Division of Economics and Business
Working Paper Series

Carbon policy and the structure of global trade

Edward J. Balistreri
Christoph Böhringer
Thomas F. Rutherford

Working Paper 2015-02
http://econbus.mines.edu/working-papers/wp201502.pdf

Colorado School of Mines
Division of Economics and Business
1500 Illinois Street
Golden, CO 80401

April 2015

Colorado School of Mines
Division of Economics and Business
Working Paper No. **2015-02**
April 2015

Title:
Carbon policy and the structure of global trade*

Author(s):
Edward J. Balistreri
Division of Economics and Business
Colorado School of Mines
Golden, CO 80401-1887
ebalistr@mines.edu

Christoph Böhringer
Chair of Economic Policy
Department of Economics
University of Oldenburg
D-26111 Oldenburg
Germany
christoph.boehringer@uni-oldenburg.de

Thomas F. Rutherford
Optimization Theme
Wisconsin Institute for Discovery, and
Department of Agricultural and Applied Economics
University of Wisconsin
Madison, WI 53715
rutherford@aae.wisc.edu

ABSTRACT
Alternative perspectives on the structure of international trade have important implications for climate policy and its interaction with global markets. In this paper we consider carbon policy in the context of three important alternative trade formulations. First, is a neo-classical model based on trade in homogeneous products, which is the natural context for considering competitive effects of trade and environmental policy. Second is a model based on regionally differentiated goods consistent with the Armington assumption adopted in the policy simulation literature. Finally, we consider a monopolistic-competition model, consistent with Melitz (2003), which is the focus of many contemporary theoretic investigations in international trade. These structures have important implications for carbon leakage and the spatial distribution of energy-intensive production. Furthermore, predictions about the transmission of policy burdens to non-participating countries are critically dependent on the assumed structure of trade.

JEL **classifications: F12, F18, Q54, Q56**
Keywords: Heterogeneous firms, carbon leakage, competitiveness.

*The authors thank participants of seminars at the Colorado School of Mines, the Western Economic Association meetings, the University of Idaho and Washington State University for helpful comments and discussion.

1 Introduction

Countries considering the adoption of environmental regulations are rightly concerned with the potential for these policies to be undermined through external market adjustments. In the context of carbon policy, emissions abatement by a limited coalition of countries can put energy-intensive production within the coalition at competitive risk. The potential for carbon leakage emerges, where the policy induces an escalation of emissions outside the coalition. The global distribution of burdens are an additional concern, as countries outside of the coalition might be affected by the policy in a way that makes them more, or less, likely to join. One's perspective on global markets can have a profound influence on debates surrounding these concerns. In this paper we quantify the structural sensitivity of welfare impacts and carbon leakage by adopting three important alternative perspectives on international markets.

The fundamental argument for international cooperation on climate policy is without question. There are undoubtedly important global cost savings from reducing emissions where it is cheapest to do so, regardless of how we think international markets operate. Individual countries are in different positions, however, regarding their desire and ability to contribute to climate change mitigation. Even if there were agreement on global targets, international negotiations must address the politically salient issue of burden sharing. In recent papers, for example, Libecap (2014) highlights the difficulty of assigning and enforcing property rights in international environmental agreements, and Nordhaus (2015) focuses on *free riding* as the primary impediment to international agreements on climate policy. The challenges of international cooperation have resulted in limited and uncoordinated action, to date. There is still potential, however, for a substantial group of developed countries to move forward as a unified coalition.[1] In this context it is important to consider and quantify

[1]The international community continues to negotiate on coordinated action through the United Nations Framework Convention on Climate Change (UNFCCC), including the upcoming Conference of the Parties

the role of international markets as they interact with abatement policies.

The climate-policy simulation literature provides important insights into the interactions of abatement and international markets. This literature relies on Computable General Equilibrium (CGE) models, which are adept at translating unprecedented policy shifts into structurally consistent quantitative outcomes. Studies in this literature, however, overwhelmingly adopt a particular set of structural assumptions about international trade. Countries are assumed to produce regionally differentiated goods under perfect competition, and these imported and domestically produced differentiated goods are combined in a Constant-Elasticity-of-Substitution (CES) demand system. This is often referred to as the Armington assumption, after its seminal proposal and application by Armington (1969). This particular structure has empirical advantages, but it has been criticized for its inconsistency with micro-level observations and questionable counterfactual implications.[2] Our point is that the Armington structure is a single (convenient) lens under which we view the data. This potentially narrows our perspective on the probable interactions between abatement and international markets.

To give one example, consider the recent Energy Modeling Forum study—EMF 29.[3] The EMF 29 working group drew together 12 modeling groups to investigate the role of border carbon adjustments in unilateral climate policy. In our overview article, Böhringer et al. (2012), we point out that most models indicate significant shifting of abatement burdens to

session 21 (COP 21) scheduled for December 2015 in Paris France. Nordhaus (2015) argues that, with modest trade penalties for non-participants, an effective—and stable—international coalition could emerge.

[2]Balistreri and Rutherford (2013) and McDaniel and Balistreri (2003) provide explanations for the widespread adoption of the Armington assumption. Notable critiques on the implications are offered by Kehoe (2005) and Brown (1987), while Melitz and Redding (2015) argue for the importance of micro-level structures. With the exceptions of Babiker (2005) and Balistreri and Rutherford (2012) climate-policy CGE models adopt the Armington trade structure. The Armington assumption has also been used by theorists as a justifications for the *gravity* relationship observed in trade flows [e.g., Anderson (1979)]. Newer trade theories developed by Krugman (1980), Eaton and Kortum (2002), and Melitz (2003) naturally produce the same *gravity* relationship.

[3]The Energy Modeling Forum (EMF) is organized by Stanford University (Professor John Weyant, Director) with a mission to communicate the results from alternative numeric models in the context of a carefully controlled comparison study (`https://emf.stanford.edu`).

non-abating countries through terms-of-trade adjustments. The average ratio of coalition (Annex 1 except Russia) welfare costs to non-coalition welfare costs was 3:1 across models (under the reference scenario).[4] This result is surprising from the perspective of neo-classical trade and, as we argue here, is critically dependent on the Armington perspective adopted in 11 of the 12 models compared.[5] The result is surprising because, under the abatement scenario, non-coalition countries face lower global energy prices and higher prices for their energy-intensive exports. From a neo-classical perspective, it would seem that these direct impacts on comparative advantage would outweigh the negative impacts of higher import prices of goods produced by the coalition and lower incomes in export markets. This is not the case in the empirical Armington applications. The finding is important because much of the policy debate centers on the neo-classical intuition. The idea that non-coalition countries can free ride on the abatement of the coalition might need revision if the Armington structure is accepted.

In this study we consider two alternatives to the Armington structure and highlight the different conclusions that are reached. The neo-classical perspective is captured by assuming a homogeneous-goods trade structure where energy-intensive goods (like iron and steel) trade on world markets at a single price. Conclusions about changes in trade flows and the distribution of policy burdens are dramatically different relative to the Armington structure, even if the Armington trade elasticities are assumed to be very high. The empirical relevance of the homogeneous-goods model might be brought into question, however, because it only explains net trade abstracting from the observed gross trade (so called cross hauling). The other alternative to the Armington structure, the Melitz (2003) model of heterogeneous

[4] Relative to the reference scenario border carbon adjustments significantly shifted more burden toward the non-coalition.

