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ABSTRACT

This paper investigates the role of income-driven differences in consumption patterns in explaining and projecting energy demand and CO_2 emissions. We develop and estimate a general-equilibrium model with non-homothetic preferences across a large set of countries and sectors, and trace embodied energy consumption through intermediate use and trade linkages. Consumption of energy goods is less than proportional to income in rich countries, and more income-elastic in low-income countries. While income effects are weaker for embodied energy, we find a significant negative relationship between income elasticity and CO_2 intensity across all goods. These income-driven differences in consumption choices can partially explain the observed inverted-U relationship between income and emissions across countries, the so-called environmental Kuznet curve. Relative to standard models with homothetic preferences, simulations suggest that income growth leads to lower emissions in high-income countries and higher emissions in some low-income countries, with only modest reductions in world emissions on aggregate.

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1 Introduction

Energy consumption is associated with a number of negative externalities. Fossil fuel combustion, in particular, leads to emissions of carbon dioxide (CO_2) a greenhouse gas responsible for global climate change. World energy consumption and emissions have been increasing almost constantly, and understanding the determinants behind emission levels is necessary to guide policy making and improve forecasting. At the same time, demand for energy — like that of most goods — varies significantly across income levels. There is for example widespread expectation of a rapid increase in energy consumption in emerging economies as households approach middle-income levels (Wolfram et al., 2012). On the other hand, empirical evidence from high- and middle-income countries tends to point the other way: rich households spend a smaller share of their income on energy. However, most studies on the role of per capita income focus on a single country and do not examine implications for multiple countries in general equilibrium.

This paper investigates how per capita income influences energy demand and CO_2 emissions across countries through differences in consumption patterns. We do so by introducing identical yet non-homothetic (income-dependent) consumer preferences within a multi-regional, multi-sectoral general-equilibrium model which accounts for differences in technologies, input-output linkages and trade. Our first objective is to estimate the extent to which per capita income influences the average energy and CO_2 intensity of consumption by systematically shifting consumption patterns towards more or less energy-intensive goods. We find that consumption patterns contribute to the observed inverted-U relationship between income and CO_2 intensity, a variant of the Environmental Kuznets Curve (EKC). The second objective is to estimate whether and how we can expect further growth in per capita income to affect changes in emissions. Results indicate little scope for shifts in consumption choices to single-handedly reduce the CO_2 intensity of world GDP in the short run: while income growth leads to lower emissions in many countries once we account for non-homothetic consumption, weaker income effects for embodied energy and higher emissions in some low-income countries imply modest world average effects.

Our framework allows a number of contributions. First, we paint an aggregate cross-country picture of the relationship between income, consumption and emissions. A number of 'micro' survey-based studies find that the household demand for energy varies systematically with income, but only provide scattered, country-specific evidence (typically from high-income countries). Conversely, 'macro' studies of the relationship between income and CO_2 emissions across countries, such as EKC studies, have not focused on the importance of consumption patterns. Global or regional emissions projections exercises also often do not model non-homothetic preferences, implicitly assuming an income elasticity of one. The second contribution is accounting for global input-output linkages. The demand for energy goes well beyond direct consumption and a large share of emissions is "embodied" in the consumption of non-energy goods. As incomes rise, the evolution of emissions depends on consumption shifts being biased towards more or less energy-intensive goods. Such bias includes, for instance, the well documented shift away from industrial sectors to comparatively clean service sectors. Third, our general equilibrium framework allows us to distinguish consumption effects from production-driven differences in emission levels. While EKC studies have been criticized for lacking structure or causal interpretation (Levinson and O'Brien, 2018), we identify the role of per capita income in determining emissions through changes in consumption choices. This allows to pinpoint its role in simulations.

Our multi-regional general equilibrium model is an extension of Caron, Fally and Markusen (2014). The identification strategy estimates sectoral income elasticities of consumption from cross-country variations in consumption patterns while disentangling demand from supply-side effects. Failing to do so, we might for example confound the fact that high-income countries consume less energy-intensive goods not because their consumers are richer but because those goods are more expensive there. Available consumer price data are hard to match to production, input-output and trade data, and are also prone to endogeneity. We sidestep these issues by constructing price index proxies from supply-side patterns of comparative advantage and trade costs estimated in a gravity model. In our benchmark specification, non-homotheticity is modeled using Constant Relative Income Elasticity (CRIE) preferences[1], but we test the sensitivity of results to alternative demand systems leading to more flexible Engel curves. The supply-side structure is an extension of Costinot et al. (2012) and Eaton and Kortum (2002) with multiple factors of production and an input-output structure as in Caliendo and Parro (2015). Fossil fuel supply is determined through the supply of a specific factor.

The model is estimated using the Global Trade Analysis Project (GTAP8) dataset — a collection of consumption[2], input-output, production and trade data for 109 countries spanning most of the per capita income spectrum and 57 sectors covering the whole economy. This dataset allows us to track the *direct* CO_2 content of consumption linked to the final consumption of CO_2-emitting energy goods (coal, natural gas, electricity and refined oil). We also use the multi-regional input-output tables to compute the *indirect* CO_2 content of consumption: emissions caused by the production of goods throughout their global supply chain.

We present our results in stages: from sector-level to country-level partial-equilibrium evidence, then to general-equilibrium simulations. We first look at the cross-sector relationship between *total* (direct and indirect) CO_2 intensities and the estimated income elasticities determined by the structure of preferences. The income elasticity of CO_2-emitting energy goods is generally below one, including that of electricity and refined oil. When including non-energy goods, we find an inverted-U relationship in which goods of intermediate income elasticity (including transportation and manufacturing sectors) have the highest total CO_2 intensity on average. However, the relationship is negative overall, with the highest income elasticity goods (mostly services) having the lowest CO_2 intensity. The inverted-U and negative relationship is significant within the set of non-energy goods as well. This findings provide preliminary evidence for a demand-side explanation of the income-emissions link: consumers

[1]We chose these preferences as they are practical to estimate, and provide a simple link between estimated coefficients and income elasticities. CRIE preferences are also easily combined with CES preferences within industries to generate gravity within industries.

[2]Throughout, we use consumption to describe final demand. In our data and model, it includes household, government and investment demand.

at different income levels consume baskets of different average CO_2 intensity.

We then investigate how this translates into differences in the average CO_2 content of consumption baskets (bundles) across countries, expressed in kg of CO_2 per dollar of consumption — i.e. a measure of CO_2 intensity. The data exhibit considerable cross-country variation, but also reveal a distinct asymmetric inverted-U and overall negative relationship between per capita income and both the direct and total average CO_2 contents of consumption: lower middle-income countries have the highest emissions intensities; high-income countries the lowest. This is consistent with the EKC literature which has identified an inverted-U pattern for the CO_2 *intensity* of GDP (but not total emissions). While, unsurprisingly, a large part of the observed decrease in emissions intensities with income is to be attributed to technological differences (or within-sector shifts in consumption which we do not observe), differences in consumption patterns play a substantial role: they explain 33% of the cross-country variability in the total CO_2 intensity of consumption and generate a relationship in which intensities are lowest at high incomes.

To identify the role of per capita income, we re-estimate average CO_2 content of consumption using fitted consumption patterns generated from identical but non-homothetic preferences. Results confirm that income itself, through its influence on consumption patterns, explains a significant part of the variability in CO_2 contents across countries. While we find here that the influence of income-driven consumption patterns on direct consumption emissions is stronger than on total consumption emissions, it is still strong when non-energy goods are included: differences in income cause the predicted average CO_2 content to drop from an average of 0.733 kg/$ for low-income countries to 0.461 kg/$ for high-income countries. Interestingly, we find that the average CO_2 embodied in each dollar of *imported* consumption also decreases in per capita income (which runs contrary to the pollution-heaven hypothesis) and that non-homothetic preferences can partially explain this negative correlation.

Having established per capita income as an important determinant of CO_2 intensity, we then investigate the potential for growth in income to shift consumption patterns in a way which affects aggregate energy use and emissions, absent any improvements in technology. Using our general-equilibrium model, we simulate a counterfactual increase in income and estimate resulting changes in consumption emissions. While the equilibrium change in energy consumed ultimately also depends on the supply of energy, we find, for plausible values of supply elasticity, a strong reduction in the direct CO_2 intensity of consumption. Accounting for general-equilibrium effects, we find that a 1% increase in income increases direct consumption emissions by only 0.88% on average (compared to the 1% increase which we would obtain with homothetic preferences). More flexible demand specifications and higher supply elasticity of fossil fuels lead to an even stronger negative effect. Income effects for the total CO_2 content of consumption baskets (including CO_2 embodied in non-energy goods) are considerably weaker on aggregate: our benchmark estimate for the income elasticity of the world's CO_2 content of consumption (which equals that of production) is 0.97. However, the near-homothetic world average effect hides significant heterogeneity. For both the direct and total CO_2 content, low-income countries have elasticities that are higher than one (that is, are still to the left of their intensity peak such that their consumption patterns are predicted to change in way which increases emissions), while most middle- and high-income countries have elasticities that are far below the world average.

All of these results follow through when considering the secondary energy intensity of consumption instead of its CO_2 intensity. However, including other greenhouse gases (CH_4, N_2O and fluorinated gases) changes the picture because goods with the lowest income elasticity (such as agriculture) are responsible for the highest emissions of these gases. This leads to a negative cross-sectoral correlation between total GHG-intensity and income elasticity which turns the inverted-U cross-country relationship identified for CO_2 strictly negative.

The paper proceeds as follows. After an overview of related literature, Section 2 describes our theoretical framework, including the equations describing counterfactual equilibria. Section 3 describes implications of equilibrium outcomes (consumption, production) on CO_2 emissions. Section 4 describes the data and econometric estimation strategy. Section 5 describes all results including a decomposition of CO_2 contents and simulations outcomes. Section 6 presents extensions to the benchmark model.

Context and related literature

Our paper relates to at least three distinct lines of research: i) literature on the "Environmental Kuznet Curve" (EKC) describing how aggregate emissions depend on GDP per capita and stages of development; ii) studies of income effects in energy consumption based on household microdata; iii) models of emissions forecasting.

We focus on income-driven shifts in consumption patterns, which directly affect the energy intensity of GDP, a critical ingredient in understanding cross-country differences in emission levels.[3] This relates to various studies documenting the link between GDP per capita and aggregate emissions. To our knowledge, existing studies either focus on documenting aggregate outcomes, or if they link emissions to sectoral composition, do not explicitly model and estimate income effects in consumption.

Existing evidence suggests heterogeneous and complex relationships between per capita income and the aggregate energy intensity of GDP. The energy intensity of most high-income countries, as well as that of the world, has been declining for decades (Raupach et al., 2007), while most of the developing world has a stable or increasing energy intensity of GDP.[4] Although total CO_2, contrary to a number of other pollutants, tends to increase with income, the literature has found evidence for an inverted-U relationship between CO_2 per capita or CO_2 intensity (in kg/\$) and income across countries: see Schmalensee et al. (1998), Dietz and Rosa (1997), Roberts and Grimes (1997) for cross-

[3] Cross-country differences in emissions, as well as their evolution, can be decomposed into differences in population, GDP per capita, the energy intensity of GDP and the emissions intensity of energy. This is also known as the Kaya identity (Yamaji et al., 1991), in which $F = P \times \frac{G}{P} \times \frac{E}{G} \times \frac{F}{E}$, where P refers to population, G is GDP and E is primary energy consumption. Emissions are thus influenced by $g = G/P$, per capita GDP; $e = E/G$, the energy intensity of GDP; and $f = F/E$, the carbon intensity of energy. We focus on the role of e and the degree to which it is determined by consumption patterns.

[4] Raupach et al. (2007) find that it has declined by about 15% between 1980 and 2005, or by more than 40% if GDP is evaluated at purchasing power parity. See Figure 2 of Raupach et al. (2007) for world levels and Figure 4 for a country decomposition. Evaluating GDP at purchasing power parity increases the weight put on developing economies. In the present paper, GDP and income are evaluated at market exchange rates.

country studies or Aldy (2005) for a comparison across US states. This EKC suggests that countries become comparatively cleaner, per dollar, after reaching a certain level of development. Most EKC studies are based on aggregate energy and emissions data. Using sectorally-disaggregated datasets, several papers in the multi-regional input-output literature have also identified evidence for both a consumption and a production-based EKC (see Peters, 2008). Hertwich and Peters (2009) estimate a cross-country elasticity of CO_2 to income of 0.81 on average, and their results suggest an inverted-U curve for emissions intensities.

Economists, among others Grossman and Krueger (1995), have suggested decomposing the relationship between income and environmental quality between scale, technique and composition. Focusing on local pollutants (not CO_2), they have identified an EKC turning point at relatively low income levels, and argued that it could be caused by composition effects. Only a limited number of studies have focused specifically on the role of sectoral composition effects. Existing work tends to be reduced-form in nature, without examining the structure of preferences and non-homotheticities driving these composition effects. In a paper similar in spirit to ours, Medlock and Soligo (2001), using a three-sector model, time series data and controlling for prices, have found that structural shifts between agriculture, transportation and industrial sectors generate an EKC turning point. However, they do not focus on consumption patterns specifically and do not distinguish production from consumption effects.[5]

A distinct but related strand of the literature investigates the relationship between income, consumption patterns and CO_2 emissions at the household level, typically based on single-country survey data. There is unambiguous evidence of income-driven consumption effects: differences in income significantly affect household energy use. Most studies which focus on industrialized countries find direct energy consumption to be a necessity good (see Wier et al., 2001 or Munksgaard et al., 2001 among others), in line with our findings. Kerkhof et al. (2009) compare estimates across countries and investigate how emissions from households in the UK, the Netherlands, Norway and Sweden respond to income. They find heterogeneous effects: in the UK and Netherlands, rising income means declining emissions intensities. In Sweden and Norway, emission intensities are lower but increase with income. They attribute these differences to housing and heating patterns across income levels.

Also focusing on household behaviour but with a structural approach, Levinson and O'Brien (2018) find strong evidence for consumption effects in the US. They estimate "Environmental Engel Curves": the relationship between income and the consumption of various pollutants (not including CO_2). These also identify demand-side effects by holding prices constant and include indirect emissions. They find such Engel curves to be concave, with an income elasticity of energy that is lower than one. Our approach, while focusing instead on energy and CO_2 over a large number of countries, is similar.

Much less is known about this relationship in the developing world, where most of the future

[5] Also related is Shapiro and Walker (2014), who decompose the evolution of CO_2 emissions in US manufacturing over the last decades and report that consumer preferences have not changed in a way which substantially affects the level of emissions. While they control for environmental stringency, trade costs and productivity improvements to come to this conclusion, their data only cover manufacturing goods, do not include input-output linkages, and they do not attempt to make economy-wide statements about the role of preferences.

growth in energy demand is expected to occur. Studies looking at the determinants behind energy use (fossil fuels and electricity) include Farsi et al. (2007) for a survey of urban Indian households, and Golley and Meng (2012) or Cao et al. (2016) for a survey of urban Chinese households. These studies present a mixed picture regarding the relationship between energy intensities and income. Others focus more directly on the relationship between income and the demand for energy-intensive appliances. Davis and Gertler (2015), for example, point to large possible increases in the adoption of air conditioning. Gertler et al. (2016) review the implications of growing demand for appliances in the developing world, relying on survey data describing household appliance and vehicle purchases collected in several large developing countries. In a simple reduced-form estimation based on country-level data, they find that the income elasticity of energy demand displays an inverted-U pattern that remains below one in all countries and peaks around 0.8. Exploiting randomized cash transfers, they also identify an S-shaped relationship between expenditure levels and ownership of energy-intensive appliances (such as refrigerators) in which ownership of these durables evolves from very low levels to saturation levels at particular stages of development. Similar S-shape patterns have been identified in the case of Chinese households by Zhao et al. (2011). These findings are in line with Wolfram et al. (2012) who predicted large coming increases in developing-world energy demand, as large populations are just at the beginning of the energy-intensive appliance purchase process.

Our paper differs from the above in that, despite relying on aggregated consumption data, it covers a wide range of countries across a broader income spectrum. Although we do not model the demand for energy-consuming appliances directly, our dataset tracks the direct demand for secondary energy which these appliances use (mainly electricity, oil and natural gas). It can thus implicitly pick up S-shaped appliance adoption patterns. These can indeed lead to an inverted-U relationship between aggregate energy intensity and per capita income, as households progress from purchasing energy-consuming appliances (increasing energy intensity) to being saturated in these appliances (decreasing energy intensity). Furthermore, our dataset allows the estimation of the indirect (embodied) usage of energy — an element usually not considered in the literature — and allows us to examine general-equilibrium implications by combining both the demand and supply sides.

Finally, our paper also relates to an extended literature on energy and emissions projection modeling. Despite the evidence that energy intensity varies systematically with income levels, the relationship has been given little attention in these exercises. This is surprising, given that a variety of decision makers benefit from reliable projections, including climate impact and adaptation managers, energy resource and technology managers, government officials, and others responsible for developing regional and national policy related to energy use or climate change.

The Intergovernmental Panel on Climate Change (IPCC), which provides "Representative [emissions] concentration pathways" for earth system modelers to use as inputs, does not attempt to generate explicit predictions of future emission intensity. Instead, they favor a set of alternative scenarios in which changes in emissions intensity are implicitly considered but are not based on empirical estimates. The International Energy Agency's World Energy Outlook (IEA, 2013), one of the most comprehensive energy demand forecasting exercises, allows for income elasticity of household demand to deviate from unity for a limited number of residential demand components. These are limited to residential buildings and include water heating, appliances, lighting, cooking and cooling. Their elasticity estimates are also unpublished, and only cover a limited number of countries.

Most of the computable general equilibrium models used for energy and emissions projections (e.g. Paltsev et al., 2005) either rely on homothetic (generally constant elasticity of substitution) demand systems, or when they do allow consumption patterns to vary with income, do so with crudely calibrated elasticities. Dai et al. (2012) recognize the need to account for non-homothetic behavior in such models. In attempting to improve the forecasts of emissions growth in China, they provide non-parametric income elasticity estimates. However, they do not include these estimates within the model and instead use arbitrary scenarios describing the growth paths of future expenditure shares.

To the best of our knowledge, our paper is the first to consistently estimate income elasticity across a wide range of sectors for a set of countries covering most of the world economy, and describe their relationship with CO_2 intensity across sectors. It is unique in pinpointing the role of per capita income growth, through its influence on consumption patterns, in determining future worldwide emissions.[6]

2 Theoretical framework

We rely on the general equilibrium model of consumption, production and international trade introduced in Caron, Fally and Markusen (2014), which we extend to track energy demand and CO_2 emissions. The model's supply-side is an extension of Costinot et al. (2012) and Eaton and Kortum (2002) with treatment of intermediate inputs as in Caliendo and Parro (2015). The demand side formulation allows for non-homothetic preferences. We use this general-equilibrium structure to estimate all key parameters of interest and conduct counterfactual simulations.

2.1 Model setup

2.1.1 Demand

In our benchmark specification, we adopt a demand system derived from constant relative income elasticity (CRIE) preferences, as in Fieler (2011) and Caron et al. (2014), with early analyses and applications found in Hanoch (1975) and Chao and Manne (1982). In section 6.1, we examine the sensitivity of our results to the use of non-homothetic CES preferences as in Comin et al. (2015).

Consider a set of heterogeneous industries k, each of which is composed of a continuum of product varieties indexed by $j_k \in [0, 1]$. Preferences take the form:

$$U = \sum_k \alpha_{1,k} Q_k^{\frac{\sigma_k - 1}{\sigma_k}}$$

[6] In an orthogonal approach, van Benthem (2015) uses long time series to estimate whether energy consumption patterns in the developing world have converged to those of rich countries faster than their income. While he finds limited evidence for such "energy leapfrogging" overall, there is evidence that the consumption patterns of countries of similar levels of income have become more energy-intensive over time. That framework however doesn't allow identifying whether these shifts are due to changes in preferences or changes in technology.

where $\alpha_{1,k}$ is a constant (for each industry k) and Q_k is a CES aggregate:

$$Q_k = \left(\int_{j_k=0}^{1} q(j_k)^{\frac{\xi_k - 1}{\xi_k}} dj_k \right)^{\frac{\xi_k}{\xi_k - 1}}$$

Preferences are identical across countries, but are non-homothetic if σ_k varies across industries. The ratio of income elasticities of demand between goods i and j is given by σ_i/σ_j and is constant. The CES price index of goods from industry k in country n, $P_{nk} = \left(\int_0^1 p_{nk}(j_k)^{1-\xi_k} dj_k \right)^{\frac{1}{1-\xi_k}}$, determine individual expenditures ($P_{nk}Q_{nk}$) in country n for goods in industry k. These are:

$$d_{nk} = \lambda_n^{-\sigma_k} \alpha_{2,k} (P_{nk})^{1-\sigma_k} \tag{1}$$

where λ_n is the Lagrangian multiplier associated with the budget constraint of individuals in country n, and $\alpha_{2,k} = (\alpha_{1,k} \frac{\sigma_k - 1}{\sigma_k})^{\sigma_k}$. The Lagrangian λ_n is determined by the budget constraint: total expenditures must equal total income. The income elasticity of demand η_{nk} for goods in industry k and country n equals:[7]

$$\varepsilon_{nk} = \sigma_k \cdot \frac{\sum_{k'} d_{nk'}}{\sum_{k'} \sigma_{k'} d_{nk'}} \tag{2}$$

2.1.2 Production and trade in non-energy sectors

The focus of the analysis being on the demand-side, we formulate a flexible structure of supply which will allow us to control for any pattern of comparative advantage forces at the sector level.

Production of primary energy sectors (defined below) $k \in \mathcal{P}$ is distinguished from that of non-energy sectors $k \notin \mathcal{P}$ in order to allow calibration of their supply elasticity, which is critical to the general equilibrium response of emissions. For non-energy sectors, we assume Cobb-Douglas production functions with constant returns to scale where production depends on factors and bundles of intermediate goods from each industry (the production function of primary energy sectors is described later).

