PER CAPITA INCOME, CONSUMPTION PATTERNS, AND CO_2 EMISSIONS

Justin Caron and Thibault Fally*

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Abstract

This paper investigates the role of consumption choices in explaining and projecting energy demand and CO_2 emissions. We develop and estimate a general-equilibrium model with non-homothetic preferences, i.e. with consumption baskets that depend on income, for a large set of countries and sectors. Household energy consumption increases less than proportionally to income in rich countries, and is more income-elastic in developing countries. Tracing energy consumption through intermediate use and trade linkages, we find weaker but significant income effects for embodied energy: high-income-elasticity goods have lower total CO_2 intensity. Income-driven differences in consumption patterns thus partially explain the inverted-U relationship between per capita GDP and emissions intensity across countries, the so-called environmental Kuznet curve. Simulations suggest that further economic growth would change consumption choices in a way that lowers the emissions intensity of consumption in middle- and high-income countries but increases it at low incomes. Reductions in aggregate world emissions are therefore modest.

Keywords: CO_2 content of consumption, consumption patterns, emissions projections, per capita income, non-homothetic preferences, structural change, climate change.
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[*] Justin Caron: Department of Applied Economics, HEC Montreal, Montreal, QC H3T 2B1 and Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology; Cambridge, MA 02139; justin.caron@hec.ca. Thibault Fally: Department of Agricultural and Resource Economics, Giannini Hall, University of California, Berkeley CA 94720-3310; fally@berkeley.edu. This work was partly supported by the USDA NIFA Hatch project 131086. We thank our editor, Don Fullerton, and two anonymous referees, as well as Peter Berck, Larry Karp, Valerie Karplus, Mario Samano, Joe Shapiro, Niven Winchester, conference and seminar participants for very helpful comments.

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, though heterogeneously across countries, and understanding the determinants behind emission levels is necessary to guide policy making and improve forecasting. We focus here on demand and income per capita, looking at direct household energy consumption as well as indirect consumption through the purchase of goods requiring energy in production.

The literature has shown that household demand for energy varies significantly across income levels. In developed countries, studies using survey micro-data provide scattered evidence that direct energy consumption is less than proportional to income.[1] Evidence from the developing world is more limited and mixed with income elasticities both below and above one.[2] Studies focusing on the purchase of energy-intensive appliances however tend to find clear income effects towards the middle of the income distribution, suggesting significant future increases in energy demand as large populations are just beginning to purchase energy-intensive appliances.[3] Another group of studies focuses on aggregate emissions at the macro-level. Several provide evidence for an inverted-U relationship between income and CO_2 *per capita* or CO_2 *intensity* (i.e. in kg/\$) across countries or time, a variant of the so-called Environmental Kuznets Curve (EKC).[4] However, to our knowledge, no study has modeled and evaluated the contribution of non-homotheticity on the consumption side in explaining the EKC.[5]

The purpose of this paper is to investigate how per capita income influences energy demand and CO_2 emissions across countries through differences in consumption patterns. We introduce consumer preferences that are identical across countries yet non-homothetic (i.e. that allow expenditure shares to vary with income) within a multi-regional, multi-sectoral general-equilibrium model that 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 CO_2 intensity of consumption by systematically shifting consumption patterns towards more or less energy-intensive goods, reconciling the findings of micro- and macro-based studies. The sec-

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[1] See Kerkhof et al., 2009 or Munksgaard et al., 2001 among others.

[2] See e.g. Farsi et al. (2007) for a survey of urban Indian households or Cao et al. (2016) for urban Chinese households.

[3] See Davis and Gertler, 2015, Gertler et al., 2016 and Zhao et al., 2011.

[4] See Schmalensee et al. (1998) and Dietz and Rosa (1997) for cross-country studies, Raupach et al. (2007) for time series, or several others (e.g. Hertwich and Peters, 2009) using sectoral data on production and consumption.

[5] Closer to our paper, Grossman and Krueger (1995), Medlock and Soligo (2001) and Shapiro and Walker (2018) have noted the role of composition effects in consumption (and production) more specifically, but have not quantified their role.

ond objective is to estimate whether changes in consumption patterns caused by future income growth will increase or decrease overall emissions.

To do so, our first task is to provide a theoretical framework on which we build our estimation strategy and simulations. The general-equilibrium model, derived from the international trade literature, is an extension of Caron, Fally, and Markusen (2014) to track energy use and CO_2 emissions. It accounts for differences in technologies, input-output linkages and trade. The model guides our estimation and highlights the need to disentangle demand from supply-driven differences in prices, and avoid for example confounding the fact that high-income countries consume less energy-intensive goods not because their consumers are richer but because those goods are relatively more expensive there. Available consumer price data are hard to match to production, input-output and trade data, and are also prone to endogeneity. Instead, our approach allows sidesteping these issues by constructing price index proxies reflecting differences in market access identified from variations in trade costs caused by geography and other exogenous factors. In our benchmark specification, non-homotheticity is modeled using Constant Relative Income Elasticity (CRIE) preferences,[6] but we test the sensitivity of results to the use of alternative non-homothetic CES preferences which allow for more flexible Engel curves (Comin et al., 2015).

The calibration of the model and the econometric estimation of the parameters both rely on the Global Trade Analysis Project (GTAP8) dataset describing consumption, input-output, production and trade for 109 countries spanning most of the per capita income spectrum and 57 sectors covering the whole economy. It contains energy demand and CO_2 emission data from the International Energy Agency and thus 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). Combined with the multi-regional input-output tables, it also allows computing the *indirect* CO_2 content of consumption by tracing emissions caused by the production of goods throughout their global supply chain.[7]

This framework allows for two main contributions. To the best of our knowledge, this is the first paper to consistently estimate income elasticity across a wide range of sectors and countries, using flexible demand systems, and describe their relationship with CO_2 intensity. While EKC studies have been criticized for lacking structure or causal interpretation, our general equilibrium framework allows us to pinpoint and simulate the role of per capita income growth, through

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[6] These preferences are practical to estimate and provide a simple link between estimated coefficients and income elasticities. They are also easily combined with CES preferences to generate gravity within industries.

[7] Although we do not model the demand for energy-consuming appliances directly, our dataset tracks the direct demand for secondary energy used by these appliances (mainly electricity, oil and natural gas). It can thus implicitly pick up the S-shaped appliance adoption patterns documented in previous studies.

its influence on consumption patterns, in determining future worldwide emissions.[8] A second contribution is to account for global input-output linkages, thereby capturing the large share of emissions "embodied" in non-energy goods (73% of consumption emissions in our data). These are ignored in country-level studies based on household surveys.[9]

We present our results in stages: from sector-level to country-level partial-equilibrium evidence, then to general-equilibrium simulations. The income elasticity of CO_2-emitting energy sectors, including electricity and refined oil, is below one on average. Including non-energy goods, we find an inverted-U relationship: sectors of intermediate income elasticity, including transportation and manufacturing sectors, have the highest total (direct and indirect) CO_2 intensity on average. The relationship is negative overall, with the highest income elasticity goods (mostly services) having the lowest CO_2 intensity. However, while the negative relationship is economically and statistically significant, we find it to be less pronounced than the relationship between direct emissions intensity and income elasticity in which input-output linkages and the indirect energy consumption are ignored. Thus, studies focused on direct household emissions may substantially over-predict the role of income. We also find that energy goods tend to be income elastic among poor consumers and less elastic among richer consumers, indicating that flexible demand systems are needed to best describe income effects on energy consumption.

Does this sector-level relationship translate to a demand-side explanation of the link between income and emissions across countries? We compute the average total CO_2 content of consumption baskets, expressed in kg of CO_2 per dollar — i.e. a measure of the CO_2 intensity of consumption expenditures. Consistent with the EKC literature, the data reveal an asymmetric inverted-U and overall negative relationship with per capita income: lower middle-income countries have the highest emissions intensities; high-income countries the lowest. In a decomposition exercise, we neutralize differences in trade and production intensities within sectors and find that cross-country differences in consumption patterns play a substantial role: they explain 33% of the variability in the CO_2 intensity of consumption and contribute to generating the inverted-U pattern. In turn, we find that two thirds of this variability, as well as the inverted-U, can be explained using fitted consumption patterns generated by the identical but non-homothetic preferences of our model.

Interestingly, we find that the average CO_2 embodied in each dollar of *imported* consumption

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[8] In an orthogonal approach, van Benthem (2015) uses long time series to estimate convergence of energy consumption patterns across countries, but without distinguishing changes in technology from non-homotheticities in consumption.

[9] As such, this paper is similar in spirit to Levinson and OBrien (2019) who, using a structural approach, also find strong evidence for consumption effects (including indirect) across households in the U.S., and document "Environmental Engel Curves" for various pollutants (not including CO_2) similar to what we find across countries for CO_2 emissions.

also decreases in per capita income (again partially driven by non-homothetic preferences). This runs contrary to the predictions of the pollution-haven hypothesis, which postulates that high-income countries will outsource the production of pollution-intensive goods to low-income countries, e.g. because they have less stringent environmental policies.

Having established per capita income as an important determinant of CO_2 intensity, we then investigate the potential for further growth to affect aggregate energy use and emissions. To single out the effect of income and shifting consumption patterns, we use our general-equilibrium model to simulate a counterfactual increase in income driven by neutral productivity growth. Changes in equilibrium emissions depend on the supply elasticity of fossil fuels and other feedbacks caused by input linkages (e.g. changes in the prices of intermediate goods and factors of production) and by trade (e.g. demand shifting from high- to low- income countries). Accounting for such general-equilibrium effects and using plausible values of supply elasticity, we find a weakly negative income effect when averaged over all countries: a uniform 1% increase in income increases the world's total CO_2 content of consumption (which equals that of production) by 0.97% (compared to the 1% increase that we would obtain with homothetic preferences). This near-homothetic world average effect however hides significant heterogeneity. In low-income countries, a 1% increase in income leads on average to a 1.05% increase in total CO_2 content of consumption. In middle- and high-income countries, increases of 0.97% and 0.95% imply that income growth would reduce the CO_2 intensity of consumption. Again, this response to income is considerably less than what we find by focusing on direct consumption emissions only.

Our findings indicate that 'consumption-driven' booms in emissions in the lowest-income countries are likely to be limited in scope and compensated by reductions in high-income countries. They also suggest an increasing potential for shifting consumption patterns to reduce emissions in the long run as more countries move past their peak intensity levels. On the other hand, there is no silver bullet: consumption-driven decarbonization will not be nearly quick enough to reduce the CO_2 intensity of world GDP and substantially contribute to solving the climate change problem in the short run.

These results can serve more systematically as input for energy and emissions projection modeling (global or regional). Despite the above empirical evidence and its implications regarding the systematic relationship between energy intensity and income, little attention has been given to household consumption patterns or non-homothetic preferences, even in respected modeling exercises. This is true for Integrated Assessment Models (IAMs)[10], energy-sector models[11]

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[10] For instance, the Intergovernmental Panel on Climate Change (IPCC), which aims to provide "Representative [emissions] concentration pathways", does not attempt to generate explicit predictions of future emission intensity.

[11] The International Energy Agency's World Energy Outlook (IEA, 2019), one of the most comprehensive energy demand forecasting exercises, allows for income elasticity of household demand to deviate from unity but

or economy-wide Computable General Equilibrium (CGE) models.[12]

The remainder of the paper proceeds as follows. Section 2 describes our theoretical framework. Section 3 describes implications of equilibrium outcomes 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 A.1 of the online Appendix extends results to secondary energy demand and the addition of other greenhouse gases (including methane).

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

We estimate and simulate our model with different demand specifications to examine the sensitivity of results to functional forms. Our benchmark demand system is derived from constant relative income elasticity (CRIE) preferences, as in Fieler (2011), Caron et al. (2014) and Hanoch (1975). These preferences take the form:

$$U_n = \sum_k \alpha_{1,k} Q_{nk}^{\frac{\sigma_k - 1}{\sigma_k}}$$

where $\alpha_{1,k}$ is a constant (for each industry k) and $Q_{nk} = \left(\int_{j_k=0}^{1} q_n(j_k)^{\frac{\xi_k - 1}{\xi_k}} dj_k \right)^{\frac{\xi_k}{\xi_k - 1}}$ is a CES aggregate of quantities $q_n(j_k)$ over the continuum of product varieties, indexed by $j_k \in [0, 1]$, which compose industry k. Preferences are identical across countries[13], but non-homothetic if σ_k varies across industries. The ratio of the income elasticity of demand between goods i and

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only for a limited number of residential demand components and only cover a limited number of countries.

[12] Most CGE models used for energy and emissions projections (e.g. Chen et al., 2015) either rely on homothetic demand systems, or when they do allow consumption patterns to vary with income, do so with crudely calibrated elasticities.

[13] Since we rely only on cross-sectional data, this assumption is necessary to both identify income elasticities and make statements about the evolution of emissions across countries.

j is given by σ_i/σ_j and is constant. The CES price index of goods from industry k in country n, $P_{nk} = \left(\int_0^1 p_{nk}(j_k)^{1-\xi_k} dj_k\right)^{\frac{1}{1-\xi_k}}$, determines individual expenditures in country n for goods in industry k. Multiplying by the number of consumers L_n, expenditures $D_{nk} \equiv L_n P_{nk} Q_{nk}$ are given by:

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

where λ_n is the Lagrange 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 income elasticity of demand η_{nk} for goods in industry k and country n equals:[14]

$$\eta_{nk} = \sigma_k \cdot \frac{\sum_{k'} D_{nk'}}{\sum_{k'} \sigma_{k'} D_{nk'}} \tag{2}$$

CRIE preferences yield a wide distribution of income elasticity estimates with a relatively parsimonious functional form. Resulting Engel curves are close to log-linear and provide a good approximation of behavior in many sectors.

For some goods, however, Engel curves may follow more complex patterns. Empirical evidence suggests, for instance, that the income elasticity of energy goods varies considerably across the income spectrum (Cao et al., 2016 and Gertler et al., 2016 among others). We thus also consider alternative specifications derived from "Non-homothetic CES" (NH CES) preferences based on implicitly-additive utility, developed in Hanoch (1975) and more recently used in Comin et al. (2015). These preferences allow for richer income effects while keeping simple price effects. Utility U_n for consumers in country n is implicitly defined as the solution of:

$$\sum_k \left(\frac{Q_{nk}}{g_k(U_n)}\right)^{\frac{\sigma-1}{\sigma}} = 1 \tag{3}$$

This specification imposes constant elasticity of substitution σ across goods but $g_k(U_n)$ can take any form that is monotonically increasing in U_n, thus allowing for very flexible Engel curves if σ is different from unity. We consider three alternative specifications for $g_k(U_n)$: a log-linear case (the main case emphasized in Comin et al., 2015) and two "augmented" specifications that allow for more flexible Engel curves while remaining parsimonious:

$$\begin{aligned} \text{Log-linear NH CES:} \quad \log g_k(U_n) &= \log \alpha_k + \rho_k \log U_n && (4) \\ \text{Shifter NH CES:} \quad \log g_k(U_n) &= \log \alpha_k + \rho_k \log(U_n + b_k) && (5) \\ \text{Quadratic NH CES:} \quad \log g_k(U_n) &= \log \alpha_k + \rho_k \log U_n - b_k (\log U_n)^2 && (6) \end{aligned}$$

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[14] 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: $\frac{\eta_{nk}}{\eta_{nk'}} = \frac{\sigma_k}{\sigma_{k'}}$ and is constant across countries.

In the "Shifter" specification, b_k plays a similar role as in Stone-Geary preferences. We describe in Appendix A.5 how these preferences, combined with the budget constraint, are used to obtain expressions for individual expenditures and income elasticity.