[5] The model used in Balistreri and Rutherford (2012) considers a Melitz structure as an alternative to Armington. In Balistreri and Rutherford (2012) non-coalition welfare increases in the reference scenario. Our findings in that paper prompted our deeper exploration of carbon policy and the structure of trade in this paper.

firms, preserves the basic neo-classical implications: larger trade responses, more leakage, and a dramatic shift in the policy burden away from non-coalition exporters of energy intensive goods. Under the Melitz structure non-coalition exporters of energy-intensive goods enjoy a substantial welfare increase related to the competitive effects of coalition abatement. Under the Melitz structure non-coalition free riding on coalition abatement is reinforced by the competitive effects.

The paper is organized as follows: In Section 2 the alternative trade models are presented and their calibration is discussed. In Section 3 the climate policy experiment is implemented and results across the alternative structures are presented. Section 4 offers concluding remarks. All programs used to generate the results in this paper are available from the authors.

2 Models

Our analysis begins with three models calibrated to a common benchmark set of global social accounts. First, is a neo-classical model based on trade in homogeneous products, which is consistent with the principals of trade theory and forms the foundation for our views on competitive effects. Second is a model based on regionally differentiated goods consistent with the Armington assumption overwhelmingly adopted in the policy-simulation literature. Finally, we consider a monopolistic-competition model, consistent with Melitz (2003), which is the focus of international trade theories built around micro-level observations on competitive selection and firm-level export behavior.

2.1 Heckscher–Ohlin (H-O) Structure

The Heckscher-Ohlin (H-O) trade structure operates on a simple set of arbitrage conditions for homogeneous goods. The set of goods of interest for the alternative structures in our analysis is given by $i \in \{\texttt{CRP, NMM, I\_S, NFM}\}$, where

- `CRP`: Chemical, rubber, plastic products;
- `NMM`: Non-metallic mineral products;
- `I_S`: Ferrous metals; and
- `NFM`: Non-ferrous metals.

These represent the energy-intensive and trade-intensive sectors. These sectors are the most exposed to the competitive effects of sub-global carbon policy. We will refer to the structure that treats these four goods as homogeneous tradables as the H-O model, although technically our general equilibrium model departs significantly from the simple two-good, two-factor, two-country Heckscher-Ohlin model from trade theory. The key is that trade in the focus commodities is based on the principals of neo-classical trade theory with incomplete specialization.

The theory follows directly from the familiar arbitrage conditions. Let a region's export activity for commodity i be given by EX_{ir} and its import activity be given by IM_{ir}. Let the price of good i in region r be given by c_{ir}, which equals the marginal cost of production under our H-O assumption of perfect competition. With an export tax rate of tx_{ir}, the export activity will satisfy the condition that the gross of tax marginal cost equals the world-market price (PW_i). Some export activities might be slack, however, indicating that the gross of tax marginal cost is at or above the world-market price. To accommodate this situation we represent arbitrage using the following complementary-slack condition:

$$c_{ir}(1 + tx_{ir}) - PW_i \geq 0 \quad \perp \quad EX_{ir} \geq 0. \tag{1}$$

Where the *perp* symbol indicates the complementary slack relationship between the two expressions.[6] In words condition (1) reads as follows: if profitable the export activity will

[6]Mathematically our notation indicates the following three conditions embodied in (1): $c_{ir}(1 + tx_{ir}) - PW_i \geq 0$; $EX_{ir} \geq 0$; and $EX_{ir}\,(c_{ir}(1 + tx_{ir}) - PW_i) = 0$.

intensify to the point that profits are driven to zero, and if the export activity is unprofitable exports will be zero. We have a similar arbitrage condition for regional import activities,

$$(PW_i + \sum_j \phi_{jir} PT_j)(1 + tm_{ir}) - c_{ir} \geq 0 \quad \perp \quad IM_{ir} \geq 0, \tag{2}$$

although this is complicated by transport margins. In condition (2) tm_{ir} is the import tariff rate, PT_j is the price of transport service j, ϕ_{jir} are coefficients representing the cost markup paid to transport service j on the value of commodity i shipped to region r. Thus, in condition (2) arbitrage indicates that a region intensifies imports up to the point that the gross cost of importing equals the domestic marginal production cost. The transport services include air, water, and other, which we will denoted $j \in \{\texttt{ATP}, \texttt{WTP}, \texttt{OTP}\}$.

We finalize our description of the H-O formulation with the market clearance conditions. The world market prices for good i adjusts such that international markets clear:

$$\sum_r EX_{ir} = \sum_r IM_{ir}. \tag{3}$$

The trade activities are tied back to the domestic market through market clearance in the commodities that trade at c_{ir} within the region. Let Y_{ir} be the production quantity of good i in region r, and let Q_{ir} be the total of final and intermediate-input demand for good i in region r. Market clearance in region r of good i is then given by

$$Y_{ir} + IM_{ir} - EX_{ir} = Q_{ir}. \tag{4}$$

Conditional on the endogenous variables determined in the broader general equilibrium (Y_{ir}, Q_{ir}, and PT_j), the four equations, (1) through (4), determine the variables, EX_{ir}, IM_{ir}, PW_i, and c_{ir}, that describe the H-O trade equilibrium. This system allows us to numerically apply the foundational neoclassical trade theory. One feature of this structure, however, is that either the import or export activity will be slack in a given region for a given good under nontrivial trade costs. The model will not feature an equilibrium where a region both imports and exports a good. Two-way trade, or *cross hauling*, is, however, observed in all trade data. This presents a challenge for empirical application and calibration. In short, if we are to apply the H-O structure we have to modify the data to net out two-way trade from the gross flows, calibrating the model to net trade only.

2.2 Armington Structure

An alternative potential solution to the observation that countries engage in two-way trade is to consider that goods under the same industrial classification from different countries are not identical. This is the Armington (1969) assumption of regionally differentiated goods. Under this structure two-way trade is readily accommodated. Countries demand both domestic and foreign varieties which are imperfect substitutes. Calibration to observed trade is simply a matter of establishing preference weights that match the benchmark observation. Responses to relative price changes are then controlled through the assumed elasticity of substitution.

As the Armington assumption applies to numeric simulation models, consider a composite commodity that is the Constant Elasticity of Substitution (CES) aggregate of domestic and foreign varieties. Denote the price of this composite in region s as P_{is}. We will refer to P_{is} as the Armington price index which equalizes the minimized unit cost of the composite. Supply of the composite is governed by a competitive activity A_{is} that intensifies up to the point that marginal cost equals marginal benefit (given by P_{is}). In equilibrium we have

$$P_{is} = \psi_{is} \left[\sum_r \theta_{irs} \left[(1 + tm_{irs})[c_{ir}(1 + tx_{ir}) + \sum_j \phi_{jirs} PT_j] \right]^{1-\sigma_i} \right]^{\frac{1}{1-\sigma_i}}, \tag{5}$$

where the right-hand side is the minimized unit cost (marginal cost) of the composite as a function of regional prices (c_{ir}), transport costs, and the trade policy instruments. Equation (5) is empirically operationalized by setting values for the scale and distribution parameters, as well as the elasticity of substitution, σ_i. The true price index of good i in region s is reflected in P_{is}, and this is the price paid for intermediates or in final demand. Market clearance for the composite is thus given by

$$A_{ir} = Q_{ir}. \tag{6}$$

Market clearance for regional output must now account for bilateral demand, which we denote X_{irs} (where r is the source region and s is the sink region):

$$Y_{ir} = \sum_s X_{irs}. \tag{7}$$

The X_{irs} are conditional demands derived by scaling the right-hand side of equation (5) up to a cost function (by multiplying by A_{is}) and applying Shephard's Lemma:

$$X_{irs} = \psi_{is} A_{is} \theta_{irs} \left[\frac{P_{is}}{(1 + tm_{irs})[c_{ir}(1 + tx_{ir}) + \sum_j \phi_{jirs} PT_j]} \right]^{\sigma_i}. \tag{8}$$

Conditional on the variables determined in the broader general equilibrium (Y_{ir}, Q_{ir}, and PT_j), the four equations, (5) through (8), determine the variables, A_{ir}, X_{irs}, P_{is}, and c_{ir}, that describe the Armington trade equilibrium. Integrating these with the broader general equilibrium yields a model consistent with most simulation models used to examine climate policy.