We assume that factors of production are perfectly mobile across sectors but immobile across countries. We denote by w_{fn} the price of factor f in country n. Factor intensities for each industry k and factor f are denoted by β_{ikf}, and may vary across countries i. We denote by γ_{ihk} the share of the input bundles from industry h in total costs of industry k (direct input-output coefficient) in country i, and each input bundle is a CES aggregate of all varieties available in this industry. For sake of exposition we assume that the elasticity of substitution between varieties is the same as for final goods (see discussion in footnote 9). Total factor productivity $Z_{ik}(j_k)$ varies by country, industry and variety. We assume iceberg transport costs $d_{nik} \geq 1$ from country i to country n in sector k. The unit

[7] It is clear from Equation 2 that the ratio of the income elasticities of any pair of goods k and k' equals the ratio of their σ parameters: $\frac{\varepsilon_{nk}}{\varepsilon_{nk'}} = \frac{\sigma_k}{\sigma_{k'}}$ and is constant across countries.

cost of supplying variety j_k to country n from country i equals:

$$p_{nik}(j_k) = \frac{d_{nik}}{Z_{ik}(j_k)} \prod_f (w_{if})^{\beta_{ikf}} \prod_h (P_{ih})^{\gamma_{ihk}}$$

where P_{ih} is the price index of goods h in country i and $\sum_f \beta_{ikf} + \sum_h \gamma_{ihk} = 1$ in each country i, ensuring constant returns to scale.

There is perfect competition for the supply of each variety j_k. Hence, the price of variety j_k in country n in industry k equals $p_{nk}(j_k) = \min_i\{p_{nik}(j_k)\}$. We follow Eaton and Kortum (2002) and assume that productivity $Z_{ik}(j_k)$ is a random variable with a Frechet distribution. This setting generates gravity within each sector. Productivity is independently drawn in each country i and industry k, with a cumulative distribution $F_{ik}(z) = \exp\left[-(z/z_{ik})^{-\theta_k}\right]$ where z_{ik} is a productivity shifter reflecting average TFP of country i in sector k. Given the Frechet distribution, we obtain a gravity equation for each industry. As in Eaton and Kortum (2002), θ_k is related to the inverse of productivity dispersion across varieties within each sector k. Note that we also assume $\theta_k > \xi_k - 1$ to ensure a well-defined CES price index within each industry. As in Costinot et al. (2012), we also allow the shift parameter z_{ik} to vary across exporters and industries, controlling for any pattern of Ricardian comparative advantage forces at the sector level. Each country i is populated by a number L_i of individuals. The total supply of factor f is fixed in each country and denoted by V_{if}. Each individual is endowed by V_{if}/L_i units of factor V_{fi} implying no within-country income inequality.[8]

2.1.3 Energy sectors and CO_2 emissions

Primary and secondary energy sectors. Among energy sectors $k \in \mathcal{E}$, we differentiate primary sectors, $\mathcal{P}$, and secondary sectors, $\mathcal{S}$. Coal, natural gas and crude oil (as well as renewables and nuclear, which we ignore here as they do not emit CO_2) are considered to be "primary energy" sectors. "Secondary energy" describes sectors which can directly be used as inputs to production and/or in final demand. These include refined oil and electricity as well as coal and gas which can be both primary and secondary. Most CO_2 is emitted during the consumption (intermediate of final) of secondary energy or the transformation of primary energy into electricity, while a smaller amount is emitted during the refining of oil, gas and coal.

Production function. The production of primary energy goods (the fossil fuel sectors) requires the input of a "natural resource" factor of production that is specific to each sector. The endowments of these factors are fixed, so the supply elasticity of these fossil fuel sectors depends on the possibility to adjust factors that are mobile across sectors to complement natural resources (example: using capital and labor to extract more oil out of the same resource).

We assume that primary energy sectors combine their sector-specific natural resources with the other mobile inputs in a CES upper-tier with elasticity of substitution ν_k. The mobile inputs enter

[8] In a robustness check in Caron et al. (2014), we extend the model and estimation strategy to account for within-country income inequality and find very similar estimates, if not slightly wider differences in income elasticities.

as a lower-tier Cobb-Douglas composite of capital, labor and intermediate goods with cost c_{ik}. We denote by $w_{R,ik}$ the cost of natural resources that are specific to each energy sector $k \in \mathcal{P}$ and country i. The overall cost of production is thus:

$$p_{nik}(j_k) = \frac{d_{nik}}{Z_{ik}(j_k)} \left[\mu_{R,ik}\, w_{R,ik}^{1-\nu_{ik}} + (1-\mu_{R,ik})\, c_{ik}^{1-\nu_{ik}}\right]^{\frac{\beta_{ik}}{1-\nu_{ik}}} \prod_h (P_{ih})^{\gamma_{ihk}} \tag{3}$$

where P_{ih} is the price index of goods h in country i and where c_{ik} is the cost of non-resource factors in industry k in country i:

$$c_{ik} = \prod_f (w_{if})^{\frac{\beta_{ikf}}{\beta_{ik}}} \tag{4}$$

with $\sum_f \beta_{ikf} = \beta_{ik}$ and $\beta_{ik} + \sum_h \gamma_{ihk} = 1$ in each country i to ensure constant returns to scale. The parameter $\mu_{R,ik}$ reflects how much industry $k \in \mathcal{P}$ relies on natural resources.

Given the limited supply of the fixed factor, the elasticity of supply of primary energy good k is less than infinite:

$$\zeta_{ik} \;=\; \frac{\partial \log Y_{ik}}{\partial \log p_{ik}} - 1 \;=\; \frac{\nu_{ik}\,(1-\varphi_{R,ik})}{\beta_{ik}\,\varphi_{R,ik}} \;+\; \frac{1}{\beta_{ik}} - 1$$

as long as $\mu_{R,ik} > 0$ (see derivation in Appendix). As we will discuss, this elasticity of supply substantially influences the responses in equilibrium energy consumption (in quantities) to demand shocks.

The production of secondary energy goods $k \in \mathcal{S}$ is modeled in the same fashion as non-energy sectors $k \notin \mathcal{E}$ and can be seen as a special case where $\mu_{R,ik} = 0$.

Emissions. CO_2 emissions occur during the consumption of fossil fuels. Emissions related to the use of energy sector $k \in \mathcal{E}$ as an input to sector h in country i is assumed to depend linearly on quantities of k consumed in h:

$$CO2_{ikh} = \eta^C_{ikh} Q_{ikh} \tag{5}$$

where the coefficients η^C_{ikh} are fixed and country-sector specific, and where $Q_{ikh} \equiv \frac{\gamma_{ikh} Y_{ih}}{P_{ik}}$ represents absorption of energy good k, in terms of quantities, by industry h in country i. Emission coefficients η^C_{ikh} represent physical quantities of CO_2, in kilograms, and depends on energy good k being used (e.g. refined petroleum) and the buying industry h (e.g. chemicals or transportation). Coefficients may vary according to industry depending on the share of fossil fuels combusted as opposed to transformed. The consumption of electricity does not emit CO_2 and the η^C_{ikh} coefficients are zero for that sector.

Some CO_2 emissions are also directly related to final consumption of secondary energy goods (again, except electricity):

$$CO2_{ikF} = \eta^C_{ikF} Q_{ikF} \tag{6}$$

where $Q_{ikF} \equiv \frac{D_{ik}}{P_{ik}}$ reflects the quantities of energy goods $k \in \mathcal{S}$ consumed as final goods.

From the quantity-based coefficients η^C, we can derive value-based coefficients (based on benchmark energy prices) to describe emissions from each dollar of production or consumption. We compute

$$\beta_{ik}^{C} \;=\; \frac{1}{Y_{ik}} \sum_{h} CO2_{ihk} \;=\; \sum_{h} \frac{\eta_{ihk}^{C} \gamma_{ihk}}{P_{ih}}$$

as the amount (in kg) of CO_2 emissions per dollar of output of sector k. Similarly,

$$\beta_{ikF}^{C} \;=\; \frac{CO2_{ikF}}{P_{ik} Q_{ikF}} \;=\; \frac{\eta_{ikF}^{C}}{P_{ik}}$$

corresponds to the emissions caused by a dollar of final consumption of fossil fuels.

We refer to section 3 for further details on CO_2 emissions accounting, linking emissions in upstream industries (potentially from different producing countries) to the composition of final demand.

2.2 Equilibrium

We now define the equations which determine the equilibrium. On the demand side, total expenditures D_{nk} of country n in final goods k simply equals population L_n times individual expenditures as described by Equation 1. This gives:

$$D_{nk} = L_n (\lambda_n)^{-\sigma_k} \alpha_{2,k} (P_{nk})^{1-\sigma_k} \tag{7}$$

where $\alpha_{2,k}$ is the industry constant defined in equation 1. λ_n is the Lagrangian multiplier associated with the budget constraint:

$$L_n I_n = \sum_{k} D_{nk} \tag{8}$$

where I_n denotes per-capita income.

Total demand X_{nk} for goods k in country n is the sum of the demand for final consumption D_{nk} and intermediate use:

$$X_{nk} = D_{nk} + \sum_{h} \gamma_{nkh} Y_{nh} \tag{9}$$

where Y_{nh} refers to total production in sector h.

We denote by X_{nik} the value of trade *from* country i *to* country n, with:

$$X_{nik} = \frac{S_{ik} (d_{nik})^{-\theta_k}}{\Phi_{nk}} X_{nk} \tag{10}$$

where S_{ik} and Φ_{nk} are defined as follows. The "supplier effect", S_{ik}, is inversely related to the cost of production in country i and industry k. It depends on the total factor productivity parameter z_{ik} and the prices of intermediate goods and factors:

$$S_{ik} = z_{ik}^{\theta_k} \left(\prod_{f} (w_{fi})^{\beta_{ikf}} \right)^{-\theta_k} \left(\prod_{h} (P_{ih})^{\gamma_{ihk}} \right)^{-\theta_k} \tag{11}$$

The parameter θ_k is inversely related to the dispersion of productivity within sectors, implying that differences in productivity and factor prices across countries have a stronger impact on trade flows in sectors with higher θ_k.

For primary energy goods, the supplier effect also depends on fixed natural resources:

$$S_{ik} = z_{ik}^{\theta_k} \left[\mu_{R,ik}\, w_{R,ik}^{1-\nu_{ik}} + (1-\mu_{R,ik})\, c_{ik}^{1-\nu_{ik}}\right]^{-\frac{\beta_{ik}\theta_k}{1-\nu_{ik}}} \left(\Pi_h (P_{ih})^{\gamma_{ikh}}\right)^{-\theta_k} \tag{12}$$

with $c_{ik} = \prod_f (w_{if})^{\frac{\beta_{ikf}}{\beta_{ik}}}$ as described in the previous section.

In turn, we define Φ_{nk} as the sum of exporter fixed effects deflated by trade costs:

$$\Phi_{nk} = \sum_i S_{ik}(d_{nik})^{-\theta_k} \tag{13}$$

This Φ_{nk} acts as an "inward multilateral trade resistance index" and is closely related to the price index, as in Eaton and Kortum (2002):

$$P_{nk} = \alpha_{3,k}(\Phi_{nk})^{-\frac{1}{\theta_k}} \tag{14}$$

with $\alpha_{3,k} = \left[\Gamma\left(\frac{\theta_k+1-\xi_k}{\theta_k}\right)\right]^{\frac{1}{\xi_k-1}}$ where Γ denotes the gamma function.[9]

Finally, two other market clearing conditions are required to determine factor prices and income in general equilibrium. Given the Cobb-Douglas production function, total income from a particular factor equals the sum of total production weighted by the factor intensity coefficient β_{ikf}. With factor supply V_{fi} and factor price w_{fi} for factor f in country i, factor market clearing implies:

$$V_{fi}w_{fi} = \sum_{k\notin\mathcal{P}} \beta_{ikf}Y_{ik} + \sum_{k\in\mathcal{P}} Y_{ik}\frac{\beta_{ikf}(1-\mu_{R,ik})c_{ik}^{1-\nu_{ik}}}{\mu_{R,ik}w_{R,ik}^{1-\nu_{ik}} + (1-\mu_{R,ik})c_{ik}^{1-\nu_{ik}}} \tag{15}$$

where $\frac{\beta_{ikf}(1-\mu_{R,ik})c_{ik}^{1-\nu_{ik}}}{\mu_{R,ik}w_{R,ik}^{1-\nu_{ik}}+(1-\mu_{R,ik})c_{ik}^{1-\nu_{ik}}}$ is the share of spending on factor f, and output equals the sum of outward flows $Y_{ik} = \sum_n X_{nik}$.

For natural resources, in each primary energy sector $k \in \mathcal{P}$ and country i, market clearing yields:

$$R_{ik}w_{R,ik} = \frac{\beta_{ikf}Y_{ik}\mu_{R,ik}w_{R,ik}^{1-\nu_{ik}}}{\mu_{R,ik}w_{R,ik}^{1-\nu_{ik}} + (1-\mu_{R,ik})c_{ik}^{1-\nu_{ik}}} \tag{16}$$

In turn, per-capita income is determined by:

$$I_i = \frac{1}{L_i}\sum_f V_{fi}w_{fi} \tag{17}$$

[9]This can be generalized by allowing the elasticity of substitution for intermediate use to differ from the elasticity of substitution for final use, and depends on the parent industry. This does not affect the elasticity of the price index w.r.t. Φ_k as long as θ_k does not depend on the final use. Differences in elasticities of substitution would be captured by the industry fixed effect that we include in our estimation strategy and would not affect our estimates.

By Walras' Law, trade is balanced at equilibrium. Given the equilibrium X_{nk} and P_{nk} of energy sectors, we can then back out emissions using equations 5 and 6.

2.3 Counterfactual equilibria

Following Dekle et al. (2007) and Caliendo and Parro (2015), the model lends itself naturally to counterfactual simulations. Using a set of observed variables and a limited number of parameters to estimate, the above equilibrium conditions can be reformulated to define a counterfactual equilibrium relative to our baseline equilibrium.[10] Specifically, using "exact hat algebra" where $\widehat{Z} = Z'/Z$ denotes the relative change in variable Z, we obtain the following set of equilibrium conditions:

$$\widehat{D_{nk}} = \widehat{\lambda_n}^{-\sigma_k} \widehat{P_{nk}}^{1-\sigma_k} \tag{18}$$

$$\widehat{I_n} = \frac{\sum_k \widehat{D_{nk}} D_{nk}}{\sum_k D_{nk}} \tag{19}$$

$$\widehat{X_{nk}} = \frac{D_{nk}\widehat{D_{nk}}}{X_{nk}} + \sum_h \frac{\gamma_{nkh} Y_{nh} \widehat{Y_{nh}}}{X_{nk}} \tag{20}$$

$$\widehat{X_{nik}} = \widehat{S_{ik}}\, \widehat{d_{nik}}^{-\theta_k} \widehat{P_{nk}}^{\theta_k} \widehat{X_{nk}} \tag{21}$$

$$\widehat{P_{nk}} = \left[\sum_i \pi_{nik} \widehat{S_{ik}}\, \widehat{d_{nik}}^{-\theta_k} \right]^{-\frac{1}{\theta_k}} \tag{22}$$

$$\widehat{S_{ik}} = \widehat{z_{ik}}^{\theta_k} \left[\beta_{R,ik}\, \widehat{w_{R,ik}}^{1-\nu_k} + (1-\beta_{R,ik})\, \widehat{c_{ik}}^{1-\nu_k} \right]^{-\frac{\theta_k \beta_{ik}}{1-\nu_k}} \left(\prod_h \widehat{P_{ih}}^{\gamma_{hk}} \right)^{\theta_k} \tag{23}$$

$$\widehat{c_{ik}} = \prod_f \widehat{w_{fi}}^{\frac{\beta_{fk}}{\beta_{ik}}} \tag{24}$$

$$\widehat{w_{if}} = \frac{1}{V_{if} w_{if}} \left[\sum_{k \notin \mathcal{P}} \beta_{ikf} Y_{ik} \widehat{Y_{ik}} + \sum_{k \in \mathcal{P}} \beta_{ikf} Y_{ik} \widehat{Y_{ik}} \widehat{c_{ik}}^{1-\nu_k}\, \widehat{\chi_{ik}}^{\nu_{ik}-1} \right] \tag{25}$$

$$\widehat{w_{R,ik}} = \widehat{Y_{ik}} \left(\frac{\widehat{c_{ik}}}{\widehat{w_{R,ik}}} \right)^{\nu_k - 1} \quad \text{for } k \in \mathcal{P} \tag{26}$$

$$\widehat{I_i} = \frac{\sum_f V_{fi} w_{fi} \widehat{w_{fi}} + \sum_{k \in \mathcal{P}} R_{ik} w_{R,ik} \widehat{w_{R,ik}}}{\sum_f V_{fi} w_{fi} + \sum_{k \in \mathcal{P}} R_{ik} w_{R,ik}} \tag{27}$$

$$\widehat{CO2_{nhk}} = \frac{\widehat{Y_{nk}}}{\widehat{P_{nh}}} \quad \text{for } h \in \mathcal{E} \tag{28}$$

where production equals $Y_{nk} = \sum_i \pi_{ink} X_{ik}$ and trade shares are defined as $\pi_{nik} = \frac{X_{nik}}{X_{nk}}$.

As will be further discussed in Section 5.5, our counterfactual equilibria reflect the impact of productivity growth $\widehat{z_{ik}} = \frac{z'_{ik}}{z_{ik}}$ across sectors k and countries i. We simulate a uniform 1% (Hicks-Neutral) productivity increase across all countries and sectors. Knowing the values of variables D_{nk},

[10] This approach, sometimes described as the "calibrated share form", has also been used in the Computable General Equilibrium literature. See Rutherford (2002).

I_n, X_{nk}, X_{nik} and $V_{fi}w_{fi}$ in the baseline equilibrium as well as parameters σ_k, θ_k, γ_{hk} and β_{fk}, we can solve for all changes $\widehat{D_{nk}}$, $\widehat{\lambda_n}$, $\widehat{I_n}$, $\widehat{P_{nk}}$, $\widehat{S_{nk}}$ and $\widehat{w_{fn}}$ for any given change in productivity $\widehat{z_{ik}}$.

3 Implications for CO_2 emissions

3.1 CO_2 content of consumption, production and imports

There are several ways to illustrate the link between income and CO_2 emissions. While this paper focuses on how consumption patterns affect consumption emissions both directly and indirectly, we also show how they affect production emissions and emissions embodied in imported consumption.

Input-output linkages and total emission coefficients Being interested in the total impact of consumption patterns on CO_2 emissions, we need to track the production of goods across all source countries and sectors generated by a dollar of final consumption in each sector and country. This requires 1) import shares π_{nih} to inform how total demand from country n leads to production in country i; and 2) requirement coefficients γ_{nhk} (coefficients of the Cobb-Douglas production function) to track the demand for inputs from industry h by the parent industry k in country n. The $\pi_{nih}\gamma_{nhk}$ product provides the direct requirement coefficients of a multi-regional input-output matrix A. Production of good h in country i must equal final demand plus intermediate demand by downstream industries, such that we obtain:

$$Y_{ih} = \sum_{n} \pi_{nih} D_{nh} + \sum_{n,k} \pi_{nih} \gamma_{nhk} Y_{nk} \tag{29}$$

Building on this standard input-output accounting equality, we obtain the γ^{tot}_{nikh} coefficients of the $(I-A)^{-1}\pi$ matrix (also called "total requirement coefficients" associated with the "Leontief inverse"). These inform on the dollar amount of production in country i in industry h ultimately generated by each dollar of final demand for product k in country n.[11] These total requirement coefficients γ^{tot}_{nikh} are used to define total CO_2 coefficients:

$$\beta^{Ctot}_{ik} \;=\; \sum_{n,h} \beta^{C}_{nh} \gamma^{tot}_{inhk}$$

i.e. the emissions embodied in each dollar of production of good k in country i. Summing across all source countries, we can use these to define indirect CO_2 consumption coefficients, $\beta^{Cindir}_{ikF} = \sum_n \pi_{ink} \beta^{Ctot}_{nk}$, which in turn define total CO_2 consumption coefficients β^{Ctot}_{ikF}:

$$\beta^{Ctot}_{ikF} \;=\; \sum_{n} \pi_{ink} \beta^{Ctot}_{nk} + \beta^{C}_{ikF} \;=\; \beta^{Cindir}_{ikF} + \beta^{C}_{ikF} \tag{30}$$

[11] In matrix form, we have: $y = \pi D + Ay$. Inverting, we obtain: $y = (I-A)^{-1}\pi D$.

i.e. the indirect (for all goods) and direct (for fossil fuels only) emissions associated with the consumption of each dollar of good k in country i sourced from all countries n.

Using these coefficients, we can easily compute measures of country-level CO_2 contents. In order to facilitate decompositions in Section 5.4, we take care to describe each as functions of final demand D_{nk}.

Direct CO_2 content of consumption We first examine direct consumption emissions, i.e. CO_2 caused by the consumption of fossil fuels (refined oil, natural gas and coal) as final goods. As is common in the literature, we also include the emissions embodied in electricity consumption even though these emissions do not occur directly in final demand. We thus define, for each country n:

$$EC_n^{dir} = \sum_{k \in \mathcal{S}} CO2_{nkF} + \beta^{Ctot}_{n,ele,F} D_{n,ele} = \sum_{k \in \mathcal{S}} \beta^{C}_{nkF} D_{nk} + \beta^{Ctot}_{n,ele} D_{n,ele} \tag{31}$$

Total CO_2 content of consumption We then track indirect consumption emissions, i.e. CO_2 caused by production in all countries to satisfy final demand in country n:

$$EC_n^{indir} = \sum_{k} \beta^{Cindir}_{nkF} D_{nk} \tag{32}$$

Such that total (direct and indirect) consumption-related emissions EC_j^{tot} are:

$$EC_n^{tot} = \sum_{k \in \mathcal{S}} \beta^{C}_{nkF} D_{nk} + \sum_{k} \beta^{Cindir}_{nkF} D_{nk} = \sum_{k} \beta^{Ctot}_{nkF} D_{nk} \tag{33}$$

Note that in general, because of international trade, emissions (indirectly) embodied in consumption differ from emissions from domestic production since domestic consumption may rely on imports and domestic production may be consumed elsewhere.

Production emissions Production emissions in country n are the sum of emissions occurring during the production of all sectors k in n.[12] As described above, production Y_{nk} can be linked to the sector and location of final demand using total requirement coefficients, such that:

$$EY_n = \sum_{hk} CO2_{nhk} = \sum_{k} \beta^{C}_{nk} Y_{nk} = \sum_{i,k} \pi_{ink} \beta^{Ctot}_{nk} D_{ik} \tag{34}$$

Total CO_2 content of imported consumption We can also go a bit further and decompose the indirect emissions content of consumption into its domestic and imported components. The emissions embodied in country j's imported final demand are given by[13]:

[12] We do not define production emissions as the emissions content of production, which would include the emissions embodied in intermediate goods produced in other countries.