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 that 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 quantity of CO_2 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. Factors of production are assumed perfectly mobile across sectors but immobile across countries. We denote by w_{fn} the price of factor f in country n. The total supply of factor f is fixed in each country.[15] Factor intensities for each industry k and factor f are denoted by β_{ikf}, and may vary across countries i. γ_{ihk} is the share of the input bundles from industry h in total costs of industry k in country i (direct input-output coefficient), 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. Total factor productivity $Z_{ik}(j_k)$ varies by country, industry and variety. The unit cost of supplying variety j_k in country i is then equal to $p_{ik}(j_k) = \frac{C_{ik}}{Z_{ik}(j_k)}$ and the average cost C_{ik} is determined by:

$$C_{ik} \;=\; {z_{ik}}^{-1} \prod_f {w_{if}}^{\beta_{ikf}} \prod_h {P_{ih}}^{\gamma_{ihk}} \tag{7}$$

where z_{ik} denotes a productivity shifter reflecting average TFP of country i in sector k, and P_{ih} denotes the price index of goods h in country i. We assume $\sum_f \beta_{ikf} + \sum_h \gamma_{ihk} \;=\; 1$ in each country i, ensuring constant returns to scale. An implication of this cost structure is that total demand X_{nk} (absorption) for goods k in country n is the sum of final demand D_{nk} and intermediate use, following:

$$X_{nk} = D_{nk} + \sum_h \gamma_{nkh} Y_{nh} \tag{8}$$

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

We assume perfect competition for the supply of each variety j_k, and iceberg transport costs

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[15] Denoting factor supply of country i by V_{if}, each individual is endowed by V_{if}/L_i units of factor f implying no within-country income inequality.

$\tau_{nik} \geq 1$ (akin to an ad valorem tax) to ship goods from country i to country n in sector k. Hence, the price of variety j_k in country n in industry k equals $p_{nk}(j_k) = \min_i\{\tau_{nik}p_{ik}(j_k)\}$. We follow Eaton and Kortum (2002) and assume that productivity $Z_{ik}(j_k)$ is a random variable with a Frechet distribution. Productivity is independently drawn in each country i and industry k, with a cumulative distribution $F_{ik}(z) = \exp\left[-z^{-\theta_k}\right]$; productivity is more dispersed in sectors with smaller θ_k. This setting generates 'gravity' within each sector, which will subsequently allow us to recover trade costs and cross-country differences in productivity independently from demand-side parameters.[16] This setting yields the following gravity equation in each sector:

$$X_{nik} = \frac{(C_{ik}\tau_{nik})^{-\theta_k}}{\Phi_{nk}} X_{nk} \tag{9}$$

where we denote by X_{nik} the value of trade *from* country i *to* country n (and where $X_{nk} = \sum_i X_{nik}$ denotes total absorption as in equation 8). In turn, Φ_{nk} is defined as:

$$\Phi_{nk} = \sum_i (C_{ik}\tau_{nik})^{-\theta_k} \tag{10}$$

This sum of supplier costs across all source countries, deflated by trade costs, is closely related to the price index.[17] As in Eaton and Kortum (2002), we obtain a log-linear relationship, up to a constant term $\alpha_{3,k}$:

$$P_{nk} = \alpha_{3,k}\Phi_{nk}^{-\frac{1}{\theta_k}} \tag{11}$$

2.1.3 Energy sectors and CO_2 emissions

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 as they do not emit CO_2) are considered to be "primary energy" sectors. "Secondary energy" describes sectors directly 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 absorption (intermediate and final consumption) 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.

The production of primary energy goods (the fossil fuel sectors) requires the input of a

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[16] Gravity equations are commonly used in the trade literature to decompose trade flows into supply effects, demand-side effects and a dyadic term capturing trade costs (a function of distance and other bilateral determinants). Contrary to other trade models (e.g. Armington), the Eaton and Kortum (2002) model does not require assuming heterogeneous preferences across countries to fit observed trade flows, relying instead on differences in productivity between varieties within sectors to generate intra-sectoral trade.

[17] We assume $\theta_k > \xi_k - 1$ to ensure a well-defined CES price index within each industry.

"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 of adjusting factors that are mobile across sectors to complement natural resources (example: using capital and labor to extract more oil out of the same resource). Sector-specific natural resources are combined with the other mobile inputs in a CES upper-tier with elasticity of substitution ν_k. The mobile inputs enter 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. Thus, the average cost C_{ik} is determined by:

$$C_{ik} \; = \; {z_{ik}}^{-1} \left[\mu_{R,ik} \, w_{R,ik}^{1-\nu_{ik}} + (1-\mu_{R,ik}) \, c_{ik}^{1-\nu_{ik}} \right]^{\frac{\beta_{ik}}{1-\nu_{ik}}} \prod_h (P_{ih})^{\gamma_{ihk}} \tag{12}$$

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:

$$c_{ik} = \prod_f (w_{if})^{\frac{\beta_{ikf}}{\beta_{ik}}} \tag{13}$$

with $\sum_f \beta_{ikf} = \beta_{ik}$ and $\beta_{ik} + \sum_h \gamma_{ihk} = 1$ in each country i. The parameter $\mu_{R,ik}$ reflects industry $k \in \mathcal{P}$'s reliance 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 A.3). As we will discuss, this elasticity of supply substantially influences the response of equilibrium energy consumption (in quantities) to demand shocks.

Finally, 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 related to the use of energy sector $k \in \mathcal{E}$ as an input to sector h is assumed to depend linearly on quantities of k consumed in h:

$$CO2_{ikh} = \kappa^C_{ikh} Q_{ikh} \tag{14}$$

where $Q_{ikh} \equiv \frac{\gamma_{ikh} Y_{ih}}{P_{ik}}$ represents intermediate consumption of energy good k, in terms of quantities, by industry h in country i. Emission coefficients κ^C_{ikh} represent physical quantities of CO_2, in kilograms, vary across countries, and are specific to the energy good k being used (e.g.

refined petroleum). They can also vary according to the buying industry (e.g. chemicals or transportation) depending on the share of fossil fuels combusted as opposed to transformed. The consumption of electricity does not emit CO_2 and the κ^C_{ikh} coefficients are zero for that sector. Some CO_2 emissions are also directly related to final consumption of secondary energy goods $Q_{ikF} \equiv \frac{D_{ik}}{P_{ik}}$ (for all $k \in \mathcal{S}$ except electricity): $CO2_{ikF} = \kappa^C_{ikF} Q_{ikF}$.

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

$$\beta^C_{ik} = \frac{1}{Y_{ik}} \sum_h CO2_{ihk} = \sum_h \frac{\kappa^C_{ihk} \gamma_{ihk}}{P_{ih}} \qquad \text{and} \qquad \beta^C_{ikF} = \frac{CO2_{ikF}}{P_{ik} Q_{ikF}} = \frac{\kappa^C_{ikF}}{P_{ik}}$$

as the amounts (in kg) of CO_2 emissions *per dollar* of output of sector k or *per dollar* of final consumption of fossil fuels. Section 3 further details CO_2 emissions accounting, linking emissions in upstream industries (potentially from different producing countries) to the composition of final demand.

2.2 Equilibrium

2.2.1 Baseline equilibrium

We now define an equilibrium. On the final demand side, total expenditures D_{nk} of country n in final goods k are given by Equation 1, with the budget constraint: $L_n I_n = \sum_k D_{nk}$, where I_n denotes per-capita income.

Total expenditures X_{nk} (absorption, sum of both final demand and intermediates) and production values satisfy the standard input-output accounting equality given by Equation 8. The value of trade X_{nik} is determined by the gravity equation, described in Equations 9 and 10. In turn, the price index P_{nk} follows Equation 11. Appendix A.2.1 describes the remaining set of income balance and market clearing conditions.

2.2.2 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, all equilibrium conditions can be reformulated to define a counterfactual equilibrium relative to our baseline equilibrium.[18] Specifically, we express our model using "exact hat

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

algebra" where $\widehat{Z} = Z'/Z$ denotes the relative change in variable Z. The simulation equation for demand (CRIE), for example, becomes $\widehat{D_{nk}} = \widehat{\lambda_n}^{-\sigma_k} \widehat{P_{nk}}^{1-\sigma_k}$, the absorption equation becomes $\widehat{X_{nk}} = \frac{D_{nk}\widehat{D_{nk}}}{X_{nk}} + \sum_h \frac{\gamma_{nkh} Y_{nh}\widehat{Y_{nh}}}{X_{nk}}$, etc. The full set of equilibrium conditions, reformulated in terms of relative changes, are described in Appendix A.2.2.

As will be further discussed in Section 5.4, our counterfactual equilibria reflect the impact of productivity growth $\widehat{z_{ik}} = \frac{z'_{ik}}{z_{ik}}$. We simulate a uniform 1% (Hicks-Neutral) productivity increase across all sectors k and countries i. Note that z_{ik} is defined as a shifter in Equations 7 and 12 defining input costs C_{ik}. Using the values of variables D_{nk}, 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 changes in $\widehat{D_{nk}}$, $\widehat{\lambda_n}$, $\widehat{I_n}$, $\widehat{P_{nk}}$, $\widehat{C_{nk}}$ and $\widehat{w_{fn}}$ caused by a given change in productivity $\widehat{z_{ik}}$.

3 Implications for CO_2 emissions

3.1 CO_2 content of consumption, production and imports

Input-output linkages and total emission coefficients by sector Being interested in the total impact of consumption patterns on CO_2 emissions, we need to track the production of goods in all countries and sectors caused 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) input requirement coefficients γ_{nhk} (Cobb-Douglas coefficients and input shares of total costs) 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:

$$Y_{ih} = \sum_n \pi_{nih} D_{nh} + \sum_{n,k} \pi_{nih}\gamma_{nhk} Y_{nk} \tag{15}$$

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 and industry h ultimately generated by each dollar of final or intermediate demand for product k in country n.[19] They are used to define total CO_2 coefficients:

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

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

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, $\beta_{ikF}^{Cindir} = \sum_n \pi_{ink}\beta_{nk}^{Ctot}$. Combining with direct CO_2 coefficients, we finally obtain *total* CO_2 consumption coefficients β_{ikF}^{Ctot}:

$$\beta_{ikF}^{Ctot} \;=\; \sum_n \pi_{ink}\beta_{nk}^{Ctot} + \beta_{ikF}^{C} \;=\; \beta_{ikF}^{Cindir} + \beta_{ikF}^{C} \tag{16}$$

i.e. the sum of 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.

The CO_2 content by country The above coefficients can then be used to compute the CO_2 contents of consumption, production and imports at the country-level . In order to facilitate decompositions in Section 5.4, we take care to describe each as functions of final demand D_{nk}.

Our main metric of focus, the total CO_2 content of consumption, EC_n^{tot}, is for each country n the sum of the direct content caused by the consumption of fossil fuels by households, $\sum_{k\in\mathcal{S}} \beta_{nkF}^{C} D_{nk}$, and the indirect content $EC_n^{indir} = \sum_k \beta_{nkF}^{Cindir} D_{nk}$, i.e. the CO_2 caused by production in all countries to satisfy final demand in country n. It can thus also conveniently be expressed as a function of β_{nkF}^{Ctot} and country n's consumption vector:

$$EC_n^{tot} = \sum_{k\in\mathcal{S}} \beta_{nkF}^{C} D_{nk} + \sum_k \beta_{nkF}^{Cindir} D_{nk} = \sum_k \beta_{nkF}^{Ctot} D_{nk} \tag{17}$$

We will also contrast total consumption emissions to the direct CO_2 content of consumption. As is common in the literature, we include the CO_2 embodied in electricity consumption in the latter even though they do not occur directly in final demand, and compute $EC_n^{dir} = \sum_{k\in\mathcal{S}} \beta_{nkF}^{C} D_{nk} + \beta_{n,ele}^{Ctot} D_{n,ele}$. In a separate exercise, we single out imports by computing the emissions embodied in country j's imported final demand as $EC_n^{Imp} = \sum_{i\neq n,k} \pi_{nik}\beta_{ik}^{Ctot} D_{nk}$.[20]

Finally, we also compute production emissions EY_n, defined as the sum of emissions occurring during the production of all sectors k in n.[21] As described above, production Y_{nk} can be linked to the sector and location of final demand using total requirement coefficients, such that $EY_n = \sum_{hk} CO2_{nhk} = \sum_k \beta_{nk}^{C} Y_{nk} = \sum_{i,k} \pi_{ink}\beta_{nk}^{Ctot} D_{ik}$. 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

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[20] These do not equal total emissions embodied in imports, which would include imported intermediates and are therefore not the focus of this study.

[21] 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.

may be consumed elsewhere.

3.2 Counterfactual changes in CO_2 emissions

The above equations describe the link between emission content and observed demand patterns (through D_{nk}). We now further explore how changes in income affect emissions through changes in consumption patterns, explicitly linking these changes to the structure of preferences. To focus on demand-side mechanisms, we consider the effect of a country- and sector-neutral increase in income caused by uniform factor productivity growth, $\hat{z}$.[22]

This counterfactual is motivated by two key points. First, it is a natural case to study the effect of non-homotheticity. 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 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 sectors, 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. The input-output coefficients also remain fixed thanks to the Cobb-Douglas upper tier. We can therefore continue to use the tools developed in the previous sub-section to describe trade and input-output linkages.

Our key variable of interest to illustrate the effect of income growth is the country-level income elasticity of emissions, $E_n^{ECtot} = \frac{\widehat{EC}_n^{tot}}{\widehat{z}_n}$, i.e. the change in the CO_2 content of consumption following a given change in factor productivity $\widehat{z}$ (which as first approximation equals changes in real income).[23] Also of interest are the changes in the CO_2 content of worldwide consumption caused by uniform productivity growth, $\widehat{EC}_{world}^{tot}$, a weighted average across all countries. Note that at the world level, indirect emissions embodied in consumption equal total production emissions, so $\widehat{EC}_{world}^{indir} = \widehat{EY}_{world}$.

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[22] In our benchmark specification, the productivity shock is applied uniformly to all sectors and countries. In our simulations, we also test the sensitivity of results to the exclusion of growth in fossil fuel resource productivity and to heterogeneous growth across countries.

[23] 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.

Partial equilibrium approximations In section 5.4, we will display elasticities computed from the general equilibrium changes in $\widehat{EC}_n^{tot}$.

First, we present first-order analytical approximations to develop intuition regarding changes in emissions (full derivation is detailed in Appendix A.4). Changes in direct consumption emissions are determined by changes in final consumption of energy minus, for primary energy goods, the change in energy prices (see Equation A.14): $\log \widehat{CO2}_{nkF} = \log \widehat{D_{nk}} - \log \widehat{P_{nk}}$. Approximating $\log \widehat{D_{nk}}$ as a function of income elasticity η_{nk} (using expressions A.20 and A.23) and $\log \widehat{P_{nk}}$ as a function of the the supply elasticity ζ_{ih} and summing over energy goods, we obtain changes in direct consumption emissions as a function of productivity growth, $\log \hat{z}$. The derivation of indirect consumption emissions is similar, but requires keeping track of changes in demand and prices in all countries through the total input-output coefficients. Taking the two together, we obtain the following approximated change in total consumption emissions:[24]

$$\log \widehat{EC_n^{tot}} \quad \approx \quad \left[1 + \underbrace{\sum_k sh_{nk}^{ECtot} \left(\eta_{nk} - 1 \right)}_{\substack{\text{Non-homothetic} \\ \text{consumption effect}}} - \underbrace{\sum_{h \in \mathcal{P}, i} sh_{ih,n}^{ECtot} \frac{(\eta_{ih}^{tot} - 1)}{1 + \zeta_{ih}}}_{\substack{\text{Supply} \\ \text{feedback}}} \right] \log \hat{z} \tag{18}$$

where $sh_{nk}^{ECtot} = \frac{\beta_{nkF}^{Ctot} D_{nk}}{EC_n^{tot}}$ is the share of the total emissions caused by the consumption of sector k in country n's total consumption emissions, and $sh_{ih,n}^{ECtot} = \frac{\beta_{nhF}^{C} D_{nh} \pi_{nih} + \sum_k \beta_{ih}^{C} \gamma_{nikh}^{tot} D_{nk}}{EC_n^{tot}}$ is the share of emissions from by fossil fuel h sourced from country i in country n's consumption emissions, both directly and indirectly.

This approximation has the following interpretation. First, it shows that growth in emissions is directly driven by productivity growth $\log \hat{z}$. Then, the middle term in the brackets reflects the non-homothetic demand effect, and is related to the correlation between income elasticity η_{nk} (which drives growth in final demand for sector k) and each sector's share of consumption emissions sh_{nk}^{ECtot}, which itself is a function of its total CO_2 intensity β_{nkF}^{Ctot}. The income elasticity of secondary energy sectors is on average below one, so productivity growth will pull direct consumption emissions downwards. This generalizes to indirect emissions, as we will find that sectors with high CO_2 intensity, and thus high shares of indirect emissions, have on average lower income elasticity η_{nk} than sectors with low CO_2 intensity.