2.3 Melitz Structure

In this section we describe the heterogeneous-firms trade structure as it is applied to the energy-intensive tradable sectors. As in the H-O and Armington structures, let demand for the sector i composite in region r be given by Q_{ir} which includes intermediate and final demand. In this case, however, Q_{ir} is demand for the Dixit-Stiglitz composite of firm-level varieties from around the world. On the supply side we again have production of Y_{ir} which has a unit cost of c_{ir}. In the Melitz structure we consider this a composite input which is used by the monopolistically competitive firms to cover variable costs, as well as the sunk costs associated with establishing the firm, and the bilateral fixed costs associated with operating in a given bilateral market.

The composite Q_{ir} (used in intermediate and final demand) is assumed to be made up of a continuum of firm varieties. Using the dual form, we specify the Dixit-Stiglitz price index for this composite commodity in region s (analogous to the Armington price index of regional varieties introduced in the previous section). Let $\omega_{irs} \in \Omega_{ir}$ index the differentiated i goods sourced from region r shipped into region s. Let $p_{irs}(\omega_{irs})$ be the gross price of variety ω_{irs} and let σ_i, again, be the constant elasticity of substitution between the varieties. The price index is given by

$$P_{is} = \left[\sum_r \int_{\omega_{irs}} [p_{irs}(\omega_{irs})]^{1-\sigma_i} d\omega_{irs} \right]^{\frac{1}{1-\sigma_i}}. \tag{9}$$

Melitz (2003) simplifies the price index by specifying the price optimally changed by a representative firm from region r supplying market s. Denote this price $\tilde{p}_{irs}$ which is the gross price set by the firm engaged in exporting from r to s that has the CES-weighted average productivity. Using this price, and scaling it up by the measure of the number of firms, N_{irs}, operating on the r to s link, we have Melitz's simplified price index:

$$P_{is} = \left[\sum_r N_{irs} (\tilde{p}_{irs})^{1-\sigma_i} \right]^{1/(1-\sigma_i)}. \tag{10}$$

Notice that trade costs and policy instruments do not enter equation (10), which is consistent with our definition of $\tilde{p}_{irs}$ as gross of these margins. Trade costs and trade policy distortions will enter the optimal markup equation. The quantity supplied by the average firm must satisfy demand which is derived by applying Shephard's Lemma:

$$\tilde{q}_{irs} = Q_{is} \left(\frac{P_{is}}{\tilde{p}_{irs}} \right)^{\sigma_i}. \tag{11}$$

Consider a small profit-maximizing firm facing this demand. Consistent with the large-group monopolistic competition assumption, the *small* firm does not consider its impact on the aggregate price index (P_{is}). Now, let c_{ir} indicate the price of the composite i input in region r, and let $\tilde{\varphi}_{irs}$ indicate the productivity of the firm (such that the marginal cost of production is $c_{ir}/\tilde{\varphi}_{irs}$). Setting marginal cost equal to marginal revenue yields the optimal markup condition for the average firm:

$$\tilde{p}_{irs} = \frac{c_{ir}\tau_{irs}(1 + t_{irs})}{(1 - 1/\sigma_i)\tilde{\varphi}_{irs}}, \tag{12}$$

where we introduce τ_{irs} as a calibrated *iceberg* trade cost factor. Equivalently, we could reinterpret τ_{irs} as a calibrated idiosyncratic taste bias [see Balistreri and Rutherford (2013)]. In that case the τ_{irs} act as quality adjustments that normalize the prices as they enter equation (10). The other introduced trade costs are the ad valorem tariff rates, given by t_{irs}.

To determine which firms operate in which market we need to identify the marginal firm (earning zero profits) in each bilateral market, and then relate the marginal firm to the average firm through a well specified productivity distribution. Let M_{ir} indicate the mass of region-r firms that are entered (in that they have incurred the sunk cost). These firms are assumed to receive their productivity draw from a Pareto distribution with probability density

$$g(\varphi) = \frac{a}{\varphi} \left(\frac{b}{\varphi} \right)^{a}; \tag{13}$$

and cumulative distribution

$$G(\varphi) = 1 - \left(\frac{b}{\varphi}\right)^{a}, \tag{14}$$

where a is the shape parameter and b is the minimum productivity. On each bilateral link there will be a productivity level φ^*_{irs} at which optimal pricing yields zero profits. A firm drawing φ^*_{irs} is the marginal firm. Firms drawing a productivity above φ^*_{irs} will earn positive profits and, therefore, operate. Firms drawing a productivity below φ^*_{irs} will choose not to operate on the r to s link.

Denoting the fixed cost (in composite input units) associated with operating on the r to s link as f_{irs}, the marginal firm earns zero profits at

$$c_{ir} f_{irs} = \frac{r(\varphi^*_{irs})}{\sigma_i(1 + t_{irs})}, \tag{15}$$

where $r(\varphi^*_{irs})$ is the revenue of the marginal firm which depends on the location of φ^*_{irs}. Following Melitz (2003), however, we simplify the model by defining all of the conditions in terms of the average firm, rather than the marginal firm. To do this we need to relate the productivities and revenues of the average firm relative to the marginal firm in each market. Noting that there will be $N_{irs}/M_{ir} = 1 - G(\varphi^*_{irs})$ firms operating we can integrate over that portion of the Pareto distribution to find the CES weighted average productivity $\tilde{\varphi}_{irs}$ as a function of the marginal productivity:

$$\tilde{\varphi}_{irs} = \left[\frac{a}{a + 1 - \sigma_i}\right]^{\frac{1}{\sigma_i - 1}} \varphi^*_{irs}. \tag{16}$$

Given the firm-level demand and pricing conditions [equations (11) and (12)] we can establish the ratio of the revenues of the average to the marginal firm:

$$\frac{r(\tilde{\varphi}_{irs})}{r(\varphi^*_{irs})} = \left(\frac{\tilde{\varphi}_{irs}}{\varphi^*_{irs}}\right)^{\sigma_i - 1}. \tag{17}$$

Equations (16) and (17) allow us to represent (15) purely in terms of the average firm. This is the key zero-cutoff-profits condition that determines the number of firms operating in each bilateral market:

$$c_{ir} f_{irs} = \frac{\tilde{p}_{irs} \tilde{q}_{irs}}{(1 + t_{irs})} \frac{(a + 1 - \sigma_i)}{a \sigma_i}. \tag{18}$$

