Doctoral Thesis

Three essays on International trade policy and welfare

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THREE ESSAYS ON INTERNATIONAL TRADE POLICY AND WELFARE

A dissertation submitted to

ETH ZURICH

for the degree of

Doctor of Sciences

presented by

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2012
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1 Abstract

This thesis is a collection of three essays in international trade. The thesis broadly addresses various aspects of trade related policies and their effects on consumer welfare. In the first chapter, I examine how global trade liberalization would affect different consumers and countries in terms of real welfare, inequality and international trade. For that, I develop a multi-country model of international trade with heterogeneous consumers and non-homothetic preferences. I use the model to quantify the bias in the conventional estimates of gains from trade calculated under the assumption of a representative consumer. The model predicts heterogeneous income and price effects that are translated into consumer-specific welfare gains and further quantified in a counterfactual trade liberalization experiment. I find that conventional measures, such as average real income per capita, are adequate welfare measures mostly for consumers in the right tail of the income distribution. This measure overestimates the gains from global trade liberalization by up to 9% and 88% for the median and the poorest consumer, respectively. In terms of the aggregate country-level welfare gains, the measurement error is between -6% and 8% in the utilized experiment.

The second chapter (coauthored with Peter Egger) quantifies the effect of asymmetry in trade costs on the world income distribution. Earlier work by Waugh (2010) suggests that asymmetric market access costs across exporting countries are a major reason for differences in real per-capita income around the globe: 20% – 33% (depending on the measure) of world income inequality could be explained by cross-country trade cost asymmetries alone. We show that these results were driven by what we call model under-specification, an ill-suited model calibration which fails to match data on per-capita incomes well enough, and a counterfactual experiment inconsistent with the theoretical model and the idea of a reduction in country-specific market access cost asymmetries as such. We use the same (Eaton-Kortum-type) structural model and data, estimate all model parameters while respecting general equilibrium constraints, and calibrate it to the data. The obtained results suggest a largely different picture: the complete abolition of exporter-specific trade cost asymmetries leads to no more than a 1.5% – 6% reduction in the income inequality around the globe. Moreover, in the presence of large trade imbalances, a reduction in such trade cost asymmetries may even have a detrimental effect on income equalization between poor and rich countries.

In the concluding third chapter (coauthored with Peter Egger), we quantitatively assess the impact of alternative environmental policies on energy demand, global $CO_2$ emissions, trade, and welfare. For this, we develop a structural Eaton-Kortum type general equilibrium model of international trade which includes an energy sector. We estimate the key parameters of that model and calibrate it to domestic prices and production using data for 31 OECD countries and the rest of the world in the year 2000. The model helps assessing the relative welfare effects under alternative environmental policies. We find that, when negative externalities on foreign countries from energy consumption are absent, taxing energy resources as an input in energy production is preferable to taxing domestic energy production in terms of minimizing $CO_2$ emissions subject to a given welfare change.
However, with negative externalities on foreign customers domestic energy output should be taxed to minimize world $CO_2$ emissions given a certain level of welfare change for all countries. We also find that border tax adjustment leads to an increase in world emissions of $CO_2$. This finding suggests that this often advocated measure against carbon leakage is not necessarily optimal in general equilibrium with international externalities.
Zusammenfassung

Diese Dissertation umfasst drei Essays, die verschiedene Aspekte der Außenhandelspolitik und deren Auswirkungen auf die Wohlfahrt der Verbraucher behandeln.

Im ersten Kapitel untersuche ich die Effekte einer Handelsliberalisierung für die reale Wohlfahrt, die wirtschaftliche Ungleichheit der Haushalte und die internationalen Handelsströme. Dafür entwickle ich ein Multi-Länder-Modell des internationalen Handels mit heterogenen Konsumenten und nicht-homothetischen Präferenzen. Ich benutze das Modell, um die Verzerrungen in den herkömmlichen Schätzungen der Handelsgewinne, welche unter der Annahme eines repräsentativen Konsumenten berechnet werden, zu quantifizieren. Das Modell prognostiziert heterogene Einkommens- und Preiseffekte, die in konsumentenspezifische Wohlfahrtsgewinne übersetzt werden und dann mit einem kontrafaktilchen Handelsliberalisierungsexperiment quantifiziert werden. Die Ergebnisse zeigen, dass konventionelle erklärende Variablen, wie beispielsweise das durchschnittliche Realeinkommen pro Kopf, nur für die Verbraucher im rechten Teil der Einkommensverteilung Aussagekraft besitzen. Diese Variablen überschätzen die Gewinne einer globalen Handelsliberalisierung um bis zu 9 zu 88 herkömmliche Maßstäbe zwischen -6% und 8%.


2 Introduction

This thesis consists of three chapters that assess the effects of different trade policy instruments on domestic economic variables such as consumer welfare and income inequality, as well as on global outcomes, such as the world income distribution and the environment. The three chapters share a common methodological approach. The policy effects are calculated using multi-industry, multi-country, general-equilibrium models of trade calibrated to real data.

In the first chapter, I examine how trade liberalization affects different consumer groups. I argue that it is elemental to calculate potential gains from trade for each consumer. I show that one must use aggregate measures of welfare such as average real income per capita with caution for two reasons. First, it is well established that different income groups have different consumption patterns. While the rich are more likely to consume luxury goods, the poor spend large share of their income on food. This tendency is particularly evident in developing economies. I argue that these large differences in consumption patterns must be taken into account when evaluating potential welfare gains from trade. Second, individuals also vary in their income structure. The rich own a lot of capital and do not depend much on governmental transfers. On the other hand, income of the poor may almost entirely consist of redistributional transfers and rebates. Trade liberalization is likely to affect both factor prices and size of government tariff revenues. This heterogeneity in the structure of income must also be considered when evaluating potential effects of trade liberalization policies. To capture both the price and income dimension of heterogeneity, I introduce non-homotheticity of preferences and country-specific distribution of capital. To the best of my knowledge, this paper is the first to introduce both margins of heterogeneity into a multi-country model of trade. I calibrate the model to real data on 92 countries. The model closely fits the data on GDP, income distribution and bilateral trade flows. I quantify the gains from global abolishment of tariffs for different consumer
groups. The results indicate that commonly accepted measures of welfare gains, such as changes in average real income per capita, accurately reflect changes in welfare for rich consumers only. Otherwise, using such measures entails large errors on both aggregate and individual levels.

In the second chapter, we assess the role of asymmetric trade costs in shaping the world income distribution. For that, we first develop a novel approach of estimating structural gravity equations. New trade models, such as Eaton and Kortum (2002), provide elegant ways to derive gravity equation which is often utilized in empirical trade research. We argue that estimating structural parameters, such as trade costs, must be consistent with the underlying assumptions and structure of the theoretical model. Otherwise, inconsistent estimates significantly bias the results. We apply our method to calculate the effect of a counterfactual elimination of asymmetries in trade costs in Eaton-Kortum type models and find it to be insignificant. Our results indicate that previous work by Waugh (2010), who suggested that elimination of asymmetries in trade costs would reduce inequality in average real GDP per worker across countries by up to 33%, was driven by inconsistent estimation and ill-suited general equilibrium modeling. From the policy perspective, complete elimination of asymmetric market access costs across exporters offers little benefit in terms of reducing world income inequality.

The third chapter examines issues on the crossover of environmental economics and international trade. Many developed and developing countries pledge to reduce their $CO_2$ emissions through domestic environmental policies. Naturally, not only would environmental policies affect carbon emissions but also economic outcomes such as international trade and welfare. We compare alternative policy instruments such as taxing energy inputs, taxing production of energy, and energy import tariffs in terms of their welfare costs subject to reduction in carbon emission levels. For that, we develop a general equilibrium model that includes an energy producing sector. We calibrate the model to 31 OECD
member countries and the rest of the world in the year 2000. Our empirical and modeling approach allows us to monetize carbon emissions using the notion of social cost of carbon. We consider change in prices, income, and the level of $CO_2$ emissions with and without cross-border spill-over effects of carbon in purely monetary terms. We find that depending on the degree of environmental spill-over effects either taxing domestic energy production or taxing energy inputs could be optimal.

The thesis contributes to the literature in several ways. First, we contribute to the theoretical debate of how one should measure welfare gains from trade. We show that heterogeneity in price and income effects across different consumer groups must be taken into account to avoid making large measurement error in the estimates of potential welfare gains. Second, we propose a novel procedure of estimating structural gravity equation. This procedure is important for consistent estimation of structural parameters in general equilibrium models of trade. Third, we also develop a novel approach to model $CO_2$ emissions in a model with energy producing sector and international trade. Finally, we provide clear quantitative predictions of every policy that we consider. Because our strategy was to calibrate the models to real data and achieve close fit in terms of key economic variables, our results are easily interpretable and represent natural policy benchmarks.

The three chapters follow below.
3  On Measuring the Welfare Gains from Trade under Consumer Heterogeneity

1  Introduction

An overwhelming majority of economists believe that free international trade is welfare enhancing. In fact, this conventional wisdom may have been the least disputable one in the profession\(^1\). The general public, however, seems to have mixed feelings towards globalization, with many people consistently opposing free trade policies. Surveys often indicate that up to half of the population views free trade as potentially harmful\(^2\). What is the reason for this large gap between one of the most robust theoretical and empirical results in economics and general perception of the public?

I argue that the reason for this disparity stems from the assumption of a representative consumer. I show that this assumption is a source of large measurement errors in the estimates of welfare gains from trade for certain consumer groups. For that, I build a multi-country model of trade with non-homothetic preferences and heterogeneous consumers, and demonstrate that welfare gains from trade in a counterfactual global trade liberalization experiment largely differ both qualitatively and quantitatively across individuals.

The model predicts that under trade liberalization different consumer groups experience

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\(^{1}\)The survey data among economists across different periods show that on average only about 5% of economists believe that tariffs do not reduce welfare. See Alston, Kearl and Vaughan (1992), Poole (2004) and others.

\(^{2}\)According to the survey conducted by the Pew Research Center in 2010, only 35% of respondents agreed that free trade agreements such as NAFTA and WTO policies are good for the United States. In fact, 44% of the respondents indicated that they consider free trade agreements to be bad for the United States.
heterogeneous changes in their total nominal incomes and consumer price indices. This heterogeneity must be taken into account when evaluating welfare gains because measures based on aggregate income and aggregate price indices, such as average real income per capita, may (under)overstate gains from trade by up to (13%) 88% depending on the consumer group and the country. In terms of aggregate welfare, the differences between changes in average real income per capita and changes in true aggregate gains are between -6% and 8%.

Differences in the consumption patterns across consumers are the first source of heterogeneity in welfare gains from trade. The poor and the rich consume different bundles of goods. For example, an abolishment of import tariffs on luxury cars and premium wines will have positive price effects on the rich, but will offer no gains to the poor, whose consumption baskets do not include those goods. The non-homothetic preference structure that I employ here allows calculating unique price indices based on the expenditure shares of each individual. I use these price indices to deflate the nominal income of each consumer and calculate adequate estimates of the welfare gains.

Consumers also differ in terms of their nominal incomes. I assume that each country has a unique distribution of physical capital, so that the factor returns are distributed unevenly

---

3Fajgelbaum, Grossman and Helpman (2011) formulate a model with non-homothetic preferences, horizontal and vertical product differentiation. They show that income distribution, in terms of the numeraire good, remains unchanged after a trade liberalization episode but not in terms of real consumption. Two empirical case studies discuss the bias from calculating welfare gains using a price index common to all consumers. Porto (2006) calculates welfare gains for different consumer groups in Argentina from joining MERCOSUR. Recently, Broda and Romalis (2009) have argued that welfare gains for low-income groups in the US have been underestimated by using the price index of a representative consumer. The authors also argue that around 50% of the documented increase in income inequality in the US between 1994 and 2005 is due to the problem of using a uniform price index.
across individuals. On the other hand, total government transfers such as foreign aid and tariff revenues are distributed equally among all consumers. Trade liberalization affects factor prices and government transfers which exert heterogeneous income effects. Depending on the relative shares of factor returns and government transfers in total income, each consumer faces a potential trade-off between change in factor prices and the size of tariff revenues in case of a trade liberalization.

Recently, non-homothetic preferences have been reintroduced into the models of international trade (for example see Markusen, 2010; Simonovska, 2010; Fieler, 2011). The authors show that non-homotheticity plays an important role in explaining bilateral trade patterns across several margins. However, these papers are mainly concerned with consumer heterogeneity across countries and not within a single country. In that sense, they still evaluate potential welfare gains through the lens of a representative consumer which, as I argue, can be a source of large bias.

I recognize the importance of large differences in the consumption patterns across countries in explaining bilateral trade flows. I also add an additional dimension – differences in the consumption patterns within a single country. Besides identifying differences in welfare gains from trade of consumers within each country, this approach also delivers quantitative predictions documented in the empirical literature but currently missing in computable general equilibrium work. The model provides the missing two-way link between international trade and within-country income inequality (for example see Goldberg and Pavcnik 2004, 2007; Harrison, McLaren and McMillan, 2010). On the one hand, the

Another way to introduce heterogeneity in incomes is to account for heterogeneous wages associated with heterogeneous profits across firms in the presence of labor market frictions (see Egger and Kreickermeier, 2009; Helpman, Itskhoki and Redding, 2010; Davis and Harrigan, 2011 and others). For example, Davis and Harrigan (2011) introduce labor market frictions into Melitz (2003) model and show while trade liberalization raises the average wage in their model, it negatively impacts workers that had relatively high wages in the pre-trade equilibrium. Several empirical studies point to the heterogeneous income effects from trade liberalization. Artuc, Chaudhuri and McLaren (2010) use a dynamic labor adjustment model and estimate how trade liberalization affects different types of workers. McLaren and Hakobyan (2010) use US Census data to estimate local welfare effects for heterogenous workers from joining NAFTA. Helpman, Itskhoki and Redding (2008, 2010) explore the link between wages, income inequality and unemployment in general equilibrium models of trade with heterogenous firms and workers.
distribution of income shapes import demand schedules, so that developing countries with relatively high income inequality and low average income are likely to import a higher share of manufacturing goods than countries with low income inequality and low average income. On the other hand, trade liberalization raises income inequality through heterogeneous income and price effects on average.

In the next subsection, I illustrate the fundamental problem with current approaches that quantify welfare gains using aggregate measures such as average real income per capita. I present the model in Section 3. In Section 4, I estimate the parameters of the model and describe the calibration procedures. Section 5 discusses novel predictions of the model that are consistent with a number of empirically established facts. I conduct a counterfactual trade liberalization experiment to assess the validity of conventional welfare metrics and evaluate consumer-specific welfare gains in Section 6. The last subsection offers a brief conclusion.

2 Consumer heterogeneity and measures of welfare

Let \(d = 1, \ldots, D\) denote the type of consumer in country \(i\) and let \(Y_{id}\) denote his total nominal income. Suppose there are \(g = 1, \ldots, G\) different goods available for consumption. Let \(s_{g, id}\) be the share of income that consumer \(d\) spends on good \(g\), so that \(\sum_{g=1}^{G} s_{g, id} = 1\). The shares \(s_{g, id}\) vary across consumers and depend on the individual income level \(Y_{id}\). For example, poor consumers spend a larger share of their income on food relative to rich consumers. The welfare of consumer \(d\) in country \(i\) is then measured as:

\[
\omega_{id} = \frac{Y_{id}}{P_{id}}, \quad \text{where} \quad P_{id} = \prod_{g=1}^{G} p_{g}^{s_{g, id}}. \tag{3.1}
\]

Here, \(P_{id}\) is \(d\)'s price index calculated using a country-specific vector of prices \(p_{g}\) and consumer-specific expenditure shares \(s_{g, id}\).\(^5\)

\(^5\)Broda, Leibtag and Weinstein (2009) discuss the importance of using consumer-type specific price indices such as \(P_{id}\) here.
Next, consider the average real income per capita:

$$\bar{y}_i = \frac{\bar{Y}_i}{P_i},$$

where $\bar{Y}_i = \frac{1}{L_i} \sum_{d=1}^{D} Y_{id}$ and $P_i = \Pi_{g=1}^{G} s_{gi}$. \hspace{1cm} (3.2)

Here, $L_i$ is the total number of consumers in $i$ and $s_{gi}$ is the country-specific expenditure share on good $g$. Two sources of the measurement error about welfare in models assuming homogenous consumers are immediately clear. First, under consumer heterogeneity average nominal income $\bar{Y}_i$ differs from individual total income $Y_{id}$. Second, depending on the level of income, consumer $d$’s expenditure shares $s_{g, id}$ also deviate from country-level expenditure shares $s_{gi}$.

Let me define the measurement error ($me_{id}$) for consumer $d$ in $i$ as follows:

$$me_{id} \equiv 100 \times \left( \frac{\bar{y}_i}{\omega_{id}} - 1 \right) = 100 \times \left( \frac{Y_{id}}{\bar{Y}_i} \frac{P_i}{P_{id}} - 1 \right).$$ \hspace{1cm} (3.3)

Here, $me_{id}$ measures by how much (in percent) $\bar{y}_i$ overestimates true welfare of consumer $d$. It is clear from (3.3) that $me_{id}$ will be especially high for consumers whose income deviates relatively more from the mean and for countries with higher income inequality across different $d$’s. In a representative consumer framework $Y_{id} = \bar{Y}_i$ and $P_{id} = P_i$, so that (3.3) collapses to $me_{id} = 0$. This is assumed in conventional models of trade. It turns out that the model used in this paper suggests that the range and the mean of $me_{id}$ are extremely large. Hence, if one evaluates welfare gains from trade liberalization without accounting for consumer heterogeneity, one will overestimate the gains for some consumers and underestimate them for others. For instance, rich consumers would benefit if trade liberalization led to a reduction in prices of luxury goods. On the other hand, poor consumers would not gain much because they do not consume any luxury goods in the first place. However, looking at the reduction in a common price index driven solely by the decrease in the price of luxury goods, one may wrongly conclude that trade liberalization
is beneficial for all consumers. The measurement errors in terms of quantified aggregate gains from trade are also large.

I use a general equilibrium model of trade calibrated to real data on $Y_{id}$ and $P_{id}$ and show that under a counterfactual trade liberalization $me_{id}$’s are very large, especially for consumers in the left tail of the income distribution.

3 Model

The production side of the model is in the spirit of Eaton and Kortum (2002). There are $N$ countries in the world. Each country $i = 1\ldots N$ is endowed with $L_i$ units of labor and $K_i$ units capital. Each country hosts a measure of heterogeneous firms in three sectors: agricultural, manufacturing and non-tradable. Manufacturing and agricultural goods can be traded subject to sector-specific iceberg trade costs from country $n$ to country $i - \tau_{m,in}$ and $\tau_{a,in}$ respectively.\footnote{The usual triangularity (non-arbitrage) assumption applies.}

The factors of production are assumed to be completely mobile across sectors but not countries.

I introduce consumer heterogeneity in the spirit of Mayer (1984) by assuming that each household owns a unit of labor and $d$ units of capital.\footnote{There are alternative ways to introduce heterogeneity in workers. Differences in abilities (Blanchard and Willmann, 2011), skill intensities (Costinot and Vogel, 2010) or distribution of human capital endowments (Bougheas and Riezman, 2007) are all viable options. The solution of the model does not depend on the interpretation of capital, $k_{id}$. Here, I interpret capital as physical capital without loss of generality.} Households vary according to their endowment of capital and can be of type $d = 1,\ldots, D$. Here, $d$ stands for the decile in the capital distribution.\footnote{I use deciles to approximate the distribution of capital simply because no data are available on a more disaggregated level. On the other hand, I find that using less disaggregated measures such as quartiles or quintiles would convolute the differences between the poor and the rich to the point when income inequality is no longer as important (for example see Fieler, 2011).} The distribution of capital is assumed to be exogenous, stationary and country-specific. Hence, households are homogeneous within a decile in any country $i$ but not across countries and/or deciles.

The preference structure is non-homothetic which ensures that differences in the level of
real income are mapped into the differences in consumption patterns of consumers across deciles and countries. Depending on the level of real income, some consumers may choose not to consume (or consume little) of certain goods. Both the extensive and intensive margins of import demand are important in this context.

A large class of general equilibrium models of trade deliver identical predictions in terms of welfare gains from trade (see Arkolakis, Costinot and Rodriguez-Clare, 2010). The two necessary conditions for this remarkable result are a CES demand system and a structural gravity equation. This model deviates in two major ways from such an approach: consumer heterogeneity and non-homothetic preferences. The combination of these two guarantees that the predictions of the model here differ from the canonical models of trade (Eaton and Kortum, 2002; Anderson and van Wincoop, 2003; Bernard, Jensen, Eaton and Kortum, 2003; Melitz, 2003) and provides novel quantitative insights about the welfare gains from trade liberalization at both individual and aggregate levels.

3.1 Households

Households of type $d$ in country $i$ maximize consumption of the non-tradable good, $c_{ni}$, the tradable manufacturing good, $c_{mi}$, and the tradable agricultural good, $c_{ai}$, according to the following nested Stone-Geary utility function:

$$U = (c_{ni}^{\beta} c_{mi}^{1-\beta})(c_{ai} - \mu)^{1-\alpha} \text{ s.t. } y_{id} = c_{ni} p_{ni} + c_{mi} p_{mi} + c_{ai} p_{ai},$$

where $p_{ni}$, $p_{mi}$, and $p_{ai}$ are prices of the non-tradable, manufacturing, and agricultural goods, respectively. Let me denote labor as $l_i$ and capital as $k_i$, then total per-capita income of a household of type $d$ in $i$ is $y_{id} = (l_i w_i + k_i r_i) + v_i$, where $w_i$ is the wage rate, $r_i$ is the capital rental rate, and $v_i$ are total per-capita transfers.

---

9 Total per capita transfers subsume tariff and tax revenues, and transfers from other countries including foreign aid.
The utility function in (5.1) captures non-homotheticity of preferences through the term \( \mu \), which can be interpreted as a subsistence level of income\(^{10}\). As long as \( y_{i,d} > \mu p_a \) the value of final demands of type-\( d \) consumers in country \( i \) are given by:

\[
c_{ai,d}p_{ai} = (1 - \alpha)y_{id} + \alpha \mu p_{ai}, \tag{3.5}
\]

\[
c_{ni,d}p_{ni} = \alpha \beta (y_{id} - \mu p_{ai}), \tag{3.6}
\]

\[
c_{mi,d}p_{mi} = \alpha (1 - \beta)(y_{id} - \mu p_{ai}), \tag{3.7}
\]

and \( c_{ni,d}p_{ni} = c_{mi,d}p_{mi} = 0 \), and \( c_{ai,d}p_{ai} = y_{id} \) whenever \( y_{id} \leq \mu p_a \). The demand equations in (3.5)-(3.7) can be normalized by total income of consumers of type \( d \) to get expenditure shares in that decile. For instance, consumer of type \( d \) in country \( i \) spends \( s_{ai,d} \equiv \frac{c_{ai,d}p_{ai}}{y_{id}} \) on agricultural goods.

For a given distribution of \( y_{id} \), I also derive country-level income shares spent on non-tradables, tradables and agricultural goods – \( s_{ni}, s_{mi}, \) and \( s_{ai} \) – respectively, which are defined as follows:

\[
s_{ni} = \frac{\sum_{d=1}^{D} c_{ni,d}p_{ni}}{\sum_{d=1}^{D} y_{id}}; \quad s_{mi} = \frac{\sum_{d=1}^{D} c_{mi,d}p_{mi}}{\sum_{d=1}^{D} y_{id}}; \quad s_{ai} = \frac{\sum_{d=1}^{D} c_{ai,d}p_{ai}}{\sum_{d=1}^{D} y_{id}}, \tag{3.8}
\]

Let me also define \( \bar{y}_i = \frac{1}{D} \sum_{d=1}^{D} y_{id} \) as the average level of real income per capita. This will turn out to be useful in subsequent subsections.

### 3.2 Production

I model production in the spirit of Eaton and Kortum (2002) because multi-country Ricardian\(^{11}\) models calibrated to real data mimic both aggregate trade flows and average levels of output.

---

\(^{10}\) For further discussion of Stone-Geary preferences refer to Markusen (2010).

\(^{11}\) Although, the model here departs from the conventional Ricardian models in terms of consumer heterogeneity and non-homothetic preferences, the production structure specified here is identical to the one specified in Eaton and Kortum (2002).
of real income per capita with high accuracy. This allows me to provide clear quantitative predictions in the counterfactual subsection that have straightforward interpretations relative to the benchmark data.

Each country is endowed with a fixed measure of capital and labor. Besides these two factors of production, firms in all sectors employ Spence-Dixit-Stiglitz (SDS hereafter) aggregates of the non-tradable and manufacturing goods, and firms in the agricultural sector also employ the SDS aggregate of the agricultural goods. This way of modeling sectoral production is consistent with the data in input-output tables.

