat{P}_C$, $\hat{P}_D$ price of the clean and dirty good; $\hat{P}_Z$, $\hat{Z}$ price and aggregate quantity of pollution; $\hat{Z}_C$, $\hat{Z}_D$ pollution inputs to clean and dirty production; $\hat{K}_C$, $\hat{K}_D$ capital inputs to clean and dirty production; $\hat{\rho}_C$, $\hat{\rho}_D$ marginal product of capital in clean and dirty production; $\hat{U}$ household utility; Λ emission leakage rate; $\mathcal{D}_M, \mathcal{D}_S$ denominator in malleable and sector-specific capital scenarios.
Parameters: θ_C, θ_D pollution share of production cost in clean and dirty sector; λ, γ dirty sector share of aggregate capital and pollution; ϕ dirty good share of household expenditure; η elasticity of aggregate pollution supply; σ_C, σ_D elasticity of substitution between capital and pollution in clean and dirty sector; σ_U elasticity of substitution between clean and dirty good in household.

3.1.3 Factor Market Closure

Our model is closed through the markets for capital and pollution. Aggregate emissions are given by the supply schedule, $Z = P_Z^{\eta}$, where $\eta > 0$ is the elasticity of pollution supply, as shown in eq. (11). The log-differential change in the supply-demand balance for pollution is then given by eq. (12), in which $\gamma = Z_D/Z$ is the dirty industry's benchmark share of total pollution. The specification of the capital market depends on the mobility assumption. Letting $\lambda = K_D/K$ denote the share of malleable capital in the dirty sector, we take the log-differential of the aggregate supply-demand capital balance to obtain eq. (13).

Our model consists of eqs. (1)-(13) along with the condition $\hat{\rho}_C = \hat{\rho}_D = \hat{\rho}$ in the malleable capital scenario and the condition condition $\hat{K}_C = \hat{K}_D = 0$ in the sector-specific case. This yields a system of 13 equations in 14 unknowns ($\hat{P}_C$, $\hat{P}_D$, $\hat{P}_Z$, $\hat{\mu}$, $\hat{\rho}_C$, $\hat{\rho}_D$, $\hat{X}_C$, $\hat{X}_D$, $\hat{Z}_C$, $\hat{Z}_D$, $\hat{K}_C$, $\hat{K}_D$, $\hat{U}$, Λ). To solve each system we first designate the marginal utility of income as the numeraire by setting $\hat{\mu} = 0$, and then obtain algebraic solutions to the remaining variables as functions of an increase in the pollution tax, $\hat{\tau}$.

3.2 Analytical Results

The solutions to both models are straightforward but tedious to obtain. In general, the signs of the log-changes in the variables depend on the values of the parameters, so additional structure is necessary to interpret the algebraic results.[7] In the case of a stock externality such as climate change, the reduction in environmental quality from the marginal unit of emissions is very small, and with it pollution's marginal disutility, $\delta \to 0$ (cf Newell and Pizer, 2008). The fact that fossil fuel CO_2 precursors are a small share of the cost of non-energy-intensive production allows us to dramatically simplify the analytical results by focusing on the limiting case where $\theta_C \to 0$. In developed economies, dirty production generates a substantial share of aggregate emissions but makes up a modest fraction of household expenditure and employs a small proportion of aggregate capital, which suggests that $\phi > \lambda$ and $\gamma > \lambda$. Finally, the direction of leakage depends on whether households possess fewer substitution options than firms in the dirty sector ($\sigma_U \gtrless \sigma_D$, following Fullerton et al., 2011), and on whether the dirty industry's or the household's substitution possibilities are bounded ($\sigma_U, \sigma_D \gtrless \sigma^\star = \eta\phi\theta_D/\gamma$).

To save space, the algebraic details are consigned to the appendix (Table A.1). With the aforementioned restrictions the emission tax increase has an unambiguous effect on the signs of key variables in the economy. Irrespective of capital's malleability, $\hat{\tau}$ reduces the dirty sector's use of pollution and increases the dirty good's price, inducing a decline in both its production and consumption that generates a welfare loss. The aggregate quantity and pre-tax price of pollution both decline, along with the price of the clean good. Malleability facilitates capital displacement, which is accompanied by a decline in the capital rental rate. In the case where $\sigma_U > \sigma_D$ this induces movement of capital from the dirty to the clean sector and an expansion of clean output. Clean sector emissions expand once $\sigma_D > \sigma^\star$. If capital is immobile the rental rate rises in the

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[7] The complete algebraic results are available from the authors upon request.

clean sector. The dirty sector's rate of return only falls if $\sigma_U > (1-\phi)\sigma_D$, and then goes on to induce an expansion of clean output and emissions if $\sigma_U > \sigma^\star$.

The intuition is straightforward. When $\sigma_D > \sigma_U$ households' commodity demands are relatively inelastic, with consumption of the dirty good declining only slowly as its price increases, but dirty production is easily maintained by substituting capital for pollution as the tax increases the latter's price. With sector-specific capital there is no such scope for input substitution, causing the fall in the quantity of pollution to bid up the marginal product of capital. If capital is intersectorally mobile, the ease of input substitution in the dirty sector will increase the demand for capital, which ends up drawing capital away from the clean sector: Fullerton et al.'s (2011) abatement resource effect. However, our more realistic model structure introduces an important qualification to its implication for leakage, namely that pollution in the clean sector is only guaranteed to decline if the elasticity of substitution in dirty production is sufficiently small relative to the elasticity of pollution supply. Conversely, when $\sigma_U > \sigma_D$ household demands for commodities are relatively elastic and the dirty sector's input demands are relatively inelastic. The tax-induced increase in the cost of pollution, combined with capital's limited substitutability, increases the dirty sector's production cost relative to its conditional demand for capital. The price-sensitivity of households' demand for the dirty good then induces a decline in its demands for pollution and capital, both of which migrate to the clean sector, whose output expands to substitute for consumption of the dirty good.

The impact of malleability on emission leakage can be elucidated by plugging the substitution relations (9) and (10) into the definition of leakage (8):

$$\Lambda = \left(\frac{\gamma-1}{\gamma}\right)\left[\frac{\hat{K}_C - \sigma_C(\hat{P}_Z - \hat{\rho})}{\hat{K}_D - \sigma_C(\hat{P}_Z + \hat{\tau} - \hat{\rho})}\right]. \tag{8'}$$

The action is in the quotient in square braces. We first consider the case where $\sigma_U > \sigma_D > \sigma^\star$. The numerator is positive, the denominator is negative, and the leakage rate is positive. Ignoring for the moment general equilibrium effects on prices, and recalling that $\hat{K}_C > 0$ and $\hat{K}_D < 0$, if we set $\hat{K}_C = \hat{K}_D = 0$ the denominator increases and the numerator declines, with the former becoming less negative and the latter less positive. Since for small λ, $\|\hat{K}_C\| < \|\hat{K}_D\|$ by eq. (13), the first effect exceeds the second, amplifying leakage. Our CGE model results for the EU ETS are captured by the parametrization $\sigma^{\star} > \sigma_D > \sigma_U$, in which the leakage rate and the bracketed numerator and denominator in (8′) are all negative. Now, $\hat{K}_C < 0$ and $\hat{K}_D > 0$, so setting these variables to zero induces a small increase (shrinkage) in the numerator and a large decrease (expansion) in the denominator, rendering Λ less negative and attenuating negative leakage.