Finally, the third term in the brackets reflects the attenuating effect of reductions in energy prices caused by lower-than-proportional demand for primary energy. It corresponds to the sum

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[24] Appendix A.4 provides separate expressions for direct (Eq. A.24) and indirect emissions (Eq. A.25) and a similar approximation for changes in production emissions (Eq. A.26).

of the increase in prices of all the fossil fuels in all countries ultimately consumed in country n, approximated by $\frac{\eta_{ih}^{tot}-1}{1+\zeta_{ih}}$, weighted by their share of indirect consumption emissions in n. It is thus a function of the supply elasticity of fossil fuels ζ_{ih}, and their "total income elasticity" defined as $\eta_{ih}^{tot} = \frac{1}{Y_{jh}} \sum_{n,k} \gamma_{nikh}^{tot} D_{nk} \eta_{nk}$, i.e. the income elasticity of total demand (or absorption).[25]

Finally, changes in total world emissions, $\widehat{EC}_w^{total}$, can be approximated by the average of all $\widehat{EC}_n^{total}$ weighted by each country's share of worldwide emissions. In Section 5.4, we will compare all of these approximations to exact changes obtained through numerical simulations.

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 covering 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.[26] All values represent the 2007 economy. The full list of sectors and countries in the dataset can be found in Tables A.6 and A.7 of the Appendix. Throughout the analysis, we define final demand as the sum of household, government and investment final demand (as defined in GTAP).

Two weaknesses of the GTAP data should be recognized. First, not all data are directly observed in all countries for the same year. Some values are extrapolated from previous years, and some missing sectors are imputed proportionally to world averages or to similar countries. Second, the data have been adjusted to provide a balanced micro-consistent dataset that can be used for computable general equilibrium analysis. This procedure modifies the raw data by an undocumented amount. Our study is mostly focused on "average" effects across sectors or countries (as opposed to making country-specific statements). We thus consider these limitation to be acceptable, given GTAP's clear advantage of supplying harmonized consumption, production and trade data for a wide range of countries.

The dataset is complemented with physical energy use data from the International Energy

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[25] The term cancels the non-homothetic demand effect if the supply elasticity ζ_{ik} is zero 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).

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

Agency's (IEA) "Extended Energy Balances", describing both primary and secondary energy use, expressed in millions of tonnes of oil equivalent (Mtoe), for all countries and sectors.[27] It also includes corresponding carbon dioxide emissions by fossil fuel, expressed in millions of tonnes (MtCO_2), for both intermediate and final consumption.[28] 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).[29] These are 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.

The gravity estimations rely on bilateral variables describing physical distance, common language, colonial link and contiguity obtained from CEPII.

4.2 Using gravity to estimate cross-country price differences

The estimation of the model's key parameters closely follows Caron et al. (2014, 2020), although with a more recent dataset and a number of additional robustness checks. The main challenge is to disentangle demand and supply side effects. For instance, a country with 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. If comparative advantage is correlated with income, these patterns may bias our cross-sectional estimates of income elasticity. Using gravity equations allows estimating 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 re-write Equation 9 as a function of the stochastic equivalent of trade flows X_{nik}, in logs, and allow trade costs τ_{nik} to depend on a number of factors such as distance and contiguity. This yields a set of gravity equations in which C_{ik}, Φ_{nk} and X_{nk} are captured using exporter (FX_{ik}) and importer (FM_{nk}) fixed effects:

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

These gravity equations are estimated for each sector separately using Poisson pseudo maxi-

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

[28] The dataset only covers CO_2 related with fossil fuel use. Some industrial processes, notably cement manufacturing, also produce CO_2, but account for less than 5% of total emissions.

[29] 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). They correspond to a third of total GHG warming potential.

mum likelihood regressions (as in Fally, 2015) and provide estimates of trade costs and patterns of comparative advantage. Following the strategy developed by Redding and Venables (2004), we then use the estimates of $\log C_{ik}$ (from $\widehat{FX}_{ik}$), and $\log \tau_{nik}$ (using all transport cost proxies, such as distance and continuity, and their coefficients) to construct an estimate of our price index proxy Φ_{nk} as:

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

In a second step, the $\widehat{\Phi}_{nk}$ 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.[30]

4.3 Estimating non-homothetic preferences

The value of expenditures, per industry, is determined by Equations 1 (CRIE) and A.28 (NH CES). Their stochastic equivalents, expressed in per capita terms by dividing by L_n, are estimated in logs as:

$$\begin{aligned}\text{CRIE:} \quad & \log\left(\frac{D_{nk}}{L_n}\right) = \log \alpha_k + -\sigma_k.\log \lambda_n + \frac{\sigma_k - 1}{\theta_k}.\log \widehat{\Phi}_{nk} + \varepsilon_{nk} \\ \text{Log-linear NH CES:} \quad & \log\left(\frac{D_{nk}}{L_n}\right) = (1-\sigma)[\log \alpha_k + \frac{\epsilon_k - \sigma}{1-\sigma}\log(U_n)] + \sigma \log e_n + \frac{\sigma - 1}{\theta_k}.\log \widehat{\Phi}_{nk} + \varepsilon_{nk} \\ \text{Shifter NH CES:} \quad & \log\left(\frac{D_{nk}}{L_n}\right) = (1-\sigma)[\log \alpha_k + \rho_k \log(U_n + b_k)] + \sigma \log e_n + \frac{\sigma - 1}{\theta_k}.\log \widehat{\Phi}_{nk} + \varepsilon_{nk} \\ \text{Quadratic NH CES:} \quad & \log\left(\frac{D_{nk}}{L_n}\right) = (1-\sigma)[\log \alpha_k + \rho_k \log U_n - b_k(\log U)^2] + \sigma \log e_n + \frac{\sigma - 1}{\theta_k}.\log \widehat{\Phi}_{nk} + \varepsilon_{nk}\end{aligned}$$

in which α_k is a sector-specific preference parameter that varies across industries only. With CRIE preferences, 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 equation, income and price elasticities are estimated separately. Final demand d_{nk} must satisfy the budget constraint that determines the Lagrangian multiplier λ_n: a higher income per capita is associated with a smaller λ_n. No closed-form solution expresses 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 the demand

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[30] In the second step, instrumenting by $\widehat{\Phi}_{nk}$'s computed by excluding the own market n in the summation leads to very similar results, see e.g. Caron et al. (2020).

and budget equations are estimated simultaneously using constrained non-linear least square regressions. 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.

The estimation of the three NH CES specifications is similar and described in more detail in Appendix A.5. U_n is determined using the budget constraint, similarly to λ_n.

5 Empirical results: income, consumption and CO_2

5.1 Consumption patterns and income elasticity estimates

Consumption patterns vary considerably with income. The share of household expenditures spent on electricity drops from 1.9% in low-income countries to 1.6% in middle-income countries and to only 0.9% in high-income countries.[31] For the refined oil consumed directly by households for heating and private transportation (not including purchased commercial transportation), the share similarly drops from 1.8% to 1%. Beyond direct energy consumption, significant differences exist for all goods: the share of agricultural goods drops from 28% to 5.9%, that of market-supplied transportation (ground, sea and air) from 4.4% to 2.4%. Manufacturing peaks at lower-middle income levels (42%) then declines more moderately to 31.5%. The share of services increases constantly from 25.6% to 58.1%.

Our estimation procedure helps us identify the role of income in explaining these shifts in consumption patterns. The first step was to estimate supply-side parameters describing comparative advantage and trade costs. The results from the gravity equations are standard. Summary statistics can be found in Appendix Table A.3 and estimates imply price index proxies that vary substantially between countries. These proxies are used, in a second step, to estimate the demand systems and back out income elasticity.

Table A.4 in Appendix provides regression statistics for both CRIE and NH CES preferences. Regressions and the corresponding statistics we report, including the R^2, are weighted by each sector's mean expenditure share. We start with CRIE estimates. As documented in Caron et al. (2014), the constrained NLLS estimation of demand patterns derived from CRIE fits the data well, with an R^2 of 0.85 (0.86 for energy goods only).[32] This high R^2 is partially explained by large average differences in expenditures shares captured by the α_k constant. A "partial R^2"

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[31] We classify countries based on World Bank guidelines for 2007. GNI/capita cut-offs: low-income 935$ and below; lower-middle-income 3705$; upper-middle-income 11455$. There are 16, 27, 24 and 42 countries in each income class.

[32] Appendix Figure A.5 illustrates the fit. It is good for electricity and refined oil, which are widely adopted by households, while a substantial amount of unexplained heterogeneity remains in the coal and, to a lesser extent, natural gas sectors, the adoption of which often driven by idiosyncratic historical factors.

measure reveals that income and price differences capture 0.323 of the variability left unexplained by a homothetic model in which $\sigma_k = 1$. The F-stat on the σ parameters being significantly different from unity indicates strongly significant non-homotheticities in consumption patterns (12.01 across all goods, 6.69 for secondary energy goods, both with a p-value < 0.001).

The resulting income elasticity estimates exhibit considerable variability across sectors, despite our assumption of homogeneous within-country income potentially biasing estimates towards one.[33] Table 1 displays the income elasticity of energy sectors and broad non-energy aggregates, estimated with CRIE preferences. Appendix table A.6 provides estimates for all 50 sectors. These estimates actually vary across countries, as CRIE preferences generate income elasticity that declines with income for all sectors (see Equation 2 and Figure 1), so for exposition purposes we display estimates evaluated at mean expenditure shares. We focus first on the "direct" income elasticity (η). Estimates range from 0.16 (cereal grains) to 1.82 (natural gas), with a standard deviation of 0.35. The income elasticity of energy goods is generally below one, with average values of 0.81 for electricity, 0.78 for refined oil and 0.95 for coal. Natural gas is the exception, with an income elasticity of 1.82, but the sector only accounts for 4% of the total CO_2 embodied in consumption, while electricity and oil account for 12 and 11%. The "direct" consumption of energy adds up to about 27% of the emissions associated with consumption, with the rest attributed to the consumption of non-energy goods. Within these, agricultural sectors have an average income elasticity of 0.67, manufacturing of 1.00 and services of 1.07.

CRIE preferences yield Engel curves that are close to log-linear[34], a relationship between income and consumption 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. We use more flexible NH CES specifications to test for this regularity with our more disaggregated sectoral data. Comparing regression statistics from CRIE to those from our three NH CES specifications (see Table A.4) reveals the overall fit, reflected by the R^2, to be similar. Information criteria (AIC and BIC) actually suggest CRIE to be preferable to NH CES, despite the additional parameters, reflecting additional flexibility in the estimation of price elasticity (the θ_k are estimated, not calibrated). Focusing specifically on the role of non-homotheticity, however, the partial R^2 shows that the two "augmented" NH CES specifications with flexible forms (quadratic and shifter) improve the fit relative to the standard

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[33] This assumption could lead 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 et al. (2014) finds that the distribution of income elasticity estimates is only slightly larger when integrating within-country income distributions. Yet, the literature has found significant effects. Auffhammer and Wolfram (2014) find that accounting for the spread of the income distribution in China significantly improves estimates of energy-consuming household appliance adoption (and thus energy use). Micro data could help us quantify biases related to within country heterogeneity.

[34] As in Caron et al. (2014), we find a -98% correlation between the estimated $\log \lambda_n$ and $\log I_n$.

Table 1: Average income elasticity, CO_2 intensity (in kg per \$), and share of total CO_2 in consumption
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	Income elasticity		CO_2 intensity		Share of tot.
Sector	Direct (η_{nk})	Total (η_{nk}^{tot})	Direct (β_{nkF}^{C})	Total (β_{nkF}^{Ctot})	CO_2 in cons.
Refined oil (p_c)	0.78	0.91	4.72	5.26	0.11
Electricity (ely)	0.81	0.94	5.61	6.30	0.12
Coal (coa)	0.95	0.95	55.95	56.81	0.01
Natural gas (gas)	1.82	1.08	10.73	10.94	0.04
Agriculture	0.67	0.78	0.09	0.51	0.072
Transportation	0.86	0.94	0.84	1.44	0.078
Manufacturing	1.00	1.00	0.09	0.57	0.343
Services	1.07	1.04	0.02	0.25	0.237

Notes: CRIE income elasticities evaluated at mean expenditure shares. CO_2 intensities are world weighted averages. The share of the total CO_2 in consumption is the weighted average of $sh_{nk}^{ECtot} = \frac{\beta_{nkF}^{Ctot} D_{nk}}{EC_n^{tot}}$.

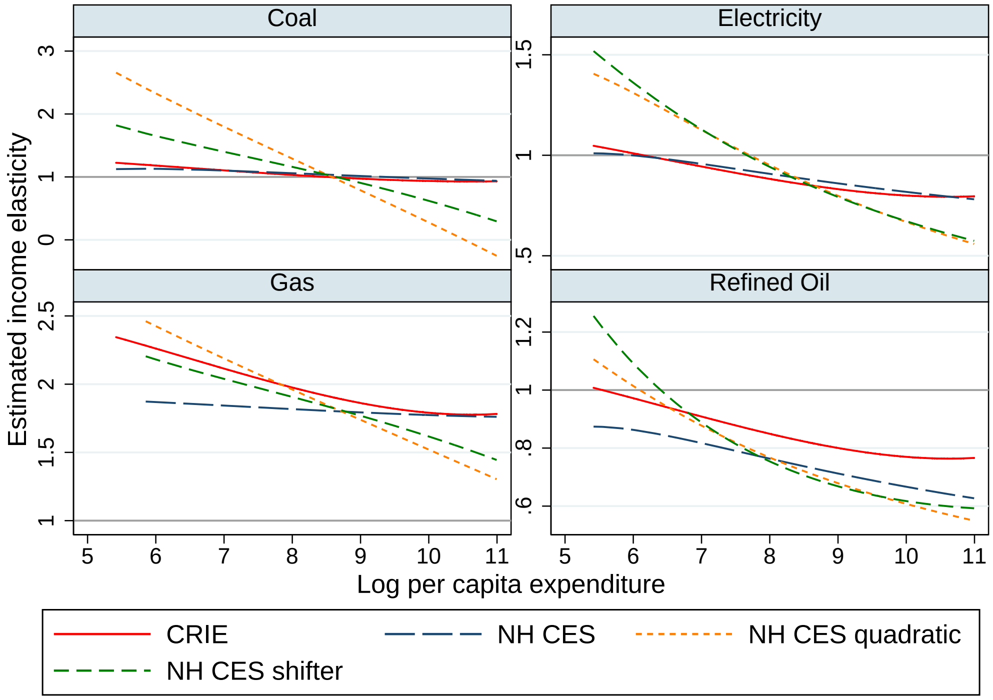

Figure 1: The estimated (direct) income elasticity of energy goods across the spectrum of (log) per capita income for the countries in our dataset. Differences across demand specifications. Local linear regression smoothing.

log-linear NH CES. The b_k coefficients, i.e. the flexible Engel terms, are jointly significant in both cases.

While the increase in fit is driven by a limited number of sectors — most b_k's are not individually significant — more flexible Engel curves particularly matter for energy goods: while income elasticities are similar across specifications at middle-incomes, the "augmented" NH CES specifications generate significantly higher cross-country variation in income elasticities (see Appendix Figure A.5). The difference between the average income elasticity of energy goods and the average in countries with below-median per capita income is more than three times larger with 'NH CES quadratic' than with CRIE: 0.92 to 0.88 for CRIE; 0.92 to 0.73 for NH CES quadratic. The F-stat of joint significance of energy good b_k's is also considerably higher than the average F-stat. Hence, we conclude that while CRIE provides a good fit for most sectors, having more flexible income effects may be desirable for some, including energy goods. Note that we find no substantial difference in the performance of the NH CES "quadratic" and "shifter" specifications, so we will focus on results from the "quadratic" specification.