**Non-tradable sector**

Let $n_i$ be the output of the non-tradable good, $m_i$, the quantity of the manufacturing aggregate and $a_i$, the quantity of the agricultural aggregate. I assume that each country has a unit measure of firms in the non-tradable sector producing identical non-tradable output using constant-returns-to-scale technology:

$$n_i = (l_i^\nu k_i^{1-\nu})^{\phi} (n_i^{\rho} m_i^{1-\rho})^{1-\phi}, \quad (3.9)$$

accordingly the price of the non-tradable good is:

$$p_{ni} = \Gamma_n (w_i^{\rho} r_i^{1-\rho})^{\phi} (p_{ni}^{\rho} p_{mi}^{1-\rho})^{1-\phi}, \quad (3.10)$$

where $\Gamma_n$ is a sector-specific constant.

**Manufacturing sector**

Each country hosts a measure of firms each producing a unique variety with a productivity
drawn from a Fréchet distribution. The productivity is a realization of a random variable $z_{mi}$ distributed according to:

$$F_{mi}(z_{mi}) = \exp(-\lambda_{mi} z_{mi}^{-\theta_m}),$$  \hspace{1cm} (3.11)

where $\lambda_{mi}$ is a country-specific productivity parameter and $\theta_m$ is a dispersion parameter which is common across all countries. Each firm in the sector employs labor, capital, non-tradable and manufacturing aggregates in the following way:

$$m_i(q) = z_{mi}(q)(l_i^{1-\nu}k_i^{1-\nu})^\xi(n_i^{\zeta}m_i^{1-\zeta})^{1-\xi},$$ \hspace{1cm} (3.12)

where $q$ denotes different varieties of the manufacturing goods. The probabilistic representation of technologies allows me to derive the average variable cost of a producer of a manufacturing variety in country $i$:

$$\kappa_{mi} = \Gamma_m \lambda_{mi}^{\theta_m} (w_i^{\nu}r_i^{1-\nu})^\xi (n_i^{\zeta}m_i^{1-\zeta})^{1-\xi},$$ \hspace{1cm} (3.13)

where $\Gamma_m$ is a sector-specific constant. The average variable cost $\kappa_{mi}$ along with the sector-specific iceberg trade costs $\tau_{m,i\ell}$ and the ad-valorem tariff rate $t_{m,i\ell}$ are sufficient to derive the aggregate price of tradables in $i$ as follows:

$$p_{mi} = \left( \sum_{\ell}^N (\kappa_{\ell} \tau_{m,i\ell} t_{m,i\ell})^{-\frac{1}{\theta_m}} \right)^{-\frac{1}{\theta_m}}.$$ \hspace{1cm} (3.14)

**Agricultural sector**

Similar to the firms in the tradable sector, firms in the agricultural sector each produces a unique variety with a total factor productivity parameter drawn from a country-specific
productivity distribution\footnote{The productivity distributions of the tradable and agricultural sectors are identical in terms of the family class but not the underlying parameters. I estimate the parameters for each of them in the following subsections.}

\begin{equation}
F_{ai}(z_{ai}) = \exp(-\lambda_{ai} z_{ai}^{-\theta_a}).
\end{equation}

The respective expression of the production function of a producer of an agricultural variety \(h\) in \(i\) is:

\begin{equation}
a_i(h) = z_{ai}(h) (\nu_i k_{i}^{1-\nu})^\gamma (n_i \rho_i \alpha_i^{1-\epsilon-\rho})^{1-\gamma}.
\end{equation}

An important feature of the production of agricultural goods is their dependence on the aggregate agricultural input. This is not the case for the firms in the non-tradable and manufacturing sectors\footnote{This approach is consistent with Caliendo and Parro (2011) who use input-output tables to account for the inter-dependence of industries. My formulation uses information from the input-output tables in a similar way but on a more aggregate level.}. This modeling choice is consistent with the data on the production inputs in the three sectors. The price of the agricultural aggregate can be expressed using average variable cost in \(i\)’s partner countries, \(\kappa_{an}\), iceberg trade costs specific to that sector, \(\tau_{a, in}\), and an import tariff \(t_{a, in}\):

\begin{equation}
p_{ai} = \left( \frac{\sum_{\ell} (\kappa_{a,\ell} \tau_{a, i,\ell} t_{a, in})^{-\theta_a}}{\theta_a} \right)^{-\frac{1}{\theta_a}}.
\end{equation}

\section*{3.3 International trade}

International trade occurs in the manufacturing and agricultural sectors. Firms producing identical varieties in different countries compete vis-à-vis each other given geographical and policy barriers to trade. The probabilistic representation of technologies permits the derivation of trade shares in a straightforward way:
\[ x_{m,in} = \frac{(\kappa_{mn}t_{m,in})^{-\theta_m}}{\sum_{\ell}^{N} (\kappa_{m\ell}t_{m,\ell})^{-\theta_m}}, \quad \text{and} \quad x_{a,in} = \frac{(\kappa_{an}t_{a,in})^{-\theta_a}}{\sum_{\ell}^{N} (\kappa_{a\ell}t_{a,\ell})^{-\theta_a}} \] (3.18)

Trade shares, however, are not sufficient to close the model. It is necessary to derive total spending of each country on both manufacturing and agricultural goods and specify the market clearing conditions. To do this I derive \( i \)'s total absorption capacities of manufacturing and agricultural goods, respectively. Let \( Y_{ni}, Y_{mi}, \) and \( Y_{ai} \) be the total sectoral output of the non-tradable, manufacturing, and agricultural goods, respectively, and let \( D_{ni}, D_{mi}, D_{ai} \) be net imports in the respective sectors. Consistent with Bernand, Eaton, Jensen and Kortum (2003), I define total absorption in a sector as total output plus net imports. The absorption, however, is nothing but the sum of intermediate and final demands. Hence, the following identity must hold:

\[
\begin{pmatrix}
Y_{ni} \\
Y_{mi} \\
Y_{ai}
\end{pmatrix} + 
\begin{pmatrix}
D_{ni} \\
D_{mi} \\
D_{ai}
\end{pmatrix} = 
\begin{pmatrix}
(1-\phi)\rho & (1-\phi)(1-\rho) & 0 \\
(1-\xi)\zeta & (1-\xi)(1-\zeta) & 0 \\
(1-\gamma)\epsilon & (1-\gamma)(1-\epsilon) & 0
\end{pmatrix} 
\begin{pmatrix}
Y_{ni} \\
Y_{mi} \\
Y_{ai}
\end{pmatrix} + 
\begin{pmatrix}
s_{ni} & 0 & 0 \\
0 & s_{mi} & 0 \\
0 & 0 & s_{ai}
\end{pmatrix} 
\begin{pmatrix}
Y_i \\
Y_i \\
Y_i
\end{pmatrix},
\] (3.19)

here \( Y_{i} \) is total income of consumers in \( i \). Let \( f_{ni}, f_{mi} \) and \( f_{ai} \) be the ratio of the absorption capacities of the non-tradable, manufacturing and agricultural sectors, respectively, to total expenditures in \( i \), then (3.19) can be reformulated as follows:

\[
\begin{pmatrix}
Y_{ni} \\
Y_{mi} \\
Y_{ai}
\end{pmatrix} + 
\begin{pmatrix}
D_{ni} \\
D_{mi} \\
D_{ai}
\end{pmatrix} = 
\begin{pmatrix}
f_{ni} & 0 & 0 \\
0 & f_{mi} & 0 \\
0 & 0 & f_{ai}
\end{pmatrix} 
\begin{pmatrix}
Y_{i} \\
Y_{i} \\
Y_{i}
\end{pmatrix},
\] (3.20)

Here \( f_{ni}, f_{mi} \) and \( f_{ai} \) are functions of production parameters, sectoral trade imbalances, and country-level consumption shares, defined by consumption shares of consumers of each type \( d \) in \( i \). The latter depend on both the average level of income per capita and the level of income in different deciles in each country.
To close the model, I assume that total imports, $IM_i$, equal total exports, $EX_i$ up to a country-specific constant $D_i$:

\begin{align}
D_i &= EX_i - IM_i, \quad \text{where} \\
IM_i &= (L_i w_i + K_i r_i + L_i v_i) \sum_{n=1}^{N} (f_{mi} x_{m,in} + f_{ai} x_{a,in}), \quad \text{(3.22)} \\
EX_i &= \sum_{n=1}^{N} (L_n w_n + K_n r_n + L_n v_n) (f_{mn} x_{m,ni} + f_{an} x_{a,ni}). \quad \text{(3.23)}
\end{align}

The central difference of (4.6) from the Ricardian models with homothetic preferences and/or homogeneous consumers is in terms $f_{mi}$ and $f_{ai}$. In those models, the shares are assumed to be constant across all countries and consumers. On the contrary, here $f_{mi}$ and $f_{ai}$ can be viewed as a link between the non-homotheticity of preferences, consumer heterogeneity, and total import demand.

4 Calibration

I calibrate the model to 92 countries in the world\footnote{The limitations of the data do not allow me to extend the sample further. However, the 92 countries in the sample include all large countries in the world. Hence, the calibrated model is very close to reflecting the world in economic terms. The sum of GDP’s of the 92 countries in the sample constituted to about 93% of total world GDP in 1996.}. The reference year for all the data is 1996. I describe the data sources in the Appendix.

For the counterfactual experiment I need to calibrate the parameters of the utility function and the production functions in the three sectors. I also need to estimate $\theta_m$ and $\theta_a$. I solve for the counterfactual values in the spirit of Dekle, Eaton and Kortum (2007) and do not have to estimate $\lambda_{mi}$, $\lambda_{ai}$, $\tau_{m,in}$, and $\tau_{a,in}$ since those are taken as primitives (constants) in the model.
4.1 Parameters of the utility function

Calculating $\beta$, which governs the ratio of the consumption of non-tradable to manufacturing goods, is straightforward given the data on households’ spending. This share is constant across countries and does not vary much with the average level of per-capita income. This is confirmed in the left panel of Figure 1 where I plot the ratio of the total non-tradable consumption in each country to the total manufacturing consumption. It is then straightforward to infer the value of $\beta$ from the following:

$$\frac{\beta}{1-\beta} = \frac{1}{N} \sum_{i=1}^{N} \frac{p_{ni}}{p_{mi}} \sum_d c_{ni,d} \sum_d c_{mi,d}$$  \hspace{1cm} (3.24)

The calculated average is (1.96) with a standard deviation of (0.62) which implies $\beta = 0.38$. Estimating the remaining two parameters $\alpha$ and $\mu$ is more challenging because, unlike $\beta$, the share of income spent on agricultural goods is not constant across countries and is consistently correlated with real income of an average household in country $i$. The relationship is seemingly non-linear as shown in the right panel of Figure 1 where I plot the ratio of total consumption in agricultural goods to the remaining expenditures.

The reason for this strong relationship is the non-homotheticity of household preferences. This has been well documented in the literature. Modernizing this relationship using Stone-Geary preferences has two advantages. First, the utility function leads to tractable linear demand functions. Second, the parameters of the utility function have straightforward and intuitive interpretation.

---

18 This is the maximum number of observations of the data in Penn World Tables. Benchmark year 1996.
20 Tombe (2012) uses Stone-Geary preferences to explain trade patterns in food products between poor and rich countries. A minor departure of this paper from the literature is in the specification of the utility function – a nested functional form which is easier to calibrate and interpret.
Calibrating $\alpha$ and $\mu$ is a non-standard optimization problem. To estimate these parameters, I minimize the squared distance between country-level expenditure shares predicted by the model as described in (3.8) in Section 2:

$$\min_{\alpha, \mu} \sum_{i=1}^{N} (s_{ai} - s_{ai}(\alpha, \mu))^2 \text{ s.t. } \alpha \in [0, 1],$$

(3.25)

where $s_{ai}$ are the data and $s_{ai}(\alpha, \mu)$ is the function of $\alpha$ and $\mu$, which given the value of $\beta$ and the data on $y_{id}$ and $p_{ai}$, is calculated as in (3.8). Solving (3.25) yields $\alpha = 0.8860$ and $\mu = 0.0017$. The fit of calibration is good, the correlation between the predicted and actual $s_{ai}$ is 0.92.\footnote{For this calibration exercise and throughout the rest of this paper, all income values are normalized such that the average real income per capita in the USA is unity.}

4.2 Parameters of the production functions

The only parameter common to all three production functions is the capital-labor ratio parameter $\nu$. Consistent with the literature in macroeconomics and international trade (for example, see Gollin, 2002), I set $\nu = 0.67$.\footnote{For this calibration exercise and throughout the rest of this paper, all income values are normalized such that the average real income per capita in the USA is unity.}
The rest of the production parameters are calculated using input-output tables as follows. The parameters \{\phi, \xi, \gamma\} govern the share of value added in the non-tradable, manufacturing and agricultural sectors, respectively. I calculate them as a ratio of value added to the total output in the respective sector. Similarly, the parameters \{\varrho, \zeta, \epsilon, \rho\} are calculated from the ratio of total non-tradable input to total manufacturing input. Cross-country averages and standard deviations of the production parameters are provided in Table 6.

Table 1: Production parameters

<table>
<thead>
<tr>
<th></th>
<th>(\phi)</th>
<th>(\xi)</th>
<th>(\gamma)</th>
<th>(\varrho)</th>
<th>(\zeta)</th>
<th>(\epsilon)</th>
<th>(\rho)</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean</td>
<td>0.5474</td>
<td>0.2919</td>
<td>0.4995</td>
<td>0.6822</td>
<td>0.3154</td>
<td>0.2780</td>
<td>0.3829</td>
</tr>
<tr>
<td>std.deviation</td>
<td>0.0574</td>
<td>0.0363</td>
<td>0.1101</td>
<td>0.1046</td>
<td>0.0842</td>
<td>0.0778</td>
<td>0.1243</td>
</tr>
<tr>
<td>N</td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>39</td>
</tr>
</tbody>
</table>

Notes: The parameters were calculated using the data on Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Czech Rep., Denmark, Estonia, Finland, France, Germany, Greece, Hungary, India, Indonesia, Ireland, Italy, Japan, Korea, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain; Sweden, Switzerland, Turkey, UK, USA, Vietnam. The data for other countries in the sample were unavailable.

I estimate the trade elasticities in the manufacturing and the agricultural sectors – \(\theta_m\) and \(\theta_a\) – using the data on trade flows and tariffs. Let \(X_{m,in}\) denote manufacturing trade flow from \(n\) to \(i\). Normalize trade flows by the value of domestic sales to get a familiar structural gravity equation:

\[
\frac{X_{m,in}}{X_{m,ii}} = \left(\frac{\kappa_n \tau_{m,in} \tau_{m,in}}{\kappa_i}\right)^{\theta_m} \text{ where } \tau_{m,in} = (\tau_{m,i} \tilde{\tau}_{m,in} \tau_{m,n}). \tag{3.26}
\]

I assume total trade costs \(\tau_{m,in}\) to be log-additive with tariffs and consist of an exporter-specific asymmetric component – \(\tau_{m,n}\), an importer specific asymmetric component – \(\tau_{m,i}\), and a symmetric component \(\tilde{\tau}_{m,in}\). Consistent with the literature, I proxy for the symmetric component of trade costs \(\tilde{\tau}_{m,in}\) using a distance measure and an adjacency dummy\(^{22}\). The two asymmetric trade cost components will be captured by respective

\(^{22}\)The coefficients on distance and adjacency variables have the expected signs and due to the solution strategy are of no particular interest, hence not reported.
country-specific fixed effects. I estimate the following stochastic version of (3.26):

$$\frac{X_{m,in}}{X_{m,ii}} = \exp[\log(ex_n) + \log(im_i) - \theta_m \log(t_{m,in}) - \theta_m \log(\bar{\tau}_{m,in})] + \text{error}_{in}, (3.27)$$

where $im_i$ and $ex_n$ are catch-all importer and exporter fixed effects, respectively. Notice that the coefficient on tariffs between $i$ and $n$ identifies $\theta_m$ I estimate $\theta_a$ using data on $X_{a,in}$ and $t_{a,in}$ in the same fashion. I chose to estimate (3.27) in levels rather than in logs to avoid the problem of zeros. The trade data for the 92 countries include a considerable number of zeros and dropping those may lead to inconsistent marginal effects. In practice, I maximize the respective Poisson Pseudo Maximum Likelihood function as advocated by Santos Silva and Tenreyro (2006). The estimates are $\hat{\theta}_m = 6.53(1.23)$ and $\hat{\theta}_a = 12.07(1.16)$.

The values of $\theta_m$ and $\theta_a$ suggest that differences in technology and factor prices are relatively larger and more important for trade in the agricultural sector. This is consistent with Tombe (2012) who points out that the productivity gap between rich and poor countries is especially pronounced in agriculture.

### 4.3 Benchmark distribution of capital

I use the data on the distribution of income to calibrate the model to the observed levels of heterogeneity across consumers. The benchmark level of real income is:

$$y_{id} = (l_i w_i + r_i k_{id}) + v_i, \quad (3.28)$$

---

23Caliendo and Parro (2011), Ramondo and Rodriguez-Claire (2009), Egger and Nigai (2011, 2012) use tariffs to identify the elasticity of trade. The critique of Simonovska and Waugh (2011) is not particularly pertinent to the methodology here because: (i) I do not use price data for identification of the trade elasticity and (ii) the results for manufacturing sector are reasonably close to Simonovska and Waugh (2011) and other estimates in the literature. For example see Donaldson, Costinot and Komunjer (2012).

24For example, see Baldwin and Harrigan (2011) or Chor (2010).

25Standard errors in parenthesis are based on Eicker-White sandwich estimates and are robust to heteroskedasticity of an unknown form.
here capital ownership, $k_{id}$, is the only source of heterogeneity. Total government transfers, $v_i$, include foreign aid, credits and tariff revenues. I calculate $v_i$ as the sum of the current account balance (net of trade deficit) and tariff revenues given benchmark levels of tariffs $t_{m,in}$ and $t_{a,in}$.\footnote{All values here are in real terms per capita.} I, then, use the data on the income distribution in each country to pin down the values of $k_{id}$.

5 Predictions of the model

General equilibrium models of trade often fail to predict two stark relationships between trade and income that are evident in the data: (i) trade increases in income per capita, and (ii) trade and within-country income inequality are correlated. Many recent papers have tackled the former issue by incorporating non-homothetic preferences into trade models. My approach is consistent with previous work and provides predictions in line with the data. The latter issue, however, has been largely ignored in general equilibrium analysis of trade. Numerous empirical studies have suggested that trade liberalization episodes have been characterized by a substantial increase in income inequality. For an excellent overview of recent advances in the research of trade and inequality refer to Goldberg and Pavcnik (2004, 2007). In addition, a number of empirical papers have found a considerable amount of evidence in support of Linder’s (1961) hypothesis – countries with similar income distributions tend to trade more. I introduce within country differences in capital owned by households, which, together with a non-homothetic preference structure, link income inequality to total import demand. The model delivers predictions in line with the empirical findings on trade and income inequality.

5.1 Trade and per-capita income

It is a well established fact that total bilateral trade increases with per capita incomes of both exporter and importer. Hence, it is essential for a model to provide clear-cut predic-
tions with respect to this relationship. Fieler (2011) criticizes conventional trade models because they predict that trade increases in total income, regardless of the distribution of population relative to average income. On the other hand, the data suggest that trade increases in real income per capita rather than population. The model here captures this feature of the data well and is not subject to Fieler’s critique.

To illustrate that the model does provide predictions consistent with empirical findings consider the following. Recall that $X_{m,in}$ and $X_{a,in}$ are total trade flows from $n$ to $i$ in manufacturing and agricultural goods, respectively. These can be decomposed into the supply and demand effects.

$$X_{m,in} = x_{m,in} \times f_{mi} \times Y_i,$$  \hspace{1cm} (3.29)

and a similar expression for $X_{a,in}$. Notice that $x_{m,in}$ depends only on technology and relative factor prices, and is independent of the structure of preferences. However, $f_{mi}$, the share of aggregate expenditure $Y_i$ spent on tradables depends on $s_{mi}$. To see the argument in a simple way assume that $y_{i,d} > \mu_p a$ for all $d$. Then we can decompose total bilateral imports of $i$ from $n$ from (3.29) as follows:

$$X_{m,in} = \Phi x_{m,in} \times \frac{\sum_{d=1}^{D} L_{id}(y_{id} - \mu_p a)}{\sum_{d=1}^{D} L_{id}y_{id}} \times \sum_{d=1}^{D} L_{id}y_{id} = \Phi x_{m,in} \times L_i \times (\bar{y}_i - \mu_p a),$$  \hspace{1cm} (3.30)

where $\Phi$ is a constant. The model predicts that bilateral imports $X_{m,in}$ are increasing in average real income per capita, $\bar{y}_i$ faster than in the population $L_i$, ceteris paribus. The same holds for trade flows in agricultural goods.

\footnote{Input share parameters are assumed to be constant across all countries. Hence, the change in $f_{mi}$ is proportional to the change in $s_{mi}$.}
5.2 Income inequality and trade

Trade models based on the assumption of a representative consumer fail to capture the strong link between the income distribution and international trade. A number of empirical papers (for example, see Bernasconi, 2011) have found strong evidence of a correlation of within-country income distribution similarities across countries and bilateral trade. This goes back to Linder’s (1961) hypothesis of overlapping demands. The present model delivers predictions consistent with that hypothesis.

For simplicity, in (3.30) I reduced total country demand to a function of total population, average income per capita and prices. To do that I assumed that $y_{i,d} > \mu p_{ai}$ for all $i, d$. Of course, in reality $y_{id} \leq \mu p_{ai}$ for some $i, d$. This is where the distributional effects begin to matter.

Suppose, I endowed all countries in the world with the distribution of capital observed in the United States while keeping the average level of real income per capita unchanged. If inequality were an insignificant determinant of import demand schedules, one would not see significant changes in $f_{mi}$ (the same holds for $f_{ai}$ and $f_{ni}$). On the other hand, if one observed large changes in country-level import demand solely due to changes in the distribution of income, he could conclude that the model captures the link between income inequality and trade.

I conduct the following thought experiment to illustrate how income distribution shapes import demands at a given level of average income. I use the data on the distribution of real income in the USA and set $y_{id}$ in all other countries so that the distribution of income is exactly the same as in the USA. I keep the levels of average real income unchanged. In Figure 2 I plot changes in $f_{mi}$ versus the average real income per capita.

Poor countries, where income inequality is relatively more pronounced, would spend a lower share of their total expenditure on manufacturing if they had less income inequality.
This may seem counter-intuitive but at a given level of average real income, poor countries that exhibit relatively more income inequality must also have a higher import demand. The intuition behind is as follows. Positive demand for manufacturing goods can be realized only if at least one consumer in \( i \) has an income higher than the subsistence level. In very poor countries, an equal distribution of income would imply that no consumer has enough income to buy manufacturing goods. On the other hand, very high inequality could allow the richest households to have positive import demand. The results displayed in Figure 8 with regard to the impact of income inequality on trade is in line with the earlier empirical evidence (see Goldberg and Pavcnik, 2004; 2007) and the theoretical argument proposed by Linder (1961). This effect is completely missing in trade models with a representative consumer.

The model also has strong predictions with regard to the reverse effect, i.e., the effect of trade on income inequality. I discuss this link in the context of a counterfactual global trade policy liberalization scenario in Section 6.3.

\[ \bar{y}_i, \bar{y}_{USA} = 1 \]

Figure 2: Income Inequality and Import Demand

---

28 In terms of the quantitative predictions of the model I calculate the squared distance between benchmark Gini-coefficients for each pair of countries and correlate it to the total trade. The correlation is \(-0.11\) which suggests that countries that are more similar in terms of the income distributions trade relatively more.
To understand the mechanics behind the link between income inequality and trade, consider a hypothetical case of two countries with different income distributions and identical otherwise. For simplicity assume that $d = \{1, 2, 3\}$. Total income, population and all prices in both countries are equal to unity. Incomes are distributed as \{0.3, 0.3, 0.4\} in country 1 and as \{0.1, 0.1, 0.8\} in country 2. Further assume that $\mu p_{ai} = 0.2$ in both countries. In that case total demands for manufacturing in countries 1 and 2, respectively, are:

$$
\begin{align*}
    f_{m1} \times Y_1 &= \frac{1}{3} \times (0.3 - 0.2) + \frac{1}{3} \times (0.3 - 0.2) + \frac{1}{3} \times (0.4 - 0.2) = 0.13 \quad (3.31) \\
    f_{m2} \times Y_2 &= \frac{1}{3} \times 0 + \frac{1}{3} \times 0 + \frac{1}{3} \times (0.8 - 0.2) = 0.2, \quad (3.32)
\end{align*}
$$

This is a simple example of how countries that are different with respect to their income distribution only can have very different import demand schedules.