The impacts of malleability on welfare are less clear-cut. By substituting (4) and (5) into (1) we decompose the change in utility into the adverse effect of abatement, the beneficial effect of emission leakage and the equivocal impact of intersectoral capital reallocation:

$$\hat{U} = \underbrace{\phi\theta_D\hat{Z}_D}_{\substack{\text{Abatement}\\ \text{effect}\\ (-)}} + \underbrace{(1-\phi)\theta_C\hat{Z}_C}_{\substack{\text{Leakage}\\ \text{effect}\\ (\pm)}} + \underbrace{\phi(1-\theta_D)\hat{K}_D + (1-\phi)(1-\theta_C)\hat{K}_C}_{\substack{\text{Capital reallocation}\\ \text{effect}\\ (\pm)}} \tag{14}$$

Using (13) to eliminate $\hat{K}_C$ from this expression yields the condition for capital mobility to ameliorate the abatement-induced decline in welfare:

$$\left(\frac{\phi}{1-\phi}\right)\left(\frac{1-\theta_D}{1-\theta_C}\right) \gtrless \frac{\lambda}{1-\lambda} \quad \text{if} \quad \hat{K}_D \gtrless 0. \tag{15}$$

Crucially, our restrictions on the magnitudes of the parameters are insufficient to guarantee that (15) holds generally. Moreover, the solutions in Table A.1 do not allow us to definitively sign the change in $\hat{U}$ in moving from the malleable to sector-specific capital scenario. We therefore go on to undertake a numerical analysis using the full analytical results ($\theta_C > 0$) in the spirit of Fullerton and Heutel (2007), and use the numerical outputs of this procedure to compare the magnitudes of variables across capital mobility scenarios.

3.3 Numerical Analysis

The values of the share parameters θ_C, θ_D, λ, ϕ and γ in each region are given by the CGE model's calibration dataset. We treat the polluting input as an aggregate of the fossil fuel inputs in Table 1, and model the dirty industry as a composite of the EU ETS covered and combustion sectors, aggregating the remaining sectors to form the clean industry. The heterogeneity of the individual combustion sectors is problematic; in particular, durable and non-durable manufacturing make up a substantial fraction of economies' value added but generate a small fraction of the EU ETS' total covered emissions. It seems reasonable to assume that in combustion sectors the intensity of pollution use by LCPs is similar to that of energy supply sectors, the upshot being that they account for a small fraction of manufacturing output and capital, but a disproportionate share of manufacturing emissions. In the appendix we develop a procedure to divide the outputs of, and the capital inputs to, durable and non-durable manufacturing between our stylized clean and dirty sectors. Output, capital and emissions from the covered sectors and the polluting portion of combustion sectors are allocated to the dirty sector, while output, capital and emissions from the remainder of the combustion sectors are allocated to the clean sector, along with transportation and the rest-of-economy aggregate.

Table A.3 illustrates that although both sectors use fossil fuels, these inputs make up less than 5% of the cost of clean industries' production in the EU. The dirty sector accounts for between 3% and 14% of regions' aggregate capital, while the pollution's share of dirty production ranges from 13-49%. The share of dirty goods purchases in household expenditure ranges from 14-37%, exceeding the dirty sector's share of aggregate capital.[8] By eq. (15), the parameter values indicate that capital malleability is incapable of ameliorating welfare losses. In the absence of clear empirical guidance on elasticities we use the representative values $\sigma_U = 0.2$, $\sigma_C = 0.6$, $\sigma_D = 0.4$ and $\eta = 4$.[9] Finally, we adopt Newell and Pizer's (2008) marginal environmental benefit of 9.2×10^{-13} \$/ton CO_2, which makes δ essentially zero, as well as Fullerton and Heutel (2007)'s tax increase of 10%.

Table 8 summarizes the numerical results, whose signs are in general agreement with our analytical conclusions. On average, EU ETS regions reduce covered CO_2 emissions by about 2.5% and total emissions by a little over 1%. The broad similarities among EU economies—at least with respect to fossil fuels, CO_2-intensive sectors, and the disposition of their product—means that the results do not exhibit a great deal of dispersion, with percentage emission reductions being

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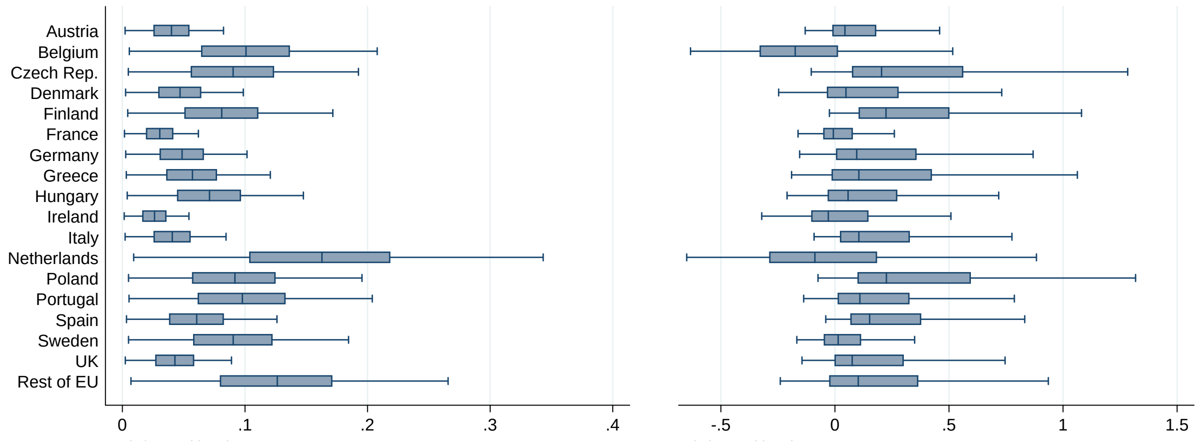
[8] Cf Fullerton and Heutel (2007), who assume that in the U.S. labor and capital make up 80% of the clean industry's costs, and that pollution accounts for 25% of the dirty industry.