Total income elasticity We now turn to the link between consumption choices and emissions, which can be illustrated in two ways. The most intuitive, described in the next sub-section, is looking at the cross-sector correlation between direct income elasticity and total CO_2 intensity in production. As an alternative way of describing the link between income and emissions, Table 1 also compares each sector's direct income elasticity in final consumption, η_k, to its "total income elasticity"[35], $\eta_{ih}^{tot} = \frac{1}{Y_{ih}} \sum_{n,k} \gamma_{nikh}^{tot} D_{nk} \eta_{nk}$. The latter 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 all goods that use k as an intermediate input. This new tool helps us link income effects to production.

Comparing the first and second columns in Table 1, we find that the direct and total income elasticity of energy goods differs significantly. The two most important of these sectors, refined oil and electricity, have higher total income elasticity, implying that they are used as intermediates to goods that 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 production (including that destined to intermediate use) is likely to be less sensitive to per capita income than their share in final demand. We note in passing that this reversion to unity is not specific to energy goods, as we find considerably less variance in total than in direct income elasticity across all sectors

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[35] See Equation A.22 in Appendix for the full derivation.

(see Appendix Figure A.6), though the two measures are clearly correlated. The structure of the input-output linkages is thus 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 more generally.[36]

Despite this, the total income elasticity of energy goods (except for natural gas) remains below unity, suggesting that income growth will reduce emissions.

5.2 Sector-level correlation of income elasticity and CO_2 intensity

As another way of illustrating the same empirical fact, Figure 2 displays the relationship between average income elasticity $\bar{\eta}_k$ by sector (derived from CRIE)[37] and average total CO_2 intensity coefficients[38] $\bar{\beta}_{kF}^{Ctot}$, in logs, computed as described in Equation 16. It 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 the lowest CO_2 requirements. This systematic relationship implies that consumers of different income levels will consume baskets of goods with different average CO_2 intensities, providing further evidence for a demand-driven link between energy use, emissions and income levels.

Table A.5 in Appendix displays the coefficients resulting from corresponding regressions of (log) CO_2 intensity on income elasticity. A linear specification yields a significant negative correlation of -0.36. A quadratic specification yields coefficients consistent with an inverted-U relationship (jointly significant). The Akaike information criteria (AIC) slightly favors the non-linear specification. The overall negative relationship partially reflects a transition away from the direct consumption of energy as final goods, as three of the four secondary energy goods, electricity (ELY), refined oil (P_C, mostly gasoline) and coal (COA), have income elasticities that are below unity on average.[39] But not only: the negative and inverted-U relationship also holds — and is indeed even stronger — when restricted to the set of non-energy goods. In broad terms, this reflects a transition from low-income elasticity, low-CO_2 intensity agricultural sectors to medium-income elasticity, high-CO_2 intensity commercial transportation 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

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[36] 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.

[37] Evaluated at mean expenditure shares. Recall however that relative income elasticity is constant with CRIE preferences, so the correlations with CO_2 intensities are unaffected by the choice of country.

[38] Emission intensity coefficients also vary between countries, but we find the correlations to be robust both within countries and using averages based on various sub-groups of countries.

[39] With the exception of natural gas (GAS) consumption.

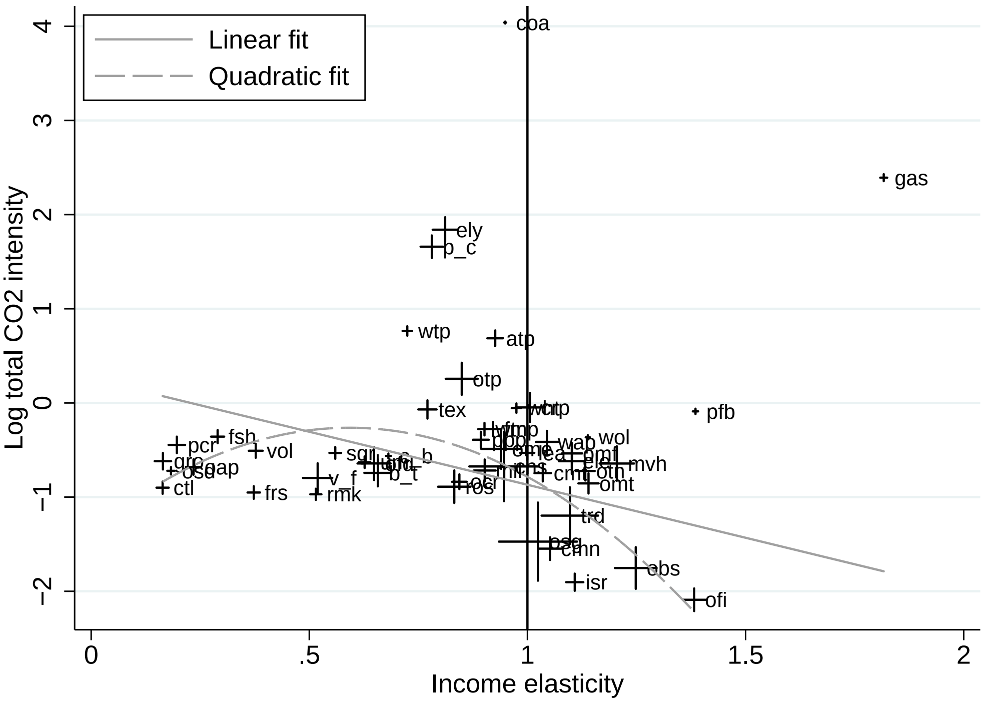

Figure 2: The correlation of income elasticities (CRIE) and CO_2 intensities at the sector-level. *Notes:* Direct income elasticity (η). Marker size reflects the sector's average share of final demand. Alternative demand systems yield similar relationships. See Appendix Table A.6 for underlying data and full sector names and Figure A.1 for the relationship between income elasticity and total green-house gas intensity (including e.g. methane) as well as secondary energy intensity.

the transition between broad sectors, as we also find a negative (but not inverted-U) relationship within the 13 manufacturing sectors.[40] Income elasticity estimates derived from NH CES preferences are highly correlated with CRIE estimates (e.g. 0.944 for quadratic NH CES), both within each country or on average. The correlations with CO_2 intensities are thus robust to the choice of demand system.

5.3 Country-level relationship between income and CO_2 contents

We now investigate the extent to which the sector-level correlation between income elasticity and CO_2 intensity translates to a country-level link between per capita income and the average CO_2 content of consumption (as well as production and imports).

Figure 3 displays the total CO_2 content of consumption for all countries, expressed as averages by dividing EC_n^{tot} (Equation 17) by the value of total expenditures, i.e. expressed as the emission intensity of each country's consumption basket in kg CO_2/\$. They are plotted against

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[40] See the last two columns of Appendix Table A.5 for regression coefficients.

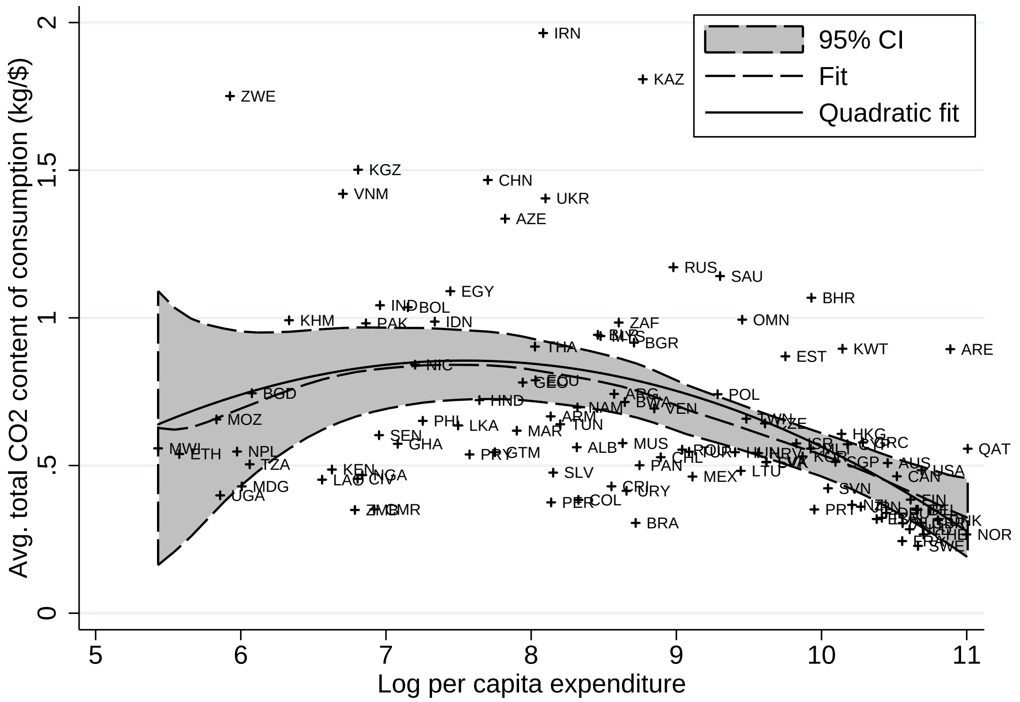

Figure 3: The average total CO_2 content of consumption (in kg/\$) against per capita total expenditures, in the data. See Appendix Figures A.7a for a comparison to the direct content (EC_n^{dir}), A.7b for the indirect content (EC_n^{indir}) and A.7d for production emissions (EY_n). See Figure A.8 for energy contents.

log per capita expenditure, which in most countries is very close to per capita income. The figure shows that, similar to the cross-sector relationships, the country-level relationship between income and the CO_2 intensity of consumption follows an inverted-U pattern with an overall negative trend. The coefficients of either a local linear regression (negative) or a quadratic regression (inverted-U, shown as the solid line) are significant with p-values smaller than 0.01.[41]

Differences in intensities between income levels are substantial: the weighted average CO_2 intensity of consumption is 1.190kg/\$ on average for lower-middle-income countries and 0.365 kg/\$ for high-income countries (0.789 and 0.654 kg/\$ for low-income and upper-middle-income countries). The shape of the quadratic and non-parametric curves also suggests that intensities peak at relatively low levels of income. The average *direct* content of consumption, EC_n^{dir} is around three times lower, reflecting the important role of indirect emissions, but follows a similar inverted-U shape (Appendix Figure A.7a). The average CO_2 content of production is also an inverted-U function of income, even though it is flatter (Figure A.7d).

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[41] Note that although income covaries significantly with the average CO_2 content, it leaves a large part the variability across countries unexplained, at least in reduced-form: the R^2 from the quadratic regressions is 0.20.

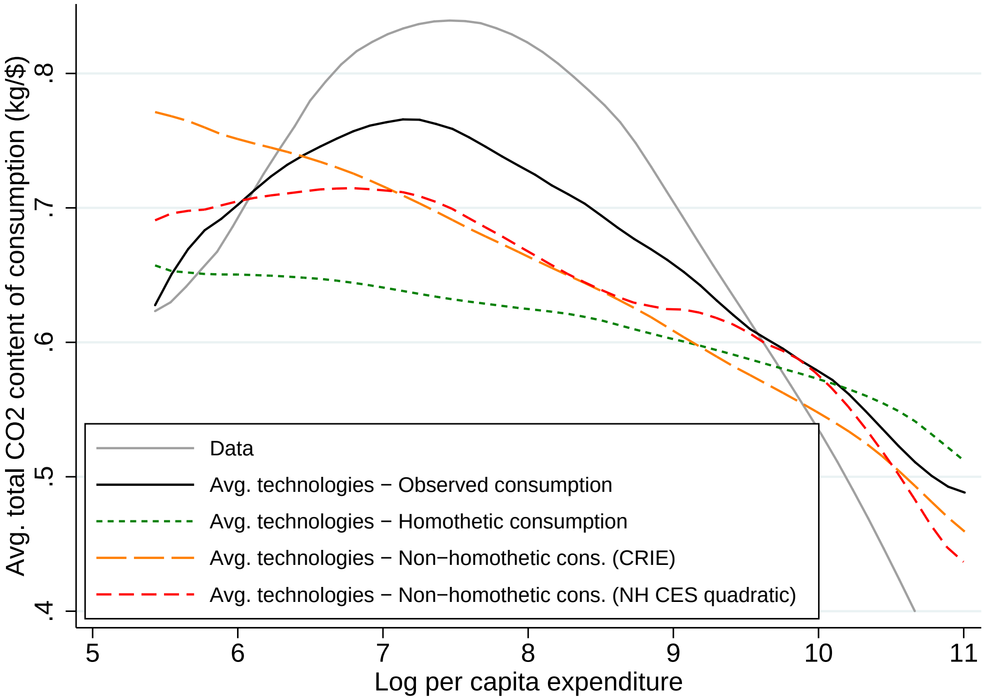

Figure 4: Decomposition of the average total CO_2 content of consumption against per capita total expenditures. Local linear regression smoothing. See Appendix Figures A.9a, A.9b and A.9d for comparisons to direct consumption, indirect consumption and production and Figure A.2 for the inclusion of GHGs beyond CO_2.

The role of consumption patterns To isolate the role of consumption patterns, we recompute the CO_2 content of consumption using country-specific consumption shares D_{nk} but average production CO_2 intensities for each sector (i.e. the weighted average $\bar{\beta}_{kF}^{Ctot}$ across countries). Doing so neutralizes differences in technologies across countries, within-sector heterogeneity (types of goods, differences in quality) and the role of trade (the sourcing of goods). The solid black line on Figure 4 displays the resulting average CO_2 content of consumption, plotted against per capita income using local linear regression. Contrasting to the light grey line representing the CO_2 content found in the data (the same line as in Figure 3), we find that differences in consumption choices greatly contribute to explaining the observed inverted-U relationship.[42] The cross-country correlation between the data and the "average technology" estimates is 72.1% (see Table 2).

Differences in consumption patterns also explain the inverted-U pattern in both the direct and indirect contents when evaluated separately (Appendix Figures A.9a and A.9b), and, in

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[42] The coefficients of either linear or quadratic coefficients significantly describe negative or inverted-U relationships with income (p-values < 0.01).

turn, contribute to explaining why production emissions EY_n decrease with per capita income (Figure A.9d).

The role of non-homotheticity We now investigate the predictive power of per capita income as a determinant, through its influence on consumption patterns, of the average CO_2 content of consumption. To do so, we use fitted consumption shares estimated with either the CRIE or NH CES demand systems, again keeping average production CO_2 intensities at the sector-level.

First, to separate price effects from income effects, we use consumption fitted by *homothetic* preferences in CRIE (imposing $\sigma_k = \sigma$ for all sectors). Resulting expenditure shares vary according to supply-driven differences in prices across countries but not differences in income. The green medium-dotted line on Figure 4 shows that they generate a weakly decreasing relationship between the average total CO_2 content of consumption and income. This suggests that the prices estimated with the gravity equations are correlated with both CO_2 intensity and income: CO_2-intensive goods are on average relatively cheaper in low-income countries. This effect is however moderate: the resulting fitted CO_2 content is only 38.6% correlated with observed content (Table 2).

Relaxing the assumption of homotheticity, i.e. allowing per capita income to determine consumption patterns, increases this correlation from 38.6% to 62.6% (with CRIE preferences), significantly closer to the 72.1% correlation obtained with observed consumption. The resulting average CO_2 content also declines significantly faster with income (see the orange long-dashed line in Figure 4 for CRIE). The magnitude of the income effect is substantial: the average CO_2 intensity of total consumption in low/middle/high-income countries is 0.733, 0.613 and 0.461 kg/\$, even though production technologies and preferences are assumed to be identical across countries in this exercise.

CRIE preferences capture the negative trend observed for middle- and high-income countries, but not the increase in average content for low-income countries. Flexible non-homothetic specifications are necessary to capture this feature of the data. The red medium-dashed line of Figure 4 shows that augmented "quadratic NH CES" preferences, while providing similar estimates for a large part of the income spectrum (middle-income and above), better replicate the inverted-U pattern generated by observed differences in consumption patterns. "shifter" NH CES preferences yield a very similar curve, while log-linear NH CES preferences are much closer to CRIE (Appendix Figure A.10).

Table 2: Decomposition of the total CO_2 intensity of consumption.