In that sense, the model here is substantially different from other trade models with non-homothetic preferences. For example, Fieler (2011) provides a brief discussion of the role of income distribution in shaping international trade flows. She finds that income inequality has a very small impact, if any, on import demand schedules. The reason for this is twofold. First, she uses quintiles of the income distribution so that differences between the richest and the poorest consumers are not as pronounced as here. Second, Stone-Geary preferences have a discontinuity at the level of subsistence so that both the extensive and intensive margins of consumption are important. Preferences specified in Fieler (2011) are continuous in a sense that each consumer always spends some part of her income on each type of good.\footnote{This is a well-known property of any CES-related demand system.}
6 Counterfactual experiment

For the counterfactual experiment, it is useful to express the model in relative changes. Let \( a \) denote benchmark and \( a' \) counterfactual values of some variable, then the relative change is \( \hat{a} = a'/a \). This approach is particularly convenient because one may assume that the primitives of the model, \( \tau_{in} \) and \( \lambda_i \), do not respond to indirect shocks and one can conduct counterfactual experiments without having estimated these unobservable fundamentals.\(^{30}\)

In the counterfactual experiment, I globally eliminate all import tariffs to assess the effect of this hypothetical policy on real income, welfare and income distribution. Tariffs are asymmetric in the outset, hence for this counterfactual exercise I reduce tariffs in an asymmetric manner:

\[
t'_{a,in} = 1 \quad \text{and} \quad t'_{m,in} = 1 \quad \text{such that} \quad \hat{t}_{a,in} = \left(t_{a,in}\right)^{-1} ; \hat{t}_{m,in} = \left(t_{m,in}\right)^{-1} \quad \text{for all} \quad i, n. \tag{3.33}
\]

which effectively means zero MFN-tariffs for all countries in both tradable sectors. I list expressions for the counterfactual values of all variables and describe the solution algorithm and the data in the Appendix.

For the comparative static experiment I choose three outcomes of interest: average real income \( \bar{y}_i \),\(^{31}\) welfare (decile-specific \( \omega_{id} \) and aggregate \( W_i \)), and the within-country income distribution.


\(^{31}\)Real income may be measured in many different ways, here I stick to the conventional definition, i.e., real income is a ratio of nominal income to a country-specific price index.
6.1 Trade liberalization, real income and welfare

Conventional wisdom suggests that trade liberalization on average has positive aggregate effects in terms of real income. First, let me consider the effect of a complete elimination of tariffs on the average real income per capita as parameterized for the year 1996. I plot the counterfactual change in $\bar{y}_i$ against its initial values in Figure 3.

![Figure 3: Trade Liberalization and Real Income Per Capita](image)

The results in Figure 3 are consistent with the large body of literature on the effects of trade liberalization. Numerous empirical and theoretical works found that trade liberalization leads to higher income per capita on average, much more so for small economies. Smaller countries gain relatively more because with lower barriers they are able to specialize on the production of goods where productivity is high. In this experiment, bigger countries lose a little in terms of the average real income per capita. The reason for this is twofold. First, the initial tariff matrices are asymmetric and developing countries initially face relatively higher tariffs. Accordingly, they benefit relatively more from trade
liberalization. Second, in the counterfactual equilibrium rich countries face tougher competition from poor countries that start exporting relatively more through specialization. In general, the results of the counterfactual exercise, as far as changes in the average real income per capita are concerned, are very much in line with both the empirical literature and other computable general equilibrium models of trade (for example, see Alvarez and Lucas, 2007). The exact counterfactual results for all countries and all relevant variables are in Tables 7-4 in the Appendix.

Next, let me examine whether average real income per capita is an adequate metric for the evaluation of welfare effects of trade liberalization for different type of consumers. For each decile \( d \) in each country \( i \), I calculate counterfactual change, \( \hat{\omega}_{id} = \frac{\omega'_{id}}{\omega_{id}} \).

In Figure 4, I plot welfare changes of the 1\(^{st}\), 5\(^{th}\) and 10\(^{th}\) deciles of the distribution of consumers in each country against the change in the average real income per capita. The results of the counterfactual exercise for all deciles are in Tables 7-4.

![Figure 4: Change in Average Real Income per Capita versus Change in Welfare (by decile)](image)

If average real income per capita were an adequate measure of welfare for all types of consumers the scatter points would lie on the 45 degree line in all three panels. Serious deviations from the 45 degree line suggest that \( \bar{y}_i \) is not an appropriate metric for

\[32\] As a sensitivity check, I conduct a counterfactual exercise which reduces trade costs symmetrically by the same margin. In that case, all countries gain but smaller countries still gain relatively more. The results are available upon request.
some consumer groups. Figure 4 shows that as one goes from the richest to the poorest households, average real income per capita becomes less and less relevant. Notice that changes in welfare and average real income per capita are practically identical for the decile of consumers with the highest income per capita. The relationship is much weaker for consumers in the 5th decile of the distribution (although still positive). Finally, the left panel of the figure suggests that changes in the average income per capita and changes in welfare for the poorest income groups are largely unrelated.

To formally show that average income per capita is not a good predictor of welfare gains (at least for some consumer groups) I run the following regression:

\[ \hat{\omega}_{id} = \pi_{d} \hat{y}_{i} + \text{error}_{id}. \]  

(3.34)

If \( \hat{y}_{i} \) were a good measure of welfare gains then \( \pi_{d} \) would be close to unity. The results in Table 2 suggest that this is true only for the highest and second highest deciles. For all other deciles the estimate of \( \pi_{d} \) is considerably different from unity, with high standard errors and low explanatory power.

<table>
<thead>
<tr>
<th>Decile</th>
<th>( \hat{\pi}_{d} )</th>
<th>std.error</th>
<th>( R^2 )</th>
<th>max</th>
<th>min</th>
<th>mean</th>
<th>std. dev.</th>
<th>( s_d^2 )</th>
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<tbody>
<tr>
<td>d = 10</td>
<td>-0.26</td>
<td>0.47</td>
<td>0.01</td>
<td>88.15</td>
<td>-11.33</td>
<td>2.34</td>
<td>12.73</td>
<td>0.49</td>
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<tr>
<td>d = 9</td>
<td>0.27</td>
<td>0.14</td>
<td>0.06</td>
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<td>1.05</td>
<td>4.6</td>
<td>0.58</td>
</tr>
<tr>
<td>d = 8</td>
<td>0.4</td>
<td>0.11</td>
<td>0.19</td>
<td>11.21</td>
<td>-7.13</td>
<td>0.85</td>
<td>3.59</td>
<td>0.61</td>
</tr>
<tr>
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<td>0.49</td>
<td>0.09</td>
<td>0.35</td>
<td>9.32</td>
<td>-6.24</td>
<td>0.71</td>
<td>2.97</td>
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<tr>
<td>d = 6</td>
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<td>0.08</td>
<td>0.49</td>
<td>8.64</td>
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<td>0.61</td>
<td>2.52</td>
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<tr>
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<td>0.07</td>
<td>0.63</td>
<td>8.08</td>
<td>-4.95</td>
<td>0.49</td>
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<td>d = 4</td>
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<td>0.75</td>
<td>6.22</td>
<td>-4.34</td>
<td>0.36</td>
<td>1.73</td>
<td>0.67</td>
</tr>
<tr>
<td>d = 3</td>
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<td>0.86</td>
<td>4.35</td>
<td>-3.68</td>
<td>0.24</td>
<td>1.34</td>
<td>0.65</td>
</tr>
<tr>
<td>d = 2</td>
<td>0.87</td>
<td>0.04</td>
<td>0.93</td>
<td>2.68</td>
<td>-2.87</td>
<td>0.1</td>
<td>0.97</td>
<td>0.57</td>
</tr>
<tr>
<td>d = 1</td>
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<td>0.03</td>
<td>0.97</td>
<td>1.01</td>
<td>-2.88</td>
<td>-0.14</td>
<td>0.59</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Notes: Standard errors are robust to an unknown form of heteroskedasticity. The number of observations for each regression is 92.

For each decile \( d \) in each country \( i \), I also calculate the measurement error \( me_{id} \). Recall, that I defined it as:
Expression in (3.35) measures by how much changes in the average real income per capita overpredict changes in decile-specific welfare. I plot $me_d$ in Figure 5.

The dispersion of $me_d$ is considerably higher for relatively poor consumers. For the poorest decile the measurement errors are in the interval $[-11\%, 88\%]$ with relatively equal shares of of positive (overprediction) errors and negative (underprediction) errors. I report the share of positive measurement errors, denoted by $s^+_d$, along with the other descriptive statistics in Table 2.

The range of $me_d$ becomes smaller as one goes from the poorest to the richest consumer. The range is between $[-5\%, 8\%]$ for the median consumer and between $[-3\%, 1\%]$ for the richest consumer, respectively. The same tendency holds for the dispersion of errors measured in terms of the standard deviation. The statistics in Table 2 suggest that overall $me_d$ is small for $d = 1$, hence $\hat{y}_i$ is a good measure of welfare for very rich consumers.

There is an inverse U-shaped relationship between $s^+_d$ and $d$. Average real income per capita tends to overestimate the gains from trade for consumers in the middle of the
income distribution. However, this measure underestimates the gains for consumers in the right tail of the income distribution. The reason for this are differences in the relative price and nominal income effects that vary across different deciles.

Policy makers may be interested in targeting certain consumer groups when considering trade liberalization policy. However, it may also be useful to have a measure of aggregate welfare gains of a country. As is well known, this is not an easy task. Welfare effects are largely heterogeneous across different consumer groups which makes evaluating overall welfare gains quite challenging. One way to proceed is to assume a simple, yet intuitive, unweighted utilitarian social welfare function such that the social welfare is the sum of utility measures across different deciles of consumers: \( W_i = \sum_d \omega_{i,d} \). Is \( \bar{y}_i \) a good measure of the overall social welfare gains? In Figure 6, I plot counterfactual changes in the average real income per capita versus changes in the measure of aggregate welfare – \( W_i \).

![Figure 6: Change in Average Real Income per Capita versus Change in Total Welfare](image)

Figure 6 suggests that average real income per capita is a noisy measure of the aggregate welfare. The range of the measurement error is between \(-6\%\) and \(8\%\). On average, changes in real income per capita tend to be larger than changes in aggregate welfare.

\[ W_i = 0.60\bar{y}_i; R^2 = 0.82 \]

Figure 6 suggests that average real income per capita is a noisy measure of the aggregate welfare. The range of the measurement error is between \(-6\%\) and \(8\%\). On average, changes in real income per capita tend to be larger than changes in aggregate welfare.

\[ ^{33} \text{The results are even stronger for some other measures of social welfare such as Rawlsian welfare function.} \]
The share of positive errors is $s^+ = 0.58$ which suggests that $\bar{y}_i$ is likely to overpredict true aggregate welfare gains.

6.2 On the mechanics of heterogeneous welfare effects

Welfare gains of poor consumers largely differ from the predictions based on the change in average real income per capita. For example, according to Figure 3 consumers in Mexico and Chile on average should gain approximately 2.5% and 1% in welfare, respectively. The effects are reversed for the poorest consumers in both countries. Welfare of poor consumers in Mexico and Chile actually falls by about 20% and 5% respectively. This is depicted in Figure 7 where I plot welfare gains of the poorest consumer groups (lowest decile of per-capita income) in all countries.

![Figure 7: Trade Liberalization and Welfare (for the 10th Decile)](image)

What exactly drives these differences? To understand the mechanics behind, I conduct an additional experiment. Up to this point, I assumed that trade liberalization takes place instantaneously. However, in order to understand the main drivers of the results, it is useful to consider liberalization as a gradual process. Let $\varsigma$ be a step function such that $\varsigma = (0, ..., 20)$, each step is a discrete jump from the benchmark towards full trade liberalization. Hence, at $\varsigma = 0$ the model is exactly as in the benchmark case, and at $\varsigma = 20$ the model is exactly as in the case of full trade liberalization. Let $t_{a,in}^{\varsigma}$ and $t_{m,in}^{\varsigma}$ be
the counterfactual values of tariffs at step \( \varsigma \) in the agricultural and manufacturing sectors, respectively. I define them as follows:

\[
t'_{a,in} = t_{a,in} - \frac{\varsigma}{20} (t_{a,in} - 1) \quad \text{and} \quad t'_{m,in} = t_{m,in} - \frac{\varsigma}{20} (t_{m,in} - 1) \quad \text{for all } i, n. \tag{3.36}
\]

For each step \( \varsigma \), I calculate the counterfactual change (in percent) in \( Y_{id}, P_{id}, \) and \( \omega_{id} \). Notice that one can decompose\(^{34}\) welfare gains \( \Delta \omega_{id} \) (hereafter \( \Delta \) denotes change in %) into the nominal income effect, \( \Delta Y_{id} \), and the price effect \( -\Delta P_{id} \) as:

\[
\Delta \omega_{id} = \Delta Y_{id} - \Delta P_{id} \tag{3.37}
\]

In Table 2 I argued that changes in average income per capita do not reflect individual welfare gains of poor consumers. In fact, if one employs \( \omega_{id} \) instead of \( \bar{y}_i \) as a measure of welfare the effects are reversed for many countries in the sample. For example, counterfactual change in \( \bar{y}_i \) in Chile is positive (around 1 % in Figure 3). On the other hand, Figure 7 suggests that the poorest decile in Chile loses in terms of welfare (around 5%). What drives this large difference? I use the decomposition in (3.37) to answer this question. The model predicts that real returns to labor and capital increase by 3% in Chile. At the same time, zero-MFN tariffs imply that consumers lose all of the tariff revenues. This trade-off is good for those who own a lot of capital and bad for those who own little.

Higher labor and capital costs increase prices of agricultural goods by relatively more.\(^{35}\) Poor consumers spend most of their income on agricultural goods. Hence, the price effect has an additional negative effect on their welfare. In Figure 8 I plot total welfare gains, income and price effects for the 1\(^{st}\), 5\(^{th}\) and 10\(^{th}\) deciles in Chile for each counterfactual

\(^{34}\) Log-linearize (3.1) and multiply both sides by 100 to get (3.37).

\(^{35}\) That the home bias is larger in the agricultural sector than in manufacturing is a well-documented fact.
Notice that as countries start reducing tariff revenues, consumers in the poorest decile lose in terms of the nominal income and prices. This happens because they own very little capital so that the increase in the price of that factor cannot compensate for losses in tariff revenues. Hence, their total welfare gains are strictly negative. Consumers in the median decile own enough capital to have positive total nominal income effects. But their decile-specific price index increases relatively more. As a result, their total welfare gains are negative. Finally, the richest households in Chile own enough capital so that their income effect overcompensates the increase in the price index. This leads to positive welfare gains. It bears noting that the price effects are strongest for the poorest consumer group.

### 6.3 Trade liberalization and income distribution

The purpose of this subsection is to demonstrate that the model delivers quantitative predictions consistent with the empirical literature in terms of the effect of trade liberalization on income inequality. The empirical evidence suggests that, during the last quarter of the twentieth century, many developing countries experienced acute increase in the income inequality part of which can be attributed to higher trade (see Goldberg and
Does the model provide credible predictions in that respect?

To answer this question I have to measure real income per capita of different consumer groups in a way consistent with the empirical literature. For that, I use decile-specific income $y_{id}$ measured as a ratio of total nominal income of consumers of type $d$ in country $i$ deflated by the country-specific price index:

$$y_{id} = \frac{Y_{id}}{L_{id}P_{ai}P_{si}}.$$  \hfill (3.38)

I use the benchmark and counterfactual values of $y_{id}$ to calculate the Gini-coefficient, denoted by $G_i$ in the pre and post-liberalization periods. I plot the results of the counterfactual experiment in Figure 9.

Figure 9: The Effect of Trade Liberalization on the Distribution of Income

Global liberalization of trade increases inequality for most countries. The majority of developing countries experiences an increase in income inequality. The effects in the rich

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A notable exception from numerous case studies conducted on the subject is Porto (2006) who estimates distributional effects of joining MERCOSUR for Argentina. The author uses household survey data and shows that on average joining MERCOSUR had positive effects on welfare of poor and middle-income consumers and reduced inequality. My results do not contradict Porto’s findings. To simulate the natural experiment examined in Porto (2006), I conduct a separate counterfactual exercise. I reduce import tariffs set by Argentina only. The model predicts that inequality in Argentina decreases by 2.2%.

I repeated the exercise using alternative measures of inequality such as the percentile ratio. The results turn out to be quantitatively robust to those manipulations.
countries are less pronounced.

Essentially, the effects of trade liberalization on the distribution of real income can be decomposed into changes in nominal income and changes in common price index as illustrated in Section 6.2. It is intuitive that a reduction in income inequality must come from either higher income of consumers in the left tail of the distribution or equivalently lower income of consumers in the right tail of the distribution. As I argued, trade liberalization is likely to raise income of the rich and reduce income of the poor which leads to the increase in income inequality as in Figure 9.

7 Conclusion

I have developed a multi-country model of trade with non-homothetic preferences and heterogeneous consumers. The model reflects empirically established facts in a few novel dimensions. For instance, the model features a strong link between income inequality within countries and trade which has been missing in quantitative models of trade.

Perhaps, one of the most important features of the model is its ability to predict large heterogeneity of consumption patterns of different consumer groups within a country. I argue that this heterogeneity must be taken into account when evaluating welfare gains from trade. I show that conventional measures thereof do not capture true welfare gains for poor and middle-income consumers and tend to introduce a measurement error in the magnitude between -6% and 8% of aggregate welfare gains.

Admittedly, one of the caveats of the model is the assumption of an exogenous and stationary capital distribution. However, in a multi-country framework endogenous accumulation and/or the non-stationary distribution of capital would complicate the model significantly. I leave this for future research.
8 Appendix

8.1 Data

The reference year for all the data is 1996. Trade data are from Feenstra, Lipsey, and Bowen (1997). I aggregate industry-level trade flows into manufacturing and agriculture trade. Trade deficit constants $D_1$, $D_{ai}$ and $D_{mi}$ are calculated as total imports minus total exports in the respective sector. Data on total GDP, average real GDP per capita, and current account balance are from the World Bank’s World Development Indicators (WDI) database.

The data on the aggregate expenditure shares $s_{ai}$, $s_{mi}$ and $s_{ni}$, and on $p_{ai}$ are from the Penn World Tables. The input-output tables are from the OECD’s Structural Analysis (STAN) database. Distance and adjacency data are from the Centre d’Études Prospectives et d’Informations Internationales (CEPII). Bilateral tariff data are from the Market Access Map Database (MacMap) which provides tariff data at the HS2 sectoral level. I calculate the average import tariff using the classification identical to the one used for the aggregation of the trade data. Whenever, tariff data were missing in the MacMap database I used tariff data provided by Mayer, Paillacar and Zignago (2008). Data on the distribution of income are from UN-WIDER World Income Inequality Database (WIID). If missing, the data were taken from Klaus and Squire (1996), and/or Milanovic and Yitzhaki (2001).

8.2 Results of the counterfactual experiment

I report all results of the counterfactual experiment in Tables 7-4.

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38Expenditure and price data were not available for all countries in the sample. If missing, the observations were imputed using average real income and price regressions where $p_{ai}$ is a dependant and $\bar{y}_i$ explanatory variable.
## Table 3: Results of the Counterfactual Experiment

| Country | AUT | BDI | BFA | BRA | CAF | CHL | CHN | CIV | COL | CYP | DNK | DOM | EGY | FJI | GBR | GRC | GTM | HOL | HRV | HUN | IND | IRE | ISL | ISR | JPN | KOR | KWT | LBN | LIB | LUK | MAR | MEX | MUS | NGR | NLD | NZL | PAN | PHL | POL | POR | PRY | QAT | ROU | RSA | SGP | SVN | SWE | SYR | THA | TWN | UNG | UMS | USA | VMR | VEN | VIE | YEM | ZAF | ZMB | ZWE |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 2010    | 2.29 | 0.56 | 0.04 | -0.26 | -0.48 | -0.65 | -0.79 | -0.92 | -1.06 | -1.27 | -1.46 | 2.43 | 0.61 | 0.08 | -0.24 | -0.47 | -0.64 | -0.79 | -0.93 | -1.07 | -1.29 | 0.00 | 4.50 |
| 2015    | 3.83 | 2.04 | 1.51 | 1.20 | 0.98 | 0.81 | 0.67 | 0.53 | 0.39 | 0.17 | -0.03 | 3.24 | 1.65 | 1.30 | 1.07 | 0.90 | 0.77 | 0.65 | 0.54 | 0.42 | 0.22 | 1.15 | 2.88 |
| 2020    | 0.74 | -0.10 | -0.21 | -0.23 | -0.21 | -0.16 | -0.09 | 0.00 | 0.11 | 0.30 | 0.38 | 0.38 | -0.32 | -0.37 | -0.35 | -0.29 | -0.20 | -0.10 | 0.02 | 0.16 | 0.42 | -0.05 | 1.02 |
| 2025    | -18.48 | -6.97 | -3.85 | -2.69 | -2.03 | -1.52 | -1.16 | -0.86 | -0.59 | -0.25 | 0.16 | -18.12 | -6.85 | -3.79 | -2.65 | -2.01 | -1.51 | -1.17 | -0.87 | -0.61 | -0.29 | -2.89 | 17.36 |
| 2030    | 9.25 | 6.92 | 5.90 | 5.08 | 4.35 | 3.67 | 2.97 | 2.27 | 1.49 | 0.61 | 0.21 | 10.53 | 8.13 | 7.08 | 6.24 | 5.51 | 4.57 | 3.45 | 2.44 | 1.39 | 0.31 | 5.04 | 1.92 |
| 2035    | 3.65 | 1.77 | 1.19 | 0.84 | 0.59 | 0.40 | 0.23 | 0.08 | -0.08 | -0.34 | -0.57 | 3.58 | 1.72 | 1.16 | 0.82 | 0.58 | 0.39 | 0.23 | 0.08 | -0.08 | -0.32 | 0.90 | 6.42 |
| 2040    | 0.09 | -0.70 | -0.91 | -1.00 | -1.06 | -1.10 | -1.08 | -1.13 | -1.13 | -1.14 | -1.05 | 0.17 | -0.66 | -0.89 | -0.99 | -1.05 | -1.10 | -1.08 | -1.13 | -1.14 | -1.15 | -0.87 | 1.97 |
| 2045    | -0.58 | -0.06 | 0.36 | 0.63 | 0.83 | 1.04 | 1.25 | 1.46 | 1.67 | 1.88 | 2.09 | 2.30 | 2.50 | 2.70 | 2.90 | 3.09 | 3.29 | 3.49 | 3.69 | 3.89 | 4.09 | 4.29 |
| 2055    | 4.29 | 2.82 | 2.48 | 2.32 | 2.25 | 2.22 | 2.22 | 2.25 | 2.32 | 2.47 | 2.59 | 1.98 | 1.90 | 1.91 | 2.01 | 2.10 | 2.22 | 2.36 | 2.56 | 2.90 | 2.25 | 1.61 |
| 2060    | 3.50 | 2.53 | 2.35 | 2.28 | 2.27 | 2.28 | 2.31 | 2.35 | 2.40 | 2.46 | 2.49 | 1.74 | 1.41 | 1.50 | 1.68 | 1.86 | 2.07 | 2.27 | 2.49 | 2.73 | 3.08 | 2.05 | 2.26 |
| 2065    | -34.18 | -3.13 | -0.40 | 0.66 | 1.17 | 1.53 | 1.79 | 1.97 | 2.16 | 2.37 | 2.41 | -34.31 | -3.16 | -0.43 | 0.69 | 1.20 | 1.53 | 1.85 | 2.17 | 2.47 | 0.54 | 6.45 |
| 2070    | 10.99 | 8.39 | 7.14 | 6.06 | 5.09 | 4.17 | 3.25 | 2.33 | 1.49 | 0.61 | 0.21 | 10.16 | 7.53 | 6.29 | 5.34 | 4.50 | 3.65 | 2.76 | 1.84 | 1.39 | 0.31 | 5.04 | 1.92 |

**Notes:**
- AUT = Austria
- BDI = Burundi
- BFA = Benin
- BRA = Brazil
- CAF = Central African Republic
- CHL = Chile
- CHN = China
- CIV = Côte d’Ivoire
- COL = Colombia
- CYP = Cyprus
- DNK = Denmark
- DOM = Dominican Republic
- EGY = Egypt
- FJI = Fiji
- GBR = United Kingdom
- GRC = Greece
- GTM = Guatemala
- HOL = Netherlands
- HRV = Croatia
- HUN = Hungary
- IND = India
- IRE = Ireland
- ISL = Iceland
- ISR = Israel
- JPN = Japan
- KOR = South Korea
- KWT = Kuwait
- LBN = Lebanon
- LIB = Libya
- LUK = Luxembourg
- MAR = Morocco
- MEX = Mexico
- MUS = The United States
- NGR = Nigeria
- NLD = Netherlands
- NZL = New Zealand
- PAN = Panama
- PHL = Philippines
- POL = Poland
- POR = Portugal
- PRY = Peru
- QAT = Qatar
- ROU = Romania
- RSA = South Africa
- SGP = Singapore
- SVN = Slovenia
- SWE = Sweden
- SYR = Syria
- THA = Thailand
- TWN = Taiwan
- UNG = Uganda
- UMS = United States
- USA = United States
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</table>
8.3 Model solution: counterfactual experiment

Dekle, Eaton and Kortum (2007) proposed a way to solve for counterfactual values in Ricardian models by expressing the variables in relative changes and using real data. The advantage of their solution algorithm is the fact that one does not have to estimate unobservable trade cost and technology primitives of the model.

In my counterfactual experiment I uniformly set all tariffs to unity. Given this exogenous change and the data on real income and trade, I can solve for all other counterfactual values as in Table 10.