As the optimal markup condition depends on $\tilde{\varphi}_{irs}$ we need to determine this in equilibrium. Given a value of the fraction of operating firms $N_{irs}/M_{ir} = 1 - G(\varphi^*_{irs})$, we can solve for φ^*_{irs} and substitute it out of (16):

$$\tilde{\varphi}_{irs} = b \left(\frac{a}{a + 1 - \sigma_i} \right)^{1/(\sigma_i - 1)} \left(\frac{N_{irs}}{M_{ir}} \right)^{-1/a}. \tag{19}$$

We now need to determine the measure of the total number of firms, M_{ir}. This is given by a free-entry condition that balances the sunk entry cost against the expected profits over the lifetime of the firm. Denote the sunk cost for region r in composite input units f^S_{ir}. Consistent with Melitz's steady-state equilibrium, a member of M_{ir} has some probability δ of death in every period. Then in the steady-state equilibrium δM_{ir} firms must be replaced each period at a total nominal cost of $\delta c_{ir} f^S_{ir} M_{ir}$. From the perspective of a given firm (with no discounting or risk aversion) the flow of expected profits would need to cover $\delta c_{ir} f^S_{ir}$. The expected profits in a given market are given by

$$\tilde{\pi}_{irs} = \frac{\tilde{p}_{irs} \tilde{q}_{irs}}{\sigma_i (1 + t_{irs})} - c_{ir} f_{irs}, \tag{20}$$

and the probability of operating in that market is N_{irs}/M_{ir}. The free-entry condition, that determines M_{ir}, equates expected profits across all markets with the sunk-cost payments:

$$c_{ir} \delta f^S_{ir} = \sum_s \frac{\tilde{p}_{irs} \tilde{q}_{irs}}{(1 + t_{irs})} \frac{(\sigma_i - 1)}{a \sigma_i} \frac{N_{irs}}{M_{ir}}, \tag{21}$$

where we have used the zero-cutoff-profit condition to substitute out the operating fixed costs. With this condition the heterogeneous-firms trade equilibrium is fully specified, but we still need a determination of demand for the composite input. The market clearance condition associated with c_{ir} must track the disposition of domestic output into the various sunk, fixed, and variable costs associated with each bilateral market. The market clearance condition is given as

$$Y_{ir} = \delta f_{ir}^{S} M_{ir} + \sum_{s} N_{irs} \left(f_{irs} + \frac{\tau_{irs} \tilde{q}_{irs}}{\tilde{\varphi}_{irs}} \right). \tag{22}$$

Conditional on regional composite demand and composite-input supply (Q_{ir} and Y_{ir}), equations (10), (11), (12), (18), (19), (21), and (22) determine the full set of variables associated with the Melitz trade equilibrium. The corresponding variables are the composite price index (P_{is}); average-firm prices, quantities, and productivities ($\tilde{p}_{irs}$, $\tilde{q}_{irs}$, and $\tilde{\varphi}_{irs}$); measures of the number of entered and operating firms (M_{ir}, and N_{irs}); and the price of the composite input (c_{ir}). Additional details on the heterogeneous-firms theory can be found in Melitz (2003) and Balistreri and Rutherford (2013).

2.4 Empirical Calibration

Apart from the alternative trade formulations the model is a standard multi-region multi-sector static representation of the global economy with detailed carbon accounting. We adopt the production structure outlined in Böhringer and Rutherford (2011) and calibrate the non-linear system to an aggregated version of the GTAP 7 data.[7] Table 1 indicates the aggregate regions, sectors, and primary factors of production.

The trade equations are calibrated to match the benchmark trade flows. This is relatively straightforward in the Armington and Melitz models. The bilateral parameters for each

[7] See Narayanan and Walmsley (2008) for a full documentation of the GTAP 7 data.

Table 1: Scope of the Empirical Model

Regions:		Goods:		Factors:	
EUR	Europe	OIL	Refined oil products	LAB	Labor
USA	United States	GAS	Natural Gas	CAP	Capital
RUS	Russia	ELE	Electricity	RES	Natural Resources
RA1	Rest of Annex 1	COL	Coal		
CHN	China	CRU	Crude Oil		
IND	India	CRP	Chemical, rubber, plastic		
EEX	Energy Exporting	NMM	Non-metallic minerals		
MIC	Middle-High Income	I_S	Ferrous metals		
LIC	Low Income Countries	NFM	Non-ferrous metals		
		ATP	Air Transportation		
		WTP	Water Transportation		
		OTP	Other Transportation		
		AOG	All other goods		

commodity [either θ_{irs} in equation (5) or τ_{irs} in equation (12)] are set to replicate the bilateral trade matrix. See Balistreri and Rutherford (2013) for additional details and discussion about the methods for trade calibration in the Armington and Melitz models.

For commodities modeled under the H-O structure the accounts are first adjusted to net out gross trade, so equation (4) is satisfied with either imports or exports for a given region equal to zero.[8] Given balanced accounts, the global quantity produced of the homogeneous goods will still equal global demand (we just eliminate the value of any cross hauling). There remain a few difficulties, however. By moving to net trade we are significantly altering (reducing and sometimes eliminating) the tax base for ad valorem trade distortions along with the flows associated with the transport margins. This generates an imbalance in government revenues and demand for transport services. To reconcile the benchmark we push any residual export taxes, which are eliminated once we move to net trade, upstream into the source

[8]The slack trade activities are calibrated to be unprofitable based on the observed trade costs (taxes and transport margins). If, however, the trade costs do not generate at least a 5% margin of unprofitability on the slack activity, a 5% margin is inserted. This allows for trade reversals in counterfactuals, but does not generate trade reversals from trivial (less than 5%) changes in relative prices.

country market for the particular commodity. Similarly, we push any residual import tariffs, which are eliminated once we move to net trade, downstream into the destination market for the particular commodity. So, for example, if we originally observe a 10% tariff on \$100 of steel imports, but the trade flow drops to \$50 when we look at net trade; then the new trade flow only generates \$5 of revenue. To reconcile this, the commodity tax on steel in the destination market is escalated such that it generates an addition \$5 of revenue. This maintains the original \$10 of revenue for the government. The same adjustment is made for transport margins. The ad valorem transport margin is maintained, but to the extent that imports are reduced, the residual demand for transport services (needed to maintain market clearance) is added as a Leontief complement to destination regional demand for the commodity in question. The goal of this calibration strategy is to maintain the trade margins, as ad valorem wedges, at the cost of manipulating domestic distortions. This choice is consistent with our focus on the trade structure, in this study, and maintaining consistent ad valorem benchmark distortions across the alternative structures.

Calibrating the trade *responses* in the Armington and Melitz models is an additional critical issue to consider. Table 2 indicates the trade elasticities. For the energy-intensive goods we consider three different sets of values for the Armington elasticities. In the low-Armington case we adopt the values from the GTAP database for substitution between imports and domestic goods. In the central case we adopt $\sigma_i = 5.58$, which is consistent with the same local response indicated in a simple Melitz model with $a_i = 4.58$. The value of a_i is estimated by Balistreri et al. (2011), and the argument that σ_i should be set at $a_i + 1$ to replicate trade responses is given by Arkolakis et al. (2008). In the high-Armington case we take the suggested value and double it: $\sigma_i = 2(a_i+1)$. All other sectors are held at consistent trade responses across the variations. Most of these values are adopted from the GTAP data. Crude oil is always treated as a homogeneous good, consistent with the estimates of σ_{CRU} in Balistreri et al. (2010a) of over 20. In addition, there is a single type of transport good

Table 2: Trade response parameters (σ_i unless otherwise noted)

	Armington			**H-O**	**Melitz**	
	Low	Central	High		σ_i	a_i
Energy Intensive Tradables:						
`CRP`	3.30	5.58	11.16	∞	3.30	4.58
`NMM`	2.90	5.58	11.16	∞	2.90	4.58
`I_S`	2.95	5.58	11.16	∞	2.95	4.58
`NFM`	4.20	5.58	11.16	∞	4.20	4.58
Other goods:						
`AOG`	2.54	2.54	2.54	2.54	2.54	
`CRU`	∞	∞	∞	∞	∞	
`COL`	3.05	3.05	3.05	3.05	3.05	
`GAS`	11.48	11.48	11.48	11.48	11.48	
`OIL`	2.10	2.10	2.10	2.10	2.10	
`ELE`	2.80	2.80	2.80	2.80	2.80	
`ATP`	∞	∞	∞	∞	∞	
`WTP`	∞	∞	∞	∞	∞	
`OTP`	∞	∞	∞	∞	∞	

for each mode available on the world market, but this is a Cobb-Douglas composite of each region's supply. Details of the transport formulation are given in Böhringer and Rutherford (2011).