Production intensities:	*average*				*observed*
Consumption patterns:	*homoth*	*non-homothetic*		*observed*	*observed*
		CRIE	*NH CES quad*		
Correlation with observed	0.386	0.626	0.646	0.721	1
Variance explained (Pseudo-R^2)	0.101	0.239	0.252	0.336	1

As an alternate way of describing the role of consumption patterns and non-homotheticity, we also compute a measure of fit, a Pseudo-R^2, which summarizes the share of cross-country variance in observed total CO_2 content explained by different fitted decompositions $\widehat{EC}_n$.[43] The Pseudo-R^2 for the total CO_2 content is 0.336 when using observed consumption patterns and average production intensities (see Table 2). 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 across countries. Any model ignoring these differences, or any predictive exercise failing to account for the evolution of consumption patterns caused by income growth will ignore 34% of the variability in the CO_2 emissions embodied in consumption, and thus production.

Using fitted non-homothetic consumption patterns explains more than two thirds of this variance, with a Pseudo-R^2 of 0.239. Conversely, imposing homothetic preferences yields an Pseudo-R^2 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.

The CO_2 content of imported consumption First, we use our model and multi-regional input-output dataset to confirm a variant of the "pollution-haven" hypothesis (not illustrated): 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. But 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. Figure 5 displays EC^{Imp} (defined in Section 3.1) and its decompositions. The solid line shows the observed relationship with income to be quite strong. Evaluating with average technologies, we find that 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-

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[43] Computed as Pseudo-$R^2 = 1 - \frac{SSR}{SSE} = 1 - \frac{\sum_n (EC_n^{true} - \widehat{EC}_n)^2}{\sum_n (EC_n^{true} - \overline{EC}_n^{true})^2}$.

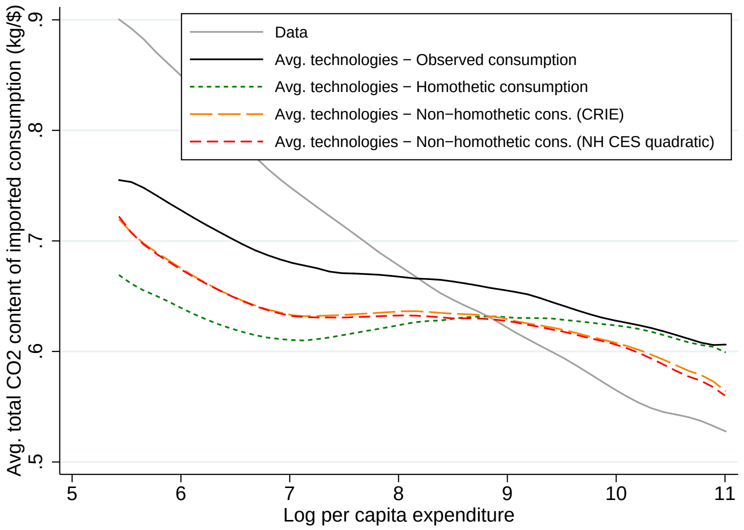

Figure 5: Decomposition of the average CO_2 content of imported consumption. Local linear regression smoothing.

income countries: it is fairly flat at middle incomes. Moreover, the large difference between the solid and dashed lines suggests that most of the downward trend is explained by differences in technologies, with high-income countries on average importing from countries with less CO_2-intensive technologies. To summarize, consumers in rich countries indeed import more of the CO_2 they consume, but also have preferences that make their imports less CO_2 intensive. Our model would thus predict a weaker "pollution-haven" effect than standard models with homothetic preferences.

5.4 Simulating a counterfactual increase in per capita income

Having established per capita income as an important determinant of emissions, we now investigate the potential for further income growth to reduce energy use and emissions through a shift in consumption patterns, including general equilibrium effects, but absent any other change in production functions (technology) or change in factor endowments.

We simulate growth in per capita income by exogenously increasing total factor productivity z (TFP) by one percent in all countries and all sectors (including fossil fuel resource factors).[44] With homothetic preferences, such uniform productivity growth would increase income and total consumption but not affect the relative demand for each sector. Emissions would thus increase uniformly by one percent in all countries, making this counterfactual a natural benchmark to

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[44] Almost identical results are obtained when simulating a 10% shock (Figure A.11). Results are also mostly insensitive to simulating a productivity shock in all but the fossil fuel sectors (see Section A.6.1 in Appendix).

highlight the role of non-homotheticity.

In section 3.2, we have described how uniform TFP growth affects emissions intensity in partial equilibrium approximations. We have shown consumption emissions to be a function of the correlation between income elasticity and CO_2 intensity, which we have then found to be negative overall. Here, we use the full model and parameter estimates described in Section 2 to simulate income growth. Counterfactual equilibria are obtained by formulating Equations A.4 to A.13 as a system of non-linear equations in GAMS and solving numerically using the non-linear PATH solver.[45]

Simulation results Figure 6 displays resulting changes in emissions, expressed as the elasticity of consumption emissions to income. Specifically, we compute the simulated counterfactual change in the CO_2 content of consumption $\widehat{EC}_n^{tot}$ divided by the change in I_n,[46] as computed with both CRIE and quadratic NH CES preferences. These can be interpreted as general equilibrium elasticities, being the outcome of counterfactual simulations that capture the response of supply to the income-driven demand shock. General-equilibrium feedbacks include price responses for all sectors and factors: for example, a relative reduction in the 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.

A value of one in Figure 6 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. The figure shows a significant role for income-driven shifts in consumption patterns, though the sign and magnitude of the income effect varies across countries. The income elasticity of CO_2 contents is on average above one in low-income countries, implying increasing CO_2 intensity of their consumption baskets: they are still shifting their consumption towards more CO_2-intensive goods. The opposite would occur in rich countries. This pattern is consistent with the inverted-U relationship described in Section 5.3.

While the overall declining relationship with income is robust to the choice of demand specification, differences between countries are more pronounced when we allow for more flexible "augmented" preferences (quadratic NH CES). The difference between the average elasticity of low- and high-income countries is 10% (1.050 to 0.952) with quadratic NH CES, compared to

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[45] 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. We use estimated values of θ_k, rescaled to an average of 4. Results are largely insensitive to this parameter (Appendix Figure A.12).

[46] We simulate an increase in $\hat{z}$ (TFP), but chose to use real income as a denominator. While very similar, elasticity to TFP exhibits slightly smaller differences between low- and high-income countries (Figure A.14).

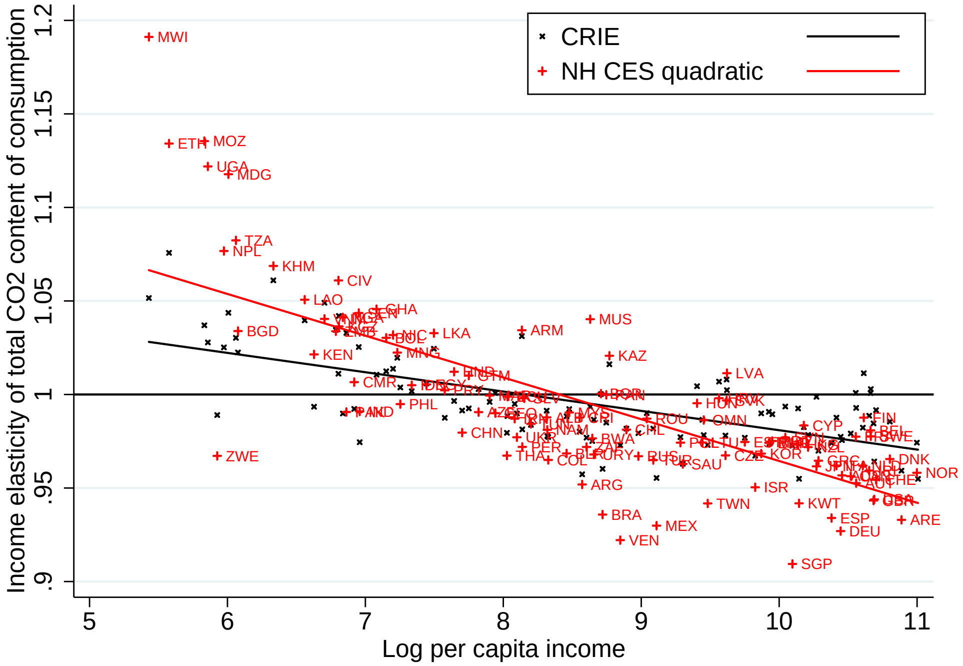

Figure 6: Simulated elasticity of the total CO_2 content of consumption to per capita income, as a function of initial per capita income. Comparison of CRIE and quadratic NH CES preferences. Supply elasticity of fossil fuels calibrated to 0.75. See Appendix Figure A.15 for a comparison to the direct CO_2 content and Figure A.13 for a comparison to alternative NH CES specifications.

5% (1.021 to 0.977) with CRIE. CRIE thus underestimates heterogeneity in the income effect's strength. We also show in appendix Figure A.13 that NH CES preferences, in their standard log-linear form, do not provide results that differ substantially from CRIE.

Average world effect With uniform productivity growth, we find that reductions in the CO_2 intensity of consumption in high-income countries outweigh increases in low-income countries. The income effect is indeed weakly negative overall and similar across specifications: the weighted average income elasticity of consumption emissions for the world is 0.962 for quadratic NH CES and 0.979 for CRIE. These figures correspond to the income elasticity of world production emissions as well. Thus, uniform income growth leads to a 2.1-3.8% smaller increase in total emissions relative to models with homothetic preferences.

This conclusion could be slightly moderated if we account for expected differences in growth rates between countries, because countries with higher emissions elasticities (as reported in Figure 6) are likely to grow faster on average. In Appendix Section A.6.2, we show that elasticities are positively correlated with both country-specific growth predictions and historical growth rates (Figure A.4). Using country-specific rates of expected income growth thus implies a smaller reduction in world emissions, though differences relative to homogeneous growth are small: the income elasticity is 0.97 instead of 0.96 (NH CES).

Direct consumption and production Figure A.15 in Appendix displays the results equivalent to Figure 6 for the direct CO_2 content of consumption, i.e. the income elasticity of emissions directly caused by households through the consumption of electricity, natural gas, coal and refined oil. The resulting average world elasticity is lower, at 0.882 (CRIE) or 0.812 (quadratic NH CES), implying that a 1% increase in per capita income in all countries would reduce the average direct CO_2 intensity of consumption by about 0.12/0.19%, considerably more the total content. This is consistent with our finding that the total income elasticity of energy goods is higher (closer to one) than their direct elasticity. Ignoring indirect energy consumption would thus lead to over-estimating the potential for consumption-driven decarbonization.

The reduction in intensity is again consistently stronger in high-income countries: their average elasticity is quite low, especially when estimated with “augmented preferences, at 0.715. Low-income countries as a whole have a weighted average elasticity of 1.059. The difference between demand specifications is more pronounced than for the total CO_2 content, pointing to the importance of allowing for flexibility in Engel curves for energy goods specifically.

Finally, moving beyond consumption, Figure A.16 in Appendix shows that the income elasticity of *production* emissions (i.e. the change in $\widehat{EY}_n$), is overall very similar to that of the (total) consumption content, though changes in trade patterns lead to some differences: low- and high-income countries see their consumption emissions rise slightly more than their production emissions. The opposite is true for middle-income countries, who see an increase in their net exports of emissions.

Calibration of fossil fuel supply elasticity While we focus on a demand-side shock, the reported changes in equilibrium emissions depend on the response of fossil fuel supply. Obtaining precise estimates of the price elasticity of supply for gas, oil and coal for all the countries in our dataset is beyond the scope of this paper. 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 are sometimes slightly larger than unity.[47] In our benchmark simulations shown above, we calibrated 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 generates relatively low supply-side response in terms of quantities and large response in terms of prices on the fossil fuel markets. Appendix Figure A.17 compares estimates to results generated

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[47] More generally, Fally and Sayre (2018) survey the literature and find that most estimates of supply elasticity for primary commodities are lower than unity.

with an elasticity of 1.5 (for natural gas only and for all three fuels), a value possibly consistent with a larger supply response in the very long run. As expected, doubling the supply elasticity increases the equilibrium shift in demand away from energy, but only moderately: the world average income elasticity of total CO_2 contents is 0.948 instead of 0.962 (quadratic NH CES).

Aside from the (downward) adjustment in levels, the distribution of effects between countries and income levels is very similar, suggesting that world markets in energy goods and energy-intensive goods are sufficiently integrated to mostly decouple the demand shocks from supply response across countries.

Partial equilibrium approximations and decomposition Section 3.2 described how TFP growth affects emissions in partial equilibrium approximations of $\widehat{EC}_n^{tot}$ (eq. 19). We find that while some deviations exist at the country-level, these first-order approximations are well correlated with the general-equilibrium estimates of Figure 6 (see Appendix Figure A.18). This suggests that while general equilibrium modeling is necessary to capture rich variability across countries, the broad patterns of the demand effect can be approximated by simple correlation formulas that only requires knowledge of income elasticity and a measure of consumption-related emissions intensity per sector. Still, the world average elasticity is further from one when evaluated in partial equilibrium, at 0.913, than in general equilibrium, at 0.962 (quadratic NH CES). Ignoring general equilibrium feedbacks[48] would lead to overpredicting the income-driven reduction in the CO_2 intensity of consumption.

The partial equilibrium approximations can also be used to decompose income effects. Appendix table A.9 illustrates how each sector contributes to $\widehat{EC}_n^{total}$ by displaying the "consumption effect" part of the approximation, i.e., $sh_{nk}^{ECtot}\left(\eta_{nk}-1\right)$, per sector. As the effect of productivity growth ($\log \hat{z}$) is not accounted for, summing across sectors yields changes in the average CO_2 *intensity* of consumption (not the level), and would be zero in the homothetic case with no income-driven consumption shifts (and not one). Of the total decline in intensity of -0.087 (i.e. 0.913-1) at the world level (with quadratic NH CES) direct energy consumption would contribute the largest share, -0.057. This is driven by reductions in electricity and refined oil despite a positive but negligible contribution from natural gas. Emissions embodied in non-energy goods contribute -0.030 to the elasticity — about 37% of the total, i.e. less than their share of consumption emissions (73%). Within these, reductions caused by shifts away from agriculture and transportation outweigh increases in emissions embodied in manufacturing and services.[49]

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[48] Approximations account for input-output and trade linkages in a static way but ignore second-order effects in consumption including changes the relative price of goods and factors. They also ignore supply response as we compute them assuming infinite supply elasticity ($\zeta = \infty$) to isolate the effect of shifting consumption patterns.

[49] At the disaggregated level, the largest reductions are in 'other types of transport', recreational and other

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 contributing 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 with income (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 Summary and concluding remarks

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 across a large number of countries covering most of the world economy and a wide range of per capita income levels. Our framework allows identifying income-driven consumption effects and simulating their impact in general equilibrium.

We confirm strong income effects for direct household energy consumption. The quantitative role of income is weaker once we include indirect consumption emissions (a large share of total emissions), but it remains significant. We find a negative/inverted-U relationship between income elasticity and total CO_2 intensity across all sectors, and show that it contributes to explaining the observed negative/inverted-U pattern between total consumption emissions intensity and income across countries. Thus, the demand-side of general equilibrium and non-homotheticity in consumption can partly explain the shape of the Environmental Kuznet Curve.

We then use general equilibrium simulations to investigate the expected impacts of future income growth. Although indirect consumption emissions reduce the income effect, and although income growth increases the CO_2 intensity of consumption in low-income countries, stronger reductions in rich countries lead to a reduction for the world on average. This reduction in intensities is however relatively weak: the elasticity of emissions to income is between 0.948 and 0.979, depending on assumptions. Projection models (e.g. Integrated Assessment Models) with homothetic demand may thus provide a reasonable approximation of aggregate changes in global consumption emissions in the short run. Yet our findings illustrate the importance of incorporating income-consumption effects to anticipate future global emission levels: reductions

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services, food products n.e.c., and construction. The largest positive contributors are trade and retail, other business services, and motor vehicles.

in the CO_2 intensity of consumption will grow stronger in the long run as more countries pass peak intensity levels, while the relative demand for energy will shift towards low-income countries and from direct to indirect consumption. Efforts to mitigate emissions should be designed accordingly.