[13] An alternative way of measuring imported consumption emissions would be to include all emissions which occur abroad at all stages of production, $EC_n^{imp} = \sum_{ik} \pi_{nik} \sum_{h,j \neq n} \beta^{C}_{ih} \gamma^{tot}_{ijhk} D_{nk}$. However, this would complicate the decomposition exercise of section 5.4. We find that both measures have a similar relationship with per capita income.

$$EC_n^{Imp} = \sum_{i \neq n,k} \pi_{nik} \beta_{ik}^{Ctot} D_{nk} \tag{35}$$

3.2 Counterfactual changes in CO_2 emissions

The above equations describing the emissions content of consumption inform only on the link between emissions and observed demand patterns, all in partial equilibrium. In this section, we further explore how a change in income affects emissions through consumption patterns, linking those more precisely to the structure of preferences. We also account for changes in relative demand and substitution between energy and other factors of production which may lead to different responses in CO_2 emissions.

In order to focus on the demand-side mechanism of shifting consumption patterns, we consider the effect of a neutral increase in income caused by counterfactual uniform factor productivity growth, $\hat{z}$. This counterfactual, increasing factor productivity uniformly across sectors and countries, is motivated by two key points.

First, it is a natural case to study the differences between homothetic and non-homothetic preferences. If preferences are homothetic, it leads to a homogeneous increase in real income $\hat{z}$ in all countries and no change in consumption patterns, production and trade. CO_2 emissions would increase uniformly by $\hat{z}$ in all countries. If preferences are non-homothetic, the ratio of income to prices still increases by $\hat{z}$ (as a first-order approximation) but income effects lead to a reallocation of expenditures across goods (changes in consumption patterns). If income elasticity is correlated with CO_2 intensity across goods, this will translate into aggregate changes in emissions that may understate or exceed those with homothetic preferences.

Second, a general-equilibrium implication of this counterfactual is that factor costs will change homogeneously across countries as a first-order approximation, which leaves trade shares π_{nik} unchanged. Note also that input-output coefficients remain fixed thanks to the Cobb-Douglas upper tier. This implies that we can continue to use some of the tools developed in the previous sub-section to describe trade and input-output linkages.

Our key variable of interest is the income elasticity of emissions. For each country, we thus compute the response of both the direct and total average CO_2 content of consumption, $\widehat{EC}_n^{dir}$ and $\widehat{EC}_n^{tot}$ (combining $\widehat{EC}_n^{dir}$ and $\widehat{EC}_n^{indir}$), as well as production emissions, $\widehat{EY}_n$, to a given proportional change in factor productivity (real per capita income) $\widehat{z}$.[14] Also of interest are the changes in the CO_2 content of worldwide consumption caused by uniform productivity growth, $\widehat{EC}_{world}^{dir}$ and $\widehat{EC}_{world}^{tot}$, summing across all countries. Note that at the world level, emissions embodied in consumption equal total production emissions so $\widehat{EC}_{world}^{indir} = \widehat{EY}_{world}$. In our benchmark specification, the productivity

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Neither measures are equal to the total emissions embodied in imports, which would include imported intermediates not necessarily consumed within the country — and are therefore not the focus of this study.

[14] These are derived from a counterfactual equilibrium following a homogeneous factor productivity increase, which is equivalent to a sectoral TFP increase $\hat{z_{ik}} = \hat{z}^{\beta_{ik}} > 1$ in all countries and sectors, where $1 - \beta_{ik}$ is the share of intermediate goods in production. Note that the effect on emissions would be different if the economy were growing due to the accumulation of certain factors or if technology growth was biased towards more or less CO_2-intensive sectors.

shock is applied to all sectors. In our simulations, we also test the sensitivity of results to the exclusion of growth in fossil fuel resource productivity.

Partial equilibrium approximation While the computation of exact changes relies on numerical methods and is delegated to our empirical section 5.5, we present here some intuition behind counterfactual changes in emissions. We do so with first-order analytical approximations in partial equilibrium, neglecting changes in relative factor prices for non-resource factors (e.g. returns to labor relative to capital). Assuming that resource factors account for a negligible share of GDP, we can normalize GDP to remain constant in each country.

The homogeneous productivity increase $\widehat{z}$ leads, as a first approximation, to a homogeneous change in prices $\widehat{P_{nk}} \approx \widehat{z}^{-1}$ for non-energy goods k. In Appendix Section A.2, we show how equations 18 and 27 can be used to obtain a simple expression for changes in demand as a function of productivity growth and income elasticity ε_{nk} (as defined in equation 2):

$$\log \widehat{D_{nk}} \approx (\varepsilon_{nk} - 1) \log \hat{z} \tag{36}$$

where ε_{nk} generally differs from unity if preferences are non-homothetic.

As we have seen previously (equation 29) we can link production to changes in demand using the "total requirement coefficients" γ^{tot}_{nikh}, with $Y_{ih} = \sum_{n,k} \gamma^{tot}_{nikh} D_{ik}$. In this counterfactual where trade shares remain constant as a first order approximation, these total requirement coefficients can also be used to characterize changes in output as a function of the changes in consumption baskets and the productivity shock $\log \hat{z}$. We obtain:

$$\log \widehat{Y}_{ih} = \frac{1}{Y_{ih}} \sum_{n,k} \gamma^{tot}_{nikh} D_{nk} \log \hat{D}_{nk} = (\varepsilon^{tot}_{ih} - 1) \log \hat{z} \tag{37}$$

$$\text{with:} \qquad \varepsilon^{tot}_{ih} = \frac{1}{Y_{jh}} \sum_{n,k} \gamma^{tot}_{nikh} D_{nk} \varepsilon_{nk} \tag{38}$$

In this equation, we define a sector's "total income elasticity" ε^{tot}_{ih} as the weighted-average of income elasticity ε_{ik} of all the final goods in which that sector's output is embodied and in all destination countries. This new tool helps describe income effects in production, including the effects of income on both a good's final demand and use as an intermediate good.

Equation 37 is a good approximation for most sectors, but less so for energy goods given that they require specific natural resources and thus have a finite supply elasticity ζ_{ih}.[15] To examine counterfactual changes in emissions, we thus need to examine changes in energy prices, which depend crucially on the supply elasticity. As a first-order approximation, accounting for the endogenous change in natural resource prices, the change in the production cost of primary energy good k is given by $\frac{1}{1+\zeta_{ik}} \log \widehat{Y}_{ik}$, where $\widehat{Y}_{ik}$ refers to the change in the value of production. From equations 13 and 14, we obtain that the change in prices in (destination) country n is an average (weighted by import

[15] For these goods, a first-order approximation is $\log \hat{Y}_{ih} = (\varepsilon^{tot}_{ih} - 1) \log \hat{z} + \frac{\theta_h}{Y_{ih}} \sum_{n,j} X_{nh} \pi_{njh} \pi_{nih} \left(\frac{\log \hat{Y}_{jh}}{1+\zeta_{jh}} - \frac{\log \hat{Y}_{ih}}{1+\zeta_{ih}} \right)$

shares π_{nik}) of the change in production costs across source countries. Combining with equation 37 on production, we can then also link the changes in energy prices to the change in consumption choices and income elasticities:

$$\log \widehat{P_{nk}} = -\log \hat{z} + \sum_i \frac{\pi_{nik}}{1+\zeta_{ik}} \log \widehat{Y}_{ik} \approx -\log \hat{z} + \sum_i \frac{\pi_{nik}(\varepsilon_{ik}^{tot}-1)}{1+\zeta_{ik}} \log \hat{z} \tag{39}$$

With these tools in hand, we can then derive expressions for the counterfactual changes in emissions embodied in consumption, production and imports.

Direct CO_2 content of consumption The changes in direct consumption emissions are determined by the change in final consumption of energy minus, for primary energy goods, the change in energy prices (see equation 28): $\log \widehat{CO2}_{nkF} = \log \widehat{D_{nk}} - \log \widehat{P_{nk}}$. Using expressions 37 and 39 and summing over energy goods, we obtain the change in direct consumption emissions as a function of productivity growth, $\log \hat{z}$:

$$\log \widehat{EC_n^{dir}} \approx \left[1 + \sum_{k \in \mathcal{S}} \frac{CO2_{nkF}}{EC_n^{dir}} (\varepsilon_{nk}-1) - \sum_{k \in \mathcal{P}} \frac{CO2_{nkF}}{EC_n^{dir}} \sum_i \frac{\pi_{nik}\,(\varepsilon_{ik}^{tot}-1)}{1+\zeta_{ik}}\right] \log \hat{z} \tag{40}$$

This approximation has an intuitive interpretation. First, it shows that growth in direct consumption emissions is directly driven by productivity growth $\log \hat{z}$. The middle term in the brackets reflects the non-homothetic demand effect: if the income elasticity of secondary energy is on average below one, it will pull direct emissions downwards (income elasticities are weighted by each good's share of direct consumption emissions in n, $CO2_{nkF}/EC_n^{dir}$). The last term reflects the attenuating effect of reductions in energy prices caused by lower-than-proportional demand for primary energy (again a function of each sector's share of direct emissions).[16]

In Section 5.5 we compare these changes in emissions, expressed as elasticities to $\log \hat{z}$, to exact simulated changes to validate our approximations.

Indirect and total CO_2 content of consumption For the indirect CO_2 content of consumption, we similarly obtain:

$$\log \widehat{EC_n^{indir}} \approx \left[1 + \sum_k \frac{\beta_{nkF}^{Cindir} D_{nk}}{EC_n^{indir}} (\varepsilon_{nk}-1) - \sum_{k,h \in \mathcal{P},i} \frac{\beta_{ih}^{C} \gamma_{nikh}^{tot} D_{nk}}{EC_n^{indir}} \frac{(\varepsilon_{ih}^{tot}-1)}{1+\zeta_{ih}}\right] \log \hat{z} \tag{41}$$

As above, this expression has a straightforward interpretation. The demand effect (middle term in the brackets) is the sum of ε_{nk} (which drives growth in final demand for k) weighted by each sector's share of embodied consumption emissions (recall from equation 33 that $EC_n^{indir} = \sum_k \beta_{nkF}^{Cindir} D_{nk}$). Thus growth in country n's EC_n^{indir} will be larger if sectors with high CO_2 intensity, and thus high

[16]It cancels the non-homothetic demand effect if the supply elasticity is zero ζ_{ik} and the direct income elasticity of each energy good is the same as its weighted total income elasticity (this would be the case if there were no intermediate use of energy, for instance).

shares of indirect emissions $\frac{\beta_{nkF}^{Cindir} D_{nk}}{EC_n^{indir}}$, have on average a high income elasticity ε_{nk}; it will instead be lower if if CO_2 intensity is negatively correlated with income elasticity. From this term we deduct the weighted sum of the growth in prices in all the fossil fuels in all countries $\frac{\varepsilon_{jf}^{tot}-1}{1+\zeta_{jf}}$ ultimately consumed in country n, weighted their share of indirect consumption emissions in n.

We then obtain the change in the total CO_2 content of consumption as:

$$\widehat{EC}_n^{total} \approx \frac{1}{EC_n^{tot}} \left[EC_n^{dir} \widehat{EC}_n^{dir} + EC_n^{indir} \widehat{EC}_n^{indir} \right] \tag{42}$$

Finally, changes in the worldwide total emissions, $\widehat{EC}_w^{total}$, can be approximated by the average $\widehat{EC}_n^{total}$, weighted by each country n's share of worldwide total emissions.

Emissions from production Changes in emissions from sector k in country n caused by burning energy inputs h are given by: $\log \widehat{CO2}_{ikh} = \log \widehat{Y_{ik}} - \log \widehat{P_{ih}}$ (equation 28). Summing across all energy inputs, and using expressions 37 and 39 above for the changes in production and prices, we obtain:

$$\log \widehat{EY}_n \approx \frac{1}{EY_n} \left[\sum_{k,h} CO2_{nkh} \varepsilon_{nk}^{tot} - \sum_{k,h \in \mathcal{P},i} CO2_{nkh} \frac{\pi_{nih}(\varepsilon_{ih}^{tot}-1)}{1+\zeta_{ih}} \right] \log \hat{z} \tag{43}$$

The first term reflects the growth of each industry k and its demand for energy input h, weighted by the share $CO2_{nkh}/EY_n$ of industry k and fuel h in total production emissions of country n (these shares add up to unity). The second term reflects the change in energy prices given the growth in demand and the finite supply elasticity.

4 Data and estimation Strategy

4.1 Data

The empirical analysis is based on the Global Trade Analysis Project (GTAP) version 8 dataset (Aguiar et al., 2012). This dataset is uniquely suited to our purposes, as it contains a consistent and reconciled cross-section of production, input-output, consumption and trade data. It provides considerable heterogeneity in energy and CO_2 intensity as well as consumption patterns across 57 sectors which cover manufacturing, agriculture, transport and services. The 109 countries in the dataset (composite regions are dropped) cover a wide range of per capita income levels and all stages of economic development.[17] All values represent the 2007 economy. The full list of sectors and countries in the dataset can be found in Tables A.1 and A.2 of the Appendix.

The dataset is complemented with physical energy use data from the International Energy Agency's (IEA) "Extended Energy Balances" . It comprises both primary and secondary energy use, expressed

[17] In comparison, the WIOD dataset (www.wiod.org) covers 40 countries across 35 sectors.

in millions of tonnes of oil equivalent (Mtoe), for all countries and sectors.[18] It also includes corresponding carbon dioxide emission data by fossil fuel, expressed in million of tonnes (MtCO_2), for both intermediate demand and final consumption, simplifying the computation of CO_2 intensity coefficients by sector.[19]

Data describing the emissions of other greenhouse gases, methane, nitrous oxides and fluorinated greenhouse gases (CH_4, N_2O and F-gases), are compiled by Amer et al. (2014). These non-CO_2 emissions are associated with the use of factors of production (capital, land), intermediate inputs (energy, chemicals) or directly in production (chemical processes, for example). These have been matched to GTAP sectors, by country, and converted into CO_2 equivalents, making them directly comparable (and additional) to CO_2 in terms of global warming potential.[20] These gases are primarily associated with agricultural production, including livestock, but a non-negligible share is emitted during other industrial processes and transport. As with CO_2 emissions, the GTAP data allow us to trace greenhouse gas emissions through the entire chain of production, accounting for trade and input-output linkages.

Despite the clear advantage of supplying harmonized consumption, production and trade data for a wide range of countries, two weaknesses of the GTAP data should be recognized. First, not all values in the dataset are directly observed in all countries for the same year. Some values are extrapolated from previous years, and some missing sectors are shared out proportionally to world averages or to similar countries. Second, the data have been adjusted to provide a balanced micro-consistent dataset which can be used for computable general equilibrium analysis. This procedure modifies the raw data by an undocumented amount.

Throughout the analysis, we define final consumption as the sum of household and government consumption as well as investment final demand (as defined in GTAP). Finally, the gravity estimations rely on bilateral variables describing physical distance, common language, colonial link and contiguity which are obtained from CEPII.[21]

4.2 Using gravity to estimate cross-country price differences

We now describe the estimation of the key parameters in the model. The estimation here closely follows Caron, Fally and Markusen (2014, 2017), although with a newer dataset and a number of additional robustness checks. The main challenge is to disentangle demand and supply side effects. For instance, a country with a comparative advantage in a certain sector will tend to have lower relative prices in that sector, leading to relatively larger production volumes as well as higher or lower demand, depending on whether elasticities of substitution are higher or lower than unity. These patterns may bias our cross-sectional estimates of income elasticity. Using gravity equations as a first

[18]Treatment of energy in the GTAP data and mapping to Extended Energy Balances data is described in https://www.gtap.agecon.purdue.edu/resources/download/2934.pdf.

[19]The dataset does not cover CO_2 emissions which are unrelated with fossil fuel use. Some industrial processes, notably cement manufacturing, produce CO_2. These emissions account for less than 5% of total CO_2 emissions.

[20]These other greenhouse gases are equivalent to about a third of total GHG emissions in terms of warming potential.

[21]Data are available at www.cepii.fr.

step, we are able to estimate patterns of comparative advantage separately from demand-side effects, which then allows us to control for supply-side effects when estimating preferences.

In a first step, we rewrite equation 10 in logs and allow trade costs d_{nik} to depend on a number of factors such as distance and contiguity. We thus obtain a set of gravity equations in which S_{ik}, Φ_{nk} and x_{nk} are captured using exporter (FX_{ik}) and importer (FM_{nk}) fixed effects:

$$\begin{aligned} \log x_{nik} &= FX_{ik} + FM_{nk} - \beta_{Dist,k} \log Dist_{ni} \; + \; \beta_{Contig,k}.Contiguity_{ni} \\ &\quad + \beta_{Lang,k}.CommonLang_{ni} \; + \; \beta_{Colony,k}.ColonialLink_{ni} \; + \; \beta_{HomeBias,k}.I_{n=i} + \varepsilon_{nik} \end{aligned}$$

This gravity equation is estimated separately for each sector using Poisson pseudo maximum likelihood regressions (as in Fally, 2015). The gravity equations are used to estimate trade costs and patterns of comparative advantage. Following the strategy developed by Redding and Venables (2004), we then use the estimates of $\log S_{ik}$ ($\widehat{FX}_{ik}$), and $\log d_{nik}$ (using all transport cost proxies and their coefficients) to construct an estimate of our price index proxy Φ_{nk} as:

$$\begin{aligned} \widehat{\Phi}_{nk} &= \sum_i \exp\Big(\widehat{FX}_{ik} - \widehat{\beta}_{Dist,k} \log Dist_{ni} \; + \; \widehat{\beta}_{Contig,k}.Contiguity_{ni} \\ &\quad + \widehat{\beta}_{Lang,k}.CommonLang_{ni} \; + \; \widehat{\beta}_{Colony,k}.ColonialLink_{ni} \; + \; \widehat{\beta}_{HomeBias,k}.I_{n=i}\Big) \end{aligned}$$

In a second step, the estimated $\widehat{\Phi}_{nk}$ are used to structurally control for supply-driven effects in the estimation of demand parameters. The advantage of these price proxies is that they are partially exogenous to country n's own demand for sector k, being determined by the country's proximity to trading partners with large comparative advantages in the sector.

4.3 Estimating non-homothetic preferences

The value of individual expenditures in an industry is determined by Equation 1, the stochastic version of which is estimated in logs as:

$$\log d_{nk} = \log \alpha_k + -\sigma_k . \log \lambda_n + \frac{\sigma_k - 1}{\theta_k} . \log \widehat{\Phi}_{nk} + \varepsilon_{nk} \tag{44}$$

in which α_k is a sector-specific preference parameter which varies across industries only and λ_n is the shadow value of the budget constraint. σ_k, our parameter of interest, drives both income and price elasticity, but as θ_k is left unconstrained in the estimation of Equation 44, income and price elasticities are estimated separately. In addition, final demand should satisfy the budget constraint (equation 8) which determines the Lagrangian multiplier λ_n: a higher income per capita is associated with a smaller λ_n. There is no closed-form solution expressing λ_n as a function of per capita income I_n except in the homothetic case where $\sigma_k = \sigma$ is constant across goods, so equations 44 and 8 are estimated simultaneously using constrained non-linear least square regressions. Regressions and the corresponding statistics we report, including the R2, are weighted by each sector's mean expenditure share. Finally, using the estimates of σ_k and observed expenditure shares, we can compute the income elasticity of consumption of each sector k in country n using equation 2.

5 Empirical results: The income-consumption-CO_2 relationship

In this section, we investigate the role of per capita income in determining CO_2 emissions levels through its impact on consumption patterns. We start by describing the estimation of preference parameters and income elasticities, correlate them to CO_2 intensity coefficients across sectors, and investigate the link between income and emissions across countries. Finally, we use the estimated general equilibrium model to simulate the extent to which per capita income growth affects CO_2 emissions.

To motivate our empirical analysis, the first four columns of Table 1 display the average expenditure share of energy goods as well as broad categories of non-energy goods in lower, lower-middle, upper-middle and high-income countries (based on World Bank guidelines for 2007).[22] Significant differences for all goods indicate large scope for income to affect consumption patterns across the spectrum of per-capita income levels.[23]

The last column of Table 1 displays each sector's (world average) share of total consumption emissions (EC^{total}). It shows that on average, the "direct" consumption of energy (mostly electricity and refined oil but also natural gas and coal) corresponds to about 27% of the emissions associated with consumption. Consumption of non-energy goods is thus associated with large shares of emissions, mostly through manufacturing and service sectors.

Table 1: Expenditure shares, income elasticity and total CO_2 intensity (in kg/$) across broad sectors

	Expenditure share (by country income group)				Income	Total CO_2	Share of tot.
	Lower	Lower-middle	Upper-middle	High-income	elasticity	intensity	CO_2 in cons.
Refined oil	0.018	0.018	0.013	0.010	0.78	5.26	0.107
Electricity	0.019	0.016	0.016	0.009	0.81	6.30	0.116
Coal	0.0002	0.0004	0.0002	0.0000	0.95	56.81	0.009
Natural gas	0.0082	0.0016	0.0018	0.0019	1.82	10.94	0.036
Agriculture	0.280	0.166	0.122	0.059	0.67	0.51	0.072
Transportation	0.044	0.041	0.052	0.024	0.86	1.44	0.078
Manufacturing	0.350	0.428	0.340	0.315	0.99	0.61	0.343
Services	0.256	0.314	0.447	0.581	1.07	0.25	0.237

Notes: Income elasticities evaluated at mean expenditure shares. Total CO_2 intensities are world weighted averages of $\bar{\beta}_k^{total}$ and are expressed in kg per $ of consumption.

[22] The classification is based on GNI/capita. The cut-off for low-income countries is 935$ and below, while it is 3705$ for lower-middle-income countries and 11455$ for upper-middle-income countries. In our dataset, there are 16, 27, 24 and 42 countries in each income class.

[23] These expenditure shares represent the share of total final demand expenditures (including investment and government expenditures). If considering the share of spending within household consumption only, expenditure shares for energy goods would be higher, corresponding to 4.3% of expenditures (on average over all countries) instead of 2.4% if considering total final demand.

5.1 Consumption patterns and income elasticity estimates

The first step in our estimation procedure is to estimate supply-side parameters describing comparative advantage and trade costs. The results from the gravity equations are standard and summary statistics can be found in Appendix Table A.3. From these, we back out our price index proxies and use them to estimate income elasticity.