3 Experiment and Results

We center our comparison of the alternative trade structures around a scenario that is widely studied in the numeric simulation literature. The experiment entails CO_2 mitigation by a coalition of developed countries (Annex I except Russia) where a global emissions target is achieved. The target is set at benchmark global emissions less 20% of benchmark coalition emissions. Given carbon leakage this indicates abatement by the coalition at something more than 20%. By holding the global target fixed we are able to make fair comparisons

Table 3: Regional welfare impacts of reference scenario across structures (% Equivalent Variation)

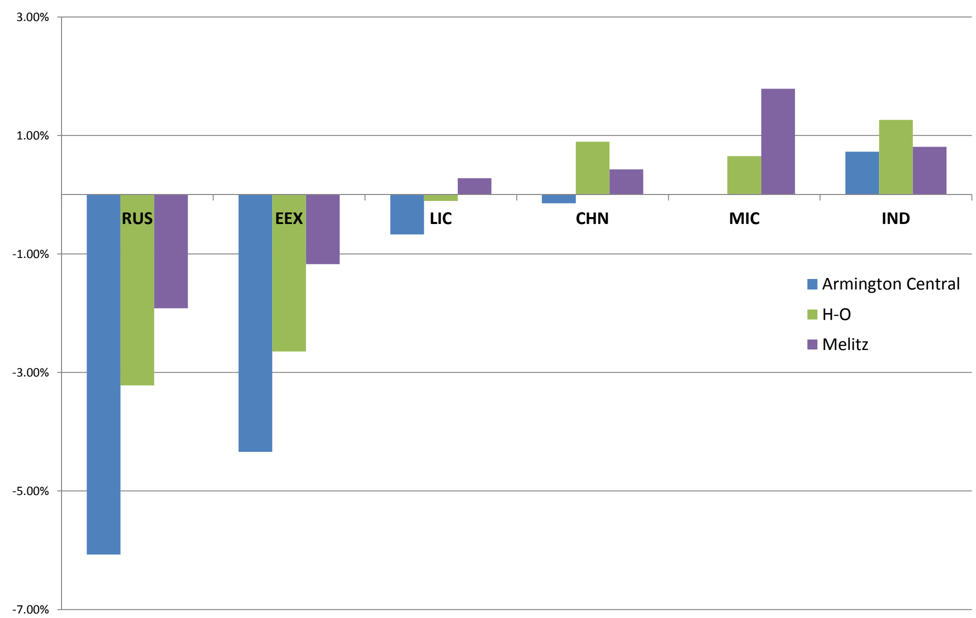
Region	Cons. ($B)	Change (%EV)		
		Armington	**H-O**	**Melitz**
Coalition				
`USA`	8267	-0.18	-0.57	-0.66
`EUR`	8075	-0.40	-0.74	-0.83
`RA1`	3914	-0.43	-0.78	-1.41
Non-Coalition				
`MIC`	2330	0.01	0.65	1.79
`EEX`	848	-4.34	-2.65	-1.17
`CHN`	796	-0.15	0.89	0.43
`IND`	434	0.73	1.26	0.81
`LIC`	349	-0.67	-0.10	0.28
`RUS`	292	-6.07	-3.22	-1.92

of mitigation costs over a common environmental outcome.[9] Our central measure of cost is regional Equivalent Variation on private consumption. Table 3 presents the percentage Equivalent Variation for the abatement scenario across the different trade structures. One finding that is immediately apparent is that, relative to the Armington structure, both the H-O and Melitz structures indicate elevated coalition costs of achieving the environmental goal. These elevated costs are the result of elevated leakage and, in the case of the Melitz structure, an adverse productivity impact in the coalition.

The non-coalition welfare impacts across structures are of considerable interest. The Armington structure indicates substantially more shifting of the policy burden onto non-coalition regions. We highlight these impacts in Figure 1. While the regions heavily dependent on energy exports (`EEX` and `RUS`) experience policy costs regardless of the trade structure, these costs are less under H-O or Melitz trade. There is considerably more opportunity to relocate production toward energy intensive goods, under the H-O and Melitz structures, which

[9]For simplicity we assume that environmental benefits, which accrue to the regional agents, is directly related to total global abatement, and that the environmental benefit is separable in welfare.

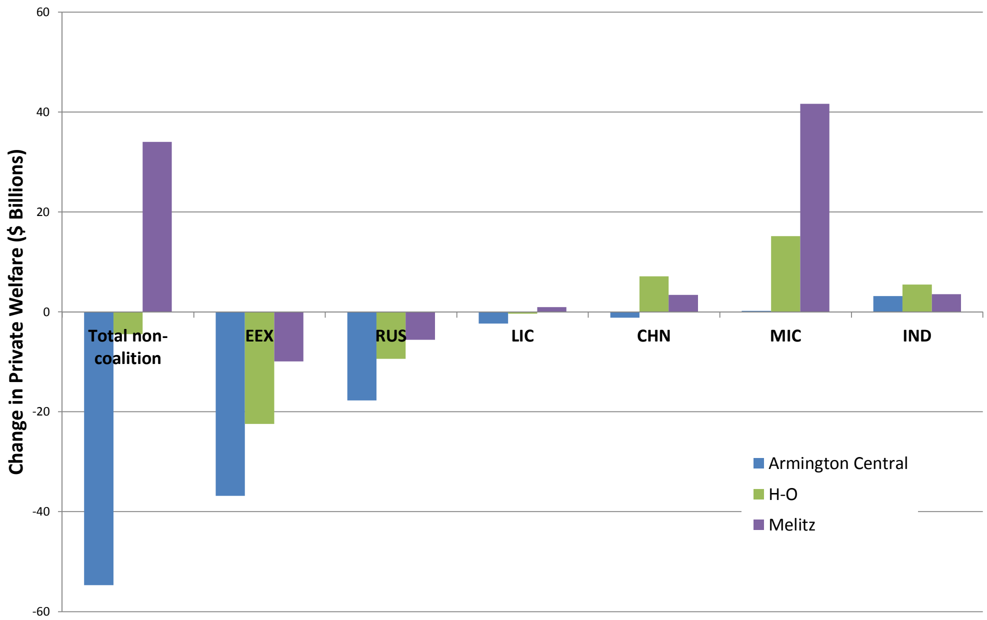
Figure 1: Non-coalition burdens across structures (% EV)



mitigates the policy burden. Trade in energy is more easily converted into trade in products that embody energy under the H-O and Melitz structures.