Finally, while we focus on well-measured CO_2 emissions, we have also applied our methodology to other greenhouse gases (CH_4, N_2O and fluorinated gases). We actually find stronger income effects if non-CO_2 greenhouse gases are accounted for: income-inelastic (necessity) goods, particularly agriculture, are particularly intensive in these gases, as discussed in Appendix A.1. Including other GHGs leads to a negative cross-sectoral correlation between total GHG-intensity and income elasticity that turns the inverted-U cross-country relationship identified for CO_2 strictly negative, with an even larger role for non-homothetic preferences. However, considering secondary energy demand (measured in oil equivalents) yields very similar relationships with income to what we find for CO_2. The paper's conclusions thus follow through for policy-makers interested in the negative externalities associated with energy use (beyond climate change).

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A Appendix – For online publication

A.1 Beyond CO_2: effects on secondary energy demand and other greenhouse gases.

A.1.1 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 A.1a displays the relationship between income elasticity and (log) total secondary energy intensity (expressed in kg of "oil equivalent" energy per $) across sectors. While CO_2 is associated with fossil fuel use in our model and data, 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, which emit 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 energy intensity across sectors is 0.990. Thus, Figure A.1a reveals a negative and inverted-U pattern similar to that found with CO_2 and the top section of Table A.1 confirms that the relationships are statistically significant. All of our results regarding the link between income and CO_2 hold for secondary energy, including the inverted-U relationship between per capita income and the average energy intensity of consumption (See Figure A.8).

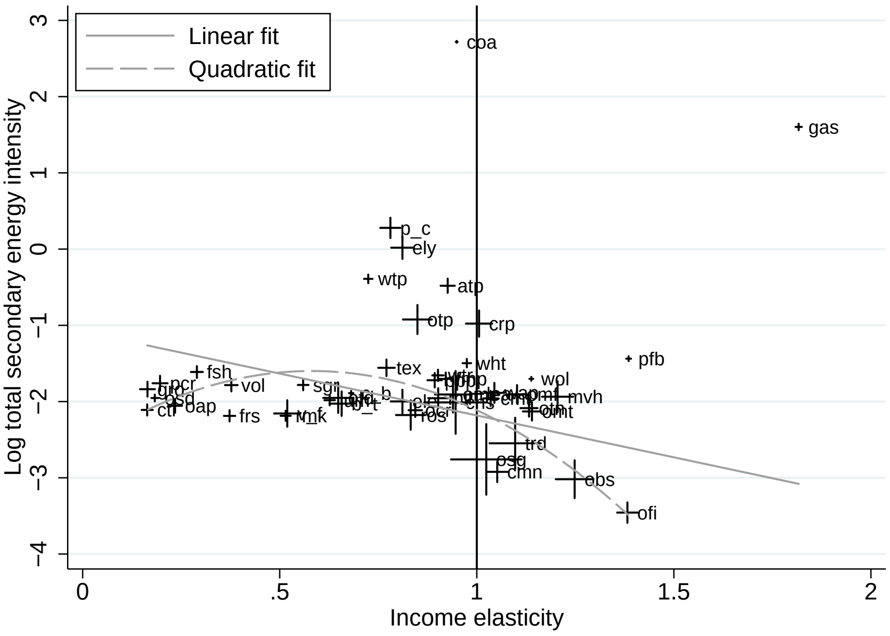
A.1.2 Other greenhouse gases (GHG)

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). These gases are primarily associated with agricultural production, including livestock, but a non-negligible share is emitted during other industrial processes and transport.

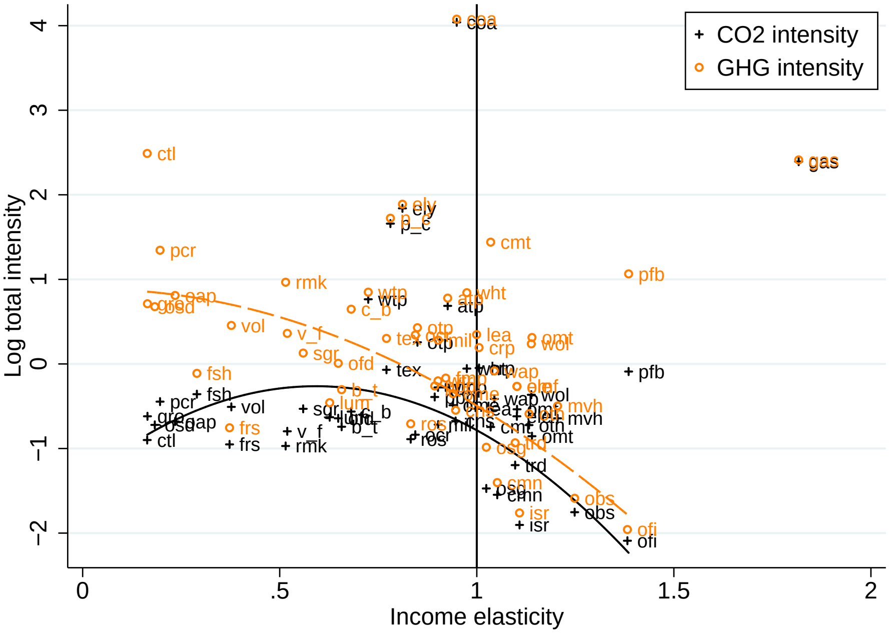
The data describing non-CO_2 GHG exhibit extremely large variance in country-level intensities, so we decide to restrain our analysis to the use of sector-level averages. The inclusion of non-CO_2 gases significantly increases the average GHG-intensity of some sectors, particularly agricultural sectors 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 A.1b, 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 A.1: the quadratic term does not improve the fit).

This translates to strong income effects at the country-level. Figure A.2 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 asymmetric 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).

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 what we found for 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.



(a) Secondary energy intensity



(b) CO_2 versus total GHG intensity

Figure A.1: Cross-sector correlation between income elasticity and intensity in secondary energy (top panel), and with CO_2 and total GHGs (bottom panel).
Notes: Secondary energy expressed in oil equivalent kg/$; total GHG intensity is expressed in CO_2 equivalent kg/$.

Table A.1: Regressions of secondary energy intensity (top panel) and GHG intensity (bottom panel) on income elasticity (beta coefficients, i.e. correlations).

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 on income elasticity and its square; p-values correspond to F-tests of joint significance of the coefficients; regressions weighted by average share of final demand.

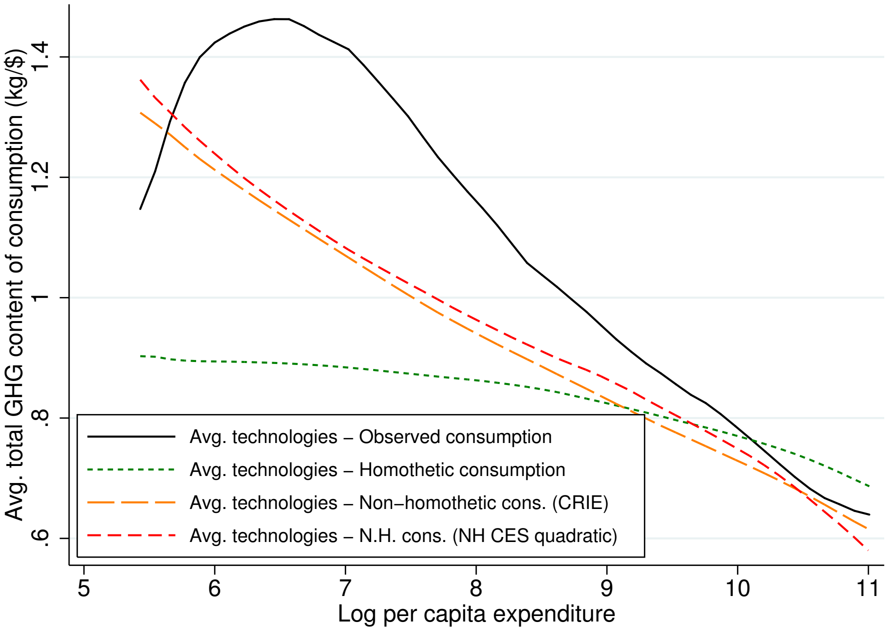


Figure A.2: Per capita income and the total GHG intensity of consumption (based on avg. production intensities). Local-regression smoothing across countries.

A.2 General equilibrium model

A.2.1 Additional equilibrium conditions

Besides the equations described in the main text, 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:

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

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:

$$R_{ik} w_{R,ik} = \frac{\beta_{ikf} Y_{ik} \mu_{R,ik} w_{R,ik}^{1-\nu_{ik}}}{\mu_{R,ik} w_{R,ik}^{1-\nu_{ik}} + (1-\mu_{R,ik})c_{ik}^{1-\nu_{ik}}} \tag{A.2}$$

In turn, per-capita income is determined by:

$$I_i = \frac{1}{L_i} \sum_f V_{fi} w_{fi} \tag{A.3}$$

By Walras' Law, trade is balanced at equilibrium. Given the equilibrium absorption X_{nk} and prices P_{nk} of energy sectors, we can back out emissions.

A.2.2 Counterfactual equilibria

The following equations describe the full set of equilibrium conditions in the model used for counterfactual simulations (with production equal to $Y_{nk} = \sum_i \pi_{ink} X_{ik}$ and trade shares defined as $\pi_{nik} = \frac{X_{nik}}{X_{nk}}$):

$$\widehat{D_{nk}} = \widehat{\lambda_n}^{-\sigma_k}\,\widehat{P_{nk}}^{1-\sigma_k} \text{for CRIE (see Section A.5.3 below for NH CES)} \tag{A.4}$$

$$\widehat{I_n} = \frac{\sum_k \widehat{D_{nk}}\, D_{nk}}{\sum_k D_{nk}} \tag{A.5}$$

$$\widehat{X_{nk}} = \frac{D_{nk}\widehat{D_{nk}}}{X_{nk}} + \sum_h \frac{\gamma_{nkh} Y_{nh} \widehat{Y_{nh}}}{X_{nk}} \tag{A.6}$$

$$\widehat{X_{nik}} = \widehat{C_{ik}}^{-\theta_k}\,\widehat{\tau_{nik}}^{-\theta_k}\,\widehat{P_{nk}}^{\theta_k}\,\widehat{X_{nk}} \tag{A.7}$$

$$\widehat{P_{nk}} = \left[\sum_i \pi_{nik}\widehat{C_{ik}}^{-\theta_k}\,\widehat{\tau_{nik}}^{-\theta_k}\right]^{-\frac{1}{\theta_k}} \tag{A.8}$$

$$\widehat{C_{ik}} = \widehat{z_{ik}}^{-1}\left[\beta_{R,ik}\,\widehat{w_{R,ik}}^{1-\nu_k} + (1-\beta_{R,ik})\,\widehat{c_{ik}}^{1-\nu_k}\right]^{\frac{\beta_{ik}}{1-\nu_k}}\left(\prod_h \widehat{P_{ih}}^{\gamma_{hk}}\right)^{-1} \tag{A.9}$$

$$\widehat{c_{ik}} = \prod_f \widehat{w_{fi}}^{\frac{\beta_{fk}}{\beta_{ik}}} \tag{A.10}$$

$$\widehat{w_{if}} = \frac{1}{V_{if} w_{if}}\left[\sum_{k\notin\mathcal{P}} \beta_{ikf} Y_{ik}\widehat{Y_{ik}} + \sum_{k\in\mathcal{P}} \beta_{ikf} Y_{ik}\widehat{Y_{ik}}\widehat{c_{ik}}^{1-\nu_k}\,\widehat{\chi_{ik}}^{\nu_{ik}-1}\right] \tag{A.11}$$

$$\widehat{w_{R,ik}} = \widehat{Y_{ik}}\,\left(\frac{\widehat{c_{ik}}}{\widehat{w_{R,ik}}}\right)^{\nu_k-1} \quad \text{for } \; k\in\mathcal{P} \tag{A.12}$$

$$\widehat{I_i} = \frac{\sum_f V_{fi} w_{fi}\widehat{w_{fi}} + \sum_{k\in\mathcal{P}} R_{ik} w_{R,ik}\widehat{w_{R,ik}}}{\sum_f V_{fi} w_{fi} + \sum_{k\in\mathcal{P}} R_{ik} w_{R,ik}} \tag{A.13}$$

$$\widehat{CO2_{nhk}} = \frac{\widehat{Y_{nk}}}{\widehat{P_{nh}}} \quad \text{for } \; h\in\mathcal{E} \tag{A.14}$$

A.3 Supply elasticity of primary energy goods

This section describes the derivation of the equation for 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 (required for fossil fuel production).

Equation A.2 yields:

$$R_{ik} w_{R,ik} = \frac{\beta_{ikf} Y_{ik}\mu_{R,ik} w_{R,ik}^{1-\nu_{ik}}}{\chi_{ik}^{1-\nu_{ik}}} \tag{A.15}$$

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:

$$\begin{aligned}
\frac{\partial \log \chi_{ik}}{\partial \log Y_{ik}} &= \varphi_{R,ik} \frac{\partial \log w_{R,ik}}{\partial \log Y_{ik}} && \text{(A.16)} \\
&= \varphi_{R,ik} \cdot \frac{1}{\nu_{ik}} + \varphi_{R,ik} \left(1 - \frac{1}{\nu_{ik}}\right) \frac{\partial \log \chi_{ik}}{\partial \log Y_{ik}} && \text{(A.17)} \\
&= \frac{\varphi_{R,ik} \cdot \frac{1}{\nu_{ik}}}{\varphi_{R,ik} \cdot \frac{1}{\nu_{ik}} + (1 - \varphi_{R,ik})} && \text{(A.18)}
\end{aligned}$$

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:

$$\zeta_{ik} = \frac{\partial \log Y_{ik}}{\partial \log p_{ik}} - 1 = \frac{\nu_{ik}\,(1 - \varphi_{R,ik}) + \varphi_{R,ik}}{\beta_{ik}\, \varphi_{R,ik}} - 1 \tag{A.19}$$

A.4 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 $\widehat{C_{ik}} \approx \widehat{z}^{\theta_k}$ 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.

We now describe how to approximate changes in demand. Taking $\widehat{P_{nk}} \approx \widehat{z}^{-1}$ as a first approximation and holding nominal income constant and using Equation A.4, 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 A.13, 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 following first-order approximation for changes in final demand:

$$\log \widehat{D_{nk}} = (\eta_{nk} - 1) \log \widehat{z} \tag{A.20}$$

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

Finally, we describe how to approximate changes in production. With $\widehat{C_{ik}} \approx \widehat{z}^{-1}$ and $\widehat{P_{nk}} \approx \widehat{z}^{-1}$, we obtain the following from the trade equation:

$$\widehat{X_{nik}} = \widehat{C_{ik}}^{-\theta_k} \widehat{P_{nk}}^{\theta_k} \widehat{X_{nk}} = \widehat{X_{nk}}$$

Next, combining with Equation A.6, $\widehat{X_{nk}} = \frac{D_{nk}\widehat{D_{nk}}}{X_{nk}} + \sum_h \frac{\gamma_{nkh} Y_{nh} \widehat{Y_{nh}}}{X_{nk}}$, 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 15 and our definition of "total income elasticity", we obtain:

$$\log \widehat{Y}_{ih} = \frac{1}{Y_{ih}} \sum_{n,k} \gamma^{tot}_{nikh} D_{nk} \log \hat{D}_{nk} = (\eta^{tot}_{ih} - 1) \log \hat{z} \tag{A.21}$$

$$\text{with:} \qquad \eta^{tot}_{ih} = \frac{1}{Y_{jh}} \sum_{n,k} \gamma^{tot}_{nikh} D_{nk} \eta_{nk} \tag{A.22}$$

where we define a sector's "total income elasticity" η^{tot}_{ih} as the weighted-average of income elasticity η_{ik} of all the final goods in which that sector's output is embodied and in all destination countries.

Equation A.21 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}.[50] 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 10 and

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

11, we obtain that the change in prices in (destination) country n is an average (weighted by import shares π_{nik}) of the change in production costs across source countries. Combining with Equation A.21 on production, we can then also link the changes in energy prices to the change in consumption choices and income elasticities:

$$\log \widehat{P_{nk}} = -\log \hat{z} + \sum_i \frac{\pi_{nik}}{1+\zeta_{ik}} \log \widehat{Y}_{ik} \approx -\log \hat{z} + \sum_i \frac{\pi_{nik}(\eta^{tot}_{ik}-1)}{1+\zeta_{ik}} \log \hat{z} \tag{A.23}$$

With these tools in hand, we can then derive expressions for the counterfactual changes in direct and indirect emissions.