As already documented in Caron et al. (2014), the constrained NLLS estimation of demand patterns described by equation 44 fits the data well, with an R2 of 0.85 (0.86 if considering energy goods only).[24] The high R2 is partially explained by large average differences in expenditures shares captured by α_k. A partial R2 measure reveals that income and price differences capture 0.323 of the variability left unexplained by a model in which $\sigma_k = 1$. The F-stat on the σ parameters being significantly different from unity indicates strongly significant non-homotheticicities in consumption patterns (12.01 across all goods, 6.69 for secondary energy goods, both with a p-value < 0.001). CRIE preferences yield Engel curves which are close to log-linear[25] which has been shown to be a good approximation of consumer behavior in a range of contexts. Comin et al. (2015), for example, find log-linearity to hold for broad sectors over a wide range or per capita income levels. Table 5 in the Extensions section provides additional regression statics and a comparison to more flexible demand systems allowing for non-linearities.

Focusing first on energy consumption, Figure 1 plots fitted and observed consumption against per capita total expenditure for the 4 secondary energy sectors. The fit is overall good, although a substantial amount of unexplained heterogeneity remains in the coal and, to a lesser extent, natural gas sectors.

Figure 3 then displays the distribution of estimated 'direct' income elasticities ε_k for all sectors, computed following equation 2 and evaluated at mean expenditure shares (income elasticity varies across countries according to observed consumption shares). Table A.1 in Appendix contains the underlying numerical values. These estimates exhibit considerable variability across sectors.[26]

5.2 Sector-level correlation of income elasticity and CO_2 intensity

Before turning to the link between consumption patterns and emissions at the country level, we look at the relationship between a sector's income elasticity and the CO_2 emissions caused by its consumption. A sector-level relationship between these parameters provides preliminary evidence for the possibility of a demand-side link between energy use, emissions and income levels.

[24] The NLLS estimation covers 49 sectors, as we drop Dwellings, which are non-tradable and for which price indice proxies are not available, as well as 6 intermediate good sectors which have zero or negligible shares of output going to final demand (pdr, oil, omn, nmm, i_s, nfm).

[25] Caron et al. (2014) find a very high correlation between the estimated $\log \lambda_n$ and $\log I_n$.

[26] Our assumption of homogeneous within-country income could actually be biasing income elasticity estimates towards one, leading us to underestimate the role of income growth: energy use in low-income countries may be driven by a small number of high-income households, for example. The bias may not be large: using a similar framework Caron, Fally and Markusen (2014), finds that the distribution of income elasticity estimates is only slightly larger when integrating within-country income distributions.

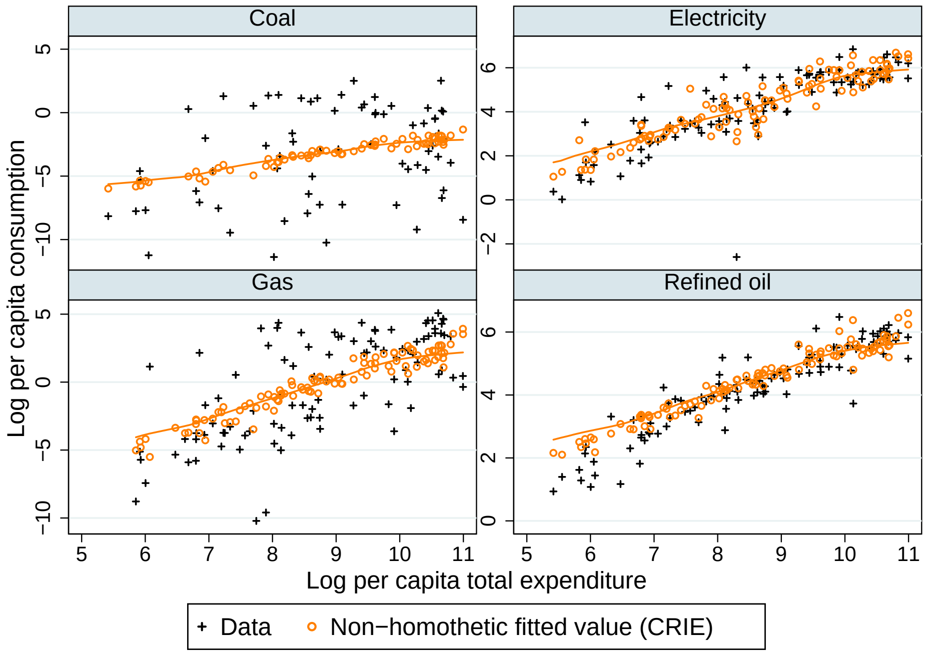


Figure 1: Per capita consumption of secondary energy goods (log) against per capita total expenditure.
Notes: the solid lines represent a kernel-weighted local polynomial smoothing of CRIE fitted values.

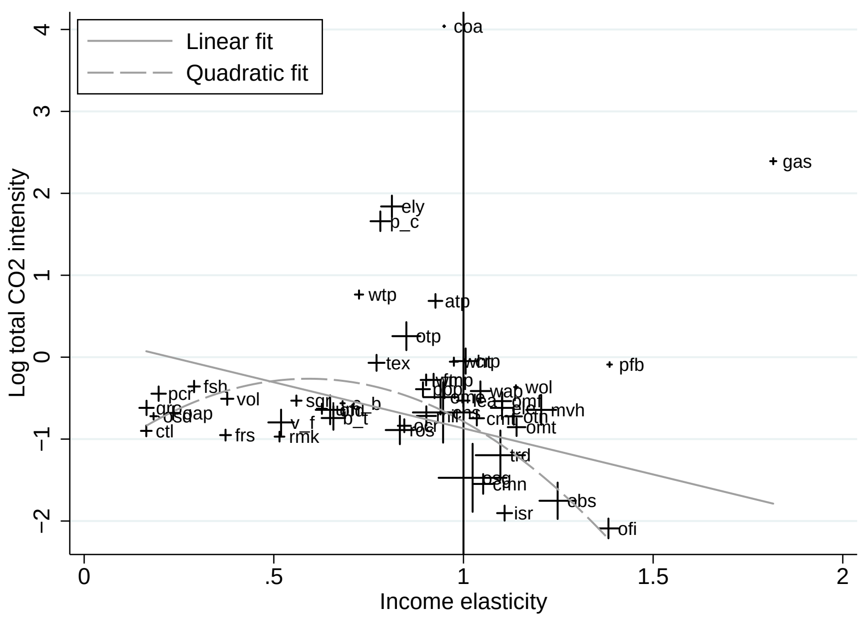


Figure 2: The correlation of income elasticities and CO_2 intensities at the sector-level.
Notes: Marker size reflects the sector's average share of final demand. See Table A.1 in Appendix for underlying data and full sector names.

Table 2: Relationship between income elasticity estimates and (log) total CO_2 intensity coefficients

Dep. var.:	CO_2 intensity (log)					
	All sectors		Non-energy only		Manufacturing only	
Beta coeff:	(1)	(2)	(1)	(2)	(1)	(2)
Income elasticity	-0.356	0.587	-0.424	1.095	-0.345	0.281
Square term		-0.972		-1.559		-0.629
P-value joint. Sign.	0.006	0.011	0.002	<0.001	0.027	0.073
AIC	104.9	103.8	66.8	61.5	11.6	13.6
Obs. (sectors)	49	49	45	45	13	13

Notes: beta coefficients; p-values of F-test of significance of the coefficient on income elasticity or the joint significance of the coefficients on income elasticity and its square; regressions weighted by average share of final demand.

Figure 2 displays the relationship between income elasticity $\bar{\varepsilon}_k$ and average total CO_2 intensity coefficients $\bar{\beta}_{kF}^{Ctot}$, in logs, computed as described in equation 30.[27] Both parameters vary across countries, so we display average values.

The figure reveals an inverted-U pattern: sectors of intermediate income elasticity have on average the highest CO_2 intensity. But it is also asymmetric and negative overall, with high income elasticity sectors having on average the lowest CO_2 requirements. This systematic relationship between income elasticity and CO_2 intensity implies that consumers of different income levels will consume baskets of goods with different average CO_2 intensities.

Both the negative and inverted-U patterns are statistically significant. Table 2 displays the beta coefficients resulting from regressions of (log) CO_2 intensity on income elasticity. Specification (1) is linear, and finds a negative correlation of -0.36 (p-value < 0.01). Specification (2) allows for a quadratic term and yields coefficients consistent with an inverted-U relationship (the coefficients are jointly significant with p-value $= 0.01$). Comparisons of the Akaike information criteria (AIC) show that the non-linear specification is slightly favored.

The negative relationship partially reflects a transition away from the direct consumption of energy as final goods, as three of the four secondary energy goods have income elasticities that are below unity on average. This can also be seen in the last three columns of Table 1, which show income elasticity and CO_2 intensity across secondary energy sectors and non-energy sectors (an exception is natural gas consumption, which is highly income elastic but accounts for just 3.6% of total consumption emissions).

Beyond this, the negative and inverted-U relationship also holds — and is even stronger — when restricted to the set of non-energy goods (middle two columns of Table 2). In broad terms, this reflects a transition from low-income elasticity, low-CO_2 intensity agricultural sectors to medium-

[27] The relationship is plotted for the 49 sectors in the dataset which are consumed as final goods. Figure 12 in Section 6.2 displays the corresponding relationship between income elasticity, secondary energy intensity and GHG intensity.

income elasticity, high-CO_2 intensity transportation[28] and medium-intensity manufacturing, to high-income elasticity, low-CO_2 intensity service sectors such as businesses and financial services (OBS, OFI). The relationship is not only driven by the transition between broad sectors, as we also find a negative (but not inverted-U) relationship within the 13 manufacturing sectors (last two columns).

Cross-country variation For exposition purposes, we have thus far focused on average income elasticity parameters, but estimates vary across countries because of variations in expenditure shares (see equation 2). CRIE preferences generates income elasticity which declines with income for all sectors. For instance, while the income elasticity of the oil and electricity sectors is below unity (0.78 and 0.81) when evaluated using average expenditure shares, their estimates vary across countries and are above one in six of the lowest income countries.

Despite these differences, note that relative income elasticity is constant with CRIE preferences, so the correlations with CO_2 intensities displayed in Table 2 are unaffected by the choice of country.[29] Cross-country differences do matter when assessing the overall direction and magnitude of the income-driven changes in CO_2, however. Whether CRIE preferences allow for sufficient cross-country variation will be further investigated in the Extensions Section 6.1.

Total income elasticity Some of the sectors displayed in Figure 2 are used primarily as intermediates with only a small share of production consumed as final goods. As an alternative way of thinking about the link between income and emissions, Figure 3 compares each sector's income elasticity in final consumption (defined as the "direct income elasticity") to the income elasticity of their total demand (or absorption). The "total income elasticity" (ε_{ih}^{tot}, computed as in equation 38) reflects the income elasticity of total demand for sector k, driven not only by an increase in its own final demand but also by an increase in the final demand of goods which use sector k as an intermediate. The "financial services nec" sector, as an example, has a very high "direct" elasticity of 1.38. Its "total" income elasticity is considerably lower, at 1.14, suggesting that a number of sectors with lower direct income elasticity use it as an input.

Figure 3 helps illustrate several facts. First, while direct and total elasticities are correlated, there is less variance in total income elasticities than direct elasticities, and the estimates exhibit smaller deviations from unity. The structure of the input-output linkages is such that many low income elasticity goods are required as intermediate inputs to sectors with higher income elasticity than theirs, and conversely for many high-income elasticity sectors. This implies that changes in per capita income will affect absorption (total demand) patterns less than final consumption patterns.[30]

Second, Figure 3 shows that the total income elasticity of energy goods (the first block of four sectors) also differs from their direct elasticity. The two most important, refined oil and electricity,

[28]The transportation sectors represent market-supplied transportation (ground, sea and air transportation) and does not include household-provided transportation, which is captured by the final demand for refined oil (p_c).

[29]Emission intensity coefficients also vary between countries, but the correlations are robust within countries and using averages based on various sub-groups of countries.

[30]This point is related to Herrendorf et al. (2013) who find that measuring structural change on a final demand basis yields a different relationship with per capita income than when measuring on a value added basis.

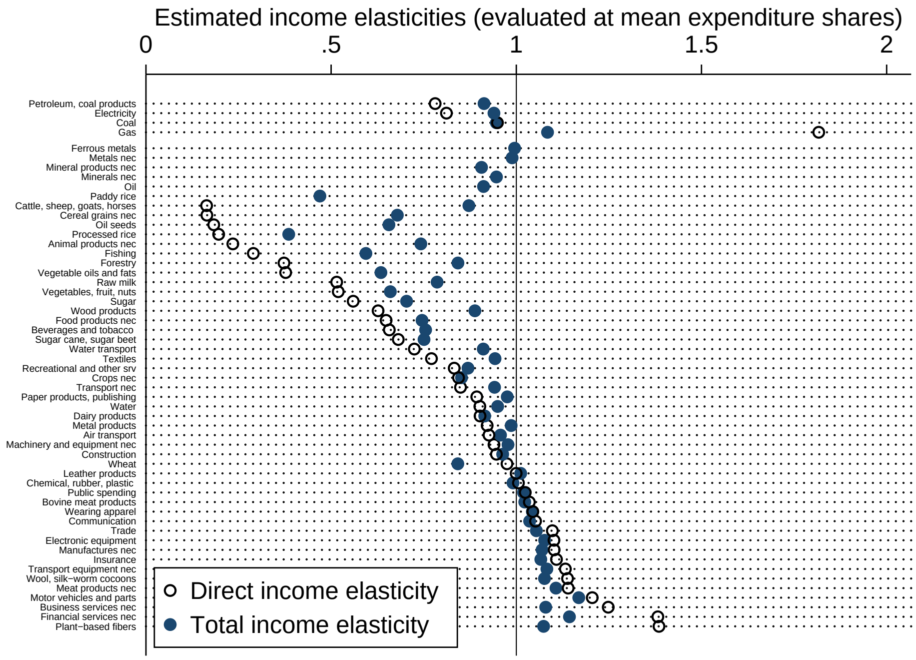


Figure 3: Direct versus total income elasticities

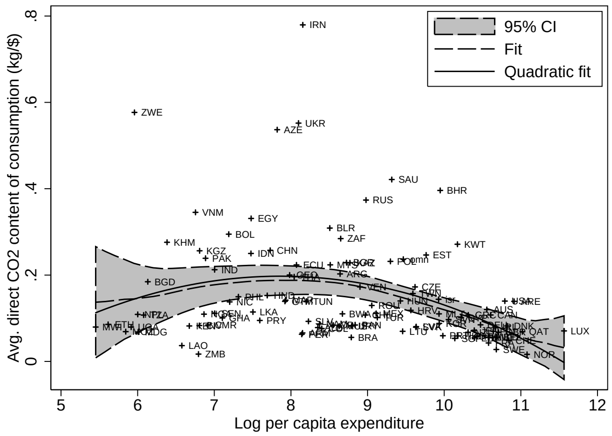
Notes: Income elasticities evaluated at mean shares. See Table A.1 in Appendix for underlying data.

have higher total income elasticity, implying that they are used as intermediates to goods which have on average a higher income elasticity than their own. On the contrary, natural gas has a considerably lower total income elasticity — easily explained by the fact that it is an important input to the production of electricity and a number of other industrial sectors with lower income elasticity. Overall, the total income elasticity of energy is much closer to unity than its direct elasticity, so the share of energy goods in total GDP is less sensitive to per capita income than their share in final demand.

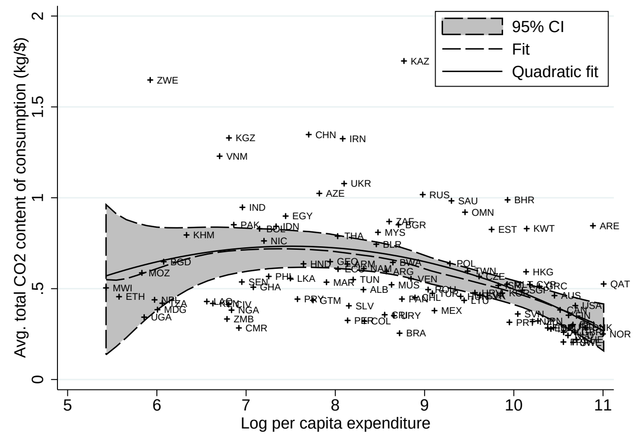
5.3 Emissions content of consumption, production and imports

We now investigate the extent to which the above sector-level relationships translate to a country-level link between per capita income and the average CO_2 content of consumption. Since preferences are non-homothetic and income elasticities are linked to CO_2 intensities, income levels will affect consumption patterns in a way which systematically affects the overall energy and CO_2 content of a country's final consumption. We also investigate the relationship between income and the emissions content of production and imports.

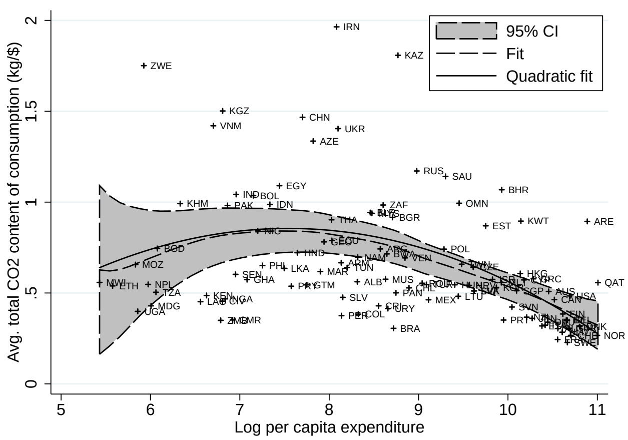
Figure 4 displays the country-level CO_2 content of consumption, EC_n^{dir}, EC_n^{indir}, EC_n^{tot}, and of production, EY_n (Equations 31 to 35), expressed as averages (i.e. as intensities, in kg CO_2/\$) by dividing them by the value of total expenditure. They are plotted as a function of log per capita expenditure (which in most regions is close to per capita income), the dashed line representing a kernel-weighted local linear regression, the shaded area the 95% confidence interval and the solid line



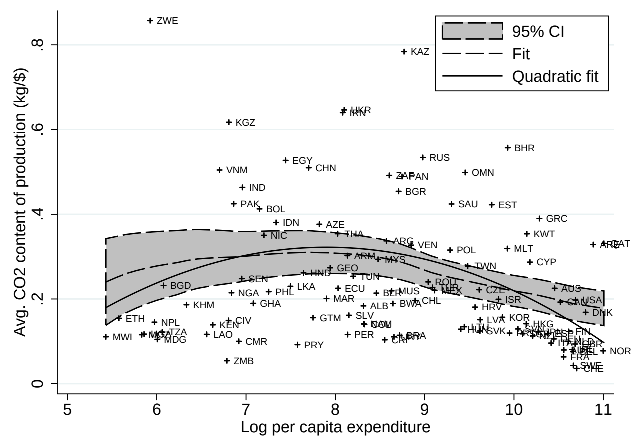
(a) Direct CO_2 content of consumption



(c) Indirect CO_2 content of consumption



(b) Total CO_2 content of consumption



(d) Total CO_2 content of production

Figure 4: Average CO_2 content in the data

the fitted prediction from a quadratic least-squares regression (a functional form commonly used in the literature to represent this relationship). The average values for the total CO_2 content of consumption are around three times as large as those of direct consumption, consistent with the fact that a large part of consumption emissions are indirect.

Similar to the cross-sector relationships, the country-level relationship between income and the average direct, indirect and total CO_2 contents of consumption (Figures 4a, 4b and 4c) follow a distinct inverted-U pattern with an overall negative trend. Indeed, the quadratic fit follows the non-parametric local regression fit quite closely. For all three, the coefficients of either a linear regression (negative) or a quadratic regression (inverted-U) are significant with p-values smaller than 0.01.

Differences in intensities between income levels are substantial. Classifying countries according to per capita income, we find that the (weighted) average CO_2 intensity of direct consumption is 0.21 kg/$ for low-income countries, 0.266 kg/$ for lower-middle-income countries, 0.158 kg/$ for upper-middle-income countries, and only 0.063 kg/$ for high-income countries. For the total CO_2 content, variations are also substantial: 0.789, 1.190, 0.654 and 0.365. We should also note that the shape of the quadratic and non-parametetric curves suggest that intensities peak at relatively low levels of income.

There is, however, a lot of variability around these patterns not explained by per capita income levels, and R-squared values from the quadratic regressions are fairly low: 0.11, 0.20 and 0.17 for direct, indirect and total consumption. Thus, although the average CO_2 content significantly co-varies with per capita income levels, most of the variability across countries is not explained by income, at least in reduced-form. Finally, Figure 4d shows that the average CO_2 content of production also follows an inverted-U pattern, even though it is flatter and the quadratic fits seems to exaggerate the pattern.

5.4 Isolating the role of consumption patterns and per-capita income

The cross-country variability observed in Figure 4 reflects more than differences in consumption patterns. In order to isolate their role, we compute weighted average (across countries) direct and total CO_2 intensity coefficients $\bar{\beta}^{C}_{nkF}$ and $\bar{\beta}^{Ctot}_{nkF}$, and use them to re-calculate EC^{dir}_n, EC^{indir}_n, EC^{tot}_n, EC^{imp}_n and EY_n. Using average production CO_2 intensities at the sector level neutralizes differences in production technologies across countries, within-sector heterogeneity (types of goods, differences in quality) and the role of trade (the sourcing of goods).