<table>
<thead>
<tr>
<th>variable</th>
<th>Benchmark</th>
<th>Counterfactual</th>
</tr>
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<tbody>
<tr>
<td>$p_{ai}$</td>
<td>$p_{ai} = (\sum_{\ell} N (\kappa_{ai} \ell t_a, it_{a, it})^{-\theta_a})^{-\frac{1}{\theta_a}}$</td>
<td>$p'<em>{ai} = p</em>{ai} \left( \sum_{\ell} N x_{a, it}(\kappa_{ai} \ell t_a, it)_{a, it})^{-\theta_a} \right)^{-\frac{1}{\theta_a}}$</td>
</tr>
<tr>
<td>$p_{mi}$</td>
<td>$p_{mi} = (\sum_{\ell} N (\kappa_{mi} \ell t_m, it_{m, it})^{-\theta_m})^{-\frac{1}{\theta_m}}$</td>
<td>$p'<em>{mi} = p</em>{mi} \left( \sum_{\ell} N x_{m, it}(\kappa_{mi} \ell t_m, it)_{m, it})^{-\theta_m} \right)^{-\frac{1}{\theta_m}}$</td>
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<tr>
<td>$p_{ni}$</td>
<td>$p_{ni} = \Gamma n (w_{i, t}^{-1 - \nu}) (p_{ni}p_{mi}^{-1 - \phi} \frac{1}{\phi})$</td>
<td>$p'<em>{ni} = p</em>{ni} (\widetilde{w}<em>{i, t}^{-1 - \nu}) (\widetilde{p}</em>{ni} \widetilde{p}_{mi}^{-1 - \phi} \frac{1}{\phi})$</td>
</tr>
<tr>
<td>$x_{m, in}$</td>
<td>$x_{m, in} = (\kappa_{mn} \ell t_m, it_{m, it})^{-\theta_m}$</td>
<td>$x'<em>{m, in} = x</em>{m, in} \left( \kappa_{mn} \ell t_m, it_{m, it})^{-\theta_m} \right)^{-\frac{1}{\theta_m}}$</td>
</tr>
<tr>
<td>$x_{a, in}$</td>
<td>$x_{a, in} = (\kappa_{an} \ell t_a, it_{a, it})^{-\theta_a}$</td>
<td>$x'<em>{a, in} = x</em>{a, in} \left( \kappa_{an} \ell t_a, it_{a, it})^{-\theta_a} \right)^{-\frac{1}{\theta_a}}$</td>
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<td>$y_{id}$</td>
<td>$y_{id} = \frac{w_{i, t}^{1 - \nu} + 1}{(p_{ai}^s p_{mi}^m p_{ni}^n)} + v_i$</td>
<td>$y'<em>{id} = \frac{\widetilde{w}</em>{i, t}^{1 - \nu} + 1}{(p_{ai}^s p_{mi}^m p_{ni}^n)} + v'_i$</td>
</tr>
<tr>
<td>$v_i$</td>
<td>$v_i = e_i + \bar{y}<em>i \sum_n (f</em>{mi} x_{t, in} t_{i, it} + f_{ai} x_{a, in} t_{a, it})$</td>
<td>$v'<em>i = e_i + \bar{y}<em>i \sum_n (f</em>{mi}' x'</em>{t, in} t'<em>{i, it} + f</em>{ai}' x'<em>{a, in} t'</em>{a, it})$</td>
</tr>
<tr>
<td>$\omega_{id}$</td>
<td>$\omega_{id} = y_{id} \frac{p_{ai}^s p_{mi}^m p_{ni}^n}{p_{ai}^s p_{mi}^m p_{ni}^n}$</td>
<td>$\omega'<em>id = y'</em>{id} \frac{\widetilde{p}<em>{ai}^s \widetilde{p}</em>{mi}^m \widetilde{p}<em>{ni}^n}{\widetilde{p}</em>{ai}^s \widetilde{p}<em>{mi}^m \widetilde{p}</em>{ni}^n}$</td>
</tr>
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</table>

Notes: Total per-capita transfers denoted as $v_i$ are calculated as a sum of tariff revenues and exogenous cross-country transfers, $e_i$ (net of trade imbalances).

To solve for the counterfactual change in wages $\widetilde{w}_i$ I use a market clearing condition as in (4.6):
\[
(\hat{w}_i Y_i + V'_i) \sum_{n=1}^{N} (f'_{mi} x'_{i,\text{in}} + f'_{ai} x'_{a,\text{in}}) - D_i = \sum_{n=1}^{N} (\hat{w}_n Y_n + V'_n) (f'_{mn} x'_{m,\text{ni}} + f'_{a,ni} x'_{a,\text{ni}}) \quad (3.39)
\]

In practice, the solution algorithm boils down to finding a fixed point for a series of contraction mappings. For further discussion refer to Alvarez and Lucas (2007) and Dekle, Eaton and Kortum (2007).
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POOLE, W. Free trade: why are economists and noneconomists so far apart? *Presentation to the Globalization and Outsourcing Conference* (June 2004).


4 Asymmetric Trade Costs, Trade Imbalances, and the World Income Distribution

1 Introduction

Pioneered by Eaton and Kortum (2002), the multi-country version of the Ricardian trade model has gained increasing importance as a tool to conduct comparative static analysis with regard to the relative importance of trade costs (geography and tariffs) and technology (total factor productivity) for trade, factor prices, and welfare (see Alvarez and Lucas, 2007; Dekle, Eaton, and Kortum, 2007; Chor, 2010; Donaldson, 2010; Waugh, 2010; Caliendo and Parro, 2011; Costinot, Donaldson, and Komunjer, 2011; Fieler (2011); Levchenko and Zhang, 2011; Shikher, 2011; for a select list of applications of that model).

One merit of this type of model is its amenity to structural estimation whereby all parameters needed for general-equilibrium-consistent comparative static analysis are estimated from the same data the model is calibrated to. While this approach tends to fit the data well, it requires the imposition of general equilibrium constraints in structural estimation to ensure compliance of the fundamental assumptions of the model with the data. The latter is often, if not typically, ignored in estimation of multi-country trade models. As a result, comparative static analysis may result in quantitatively misleading conclusions accruing to a big gap between predictions of the calibrated theoretical model and the data in a benchmark equilibrium.\footnote{In particular, suitable estimates of the vector of bilateral trade costs are vital for a quantification of the magnitude of marginal or discrete changes in trade costs on trade flows and other outcomes not only in a model as the one of Eaton and Kortum (2002) but in all so-called new trade theory models (see Krugman, 1979; Anderson and van Wincoop, 2003; Arkolakis, Costinot, and Rodriguez-Clare, 2010; for examples).} A key constraint in all structural multi-country models of bilateral trade is the one on “goods” (potentially encompassing services) market clearance...
by way of a multilateral trade balance condition (as is underlying the models of Alvarez and Lucas, 2007; or Waugh, 2010) or a multilateral trade imbalance condition (see Dekle, Eaton, and Kortum, 2007, for an example). We will demonstrate how important this constraint is for estimation and comparative static analysis when analyzing the question about the importance of exporting country-specific goods market access asymmetries for per-capita income differences around the globe. In a recent article, Waugh (2010) examined this question and produced two stunning findings. First, estimated exporter-specific trade costs are highly correlated with real per-capita income across countries. Second, eliminating the asymmetry in such trade costs reduces the world-wide variance in real per-capita income by 20%-33% (depending on the measure). Utilizing the same data-set and theoretical model, we arrive at a starkly different conclusion: eliminating exporter trade cost heterogeneity has only little bearing for real per-capita income variability across countries. This stark difference in the results has two main roots.

First, general equilibrium constraints are assumed in the theoretical models of Eaton and Kortum (2002) and Waugh (2010), and this assumption is necessary for the identification strategy of asymmetries in exporter-specific (unobserved) trade costs in Waugh (2010). Yet, Waugh’s structural empirical model does not respect this constraint (neither by imposing multilateral trade balances nor trade imbalances of a certain extent across the included countries) so that estimated exporter trade cost asymmetries partly reflect observable trade imbalances rather than trade costs alone. It turns out that poor countries in the sample display systematically greater trade deficits than developed countries so that a significant share of the correlation between the estimated exporter-specific trade costs and data on real per-capita income accrues to issues which lie beyond the utilized theoretical model. By way of general equilibrium constraints, trade imbalances affect factor prices. Both factor prices and exporter market access costs are captured by country fixed effects.

40 The latter fixes observations on countries’ trade imbalances and embeds those imbalances as parameters in the multilateral trade balance condition so that trade is balanced up to some country-specific constant.
in estimation. A model which assumes balanced trade or does not explicitly account for imbalances among the included countries results in biased country-specific effects in the sense that they do not jointly predict data on trade flows and income (GDP) without bias but eventually only the former. From the perspective of a model of trade and income (when predicting per-capita income differences is at stake), this results in biased effects of exporter-specific trade costs, technology, or factor prices.

Second, the counterfactual experiment conducted in Waugh contradicts the specified model. Given geography which specifies the symmetric level of trade costs in Waugh (2010), the counterfactual level of trade costs can not be generated by country-specific changes in export trade costs. As a consequence, the counterfactual trade cost matrix can only be generated by big country-pair-specific (i.e., preferential) changes in trade cost levels which are inconceivable within the the adopted theoretical model and available trade instruments. Moreover, Waugh’s experiment does not systematically reduce the asymmetry in exporter-specific trade costs, but it mainly changes the level of all trade costs. It turns out that reducing the exporter trade cost asymmetry per se has only little bearing for the global dispersion of real per-capita income. Hence, offering symmetric world market access to the poor will not close their gap in per-capita income to the richest in a substantial way.

The remainder of the paper is organized as follows. The next subsection briefly outlines the model. Section 3 characterizes our estimation strategy and reports the results while Section 4 describes our calibration procedure. Section 5 documents findings from a counterfactual analysis and Section 6 concludes.

\[41\] That reductions of trade friction levels are correlated with the income convergence across countries is a well-established result; see Ben-David (1993), Sachs and Warner (1995), Frankel and Romer (1999), Krueger and Berg (2003), Wacziarg and Horn Welch (2003).
We employ an Eaton-Kortum type model to infer about the importance of exporter-specific trade cost asymmetries for the dispersion of real per-capita incomes across countries. There are $N$ countries which are indexed by $i$ and endowed with $L_i$ units of labor and $K_i$ units of capital. Labor and capital are mobile domestically (across sectors) but not internationally. Each country produces in two sectors, tradable goods and non-tradables. Bilateral trade is costly and impeded by iceberg costs so that a single unit of consumption in country $i$ requires shipping of $t_{ij} \geq 1$ units from country $j$.

**Tradable sector:**

Each country hosts a *continuum* of firms in the tradable sector. Firms in the tradable sector of country $i$ face variable (and marginal) costs of $c_{ti}$ per efficiency unit. The firm producing variety $j$ operates at a total factor productivity $z(j)^{-\theta}$, with $z(j)$ being drawn from a country-specific exponential distribution with mean $\lambda_i$. The technology for producing output $q_{ti}(j)$ of variety $j$ in $i$ may be specified as:

$$q_{ti}(j) = z(j)^{-\theta}(r_i^{1-\alpha_i}k_i^{\alpha_i})^{\beta}q_{ti}^{1-\beta}, \quad (4.1)$$

where $r_i$, $k_i$, and $q_{ti}$ are labor, capital, and composite tradable good inputs, respectively. The composite tradable good $q_{ti}$ is produced via a standard Spence-Dixit-Stiglitz (SDS) CES technology that combines the cheapest available goods that are either produced domestically or imported (subject to trade costs). Using properties of the exponential distribution, it is straightforward to show that the price of the composite tradable good $p_{ti}$ is:

$$p_{ti} = \Omega_i \sum_j \left( \lambda_j \left( (w_j^{1-\alpha_j}r_j^{\alpha_j})^{\beta}P_{ij}^{1-\beta}t_{ij} \right)^{-\frac{1}{\beta}} \right)^{-\theta} = \Omega_i \left( \sum_j (c_{tj}t_{ij})^{-\frac{1}{\beta}} \right)^{-\theta}, \quad (4.2)$$

---

42. In this model, per-capita income and GDP per worker are equivalent.

43. We make the usual triangularity assumption that rules out opportunities for arbitrage.
where \( \Omega_t \) is a sector-specific constant, \( w_j \) is the wage rate in \( j \), \( r_j \) is the returns to capital in \( j \), \( p_{tj} \) is the price of tradable inputs in \( j \), and \( t_{ij} \) are trade costs on tradables produced in \( j \) and shipped to \( i \). Accordingly, \( c_{ni} = \lambda_i^{-\theta}(w_i^{1-\alpha}r_i^\alpha)^{\beta}p_{t_i}^{1-\beta} \) are the marginal (and variable) costs of a producer of tradable goods in \( i \).

**Nontradable sector:**

We assume that each country runs one representative firm in the non-tradable sector which operates at an identical Cobb-Douglas technology world-wide. Output of the non-tradable final good \( q_{ni} \) in country \( i \) is produced at

\[
q_{ni} = (r_i^{1-\alpha}k_i^\alpha)^\gamma q_{t_i}^{1-\gamma}. 
\tag{4.3}
\]

The price of the final non-tradable good is then:

\[
p_{ni} = \Omega_n(w_i^{1-\alpha}r_i^\alpha)^\gamma p_{t_i}^{1-\gamma} = \Omega_n c_{ni}, \tag{4.4}
\]

where \( \Omega_n \) is a sector-specific constant and \( c_{ni} \) are the variable (and marginal) unit costs a firm in country \( i \)'s nontradable sector faces.

**International trade:**

Recall that \( c_{ti} = \lambda_i^{-\theta}(w_i^{1-\alpha}r_i^\alpha)^{\beta}p_{t_i}^{1-\beta} \) is the marginal (and variable) cost of a producer of tradable goods in \( i \). Use \( M_{ij} \) to denote aggregate nominal imports of country \( i \) from \( j \) and \( Y_{ti} \) to denote \( i \)'s total spending on tradables. Then, through the properties of the exponential distribution, country \( i \) spends a share \( X_{ij} \equiv M_{ij}/Y_{ti} \) on tradable goods from \( j \), and

\[
X_{ij} = \frac{(c_{ij}t_{ij})^{-\frac{1}{\theta}}}{\sum_{\ell}(c_{\ell t}\ell^{-\frac{1}{\theta}}). \tag{4.5}
\]

**Goods market clearance:**

All prices can be expressed in terms of the primitives of the model \( L_i, K_i, t_{ij}, \lambda_i \) and
other technology parameters, and a wage vector with typical element \( w_i \). It is customary to solve for \( w_i \) via the international goods market clearance condition which simply states that total expenditures of country \( i \) on tradables must equal total sales of all countries \( j \) (including \( i \)) to customers in \( i \). This market clearance condition can be stated for balanced trade between all countries \( j \) (see Eaton and Kortum, 2002; Alvarez and Lucas, 2007) or unbalanced trade (see Dekle, Eaton, and Kortum, 2007). Since goods trade is not balanced among the countries included in most data-sets (as the one we use), a natural way to proceed is to assume imbalanced trade upfront.

Let \( T_{ti} = \sum_{j=1}^{N} M_{ji} \) denote the total value of tradable goods produced in \( i \) and \( Y_{ti} = \sum_{j=1}^{N} M_{ij} \) be country \( i \)'s total value of consumption of tradables. Then, we may define

\[
B_i = \frac{\sum_{j=1}^{N} (M_{ij} - M_{ji})}{\sum_{j=1}^{N} M_{ij}} \equiv \frac{Y_{ti} - T_{ti}}{Y_{ti}} \quad (4.6)
\]

as a measure of normalized (by apparent consumption) multilateral trade deficit. Hence, we simply state that the ratio of \( i \)'s total income to expenditure is some constant \((1 - B_i)\).\(^{44}\)

At an observed value of \( B_i \) and after replacing \( M_{ji} = X_{ji}Y_{tj} \) in (4.6), we can derive the aggregate market clearance condition:

\[
L_iw_i = \sum_{j=1}^{N} X_{ji} L_jw_j \left(1 - B_j\right). \quad (4.7)
\]

Of course, at \( B_i = 0 \) for all countries \( i \), we are in a standard equilibrium with balanced trade as in Eaton and Kortum, Alvarez and Lucas (2007), or Waugh (2010).

We can classify the fundamentals of the model into three categories. The first category consists of the observable endowments of labor and capital \( \{L_i, K_i\} \). The second category
includes unobservable primitives, namely the bilateral trade cost parameters \{τ_{ij}, ξ_j\}, that have to be estimated from a structural stochastic version of equation (4.5). Finally, technology parameters \{α, β, γ, λ_i, θ\} have to be either estimated from stochastic versions of equations (4.1) and (4.4) or otherwise calibrated to the data. We will discuss in particular the calibration of λ_i in Section 4 and also the choice of the remaining technology parameters in the Appendix.

3 Estimation

In this subsection, we show how to estimate \{τ_{ij}, ξ_j\} consistently with all assumptions of the model. If we normalize (4.5) by the share of domestic sales of tradables in total spending on tradables, \(X_{ii} \equiv M_{ii}/Y_{ti} = 1 - \sum_{j \neq i}^N X_{ij}\), we arrive at the deterministic relative gravity equation:

\[
\frac{X_{ij}}{X_{ii}} = \left(\frac{c_{ij} t_{ij}}{c_{ii} t_{ii}}\right)^{-\frac{1}{\theta}}.
\] (4.8)

The stochastic counterpart to (4.8) can then be expressed as:

\[
\frac{X_{ij}}{X_{ii}} = \exp \left(s_j - s_i + ξ_j + \sum_{k=1}^K β_k τ_{k,ij} + u_{ij}\right) \text{ or } \ln \frac{X_{ij}}{X_{ii}} = s_j - s_i + ξ_j + \sum_{k=1}^K β_k τ_{k,ij} + v_{ij},
\] (4.9)

where \(s_j\) and \(s_i\) are country-specific catch-all variables associated with producer prices and technology parameters of countries \(j\) and \(i\), respectively. By design, \(s_j = s_i\) whenever \(i = j\). \(u_{ij}\) and \(v_{ij}\) are stochastic terms for the models in levels and logs, respectively.

In estimating (4.8), structural empirical work typically adopts three assumptions:

(i) The stochastic counterpart to (4.8) involves either an additive or a multiplicative error term as in (4.9).

(ii) Trade costs \(t_{ij}^{-\frac{1}{\theta}}\) are modeled multiplicatively as \(t_{ij}^{-\frac{1}{\theta}} = \exp \left(ξ_j + \sum_{k=1}^K β_k τ_{k,ij}\right)\),

\[45\] See Santos Silva and Tenreyro (2006) on how the two translate into each other under specific assumptions with exponential-family-type econometric models.
where $\tau_{k,ij}$ is the $k$th observable measure of log trade costs such as log bilateral distance or an adjacency indicator and $\xi_j$ is a measure of unobservable (net) asymmetric trade costs for exporter $j$. Let us denote total symmetric trade costs as $\tau_{ij} \equiv \sum_{k=1}^{K} \beta_k \tau_{k,ij}$, then we can express total iceberg trade costs as:

$$t_{ij} \equiv \exp (-\theta \xi_j - \theta \tau_{ij}).$$

(ii) The symmetric component of trade costs $\tau_{ij}$ can be specified as

$$\tau_{ij} = \beta_1 \text{adjacency}_{ij} + \beta_2 \ln(distance_{1,ij}) + \ldots + \beta_7 \ln(distance_{6,ij}), \quad (4.11)$$

where $distance_{s,ij}$ is an indicator variable referring to the $s$th sextile of the distribution of the great circle distance between two countries $i$ and $j$. Alternatively, one could replace $\beta_2 \ln(distance_{1,ij}) + \ldots + \beta_7 \ln(distance_{6,ij})$ by $\psi \ln(distance_{ij})$.

Notice that the model principally assumes that $t_{ij} \geq 1$. However, this assumption is missing from the above list, hence, not translated into an ex-ante constraint in the estimation procedure. As a consequence, there is no guarantee that the predicted total trade costs adhere to this assumption. Some authors such as Waugh (2010) adjust trade costs for those country-pairs $ij$ where $t_{ij} < 1$ ex post which leads to biased marginal effects and is not in line with the general equilibrium approach. It is clear that an estimator with a properly specified ex-ante constraint of ($\min \hat{t}_{ij} \geq 1$) will lead to different estimates $t_{ij}$ than such a procedure. Clearly, the latter involves a gap between estimation and model calibration while the former does not.

Even more importantly, notice that estimating $t_{ij}$ based on $N(N-1)$ observations for country-pairs ($N$ equations on pairs all $ii$ are disregarded) without imposing goods

\footnote{One could include \textit{importer fixed effects} by replacing $\xi_j$ by $\xi_i$ instead. However, we follow Waugh (2010) through including \textit{exporter fixed effects} so that $t_{ij}^{\frac{1}{2}}$ is defined exactly as in (ii).}
market clearance instead of a stochastic version of $N(N-1)$ observations subject to $N$ constraints (4.7) is not the same and will almost always give very different results. The reason for this is that intranational sales $X_{ii}$ are very important and predicting bilateral international trade flows well does not guarantee to predict income or total goods sales $T_{ti}$ or total goods expenditures $Y_{ti}$ well. In some sense, disregarding (4.7) entails a model under-specification. Clearly, an approach which respects the $N$ constraints (4.7) should be able to match model estimates on total income (GDP) and, hence, real per capita income much better than one that does not.

In the context of the notation used in (4.9), we can rewrite the goods market clearance constraint in (4.7) as

$$ Y_{ti} = \frac{\sum_{j=1}^{N} \exp(s_{i} + \xi_{i} + \tau_{ji}) Y_{ij},}{\sum_{j=1}^{N} \exp(s_{t} + \xi_{t} + \tau_{j} \xi_{j}) (1 - B_{j})}, $$

(4.12)

where $Y_{ij}$ are the observed total sales of goods in country $j$. We argue that an imposition of $N$ constraints (4.12) in conjunction with the $N(N-1)$ observations on international trade in (4.9) will eventually lead to different estimates of $s_{i}$, $\xi_{i}$, and $\tau_{ji}$ than estimating (4.9) without this constraint. In particular, imposition of (4.12) will give the prediction of $Y_{ti}$ (which is proportional to total income and real income per capita) some weight which should ensure that total income and, in turn, per-capita income may be predicted better by the structural model than when disregarding (4.12) in estimation. Hence, we may summarize the two fundamental reasons for why respecting (4.12) is important as follows.

(i) The constraint (4.12) serves as an additional moment condition in (4.12) and allows to use observations on $Y_{ti}$, which is proportional to real GDP in the current context. As a consequence, the constrained model predicts real per-capita income as the variable of interest considerably better than the unconstrained one.
(ii) Estimating \([4.9]\) subject to \([4.12]\) may lead to different estimates of \(s_i, \xi_j, \tau_{ij}\), which affects the quantitative effects of changes of, say, \(\xi_j\) or \(\tau_{ij}\) in general equilibrium.

Formally, we estimate the model in levels in \([4.9]\) by maximizing the corresponding Poisson Pseudo Maximum Likelihood objective function subject to three constraints: market clearance by way of \([4.12]\) where \(Y_{ti}\) is total manufacturing absorption (which can be substituted by total real GDP); that the individual \(\xi_j\) sum up to zero (as in Waugh, 2010); and that \((\min \hat{t}_{ij} \geq 1)\).

It turns out that there are considerable differences between the estimates of \(s_i\) and \(\xi_j\) in a model which disregards the constraint in \([4.12]\) versus one that does not. We report estimates of the exporter-specific asymmetric (log) trade costs, \(\hat{\xi}_j\), the fixed effects \(\hat{s}_i\), and the parameters of the symmetric component of trade costs \(\tau_{k,ij}\) for (i) the PPML model which disregards the market clearance constraint \([4.12]\), (ii) constrained PPML which imposes market clearance but assumes \(B_i = 0\) for all \(i\), and (iii) PPML which imposes market clearance with \(B_i \neq 0\). The corresponding results are summarized in Table 6.

There are large differences in the estimated exporter effects \(\hat{\xi}_j\) between the unconstrained and the constrained estimates. For example, unconstrained results as in (i) suggest that \(100 \times (e^{-\theta \hat{\xi}_j} - 1)\) – i.e., the observable trade cost amplification factor of unobservable exporter-specific trade costs – of Benin and Rwanda amounts to 78% and 103%, respectively. The corresponding numbers for these two countries in the constrained model as in (ii) are 45% and 62%, respectively. These numbers are 47% and 57%, respectively, in the constrained model as in (iii). Hence, we conclude that ignoring goods market clearance biases coefficients of fundamental interest to a considerable degree.

\[\text{footnote}{Our results do not depend crucially on whether one estimates \([4.9]\) in logs via OLS or in levels via PPML (see Santos Silva and Tenreyro (2006) for a discussion of the difference between the two approaches).}\]
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Notes: Standard errors are reported in parentheses and are based on Eicker-White sandwich estimates. The reported $Pseudo - R^2$ corresponds to the correlation between observed and predicted values of the dependent variable.
4 Calibration

Estimating $\xi_j$ and $\tau_{ij}$ consistent with the theoretical model is important but not enough. We also need the parameters $\{\alpha, \beta, \gamma, \lambda_i, \theta\}$ in order to conduct counterfactual experiments. Let us relegate the choice of parameters $\{\alpha, \beta, \gamma, \theta\}$ to the Appendix and focus on the calibration of country-specific productivity parameter $\lambda_i$, here.