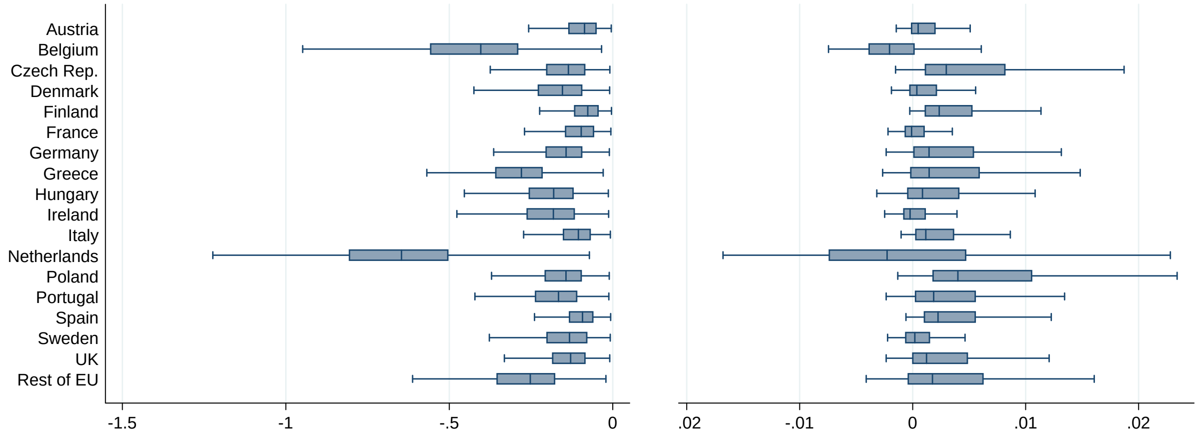
[9] Our demand side elasticity is based on energy/non-energy elasticity of substitution estimates for French and UK households from Cremer et al. (2003) and Lecca et al. (2011). On the supply side, Koetse et al.'s (2008) meta-analysis yields capital-energy substitution elasticities of 0.216 on average, and for Europe, zero in the short run and 0.79 in the long run, while van der Werf (2008) estimates similar elasticities in the range 0.9-1 for energy-intensive industries. Given our short-run focus, we select values for the dirty sector toward the lower end of this range. Our elasticity for the clean sector reflects our assumption that its firms possess more opportunities to substitute capital for pollution. Aggregate fossil fuel supply elasticities were not forthcoming; the value in the text is the upper end of the range used by Boeters and Bollen (2012). The values of $\sigma^\star$ implied by these and other parameters in Table A.3 exceed the value of σ_D.

Figure 2: Analytical Model Sensitivity Analysis



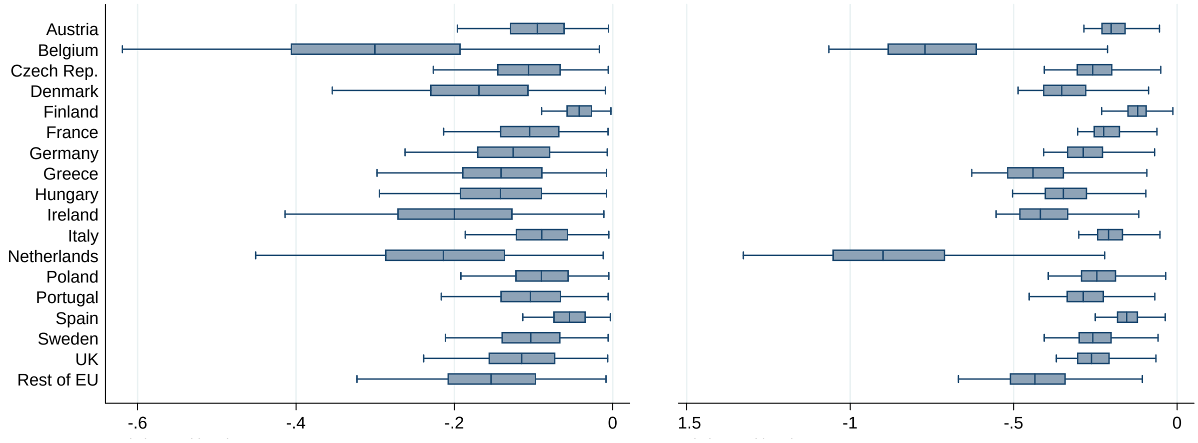
Change in clean sector capital ($\hat{K}_C$)

Change in clean sector emissions ($\hat{Z}_C$)



Abatement effect

Leakage effect



Capital reallocation effect

Welfare effect ($\hat{U}$)

Table 8: Analytical General Equilibrium Model Results for EU ETS Regions (Values in %)