In a second step, we investigate the predictive power of per capita income as a determinant, through its influence on consumption patterns, of the CO_2 content of consumption. For this, we use fitted consumption vectors from the CRIE demand system, computed under the assumption of identical but non-homothetic preferences (as estimated in equation 44). In order to distinguish the effect of supply-driven price differences from that of per capita income, consumption is also fitted with homothetic preferences by imposing $\sigma_k = \sigma$ in equation 44. Thus, three types $\Delta \in \{\text{data}, \text{homoth}, \text{non-homoth}\}$ of consumption values D_{nk} are defined:

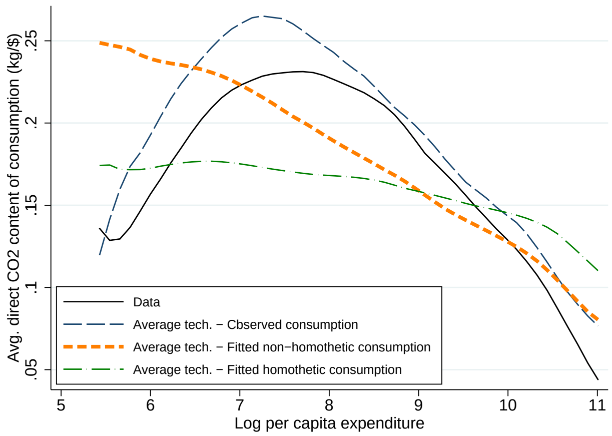
$$D^{\Delta}_{nk} = \begin{cases} D^{data}_{nk} & \text{observed} \\ D^{homoth}_{nk} = L_n \alpha_k \Phi_{nk}^{\frac{(\sigma_k - 1)}{\theta_k}} & \text{fitted, homothetic} \\ D^{non-homoth}_{nk} = L_n \alpha_k \lambda_n^{-\sigma_k} \Phi_{nk}^{\frac{(\sigma_k - 1)}{\theta_k}} & \text{fitted, non-homothetic} \end{cases}$$

Building on these fitted consumption patterns, we obtain the following decomposition of CO_2 content:

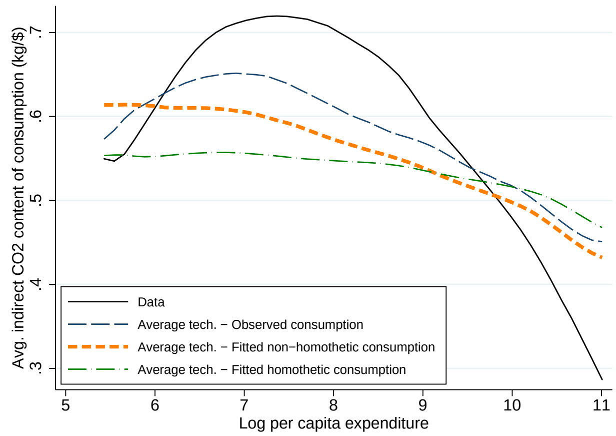
$$\overline{EC}^{dir,\Delta}_n = \sum_{k \in \mathcal{S}} \bar{\beta}^{C}_{kF} D^{\Delta}_{nk} + \bar{\beta}^{Ctot}_{ele} D^{\Delta}_{n,ele} \qquad \overline{EC}^{indir,\Delta}_n = \sum_{k} \bar{\beta}^{Cindir}_{kF} D^{\Delta}_{nk}$$

$$\overline{EY}^{\Delta}_n = \sum_{i,k} \pi_{ink} \bar{\beta}^{Ctot}_{k} D^{\Delta}_{ik} \qquad \overline{EC}^{imp,\Delta}_n = \sum_{i \neq n,k} \pi_{nik} \bar{\beta}^{Ctot}_{k} D^{\Delta}_{nk}$$

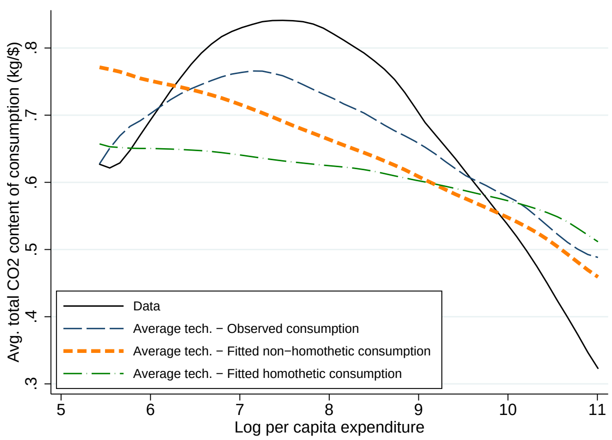
Figure 5 displays these values using kernel-weighted local linear regression to compare, in each case, the average CO_2 content observed in the data (the solid line) to values obtained with average production technologies and observed, fitted non-homothetic and fitted homothetic demand patterns



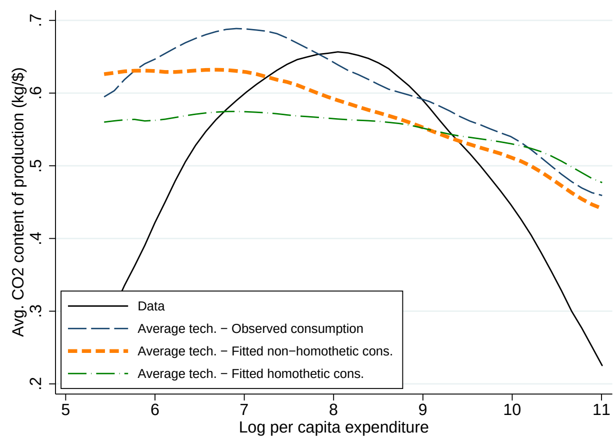
(a) Avg. Direct CO_2 content of consumption



(c) Avg. indirect CO_2 content of cons.



(b) Avg. total CO_2 content of consumption



(d) Avg. total CO_2 content of production

Figure 5: Average CO_2 content, local linear regression smoothing.

(the dashed lines). To summarize the relative fit of each decomposed element, Table 3 displays the correlation between the observed average CO_2 content (the solid line in Figure 5) and the fitted values (the dashed lines) computing using average production intensities and variations in consumption patterns.

The role of consumption patterns Differences in consumption patterns contribute to the observed inverted-U relationship between the CO_2 content of consumption and per capita income. Similarly to observed values, fitted values evaluated using observed consumption patterns but constant production intensities (Δ = data) exhibit an inverted-U relationship with per capita income with a negative overall trend for the direct (Figure 5a), indirect (Figure 5c) and the total (Figure 5b) CO_2 content. In each case, the coefficients of either linear or quadratic coefficients significantly describe negative or inverted-U relationships (p-values < 0.01).

The observation that differences in the average CO_2 content of consumption are at least partially

Table 3: Correlations between true content (with observed technologies) and fitted values

Production intensities:	*average*			*observed*
Consumption patterns:	*homoth*	*non-homoth*	*observed*	*observed*
Direct consumption	0.297	0.508	0.826	1
Indirect consumption	0.382	0.630	0.654	1
Total consumption	0.386	0.626	0.721	1

driven by consumption patterns can also be confirmed in Table 3. Using observed consumption patterns but average intensities yields estimates which are well correlated with observed values, with correlation coefficients of 0.826, 0.654 and 0.721 for the direct, indirect and total CO_2 content.

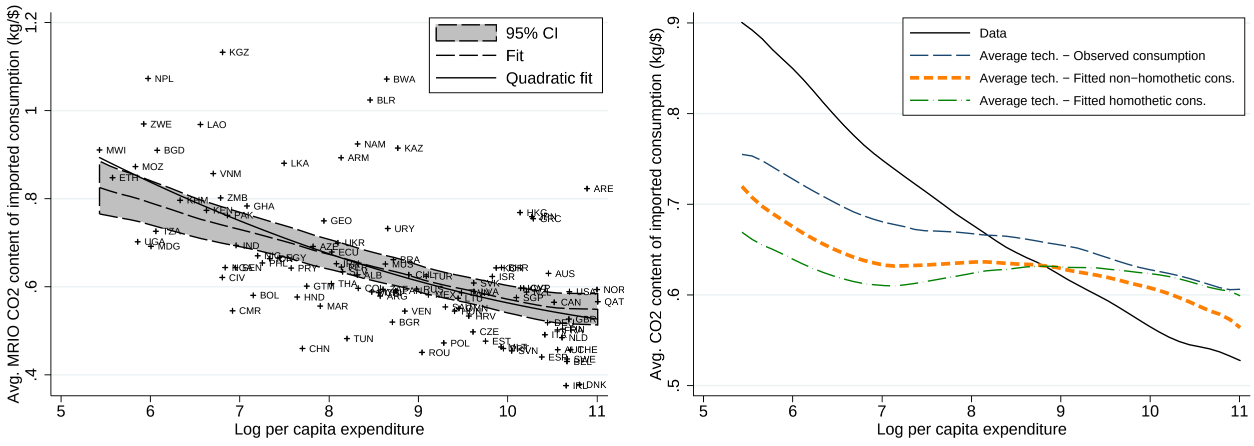
Finally, differences in consumption patterns also contribute to explaining why production emissions EY_n decrease with per capita income (see Figure 5d).

The role of non-homotheticity We then investigate the extent to which per capita income determines CO_2 contents through its role in changing consumption patterns (and thus, whether it can be used as a predictor of emissions). To see this, Figure 5 also displays the average CO_2 contents obtained with average production technologies *and* fitted consumption patterns.

As a point of comparison, we first consider consumption patterns fitted under the assumption of homothetic preferences (green medium-dotted line in Figure 5). These vary according to price differences but not income. They generate a weakly decreasing relationship between average direct, indirect and total CO_2 content of consumption and per capita income. This suggests that the cross-country price differences estimated in the gravity framework are correlated with CO_2 intensity: CO_2-intensive goods are on average relatively cheaper in low-income countries and more expensive in high-income countries. This effect is moderate, however, and Table 3 shows that the resulting fitted CO_2 content is only 29.7% (for direct) and 38.6% (for total) correlated with observed content.

Relaxing the assumption of homothetic preferences — that is, allowing per capita income to determine consumption patterns — significantly increases the correlation between fitted content and observed content: from 29.7% to 50.8% for direct; 38.2% to 63.0% for indirect; and 38.6% to 62.6% for total. These can be compared to the 82.6%, 65.4% and 72.1% correlations obtained with observed consumption patterns. The average CO_2 content declines significantly faster with income under non-homothetic preferences (see the orange small-dashed line in Figure 5). For the indirect CO_2 content, the relationship is very similar to that obtained with observed consumption. However, while the model captures the negative trend observed for middle- and high-income countries, it fails to capture the increase in average content at very low incomes.

Again grouping countries by per capita income level, we find the magnitude of the income effect predicted by the model to be substantial: the (weighted) average CO_2 intensity of total consumption is 0.733 kg/$ for low-income countries, 0.613 kg/$ for middle-income, and 0.461 kg/$ for high-income countries, in each case evaluated using average production intensities.



(a) Observed (b) Fitted

Figure 6: Average CO_2 content of imported consumption

Measure of fit and summary As an alternate way of describing the role of consumption patterns and non-homotheticity in determining cross-country patterns in emissions, we compute a measure of fit, $R2^{\text{pseudo}}$, which summarizes the share of variance in each true CO_2 content measure explained by their different fitted equivalents $\widehat{EC}_n$[31] Focusing on the total CO_2 content, we obtain an $R2^{\text{pseudo}}$ of 0.336 when using observed consumption patterns and average production intensities. In other words, the fact that consumers in different countries chose to consume different baskets of goods explains one third of the large observed differences in the total CO_2 intensity of consumption (for direct CO_2 emissions, the equivalent $R2^{\text{pseudo}}$ is even higher and equals 0.673). Any model which ignores differences in consumption patterns (or any predictive exercise which fails to account for the evolution of these patterns due to growth in per capita income) will fail to account for 34% of the variability in the CO_2 emissions embodied in consumption.

In turn, much of this variability can be explained by non-homothetic preferences. Using the fitted non-homothetic consumption patterns from our model explains more than two thirds of this variance, with an $R2^{\text{pseudo}}$ of 0.239. Conversely, imposing homothetic preferences yields an $R2^{\text{pseudo}}$ of 0.101 only. We conclude that per capita income explains a substantial part of the variability in the average CO_2 content of consumption across countries through its influence on consumption patterns. This conclusion also holds for total and indirect emissions in consumption, as depicted in Figures 5a and 5c, but to a smaller extent since income effects are weaker for intermediate goods demand (as emphasized in Section 5.2, total income elasticities tend to be closer to unity than direct elasticities).

Imported consumption Finally, we consider the role of income and consumption patterns in determining the CO_2 content of imported consumption and display EC^{Imp} (eq. 35) and its decompositions in Figure 6b. The fact that high-income countries "outsource" the production of CO_2-intensive goods,

[31]It is computed as $R2^{\text{pseudo}} = 1 - \frac{SSR}{SSE} = 1 - \frac{\sum_n (EC_n^{true} - \widehat{EC}_n)^2}{\sum_n (EC_n^{true} - \overline{EC}_n^{true})^2}$.

making them net importers of CO_2 on average, is an important and well documented phenomenon sometimes referred to as the pollution-heaven hypothesis (Copeland and Taylor, 2005). We confirm a variant of this hypothesis using our model and multi-regional input-output dataset: the share of imported CO_2 in consumption within total CO_2 in consumption is U-shaped with both the lowest- and highest-income countries importing the largest shares of the CO_2 they consume.

In addition, we identify a new mitigating mechanism: *within* imported consumption, the average CO_2 content declines with per capita income. In other words, the goods imported by higher income countries are less CO_2-intensive than those imported by lower income countries. The solid line in Figure 6b shows the observed relationship with income to be quite strong. Again evaluating with average technologies, we find most of the downward trend to be explained by the fact that high-income countries import from countries with on average less CO_2-intensive technologies (as evidenced by the large difference between the solid and dashed lines). However, once again, consumption patterns also contribute to the downward slope, part of which is generated by non-homotheticity. The effect here is mostly significant for the lowest- and highest-income countries: it is fairly flat for the middle section of the per capita income spectrum.

To summarize, consumers in rich countries indeed import more of the CO_2 they consume, but also have preferences which make their imports less CO_2 intensive. Our model would thus predict a weaker "pollution-heaven" effect than standard models with homothetic preferences.

5.5 Simulating a counterfactual increase in per capita income

Having established per capita income as a important determinant of CO_2 emissions contents, we now investigate the potential for further income growth to reduce energy use and emissions through a shift in consumption patterns, absent any other change in production functions (technology) and endowments. We simulate growth in per capita income by introducing an exogenous shock which increases total factor productivity z by one percent. In this context, a world economy with homothetic preferences would see a one percent homogeneous increase in emissions in all countries, making it a natural benchmark to highlight the role of non-homotheticities.

In section 3.2, we have described how uniform TFP growth across all sectors in all countries affects emissions intensity in partial equilibrium approximations. Here, we use the full general equilibrium model and parameter estimates described in Section 2 to simulate income growth and estimate the elasticity of emissions to income. Simulated values should be interpreted as general equilibrium elasticities as they are the outcome of counterfactual simulations which capture the response of supply to the demand shock. General-equilibrium feedback effects include price responses for all sectors and all factors: for example, a reduction in the relative consumption of energy goods (both as final goods and intermediates) is mitigated by a decrease in their relative prices. They also include trade-related effects: for instance, reductions in the price of energy goods in rich countries is mitigated by increasing demand in low-income countries. Counterfactual equilibria are obtained by formulating equations 18 to 27 as a system of non-linear equations in GAMS which is solved numerically using the non-linear

PATH solver.[32]

Calibration of energy supply elasticity Changes in total demand for fossil fuels ultimately depends on the supply and demand equilibrium. While we want to illustrate the role of the demand-side, specifically a demand shock which affects relative consumption shares across sectors, changes in the equilibrium level of emission thus also depend on the response of fossil fuel supply. Obtaining precise estimates of the price elasticity of supply of gas, oil and coal for all the countries in our dataset is beyond the scope of this paper. While the literature has made some attempts at estimating such elasticities, cleanly identified estimates are scarce, and ultimately depend on the time-scale under consideration. Nevertheless, a survey of the literature suggests that response to prices is low, with long-run estimates generally lying between 0.5 and 1 for oil and coal, while estimates for natural gas have sometimes been slightly larger than unity.[33] In our benchmark simulations, we chose to calibrate the supply elasticity of all three fuels to 0.75 — an arbitrary but plausible value in line with the long-run nature of our simulation exercise. This value generates relatively low supply-side response in terms of quantities and large response in terms of prices on the fossil fuel markets. To examine sensitivity to this assumption, we also provide results generated with a higher supply elasticity of 1.5, a value possibly consistent with supply response in the very long run.

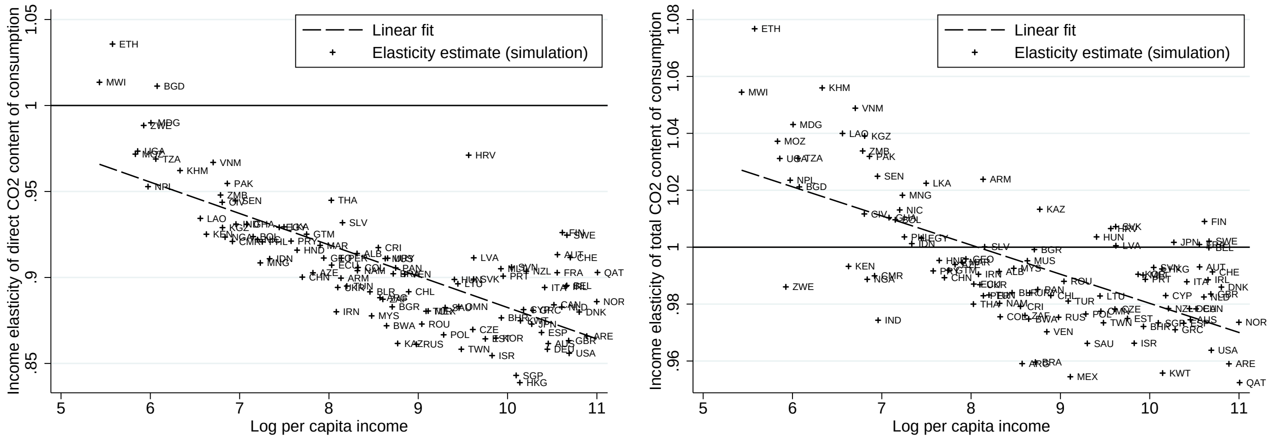
Simulation results The simulated change in emissions, $\widehat{EC}_n^{dir}$ and $\widehat{EC}_n^{tot}$, are displayed in Figures 7a and 7b in terms of elasticities to income. A value of one in Figure 7 implies that per capita income and the CO_2 content of consumption increase at the same rate, so the CO_2 *intensity* of consumption is insensitive to income. This would be the case for all countries if preferences were homothetic, as uniform productivity growth across sectors and factors (including fossil fuel resource factors) would increase income and consumption but not affect the relative demand for each sector.

Figure 7a reveals that the income elasticity of the average direct CO_2 content of consumption to income is substantially below one for all but a handful of lowest-income countries. Estimates range from 1.036 for Ethiopia to 0.839 for Hong-Kong. For the USA, the country with the world's largest share of direct CO_2 emissions, the elasticity is 0.856. The weighted average for the world is 0.882, implying that a 1% increase in per capita income in all countries would reduce the average direct CO_2 content of consumption by about 0.12%. Importantly, the reduction in CO_2 intensity is consistently stronger in high-income countries: their average elasticity is 0.867, while it is 0.897 for middle-income and 0.954 for low-income countries. The average world elasticity is thus likely to decrease as incomes converge towards high-income country levels.

Turning to the total CO_2 content of consumption in Figure 7b — the most relevant metric from a policy perspective — results are qualitatively similar but weaker. This is consistent with the findings that the total income elasticity of energy is closer to one than its direct elasticity. In 36 of the 109

[32] Fitted values are used for all baseline equilibrium outcomes (D_{nk}, Y_{nk}, etc...) to insure consistency with the model. Similar results are obtained using observed values.

[33] More generally, Fally and Sayre (2017) survey the literature and find that most estimates of supply elasticity for primary commodities tend to be lower than unity.



(a) Avg. direct CO_2 content of consumption

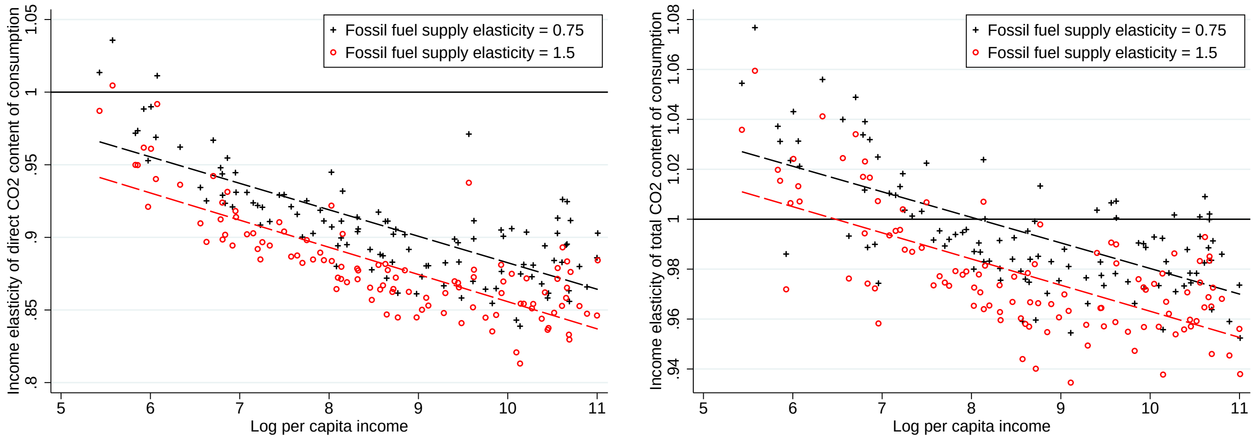
(b) Avg. total CO_2 content of consumption

Figure 7: Simulated elasticity of the CO_2 content of consumption to per capita income (supply elasticity of fossil fuels calibrated to 0.75). CRIE preferences.

countries, the simulated elasticities are above one, implying that the total CO_2 intensity of their consumption will further grow with income as they are still shifting their consumption towards more CO_2 intensive goods. This is consistent with the inverted-U pattern described in Section 5.4. Values are also higher than one in a few high-income countries such as Finland, Sweden and Japan, in most cases because of high consumption of natural gas. But as with the direct CO_2 content, there is an overall declining relationship with income: most high-income countries are predicted to see their emission intensities decline, with for instance an elasticity of 0.963 for the USA. The average elasticity for high-income countries is 0.977, while it is 0.983 for middle-income and 1.021 for low-income countries. The weighted average elasticity for the world is 0.979 (this corresponds to the income elasticity of production emissions as well). Thus, changes in consumption patterns resulting from a 1% increase in per capita income would decrease total emission intensity by 2.1% relative to models with homothetic preferences.

We have so far focused on the income elasticity of the aggregate CO_2 content of consumption (Figure 7). Figure A.3 in Appendix compares it to the income elasticity of production emissions, $\widehat{EY}_n$. The two metrics are overall very similar in levels but low- and high-income countries tend to see their consumption emissions rise more than their production emissions. The opposite is true for middle-income countries, who see an increase in their net exports of emissions.