The differences across structural assumptions are even more dramatic for the non-coalition manufacturing based economies. For example, under the Armington structure China experiences a slight loss in the scenario. While China experiences lower global energy costs and a competitive advantage in its energy intensive exports, it experiences an adverse terms-of-trade shift as imports of coalition varieties become more costly and incomes fall. The hysteresis inherent in the Armington structure indicates that the negative impacts of coalition abatement dominate for China. In contrast, under the H-O structure we show substantial gains for China when the coalition engages in CO_2 mitigation. China's energy intensive industries expand and trade patterns adjust such that it is able to avoid substantial adverse effects. We also show substantial gains for middle-income countries under the H-O trade structure (which are not available under Armington), and even more dramatic gains for

Figure 2: Non-coalition burdens across structures (Money Metric $B)



middle-income countries under the Melitz structure.

In Figure 2 we convert the non-coalition welfare changes into *money metric* measures. This allows us to aggregate the impacts. Focusing on the total non-coalition money-metric welfare changes we can see the dramatic impact our alternative structural assumption have on conclusions about policy burdens. Under the Armington structure the burden on non-coalition regions is measured to be about \$55 billion (1.1% of benchmark consumption) and under the H-O structure this drops to less than \$5 billion. Given the productivity improvements under the Melitz structure the policy burden is reversed, and we measure a \$35 billion welfare increase for the non-coalition countries in total. Our perspective on which trade structure holds must have a substantial impact on the prospects for international negotiations. The dramatic shifts in the policy burdens we show indicate that, without taking a stance on the correct structure, we are uncertain of even the qualitative nature of non-coalition burden sharing.

The substantial differences in welfare impacts across structures are largely driven by differences in the predicted global reallocation of energy intensive production. Table 4 and Figure 3 show the changes in regional production of energy-intensive goods.[10] The most dramatic shifts in output away from the coalition countries is seen under the H-O structure (a loss of $238.8 billion in sales), closely followed by the Melitz structure (a loss of $190.7 billion in sales). In contrast demand for the unique regional Armington varieties are maintained, such that we only show a $78.1 billion loss in coalition sales of energy intensive goods. Production of energy intensive goods increases in the non-coalition regions in response to the competitive advantage that coalition abatement affords. Again this response is sensitive to the structural assumptions, with the most limited response under Armington. It is very interesting to consider the global change in the value of energy-intensive production (shown in the final row of Table 4). Relative to the Armington structure, there is little change in the value of energy-intensive goods produced under the H-O and Melitz structures. Again, the indication is that there is significant hysteresis with regional Armington varieties. With perfect substitute products (H-O) or firm-level varieties (Melitz) the general equilibrium shows substantially more locational redistribution of energy intensive production in response to subglobal climate policy.

The global redistribution of energy-intensive production translates into changes in the trade equilibrium. Table 5 shows the changes in the values of energy-intensive exports by region, and Table 6 shows a decomposition of these results into the effects on each of the four energy-intensive commodities. Note that the first columns in Tables 5 and 6 indicate benchmark trade flows under the H-O structure, and the second columns indicate the actual benchmark trade flows used as the benchmark for the Armington and Melitz structures. Again, these benchmark flows are different because the H-O model operates on net trade

[10] Output is measured in value (price times quantity) where prices are measured relative to the weighted average of the regional consumer price indexes. That is, we define the numeraire as the consumption-weighted average of the regional true-cost-of-living indexes.

Table 4: Changes in the value of energy-intensive output ($B)

		Change ($B)		
	Benchmark	**Armington**	**H-O**	**Melitz**
Coalition	3861.8	-78.1	-238.8	-190.7
`USA`	1084.0	-32.2	-123.6	-70.2
`EUR`	1819.5	-20.6	-59.7	-49.1
`RA1`	958.3	-25.4	-55.5	-71.4
Non-Coalition	2263.5	51.4	228.6	186.1
`MIC`	823.8	19.8	63.6	80.8
`EEX`	204.5	14.1	55.9	59.7
`CHN`	967.2	2.8	44.7	6.6
`IND`	118.7	1.3	11.6	0.9
`LIC`	47.1	2.0	16.1	7.4
`RUS`	102.2	11.3	36.7	30.8
Global	6125.3	-26.7	-10.2	-4.5

Figure 3: Energy-intensive production across structures ($B)

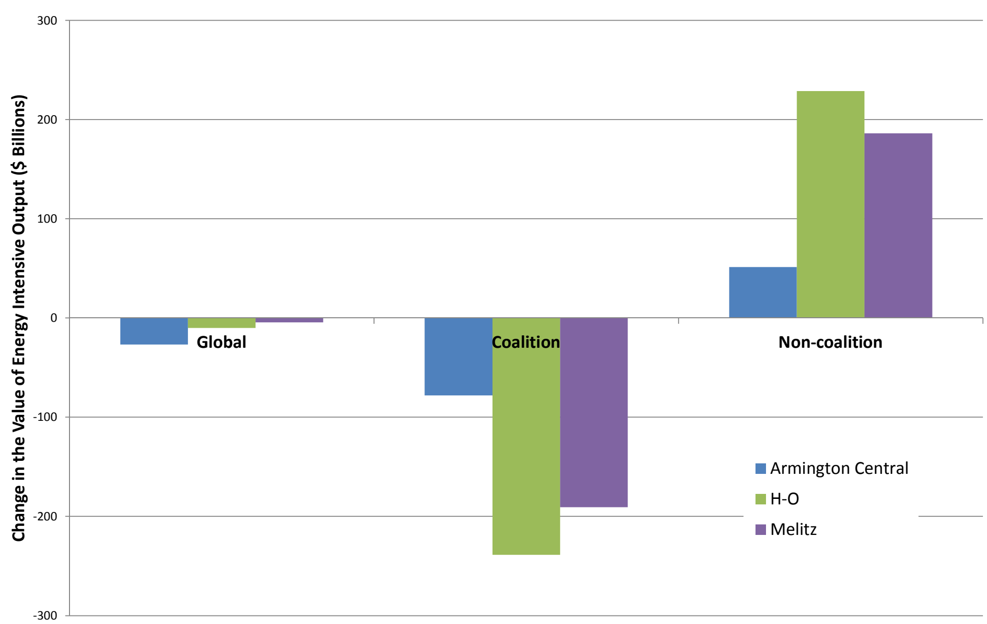


Table 5: Changes in the value of energy-intensive exports ($B)

	Benchmark (H-O)	Benchmark	Change ($B) **Armington**	**H-O**	**Melitz**
Coalition	132.1	641.2	-31.6	-82.6	-73.0
USA	6.0	178.9	-13.0	-6.0	-26.0
EUR	89.3	262.0	-7.1	-39.7	-15.7
RA1	36.8	200.2	-11.6	-36.8	-31.3
Non-Coalition	54.5	427.1	27.9	98.8	113.2
MIC	12.2	200.9	7.9	18.2	43.3
EEX	0.4	70.7	7.4	16.6	33.5
CHN	6.5	79.8	2.9	25.7	7.8
IND	1.6	18.8	0.8	7.9	1.4
LIC	2.8	11.1	0.9	2.9	4.5
RUS	31.0	45.7	8.0	27.5	22.7
Global	186.6	1068.3	-3.8	16.2	40.2

and cannot accommodate observed cross hauling (if there are transport costs). While the H-O model starts from a smaller set of benchmark flows, the perfect substitutes formulation indicates changes in trade flows that are in the range of magnitudes shown under the Melitz structure, and are much larger than the changes indicated under the Armington structure. It is interesting to note that under Armington the global value of trade in energy-intensive goods is actually reduced. This seems counterintuitive, because we would expect subglobal climate policy to intensify the use of international markets in energy intensive goods. Under Armington the substantial reduction in coalition exports of energy intensive goods is not offset by increases in non-coalition exports. The H-O and Melitz models show the expected change with substantial increases in the use of international markets.