	$\hat{P}_Z$	$\hat{P}_D$	$\hat{P}_C$	$\hat{\rho}_D$	$\hat{\rho}_C$	$\hat{X}_D$	$\hat{X}_C$	$\hat{K}_D$	$\hat{K}_C$	$\hat{Z}_D$	$\hat{Z}_C$	$\hat{Z}$	$\hat{U}$	Λ	Abatement Effect	Leakage Effect	Capital reallocation Effect
	A. Malleable Capital																
Austria	-0.19	0.97	-0.32	-0.32		-0.50	0.02	-0.24	0.02	-2.27	-0.06	-0.75	-0.11	-6.3	-0.07	-0.001	-0.04
Belgium	-0.28	1.99	-1.15	-1.17		-1.22	0.03	-0.59	0.04	-2.77	-0.49	-1.13	-0.43	-44.9	-0.29	-0.006	-0.13
Czech Rep.	-0.39	1.22	-0.50	-0.50		-0.65	0.04	-0.31	0.04	-2.33	-0.03	-1.56	-0.16	-0.6	-0.11	0.000	-0.05
Denmark	-0.30	1.12	-0.54	-0.54		-0.65	0.02	-0.31	0.02	-2.36	-0.13	-1.19	-0.20	-6.0	-0.13	-0.001	-0.07
Finland	-0.32	0.98	-0.29	-0.29		-0.48	0.03	-0.22	0.03	-2.22	0.05	-1.29	-0.08	1.6	-0.07	0.001	-0.02
France	-0.14	1.27	-0.33	-0.33		-0.63	0.01	-0.31	0.01	-2.35	-0.11	-0.54	-0.12	-18.5	-0.08	-0.001	-0.04
Germany	-0.30	1.67	-0.46	-0.47		-0.84	0.02	-0.41	0.02	-2.44	-0.08	-1.20	-0.17	-3.5	-0.11	-0.001	-0.05
Greece	-0.39	3.43	-0.70	-0.71		-1.63	0.02	-0.80	0.02	-2.87	-0.17	-1.56	-0.26	-5.5	-0.20	-0.002	-0.06
Hungary	-0.28	1.75	-0.57	-0.58		-0.90	0.03	-0.44	0.03	-2.49	-0.15	-1.12	-0.20	-8.2	-0.14	-0.002	-0.06
Ireland	-0.25	1.44	-0.59	-0.59		-0.80	0.01	-0.40	0.01	-2.46	-0.20	-0.99	-0.23	-14.8	-0.14	-0.002	-0.08
Italy	-0.25	1.70	-0.34	-0.34		-0.80	0.02	-0.39	0.02	-2.41	-0.04	-1.02	-0.12	-2.1	-0.08	0.000	-0.04
Netherlands	-0.43	3.87	-1.48	-1.52		-2.09	0.05	-1.01	0.07	-3.23	-0.58	-1.73	-0.54	-23.2	-0.43	-0.015	-0.09
Poland	-0.40	1.70	-0.49	-0.49		-0.84	0.04	-0.40	0.04	-2.42	-0.02	-1.58	-0.16	-0.3	-0.12	0.000	-0.04
Portugal	-0.29	1.74	-0.53	-0.54		-0.87	0.04	-0.42	0.04	-2.47	-0.11	-1.15	-0.17	-5.6	-0.13	-0.002	-0.04
Spain	-0.26	1.77	-0.30	-0.30		-0.80	0.03	-0.39	0.03	-2.40	0.00	-1.03	-0.10	0.0	-0.07	0.000	-0.02
Sweden	-0.17	1.16	-0.46	-0.47		-0.62	0.03	-0.29	0.04	-2.35	-0.14	-0.67	-0.15	-19.5	-0.11	-0.002	-0.04
UK	-0.26	1.69	-0.42	-0.42		-0.83	0.02	-0.40	0.02	-2.44	-0.08	-1.05	-0.15	-4.5	-0.10	-0.001	-0.05
Rest of EU	-0.36	1.97	-0.78	-0.79		-1.05	0.05	-0.50	0.05	-2.59	-0.20	-1.44	-0.26	-7.3	-0.19	-0.004	-0.07
	B. Sector-Specific Capital																
Austria	-2.14	0.51	-0.17	-0.85	-0.17	-0.27	0.00	–	–	-2.14	0.00	-0.66	-0.07	-0.2	-0.07	0.000	–
Belgium	-2.44	1.11	-0.65	-2.43	-0.65	-0.71	0.00	–	–	-2.44	-0.26	-0.88	-0.26	-27.2	-0.26	-0.003	–
Czech Rep.	-2.17	0.66	-0.27	-1.19	-0.27	-0.37	0.00	–	–	-2.17	0.05	-1.43	-0.11	1.3	-0.11	0.001	–
Denmark	-2.18	0.60	-0.29	-1.17	-0.29	-0.35	0.00	–	–	-2.18	-0.02	-1.04	-0.12	-0.9	-0.12	0.000	–
Finland	-2.11	0.52	-0.16	-0.83	-0.15	-0.27	0.00	–	–	-2.11	0.09	-1.21	-0.06	2.9	-0.06	0.001	–
France	-2.18	0.68	-0.18	-1.04	-0.18	-0.34	0.00	–	–	-2.18	-0.04	-0.46	-0.07	-7.2	-0.07	-0.001	–
Germany	-2.23	0.92	-0.25	-1.43	-0.25	-0.47	0.00	–	–	-2.23	0.01	-1.06	-0.10	0.3	-0.10	0.000	–
Greece	-2.53	2.10	-0.43	-2.96	-0.43	-1.01	0.00	–	–	-2.53	-0.06	-1.33	-0.17	-2.2	-0.17	-0.001	–
Hungary	-2.27	0.97	-0.31	-1.60	-0.32	-0.51	0.00	–	–	-2.27	-0.04	-0.97	-0.13	-2.7	-0.13	-0.001	–
Ireland	-2.24	0.78	-0.32	-1.42	-0.32	-0.44	0.00	–	–	-2.24	-0.07	-0.83	-0.13	-5.6	-0.13	-0.001	–
Italy	-2.22	0.93	-0.19	-1.31	-0.19	-0.45	0.00	–	–	-2.22	0.02	-0.91	-0.07	1.5	-0.08	0.000	–
Netherlands	-2.80	2.44	-0.93	-4.36	-0.95	-1.36	-0.01	–	–	-2.80	-0.36	-1.42	-0.39	-16.6	-0.38	-0.009	–
Poland	-2.22	0.94	-0.27	-1.47	-0.27	-0.48	0.00	–	–	-2.22	0.05	-1.43	-0.11	1.3	-0.11	0.001	–
Portugal	-2.26	0.96	-0.29	-1.55	-0.29	-0.50	0.00	–	–	-2.26	-0.03	-1.01	-0.12	-1.4	-0.12	0.000	–
Spain	-2.22	0.98	-0.17	-1.31	-0.17	-0.46	0.00	–	–	-2.22	0.04	-0.93	-0.07	2.4	-0.07	0.001	–
Sweden	-2.20	0.62	-0.25	-1.12	-0.25	-0.35	0.00	–	–	-2.20	-0.06	-0.57	-0.10	-9.3	-0.10	-0.001	–
UK	-2.23	0.93	-0.23	-1.39	-0.23	-0.46	0.00	–	–	-2.23	0.00	-0.92	-0.09	0.0	-0.09	0.000	–
Rest of EU	-2.34	1.10	-0.44	-1.99	-0.44	-0.62	0.00	–	–	-2.34	-0.08	-1.25	-0.18	-3.1	-0.18	-0.001	–

Variables: $\hat{X}_C$, $\hat{X}_D$ output of the clean and dirty good; $\hat{P}_C$, $\hat{P}_D$ price of the clean and dirty good; $\hat{P}_Z$, $\hat{Z}$ price and aggregate quantity of pollution; $\hat{Z}_C$, $\hat{Z}_D$ pollution inputs to clean and dirty production; $\hat{K}_C$, $\hat{K}_D$ capital inputs to clean and dirty production; $\hat{\rho}_C$, $\hat{\rho}_D$ marginal product of capital in clean and dirty production; $\hat{U}$ household utility; Λ emission leakage rate.

slightly larger for relatively pollution intensive regions (Poland and the Netherlands), and smaller for regions with a small fraction of total emissions in dirty sectors (France and Sweden). Leakage rates and welfare impacts are both negative and much larger than seen in the CGE model results. The former are negatively correlated with the dirty expenditure share and negatively correlated with the dirty industry's pollution cost share, while the latter are positively correlated with the pollution's share of production cost in the dirty and—to a lesser extent—the clean sector, as well as with the dirty good's expenditure share.

Crucially, our model exhibits negative leakage without the abatement resource effect, which is ruled out by the relative magnitudes of our elasticity parameters. Capital does not leave the clean industry for the dirty industry; in fact, factor reallocation works in the opposite direction, resulting in additional clean capital that substitutes for emissions. From our results in Table A.1, clean emissions decline because $\sigma_D < \sigma^\star$ and $\|\sigma_C(\gamma\sigma_D - \eta\phi\theta_D)\| > \|\theta_D(\lambda\eta + (1-\lambda)\gamma\sigma_C)(\sigma_U - \sigma_D)\|$, whose main driver is the combination of inelastic clean good demand and highly price-elastic pollution supply.

This effect turns out to have only a small mitigating impact on welfare losses. The magnitudes of the components of eq. (14) indicate that the primary abatement burden—and, to a lesser extent, the intersectoral reallocation of capital—are big drivers of welfare loss, with the sign of the leakage effect differing across regions while exerting a very slight impact. As predicted by our analytical results, capital rigidity makes leakage rates more positive, and in the present setting is sufficient to flip the sign of the clean sector emission response. The minor differences in the abatement and leakage effects in moving from the malleable to the sector-specific scenario point to capital reallocation as the source of the former's larger welfare loss. The upshot is that when capital is mobile the tax is more effective in reducing pollution, but at the cost of a substantially larger reduction in welfare.