Fossil fuel supply response As a robustness test, Figure 8 compares estimates resulting from a price elasticity of fossil fuel supply calibrated to 0.75 (as in Figure 7) to an elasticity of 1.5. Doubling the fossil fuel supply elasticity increases the strength of the shift in demand away from energy, but the difference is small: the world average income elasticity is 0.860 instead of 0.882 for the direct CO_2 content and 0.962 instead of 0.979 for the total CO_2 content. Aside from the downward adjustment, the distribution of effects between countries is very similar to our baseline counterfactual with a



(a) Avg. direct CO_2 content of consumption (b) Avg. total CO_2 content of consumption

Figure 8: Simulated elasticity of the CO_2 content of consumption to per capita income – sensitivity to fossil fuel supply elasticity. CRIE preferences.

lower supply elasticity. This suggests that world markets in energy and energy-intensive goods are sufficiently integrated to mostly decouple the demand shocks from supply response across countries.[34]

In our benchmark counterfactual, the productivity of the natural resource factor specific to each fossil fuel also increases, similarly to all production factors, which implies no effect on CO_2 intensities when preferences are homothetic. As a robustness check, we simulate a productivity shock in all but the fossil fuel sectors. This represents a world in which fossil fuel scarcity (and thus their relative price) increases, so that structural change is driven by more than just the demand effect. Figure A.4 in Appendix displays our simulation results with homothetic and non-homothetic preferences as well as the difference between the two. In this case the simulated elasticity of total CO_2 to income is smaller than unity (0.806 for the world) even with homothetic preferences. The difference between non-homothetic and homothetic preferences is however very similar to what occurs with resource productivity growth, suggesting that interactions between rising relative costs of energy and the income effect are not important. The average world elasticity is again slightly lower with non-homothetic preferences, at 0.778. While the results differ from country-to-country (especially for some small resource producing countries), the negative relationship with income persists (and is actually slightly stronger).

Comparison to partial equilibrium approximations Section 3.2 described how uniform TFP growth across all sectors in all countries affects emissions in partial equilibrium approximations of $\widehat{EC}_n^{dir}$ (eq. 40) and $\widehat{EC}_n^{tot}$ (eq. 41). Figure A.2 in Appendix compares the simulated results shown above, which incorporate all general-equilibrium feedbacks, to their approximated value. These first-order approximations account for input-output linkages, trade linkages, and changes in the price of

[34] If countries were in complete autarky, low supply elasticity would push the income elasticity of CO_2 towards one in all countries.

Table 4: Decomposing the income elasticity of the CO_2 intensity of consumption.

	Country					Totals by income level			
	Ethiopia	China	Japan	USA	Germany	low	middle	high	**World**
Coal		0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Natural gas		0.002	0.002	0.001	0.003	0.001	0.002	0.003	0.002
Refined oil	-0.018	-0.010	-0.015	-0.014	-0.017	-0.018	-0.017	-0.018	-0.017
Electricity	0.000	-0.022	-0.022	-0.019	-0.036	-0.007	-0.021	-0.021	-0.021
Total energy goods	-0.018	-0.031	-0.035	-0.032	-0.051	-0.025	-0.036	-0.036	-0.036
Manufacturing	0.060	0.013	-0.008	-0.003	-0.004	0.044	0.012	-0.004	0.004
Services	0.021	0.020	0.011	-0.014	0.009	0.026	0.018	0.001	0.010
Transportation	0.003	-0.007	-0.012	-0.017	-0.013	-0.003	-0.010	-0.017	-0.013
Agriculture	-0.035	-0.031	-0.012	-0.010	-0.017	-0.046	-0.032	-0.013	-0.023
Total non-energy goods	0.046	-0.006	-0.022	-0.045	-0.026	0.020	-0.013	-0.033	-0.023
Total	0.027	-0.037	-0.057	-0.077	-0.076	-0.005	-0.049	-0.070	-0.059

primary energy in a static way but ignore second-order effects in consumption and the relative price of other goods and factors. Interested primarily in the effect of shifting consumption patterns, we compute approximations assuming infinite supply elasticity ($\zeta = \infty$). This isolates the consumption shift mechanism which is a function of the correlation between income elasticity and the share of each sector in consumption emissions. The figure shows that while there are country-to-country differences between the approximated and simulated elasticity, the approximation is overall very good (the average level is closer to zero in general equilibrium because of the calibrated supply elasticity). This suggests that while general equilibrium modeling is necessary to capture rich patterns of variability in estimates across countries, the broad patterns of the demand effect can be estimated by a simple correlation formula which only requires knowledge of income elasticity and a measure of consumption-related emissions per sector (see equations 40 and 41).

Decomposition by sector The partial equilibrium approximations of the total emissions contents ($\widehat{EC}_n^{total}$) can also be used to decompose the correlation driving the consumption effect. Table 4 displays how each sector contributes to $\widehat{EC}_n^{total}$ by displaying $\frac{\beta_{nkF}^{Ctotal} D_{nk}}{EC_n^{total}}(\varepsilon_{nk} - 1)$ per sector. It does so for a subset of countries and shows weighted average values for low-, middle- and high-income countries and for the world. As the numbers do not include the effect of productivity growth ($\log \hat{z}$), summing across sectors yields changes in the average CO_2 *intensity* of consumption, not emission levels (numbers would sum up to zero in the homothetic case with no income-driven consumption shifts).

The approximated average for the world as whole is -0.059 (last column), implying that an increase in productivity leads to a moderate decrease in the CO_2 intensity of consumption. Direct energy consumption would contribute to more than half of that decline (elasticity of -0.036), driven by reductions in electricity and refined oil (-0.021 and -0.017) despite a positive but negligible contribution from natural gas. Emissions embodied in non-energy goods contribute -0.023 to the elasticity — about

40% of the total. Reductions caused by shifts away from agriculture (-0.023) and transportation (-0.013) outweigh increases in emissions embodied in manufacturing and services.[35]

Sectoral contributions also vary significantly across income levels. In low-income countries, shifts in the patterns of non-energy good consumption lead to an increase in CO_2 intensity. In Ethiopia, for example, the only broad non-energy sector which contributes to a decline in intensities is agriculture. Both refined oil and electricity contribute to reductions in intensities even in middle-income countries (including China). In high-income countries, all broad non-energy sectors except services contribute to reductions in intensities. Interestingly, the contribution of (direct) energy consumption decreases substantially as income increases (from 73% in middle-income countries to 52% in high-income countries): shifts in the composition of non-energy consumption will be increasingly important in the long-run.

6 Extensions

We now extend the results described in Section 5 along two dimensions: i) using a more flexible demand system to test the robustness of results to the functional form imposed by Constant Relative Income Elasticity (CRIE) preferences; and ii) going beyond CO_2 to investigate the effect of consumption patterns on additional greenhouse gases and secondary energy demand.

6.1 Alternative specifications with more flexible Engel curves

CRIE preferences yield a wide distribution of income elasticity estimates with a relatively parsimonious functional form. Resulting Engel curves are close to log-linear which provides a good approximation of behavior in many sectors. For some goods, however, Engel curves may follow more complex patterns. For energy goods, for instance, there is empirical evidence of income elasticity varying considerably across the income spectrum (Cao et al., 2016 and Gertler et al., 2016 among others).

Non-homothetic CES We test the importance of allowing for richer income effects by estimating "Non-homothetic CES" (NH CES) preferences based on implicitly-additive utility, developed in Hanoch (1975) and more recently used in Comin et al. (2015). While imposing constant elasticity of substitution across goods, they allow for more flexible Engel curves. Utility U_n for consumers in country n is implicitly defined as the solution of:

$$\sum_k \left(\frac{Q_{nk}}{g_k(U_n)} \right)^{\frac{\sigma-1}{\sigma}} = 1 \tag{45}$$

Combining with the budget constraint, we obtain the following expression for expenditures in good k in country n:

$$X_{nk} = Q_{nk} P_{nk} = g_k(U_n)^{1-\sigma} L_n e_n^{\sigma} P_{nk}^{1-\sigma} \tag{46}$$

[35] At a more disaggregated level of detail (not shown in the table), we find that sectors contributing to the largest reductions are other types of transport, recreational and other services, food products n.e.c., and construction. The largest positive contributors are trade and retail, other business services, and motor vehicles.

U_n plays a role similar to λ_n in the benchmark CRIE specification. There is no analytical expression for U_n, but it is the unique solution satisfying the budget constraint $\sum_k X_{nk} = L_n e_n$, using expression 46 for X_{nk}. Uniqueness is guaranteed if $\sigma \neq 1$ and g_k is strictly increasing in U_n, but $g_k(U_n)$ can otherwise take any form, thus allowing for flexible Engel curves as long as σ is sufficiently different from unity. The income elasticity of consumption is given by:

$$\frac{\partial \log x_{nk}}{\partial \log e_n} = \sigma + (1-\sigma) \cdot \frac{\varepsilon^g_{nk} \sum_{k'} x_{nk'}}{\sum_{k'} x_{nk'} \varepsilon^g_{nk'}} \tag{47}$$

where $\varepsilon^g_{nk} = \frac{\partial \log g_k}{\partial \log U_n}$ denotes the elasticity of g_k in U_n. One can see that if ε^g_{nk} is constant across goods, preferences are homothetic.[36] This implicit utility function does not impose any link between income elasticity and price elasticity (σ), unlike directly-separable utility functions such as CRIE where income elasticity is proportional to price elasticity across sectors for any country.

We consider three alternative specifications for $g_k(U_n)$. First, a "log-linear" case with $g_k(U_n) = \alpha_k U_n^{\frac{\epsilon_k - \sigma}{1-\sigma}}$ (the main case emphasized in Comin et al., 2015) which yields:

$$X_{nk} = \alpha_k L_n e_n^{\sigma} U_n^{\epsilon_k - \sigma} P_{nk}^{1-\sigma} \tag{48}$$

It is very similar to our baseline specification, except that price elasticities are constant and equal to σ across all sectors. We also estimate two "augmented" specifications which allow for more flexible Engel curves while remaining parsimonious:

$$\text{Shifter NH CES:} \quad \log g_k(U) = \log \alpha_k + \rho_k \log(U_n + b_k) \tag{49}$$

$$\text{Quadratic NH CES:} \quad \log g_k(U) = \log \alpha_n + \rho_k \log U_n - b_k (\log U)^2 \tag{50}$$

where in each case b_k is a constant parameter for each sector k. The first introduces a sector-specific "shifter" b_k, which plays a similar role as in Stone-Geary preferences, Simonovska (2015), and others. Depending on the sign of b_k, ε^g_{nk} may be either decreasing or increasing in U_n, i.e. decreasing or increasing in income. The second introduces a quadratic form. This case is more simple with the caveat that g_k must remain increasing in U_n ($g_k(U_n)$ can be replaced by a flat portion if $\log U_n > \frac{\rho_k}{2b_k}$).

Estimation We estimate these preferences using the same data as in the benchmark with CRIE preferences and follow the same approach to identify the unobserved country variable U_n (similar to λ_n).[37] We calibrate trade elasticity θ to be equal to 4, a common value in the literature.[38]

Table 5 displays regression statistics for the three NH CES specifications and compares them to the estimation of CRIE, while Figure 9 displays fitted consumption and implied income elasticties for

[36] These preferences are homothetic if $\sigma = 1$ and close to homothetic if $\sigma \approx 1$. If $\sigma < 1$, the income elasticity has a lower bound at σ, since $\varepsilon^g_{nk} > 0$ for all sectors k. If $\sigma > 1$ the income elasticity has an upper bound at σ.

[37] That is, we estimate a constrained regression imposing the budget constraint to determine U_n. One could also treat U_n as a free parameter for each country: this alternative approach yields similar estimates (as it does for CRIE).

[38] Contrary to CRIE in which θ is identified in each sector using the restrictions on price and income elasticity, there is no explicit link between the elasticities in non-homothetic CES preferences so we chose to calibrate θ.

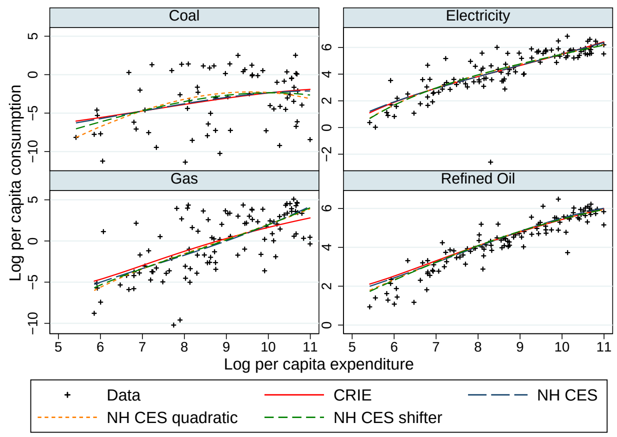
Table 5: NLLS estimation of final demand – regression statistics across demand systems

	(1)	(2)	(3)	(4)
Demand system:	CRIE	NH CES	NH CES	NH CES
Specification:		Log-linear	Quadratic	Shifter
Estimated σ	/	3.15	3.15	3.15
Weighted av. income elasticity of energy goods	0.88	0.83	0.73	0.75
- low-income countries only	0.92	0.88	0.92	0.91
Weighted av. coeff on Φ_{nk}	0.51	0.42	0.43	0.43
- energy goods only	0.34	0.42	0.43	0.43
F-stat $\rho_k = 0$ (non-homotheticity)	12.01	16.05	9.86	9.83
- energy goods only	6.69	14.39	7.71	7.69
F-stat $b_k = 0$ (flexible Engel terms)	/	/	3.32	3.27
- energy goods only	/	/	15.32	15.29
R2	0.85	0.84	0.84	0.84
Partial R2	0.32	0.27	0.30	0.30
AIC	-2.01	-1.95	-1.96	-1.96
BIC	-1.69	-1.69	-1.65	-1.65
Parameters	256	208	257	257
Observations	5341	5341	5341	5341

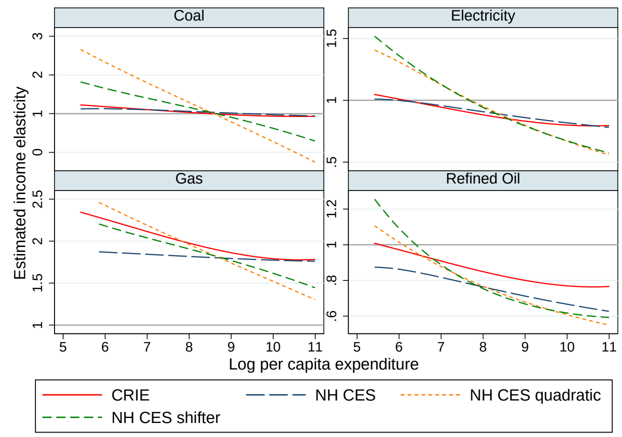
energy goods under NH CES and CRIE. [39] The overall fit, reflected by the R2 statistic, is similar across specifications. The partial R2, AIC and BIC suggest CRIE to be preferable despite additional parameters. Focusing on the role of non-homotheticity, however, the partial R2 and Figure 9b show the two "augmented" specifications with flexible forms (columns 3 and 4) slightly improve the fit relative to the log-linear NH CES. The b_k coefficients (flexible Engel terms) are jointly significant in both cases, but the increase in fit is driven by a subset of sectors — most b_k's are not individually significant. The information criteria are not conclusive as to whether the inclusion of additional parameters (relative to log-linear NH CES) is justified, as AIC is lower but not BIC.

Added flexibility is more important for energy goods, however. The F-stat of joint significance of the flexible (quadratic or shifter) Engel terms (the b_k's) is considerably higher than for all goods taken together. Their inclusion significantly changes the variation in income elasticities for energy goods, more than tripling the difference between the average income elasticity of energy goods in all countries versus low-income countries (below the median per capita income): 0.92 relative to 0.88 for CRIE; 0.92 relative to 0.73 for NH CES quadratic. Hence, while CRIE provides a good fit for most sectors, we conclude that having more flexible income effects may be desirable for energy goods. There is no substantial difference between the performance of the "quadratic" or "shifter" specifications, so we chose the quadratic specification for subsequent results unless otherwise indicated.

[39] Note that we estimate the price elasticity σ to be fairly high (3.15) compared to Comin et al. (2015) for instance. This can be explained by the larger number of sectors in our sample, as aggregation tends to be associated with lower estimates. Higher elasticities also improve the fit of income effects with the implicit utility approach: as noted in equation 47, income elasticity is bounded by the price elasticity.

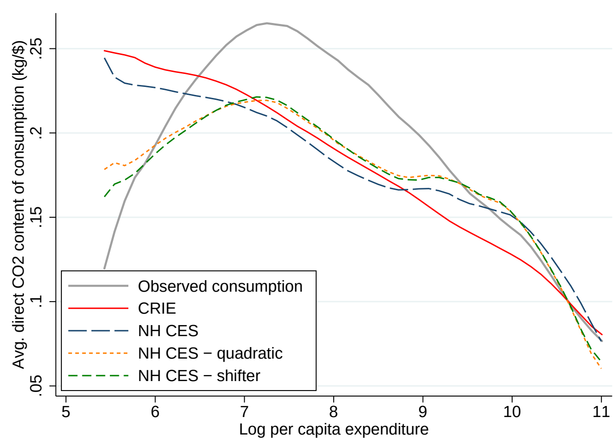


(a) Fitted log consumption

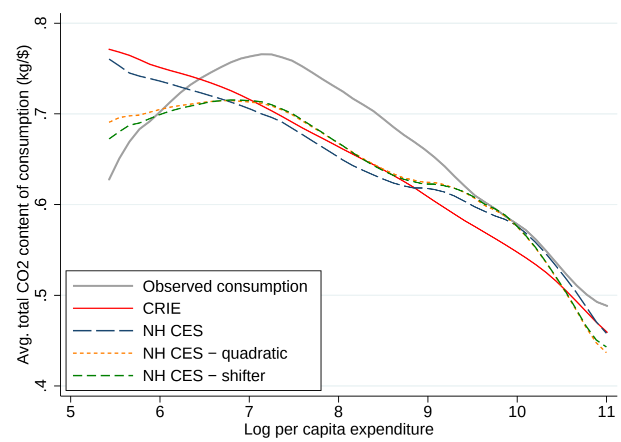


(b) Income elasticity estimates

Figure 9: Consumption and income elasticities against log per capita income - across specifications



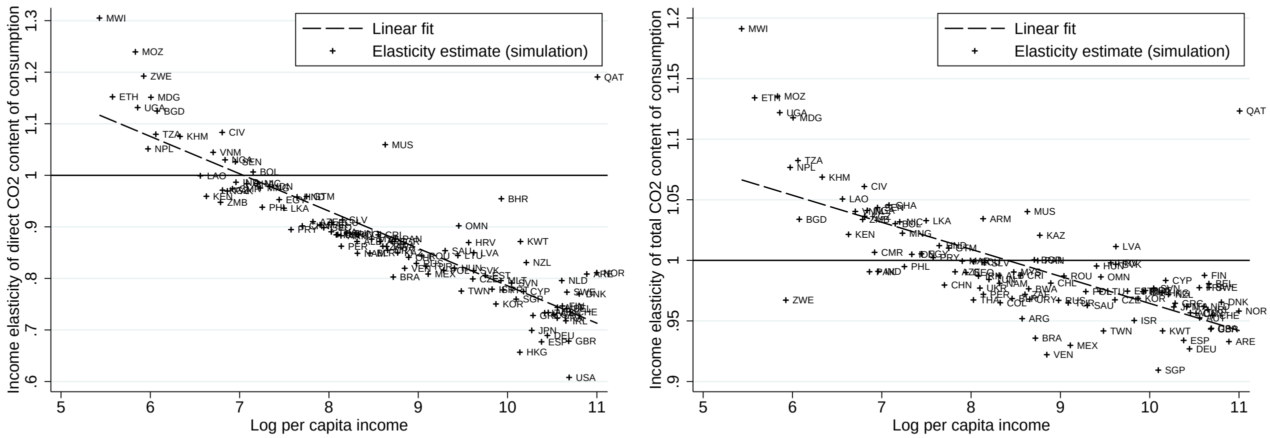
(a) Avg. direct CO_2 content of consumption



(b) Avg. total CO_2 content of consumption

Figure 10: Comparison between demand systems of the average CO_2 content, evaluated using average production intensities. Local polynomial smoothing.

Improvements in the estimation of the income-consumption-CO_2 relationship Cross-specification differences are obvious when looking at the resulting income elasticity estimates of energy goods in Figure 9b: differences in income elasticity between rich and poor countries are larger for the augmented specifications (Shifter and Quadratic NH CES). This does not substantially affect the cross-sector relationship between income elasticity and CO_2 intensity (evaluated at world average income), but leads to significant differences across countries. Figure 10 plots the relationship between per capita income and the average direct and total CO_2 contents of consumption for each demand specification. All curves are evaluated using average production intensities to focus on the role of consumption patterns. Log-linear NH CES and CRIE preferences yield very similar curves. However, the augmented NH CES specifications, while providing similar estimates for a large part of the income



(a) Avg. direct CO_2 content of consumption

(b) Avg. total CO_2 content of consumption

Figure 11: Using quadratic Non-homothetic CES preferences – Simulated elasticity of the CO_2 content of consumption to per capita income (fossil fuel supply elasticity calibrated at 0.75).

spectrum (middle-income countries and above), are now able to replicate the increasing intensities for low-income countries and, therefore, the inverted-U pattern generated by observed differences in consumption patterns.

Counterfactual simulation results Non-homothetic CES preferences can be integrated within the general equilibrium model similarly to preferences in the benchmark calibration.[40] Figure 11 replicates the results of Figure 7, displaying $\widehat{EC}_n^{dir}$ and $\widehat{EC}_n^{tot}$ with augmented quadratic NH CES preferences. Relative to CRIE, the income effect is stronger and the difference between low- and high-income countries considerably more significant for the direct CO_2 intensity of consumption. A much larger group of countries have elasticity estimates above 1 and low-income countries as a whole have a weighted elasticity of 1.059 (up from 0.954 for CRIE). High-income countries have a much lower elasticity, at 0.715 (compared to 0.867). The world average, overall, is also lower at 0.812 (compared to 0.882). Comparing elasticities across all NH CES specifications (Figure A.5), we find that the "augmented" terms drive these differences: NH CES preferences, in their standard log-linear form, do not otherwise provide results which differ substantially from CRIE.