First, given trade flows $X_{ji}$ for all $ji$ and $L_j$ and $B_j$ for all $j$, we can solve for the vector of wages with element $w_i$ from the market clearance condition:

$$L_iw_i = \sum_{j=1}^{N} X_{ji} \frac{L_jw_j}{1 - B_j}. \quad (4.13)$$

Given $w_i$, we can express the price of tradables $p_{ti}$ in (4.2) and returns to capital $r_i$ from the first-order conditions of the final good producer. Recall that $\exp(-\theta s_i) \equiv c_{ij} = \lambda_i^{-\theta}(w_1^{1-\alpha} r_i^\alpha)^\beta p_{ti}^{1-\beta}$. Hence, given solutions for $w_i$, $r_i$ and $p_{ti}$ we can recover $\lambda_i$ from $s_i$.

The crucial point in the calibration procedure is selecting parameters so as to match data on the key variables of interest in the best possible way.

Balanced Trade

In reality trade is not balanced. In the sample of 77 countries used in this study the average value of $B_i$ is 0.16 with a standard deviation of 0.21. Imbalances are strongly correlated with real GDP per capita (the correlation coefficient is $-0.54$) and are higher for less developed countries. For some countries, trade imbalances are as high as 80% of total absorption in manufacturing.

However, it may be convenient to assume that trade is balanced ($B_i = 0$ for all $i$) nonetheless for two reasons. First, the solution of the model becomes slightly easier computationally.

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48 Clearly, for solutions of $w_i$ which are consistent with the estimated model, we need to use predictions $\hat{X}_{ji}$ rather than observations $X_{ji}$ in (4.13).

49 In practice, this calibration involves an iterative procedure until the fixed point in $\{w_i, r_i, p_{ti}, \lambda_i\}$ is found.
tionally. Second, disregarding imbalances may result in comparative static effects which are, on average, not too dissimilar from the ones of a model which allows for imbalanced trade. For the data at hand, assuming multilaterally balanced trade does not entail a severe bias if this assumption is imposed in the estimation and calibration procedures. Assuming balanced trade in estimation of (4.9) is straightforward. We simply modify the constraint in (4.12) by setting $B_i = 0$ for all $i$ so as to obtain

$$Y_{ti} = \sum_{j=1}^{N} \frac{\exp(s_i + \xi_i + \tau_{ji})}{\sum_{\ell=1}^{N} \exp(s_{\ell} + \xi_{\ell} + \tau_{j\ell})} Y_{tj}. \quad (4.14)$$

Notice that in the presence of imbalanced trade in the data the imposition of balanced trade in equilibrium renders the use of $\hat{X}_{ji}$ instead of $X_{ji}$ particularly pertinent in (4.13). In what follows, we refer to the approach which assumes balanced trade in the estimation of (4.9) subject to (4.12) given data on $Y_{ti}$ and the corresponding calibration of $\lambda_i$ as Model A.

**Unbalanced Trade**

The data on $B_i$ are observable. With this approach, we estimate (4.9) subject to (4.12) given the data on $B_i$ and $Y_{ti}$. Here, we can use data $X_{ij}$ rather than predictions $\hat{X}_{ij}$ in (4.13) to recover $\lambda_i$, since $B_i$ inter alia absorbs all differences between $X_{ij}$ and $\hat{X}_{ij}$ in the aggregate for a country. In what follows, we refer to this approach as Model B.

We argue that Models A and B significantly outperform more common estimation/calibration approaches such as running (4.9) without using the information in (4.12) and calibrating the model to the data on trade shares ignoring imbalances in (4.13).
(model C) as in Waugh (2010) or running (4.9) without using the information in (4.12) and calibrating the model to the data on trade shares and imbalances in (4.13) (model D).

4.1 Quantitative comparison of Models A-D

To demonstrate that Models A and B are preferable over Models C and D, we compare the fit of calibration between these models with respect to the central variable of interest, namely real GDP per capita, $y_i$. In Figure 10, we plot the deviation of the prediction of $y_i$ from its true value (we define it as a ratio of true $y_i$ to the model’s prediction) against the data on imbalances $B_i$ using Waugh’s original estimates by way of Model C (left panel) and Model A (right panel).

The left panel clearly indicates that $y_i$ is consistently overpredicted in Waugh (2010) for those countries with higher trade imbalances and underpredicted for those with lower imbalances. On the other hand, consistent with the assumption of balanced trade Model A’s error in predicting $y_i$ is purely random with respect to the data on imbalances $B_i$.

The difference becomes even more transparent in Figure 18 where we plot the data on $y_i$ versus predictions of Models A-D. First, predictions of Model A and Model B are very close to each other and predict the data well for both poor and rich countries. Model C (Waugh’s, 2010, benchmark model) consistently overpredicts $y_i$ for both rich and poor countries but by a considerably larger margin for rich countries. Finally, Model D does

---

Waugh (2010) assumes that the trade is balanced in his theoretical model. However, he estimates a log-linear version of (4.9) without the constraint in (4.12) and calibrates the model based on $B_i = 0$ for all $i$ to the data on trade shares $X_{ij}$. This is exactly what is done in Model C. Accordingly Model C is based on OLS, while Models A, B, and D are based on PPML. Moreover, Models A, B, and D use a calibration which fits the data better than the one used by Waugh (2010) and Model C (see the Appendix for details). Hence, there is a discrepancy between Model C and the other ones which relates also to the estimator and parametrization used rather than the structural model implementation alone. However, we can show that neither using OLS versus PPML nor using one or the other calibration is elemental for the differences in the comparative static results between those models. But rather the main drivers are the lack of imposition of (4.12) which leads to biased estimates of $s_j$, $\xi_j$, and $\tau_{ij}$ and the use of unbalanced trade data $X_{ij}$ rather than balanced model predictions $\hat{X}_{ij}$ in calibrating $\lambda_i$ through (4.13). Hence, there are fundamental gaps between the theoretical model and its implementation which lead to predictions of $y_i$ that are biased as will be shown below.
better than Model C in terms of poor countries and worse in terms of rich countries.

We also compare the predictions of these four models with respect to $y_i$ in Table 10, where we report the first two moments of the distribution of $y_i$ and two inequality measures that we will employ in the counterfactual experiments below: the variance in log real per-capita income across countries ($\text{var}(\ln y_i)$) and the 90-to-10 centile gap in real per capita income ($y_{90}/y_{10}$).

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Data</th>
<th>Model A</th>
<th>Model B</th>
<th>Model C</th>
<th>Model D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.34</td>
<td>0.35</td>
<td>0.36</td>
<td>0.47</td>
<td>0.43</td>
</tr>
<tr>
<td>Variance</td>
<td>0.09</td>
<td>0.10</td>
<td>0.10</td>
<td>0.20</td>
<td>0.19</td>
</tr>
<tr>
<td>$\text{var}(\ln y_i)$</td>
<td>1.38</td>
<td>1.39</td>
<td>1.37</td>
<td>1.30</td>
<td>1.67</td>
</tr>
<tr>
<td>$y_{90}/y_{10}$</td>
<td>25.6</td>
<td>20.9</td>
<td>21.3</td>
<td>25.7</td>
<td>29.3</td>
</tr>
</tbody>
</table>

Quite obviously, Models A and B significantly outperform Model C (Waugh, 2010) and Model D in terms of matching the data on $y_i$.

5 Comparative static analysis

In this subsection, we ask how the world income distribution would change if all exporters were granted identical market access so that trade costs were bilaterally symmetric. First,
we show that Waugh’s (2010) results were partly driven by the aforementioned problems with estimation and calibration. Second, we demonstrate that Waugh’s counterfactual experiments largely contradict one of the key assumptions of the model and cannot answer the question at hand. Then, we conduct two novel counterfactual experiments and show that a complete elimination of asymmetries would have a negligible impact on the world income distribution.

The central counterfactual exercise in Waugh (2010) boils down to setting counterfactual total trade costs to

$$t_{ij}^c = \min(t_{ij}, \hat{t}_{ji}).$$

(4.15)
Waugh (2010) claims that this allows one to quantify the effect of an elimination of export market access asymmetries on world income inequality.

We set $t_{ij}^c = \min(\hat{t}_{ij}, \hat{t}_{ji})$ for Model A and Model B and compare the response of $\log y_i$ and $y_{90}/y_{10}$ implied by these models to Waugh’s (2010) results. The results are reported in Table 7. We report two results for Model B. They reflect two different assumptions on the response of $B_i$ to changes in trade costs. First, we assume that trade imbalances do not respond to a reduction in trade costs - $B_i^c = B_i$. We view this as a lower bound and denote it by Model B(L). Second, we assume that trade imbalances are elastic to the level of trade costs and $B_i^c = 0$ for all $i$. We consider this as an upper bound and denote this model by Model B(U). We discuss why these two extremes constitute lower and upper bounds in the following subsection.

Table 8: World Income Distribution and Trade Costs

<table>
<thead>
<tr>
<th>Model</th>
<th>Model</th>
<th>$\log y_i$</th>
<th>change in %</th>
<th>$y_{90}/y_{10}$</th>
<th>change in %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Benchmark</td>
<td>$\min(t_{ij}, t_{ji})$</td>
<td>Benchmark</td>
<td>$\min(t_{ij}, t_{ji})$</td>
<td>Benchmark</td>
</tr>
<tr>
<td>Waugh (2010)</td>
<td>1.30</td>
<td>1.05</td>
<td>$-20%$</td>
<td>25.7</td>
<td>17.3</td>
</tr>
<tr>
<td>Model A</td>
<td>1.39</td>
<td>1.22</td>
<td>$-12%$</td>
<td>20.9</td>
<td>17.92</td>
</tr>
<tr>
<td>Model B(U)</td>
<td>1.37</td>
<td>1.23</td>
<td>$-10%$</td>
<td>21.3</td>
<td>18.3</td>
</tr>
<tr>
<td>Model B(L)</td>
<td>1.37</td>
<td>1.24</td>
<td>$-10%$</td>
<td>21.3</td>
<td>18.4</td>
</tr>
</tbody>
</table>

Table 7 reveals that Waugh’s (2010) claims are largely driven by the aforementioned problems in the model estimation and calibration. Waugh (2010) overestimates the impact of the changes in trade costs on international income differences by a factor of two for $\log y_i$ and by an even larger margin for $y_{90}/y_{10}$.

Yet, we argue that setting $t_{ij}^c = \min(\hat{t}_{ij}, \hat{t}_{ji})$ is only vaguely related to a reduction of asymmetric exporter-specific trade costs and the results in Table 7 should be interpreted with caution. Notice that this counterfactual experiment entails an extremely large exogenous reduction in all trade costs, not only asymmetric exporter-specific ones. To see
this, consider the following. Recall that total trade costs from (4.9) are

\[ \hat{t} = \exp \left( -\theta \hat{\xi}_j - \theta \hat{\tau}_{ij} \right), \]  

(4.16)

where \( \hat{\xi}_j \) is the exporter-specific asymmetric component and \( \hat{\tau}_{ij} \) is the parameterized bilateral symmetric component of trade costs. However, \( \hat{t}_{ij}^c = \min(\hat{t}_{ij}, \hat{t}_{ji}) \) in the context of the theoretical model and at constant \( \hat{\tau}_{ij}^c = \hat{\tau}_{ij} \) (distance, etc., is held fixed) requires that the estimated exporter fixed effect \( \hat{\xi}_j \) – a unilateral, single-indexed variable – must take an \( ij \)- (double) index in counterfactual equilibrium to enable \( \hat{t}_{ij}^c = \min(\hat{t}_{ij}, \hat{t}_{ji}) \). Hence, at constant \( \hat{\tau}_{ij} \) as assumed in Waugh (2010) the counterfactual equilibrium is inconsistent with the specifications in (4.9) and (4.16).

Notice that one key identification assumption in Waugh (2010) is that \( \xi_j \) must be exporter-specific and cannot vary across importers. Let us fix \( \hat{\tau}_{ij}^c = \hat{\tau}_{ij} \) and decompose \( \hat{t}_{ij}^c \) as follows:

\[ \hat{t}_{ij}^c = \min(\hat{t}_{ij}, \hat{t}_{ji}) = \exp \left( -\theta \tau_{ij} - \theta \max(\hat{\xi}_i, \hat{\xi}_j) \right). \]  

(4.17)

Hence, we should be able to recover \( \hat{\xi}_j^c \) as follows:

\[ \hat{\xi}_j^c = \max(\hat{\xi}_i, \hat{\xi}_j) = -\frac{1}{\theta} \ln(\hat{t}_{ij}^c) - \hat{\tau}_{ij} \]  

(4.18)

In order for \( \hat{\xi}_j^c \) to satisfy (4.16) – a key identification assumption – it cannot vary across importers and, hence, it must be the case that

\[ \hat{\xi}_j^c = \max(\hat{\xi}_k, \hat{\xi}_j) \text{ for all } k \]  

(4.19)

Notice that (4.19) can hold if \( \hat{\xi}_j = \max(\hat{\xi}_k) \) or \( \hat{\xi}_j = \hat{\xi}_k \) for all \( k \). In either case, the variance of \( \hat{\xi}_j \) would have to be zero. Certainly, this is not the case as can be seen from Waugh’s (2010) estimates.
To give an example, we illustrate in Figure 12 to which extent Zimbabwe’s counterfactual $\hat{\xi}_{ZWE}$ has to vary across importers to accommodate (4.17). Obviously, $\hat{\xi}_{ZWE}$ varies tremendously across importers $i$ which is inconsistent with the identification assumption of the model. In the figure, we plot the average $\hat{\xi}_{ZWE} = \frac{N}{N-1} \sum_{i=1}^{N} \hat{\xi}_{ZWE,i} = 0.45$ as a solid horizontal line. The standard deviation of $\hat{\xi}_{ZWE,i}$ amounts to 2.14. A variance decomposition of $\hat{\xi}_j$ derived as in (4.18) versus $\hat{\xi}_{c,j}$ for all exporting countries in the data is given in the upper bloc of Table 9.

By construction, all of the variation of $\hat{\xi}_j$ is exporter-specific in the outset. Yet, in counterfactual equilibrium $\hat{\xi}_j$ is not exporter-specific and only about 40% of the variance in $\hat{\xi}_j$ is exporter-specific, while the rest is attributed to the variance across country-pairs. Notice that if $\hat{\xi}_j$ had been constructed like that, it could not have been identified! The reason is that, unlike $\hat{\tau}_{ij}$, which is based on observable variables such as distance, nothing about $\hat{\xi}_j$ is observable. Hence, beyond the problems associated with the lack of imposition of market clearance, Waugh’s (2010) counterfactual model is inconsistent with the identifying assumptions that have to be met in order to estimate $\xi_j$ consistently. This also shows in the variance decomposition of $\hat{t}_{ij}$ and $\hat{t}_{ij}^c$ in the lower bloc of Table 9.

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Figure 12: $\hat{\xi}_{ZWE}$ ACROSS IMPORTERS $i$
Table 9: Variance Decomposition of $\hat{\xi}_j$, $\hat{\xi}^c_j$, $\hat{t}_{ij}$, and $\hat{t}^c_{ij}$

<table>
<thead>
<tr>
<th>Variance component</th>
<th>$\xi_j$ Sum of Squares</th>
<th>$\xi^c_j$ Sum of Squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exporter-specific</td>
<td>41851.63</td>
<td>11723.08</td>
</tr>
<tr>
<td>Residual (Pair-specific)</td>
<td>0</td>
<td>16777.78</td>
</tr>
<tr>
<td>Total</td>
<td>41851.63</td>
<td>28500.86</td>
</tr>
<tr>
<td>Adj. R²</td>
<td>1</td>
<td>0.41</td>
</tr>
<tr>
<td>Observations (Pairs)</td>
<td>5,852</td>
<td>5,852</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variance component</th>
<th>$t_{ij}$ Sum of Squares</th>
<th>$t^c_{ij}$ Sum of Squares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exporter-specific</td>
<td>33016.86</td>
<td>4877.70</td>
</tr>
<tr>
<td>Residual (Pair-specific)</td>
<td>6359.02</td>
<td>10873.40</td>
</tr>
<tr>
<td>Total</td>
<td>39375.88</td>
<td>15751.09</td>
</tr>
<tr>
<td>Adj. R²</td>
<td>0.84</td>
<td>0.30</td>
</tr>
<tr>
<td>Observations (Pairs)</td>
<td>5,852</td>
<td>5,852</td>
</tr>
</tbody>
</table>

We plot total trade costs in the benchmark versus their respective counterfactual values in Figure [13]. To facilitate an easy comparison between the benchmark and counterfactual trade costs we plot them in the familiar iceberg form. We also plot benchmark average trade costs and their counterfactual counterpart as solid vertical and horizontal lines, respectively. Notice that all bilateral trade costs have unambiguously decreased from the benchmark to the counterfactual equilibrium as is clear from setting $t^c_{ij} = \min(\hat{t}_{ij}, \hat{t}^c_{ji})$. 

Figure 13: $\hat{t}_{ij}$ versus $\hat{t}^c_{ij}$
The average trade cost fell by more than one-third! However, what is interesting to see is that a blunt reduction of all trade costs by one-third would not be enough to generate the effects on trade flows in Waugh (2010). It turns out that it is necessary to completely eliminate exporter-specific trade costs and to reduce all bilateral trade costs by more than 25% in order to generate the desired impact on bilateral exports. Hence, symmetric exporter-specific market access can in no way induce the effect found in Waugh (2010).

5.1 Asymmetric trade costs and income differences

To assess the importance of the asymmetric component of trade costs on the world income distribution, let us use Models A and B. There is a clear trade off between these two models in terms of matching the data on trade imbalances and assumptions about $B_i$.

An advantage of Model A is that we do not have to make assumptions about the response of $B_i$ to changes in $\xi_i$. However, this model cannot match the data on trade imbalances. On the other hand, Model B helps predicting further features of the data (i.e., trade imbalances) at the cost of additional, potentially restrictive assumptions with regard to the response of $B_i$ to exogenous shocks.

To maximize the accuracy of our counterfactual outcomes we employ both models. With regard to Model B and the response of $B_i$ to changes in $\xi_j$ we adopt two alternative assumptions. First, we assume that trade imbalances are completely inelastic to $\xi_j$. This approach is in the spirit of Caliendo and Parro (2011) and the counterfactual outcome calculated under this assumption is our lower bound, referred to as Model B(L) above. To establish the upper bound – dubbed Model B(U) above – we assume that under symmetric trade costs trade imbalances converge to zero.\footnote{This assumption may seem arbitrary but there is some evidence that trade cost asymmetries are correlated with imbalances. The correlation between $\xi_i$ and $B_i$ is positive and roughly equals 0.50. In any case, we use this assumption only for establishing the upper bound of the response.}

In order to assess the importance of asymmetries in trade costs for international income
differences one has to keep average trade costs unaffected while reducing the asymmetric trade cost component. In our view, there are two types of comparative static experiments that adhere to this requirement. For instance, one could eliminate all differences in exporter-specific unobservable trade costs, $\xi_j$. Notice that $\hat{\xi}_j$ is centered around zero so that setting counterfactual values $\xi^c_j = 0$ for all exporters $j$ does not affect the average level of trade costs in the world economy. Below, we refer to this as Experiment 1. Alternatively, one could eliminate trade cost heterogeneity at large by setting all counterfactual bilateral trade costs to the average level, $t^c_{ij} = \bar{t} \equiv \frac{1}{N(N-1)} \sum_{j=1}^{N} \sum_{i \neq j} t_{ij}$. By definition, also the latter does not affect the average level of trade costs in the world economy. Below, we refer to this as Experiment 2. We will contrast these experiments with the outcome of a gradual and symmetric reduction of trade cost levels after the asymmetries in the two experiments had been removed. This will illustrate that the stark response of real per-capita income in Waugh (2010) is mainly due to the change in trade cost levels rather than their asymmetry across exporters.

**Experiment 1:**

Experiment 1 consists of two steps. In the first step, we gradually eliminate the heterogeneity across $\hat{\xi}_j$ ceteris paribus. Here, we stepwise reduce unobservable exporter-specific trade costs by defining counterfactual values of $\xi^1_{k,j}$ for each exporter of the form:

$$\xi^1_{k,j} = \hat{\xi}_j (1 - \kappa)$$

where $\kappa \in \{0, 0.01, \ldots, 1\}$. (4.20)

We eliminate all asymmetries in $\xi_j$ at $\xi^1_{1,j} = 0$. As $\kappa$ increases, the variance of the distribution of fixed exporter-specific trade costs degenerates. In Figure 14 we illustrate the response of two measures of real per-capita income dispersion – the variance, $\text{var}(\ln y_k)$, on the left and the 90-to-10 percentile gap, $y_{90}/y_{10}$, on the right – to an increase in $\kappa$ (less heterogeneity in unobservable exporter-specific trade costs, $\hat{\xi}^1_j$) as predicted by Model A (broken line), Model B(L) (solid line with delimiter) and Model B(U) (solid line).
For the lower bound response in Model B we keep all counterfactual $B_1^i = B_i$. For the upper bound we adjust them using $\kappa$ such that $B_{\kappa,i}^1 = B_i(1 - \kappa)$.

At the vertical delimiter, $\xi_j^1 = 0$ for all $j$ and $\hat{t}_{ij}^1$ is perfectly symmetric bilaterally for all $ij$. It turns out that a complete elimination of the exporter-specific unobservable trade costs displays a negligible impact on international real per-capita income inequality. Depending on the preferred model $y_{90}/y_{10}$ changes by $[-6.18\%, 0.56\%]$ and $\text{var} (\ln y_i)$ by only $[-1.51\%, 2.58\%]$.

![Graph showing comparative static analysis](image)

**Figure 14: COMPARATIVE STATIC ANALYSIS: EXPERIMENT 1**

Notice that only Model A predicts negligible negative effect. Predictions of Model B are in the non-negative interval. The reason for this is twofold. First, consistent with Dekle, Eaton and Kortum (2007) a reduction in trade deficits leads to a reduction in earnings in countries with relatively higher trade deficits and vice versa. It is established that poor countries have higher trade deficits. Hence, they will experience a relatively higher decrease in wages. Second, even though poor countries gain in terms of getting symmetric access to foreign markets, they lose in terms of prices of tradables because large exporters

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52 Notice that observable trade costs $t_{ij}$ are still heterogenous across countries after setting $\xi_j^1 = 0$ for all $j$ due to the differences in distances and adjacency variables. Hence, raising $\omega$ in Experiment 1 reduces trade cost asymmetries across exporters and trade cost levels in $t_{ij}$, unlike in Experiment 2. Hence, Experiment 2 is cleaner than Experiment 1 in terms of disentangling effects of trade cost levels from those of asymmetries.
such as the United States now have relatively higher export costs.

Let us denote counterfactual trade costs at $\xi_{1,j} = 0$ by $t_{ij}$. In the second step, we gradually reduce $t_{ij}$ until $\min(t_{ij} : i \neq j) = 1$, defining values of $t_{\omega,ij}$ for each country pair of the form:

$$t_{\omega,ij} = t_{ij}(1 - \omega), \text{ where } \omega \in \{0, 0.01, \ldots, 1 : \min(t_{\omega,ij} : i \neq j) \geq 1\}.$$  \hspace{0.5cm} (4.21)

Hence, as $\omega$ rises, $t_{ij}$ approaches unity. The lines to the right of the delimiter in Figure 14 plot the response of $\text{var(ln } y_i\text{)}$ and $y_{90}/y_{10}$ to the changes in $\omega$. Reducing observable trade costs $t_{ij}$ gradually leads to relatively bigger responses in the income dispersion than reducing unobservable exporter-specific trade cost heterogeneity. However, we have to reduce $t_{ij}$ by about 40% in order to reduce income inequality by 20% in case of $\text{var(ln } y_i\text{)}$.

We have to admit that the second step of Experiment 1 is likely to be irrelevant in terms of policy making. Naturally, we do not suggest that a completely frictionless world is a viable option. However, the purpose of the step is to show that in order to arrive at Waugh’s (2010) results, one would have to reduce general trade costs by an unattainable margin.

**Experiment 2**

Experiment 2 allows us to disentangle changes in the *asymmetry* versus the *level* of overall (observable and unobservable) trade costs. Here, we stepwise reduce trade costs by defining counterfactual values $t_{\kappa,ij}^2$ for each pair of countries:

$$t_{\kappa,ij}^2 = \hat{t}_{ij} + \kappa(\bar{t} - \hat{t}_{ij}) \text{, where } \kappa \in \{0, 0.01, \ldots, 1\}.$$  \hspace{0.5cm} (4.22)

Notice that $t_{0,ij}^2$ corresponds to the benchmark estimate of bilateral trade costs, whereas $t_{1,ij}^2 = \bar{t}$.