Given the dependence of our results on the values of the elascitities of substitution and pollution supply, we test the robustness of our conclusions through sensitivity analysis. Our strategy is to perform 1,000 Monte Carlo simulations of the numerically calibrated analytical model with the elasticities specified as random draws from independent uniform distributions. Specifically, we choose $\sigma_C, \sigma_D, \sigma_D \sim \mathscr{U}(0,1)$ and $\eta \sim \mathscr{U}(0,6)$. The results, shown in Figure 2, support our prior findings. The abatement resource effect never arises, as capital moves from the dirty to the clean sector. Negative leakage does arise in every region and is strongly correlated with the pollution supply elasticity, but under our parameter assumptions it is generally unlikely in all but a few key economies (Belgium, Denmark, France, Ireland, Netherlands and Sweden). The implication for welfare is that the leakage effect is much more likely to mitigate utility losses, but it can have an exacerbating impact, especially in the regions identified above. Even so, this effect is an order of magnitude smaller than the main impacts of abatement and capital reallocation, whose influence is uniformly negative.

4 Conclusions

This paper has analyzed the role that capital malleability plays in the implementation of partial carbon pricing, taking as policy application Phase II of the European Union Emissions Trading Scheme (EU ETS). An analysis with a multi-region, multi-sector Computable General Equilibrium (CGE) model was complemented by constructing and numerically parametrizing a simple two-sector analytical general equilibrium model in order to simplify the complex interactions simulated within the CGE model.

The analysis has shown that a partial policy, such as the EU ETS, can result in a negative internal carbon leakage rate, with emissions declining not only in capped sectors but also in non-regulated ones. While negative leakage may be thought to follow from a resource abatement effect, a sensitivity analysis on the values of the elasticities disproves this hypothesis. The decline in emissions from cleaner sectors results from the combination of inelastic demand for the clean good and a highly price-elastic pollution supply. This negative leakage effect is stronger with malleable capital. When capital is sector-specific, the marginal productivity of fossil fuel commodities is generally lower and thus leads to lower equilibrium prices and demand within the EU.

The welfare consequences of the EU ETS are found to be positive in some countries and negative in others. They are generally small but larger when capital is malleable. A decomposition analysis within the analytical model is used to show that the sign and magnitude of the welfare impacts are determined by a combination of an unambiguously negative abatement effect, a capital reallocation effect likely to exacerbate welfare losses, and a leakage effect likely to mitigate declines in utility. This explains why capital malleability results in larger reductions or lower increases in welfare. The robustness of these results is verified with the sensitivity analysis on the elasticities of substitution.

The results of the paper have demonstrated the relevance of the consideration of capital malleability in the study of the costs and effectiveness of short-term climate regulations. The paper has also shown the sensitivity of results to the values of the substitution and demand elasticities. Abstracting from the analytical frameworks used, this illustrates the importance of considering the possibilities of substitution across inputs in production and the responsiveness of individuals in replacing the dirty taxed goods with the clean ones when evaluating the costs of climate policy.

From a policy perspective, the findings on the negative leakage show that a partial climate policy is likely to have co-benefit in reduced emissions in non-regulated sectors. Disregarding bureaucratic costs of implementation, this also suggests that extending the policy to all sectors may not incur in large additional economic costs. Finally, the results from the CGE model analysis show that welfare changes are significantly correlated with the net sales of allowances, which underlines the importance of income effects associated with the initial allowance allocation.

Appendix

There are four steps to the calibration:

1. From the CGE model calibration we know the distribution of the benchmark value of fossil fuel intermediate inputs between covered (dirty) and nontrading (clean) sectors, and within combustion sectors between the uses of fossil fuels that correspond to those covered by the EU ETS (dirty) and those outside the program (clean). These quantities ($Z_{D,r}^{\text{Cov.}}$, $Z_{C,r}^{\text{Nontrad.}}$, $Z_{D,r}^{\text{Comb.}}$ and $Z_{C,r}^{\text{Comb.}}$, respectively) are calculated in eqs. (A.1)-(A.4). As emphasized in the text, we do not observe how the combustion sectors' output, capital or disposition of their product to final consumption are distributed between the clean and dirty industries, with the challenge being to develop a method for apportioning these variables.

2. Our approach assumes that covered emissions in combustion sectors are generated by large combustion plants. We select archetypical energy supply sectors within the CGE model for which LCPs make up a large fraction of output ($a = \{$Electric power, Refined petroleum/coal, Gas production/distribution$\}$), and use GTAP benchmark input-output data for these sectors to calculate region-specific average ratios of output to covered fossil fuels (ξ_r^{YZ}) and capital to covered fossil fuels (ξ_r^{KZ}), as shown in (A.5)-(A.6).

3. These coefficients are combined with GTAP benchmark data to disaggregate combustion sectors' output and capital input into clean and dirty components ($X_{D,r}^{\text{Comb.}}$, $X_{C,r}^{\text{Comb.}}$, $K_{D,r}^{\text{Comb.}}$ and $K_{C,r}^{\text{Comb.}}$). As well, we assign output and capital of the EU ETS covered sectors to the dirty industry ($X_{D,r}^{\text{Cov.}}$, $K_{D,r}^{\text{Cov.}}$), and output and capital of nontrading sectors to the clean industry ($X_{D,r}^{\text{Nontrad.}}$, $K_{D,r}^{\text{Nontrad.}}$). The details are given in (A.7)-(A.14).

4. The results of steps 1 and 3 facilitate straightforward computation of θ_D, θ_C and λ, (A.15)-(A.17), while γ is computed from the CGE model's emission accounts (A.18). Finally, we divide the aggregate value of consumption into clean and dirty components. Imports complicate this calculation. We can assume that households' use of their own region's covered (nontrading) sectors' product represents domestic dirty (clean) consumption, and their use of combustion sectors' product is split between domestic dirty and clean consumption in the same proportion as output ($\xi_{D,i,r}^{YY}$), given by (A.19). But this method founders on our inability

to distinguish between clean and dirty production in *non* EU ETS regions' combustion sectors. Our simple solution is to adopt a worst-case designation of all consumption of imports from covered and combustion sectors as dirty, which enables us to calculate ϕ as in (A.20).

Table A.1: Analytical Model Results (Assuming $\theta_C \to 0$)