Results for the total CO_2 content are closer to CRIE on average, but "augmented" specifications again yield larger differences across countries (Figure 11b). The range between high- and low-income countries is 10% (1.050 to 0.952) with quadratic NH CES, compared to 5% (1.021 to 0.977) with CRIE (see Appendix Figure A.5 for other specifications). Similar conclusions are obtained with

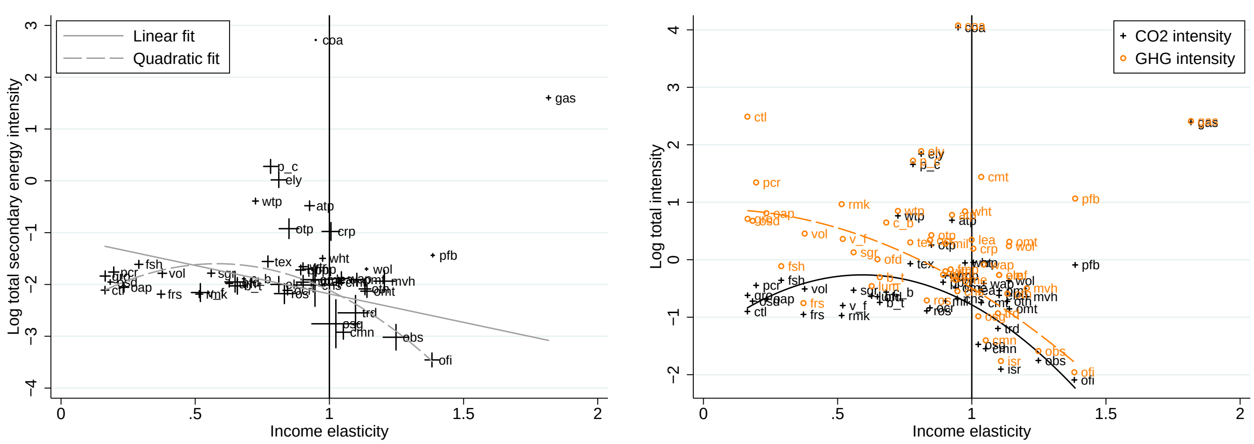
[40] Taking the change ratios of final demand (equation 46), we obtain: $\widehat{D}_{nk} = \widehat{g_k(U)}^{1-\sigma} \widehat{e_n}^{\sigma} \widehat{P}_{nk}^{1-\sigma}$ with: $\widehat{g_k(U)} = \widehat{U_n}^{\frac{\epsilon_k - \sigma}{1-\sigma}}$, $\log \widehat{g_k} = \rho_k \log \left(\frac{U_n \widehat{U_n} + b_k}{U_n + b_k} \right)$ and $\log \widehat{g_k} = \rho_k \log \widehat{U_n} - b_k \left((\log \widehat{U_n} + \log U_n)^2 - (\log U_n)^2 \right)$ for the log-linear, shifter and quadratic specfications, respectively. Like the Lagrange multiplier in our benchmark case with CRIE preferences, the change in utility $\widehat{U_n}$ is constrained by the consumer budget and is thus determined by the change in income. The above equations and the budget constraint allow us to determine $\widehat{D}_{nk}$ and $\widehat{U}_n$ depending on other outcome variables (changes in income $\widehat{e}_n$ and prices $\widehat{P}_{nk}$) and estimated parameters.

partial equilibrium approximations: the income elasticity of total CO_2 consumption in this case is 0.913 for the world on average, 0.889 for high-income countries (see full results in Appendix Figure A.7).

6.2 Beyond CO_2: effects on secondary energy demand and other greenhouse gases.

Secondary energy demand Section 5.2 has documented the relationship between income, consumption patterns and CO_2 emissions. We now focus directly on the final demand for secondary energy, which in itself can be of interest to a variety of stakeholders, as fossil fuels are exhaustible and energy is associated with a number of production and consumption externalities beyond CO_2. These include local pollutants (SO_2, NO_x) but also externalities associated with non-fossil fuel electricity production such as nuclear waste disposal, flooding caused by hydroelectricity generation, etc.

Figure 12a displays the relationship between income elasticity (reverting back to CRIE preferences) and the log total secondary energy intensity (expressed in kg of "oil equivalent" energy per \$) across sectors. While CO_2, in our model and data, is associated with fossil fuel use, there are some differences between CO_2 and secondary energy intensity. Fossil fuels vary in the amount of CO_2 emitted per unit of energy delivered (coal for instance is significantly more CO_2 intensive). Electricity has higher energy content, as it is produced using a mix of primary energy sources, each emitting different amounts of CO_2, including some, like nuclear, solar or wind, emitting none. The chemicals sector also has slightly higher secondary energy than CO_2 intensity, as it transforms some fossil fuels without burning them. Overall, though, differences are small: the correlation between CO_2 and secondary intensity across sectors is 0.990. Figure 12a reveals a negative and inverted-U pattern similar to that found with CO_2 and Table 6 confirms that the relationships are statistically significant. All of our results regarding the link between income and CO_2 thus hold for secondary energy.



(a) Secondary energy intensity

(b) CO_2 versus total GHG intensity

Figure 12: Income elasticity and intensity in secondary energy, CO_2 and total GHGs at the sector-level.
Notes: Secondary energy expressed in oil equivalent kg/\$; total GHG intensity expressed in CO_2 equivalent kg/\$.

Table 6: Correlations between income elasticity, secondary energy intensity and GHG intensity.

Dep. var.:	Secondary energy intensity (log)					
	All sectors		Non-energy only		Manufacturing only	
Beta coeff:	(1)	(2)	(3)	(4)	(5)	(6)
Income elasticity	-0.359	0.497	-0.418	1.026	-0.218	0.634
Square term		-0.882		-1.483		-0.856
P-value joint. Sign.	0.006	0.011	0.002	< 0.001	0.069	0.244
AIC	102.6	102	70.51	66	18.22	20.13
Dep. var.:	**GHG intensity (log)**					
Income elasticity	-0.599	-0.427	-0.675	-0.298	-0.322	0.648
Square term		-0.177		-0.386		-0.974
P-value joint. Sign.	<0.001	<0.001	<0.001	<0.001	0.061	0.113
AIC	99.53	101.4	70.53	71.9	15.59	17.46
Obs. (sectors)	49	49	45	45	13	13

Notes: beta coefficients; p-values of F-test of significance of the coefficient on income elasticity or the joint significance of the coefficients on income elasticity and its square; regressions weighted by average share of final demand.

Other greenhouse gases (GHG) CO_2 is the most prevalent GHG and thus the primary driver of global climate change. Being directly proportional to fossil fuel use, it is the most easily measurable GHG with reliable emissions data available for a large range of countries. We now investigate the relationship between income and a larger set of GHGs, including not only CO_2 but methane, nitrous oxides and fluorinated greenhouse gases (CH_4, N_2O and F-gases), which are caused mostly by energy and agricultural production. The data describing non-CO_2 GHG exhibit extremely large variance in country-level intensities, so we decide to restrain our analysis to the use of sector-level averages.

The inclusion of non-CO_2 gases significantly increases the average GHG-intensity of some sectors, particularly agricultural sectors such as cattle, cattle meat, raw milk or processed rice, but also, to a smaller extent, some manufacturing sectors such as chemicals. The intensity of energy goods is mostly unaffected. As is clear in Figure 12b, intensity in non-CO_2 GHGs is heavily biased towards low-income elasticity sectors and the inverted-U relationship across sectors disappears in favor of a strongly negative relationship (see bottom of Table 6: the quadratic term does not improve the fit).

This translates to country-level patterns. Figure 13 plots per capita income and the average total GHG content of consumption — all evaluated at average production intensities. As with CO_2, observed consumption patterns create an inverted-U curve, but its peak occurs at considerably lower income levels. The magnitude of the composition of consumption effect is stronger than when considering CO_2 on its own: evaluated at average technologies, the average GHG content of consumption (in CO_2-equivalent kg/\$) is 1.366 for low-income countries, 0.858 for middle-income countries and 0.602 for high-income countries (equivalent values for CO_2 are 0.732, 0.663 and 0.509).

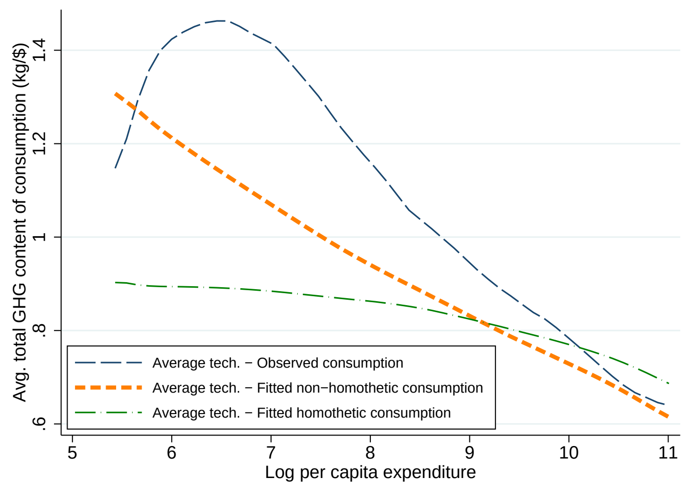


Figure 13: Income and the total GHG intensity of consumption (based on avg. production intensities).

Non-homothetic fitted consumption patterns again replicate the downward sloping part of the curve. They capture a larger part of the variation between income levels than with CO_2 (from 1.011 kg/$ for low-income countries to 0.583 for high-income countries), in part because the shift away from agriculture is well captured by non-homothetic preferences.

7 Summary and concluding remarks

This paper has analyzed the importance of consumption patterns in determining CO_2 emissions across a large number of countries covering most of the world economy and a wide range of per capita income levels. Our framework has allowed identifying income-driven consumption effects and simulating their impact in general equilibrium. We have found an important role for income with non-homothetic behavior prevalent for most consumption goods including energy.

The literature, mostly based on country-specific estimates, has documented income effects in direct energy consumption, such as rapidly rising energy demand in the developing world and the generally low income elasticity of energy in high-income countries. Our study summarizes the situation for many countries. While differences in the direct consumption of energy across income levels create an inverted-U relationship between the average CO_2 content of a country's consumption and its level of income, the effect is overall negative: high-income countries consume less energy and CO_2 per dollar. Differences are quantitatively important, especially when estimated with flexible Engel curves.

More unique is our inclusion of the emissions embodied in the consumption of non-energy goods. Indirect emissions correspond to a large share (73%) of consumption emissions — so clearly matter — and taking them into account considerably reduces the quantitative role of income. Indeed, the structure of technology as reflected by the input-output tables is such that the total income elasticity of energy is closer to one than its direct income elasticity: CO_2-emitting energy goods exhibit low income elasticity of consumption, but are used as intermediates for high income elasticity goods.

Thus, energy goods correspond to rapidly decreasing shares of consumer expenditures, but the total energy embodied in consumption does not decrease as strongly with income, contrary to what could be inferred from single-country studies focused on direct energy demand.

Despite this, income effects remain significant: total demand for energy has an income elasticity that is lower than one on average, driven by a negative correlation between income elasticity and total CO_2 intensity across sectors. The shape of the cross-country patterns in emissions can therefore be replicated by consumption shares generated by non-homothetic preferences. Per capita income explains about half of the variability in the total CO_2 contents of consumption left unexplained by a model with homothetic preferences, and can thus be used as a predictor of consumption-driven changes in emissions.

With this finding in hand, we simulate the response of world CO_2 emissions to income growth. Consumption effects are large for the direct CO_2 content of consumption: its world elasticity to income is 0.812-0.882 (on average across all countries) depending on the specification of preferences. Consistent with cross-sector findings, the impact of income growth on total emissions is weaker: the income elasticity of the total world CO_2 contents of consumption (and thus of production) is 0.96-0.97 — it will increase only 3% to 4% slower than increase in income. Results for total emissions are robust to using alternative demand systems, while direct emissions are more sensitive to modeling choices. Despite the near-homothetic aggregate effect for the world, our results indicate a very heterogeneous role for income growth across countries: the income elasticity of CO_2 contents is considerably lower in high-income countries, both for the direct and total contents. The decarbonising effect of consumption patterns thus has the potential to grow stronger in the long run when all or most countries pass peak intensity levels. Finally, while we focus on well-measured CO_2 emissions, our estimates suggest a stronger income effect if non-CO_2 greenhouse gases are accounted for: income-inelastic (necessity) goods are particularly intensive in these gases.

Our findings indicate that 'consumption-driven' booms in emissions in the lowest-income countries are likely limited in scope and maybe be compensated by reductions in high-income countries. On the other hand, there is no silver bullet: consumption-driven decarbonisation will not be nearly quick enough to solve the climate change problem on its own. While our findings are important for anticipating future global emission levels, they also have further implications for policy: the relative demand for energy is shifting towards low-income countries and from direct to indirect consumption. CO_2 reduction efforts should be designed accordingly.

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A Appendix – For online publication

A.1 Supply elasticity of primary energy goods

This section describes the steps leading to the equation describing the supply elasticity of primary energy goods $k \in \mathcal{P}$ in countries i. We hold wages constant (treating mobile inputs as infinitely elastic) but account for changes in the cost of natural resource factors (entering fossil fuel production).

Equation 16 yields:

$$R_{ik} w_{R,ik} = \frac{\beta_{ikf} Y_{ik} \mu_{R,ik} w_{R,ik}^{1-\nu_{ik}}}{\chi_{ik}^{1-\nu_{ik}}} \tag{A.1}$$

where $\chi_{ik} = \left[\mu_{R,ik} w_{R,ik}^{1-\nu_{ik}} + (1-\mu_{R,ik}) c_{ik}^{1-\nu_{ik}}\right]^{\frac{1}{1-\nu_{ik}}}$ denotes the cost of factors of production (excluding intermediate goods). This yields:

$$w_{R,ik} = \chi_{ik} \left(\frac{\beta_{ikf} Y_{ik} \mu_{R,ik}}{R_{ik} \chi_{ik}}\right)^{\frac{1}{\nu_{ik}}}$$

and

$$\frac{\partial \log w_{R,ik}}{\partial \log Y_{ik}} = \frac{1}{\nu_{ik}} + \left(1 - \frac{1}{\nu_{ik}}\right) \frac{\partial \log \chi_{ik}}{\partial \log Y_{ik}}$$

In turn, taking $w_{R,ik}$ as endogeneous in the cost function in $\chi_{ik} = \left[\mu_{R,ik} w_{R,ik}^{1-\nu_{ik}} + (1-\mu_{R,ik}) c_{ik}^{1-\nu_{ik}}\right]^{\frac{1}{1-\nu_{ik}}}$, and denoting by $\varphi_{R,ik} = \frac{\mu_{R,ik} w_{R,ik}^{1-\nu_{ik}}}{\mu_{R,ik} w_{R,ik}^{1-\nu_{ik}} + (1-\mu_{R,ik}) c_{ik}^{1-\nu_{ik}}}$ the share of natural resources in total factor costs (net of intermediate goods), we obtain:

$$\frac{\partial \log \chi_{ik}}{\partial \log Y_{ik}} = \varphi_{R,ik} \frac{\partial \log w_{R,ik}}{\partial \log Y_{ik}} \tag{A.2}$$

$$= \varphi_{R,ik} \cdot \frac{1}{\nu_{ik}} + \varphi_{R,ik} \left(1 - \frac{1}{\nu_{ik}}\right) \frac{\partial \log \chi_{ik}}{\partial \log Y_{ik}} \tag{A.3}$$

$$= \frac{\varphi_{R,ik} \cdot \frac{1}{\nu_{ik}}}{\varphi_{R,ik} \cdot \frac{1}{\nu_{ik}} + (1 - \varphi_{R,ik})} \tag{A.4}$$

As the output price p_{ik} depends on $\chi_{ik}^{\beta_{ik}}$ (taking other input prices as given), we need to multiply the inverse supply elasticity by β_{ik}:

$$\frac{\partial \log p_{ik}}{\partial \log Y_{ik}} = \beta_{ik} \frac{\partial \log \chi_{ik}}{\partial \log Y_{ik}} = \frac{\beta_{ik}\, \varphi_{R,ik}\, \frac{1}{\nu_{ik}}}{\varphi_{R,ik} \cdot \frac{1}{\nu_{ik}} + (1 - \varphi_{R,ik})}$$

This implies that the supply elasticity is:

$$\zeta_{ik} = \frac{\partial \log Y_{ik}}{\partial \log p_{ik}} - 1 = \frac{\nu_{ik}\,(1 - \varphi_{R,ik}) + \varphi_{R,ik}}{\beta_{ik}\, \varphi_{R,ik}} - 1 \tag{A.5}$$

A.2 Analytical approximations of Section 3

Under the assumption that the productivity increase $\widehat{z}$ augments all factors of production in all countries, the change in price $\widehat{P_{nk}}$ corresponds to $\widehat{z}^{-1}$ when we neglect the feedback effect of wages on prices, holding world nominal GDP constant as our normalization. Similarly, there is no change in the cost of non-resource factors $\widehat{w_{nf}} \approx 0$ (assuming that the share of resource factors is negligible). We obtain that $\widehat{S_{ik}} \approx \widehat{z}^{\theta_k}$ for each exporter i in industry k, which implies that import shares $\pi_{nik} = \frac{X_{nik}}{X_{nk}}$ remain constant. In addition, direct input-output coefficients are determined by the Cobb-Douglas upper tier, hence both global and domestic linkage coefficients remain constant as a first-order approximation.

Next, we describe the steps leading to equation 36. Taking $\widehat{P_{nk}} \approx \widehat{z}^{-1}$ as a first approximation, holding nominal income constant and using equation 18, we get:

$$\log \widehat{D_{nk}} = -\sigma_k \log \widehat{\lambda_n} + (\sigma_k - 1) \log \widehat{z}$$

Given the constraint on total expenditures provided by equation 27, we need:

$$0 = \log \widehat{e_n} \approx \frac{\sum_k D_{nk} \log \widehat{D_{nk}}}{\sum_k D_{nk}} = \frac{\sum_k D_{nk} \left(-\sigma_k \log \widehat{\lambda_n} + (\sigma_k - 1) \log \widehat{z}\right)}{\sum_k D_{nk}}$$

Solving for $\log \widehat{\lambda_n}$ yields: $\log \widehat{\lambda_n} = \frac{\sum_k (\sigma_k - 1) D_{nk}}{\sum_k \sigma_k D_{nk}} \log \widehat{z}$. Re-incorporating the solution for $\log \widehat{\lambda_n}$ into the equation describing changes in demand, we obtain the first-order approximation provided in the text:

$$\log \widehat{D_{nk}} = (\varepsilon_{nk} - 1) \log \widehat{z}$$

where $\varepsilon_{nk} = \frac{\sigma_k \sum_{k'} D_{nk'}}{\sum_{k'} \sigma_{k'} D_{nk'}}$ is the income elasticity of demand in sector k, country n.

Finally, we describe how to obtain equation 38, which allows us to describe the changes in production. With $\widehat{S_{ik}} \approx \widehat{z}^{\theta_k}$ and $\widehat{P_{nk}} \approx \widehat{z}^{-1}$, we obtain from the trade equation:

$$\widehat{X_{nik}} = \widehat{S_{ik}}\, \widehat{P_{nk}}^{\theta_k}\, \widehat{X_{nk}} = \widehat{X_{nk}}$$

Next, combining with equation 20, $\widehat{X_{nk}} = \frac{D_{nk}\widehat{D_{nk}}}{X_{nk}} + \sum_h \frac{\gamma_{nkh} Y_{nh} \widehat{Y_{nh}}}{X_{nk}}$, we obtain:

$$\begin{aligned} Y_{ik}\widehat{Y_{ik}} &= \sum_n \pi_{nik} X_{nk} \widehat{X_{nk}} \\ &= \sum_n \pi_{nik} D_{nk} \widehat{D_{nk}} + \sum_n \sum_h \pi_{nik} \gamma_{nkh} Y_{nh} \widehat{Y_{nh}} \end{aligned}$$

Taking logs (as a first order approximation) and using the Leontief total coefficients defined after equation 29 and our definition of "total income elasticity", we obtain:

$$\log \widehat{Y_{ik}} = \sum_n \sum_h \frac{\gamma^{tot}_{nikh} D_{nh}}{Y_{ik}} \log \widehat{D_{nh}} = \sum_n \sum_h \frac{\gamma^{tot}_{nikh} D_{nh}}{Y_{ik}} (\varepsilon_{nh} - 1) \log \widehat{z} = (\varepsilon^{tot}_{ik} - 1) \log \widehat{z}$$

A.3 Additional tables and figures

Table A.1: Sector description, income elasticity (direct and total), CO_2 intensities.

		Income elasticity		CO_2 intensity		sec. energy	GHG
Code	Description	Direct	Total	Direct	Total	int. total	int. total
pdr	Paddy rice		0.439	0.104	0.464	0.124	6.799
omn	Minerals nec		0.730	0.212	0.960	0.223	1.060
nmm	Mineral products nec		0.805	0.751	1.701	0.433	1.850
i_s	Ferrous metals		0.823	0.428	1.817	0.431	1.981
oil	Crude oil		0.844	0.192	0.407	0.114	0.628
nfm	Metals nec		0.879	0.117	1.453	0.308	1.662
ctl	Cattle, sheep, goats, horses	0.164	0.603	0.062	0.407	0.121	12.051
gro	Cereal grains nec	0.164	0.544	0.188	0.539	0.159	2.038
osd	Oil seeds	0.183	0.544	0.156	0.486	0.142	1.968
pcr	Processed rice	0.196	0.754	0.118	0.641	0.172	3.836
oap	Animal products nec	0.235	0.647	0.075	0.506	0.128	2.247
fsh	Fishing	0.290	0.726	0.334	0.699	0.200	0.895
frs	Forestry	0.373	0.814	0.128	0.386	0.112	0.470
vol	Vegetable oils and fats	0.377	0.649	0.072	0.602	0.168	1.577
rmk	Raw milk	0.515	1.098	0.048	0.379	0.112	2.629
v_f	Vegetables, fruit, nuts	0.519	0.567	0.111	0.451	0.116	1.436
sgr	Sugar	0.560	0.699	0.119	0.588	0.168	1.137
lum	Wood products	0.627	0.816	0.033	0.533	0.138	0.633
ofd	Food products nec	0.648	0.819	0.059	0.526	0.142	1.008
b_t	Beverages and tobacco	0.657	0.807	0.072	0.476	0.132	0.738
c_b	Sugar cane, sugar beet	0.681	0.728	0.117	0.570	0.151	1.911
wtp	Water transport	0.725	0.978	0.740	2.148	0.677	2.338
tex	Textiles	0.771	0.885	0.068	0.933	0.211	1.353
p_c	Petroleum, coal products	0.781	0.879	4.718	5.256	1.321	5.604
ely	Electricity	0.811	0.943	5.610	6.297	1.019	6.612
ros	Recreational and other srv	0.832	1.060	0.025	0.411	0.113	0.493
ocr	Crops nec	0.844	0.901	0.125	0.433	0.121	1.409
otp	Transport nec	0.849	0.960	0.773	1.293	0.397	1.535
ppp	Paper products, publishing	0.893	1.000	0.107	0.677	0.179	0.771
wtr	Water	0.902	1.108	0.105	0.757	0.191	0.819
mil	Dairy products	0.902	0.873	0.054	0.488	0.141	1.325
fmp	Metal products	0.921	0.948	0.035	0.757	0.182	0.846
atp	Air transport	0.926	1.034	1.264	1.988	0.619	2.179
ome	Machinery and equipment nec	0.940	1.012	0.021	0.614	0.149	0.704
cns	Construction	0.946	0.899	0.020	0.509	0.134	0.579
coa	Coal	0.949	0.924	55.952	56.809	15.166	58.973
wht	Wheat	0.975	0.847	0.204	0.947	0.224	2.323
lea	Leather products	1.000	1.024	0.024	0.589	0.150	1.414
crp	Chemical, rubber, plastic	1.006	0.945	0.164	0.953	0.376	1.214
osg	Public spending	1.024	1.031	0.025	0.229	0.063	0.373
cmt	Bovine meat products	1.035	0.920	0.041	0.474	0.141	4.222
wap	Wearing apparel	1.045	0.955	0.033	0.662	0.152	0.920
cmn	Communication	1.052	1.021	0.011	0.213	0.054	0.246
trd	Trade	1.097	1.028	0.024	0.302	0.078	0.394
omf	Manufactures nec	1.102	1.098	0.043	0.585	0.149	0.766
ele	Electronic equipment	1.102	1.077	0.011	0.539	0.136	0.767
isr	Insurance	1.108	1.172	0.005	0.149	0.037	0.172
otn	Transport equipment nec	1.133	1.124	0.020	0.485	0.124	0.555
wol	Wool, silk-worm cocoons	1.138	1.323	0.159	0.695	0.182	1.268
omt	Meat products nec	1.140	0.999	0.025	0.426	0.119	1.367
mvh	Motor vehicles and parts	1.205	1.026	0.012	0.526	0.144	0.608
obs	Business services nec	1.248	1.108	0.016	0.173	0.049	0.204
ofi	Financial services nec	1.382	1.138	0.005	0.124	0.032	0.141
pfb	Plant-based fibers	1.385	1.093	0.274	0.914	0.238	2.900
gas	Natural gas	1.817	0.862	10.732	10.940	4.968	11.165

Notes: Income elasticity based on the benchmark CRIE specification, evaluated using average expenditure shares.