*After* having eliminated completely trade cost asymmetries at $\kappa = 1$ and $t_{1,ij}^2 = \bar{t}$, we
can gradually reduce $\bar{t}$ towards unity in order to see how the dispersion in real per-capita incomes responds to changes in trade cost levels versus trade cost asymmetry:

$$t^2_{\omega,ij} = \bar{t}(1 - \omega), \text{ where } \omega \in \{0, 0.01, \ldots, 1\}. \tag{4.23}$$

As $\omega$ approaches unity, $t^2_{\omega,ij}$ converges towards unity so that $t^2_{0,ij} = \bar{t}$ and $t^2_{1,ij} = 1$. Both the responses of $\text{var}(\ln y_i)$ and of $y_{90}/y_{10}$ to changes in $\kappa$ and $\omega$ are summarized in Figure 15 in the same fashion as in Experiment 1. We treat $B^c_i$ exactly as discussed in Experiment 1.

Again, eliminating trade cost asymmetries has little bearing for the dispersion of real per-capita income around the globe. Depending on the model, a complete abolition of trade cost asymmetry leads to only minor change in $\text{var}(\ln y_i) - [-0.15\%, 4.56\%]$, and in $y_{90}/y_{10}$ – $[-6.36\%, 1.91\%]$. Consistent with the results of Experiment 1, these results suggest that in the presence of trade imbalances a mere reduction in trade cost asymmetries may actually increase income inequality around the globe.

The results of Experiment 2 confirm that to achieve a reduction in real per-capita income dispersion by about 20% for $\text{var}(\ln y_i)$ and by 33% for $y_{90}/y_{10}$ as in Waugh (2010), one
would have to reduce average trade cost levels (beyond exporter trade cost asymmetry) on the globe by a magnitude of at least 25% which of course is not attainable.

6 Conclusion

We propose a way to translate all fundamental assumptions of Eaton-Kortum-type general equilibrium models into a structural estimation of unobservable parameters to avoid creating a wedge between the theoretical model and its structural implementation. We show that ignoring this link may lead to highly biased results.

We revisit Waugh’s (2010) analysis to assess the importance of asymmetric trade costs for the world real income distribution and come to starkly different conclusions. We show that a complete abolition of asymmetries in trade costs has close-to-negligible effects on the equalization of real per-capita income across countries. To do that we disentangle trade-imbalances from pure trade-cost-asymmetries and conduct counterfactual experiments that do not violate assumptions of the theoretical model. Our experiments allow us to compare the effect of the reduction in asymmetric versus symmetric general trade costs. We conclude that a reduction in general symmetric trade costs might significantly reduce differences in real per-capita incomes (an old wisdom from the literature), but these reductions would have to be implausibly large to counteract the effects of geographical and cultural barriers to trade.

7 Appendix

7.1 Data

With one exception, the data underlying this study are the same as the ones in Waugh (2010), available at the AER website. The only other data we use are simply averaged bilateral tariff rates from Mayer, Paillacar, and Zignano (2008) for the average year between 1995-1997 (the reference year of all other data is 1996). The advantage of utilizing
such data is that $\theta$ can then be identified without using disaggregated price data. We discuss the estimation of $\theta$ in the next paragraph.

### 7.2 Choice of parameters

We mostly use the same parameters to calibrate the model as Waugh (2010). However, we use alternative values of $\theta$ and $\gamma$. The latter allows us to match first and second moments of the distribution of real per-capita income better than Waugh’s calibration does. In particular, using a value of $\gamma = 0.60$ instead of $\gamma = 0.75$ as in Waugh helps improving the fit of the variance in real per-capita income, $\text{var}(\ln y_i)$, as well as the 90-to-10 percentile ratio, $y_{90}/y_{10}$. Our choice of $\gamma$ seems to be well in line with the data.

### Table 10: PPML estimates with tariffs

<table>
<thead>
<tr>
<th>country</th>
<th>$\xi_1$ (SE)</th>
<th>$\xi_2$ (SE)</th>
<th>country</th>
<th>$\xi_1$ (SE)</th>
<th>$\xi_2$ (SE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>United States</td>
<td>1.91 (0.14)</td>
<td>1.79 (0.23)</td>
<td>Republic of Korea</td>
<td>0.39 (0.14)</td>
<td>2.74 (0.27)</td>
</tr>
<tr>
<td>Argentina</td>
<td>1.38 (0.08)</td>
<td>0.15 (0.13)</td>
<td>Sri Lanka</td>
<td>0.10 (0.07)</td>
<td>1.43 (0.18)</td>
</tr>
<tr>
<td>Australia</td>
<td>0.22 (0.11)</td>
<td>2.65 (0.47)</td>
<td>Mexico</td>
<td>1.15 (0.3)</td>
<td>0.89 (0.3)</td>
</tr>
<tr>
<td>Austria</td>
<td>1.28 (0.06)</td>
<td>1.03 (0.18)</td>
<td>Mali</td>
<td>0.15 (0.15)</td>
<td>2.94 (0.28)</td>
</tr>
<tr>
<td>Belgium</td>
<td>0.78 (0.21)</td>
<td>2.19 (0.45)</td>
<td>Mozambique</td>
<td>2.1 (0.15)</td>
<td>0.18 (0.15)</td>
</tr>
<tr>
<td>Benin</td>
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Notes: $\theta = 0.14$. Standard errors are reported in parentheses and are based on Eicker-White sandwich estimates. The reported Pseudo $R^2$ corresponds to the correlation between observed and predicted values of the dependent variable.
For instance, according to the OECD’s Structural Analysis Database (STAN) average value added in the non-tradable sector among OECD countries in 2000 amounted to about 55% of total value added which is consistent with a value of $\gamma = 0.55$. Since our sample includes OECD and non-OECD countries, it is plausible that the corresponding value is slightly higher than within the OECD.

Waugh (2010) estimates $(1 - \beta) = 1/3$ from data in the examined country sample. The choice of $(1 - \alpha) = 1/3$ is consistent with conventional values used in the literature and the same as in Waugh.

In order to identify $\theta$, we add a measure of tariff barriers to the specification of $t_{ij}$. Then, the coefficient on the log of one plus the average bilateral tariff rate, the only observable ad-valorem measure of trade costs in $\ln t_{ij}$, is $\theta^{-1}$. The corresponding estimates under this specification have to be interpreted with caution. Since, tariffs are asymmetric, part of the exporter-specific effects $\hat{\xi}_j$ as estimated in Table 6 now will accrue to the asymmetry in tariffs. The corresponding estimation results for the cum-tariffs model are summarized in Table 10. The coefficient on the tariff measure is $-7.36$, so that $\hat{\theta} \approx 0.14$. The relatively good fit of the proposed calibration relative to Waugh’s is robust to reasonable perturbations of $\theta$ and $\gamma$.

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53 Developed countries consistently faced higher tariffs in manufacturing in 1996 than developing countries did.
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5 Energy Demand and Trade in Quantitative General Equilibrium

1 Introduction

The reduction of energy consumption is one of the central issues mankind struggles with in the wake of the 21st century. Energy consumption brings about negative externalities on domestic and foreign consumers through emissions and pollution and eventually affects the planet’s climate. It is more or less uncontroversial that the world as a whole and some countries in specific have to lower their respective energy consumption levels. Already now, many countries provide incentives to reduce energy demand and/or encourage usage of more environmentally friendly technologies. However, it is controversially debated how, by how much, and where cuts in energy consumption should be implemented in general.

Economists have for long analyzed problems associated with energy as a production factor at both the microeconomic and macroeconomic levels. For instance, earlier macroeconomic work points to the role of oil as one energy resource for the business cycle and suggests that energy price shocks predated almost all of the recessions since World War II (see Hamilton, 1983, 2005, 2009). In general, energy prices are viewed to affect economic output through five channels (see Kehoe and Serra-Puche, 1991; Rotemberg and Woodford, 1996; Bernanke, Gertler and Watson, 1997; Atkeson and Kehoe, 1999; and Barsky and Killan, 2004): final goods output prices through mark-up pricing over marginal costs which include energy costs; current account deficits through higher energy import bills; sectoral employment shifts; the timing of investments; and monetary response. Macroeco-

54For instance, the European Union Emission Trading Scheme (EU ETS) places a green tax on the emitters of relatively high volumes of carbon dioxide within the member countries of the European Union. The United States discuss to launch a Cap and Trade Program, a similar program that entails placing an extra cost on producers with pollutant technologies.
nomic consequences besides the downturn in real output are reduced productivity growth and higher inflation.

With few exceptions, trade economists have paid little attention to the interplay between goods trade and energy demand. Energy, however, should be relevant to many issues that are at the heart of international trade. For instance, changes in energy prices should have an impact on the pattern of specialization (see Gelragh and Mathys, 2011). This implies that tariffs on goods (not even directly on embodied energy or carbon consumption) will affect energy demand to the extent that tradable and nontradable goods differ in their energy intensity. Moreover, changing energy prices should have an impact on the volume of trade. As countries differ starkly with regard to their productivity in energy production, and shocks on energy prices and local energy supply display a country-specific pattern, changes in the pattern of energy prices across countries affect the volume of trade. We argue that it is important to model this link between energy demand and trade explicitly.

In general, most of the work on the matter is concerned with the problem of carbon leakage rather than energy demand at large. The problem of carbon leakage is that a reduction in carbon emissions in one country or a group of countries will lead to an increase in emissions elsewhere. This problem has been extensively studied in various frameworks. For example, Babiker and Rutherford (2005) use a multi-country multi-commodity computable general equilibrium model to study different policy measures such as carbon import tariffs, voluntary export restraints, and carbon taxes on domestic exporters aimed at the

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55 Steinbuks and Neuhoff (2010) suggest that one reason for specialization effects of energy demand and supply for trade is the variance of energy input coefficients across sectors. Sato, Grubb, Cust, Chan, Korppoo, and Ceppiet (2007) study the possible effects of the EU’s Emissions Trading System (ETS) on industry market shares and profitability. They conclude that, while most industries should benefit from the program, the tradable sector is expected to experience a reduction in market share relative to the nontradable sector.

56 For instance, Graus and Worrell (2007) found significant differences in efficiencies in fossil power generating plants across countries. This suggests differences in comparative advantage due to differences in the efficiency of energy production and in energy prices. Finally, international goods transactions involve transport as an energy-intensive activity so that energy price shocks inter alia translate into higher non-tariff trade costs. Bridgman (2008) illustrates that this effect may explain a large part of the downturn in the growth of international trade in the 1970s, a time when tariffs were significantly liberalized.
reduction of CO$_2$ and their implications for carbon leakage and welfare. The authors find that voluntary export restraints are an efficient measure of reducing carbon leakage but also the most costly in terms of welfare loss.

Border tax adjustment is often advocated as an effective measure to either reduce or completely eliminate carbon leakage. Recently, Elliott, Foster, Kortum, Munson, Pérez, and Weisbach (2010) examine the effects of different tax policies on carbon emissions. The authors use a computable general equilibrium model to quantify the comparative effects of different forms of carbon taxes on emissions and conclude that border tax adjustment can be used to completely eliminate carbon leakage induced by a carbon tax on producers. The authors argue that the combination of these two instruments is an effective policy to lower global emissions without inducing carbon leakage. A number of other papers such as Ismer and Neuhoff (2007) or Manders and Veendendaal (2008) also argue that border tax adjustment is an effective measure to eliminate carbon leakage. The motivation behind is the following. It is necessary to tax imports from countries that do not comply with environmental regulations in order to level the field for domestic producers. Active environmental policies are in a sense an additional tax on domestic producers, and an adjustment could neutralize this disadvantage.

We contribute to the existing literature in several dimensions. First, we model energy as a secondary production factor. There are three sectors, one producing energy, one producing non-tradable goods, and one producing tradable goods. Energy producers use an energy resource input, labor, and other traded inputs. Firms in both tradable and non-tradable goods sectors do not use energy resources but they use produced energy goods such as electricity. Hence, policies aimed at reducing CO$_2$ emissions will affect energy producers directly and subsequently all other production sectors in the economy. Likewise, policies that affect the price of tradables and/or wages will affect energy producers as well. These interdependencies are important for assessing effects of policy instruments.
in terms of both welfare and global emissions. Second, we propose a novel approach in modeling the negative externalities of energy endowments and energy production on domestic consumers and, eventually, also foreign consumers (cross-border spillovers) and calibrating them to observable data in our general equilibrium analysis.

The focus of this paper is on analyzing the economic consequences of instruments that affect energy demand directly (such as ad-valorem taxes on the price of energy) or more indirectly (such as a tax on the use of energy resource inputs) for outcomes such as trade and welfare. We also analyze effects that import tariffs on tradable goods and energy goods have on energy demand, trade, and welfare. For the quantitative analysis, we formulate a structural general equilibrium model in the vein of Eaton and Kortum (2002) which we estimate and calibrate to 31 OECD economies and a rest of the world in the year 2000. The calibrated version of this model serves to conduct comparative static effects consistent with general, multi-country, large-open-economy equilibrium. The model is static\textsuperscript{57} and consists of three sectors, a final goods sector, an intermediate goods sector, and an energy sector. Energy production uses energy resources (some) countries are endowed with, tradable intermediate goods, and local labor. Final and intermediate goods production employ produced energy, tradable intermediates, and local labor. In this model, tariffs on tradable intermediates may be used as indirect instruments to reduce the demand for energy, while ad-valorem taxes on the energy price or a tax on energy resource inputs are more direct instruments to achieve that goal.

Among a host of findings in the paper which we will explore below, it is worth mentioning that a given goal of reducing energy demand may be met at a lower level of global \( CO_2 \) emissions given the same level of total welfare costs when using a direct tax on energy producers rather than taxing the use of energy resource inputs in the energy sector. We also find that – in the presence of negative externalities on foreign customers through

\textsuperscript{57}Miguel and Banzano (2006) examine optimal oil tax policies for a small open economy in a dynamic setting. The authors find that: among the considered instruments and in the absence of international externalities any distortive tax is not optimal.
energy consumption – border tax adjustment, which is often advocated as an effective
ingredient against carbon leakage, leads to higher $CO_2$ emissions and may not be optimal
in general equilibrium with spill-over effects.

The remainder of the paper is organized as follows. Section 2 summarizes the model set-
up. Section 3 is dedicated to the structural estimation of the model’s key parameters and
to the calibration. We conduct several counterfactual experiments using the calibrated
model in Section 4 to shed light on how the energy sector alters the effects of trade
liberalization on world general equilibrium and how import tariffs versus taxes on energy
production affect welfare and energy demand differently in large as compared to small
economies. We summarize the most important results and provide conclusions in the last
subsection.

2 The model

The purpose of the model is to help us shed light on how the energy sector affects welfare
from the viewpoint of consumers and how different policy instruments that can be used to
reduce energy demand affect welfare. For this, we distinguish between energy goods that
are directly consumed by firms and households and energy resources that are indirectly
consumed, through their use in the production of energy goods rather than through direct
consumption. In broad terms, we associate energy goods with refined energy products
such as various petroleum products and electricity. Energy resources are commodities such
as oil and coal which some but not all countries are endowed with. Before proceeding to
the formal description of the model, it is useful to establish several stylized facts about
energy production, energy resource endowments and trade.

1. Energy resource endowments are distributed unequally across economies. Countries
can not accumulate and/or produce energy endowments. This does not contradict the existence of conservation programs.
2. Trade in energy resources is centralized and the prices of those resources are determined globally. For example, the raw oil market is highly centralized and raw oil is generally traded at a more or less common world price.

3. The production of energy goods such as electricity and refined petroleum products uses (among other factors) locally available and/or imported energy resources. Energy resources are not directly used in the production of goods or the consumption of households.

4. Energy goods such as electricity and refined petroleum products are traded but much less so than manufacturing goods.

5. Energy production and consumption exerts negative externalities (e.g., through pollution or global warming) not only on domestic but also on foreign consumers.

We incorporate these features of the data into the model in order to study comparative welfare effects of several policy instruments that may be used to reduce energy demand. We follow Eaton and Kortum (2002) and Alvarez and Lucas (2007) in broad terms in considering a multi-country Ricardian model. In our quantitative analysis, we calibrate the model so as to match bilateral and unilateral empirical data for $N = 32$ countries. Of the 32 countries, 31 are individual OECD members and one is a rest of the world.

Each country $i$ is endowed with $L_i$ units of labor which is perfectly mobile between sectors but not across countries. The labor force is employed locally by three different types of firms: a final good producer, intermediate goods producers, and energy producers. This leads to identical wage costs across sectors but not countries. Countries are endowed with a limited supply of a perfectly homogeneous energy resource per capita which is used in the production of energy goods only. We denote country $i$’s aggregate domestic demand for energy resources by $L_i g_{ci}$ and its aggregate endowment by $L_i g_{ei}$. Hence, $g_{ci}$ and $g_{ei}$ are per-capita levels of demand and endowment of energy resources.
Trade occurs in three dimensions. First, countries trade in intermediate goods as in Eaton and Kortum (2002), and Alvarez and Lucas (2007). Second, countries also trade in energy goods. Trade in both intermediates and energy goods is subject to sector-specific trade costs. Finally, the homogeneous energy resource is freely tradable at a common world price $p_g$.

Trade costs at large encompass transaction costs and tariff barriers. We assume that trade is balanced multilaterally and, hence, there is no sector beyond the ones mentioned. Intermediate and energy goods can be used locally only after aggregating them by using a Spence-Dixit-Stiglitz technology (SDS). The corresponding aggregates per capita are referred to as $q_i$ for intermediate goods and as $e_i$ for energy goods hereafter. Households receive positive utility only from consuming the final good. Their budget decreases in (local or global) externalities induced by the production of energy.

2.1 Consumers

Consumers receive utility $u_i$ from final good consumption $c_i$:

$$u_i(c_i) = c_i.$$  \hfill (5.1)

Their budget constraint reads

$$p_{ci}c_i \leq l_iw_i + r_i + x_i - f(e_i),$$  \hfill (5.2)

where $p_{ci}$ is the consumer price of $c_i$, $l_iw_i$ denotes per-capita income from labor, $r_i$ subsumes total per-capita transfers such as tariff and tax revenues, $x_i$ denotes per-capita revenue from net exports of energy resources, and $f(e_i)$ is the dollar-equivalent social

\footnote{As in most Ricardian models, we refer to $L_i$ as a primary factor endowment bundle in a broad sense. It may either consist of labor in a narrow sense alone or of a bundle of capital, labor in a narrow sense, and other factors (see Alvarez and Lucas (2007) for details). We use $l_i$ to denote the per-capita endowment of $L_i$.}
cost per consumer in \( i \) associated with per-capita energy consumption (with or without cross-border externalities). We will specify \( f(e_i) \) below.

Here we include pollution in the budget constraint and not in the utility function because from the standpoint of an individual consumer there is no way to substitute away from pollution towards consumption of goods and vice versa. This approach is consistent with Copeland and Taylor (2004) who assume that the objective function is to maximize national income subject to a given level of pollution.

### 2.2 Producers of intermediate goods

As in Eaton and Kortum (2002), producers of differentiated goods produce a unique product per firm \( j \) based on a Cobb-Douglas technology with total factor productivity parameter \( z_i(j)^{-\theta} \). The latter is drawn for each country from a distribution function. Following Alvarez and Lucas (2007), we assume that \( z_i(j)^{-\theta} \) has exponential distribution with country-specific parameter \( \lambda_i \). A mass of intermediate firms in \( i \) together employs \( l_{qi}, q_{qi}, \) and \( e_{qi} \) amounts of labor, intermediate input, and energy, respectively, and each of them solves the following profit maximization problem:

\[
\max_{l_{qi}(j), q_{qi}(j), e_{qi}(j)} \left\{ p_i(j) z_i(j)^{-\theta} l_{qi}(j)^\epsilon q_{qi}(j)^\nu e_{qi}(j)^\mu - p_{qi} q_{qi}(j) - w_i l_{qi}(j) - p_{ei} e_{qi}(j) \right\}, \quad (5.3)
\]

where \( \epsilon, \nu, \) and \( \mu \) are the cost shares for labor, intermediate goods, and energy goods, respectively. Solving the problem yields the equilibrium price for an individual good \( j \):

\[
p_i(j) = Az_i(j)^\theta \left[ w_i p_{qi}^{\epsilon} e_{qi}^{\mu} \right], \quad \text{where } \Psi_q = \epsilon^{-\epsilon} \nu^{-\nu} \mu^{-\mu}, \epsilon + \nu + \mu = 1. \tag{5.4}
\]

Notice that \( q_{qi} \) refers to the amount of composite intermediate good \( q_i \) devoted to the production of intermediate goods. Accordingly, \( e_{qi} \) is the amount of total energy per capita \( e_i \) and \( l_{qi} \) is the amount of total labor per capita \( l_i \) which is used in the intermediate
goods sector. The composite production of intermediate goods per capita $q_i$ aggregates all varieties $j$ via the Spence-Dixit-Stiglitz function:

$$q_i = \left( \int_0^\infty q_i(j) \frac{\sigma - 1}{\sigma} dj \right)^{\frac{\sigma}{\sigma - 1}},$$  

(5.5)

where $\sigma > 1$ is the elasticity of substitution between intermediate good varieties. Let $t_{in} \geq 1$ denote an ad-valorem tariff factor that country $i$ places on all the imported intermediate goods from country $n$ and let $Y_{qi}$ denote total demand for intermediate goods by country $i$. Let $\pi_{in}$ be the share of $Y_{qi}$ that $i$ spends on intermediate goods from country $n$. Then, we can formulate respective returns to the factors of production in the intermediate goods sector as:

$$L_i p_{qi} q_{qi} = \nu \sum_{n=1}^{N} \pi_{ni} Y_{qn} t_{ni}^{-1},$$  

(5.6)

$$L_i p_{ei} e_{qi} = \mu \sum_{n=1}^{N} \pi_{ni} Y_{qn} t_{ni}^{-1},$$  

(5.7)

$$L_i w_i l_{qi} = \epsilon \sum_{n=1}^{N} \pi_{ni} Y_{qn} t_{ni}^{-1}.$$  

(5.8)

2.3 Producers of energy

The producer of energy product variety $m$ in country $i$ faces a total factor productivity parameter of $z^{-\theta e}(m)$ drawn from the exponential distribution with mean $\lambda_i^e$. Energy producer $m$ uses $l_{ei}(m)$ units of labor per capita (or per unit of the primary factor bundle in general), $q_{ei}(m)$ units of the SDS (intermediate) good per capita, and $g_i(m)$ units of the energy resource input per capita at world price $p_g$. The optimization problem of a
firm producing variety $m$ in country $i$ is:

$$\max_{l_{ei}(m),q_{ei}(m)} \left\{ p_{ei}(m)z_{ei}(m) - \theta_{ei}l_{ei}(m) - q_{ei}(m)g_i(m) + w_i l_{ei}(m) - p_{ei}q_{ei}(m) - p_q g_i(m) \right\}. \quad (5.9)$$

The first-order condition yields the usual expression for the price of variety $m$ as in (5.4).

We are interested in comparing different policy instruments that can be utilized to reduce energy demand. Let $\tau_i$ denote a flat tax rate placed on the production of all energy goods and let $\kappa_i$ denote a tax rate on the homogeneous energy resource input used in the production of energy goods. In the presence of $\tau_i$ and $\kappa_i$, the price per unit of energy variety $m$ located in $i$ is:

$$p_{ei}(m) = \Psi_e \tau_i \kappa_i \chi^e_i(m)^{\theta_e} w_i^{\xi} p_{qi}^{\gamma} p_g^x,$$

where $\Psi_e = \zeta^e - \xi^e - \chi^e, \zeta + \xi + \chi = 1. \quad (5.10)$

Let $t^e_{in} \geq 1$ denote an ad-valorem tariff factor that $i$ places on all imports of energy products from $n$ and let $g_{ci}$ be the per-capita amount of energy resource input used in the production of energy. As in the case of intermediate producers, we can define total returns to the factors of production for the mass of energy producers as:

$$L_i w_i l_{ei} = \zeta \sum_{n=1}^N \pi_{ni}^e Y_{en}(t^e_{ni})^{-1} \quad (5.11)$$

$$L_i p_q q_{ei} = \xi \sum_{n=1}^N \pi_{ni}^e Y_{en}(t^e_{ni})^{-1} \quad (5.12)$$

$$\kappa_i L_i p_g g_{ci} = \chi \sum_{n=1}^N \pi_{ni}^e Y_{en}(t^e_{ni})^{-1} \quad (5.13)$$

Here 'e' subscripts and superscripts stand for energy and represent variables analogous to the ones denoted sub- and superscribed by 'q' in equations (5.6)-(5.8). All energy varieties
\( m \) are aggregated prior to intermediate and final consumption via the SDS function:

\[
e_i = \left( \int_0^\infty e_i(m)^{\rho-1} \, dm \right)^{\frac{1}{\rho-1}},
\]

where \( \rho > 1 \) is the elasticity of substitution between energy good varieties.