	A. Malleable Capital		B. Sector-Specific Capital	
$\hat{X}_C$	$-\mathcal{D}_M^{-1}\theta_D\lambda(\eta+(1-\gamma)\sigma_C)(\sigma_U-\sigma_D)\hat{\tau}$	$\pm$	$\mathcal{D}_S^{-1}\theta_C(\gamma\sigma_U-\eta\phi\theta_D)\sigma_C\sigma_D\hat{\tau}$	$\pm$
$\hat{X}_D$	$-\mathcal{D}_M^{-1}\theta_D(\eta+(1-\gamma)\sigma_C)(\lambda\sigma_D+(1-\lambda)\sigma_U)\hat{\tau}$	$-$	$-\mathcal{D}_S^{-1}\theta_D(\eta+(1-\gamma)\sigma_C)\sigma_D\sigma_U\hat{\tau}$	$-$
$\hat{P}_C$	$-\mathcal{D}_M^{-1}\phi\theta_D(\eta+(1-\gamma)\sigma_C)\hat{\tau}$	$-$	$-\mathcal{D}_S^{-1}\phi\theta_D(\eta+(1-\gamma)\sigma_C)\sigma_D\hat{\tau}$	$-$
$\hat{P}_D$	$\mathcal{D}_M^{-1}(1-\phi)\theta_D(\eta+(1-\gamma)\sigma_C)\hat{\tau}$	$+$	$\mathcal{D}_S^{-1}(1-\phi)\theta_D(\eta+(1-\gamma)\sigma_C)\sigma_D\sigma_U\hat{\tau}$	$+$
$\hat{K}_C$	$\mathcal{D}_M^{-1}\lambda\theta_D(\eta+(1-\gamma)\sigma_C)(\sigma_U-\sigma_D)\hat{\tau}$	$\pm$	0	
$\hat{K}_D$	$-\mathcal{D}_M^{-1}(1-\lambda)\theta_D(\eta+(1-\gamma)\sigma_C)(\sigma_U-\sigma_D)\hat{\tau}$	$\pm$	0	
$\hat{\rho}_C$	$-\mathcal{D}_M^{-1}\phi\theta_D(\eta+(1-\gamma)\sigma_C)\hat{\tau}$	$-$	$\mathcal{D}_S^{-1}\theta_D(\eta+(1-\gamma)\sigma_C)\sigma_D\hat{\tau}$	$+$
$\hat{\rho}_D$			$-\mathcal{D}_S^{-1}\theta_D(\eta+(1-\gamma)\sigma_C)(\sigma_U-(1-\phi)\sigma_D)\hat{\tau}$	$-$
$\hat{Z}_C$	$\mathcal{D}_M^{-1}[\theta_D(\lambda\eta+(1-\lambda)\gamma\sigma_C)(\sigma_U-\sigma_D)+\sigma_C(\gamma\sigma_D-\eta\phi\theta_D)]\hat{\tau}$	$\pm$	$\mathcal{D}_S^{-1}(\gamma\sigma_U-\phi\eta\theta_D)\sigma_C\sigma_D\hat{\tau}$	$\pm$
$\hat{Z}_D$	$-\mathcal{D}_M^{-1}(\eta+(1-\gamma)\sigma_C)((1-\lambda)\theta_D\sigma_U+(1-(1-\lambda)\theta_D)\sigma_D)\hat{\tau}$	$-$	$-\mathcal{D}_S^{-1}(\eta+(1-\gamma)\sigma_C)\sigma_D\sigma_U\hat{\tau}$	$-$
$\hat{Z}$	$-\mathcal{D}_M^{-1}\eta[\theta_D(\gamma-\lambda)\sigma_U+(\theta_D\lambda+(1-\theta_D)\gamma)+\phi(1-\gamma)\theta_D\sigma_C]\hat{\tau}$	$-$	$-\mathcal{D}_S^{-1}\eta\sigma_D(\gamma\sigma_U+(1-\gamma)\phi\theta_D\sigma_C)\hat{\tau}$	$-$
$\hat{P}_Z$	$-\mathcal{D}_M^{-1}(\eta+(1-\gamma)\sigma_C)((1-\lambda)\theta_D\sigma_U+(1-(1-\lambda)\theta_D)\sigma_D)\hat{\tau}$	$-$	$-\mathcal{D}_S^{-1}\sigma_D(\gamma\sigma_U+(1-\gamma)\phi\theta_D\sigma_C)\hat{\tau}$	$-$
$\hat{U}$	$-\mathcal{D}_M^{-1}\theta_D(\eta+(1-\gamma)\sigma_C)((\phi-\lambda)\sigma_U+\lambda\sigma_D))\hat{\tau}$	$-$	$-\mathcal{D}_S^{-1}\phi\theta_D(\eta+(1-\gamma)\sigma_C)\sigma_D\sigma_U\hat{\tau}$	$-$
Λ	$\left(\frac{1-\gamma}{\gamma}\right)\left[\frac{\theta_D(\lambda\eta+(1-\lambda)\gamma\sigma_C)(\sigma_U-\sigma_D)+\sigma_C(\gamma\sigma_D-\eta\phi\theta_D)}{(\eta+(1-\gamma)\sigma_C)(\sigma_D+(1-\lambda)\theta_D(\sigma_U-\sigma_D))}\right]$	$\pm$	$\left(\frac{1-\gamma}{\gamma}\right)\left[\frac{(\gamma\sigma_U-\phi\eta\theta_D)\sigma_C}{(\eta+(1-\gamma)\sigma_C)\sigma_U}\right]$	$\pm$
$\mathcal{D}$	$(1-\gamma)\sigma_C+(\theta_D\lambda+(1-\theta_D)\gamma)\sigma_D+\theta_D(\gamma-\lambda)\sigma_U+\eta(1-\phi\theta_D)$	$+$	$(1-\gamma)(\theta_D\sigma_D+(1-\theta_D)\sigma_U)\sigma_C+(\gamma\sigma_U+\eta(1-\phi)\theta_D)\sigma_D+\eta(1-\theta_D)\sigma_U$	$+$

Variables: $\hat{X}_C$, $\hat{X}_D$ output of the clean and dirty good; $\hat{P}_C$, $\hat{P}_D$ price of the clean and dirty good; $\hat{P}_Z$, $\hat{Z}$ price and aggregate quantity of pollution; $\hat{Z}_C$, $\hat{Z}_D$ pollution inputs to clean and dirty production; $\hat{K}_C$, $\hat{K}_D$ capital inputs to clean and dirty production; $\hat{\rho}_C$, $\hat{\rho}_D$ marginal product of capital in clean and dirty production; $\hat{U}$ household utility; Λ emission leakage rate; $\mathcal{D}_M, \mathcal{D}_S$ denominator in malleable and sector-specific capital scenarios.
Parameters: θ_C, θ_D pollution share of production cost in clean and dirty sector; λ, γ dirty sector share of aggregate capital and pollution; ϕ dirty good share of household expenditure; η elasticity of aggregate pollution supply; σ_C, σ_D elasticity of substitution between capital and pollution in clean and dirty sector; σ_U elasticity of substitution between clean and dirty good in household.

Table A.2: Numerical Calibration of the Analytical General Equilibrium Model

$$Z^{\text{Cov.}}_{D,s} = \sum_e \sum_c \left((1+\overline{\tau}^{XD}_{e,c,s})\overline{q}^{D}_{e,c,s} + (1+\overline{\tau}^{XM}_{e,c,s})\overline{q}^{M}_{e,c,s} \right) \tag{A.1}$$

$$Z^{\text{Comb.}}_{D,s} = \sum_e \sum_l \omega_{e,l,s} \left((1+\overline{\tau}^{XD}_{e,l,s})\overline{q}^{D}_{e,l,s} + (1+\overline{\tau}^{XM}_{e,l,s})\overline{q}^{M}_{e,l,s} \right) \tag{A.2}$$

$$Z^{\text{Comb.}}_{C,s} = \sum_e \sum_l (1-\omega_{e,l,s}) \left((1+\overline{\tau}^{XD}_{e,l,s})\overline{q}^{D}_{e,l,s} + (1+\overline{\tau}^{XM}_{e,l,s})\overline{q}^{M}_{e,l,s} \right) \tag{A.3}$$

$$Z^{\text{Nontrad.}}_{C,s} = \sum_e \sum_{j\setminus h} \left((1+\overline{\tau}^{XD}_{e,j,s})\overline{q}^{D}_{e,j,s} + (1+\overline{\tau}^{XM}_{e,j,s})\overline{q}^{M}_{e,j,s} \right) \tag{A.4}$$