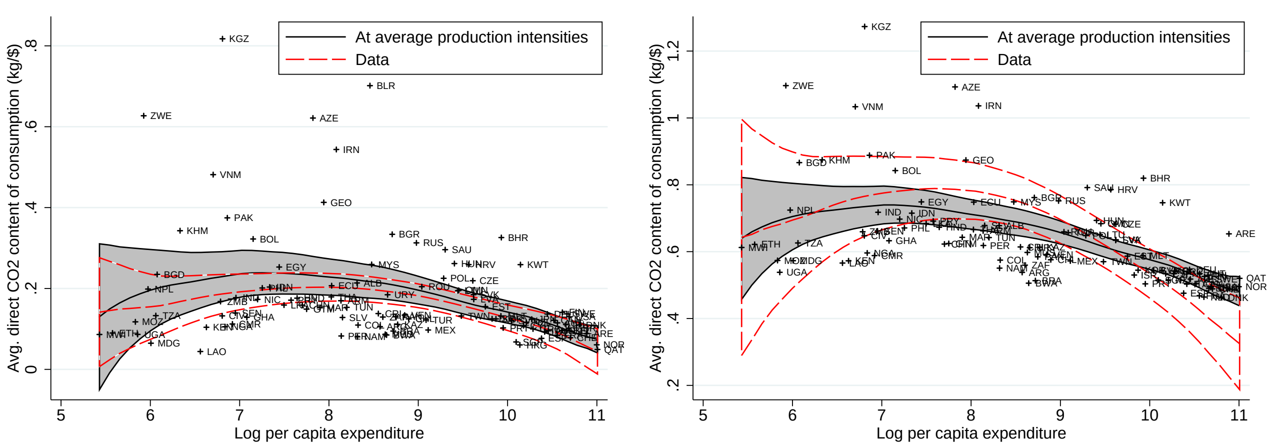
Table A.2: Countries in the dataset, with per capita income and average CO_2 content of consumption.

Code	Country	Income/cap (2007 USD)	CO_2 content of consumption, kg/$ Direct	Total	Code	Country	Income/cap (2007 USD)	CO_2 content of consumption, kg/$ Direct	Total
NOR	Norway	64911	0.016	0.210	BWA	Botswana	5835	0.110	0.675
QAT	Qatar	61070	0.069	0.536	ZAF	South Africa	5705	0.284	0.906
ARE	U. Arab Emirates	54834	0.139	0.836	ARG	Argentina	5660	0.203	0.639
CHE	Switzerland	51198	0.049	0.228	MUS	Mauritius	5599	0.082	0.548
DNK	Denmark	50104	0.082	0.270	CRI	Costa Rica	5184	0.084	0.414
USA	United States of A.	48593	0.140	0.429	MYS	Malaysia	4978	0.224	0.892
GBR	United Kingdom	44723	0.068	0.279	BLR	Belarus	4950	0.309	1.028
BEL	Belgium	43639	0.057	0.315	COL	Colombia	4458	0.076	0.342
SWE	Sweden	43473	0.028	0.200	NAM	Namibia	4330	0.087	0.637
IRL	Ireland	43036	0.080	0.325	ALB	Albania	4235	0.078	0.555
FIN	Finland	41742	0.070	0.337	SLV	El Salvador	3747	0.093	0.435
NLD	Netherlands	41484	0.056	0.254	TUN	Tunisia	3642	0.138	0.582
CAN	Canada	40381	0.108	0.413	IRN	Iran	3480	0.780	1.799
FRA	France	39291	0.043	0.216	ARM	Armenia	3467	0.066	0.588
AUT	Austria	39168	0.056	0.268	PER	Peru	3434	0.063	0.361
AUS	Australia	38406	0.120	0.442	UKR	Ukraine	3291	0.552	1.344
DEU	Germany	35371	0.085	0.307	ECU	Ecuador	3205	0.224	0.732
ITA	Italy	33884	0.058	0.276	THA	Thailand	3109	0.196	0.846
ESP	Spain	32727	0.055	0.288	GEO	Georgia	2930	0.200	0.689
JPN	Japan	32606	0.072	0.303	MAR	Morocco	2782	0.142	0.573
GRC	Greece	30157	0.108	0.509	GTM	Guatemala	2756	0.139	0.450
NZL	New Zealand	30064	0.067	0.325	AZE	Azerbaijan	2492	0.537	1.280
CYP	Cyprus	27477	0.101	0.521	CHN	China	2274	0.257	1.389
HKG	Hong Kong	26320	0.059	0.563	HND	Honduras	2188	0.153	0.660
KWT	Kuwait	26185	0.271	0.837	PRY	Paraguay	1986	0.095	0.494
SGP	Singapore	25299	0.053	0.435	LKA	Sri Lanka	1816	0.115	0.570
SVN	Slovenia	23325	0.097	0.392	EGY	Egypt	1773	0.331	1.042
PRT	Portugal	21640	0.060	0.316	IDN	Indonesia	1770	0.250	0.871
BHR	Bahrain	20903	0.396	1.026	PHL	Philippines	1502	0.150	0.607
KOR	Korea Republic of	20633	0.088	0.443	MNG	Mongolia	1441	1.188	2.625
MLT	Malta	20583	0.110	0.523	NIC	Nicaragua	1341	0.138	0.777
ISR	Israel	20473	0.144	0.505	BOL	Bolivia	1324	0.295	0.920
EST	Estonia	17396	0.247	0.768	GHA	Ghana	1218	0.101	0.519
LVA	Latvia	15274	0.081	0.459	SEN	Senegal	1102	0.111	0.535
SVK	Slovakia	15227	0.079	0.463	IND	India	1101	0.212	1.028
CZE	Czech Republic	15051	0.173	0.588	CMR	Cameroon	1012	0.084	0.315
TWN	Taiwan	14633	0.157	0.578	PAK	Pakistan	978	0.239	0.935
HRV	Croatia	14249	0.118	0.472	NGA	Nigeria	959	0.109	0.420
OMN	Oman	12916	0.237	0.955	KGZ	Kyrgyzstan	905	0.256	1.398
LTU	Lithuania	12802	0.070	0.436	CIV	Cote d'Ivoire	902	0.083	0.429
HUN	Hungary	12433	0.140	0.489	ZMB	Zambia	892	0.017	0.304
SAU	Saudi Arabia	11112	0.421	1.100	VNM	Viet Nam	858	0.345	1.288
POL	Poland	10916	0.232	0.664	KEN	Kenya	791	0.082	0.442
TUR	Turkey	9204	0.102	0.470	LAO	Laos	718	0.037	0.411
MEX	Mexico	9061	0.111	0.453	KHM	Cambodia	592	0.276	0.885
ROU	Romania	8559	0.130	0.505	BGD	Bangladesh	461	0.185	0.675
RUS	Russian Federation	7940	0.374	1.103	TZA	Tanzania	436	0.107	0.445
CHL	Chile	7864	0.107	0.478	MDG	Madagascar	406	0.068	0.402
VEN	Venezuela	7339	0.173	0.645	NPL	Nepal	404	0.109	0.472
PAN	Panama	6884	0.084	0.454	ZWE	Zimbabwe	387	0.577	1.561
URY	Uruguay	6577	0.082	0.344	UGA	Uganda	371	0.080	0.353
BRA	Brazil	6551	0.056	0.280	MOZ	Mozambique	345	0.069	0.595
KAZ	Kazakhstan	6434	0.228	1.714	ETH	Ethiopia	274	0.086	0.472
BGR	Bulgaria	6156	0.229	0.851	MWI	Malawi	233	0.080	0.499

Table A.3: Coefficients from the gravity equation estimations.

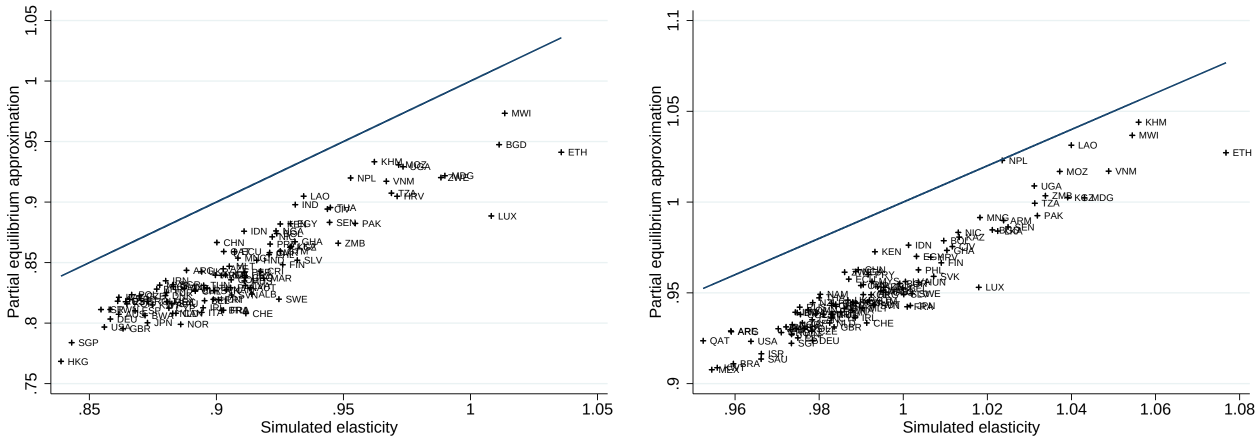
Trade cost variable:	Mean across sectors	Standard Deviation across sectors
Distance (log)	-0.879	0.636
Contiguity	0.328	0.460
Common language	0.407	0.370
Colonial link	0.320	0.534
Both access to sea	0.574	0.610
RTA	0.567	0.589
Common currency	0.586	1.034
Common legal origin	0.024	0.264
Border effect	3.767	2.128
Exporter FE	Yes	
Importer FE	Yes	
Nb. of industries	55	
Pseudo-R2 (incl. domestic)	0.999	
Pseudo-R2 (excl. domestic)	0.833	

Notes: Poisson regressions; dependent variable: trade flows. The coefficients above are estimated separately for each industry. Pseudo-R2 equal the square of the correlation coefficient between fitted and observed trade flows, including or excluding domestic flows.



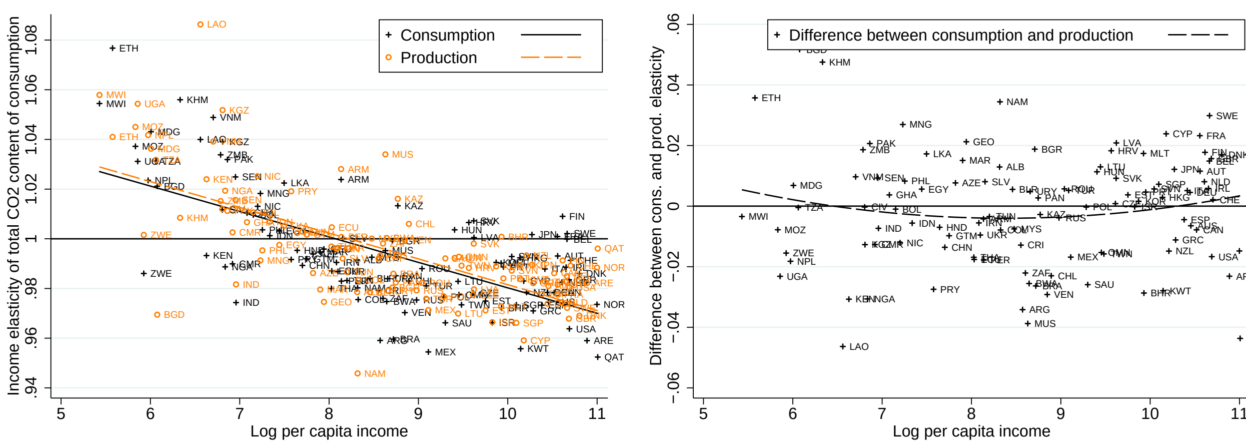
(a) Avg. direct CO_2 content of consumption (b) Avg. total CO_2 content of consumption

Figure A.1: Average total CO_2 content of consumption, evaluated at average intensities.



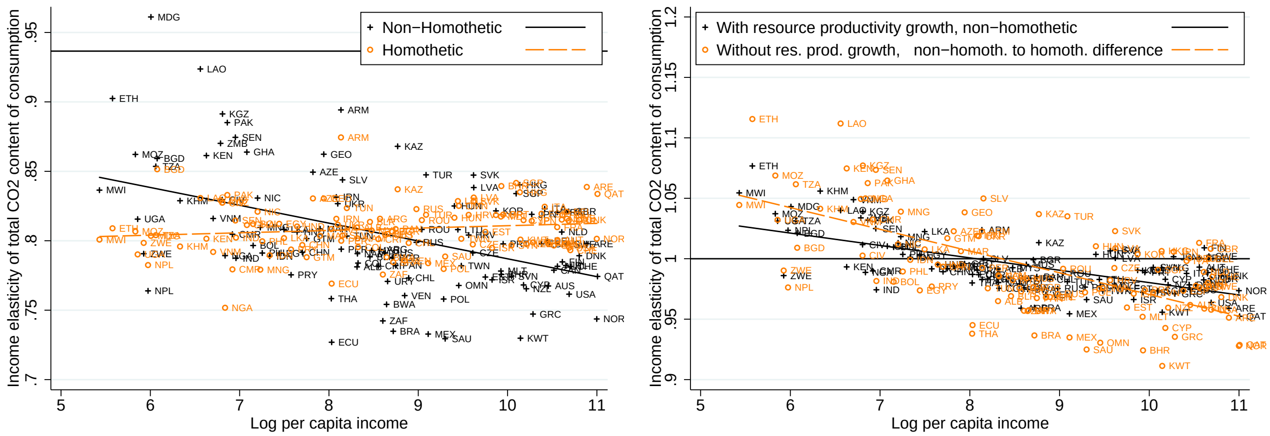
(a) Avg. direct CO_2 content of consumption (b) Avg. total CO_2 content of consumption

Figure A.2: Approximated versus simulated income elasticity of the CO_2 content of consumption (supply elasticity calibrated at 0.75 in the general equilibrium simulations).



(a) Consumption vs. production (b) Difference between cons. and prod.

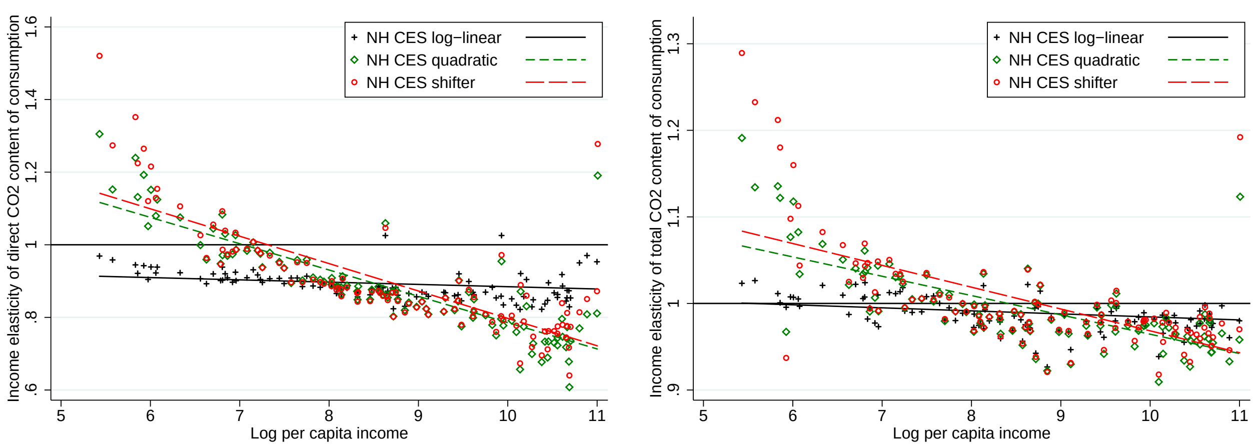
Figure A.3: Comparison of consumption and production elasticities (general equilibrium estimates with supply elasticity calibrated at 0.75).



(a) No resource productivity growth

(b) Comparison

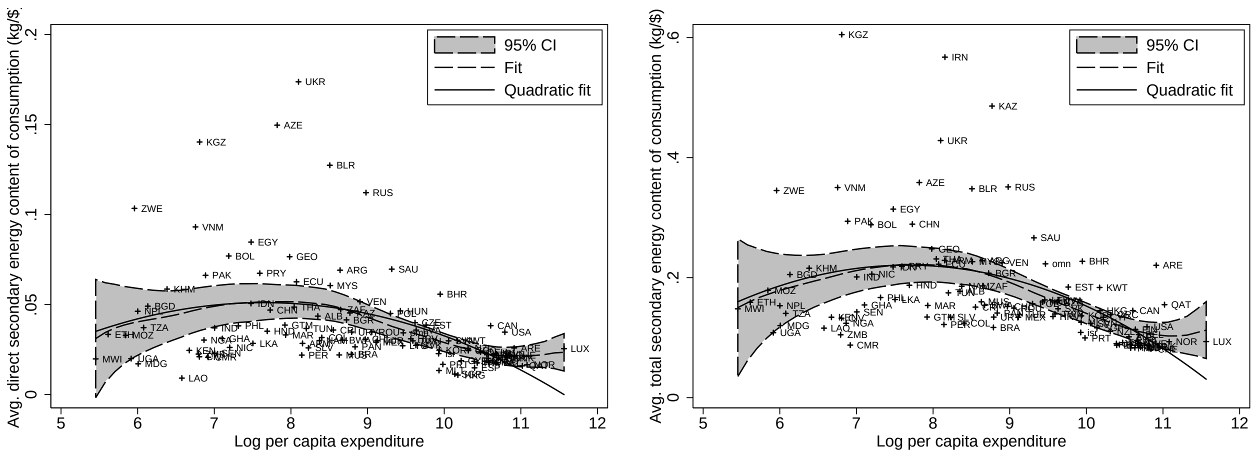
Figure A.4: Simulated income elasticity of the CO_2 content of consumption; supply elasticity = 0.75; Left panel: no resource productivity growth. Right panel: comparing with and without resource productivity growth (we plot the "NH minus H" difference between non-homothetic and homothetic for the later).



(a) Avg. direct CO_2 content of consumption

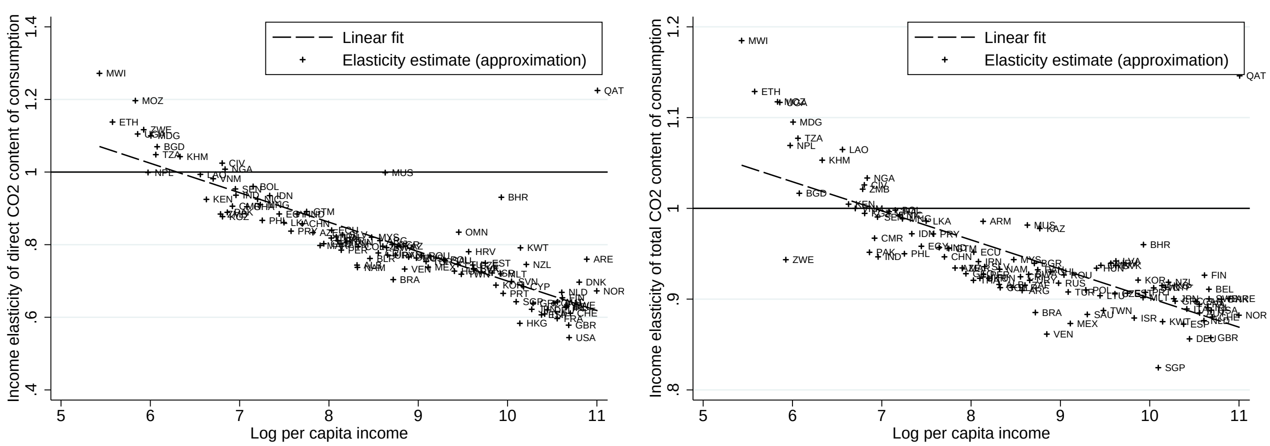
(b) Avg. total CO_2 content of consumption

Figure A.5: Sensitivity to demand system (NH CES): simulated income elasticity of the CO_2 content of consumption (fossil fuel supply elasticity calibrated at 0.75).



(a) Direct energy content of consumption (b) Total energy content of consumption

Figure A.6: Average secondary energy content in the data.



(a) Avg. direct CO_2 content of consumption (b) Avg. total CO_2 content of consumption

Figure A.7: Approximated income elasticity of the CO_2 content of consumption, based on quadratic NH CLM preferences.