### 2.4 Final good producers

Final good producers are perfectly competitive with identical constant returns to scale production functions. They employ \( l_{ci} \) units of labor at a wage rate \( w_i \) each and use \( q_{ci} \) units of the SDS bundle of intermediates and \( e_{ci} \) units of energy goods at the respective prices of \( p_{qi} \) and \( p_{ei} \) to produce \( c_i \) units of the final consumption good per capita. They sell their output at a price of \( p_{ci} \). Without loss of generality and for simplicity, assume that there is only one final good producer in each country which solves the following maximization problem involving a Cobb-Douglas technology:\(^{60}\)

\[
\max_{l_{ci}, q_{ci}, e_{ci}} \left\{ p_{ci} l_{ci}^{\alpha_{ci}} q_{ci}^{\beta_{ci}} e_{ci}^{\gamma_{ci}} - w_i l_{ci} - p_{qi} q_{ci} - p_{ei} e_{ci} \right\}, \tag{5.15}
\]

where \( \alpha, \beta, \) and \( \gamma \) are Cobb-Douglas cost share parameters for labor, the intermediate goods input bundle, and the energy goods bundle, respectively, as can be seen from the first-order conditions to this problem:

\[
\alpha p_{ci} c_i = w_i l_{ci}; \quad \beta p_{ci} c_i = p_{qi} q_{ci}; \quad \text{and} \quad \gamma p_{ci} c_i = p_{ei} e_{ci}. \tag{5.16}
\]

With perfect competition, the price of the final good is determined as:

\[
p_{ci} = \Psi_c w_i^{\alpha_{ci}} p_{qi}^{\beta_{ci}} p_{ei}^{\gamma_{ci}}, \quad \text{where} \quad \Psi_c \quad \text{is a constant and} \quad \alpha + \beta + \gamma = 1. \tag{5.17}
\]

\(^{60}\)Atkeson and Kehoe (1999) assume a constant-elasticity-of-substitution technology and abstract from material inputs to explain cross-subsection versus time-series patterns in the use of energy.
2.5 Endowment constraints

The endowment constraints are straightforward. They simply imply that firms in country \( i \) exactly employ all \( L_i \); total demand for the energy resource input in the world, \( \sum_{i=1}^{N} L_i g_{ci} \) does not exceed total world supply, \( \sum_{i=1}^{N} L_i g_{ei} \); and total demands for \( q_i \) and \( e_i \) do not exceed the respective supplies:

\[
L_i (l_{ci} + l_{ei} + l_{qi}) \leq L_i \tag{5.18}
\]

\[
L_i (q_i + q_{ei} + q_{ci}) \leq L_i q_i \tag{5.19}
\]

\[
L_i (e_{qi} + e_{ci}) \leq L_i e_i \tag{5.20}
\]

\[
\sum_{i=1}^{N} L_i g_{ci} \leq \sum_{i=1}^{N} L_i g_{ei} \tag{5.21}
\]

3 Open-economy equilibrium

In an open-economy equilibrium, both intermediate and energy SDS producers in each country may buy inputs around the world.\(^{61}\) The autarky and trade equilibria differ with respect to the distribution of prices of tradable goods available in each country. Since the parameters \( \theta \) and \( \theta_e \) govern the variances of productivity in the intermediate and energy sectors, they play a central role for the magnitude of welfare effects of trade liberalization.

To solve for the large-economy multi-country trade equilibrium, let us start with the distribution of \( p_{qi}(j) \) and \( p_{ei}(m) \) available in each country at given trade costs. We distinguish between tariffs and other trade cost factors as follows. Assume that tariff revenues from taxing imported intermediates and imported energy products are rebated as a lump-sum transfer to the consumers in \( i \). Let \( \{d_{ni}, d_{ei}^n\} \) represent the respective iceberg trade costs

\(^{61}\)In fact, if we ruled out trade in intermediate goods and energy goods, we could even solve for the closed-economy equilibrium price and quantity vectors analytically. However, the open-economy equilibrium requires numerical solutions under the adopted assumptions, because producers in \( i \) will look around for the lowest available \( p_{qi}(j) \) for \( i = 1, \ldots, N \) and \( p_{ei}(m) \) for \( i = 1, \ldots, N \) subject to trade costs.
for intermediate and energy products, respectively, expressed as the number of units of a
good that has to be shipped from \( n \) to deliver one unit of that good to \( i \). Given trade
costs, \( i \)'s producers will buy inputs \( j \) and \( m \) at prices

\[
p_{qi}(j) = \min_n \{ \Psi_n z_n(j) \theta w_n p_{qn} p_{en} d_n t_{in} : n = 1, \ldots, N \}, \tag{5.22}
\]

\[
p_{ei}(m) = \min_n \{ \Psi_n \tau_n \kappa_n \gamma_n(m) \theta e (w_n p_{qn} p_{yn} d_n t_{in}) : n = 1, \ldots, N \}. \tag{5.23}
\]

Using the properties of the exponential distribution, we can derive the distribution of
prices of intermediate goods and energy goods as follows:

\[
p_{qi} = \Omega_q \left( \sum_{n=1}^{N} \left[ w_n p_{qn} p_{en} d_n t_{in} \right]^{-\frac{1}{\theta}} \lambda_n \right)^{-\theta}, \tag{5.24}
\]

\[
p_{ei} = \Omega_e \left( \sum_{n=1}^{N} \left[ w_n p_{qn} p_{en} d_n t_{in} \right]^{-\frac{1}{\theta e}} \frac{\lambda_e}{(\tau_n \kappa_n \gamma_n)^{\frac{1}{\theta e}}} \right)^{-\theta e}. \tag{5.25}
\]

Here, \( \Omega_q \) and \( \Omega_e \) are constants. Solving the system in (5.24) and (5.25) determines the
prices of intermediate and energy bundles in each country in terms of wages.

In equilibrium, the world price for energy resources clears the market for endowments.
We derive \( p_g \) from the world supply and demand for energy resources. First, notice that
we express \( i \)'s demand for energy resources from (5.11)-(5.13) as:

\[
\frac{1}{\kappa_i \zeta} \frac{\chi L_i w_l}{p_g} L_i g_{ci} = L_i g_{ci}. \tag{5.26}
\]

Next, notice that total world demand for \( g \) can be expressed as \( \sum_{i=1}^{N} L_i g_{ci} \):

\[
\sum_{i=1}^{N} \frac{1}{\kappa_i \zeta} \frac{\chi L_i w_l}{p_g} = \sum_{i=1}^{N} L_i g_{ci}. \tag{5.27}
\]

The world price of energy resources is determined by total demand and supply. Total

\footnote{We eliminate all opportunities for arbitrage by making the usual triangular inequality assumption.}
world supply of $g$ can be inferred from the observation on energy resource endowments, \( \sum_{i=1}^{N} L_i g_{ei} \). With the latter information at hand, we can derive the world price of $g$ as:

\[
p_g = \frac{\chi \sum_{i=1}^{N} L_{i} w_{i} l_{ei} \kappa_{i}^{-1}}{\zeta \sum_{i=1}^{N} L_{i} g_{ei}},
\]

(5.28)

where \( L_{i} l_{ei} \) is aggregate primary factor (labor) employment in the energy sector of country \( i \), and \( L_{i} w_{i} l_{ei} \) is the aggregate wage bill in that country and sector.

With all factor prices expressed in terms of wages, we may solve for \( w_{i} \) by utilizing each country’s multilateral trade balance condition.

### 4 Multilateral Trade Balance

For stating the multilateral trade balance conditions, let us derive the expressions for bilateral trade flows in the model. Since there is a mass of varieties of intermediate and energy goods, the probability for country \( i \) to buy good \( j \) from country \( n \) equals the share of \( i \)'s income spent on goods from \( n \). These shares \( \pi_{in} \) and \( \pi_{en} \) equal the probability that \( p_{n}(j) \) and \( p_{e}(m) \) are lowest among all \( n \) subject to bilateral trade costs and tariffs. Hence, we can specify trade flows from \( n \) to \( i \) normalized by total expenditures of consumers in \( i \) in the same sector as follows:

\[
\pi_{in} = \Omega_{q}^{-\frac{1}{\theta}} \lambda_{n} \left( \frac{w_{n}^{e} p_{qn}^{e} p_{en}^{e} t_{in}^{e} d_{ni}}{p_{qi}} \right)^{-\frac{1}{\theta q}}
\]

(5.29)

\[
\pi_{in}^{c} = \Omega_{e}^{-\frac{1}{\theta}} \lambda_{n}^{e} \left( \frac{w_{n}^{e} p_{qn}^{e} p_{g}^{e} d_{ni}^{e} t_{in}^{e}}{p_{ei}} \right)^{-\frac{1}{\theta e}}
\]

(5.30)

where \( \Omega_{q} \) and \( \Omega_{e} \) are constants.

Beyond intermediate goods and energy goods, there is trade in energy resources. We assume multilaterally balanced trade so that total spending on imports equals total earnings from exporting. To state this relationship formally, it is useful to define a set of aggre-
gate variables. In particular, let $L_iw_i = V_i$ (aggregate primary factor income), $Li_r = R_i$ (aggregate transfers from taxes and tariffs), $L_ix_i = X_i$ (aggregate net exports of energy resources). For later reference, let us also define $Li_e = E_i$ (aggregate energy demand) and $Li_c = C_i$ (aggregate final goods demand).

At this point, let us define two additional parameters of the model – $s_q$ and $s_e$ – that represent shares of spending on intermediate and energy goods, respectively, in final consumption. Let $Y_i$ be aggregate spending of $i$. Then, $s_qY_i$ and $s_eY_i$ represent aggregate spending on intermediates and energy goods in $i$, respectively. This, in turn, can be specified as the sum of demands for intermediates and energy products of the final, intermediate, and energy producers together:

$$Y_{qi} \equiv s_qY_i = L_iw_i\left(\frac{\beta}{\alpha}l_{ci} + \frac{\xi}{\zeta}l_{ei} + \frac{\nu}{\epsilon}l_{qi}\right)$$  \hspace{1cm} (5.31)

$$Y_{ei} \equiv s_eY_i = L_iw_i\left(\frac{\gamma}{\alpha}l_{ci} + \frac{\mu}{\epsilon}l_{qi}\right)$$  \hspace{1cm} (5.32)

Because of the revenues generated by valued net exports of energy resources $X_i$ as well as total transfers $R_i$ comprised of tax and tariff revenues, the values of production and consumption are not proportional in this model. To close the model we assume that total trade is balanced\footnote{It is straightforward to follow Dekle, Eaton, and Kortum (2007) and assume that trade is balanced up to some constant $D_i$ which captures the observed trade deficit. We, however, choose to assume perfectly balanced trade as the counterfactual value of $D_i$ would be exogenous and not have a structural interpretation in the context of our analysis.}, i.e., total imports of intermediate and energy goods equal to the sum of total exports inclusive of net energy resource exports:

$$(s_q + s_e)(V_i + X_i + R_i) = \sum_{n=1}^{N}(\pi_{ni}^q s_q + \pi_{ni}^e s_e)(V_n + X_n + R_n).$$  \hspace{1cm} (5.33)

Hence, in this model GDP consists of total value added $L_iw_i$, revenues from net exports of energy resources $X_i$, and total tariff revenues $R_i$. Let us also specify $X_i = Y^e_{gi} - Y^c_{gi}$ where $Y^e_{gi}$ is total dollar value of $i$ resource endowment and $Y^c_{gi}$ is total dollar value of the
endowment consumed by $i$.

We use (5.33) for all countries to solve for $w_i$. The algorithm is discussed in more details in the calibration subsection.

5 Estimation

In this subsection, we directly estimate the elements of the vector of parameters

$$\{\alpha, \beta, \gamma, \epsilon, \nu, \mu, \zeta, \xi, \chi, \theta, \theta_e\}$$

(5.34)

from data of 31 OECD countries and one rest-of-the-world (ROW) country as described below.

5.1 Data

For measurement of $\pi_{in}$, we use data from the OECD’s STAN Industry Database and the STAN Bilateral Trade Database. In particular, we employ data on trade and production in agriculture and manufacturing at large. We define $\pi_{in}$ as the ratio of nominal exports from $n$ to $i$ in the numerator (from OECD’s STAN Bilateral Trade Database) and the total absorption capacity of $i$ in agriculture and manufacturing in the denominator (from OECD’s STAN Industry Database). The latter equals total output plus net imports in agriculture and manufacturing.

To measure tariffs $t_{in}$ and $t'_{in}$, we use sectoral (agriculture and manufacturing on the one hand and energy on the other hand) averages from Mayer, Paillacar, and Zigna (2008). We employ those data together with fixed exporter-specific effects and two variables from the Centre d’Études Prospectives et d’Informations Internationales. (CEPII) geographical database – a common land border indicator variable (adjacency) and bilateral distance between countries’ economic centers – to formulate trade costs.
The data on GDP and CO\textsubscript{2} emissions originate from the World Bank’s World Development Indicators (WDI) database. The input-output tables utilized to estimate production and consumption parameters are from OECD’s STAN Input-Output Tables. The reference year of all data is 2000.

5.2 Technology Dispersion Parameters

In order to estimate the two parameters \( \theta \) and \( \theta_e \) that govern the dispersion of technologies between countries, we use the trade flow equations as postulated in (5.30). We modify them by dividing \( \pi_{in} \) and \( \pi_{in}^e \) by the respective home sales \( \pi_{ii} \) and \( \pi_{ii}^e \). Hence, we employ a stochastic version of the following equation to estimate \( \theta \):

\[
\frac{\pi_{in}}{\pi_{ii}} = \left( \frac{\lambda_n^\theta w_n r_n p_{qn} r_{en}}{\lambda_i^\theta w_i r_i p_{qi} r_{ei}} \right)^{-\frac{1}{\theta}} (t_{in} d_{ni})^{-\frac{1}{\theta}}.
\] (5.35)

Of course, trade costs \( d_{ni} \) and \( d_{ni}^e \) are unobservable. We specify them as follows as a multiplicative function as is common in the literature:

\[
\log(d_{ni}) = e x_n + \iota_{in} + \sum_{k=1}^{6} \beta_k d_{k,ni},
\] (5.36)

\[
\log(d_{ni}^e) = e x_n^e + \iota_{in}^e + \sum_{k=1}^{6} \beta_k^e d_{k,ni},
\] (5.37)

where \( e x_n \) and \( e x_n^e \) are fixed exporter-specific effects for country \( n \) in the two sectors, \( \iota_{in} \) is an indicator variable which is unity whenever two countries share a common land border, \( d_{k,ni} \) is an indicator variable which is unity if the distance between two countries lies in the \( k \)th sextile of the distance distribution, and \( \iota \) and \( \beta_k \) as well as \( \iota_e \) and \( \beta_{ek} \) are unknown parameters. Then, we can rewrite equation (5.35) in logs as:

\[
\tilde{\pi}_{in} = c_i - c_n - \frac{1}{\theta} \left( \log(t_{in}) + e x_n + \iota_{in} + \sum_{k=1}^{K} \beta_k d_{k,ni} \right),
\] (5.38)
where \( c_i - c_n \) is the difference in symmetric exporter- and importer-specific effects so that \( ex_n \) measures the deviation of asymmetric exporter-specific trade costs from symmetric ones (see Eaton and Kortum, 2002; Waugh, 2010). The corresponding equation for the energy sector is:

\[
\pi_{in}^e = c_i^e - c_n^e - \frac{1}{\theta_e} \left( \log(t_{in}^e) + ex_n^e + \tau_{adjacency_{ni}} + \sum_{k=1}^{K} \beta_k d_{k,ij} \right).
\] (5.39)

Notice that we can estimate \( \theta \) and \( \theta_e \) using tariffs as the only observable ad-valorem trade cost factors.\(^{64}\) We estimate (5.38) and (5.39) using fixed effects subject to the constraints that \( c_i = c_n \) and \( c_i^e = c_n^e \) whenever \( i = n \).

We measure \( \pi_{in}^e \) as an aggregate of the following categories in OECD’s STAN Industry Database:

- Coke, refined petroleum products, and nuclear fuel.
- Production, collection, and distribution of electricity.
- Manufacture of gas; distribution of gaseous fuels through mains.
- Steam and hot water supply.
- Collection, purification, and distribution of water.\(^{65}\)

Estimating (5.38) and (5.39) in a nonlinear fashion is preferable over estimating it in a log-linear way for two reasons. First, zeros are not eliminated so that a sample selection bias from dropping observations is avoided. Second, one can avoid inconsistent marginal

\(^{64}\)Independently, Caliendo and Parro (2010) developed another way to estimate \( \theta \) from the data on tariffs.

\(^{65}\)It is impossible to avoid some degree of measurement error when defining certain goods as energy and others not. However, the strong reliance of these five sectors on raw energy endowment resource inputs such as coal, oil, etc., suggests that these sectors can be classified as energy producers in the sense of the model. Obviously, among the five sectors the Collection, purification, and distribution of water is not directly an energy producer. But it is an important intermediate input to goods production, and it is very energy intensive according to input-output tables. So, for quantification it appears reasonable to subsume it under the category of energy resource users and energy producers.
effects accruing to mis-specification of the stochastic process as log-additive versus level-additive when using a Poisson pseudo-maximum-likelihood (PML) model with robust standard errors (see Santos Silva and Tenreyro, 2006).\footnote{As an exponential-family multiplicative estimator, PML differs from non-linear least squares only by way of the weighting of the data.} We summarize Poisson PML model estimates for (5.38) and (5.39) in Table 11.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Intermediate</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coef.</td>
<td>Std. error</td>
</tr>
<tr>
<td>$t_{in}$</td>
<td>-4.297</td>
<td>1.065</td>
</tr>
<tr>
<td>$t_{in}^e$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Adjacency</td>
<td>0.221</td>
<td>0.113</td>
</tr>
<tr>
<td>ln($distance$):</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[ln min, ln 375)</td>
<td>-3.419</td>
<td>0.091</td>
</tr>
<tr>
<td>[ln 375, ln 750)</td>
<td>-3.909</td>
<td>0.055</td>
</tr>
<tr>
<td>[ln 750, ln 1500)</td>
<td>-4.033</td>
<td>0.052</td>
</tr>
<tr>
<td>[ln 1500, ln 3000)</td>
<td>-4.301</td>
<td>0.070</td>
</tr>
<tr>
<td>[ln 3000, ln 6000)</td>
<td>-4.551</td>
<td>0.109</td>
</tr>
<tr>
<td>[ln 6000, ln max)</td>
<td>-4.553</td>
<td>0.109</td>
</tr>
<tr>
<td>Pseudo-$R^2$</td>
<td>0.710</td>
<td>-</td>
</tr>
<tr>
<td>Num. of observations</td>
<td>1056</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes: The reported standard errors are based on Eicker-White sandwich estimates. The reported Pseudo-$R^2$ corresponds to the correlation between observed and predicted values of the dependent variable. Country-specific fixed effect coefficients are suppressed.

Recall that the coefficient on $t_{in}$ corresponds to $-\theta^{-1}$. Hence, we can infer that $\theta \simeq -\frac{1}{-4.30} \simeq 0.23$ and $\theta_e \simeq -\frac{1}{-11.05} \simeq 0.09$ respectively. Our estimates of $\theta$ for agriculture and manufacturing are consistent with the ones in Waugh and Simonovska (2011), who use a method of simulated moments estimator and estimate $\theta$ to be between 2.5 and 4.4. Interestingly, the estimate of $\theta_e$ is considerably lower than that of $\theta$. This is consistent with the results in Caliendo and Parro (2010) who estimated a lower value of $\theta$ for refined petroleum relative to manufacturing products. The intuition behind this result is that energy goods are much more homogeneous in comparison to intermediate goods classified as manufactures. Accordingly, the observed productivity dispersion should be lower as...
well.

5.3 Measuring Production Shares

Calculating $\alpha$, $\beta$, $\gamma$

We can estimate production function parameters of the final good producer by using the first-order conditions from Section 2 together with data from OECD’s STAN Industry Database. In particular, $\alpha$ can be estimated as the average ratio of total value added in total output according to equation (5.16). This ratio is directly observable for 31 OECD countries in the data. We classify the sectors contained in the data into three categories. Intermediate goods are defined as agricultural and manufacturing products, energy is defined as an aggregate of five sectors according to the above classification, and final goods are defined as an aggregate of the following services:

- Community, social, and personal services.
- Construction.
- Finance, insurance, real estate, and business services.
- Transport, storage, and communications.
- Wholesale and retail trade - restaurants and hotels.

To estimate $\alpha$, we take the ratio of value added to the total output for 31 OECD countries in 2000. The average value of $\alpha$ in our sample is 0.54. In order to pin down $\beta$ and $\gamma$ we use STAN input-output tables as follows:

$$\frac{\beta}{\gamma} = \frac{L_i p_{qi} q_{ci}}{L_i p_{ei} e_{ci}} \text{ such that } \beta + \gamma = 1 - \hat{\alpha}.$$  

(5.40)

Notice that $L_i p_{qi} q_{ci}$ is the total value of intermediates used in the production of the final goods.
good, and $L_i p_{ci} e_{ci}$ is the total value of energy used. Once we fix $\alpha$ at 0.54, we can solve for $\beta$ and $\gamma$ using observations for 31 OECD countries in 2000 as in (5.40). The calculated average values for these two parameters are $\beta = 0.34$ and $\gamma = 0.12$.

**Calculating $\epsilon$, $\nu$, and $\mu$**

Intermediate tradable goods can be largely classified into two broad classes:

- Agriculture, hunting, forestry, and fishing.
- Manufacturing.

As in the case of the non-tradable final goods sector, we calculate the average share of value added in total output using STAN Input-Output Tables. The weighted average of $\epsilon$ taken across all industries in the two sectors that we classify as tradables and across 31 OECD countries is 0.32 in the year 2000. To calculate $\nu$ and $\mu$ we pursue the same strategy as in the previous subsubsection:

$$\frac{\nu}{\mu} = \frac{L_i p_{qi} q_{qi}}{L_i p_{ci} e_{qi}} \text{ such that } \nu + \mu = 1 - \hat{\epsilon}. \quad (5.41)$$

This yields $\nu = 0.56$ and $\mu = 0.12$.

**Calculating $\zeta$, $\xi$, $\chi$**

Recall the industry classification for the energy sector from above. The weighted average of value added as a share of output in the five energy sub-sectors in our OECD STAN Industry sample is 0.35. We define the energy resource input as:

- Mining and quarrying (energy),

---

67 For the calculation of the intermediate goods and energy goods intensity of each sector, we exclude the diagonal elements of the Input-Output matrices.

68 As an alternative approach, we estimated $\mu$ and $\gamma$ using price data as in (5.17) and (5.4). From that, we obtained $\hat{\mu} \simeq 0.16$ and $0.15$. This indicates that the estimated parameters are plausible.
and calculate $\xi$ and $\chi$ in the same way as the other production parameters:

$$\frac{\xi}{\chi} = \frac{L_i p_i q_i e_i}{L_i p_i g_i c_i}$$

such that $\xi + \chi = 1 - \hat{\zeta}$. \hspace{1cm} (5.42)

Solving (5.42) obtains the parameters $\zeta = 0.35$, $\xi = 0.18$ and $\chi = 0.47$.

## 6 Calibration

One of the challenges in calibrating Eaton and Kortum (2002) type models is the estimation and specification of endowments $L_i$, technology parameters $\lambda_i$, and trade costs $d_{ni}$ and $d_{ni}^t$. To abstain from making strong assumptions on these variables, we express and analyze the model in relative changes as suggested by Dekle, Eaton, and Kortum (2007). In particular, we assume that endowment, technology and trade costs parameters are primitives of the model and do not change in any considered counterfactual experiment. Perhaps, it is instructive to consider an example. Recall that trade flows in intermediate goods can be expressed as:

$$\pi_{in} = \Omega_q^{\frac{1}{2}} \lambda_n \left( \frac{w_n p_{nq} p_{qn} t_{in} d_{ni}^t}{p_{qi}} \right)^{-\frac{1}{2}}. \hspace{1cm} (5.43)$$

Let us rewrite this expression in relative changes. Let $a'$ denote the counterfactual value of some variable $a$ and let $\hat{a} = a'/a$. Hence, $\hat{a}$ is a relative change of $a$ compared to its benchmark value. In any counterfactual experiment (5.43) can be expressed in relative changes such that:

$$\tilde{\pi}_{in} = \hat{\lambda}_n \left( \frac{\tilde{w}_n \tilde{p}_{nq} \tilde{p}_{qn} \tilde{t}_{in} \tilde{d}_{ni}^t}{\tilde{p}_{qi}} \right)^{-\frac{1}{2}}. \hspace{1cm} (5.44)$$

Under the assumption that primitives are constant entails $\hat{\lambda}_n = 1$ and $\hat{d}_{ni}^t = 1$ so that (5.44) simplifies to

$$\tilde{\pi}_{in} = \left( \frac{\tilde{w}_n \tilde{p}_{nq} \tilde{p}_{qn} \tilde{t}_{in}}{\tilde{p}_{qi}} \right)^{-\frac{1}{2}}. \hspace{1cm} (5.45)$$
Furthermore, observing \( \pi_{in} \) we can solve for counterfactual \( \pi'_{in} \) as:

\[
\pi'_{in} = \pi_{in} \left( \frac{\hat{w}_n \hat{p}_{en} \hat{r}_{en} \hat{t}_{in}}{\hat{p}_{qi}} \right)^{-\frac{1}{\rho}}.
\] (5.46)

The advantage of this approach is that, we can conduct counterfactual experiments without estimating unobservable primitives of the model and without having to solve for (observable) \( \pi_{in} \) as a function of those primitives. We express the model in relative changes in Table 7.