$$\xi^{YZ}_r = \sum_a \overline{Y}_{a,s} \Bigg/ \left[\sum_e \sum_a \omega_{e,a,s} \left((1+\overline{\tau}^{XD}_{e,a,s})\overline{q}^{D}_{e,a,s} + (1+\overline{\tau}^{XM}_{e,a,s})\overline{q}^{M}_{e,a,s} \right) \right] \tag{A.5}$$

$$\xi^{KZ}_r = \sum_a (1+\overline{\tau}^{F}_{K,a,s})\overline{v}_{K,a,s} \Bigg/ \left[\sum_e \sum_a \omega_{e,a,s} \left((1+\overline{\tau}^{XD}_{e,a,s})\overline{q}^{D}_{e,a,s} + (1+\overline{\tau}^{XM}_{e,a,s})\overline{q}^{M}_{e,a,s} \right) \right] \tag{A.6}$$

$$X^{\text{Cov.}}_{D,s} = \sum_c \overline{Y}_{c,s} \tag{A.7}$$

$$X^{\text{Comb.}}_{D,s} = \xi^{YZ}_r Z^{\text{Comb.}}_{D,s} \tag{A.8}$$

$$X^{\text{Comb.}}_{C,s} = \sum_{j\in l} \overline{Y}_{j,s} - X^{\text{Comb.}}_{D,s} \tag{A.9}$$

$$X^{\text{Nontrad.}}_{C,s} = \sum_{j\setminus h} \overline{Y}_{j,s} \tag{A.10}$$

$$K^{\text{Cov.}}_{D,s} = \sum_c (1+\overline{\tau}^{F}_{K,c,s})\overline{v}_{K,c,s} \tag{A.11}$$

$$K^{\text{Comb.}}_{D,s} = \xi^{KZ}_r Z^{\text{Comb.}}_{D,s} \tag{A.12}$$

$$K^{\text{Comb.}}_{C,s} = \sum_{j\in l} (1+\overline{\tau}^{F}_{K,j,s})\overline{v}_{K,j,s} - K^{\text{Comb.}}_{D,s} \tag{A.13}$$

$$K^{\text{Nontrad.}}_{C,s} = \sum_{j\setminus h} (1+\overline{\tau}^{F}_{K,j,s})\overline{v}_{K,j,s} \tag{A.14}$$

$$\theta_{D,s} = \left(Z^{\text{Cov.}}_{D,s} + Z^{\text{Comb.}}_{D,s} \right) \Big/ \left(X^{\text{Cov.}}_{D,s} + X^{\text{Comb.}}_{D,s} \right) \tag{A.15}$$

$$\theta_{C,s} = \left(Z^{\text{Comb.}}_{C,s} + Z^{\text{Nontrad.}}_{C,s} \right) \Big/ \left(X^{\text{Comb.}}_{C,s} + X^{\text{Nontrad.}}_{C,s} \right) \tag{A.16}$$

$$\lambda_r = \left(K^{\text{Cov.}}_{D,s} + K^{\text{Comb.}}_{D,s} \right) \Big/ \left(K^{\text{Cov.}}_{D,s} + K^{\text{Comb.}}_{D,s} + K^{\text{Comb.}}_{C,s} + K^{\text{Nontrad.}}_{C,s} \right) \tag{A.17}$$

$$\gamma_r = \sum_e \sum_h \varepsilon_{e,h,s}\omega_{e,h,s} \left(\overline{q}^{D}_{e,h,s} + \overline{q}^{M}_{e,h,s} \right) \Bigg/ \sum_e \varepsilon_{e,j,s} \left(\sum_j \left(\overline{q}^{D}_{e,j,s} + \overline{q}^{M}_{e,j,s} \right) + \overline{g}^{D}_{C,e,s} + \overline{g}^{M}_{C,e,s} \right) \tag{A.18}$$

$$\xi^{YY}_{D,i,r} = \begin{cases} 1 & i \in c \text{ (Covered)} \\ \dfrac{\xi^{YZ}_r}{\overline{Y}_{i,r}} \displaystyle\sum_e \omega_{e,i,s} \left((1+\overline{\tau}^{XD}_{e,i,s})\overline{q}^{D}_{e,i,s} + (1+\overline{\tau}^{XM}_{e,i,s})\overline{q}^{M}_{e,i,s} \right) & i \in l \text{ Combustion} \\ 0 & \text{Otherwise} \end{cases} \tag{A.19}$$

$$\phi_r = \sum_h \left(\xi^{YY}_{D,h,r}(1+\overline{\tau}^{CD}_{h,s})\overline{g}^{D}_{C,h,s} + (1+\overline{\tau}^{CM}_{h,s})\overline{g}^{M}_{C,h,s} \right) \Bigg/ \sum_i \left((1+\overline{\tau}^{CD}_{i,s})\overline{g}^{D}_{C,i,s} + (1+\overline{\tau}^{CM}_{i,s})\overline{g}^{M}_{C,i,s} \right) \tag{A.20}$$

GTAP data arrays: $\overline{Y}$ value of sectoral output; $\overline{q}^D$, $\overline{q}^M$ value of domestic and imported intermediate energy inputs to sectors; $\overline{\tau}^{XD}$, $\overline{\tau}^{XM}$ tax rates on domestic and imported intermediate energy inputs to sectors; $\overline{v}_K$ value of capital input to sectors; $\overline{\tau}^F_K$ tax rate on capital input to sectors; $\overline{g}^D_C$, $\overline{g}^M_C$ value of domestic and imported household final commodity demands; $\overline{\tau}^{CD}$, $\overline{\tau}^{CM}$ tax rates on domestic and imported household final commodity demands.

Table A.3: Calibrated Analytical Model Coefficients

	λ	θ_C	θ_D	γ	ϕ
Austria	0.06	0.01	0.13	0.31	0.25
Belgium	0.07	0.02	0.29	0.28	0.37
Czech Rep.	0.11	0.02	0.17	0.67	0.29
Denmark	0.06	0.01	0.16	0.47	0.33
Finland	0.14	0.01	0.13	0.59	0.23
France	0.04	0.02	0.16	0.19	0.21
Germany	0.05	0.02	0.21	0.48	0.22
Greece	0.03	0.02	0.40	0.51	0.17
Hungary	0.06	0.02	0.23	0.42	0.25
Ireland	0.03	0.01	0.20	0.35	0.29
Italy	0.04	0.01	0.20	0.41	0.17
Netherlands	0.07	0.04	0.49	0.44	0.28
Poland	0.09	0.02	0.22	0.65	0.22
Portugal	0.09	0.02	0.22	0.44	0.23
Spain	0.06	0.02	0.21	0.43	0.14
Sweden	0.11	0.02	0.16	0.24	0.28
UK	0.04	0.02	0.21	0.41	0.20
Rest of EU	0.10	0.02	0.27	0.52	0.28

References

Armington, P. (1969). A theory of demand for products distinguished by place of production, *International Monetary Fund Staff Papers* **16**: 159–176.