In Table 6 the details of the trade equilibrium are revealed. Notice first that moving to net trade under the H-O structure dramatically changes the benchmark. For example, we see that Russia is the only non-coalition region that is a net exporter of chemical, rubber, and plastic products. Moving to net trade reduces non-coalition exports of chemical, rubber, and plastic products from \$234.7 billion to \$2.2 billion. This is an unappealing adjustment in the data, and it highlights the challenge of bringing the traditional theory to the data. The Armington structure is immediately appealing as a solution to this challenge, but looking at the changes in exports we see substantial hysteresis in the pattern of trade. While the Armington structure might perform well local to the benchmark, it fails to represent significant disruptions in the pattern of trade. The Melitz structure with firm-level differentiated products, in contrast, is both able to accommodate the observed pattern of trade and can show responses to structural shocks that dramatically change the pattern of trade. For example, we see very small changes in iron and steel exports under the Armington structure, but under the Melitz structure there are major shifts in the pattern of trade. Under Armington, middle-income countries respond to coalition abatement by increase iron and steel exports by \$2.9 billion (an 8% increase), where as under the Melitz structure they ramp up iron and steel exports by \$32.0 billion (a 93% increase). Critically, both structures are parameterized to generate the same local trade response (the Pareto shape parameter is set equal to the Armington elasticity minus one). Similar local responses do not translate to the same policy impacts when the structures are different.

One might consider the differences observed between the Armington and Melitz structures and conclude that the Armington parameterization might be modified to better approximate trade and productivity responses.[11] To explore the sensitivity of the Armington structure to alternative parameterizations we present the welfare impacts of the abatement scenario for Low, Central, and High values of the elasticity of substitution between regional varieties. In

[11] Arkolakis et al. (2008) and Arkolakis et al. (2012) show a set of equivalence results indicating that the Armington structure can be parameterized to replicate the trade responses and welfare impacts of the Melitz structure. The conditions for equivalence are difficult to meet in an empirical simulation model of climate policy. Examples of the restrictions that would be difficult to reconcile with an empirical application include a single sector (or trivially symmetric multiple sectors) and no intermediate inputs. It is relatively easy to break the equivalence results once we move away from the sterile theoretic models. See Balistreri et al. (2010b), Costinot and Rodríguez-Clare (2015), and Melitz and Redding (2015) for additional discussion of the equivalence results.

Table 6: Detailed energy-intensive trade responses (Exports $B)

			Change ($B)		
	Benchmark (H-O)	Benchmark	**Armington**	**H-O**	**Melitz**
		CRP: Chemical, rubber, plastic products			
Coalition	84.5	445.6	-18.0	-34.9	-28.8
USA	6.0	145.2	-9.8	-6.0	-19.0
EUR	77.5	191.8	-3.8	-27.9	-5.4
RA1	1.0	108.7	-4.4	-1.0	-4.5
Non-Coalition	2.2	234.7	9.6	9.5	32.1
MIC		114.4	1.7		-0.9
EEX		47.2	4.5		22.1
CHN		44.7	0.6		4.0
IND		11.2	0.3		0.5
LIC		3.5	0.3		0.7
RUS	2.2	13.8	2.2	9.5	5.6
Global	86.7	680.3	-8.4	-25.4	3.2
		NMM: Non-metallic mineral products			
Coalition	9.6	35.8	-2.2	-9.6	-2.5
USA		7.1	-0.7		-1.2
EUR	7.6	17.0	-0.8	-7.6	-0.8
RA1	1.9	11.7	-0.7	-1.9	-0.4
Non-Coalition	7.2	26.4	2.3	27.2	4.6
MIC		9.8	1.0		1.8
EEX		3.8	0.4		0.7
CHN	6.5	10.2	0.7	25.7	1.7
IND	0.7	1.3	0.1	1.5	0.2
LIC		0.7	0.1		0.1
RUS		0.6	0.1		0.1
Global	16.8	62.2	0.1	17.6	2.2
		I_S: Ferrous metals			
Coalition	25.6	77.6	-6.9	-25.6	-27.0
USA		10.3	-0.9		-1.7
EUR	4.2	26.8	-1.6	-4.2	-5.4
RA1	21.4	40.5	-4.5	-21.4	-19.9
Non-Coalition	14.8	74.1	8.4	21.1	46.8
MIC		34.3	2.9		32.0
EEX		6.7	0.9		3.6
CHN		12.1	0.9		0.8
IND	0.8	4.1	0.3	6.4	0.6
LIC		1.1	0.1		0.5
RUS	13.9	15.8	3.1	14.7	9.3
Global	40.4	151.7	1.5	-4.5	19.8
		NFM: Non-ferrous metals			
Coalition	12.5	82.1	-4.6	-12.5	-14.7
USA		16.3	-1.7		-4.1
EUR		26.5	-0.8		-4.1
RA1	12.5	39.4	-2.1	-12.5	-6.4
Non-Coalition	30.3	92.0	7.6	41.0	29.8
MIC	12.2	42.6	2.3	18.2	10.4
EEX	0.4	13.1	1.5	16.6	7.1
CHN		12.8	0.6		1.4
IND		2.3	0.0		0.0
LIC	2.8	5.8	0.5	2.9	3.1
RUS	14.8	15.4	2.7	3.3	7.8
Global	42.8	174.1	3.0	28.5	15.1

Table 7: Armington model sensitivity to elasticities (% EV)

Region	Cons. ($B)	Armington Low	Armington Central	Armington High
Coalition				
USA	8267	-0.11	-0.18	-0.29
EUR	8075	-0.36	-0.40	-0.48
RA1	3914	-0.35	-0.43	-0.56
Non-Coalition				
MIC	2330	-0.14	0.01	0.26
EEX	848	-4.68	-4.34	-3.77
CHN	796	-0.23	-0.15	0.02
IND	434	0.70	0.73	0.78
LIC	349	-0.71	-0.67	-0.57
RUS	292	-6.70	-6.07	-5.12

Table 7 we see a relatively continuous and predictable departure from the central results when we vary the Armington elasticities. This indicates that one cannot simply reparameterize the Armington model to replicate the Melitz results. At the extreme of an elasticity of substitution equal to infinity the Armington structure should be consistent with a H-O theory. The problem with exploring this limit is that the Armington structure calibrated to gross trade flows becomes unstable relative to the H-O model, which is calibrated to net trade flows. In the High elasticity case (where the elasticity of substitution is set above 11 for the energy-intensive goods) we do not see a substantial convergence between the Armington and H-O models, although the welfare changes in the High Armington case are all between the central and H-O cases. For example, percent EV for China is -0.15 for the Central Armington case, 0.02 for the High Armington case, and 0.89 for the H-O case. Overall, when we set the Armington elasticities at even extreme values, relative to the literature, we find substantial differences across structures.