Before proceeding to counterfactuals we need to calibrate the model with particular emphasis on energy resource endowments and energy demand. First, we have to map energy resource endowments (a stock) as observed in the data and discussed in the next subsubsection into an energy resource input (a flow) in the model. Second, we need to examine the fit of the model calibration against the data in several dimensions, including energy usage. Finally, we need to specify the functional form of energy consumption and its negative (local versus global) externalities on consumers, \( f(e_i) \). The latter is vital for a welfare analysis of the suggested policy instruments.

6.1 Calibrating Energy Endowments

A relatively good measure of energy resource endowment stock is a country’s proven reserves of oil, natural gas, coal, etc. Data on such endowment stocks are available from the U.S. Energy Information Administration. The data, however, come in different units and, most importantly, reflect stocks (i.e., an integral of currently and potentially in the future usable inputs) rather than flows. Hence, those data can not be used directly in a framework as ours. However, ex ante, total output of the sector Mining and quarrying of energy resources across all countries should be proportional to total energy resource endowments on the globe. Then, on average, the output of the energy mining sector in a country should be a good measure of a country’s energy resource endowment. This can
be assessed when comparing the output of this sector to the proven reserves of energy resource endowments relative to, say, the United States.

To calculate the endowment of energy resources, we use data on proven oil and natural gas reserves as of 2000 and convert the respective values into British Thermal Units (BTUs). So, total reserves in country $i$ are simply the sum of proven oil and natural gas reserves. We then compare how well we can match (or explain) these data on energy resource endowments (stocks) by using total output of the energy mining sector (flows).

Without loss of generality, we assume that one dollar of output in the energy mining sector corresponds to one unit of endowment in the current framework. Hence, we correlate data on $L_t g_{ei}$ measured as total output of the energy mining sector with energy endowment $PR_i$ as measured by total Proven Reserves. Even though there are some outliers (mainly over-extracting Norway and under-extracting Mexico) the correlation between the two measures is very strong. In the total sample the correlation coefficient amounts to 0.66 and when excluding Norway and Mexico it is as high as 0.97. Hence, we conclude that the proposed metric is plausible to convert stocks of (valued or unvalued) energy resource inputs into flows on average.

### 6.2 Fit of Calibration

To check the fit of the calibration, we compare data on key endogenous variables such as an economy’s total value added $V_i$, its total tax and tariff revenues $R_i$ (i.e., at given tariff rates this implicitly means comparing import levels), and net exports of the energy resource inputs $X_i$ with model predictions. Since we resort to the approach advocated by Dekle, Eaton, and Kortum (2007) we assess all features in relative terms as described above.

Such a comparison can tell us to which extent the above estimated parameters and data on

---

69 We omit endowments of coal due to data limitations.

70 Technically, we assess the fit of calibration by shocking each outcome by a vector of zeros for all countries and comparing the outcome between the data and the model. Based on the obtained results, we can then recover counterfactual values of $V_i$, $R_i$, and $X_i$, in absolute dollar values. We provide a detailed description of how to solve the model in counterfactual equilibrium in the next subsection.
exogenous variables are useful to talk about real economies based on the proposed stylized model. The fit of calibration in terms of the key variables is summarized in Figure 16. The panels in Figure 16 suggest that the model predicts the data extraordinarily well.

![Figure 16: Fit of Calibration (in billion U.S. dollars)](image)

The correlation coefficient between actual and predicted values is close to unity in every dimension considered.

### 6.3 Quantifying the Negative Effect of Energy Production

For a welfare assessment of policy variables we need to specify how energy consumption – and the associated emissions – affect welfare directly. Technically, this means to specify the functional form of \( f(e_i) \) in the income constraint (5.2). We use the latter to capture direct benefits from a reduction of energy consumption in contrast to economic costs from doing so. Quantifying the welfare costs of energy consumption is admittedly not straightforward. To simplify matters somewhat, we choose to concentrate on carbon emissions that energy production entails. Specifically, we resort to the concept of the social cost of carbon (SCC) to convert carbon emissions into an equivalent dollar value. Clarkson and Deyes (2002) represent an important reference in this respect. They provide an excellent survey on the methodology behind and estimates of the SCC. The range of the estimates they report is quite wide. Thus, we will use an interval to capture the degree
of uncertainty in that regard. Ayres and Walter (1991) suggest a lower bound of roughly 35 U.S. dollars per ton of $CO_2$. The upper bound of 125 U.S. dollars per ton of $CO_2$ is supported in a recent study of Ackerman and Stanton (2011).

Quite obviously, the marginal price of carbon increases with time, consistent with a greater accumulation of carbon in the atmosphere. Therefore, we model $f(E_i) = f(L_i e_i)$ as an increasing function of energy. When specifying $f(E_i) = f(L_i e_i)$ such that its level reflects country $i$’s level of $CO_2$ emissions, $f(\cdot)$ is some continuous function, and $\omega$ is the SCC scaling factor, the consumer’s problem becomes:

$$u_i(c_i) = c_i \text{ such that } p_i c_i \leq x_i + r_i + w_i - (\omega f(CO_{2,i})).$$ (5.47)

Our approach is similar to that of Copeland and Taylor (2003, 2004) who assume that pollution is a required input in a Cobb-Douglas production function. The difference is that we go directly to the source by modeling a separate energy sector and assuming that consumption (intermediate and final) of energy is proportional to pollution.

We use data from the World Bank’s World Development Indicators on $CO_2$ emissions for the year 2000. We then regress benchmark values of total aggregate energy output, $E_i = L_i e_i$, on $CO_2$ emissions. The results are summarized in Figure [17] suggesting two conclusions. First, production of energy is clearly proportional to $CO_2$ emissions on average so that $f(CO_{2,i})$ is linear in its argument. Second, the model is able to predict total energy production quite accurately. Figure [17] suggests that

$$f(E_i) = 0.0021 E_i.$$ (5.48)

The consumer’s problem in (5.47) can then be written as:

$$u_i(C_i) = C_i \text{ such that } p_i c_i \leq x_i + r_i + v_i - (\omega f(E_i)) \text{ for } \omega \in [35, 125],$$ (5.49)
Notice that we could express (5.47) in per-capita terms. However, since consumers are homogenous, the results in per-capita and aggregate terms are identical. Real consumption for the whole economy, $C_i = L_i c_i$, can then be stated as

$$C_i = \frac{V_i + R_i + X_i - w f(E_i)}{p_{ci}}$$

for $\omega \in [35, 125]$. (5.50)

## 7 Counterfactuals

This subsection is concerned with a quantification of the relative welfare effects of the mentioned more or less direct policy instruments aimed at reducing a country’s energy demand. The four instruments considered are: a tax on the domestic energy production at large ($\tau_i$; a direct instrument); an import tariff on energy goods ($t_{in}^e$; a direct instrument); an import tariff on intermediate goods ($t_{in}$; an indirect instrument); and tax on the usage

Notice that energy production generates an input which is local in nature in the sense that intermediate goods producers cannot escape local supply by directly importing from abroad. However, the energy bundle is and corresponding prices are aggregated as indicated in (5.10). Therefore, a tax on local energy production imposes some discrimination of domestic energy producers in comparison to foreign energy producers from the perspective of domestic energy demand. Notice, however, that trade in energy goods is extremely limited to begin with. This is due to high trade costs. For example, it would be very costly to transport one unit of electricity from France to the United States. Hence the problem of domestic discrimination is minor.
of the energy resource input \((\kappa_i); \text{ a direct instrument})\).

Recall that hats denote relative changes of variables throughout and a prime indicates a counterfactual value of a variable. Then, using notation in an obvious way, an exogenous change in tax and/or tariff rates changes \((5.33)\) to:

\[
(s_q + s_e)(V'_i + X'_i + T'_i) = \sum_{n=1}^{N}(\pi'_{ni}s_q + \pi'_{ni}s_e)(V'_n + X'_n + T'_n). \tag{5.51}
\]

Recall that \(V_i = L_iw_i\) so that we can express \(V'_i = L_iw'_i\) or \(V'_i = V_i\hat{w}_i\). We can express all other variables in \((5.51)\) in the same manner. Table 7 summarizes benchmark and counterfactual values using this insight.

Hence, in the counterfactual exercises we solve for counterfactual changes \((\hat{w}_i)\) rather than levels \((w'_i)\) of wages, given benchmark and counterfactual values of the four policy instruments \(t_{in}, t_{in}^e, \tau_i, \text{ and } \kappa_i\). These instruments enter the problem in different ways and may reduce energy demand with different welfare consequences. In what follows, we will quantify these comparative welfare effects. Countries differ in their trade costs (for intermediate goods or energy), factor endowments (including energy resources), and technology. These differences may entail different responses to the policy instruments. Hence, it is important to consider responses in individual countries. While we always solve the model for all 32 economies, we single out Australia, Belgium, Norway, and the United States to discuss the responses in outcome in detail. These countries differ dramatically in their remoteness and size and, hence, in their openness.

7.1 Experiment 1: \(\tau_i\) versus \(\kappa_i\) to reduce emissions of \(CO_2\)

Commitment of countries to international treaties such as the Kyoto Protocol and the Copenhagen Accord, both legally binding and non-binding, forces them to consider reduction of pollution via domestic policy instruments. Higher taxes on domestic producers increase average marginal cost of producers and affects firms’ competitiveness. This effects
In the first experiment, we look at different policy instruments that can be used to reduce protocol experienced reduction in their exports of approximately 13-14%.

Table 12: EXPRESSING THE MODEL IN RELATIVE CHANGES

<table>
<thead>
<tr>
<th>Variable</th>
<th>Benchmark</th>
<th>Counterfactual</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_i$</td>
<td>$Y_i = V_i + X_i + R_i$</td>
<td>$Y_i' = V_i' + X_i' + T_i'$</td>
</tr>
<tr>
<td>$V_i$</td>
<td>$V_i = L_i w_i$</td>
<td>$V_i' = \tilde{w}_i V_i$</td>
</tr>
<tr>
<td>$X_i$</td>
<td>$X_i = Y_{gi} - Y_{gi}^c$</td>
<td>$X_i' = \tilde{p}<em>g Y</em>{gi}^c - \frac{\tilde{w}_i}{\tilde{k}<em>i} Y</em>{gi}^c$</td>
</tr>
<tr>
<td>$R_i$</td>
<td>$R_i = R_{qi} + R_{ei} + R_{ki} + R_{ti}$</td>
<td>$R_i' = (\tau_i' - 1)s_e V_i$</td>
</tr>
<tr>
<td>$R_{qi}$</td>
<td>$R_{qi} = (t_{in} - 1) \sum_{n=1}^{N} \pi_{in} s_q Y_i$</td>
<td>$R_{qi}' = (t_{in}' - 1) \sum_{n=1}^{N} \pi_{in}' s_q Y_i'$</td>
</tr>
<tr>
<td>$R_{ei}$</td>
<td>$R_{ei} = (t_{ei} - 1) \sum_{n=1}^{N} \pi_{ei} s_e Y_i$</td>
<td>$R_{ei}' = (t_{ei}' - 1) \sum_{n=1}^{N} \pi_{ei}' s_e Y_i'$</td>
</tr>
<tr>
<td>$R_{ki}$</td>
<td>$R_{ki} = (\kappa_i - 1)Y_{gi}^c$</td>
<td>$R_{ki}' = \frac{\kappa_i - 1}{\tilde{k}<em>i} Y</em>{gi}^c$</td>
</tr>
<tr>
<td>$R_{ti}$</td>
<td>$R_{ti} = (\tau_i - 1)s_e V_i$</td>
<td>$R_{ti}' = (\tau_i' - 1)s_e V_i'$</td>
</tr>
</tbody>
</table>

| $\pi_{in}$ | $\pi_{in} = \Omega^{-\frac{1}{2}} \lambda_n \left( \frac{w_{in}^e \rho_{in}^e \rho_{in}^d d_{in} t_{in}}{p_{qi}} \right)^{-\frac{1}{2}}$ | $\pi_{in}' = \pi_{in}' \left( \frac{\tilde{w}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in}}{p_{qi}'} \right)^{-\frac{1}{2}}$ |
| $\pi_{ei}$ | $\pi_{ei} = (\Omega')^{-\frac{1}{2}} \frac{\lambda_n}{(\tau_i \kappa_i)} \left( \frac{w_{in}^e \rho_{in}^e \rho_{in}^d d_{in} t_{in}}{p_{ei}} \right)^{-\frac{1}{2}}$ | $\pi_{ei}' = \pi_{ei}' \left( \frac{\tilde{w}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in}}{p_{ei}'} \right)^{-\frac{1}{2}}$ |
| $p_{qi}$ | $p_{qi} = \Omega \left( \sum_{n=1}^{N} \left( \frac{w_{in}^e \rho_{in}^e \rho_{in}^d d_{in} t_{in}}{p_{qi}} \right)^{-\frac{1}{2}} \lambda_n \right)^{-\theta}$ | $\hat{p}_{qi} = \left( \sum_{n=1}^{N} \left( \frac{\tilde{w}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in}}{p_{qi}'} \right)^{-\frac{1}{2}} \lambda_n \right)^{-\theta}$ |
| $p_{ei}$ | $p_{ei} = \Omega' \left( \sum_{n=1}^{N} \left( \frac{w_{in}^e \rho_{in}^e \rho_{in}^d d_{in} t_{in}}{p_{ei}} \right)^{-\frac{1}{2}} \lambda_n \right)^{-\theta}$ | $\hat{p}_{ei} = \left( \sum_{n=1}^{N} \left( \frac{\tilde{w}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in} \tilde{\rho}_{in}}{p_{ei}'} \right)^{-\frac{1}{2}} \lambda_n \right)^{-\theta}$ |
| $p_g$ | $p_g = \chi \left( \sum_{i=1}^{N} L_i w_i \kappa_i^{-1} \hat{w}_i \right) \left( \sum_{i=1}^{N} L_i g_i \kappa_i^{-1} \hat{g}_i \right)$ | $\hat{p}_g = \chi \left( \sum_{i=1}^{N} Y_{gi} \hat{w}_i \right) \left( \sum_{i=1}^{N} Y_{gi} \hat{g}_i \right)$ |

may be very large. For example, Felbermayr and Aichele (2012) use matching econometrics and show that countries who committed to the reduction in pollution under the Kyoto protocol experienced reduction in their exports of approximately 13-14%.

In the first experiment, we look at different policy instruments that can be used to reduce CO$_2$ emissions through reducing the demand for energy. Specifically, we vary $\tau_i$ (the flat tax rate on the production of all energy goods) and $\kappa_i$ (tax rate on the homogeneous energy resource input) and compare the induced change in CO$_2$ emissions given equal change in real welfare.
In Figure 18, we plot the welfare change in real terms, $\hat{C}_i$, against a given level of reduction in $CO_2$ emissions for Australia, Belgium, Norway, and the United States. Since we use the interval for the social cost of carbon (SCC; reflected by $\omega$) we plot three different lines for each instrument. The solid line in Figure 18 refers to the average level of $\omega = 80$, and the two broken lines refer to the upper and lower bound of the interval ($\omega = 35$ and $\omega = 125$, respectively). The results in Figure 18 illustrate two tendencies. First, the response of real welfare and energy demand to the two types of taxes is heterogeneous across countries. Second, among the two instruments, the tax on energy resource inputs induces relatively larger reductions in $CO_2$ emissions in $i$ at a given real welfare change than the tax on energy goods. The exception is Belgium, which relies heavily on imported energy resources. Hence, it takes advantage by importing energy goods without having to face large negative economic effects from a tax on the local production of energy.

On the other hand, Australia, Norway, and the United States maximize the reduction in domestic $CO_2$ emissions subject to the given level of change in real welfare changes by employing the energy resource tax $\kappa_i$ rather than $\tau_i$. The difference between the two
measures in terms of reduction of emissions could be quite large. For example, Figure 18 indicates that given a 5% reduction in real welfare and $\omega = 80$, $\kappa_i$ reduces emissions by 60%, and $\tau_i$ reduces them by only around 40% in Australia.

We compare the relative welfare effects in both nominal and real terms of $\kappa_i$ and $\tau_i$ in Figure 19. In particular, we plot the components of nominal GDP and the change in the real price index against the change in carbon emissions for the United States.

![Figure 19: Comparative effects of $\kappa_i$ and $\tau_i$: United States](image)

Figure 19 suggests that $\kappa_i$ and $\tau_i$ have quite similar effects on total value added $V_i = L_i w_i$. $V_i$ is slightly higher under $\kappa_i$ than under $\tau_i$ given the same level of domestic $CO_2$ emissions. Net exports of energy resources, $X_i$, are higher under $\kappa_i$. This is due to the fact that a direct tax on energy resources reduces domestic demand for it to a greater extent. Hence, the United States would benefit from a higher level of $\kappa_i$ in terms of $X_i$. On the other hand, the panel in the lower left corner of Figure 19 indicates that total transfers $R_i$ are higher under $\tau_i$ rather than under $\kappa_i$. This is due to the fact that $\tau_i$ is placed on the whole energy sector while $\kappa_i$ is placed only on energy resource inputs of that sector. Finally, the real price index $p_{ci}$ is higher under $\tau_i$. These four components together explain why $\kappa_i$ is
preferable to $\tau_i$ in terms of $CO_2$ emissions given the same welfare costs when considering the case of no cross-border externalities for the United States.

Let us emphasize that this is the result when assuming that countries completely ignore negative externalities of energy production on foreign consumers. Yet, emissions of $CO_2$ affect world climate so that energy production in one country is likely to have detrimental effects on other countries in the world. Suppose that countries care about the global rather than the national level of $CO_2$ emissions. The consumer’s problem then becomes:

$$u_i(C_i) = C_i \text{ such that } p_i C_i \leq X_i + R_i + V_i - \frac{Y_i}{Y_w} f(E_w)$$

(5.52)

Here, $E_w$ refers to the world-wide level of $CO_2$ emissions. $Y_i$ and $Y_w$ refer to $i$’s and the world’s nominal GDP in the benchmark equilibrium. Hence, we assume that $CO_2$ costs are distributed proportionately to countries’ size in terms of $Y_i$.\footnote{This assumption is not crucial for our results. We could alternatively calculate shares as a function of $L_i$. We choose the former approach because we do not observe $L_i$ directly in the Ricardian model with a bundle of production factors.}

In Figure 20, we display changes in real welfare versus changes in global emissions of $CO_2$.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure20}
\caption{Energy Demand versus Welfare}
\end{figure}
for the same four countries as before. Figure 20 suggests that once we allow for negative externalities of energy on foreign consumers and internalize them (as the social planner would), taxing energy resource inputs in energy production is no longer an optimal policy in terms of minimizing world CO$_2$ emissions. $\tau_i$ dominates $\kappa_i$ in terms of conditionally minimizing the level of world CO$_2$ emissions for all countries. Hence, the internalization of cross-border externalities flowing from energy production and consumption reverses the earlier conclusions.

The reason for this is the so-called carbon leakage, a major concern in environmental policy making. Carbon leakage implies that reducing energy demand in $i$ does not necessarily lead to a reduction in world CO$_2$ emissions, if other countries do not impose the same policies. It is often argued that, if the United States were to impose a restrictive environmental policy, their competitors would be reluctant to follow and rather increase their consumption, thereby eventually increasing global emissions. Our framework allows to explicitly address this phenomenon. Taxing energy resource inputs (raw oil and gas) reduces their world price. Countries that do not impose environmental policies gain from the reduced price of $g$ and start producing more energy, mitigating the reduction in the level of the world CO$_2$ emissions. A tax on the energy sector output $\tau_i$ does not have such distortive effects on the relative price $p_g$. This allows countries to achieve a higher reduction in the world level of CO$_2$ emissions given the change in real welfare through $\tau_i$ than through $\kappa_i$. Small open economies, of course, have a much smaller impact on the level of global CO$_2$ emissions. Australia may reduce those emissions by only 0.3% at the cost of a 10% reduction in real welfare. On the other hand, large countries may use $\tau_i$ to reduce world carbon emissions by a significant amount. For instance, the United States may reduce them by nearly 10% subject to a 10% reduction in real welfare. In comparison, a change in the United States’ $\kappa_i$ with the same effect on welfare would reduce global CO$_2$ emissions by less than 1%. 

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7.2 Experiment 2: effects of $t_{ij}$ and $t^e_{ij}$

In our second experiment, we examine the effect of trade tariffs $t_{ij}$ and $t^e_{ij}$ on the world level of carbon emissions, local energy demand, and welfare at large. There is no difference between border tax adjustment and import tariffs from the point of view of implementing a policy to prevent adverse effects of carbon leakage. For example, Elliott, Foster, Kortum, Munson, Pérez, and Weisbach (2010) argue that a border tax adjustment would completely eliminate the problem of carbon leakage. The authors agree that calculating the carbon the content of imported goods could be very costly. Hence, a border tax adjustment is likely to be in the form of a simple import tariff levied on the imports from countries that do not comply with environmental regulations.

In our framework, higher import tariffs will inter alia increase the price of intermediate goods. This, in turn, will increase the price of energy goods, reducing energy demand. On the other hand, in Eaton-Kortum type models there is an optimal level of tariffs. Hence, countries may increase their welfare by generating higher import tariff revenues. Usually, this two-way link between taxes and energy demand is missing, so that taxes can successfully neutralize carbon leakage without affecting $CO_2$ emissions directly.

In this experiment, we gradually increase $t_{ij}$ for Australia and the United States such that our counterfactual tariffs are $t'_{ij} = \delta t_{ij}$ where $t_{ij}$ is the benchmark tariff and $\delta = (1.00, 1.01, ..., 1.50)$. We plot the change in the domestic and world carbon emissions against the change in real welfare in Figure 21. As in Experiment 1, we use an interval for the value of $\omega$. Notice that a marginal increase in the level of import tariff leads to welfare gains through higher tariff revenues. The same policy, however, leads to an increase in carbon emissions. This is true for both domestic and global $CO_2$ emissions. Higher import tariffs increase the price of intermediate goods. As a consequence, producers substitute away from intermediate goods towards energy goods, thereby increasing domestic energy

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73For more details on optimal tariffs for a small open economy see Alaverez and Lucas (2007).
Figure 21: Effect of $t_{ij}$ on CO$_2$ emissions and welfare

Demand. The latter is translated into higher world energy demand and hence more global CO$_2$ emissions.

Alternatively, consider a counterfactual exercise about energy goods tariffs with $(t_{ij}') = \delta t_{ij}$ where $t_{ij}$ is the benchmark tariff and $\delta = (1.00, 1.01, ..., 1.50)$.

Figure 22: Effect of $t_{ij}^e$ on CO$_2$ emissions and welfare

Trade in energy is very limited to start with. The average of $\pi_{ii}^e$ in our sample is 0.96.
Hence, an average country in our sample imports only 4% of energy goods. Our conjecture is that unobservable trade costs are too high for more intense trade in energy goods. This low trade intensity effectively means that both small and large countries experience similar welfare and environmental effects as import tariffs on energy goods are changed. The imposition of higher energy import tariffs increases domestic \( CO_2 \) emissions. At first glance, this may seem counterintuitive as higher energy import tariffs must increase domestic energy prices and reduce energy demand. Yet, while it is correct that the domestic price of energy \( p_{ei} \) rises with \( t_{ij} \), higher energy tariffs and subsequently higher energy goods prices also increase the price of intermediate goods. The substitution effect towards energy is stronger because intermediate goods have higher production weights compared to energy. Hence, we actually observe an increase in domestic energy demand as a result. This change, however, is small and does not affect world emissions of \( CO_2 \) significantly.

8 Conclusion

We formulate a general equilibrium model of international trade and energy demand. The model mirrors major stylized facts regarding trade in both intermediate and energy goods, the unequal distribution of energy resource endowments, the centralized market for energy resources, and negative cross-border externalities induced by energy goods production. We propose novel modeling and measurement strategies with regard to the role of energy resource endowments and negative cross-border externalities associated with energy production. We model the latter as a secondary production factor which allows us to give clear-cut predictions on both trade, welfare, and environmental effects in the counterfactual exercises.

We adopt an approach to model counterfactual scenarios which does not require estimation of unobservable trade costs or technology parameters. The results for 31 OECD countries and the rest of the world suggest that taxing the use of energy resource inputs is
preferable to taxing energy goods output only in the absence of cross-border externalities of energy production. In other words, if a country completely ignores cross-border effects of energy production, a tax on energy resource input (such as raw oil and gas) usage generates lower local CO₂ emissions given the same welfare effects than when taxing local energy production at large. Once cross-border externalities are internalized and countries care about the global level of CO₂ emissions, taxing the domestic energy production becomes preferable to taxing energy resource inputs. The reason is that carbon leakage is significantly lower when taxing energy production than when taxing energy resource inputs.

We also find that border tax adjustment – which is often advocated as a counter-measure against carbon leakage – increases global CO₂ emissions. Hence, this instrument may not be optimal in general equilibrium. Our results indicate that a more aggressive energy import tariff policy would not have significant effects on outcome (neither emissions nor welfare) due to the low trade intensity of energy goods.
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