Changes in direct and indirect consumption emissions Changes in direct consumption emissions are given by:

$$\log \widehat{EC^{dir}_n} \approx \left[1 + \sum_{k\in\mathcal{S}} \frac{CO2_{nkF}}{EC^{dir}_n}(\eta_{nk}-1) - \sum_{k\in\mathcal{P}} \frac{CO2_{nkF}}{EC^{dir}_n} \sum_i \frac{\pi_{nik}\,(\eta^{tot}_{ik}-1)}{1+\zeta_{ik}}\right] \log \hat{z} \tag{A.24}$$

Changes in indirect emissions are similar, though require keeping track of trade and input-output linkages through the γ^{tot}_{nikh} coefficients:

$$\log \widehat{EC}^{indir}_n \approx \left[1 + \sum_k \frac{\beta^{Cindir}_{nkF} D_{nk}}{EC^{indir}_n}(\eta_{nk}-1) - \sum_{k,h\in\mathcal{P},i} \frac{\beta^{C}_{ih}\gamma^{tot}_{nikh} D_{nk}}{EC^{indir}_n} \frac{(\eta^{tot}_{ih}-1)}{1+\zeta_{ih}}\right] \log \hat{z} \tag{A.25}$$

Note that when presenting results, we include the (indirect) emissions caused by electricity consumption in direct emissions.

Changes in total consumption emissions From $\widehat{EC^{dir}_n}$ and $\widehat{EC^{indir}_n}$, we then obtain the change in the *total* CO_2 content of consumption as a function of their share in total consumption emissions:

$$\widehat{EC}^{total}_n \approx \frac{1}{EC^{tot}_n}\left[EC^{dir}_n \widehat{EC}^{dir}_n + EC^{indir}_n \widehat{EC}^{indir}_n\right] \tag{A.26}$$

This can easily be reformulated as the expression (Equation 19) presented in the main text.

Changes in production emissions Changes in emissions from sector k in country n caused by consuming (burning) energy inputs h are given by: $\log \widehat{CO2_{ikh}} = \log \widehat{Y_{ik}} - \log \widehat{P_{ih}}$ (Equation A.14). Summing across all energy inputs, and using expressions A.21 and A.23 for the changes in production and prices, we obtain:

$$\log \widehat{EY}_n \approx \frac{1}{EY_n}\left[\sum_{k,h} CO2_{nkh}\eta^{tot}_{nk} - \sum_{k,h\in\mathcal{P},i} CO2_{nkh}\,\frac{\pi_{nih}(\eta^{tot}_{ih}-1)}{1+\zeta_{ih}}\right]\log\hat{z} \tag{A.27}$$

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.

A.5 Non-homothetic CES preferences

A.5.1 Theory

This section describes "Non-homothetic CES" (NH CES) preferences in more detail. Combining Equation 3 with the budget constraint, we obtain the following expression for expenditures in good k in country n:

$$D_{nk} = Q_{nk}P_{nk} = g_k(U_n)^{1-\sigma}L_n e_n^{\sigma} P_{nk}^{1-\sigma} \tag{A.28}$$

where $e_n = \frac{I_n}{L_n}$ is per-capita income. 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 $\sum_k D_{nk} = I_n$, using expression A.28 for $D_{nk} = Q_{nk}P_{nk}$. 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:

$$\frac{\partial \log \frac{D_{nk}}{L_n}}{\partial \log e_n} = \sigma + (1-\sigma)\cdot\frac{\eta^g_{nk}\sum_{k'} D_{nk'}}{\sum_{k'} D_{nk'}\eta^g_{nk'}} \tag{A.29}$$

where $\eta^g_{nk} = \frac{\partial \log g_k}{\partial \log U_n}$ denotes the elasticity of g_k in U_n. One can see that if η^g_{nk} is constant across goods, preferences are homothetic.[51] 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:

$$D_{nk} = \alpha_k L_n e_n^{\sigma} U_n^{\epsilon_k-\sigma} P_{nk}^{1-\sigma} \tag{A.30}$$

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

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[51] 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 $\eta^g_{nk} > 0$ for all sectors k. If $\sigma > 1$ the income elasticity has an upper bound at σ.

Engel curves while remaining parsimonious:

$$\text{Shifter NH CES:} \quad \log g_k(U) = \log \alpha_k + \rho_k \log(U_n + b_k) \tag{A.31}$$

$$\text{Quadratic NH CES:} \quad \log g_k(U) = \log \alpha_k + \rho_k \log U_n - b_k (\log U)^2 \tag{A.32}$$

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. Depending on the sign of b_k, η^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 $\log U_n > \frac{\rho_k}{2b_k}$).

A.5.2 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). 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). We calibrate trade elasticity θ to be equal to 4, a common value in the literature.[52]

Table A.4 displays regression statistics for the three NH CES specifications and compares them to the estimation of CRIE, while Figure A.5 displays fitted consumption and implied income elasticties for energy goods under NH CES and CRIE. Note that we estimate the price elasticity σ to be fairly high, at 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 A.29, income elasticity is bounded by the price elasticity.

A.5.3 In the simulation model

Non-homothetic CES preferences can be integrated within the general equilibrium model similarly to preferences in the benchmark calibration. Taking the change ratios of final demand (Equation A.28), 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.

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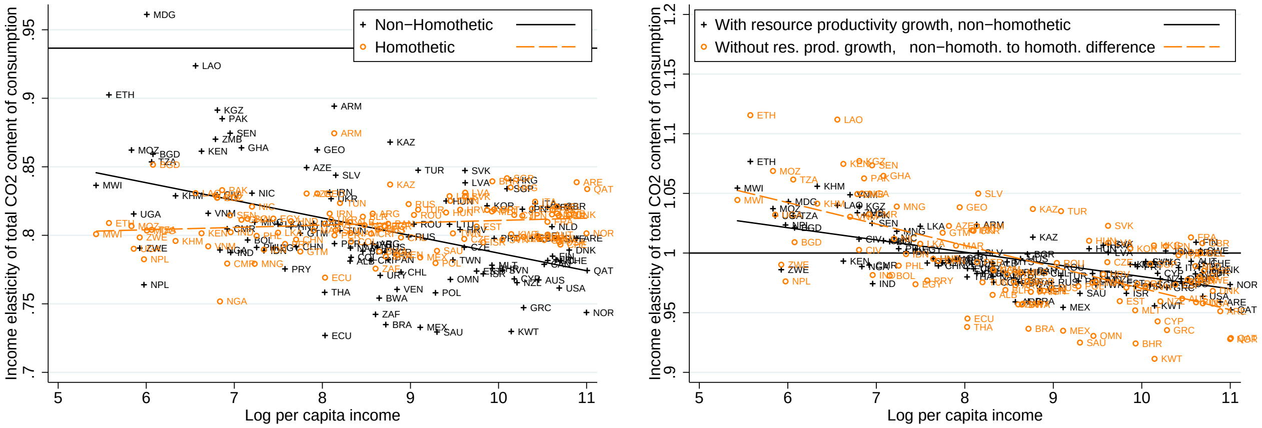
[52] Contrary to CRIE in which θ is identified in each sector using the restrictions on price and income elasticity, there is no explicit link between the elasticities in non-homothetic CES preferences so we chose to calibrate θ.

A.6 Robustness checks for the simulation exercise

A.6.1 Fossil fuel resource factor productivity growth

In our benchmark counterfactual, the productivity of the natural resource factor specific to each fossil fuel increases similarly to all other 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 (with CRIE preferences only). 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.3 shows that 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 modest. 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).



(a) No resource productivity growth

(b) Comparison

Figure A.3: Simulated income elasticity of the total CO_2 content of consumption; 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 case without productivity growth). CRIE preferences; supply elasticity = 0.75.

A.6.2 Elasticity of world emissions - sensitivity to country-specific GDP growth rates

While the main text focuses on uniform growth rates to clearly illustrate the magnitude of the non-homothetic demand effect and how it varies across countries, understanding what the magnitude of the income effect would be with *differential* growth rates is relevant for projections of world total emissions.

We thus test the sensitivity of results to the use of country-specific growth rates. We have used three alternate ways of accounting for expected growth:

- Short-term growth projections (2018-2020)
- Historical 1990-2014 average growth rates
- Historical 2005-2014 average growth rates

We start by using growth projections made available by the OECD[53] and by the World Bank for non-OECD countries[54]. Projections are currently available for 2018, 2019 and 2020. We have used the average annual forecasted growth rate across those 3 years. Such short-term estimates are influenced by business cycles which may indicate little about a country's long-term growth prospects. Our exercise is intended to have a long run interpretation, and our income elasticity estimates best apply to long-term growth rates. We have therefore also used historical growth rates, based on the assumption that past growth may be a reasonable predictor of future growth. We use observed GDP per capita data from the Penn World Table (version 9 "cgdpe"). We use both the average 1990-2014 and the average 2005-2014 annual growth rates.

Low income countries are likely to grow faster We find that the country-level income elasticities of emissions reported in the simulation section of the paper indeed tend to be positively correlated with growth rates: countries with higher country-level elasticities (generally low-income countries) are likely to grow faster on average than countries with low elasticities. This correlation is illustrated in Figure A.4, and holds both for the income elasticity of direct (left panel) and total (right panel) CO_2 content of consumption. It is true when using projected growth rates or 2005-2014 historical growth, but not when using 1990 to 2014 growth.

Effect on world emission elasticities We then re-calculate the world average income elasticity of emissions by weighing country-specific emissions elasticities (displayed in Figure 7 of the main text and denoted here by ω_n) by country-specific growth rates, $g_n = \frac{I'}{I} - 1$. To obtain a elasticity to world income, we also weigh the change in income (the denominator) by country-specific growth rates. This yields an approximate estimate of the response of world emissions to a 1% increase in world income that is heterogeneously distributed across countries:

$$\frac{\widehat{EC}_{world}}{\widehat{I}_{world}} = \frac{\sum_n EC_n \, g_n \, \omega_n}{\sum_n EC_n} \left[\frac{\sum_n I_n \, g_n}{\sum_n I_n} \right]^{-1}$$

and is computed for both direct (using EC^{dir}) and total (using EC^{tot}) consumption emissions.

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[53] https://data.oecd.org/gdp/real-gdp-forecast.htm

[54] http://www.worldbank.org/en/publication/global-economic-prospects

With homothetic preferences, our partial equilibrium approximations imply that each country's emissions increase exactly proportionally to country-specific growth in income (TFP), such that the world average income elasticity is given by:

$$\frac{\widehat{EC}_{world}}{\widehat{I}_{world}} = \frac{\sum_n EC_n\, g_n}{\sum_n EC_n} \left[\frac{\sum_n I_n\, g_n}{\sum_n I_n} \right]^{-1}$$

Table A.2 displays these elasticities of world (direct and total) consumption emissions to world income. The top row displays elasticities derived from CRIE preferences, the bottom row from NH CES quadratic preferences. With differential growth rates (either the historical observed or projected rates), it is important to recognize that world emissions would grow faster than world income even with homothetic preferences (i.e. with emissions that grow proportionally to income within each country) by a factor ranging from 1.279 to 1.597, depending on on which growth rates are assumed.

We therefore focus on the ratio of changes between non-homothetic and homothetic preferences. In case of uniform growth across countries, where the world elasticity is one with homothetic preferences, this ratio corresponds to the non-homothetic elasticity discussed in the main text (e.g. 0.884 for direct consumption emissions and CRIE preferences). This value can be compared with what is obtained with the three alternative sets of heterogeneous grow rates. In all cases, the elasticity of world emissions is higher with heterogeneous growth rates, though differences relative to homogeneous growth are small.

We conclude that heterogenous growth growth mitigates the non-homothetic consumption effect's impact on world emissions, but not significantly so, and not in a way which affects our paper's conclusions qualitatively.

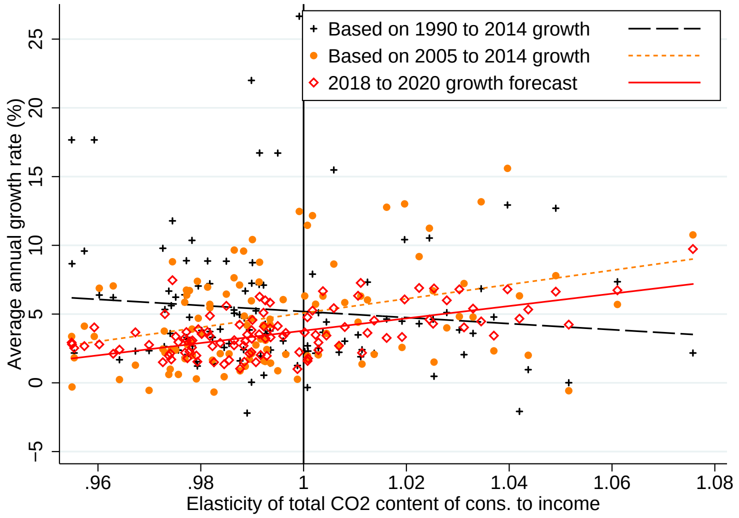


Figure A.4: Correlation between simulated general equilibrium income elasticity estimates and growth rates (historic and projected). Average total CO_2 content of consumption. Each dot represents a country.

Table A.2: Income elasticity of the CO_2 content of consumption - sensitivity to heterogeneous growth

Growth rates:	Uniform	1990-2014 observed	2005-2014 observed	2018-2020 projected	Uniform	1990-2014 observed	2005-2014 observed	2018-2020 projected
	Direct consumption emissions				Total consumption emissions			
CRIE								
Homothetic	1.000	1.691	1.808	1.341	1.000	1.537	1.597	1.279
Non-homothetic	0.884	1.515	1.623	1.199	0.981	1.515	1.577	1.259
ratio	0.884	0.896	0.898	0.894	0.981	0.986	0.987	0.984
NH CES quadratic								
Homothetic	1.000	1.822	1.911	1.355	1.000	1.596	1.655	1.295
Non-homothetic	0.817	1.623	1.702	1.171	0.965	1.559	1.620	1.261
ratio	0.817	0.891	0.891	0.865	0.965	0.977	0.979	0.974

A.7 Additional tables and figures

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-R^2 equal the square of the correlation coefficient between fitted and observed trade flows, including or excluding domestic flows.

Table A.4: 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

Notes: R2, AIC and BIC are weighted by average sector size. The estimation covers 49 sectors. We drop Dwellings (no price proxies because non-tradable) and 6 intermediate good sectors which have zero or negligible shares of output going to final demand (pdr, oil, omn, nmm, i_s, nfm).

Table A.5: Relationship between income elasticity estimates (CRIE) 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 on income elasticity and its square; p-values correspond to F-tests of joint significance of the coefficients; regressions weighted by average share of final demand.

Table A.6: 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.7: Countries in the dataset, with per capita income and average CO_2 content of consumption.

Code	Country	Income/cap	CO_2 content of consumption, kg/$		Code	Country	Income/cap	CO_2 content of consumption, kg/$	
		(2007 USD)	Direct	Total			(2007 USD)	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.8: Decomposing the income elasticity of the CO_2 intensity of consumption - CRIE

	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

Notes: Estimates based on partial equilibrium approximations. 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).

Table A.9: Decomposing the income elasticity of the CO_2 intensity of consumption - NH CES QUADRATIC

	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	0.001	0.002	0.002	0.001	0.002	0.004	0.003
Refined oil	0.031	-0.023	-0.027	-0.028	-0.033	-0.014	-0.033	-0.033	-0.033
Electricity	0.006	-0.015	-0.034	-0.041	-0.056	0.015	-0.016	-0.038	-0.027
Total energy goods	0.037	-0.037	-0.060	-0.068	-0.087	0.003	-0.047	-0.068	-0.057
Manufacturing	0.081	-0.020	-0.057	-0.038	-0.052	0.031	-0.014	-0.042	-0.027
Services	0.033	0.025	0.032	0.027	0.021	0.033	0.024	0.030	0.027
Transportation	0.022	-0.004	-0.009	-0.020	-0.010	0.003	-0.007	-0.017	-0.012
Agriculture	-0.043	-0.018	-0.006	-0.013	-0.017	-0.048	-0.022	-0.013	-0.018
Total non-energy goods	0.092	-0.017	-0.040	-0.044	-0.057	0.018	-0.019	-0.043	-0.030
Total	0.129	-0.053	-0.100	-0.112	-0.144	0.020	-0.066	-0.111	-0.087

Notes: Estimates based on partial equilibrium approximations. 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).