Boeters, S. and Bollen, J. (2012). Fossil fuel supply, leakage and the effectiveness of border measures in climate policy, *CPB Discussion Paper No. 215*, CPB Netherlands Bureau for Economic Policy Analysis.

Böhringer, C., Fischer, C. and Rosendahl, K. E. (2010). The global effects of subglobal climate policies, *The B.E. Journal of Economic Analysis & Policy* **10**: Article 13.

Bovenberg, A. and de Mooij, R. (1994). Environmental levies and distortionary taxation, *American Economic Review* **84**: 1085–1089.

Brooke, A., Kendrick, D., Meeraus, A. and Raman, R. (1998). *GAMS: A User's Guide*, GAMS Corp., Washington DC.

Burniaux, J. and Truong, T. (2002). GTAP-E: an energy-environmental version of the GTAP model, *GTAP technical paper*.

Capros, P., Georgakopoulos, T., Regemorter, D. V., Proost, S., Schmidt, T. and Conrad, K. (1997). European union: the GEM-E3 general equilibrium model, *Economic and Financial Modelling* **4**: 51–160.

Convery, F. J. (2009). Reflections—the emerging literature on emissions trading in Europe, *Review of Environmental Economics and Policy* **3**: 121–137.

Cooper, R. and Haltiwanger, J. (2006). On the nature of capital adjustment costs, *Review of Economic Studies* **73**: 611–633.

Cremer, H., Gahvari, F. and Ladoux, N. (2003). Environmental taxes with heterogeneous consumers: an application to energy consumption in France, *Journal of Public Economics* **87**: 2791–2815.

Dirske, S. and Ferris, M. (1995). The path solver: A non-monotone stabilization scheme for mixed complementarity problems, *Optimization Methods and Software* **5**: 123–159.

Dixit, A. (1989). Intersectoral capital reallocation under price uncertainty, *Journal of International Economics* **26**: 309–325.

Eisfeldt, A. L. and Rampini, A. A. (2006). Capital reallocation and liquidity, *Journal of Monetary Economics* **53**: 369–399.

Ferris, M. C. and Munson, T. S. (2000). Complementarity problems in GAMS and the PATH solver, *Journal of Economic Dynamics and Control* **24**: 165–188.

Fullerton, D. and Heutel, G. (2007). The general equilibrium incidence of environmental taxes, *Journal of Public Economics* **91**: 571–591.

Fullerton, D., Karney, D. and Baylis, K. (2011). Negative leakage, *National Bureau of Economic Research Working Paper No. 17001*.

Fullerton, D. and Metcalf, G. E. (2002). Tax incidence, *in* A. Auerbach and M. Feldstein (eds), *Handbook of Public Economics, vol. 4*, Elsevier, pp. 1787–1872.

Gapinski, J. (1985). Capital malleability, macro performance and policy effectiveness, *Southern Economic Journal* **52**: 150–166.

Goolsbee, A. (1998). The business cycle, financial performance, and the retirement of capital goods, *Review of Economic Dynamics* **1**: 474–496.

Goolsbee, A. and Gross, D. B. (1997). Estimating adjustment costs with data on heterogeneous capital goods, *NBER Working Paper No. 6342*.

Groth, C. (2008). Quantifying UK capital adjustment costs, *Economica* **75**: 310–325.

Harrison, G., Rutherford, T. and Tarr, D. (1997a). Opciones de politica comercial para Chile: una evaluacion cuantitiva, *Cuadernos de Economia* **34**: 101–137.

Harrison, G., Rutherford, T. and Tarr, D. (1997b). Quantifying the Uruguay Round, *Economic Journal* **107**: 1405–1430.

Jacoby, H. and Sue Wing, I. (1999). Adjustment time, capital malleability, and policy cost, *Energy Journal* **Special Issue on the Costs of the Kyoto Protocol: A Multi-Model Evaluation**: 73–92.

Klepper, G., Peterson, S. and Springer, K. (2003). DART97: A description of the multi-regional, multi-sectoral trade model for the analysis of climate policies, *Working Paper No. 1149*, Kiel Institute for the World Economy.

Koetse, M. J., de Groot, H. L. and Florax, R. J. (2008). Capital-energy substitution and shifts in factor demand: A meta-analysis, *Energy Economics* **30**(5): 2236 – 2251.

Lecca, P., Swales, K. and Turner, K. (2011). Rebound effects from increased efficiency in the use of energy by UK households, *Working Paper No. 1123*, University of Strathclyde Business School, Department of Economics.

Lee, H.-L. (2002). An emissions data base for integrated assessment of climate change policy using GTAP, *GTAP Working Paper*, Center for Global Trade Analysis, Purdue University.

Lee, H.-L. (2008). The combustion-based CO_2 emissions data for GTAP version 7 data base, *Working Paper*, Economics Dept., National Chengchi University.

Narayanan, B. G. and Walmsley, T. L. (2008). *Global Trade, Assistance, and Production: The GTAP 7 Data Base*, Center for Global Trade Analysis.

Newell, R. and Pizer, W. (2008). Indexed regulation, *Journal of Environmental Economics and Management* **56**: 221–233.

Olivier, J. G., Janssens-Maenhout, G. and Peters, J. A. (2012). Trends in global CO_2 emissions: 2012 report, *Technical report*, PBL Netherlands Environmental Assessment Agency.

Paltsev, S., Reilly, J., Jacoby, H., Eckaus, R., McFarland, J., Sarofim, M., Asadoorian, M. and Babiker, M. (2005). The MIT emissions prediction and policy analysis (EPPA) model: Version 4, *Joint Program on the Science & Policy of Global Change*.

Ramey, V. A. and Shapiro, M. D. (1998). Costly capital reallocation and the effects of government spending, *Carnegie-Rochester Conference Series on Public Policy* **48**: 145–194.

Ramey, V. A. and Shapiro, M. D. (2001). Displaced capital: A study of aerospace plant closings, *Journal of Political Economy* **109**: 958–992.

Reilly, J. and Paltsev, S. (2006). European greenhouse gas emissions trading: A system in transition, *in* C. de Miguel, X. Labandeira and B. Manzano (eds), *Economic Modelling of Climate Change and Energy Policies*, Edward Elgar, Cheltenham, pp. 45–64.

Rutherford, T. (2005). GTAP6inGAMS: The dataset and static model, *Technical report*.

Rutherford, T. F. (1999). Applied general equilibrium modeling with MPSGE as a GAMS subsystem: An overview of the modeling framework and syntax, *Computational Economics* **14**: 1–46.

Soderholm, P. (2001). Fossil fuel flexibility in West European power generation and the impact of system load factors, *Energy Economics* **23**: 77–97.

Sue Wing, I. (2006). The synthesis of bottom-up and top-down approaches to climate policy modeling: Electric power technologies and the cost of limiting US CO_2 emissions, *Energy Policy* **34**(18): 3847–3869.

Sue Wing, I. (2009). Computable general equilibrium models for the analysis of energy and climate policies, *in* J. Evans and L. Hunt (eds), *International Handbook on the Economics of Energy*, Edward Elgar, Cheltenham, pp. 332–366.

van der Werf, E. (2008). Production functions for climate policy modeling: An empirical analysis, *Energy Economics* **30**: 2964–2979.