Carbon leakage is a central focus of economists and policy makers interested in climate policy. In Table 8 we compare the leakage rates across structures. Leakage rates are highest

Table 8: Carbon Leakage (%)

	Armington			H-O	Melitz
	Low	Central	High		
Total	**13.4**	**14.9**	**17.3**	**23.5**	**21.8**
Decomposed by non-coalition region					
MIC	5.0	5.2	5.6	5.2	7.2
EEX	2.3	2.8	3.6	5.3	5.8
CHN	2.3	2.5	2.8	4.7	2.3
RUS	1.5	2.0	2.7	4.2	4.0
IND	1.2	1.3	1.4	2.0	1.1
LIC	1.0	1.1	1.2	2.0	1.3

under the H-O structure at 23.5% and lowest under the Armington Low-elasticity case at 13.4%. The differences across structures largely reflect the implied reallocation of energy-intensive production across the globe. Consistent with Table 4 and Figure 3 we see the highest leakage rates when there is more movement of energy-intensive production to non-coalition regions through the competitive-effects channel. Also consistent with the production results, notice that under the H-O structure China plays a much larger role in leakage and under the Melitz structure leakage is dominated by the middle-income region. Given the initial base in energy-intensive manufacturing the middle-income countries are more easily able to move resources into the Melitz sectors, where as under the H-O assumption China specializes, and dominates, the international Non-metallic Mineral Products markets (see Table 6). Given firm-level differentiation, there is less incentive to specialize under the Melitz structure.

4 Conclusion

In this paper we explore the sensitivity of conclusions about the impact of climate policy to alternative perspectives on the structure of international trade. We adopt three compelling structures for trade in energy-intensive goods. First is a model based on trade in homogeneous products consistent with traditional trade theories. Second is the Armington model of trade in regionally differentiated goods, which is widely adopted in the policy simulation literature. Third is the Melitz (2003) structure of monopolistic competition among heterogeneous firms producing unique varieties. These structures are compared in the context of a subglobal climate policy that indicates carbon leakage and international competitive effects. We find significant differences across these structures and highlight the sensitivity of policy conclusions.

Under the homogeneous-products and Melitz structures substantially larger shifts in the pattern of trade are recorded, relative to the Armington structure. This indicates significantly higher carbon leakage rates. We caution that studies adopting the Armington structure might be understating the competitive effects and carbon leakage associated with subglobal emissions abatement. Even with artificially inflated trade elasticities the Armington model generates lower leakage rates than the other two models. Dramatic action on carbon emissions likely moves us far enough away from the local point of calibration that the Armington model loses its ability to accurately characterize trade.

The most important finding is that the empirically appealing Melitz structure indicates a qualitative change in the welfare impacts in the non-coalition. Competitive effects in the Melitz structure are intensified by productivity changes. Private consumption increases in the non-coalition countries that export energy-intensive goods. This is in contrast to the Armington model, which indicates non-coalition losses. The Armington model seems out of line with the conventional intuition. Lower energy costs and higher prices for energy-intensive exports are expected to boost welfare in the non-coalition manufacturing economies. We show that this expectation is supported in the Melitz structure, but not in the Armington structure. We see our implementation of the Melitz structure as an important innovation that deserves consideration in the broader modeling community. At a minimum, we should acknowledge the potential limitations of the Armington structure.

References

Anderson, James E. (1979) 'A theoretical foundation for the gravity equation.' *The American Economic Review* 69(1), 106–116

Arkolakis, Costas, Arnaud Costinot, and Andrés Rodríguez-Clare (2012) 'New trade models, same old gains?' *American Economic Review* 102(1), 94–130

Arkolakis, Costas, Svetlana Demidova, Peter J. Klenow, and Andrés Rodríguez-Clare (2008) 'Endogenous variety and the gains from trade.' *American Economic Review: Papers & Proceedings* 98(2), 444–450

Armington, Paul S. (1969) 'A theory of demand for products distinguished by place of production.' *Staff Papers - International Monetary Fund* 16(1), 159–178

Babiker, Mustafa H. (2005) 'Climate change policy, market structure, and carbon leakage.' *Journal of International Economics* 65(2), 421 – 445

Balistreri, Edward J., and Thomas F. Rutherford (2012) 'Subglobal carbon policy and the competitive selection of heterogeneous firms.' *Energy Economics* 34, Supplement 2(0), S190 – S197

_ (2013) 'Computing general equilibrium theories of monopolistic competition and heterogeneous firms.' In *Handbook of Computable General Equilibrium Modeling: Vol 1B,* ed. Peter B. Dixon and Dale W. Jorgenson (Elsevier) chapter 23, pp. 1513 – 1570

Balistreri, Edward J., Ayed Al-Qahtani, and Carol A. Dahl (2010a) 'Oil and petroleum product Armington elasticities: A new-geography-of-trade approach to estimation.' *The Energy Journal* 31(3), 167 – 179

Balistreri, Edward J., Russell H. Hillberry, and Thomas F. Rutherford (2010b) 'Trade and welfare: Does industrial organization matter?' *Economics Letters* 109(2), 85 – 87

_ (2011) 'Structural estimation and solution of international trade models with heterogeneous firms.' *Journal of International Economics* 83(2), 95 – 108

Böhringer, Christoph, and Thomas F. Rutherford (2011) 'General equilibrium analysis based on GTAP in GAMS: Method, data, application.' Technical Report, University of Oldenburg and ETH Zürich

Böhringer, Christoph, Edward J. Balistreri, and Thomas F. Rutherford (2012) 'The role of border carbon adjustment in unilateral climate policy: Overview of an energy modeling forum study (emf 29).' *Energy Economics* 34, Supplement 2(0), S97 – S110

Brown, Drusilla K. (1987) ‘Tariffs, the terms of trade, and national product differentiation.’ *Journal of Policy Modeling* 9(3), 503–526

Costinot, Arnaud, and Andrés Rodríguez-Clare (2015) ‘Trade theory with numbers: Quantifying the consequences of globalization.’ In *Handbook of International Economics: Vol. 4,* ed. Elhanan Helpman, Kenneth Rogoff, and Gita Gopinath (Elsevier) chapter 4, pp. 197 – 261

Eaton, Jonathan, and Samuel Kortum (2002) ‘Technology, geography, and trade.’ *Econometrica* 70(5), 1741–1779

Kehoe, Timothy J. (2005) ‘An evaluation of the performance of applied general equilibrium models of the impact of NAFTA.’ In *Frontiers in Applied General Equilibrium Modeling: Essays in Honor of Herbert Scarf,* ed. Timothy J. Kehoe, T.N. Srinivasan, and John Whalley (Cambridge University Press) pp. 341–377

Krugman, Paul (1980) ‘Scale economies, product differentiation, and the pattern of trade.’ *The American Economic Review* 70(5), 950–959

Libecap, Gary D. (2014) ‘Addressing global environmental externalities: Transaction costs considerations.’ *Journal of Economic Literature* 52(2), 424–79

McDaniel, Christine A., and Edward J. Balistreri (2003) ‘A review of Armington trade substitution elasticities.’ *Économie Internationale* (94-95), 301–314

Melitz, Marc J. (2003) ‘The impact of trade on intra-industry reallocations and aggregate industry productivity.’ *Econometrica* 71(6), 1695–1725

Melitz, Marc J., and Stephen J. Redding (2015) ‘New trade models, new welfare implications.’ *American Economic Review* 105(3), 1105–46

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

Nordhaus, William (2015) ‘Climate clubs: Overcoming free-riding in international climate policy.’ *American Economic Review* 105(4), 1339–70