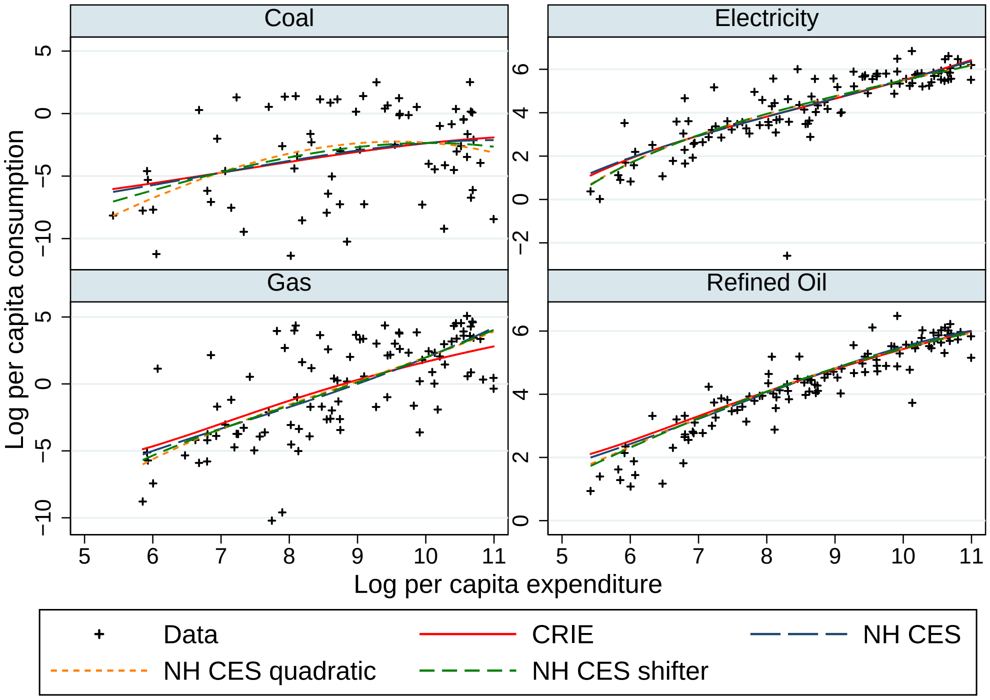


Figure A.5: Observed and fitted consumption against log per capita income - across demand specifications.

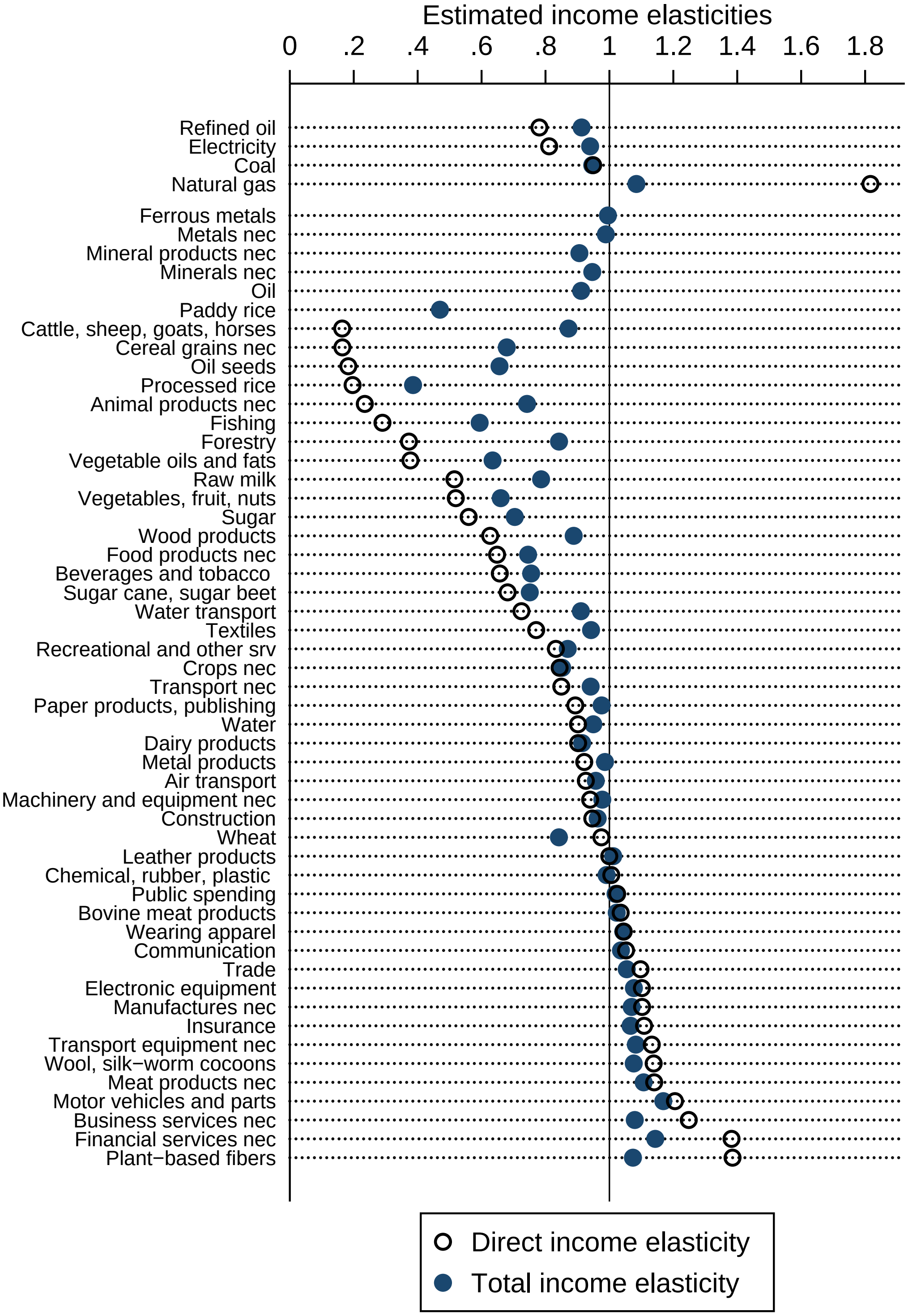
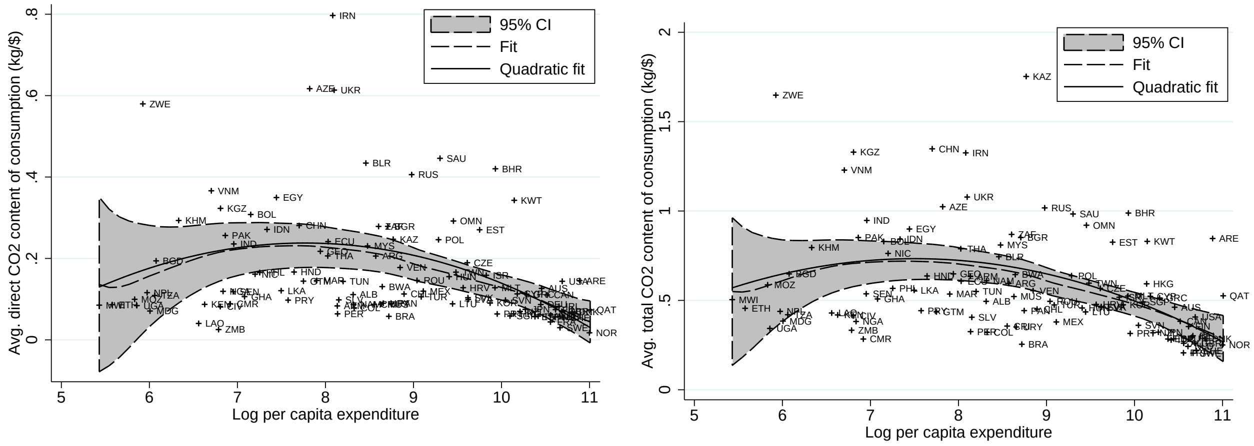
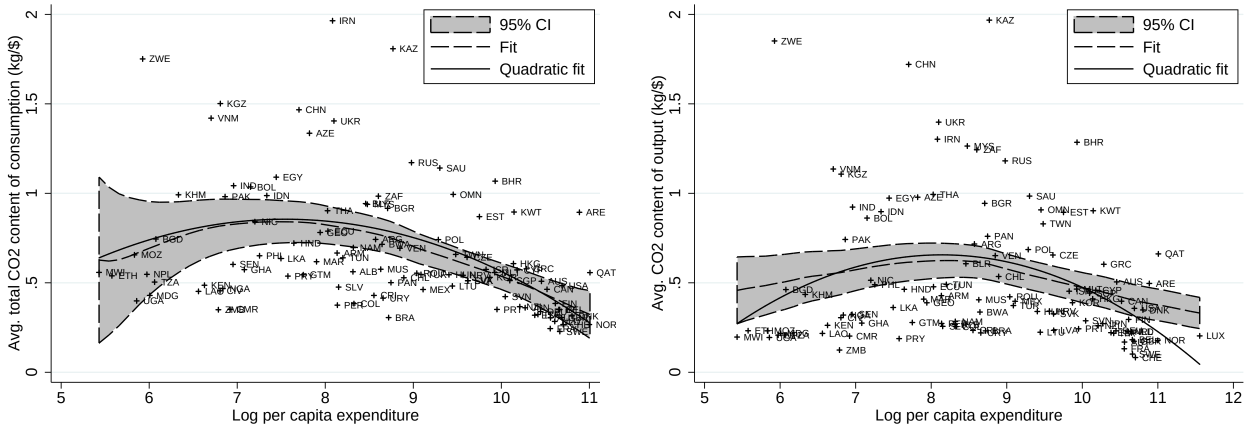


Figure A.6: Direct versus total income elasticities (CRIE preferences). Income elasticities evaluated at mean expenditure shares.



(a) Direct CO$_2$ content of consumption. Includes CO_2 caused by electricity production.

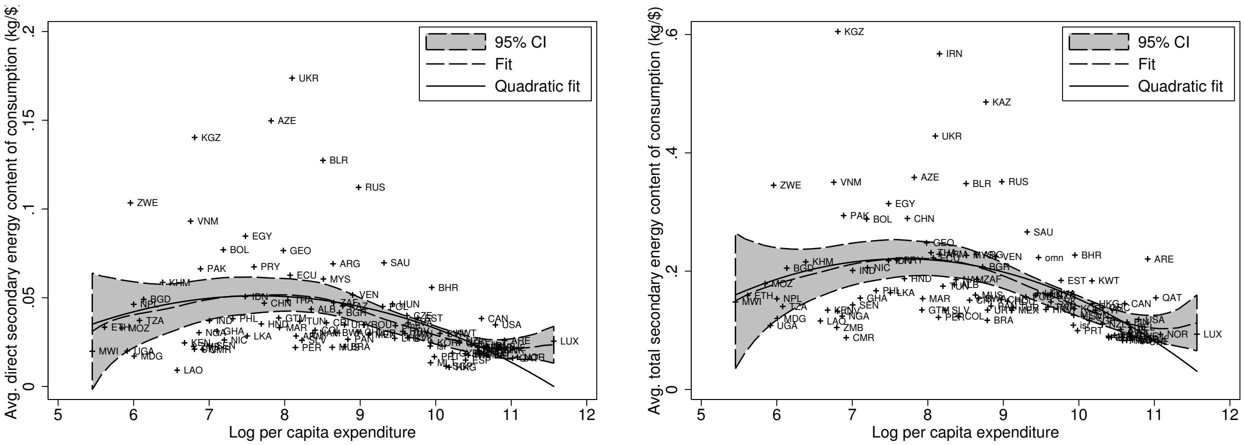
(b) Indirect CO$_2$ content of consumption



(c) Total CO$_2$ content of consumption

(d) Total CO$_2$ content of production

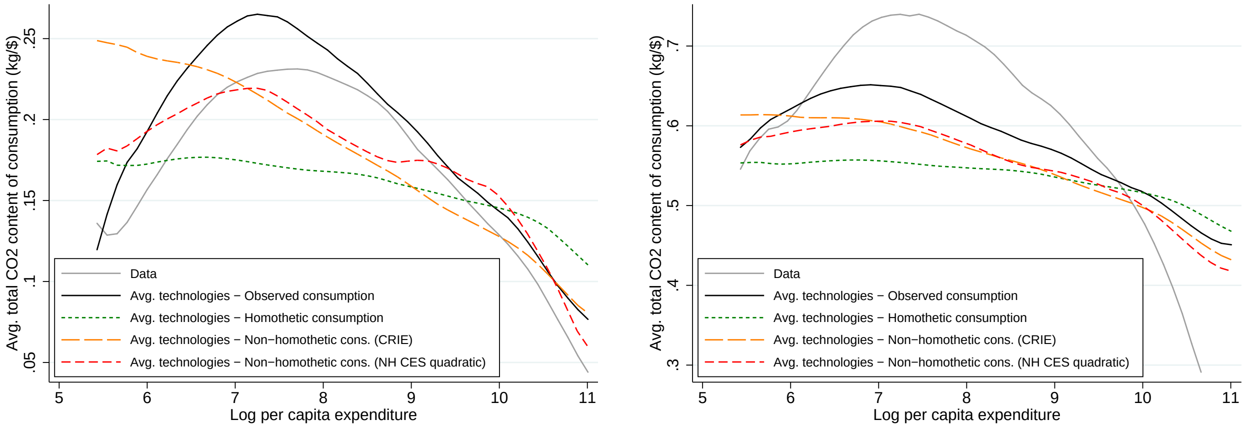
Figure A.7: Average CO_2 content in the data (in kg/$) against per capita income.



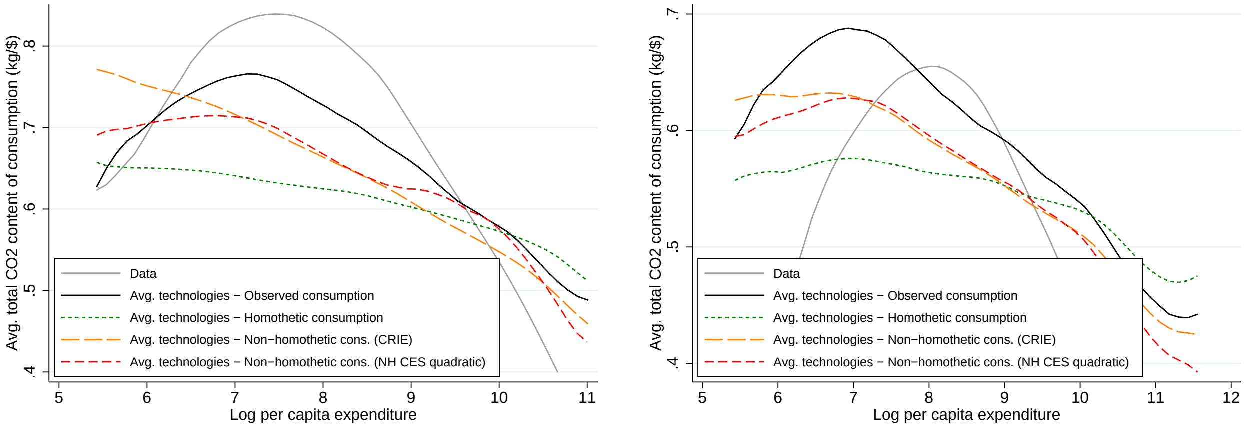
(a) Direct energy content of consumption

(b) Total energy content of consumption

Figure A.8: Average CO_2 content in the data (in kg oil equivalents/\$) against per capita income.



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



(c) Avg. total CO_2 content of consumption (d) Avg. total CO_2 content of production

Figure A.9: Average CO_2 content against per capita income. Smoothed across countries using local linear regression.

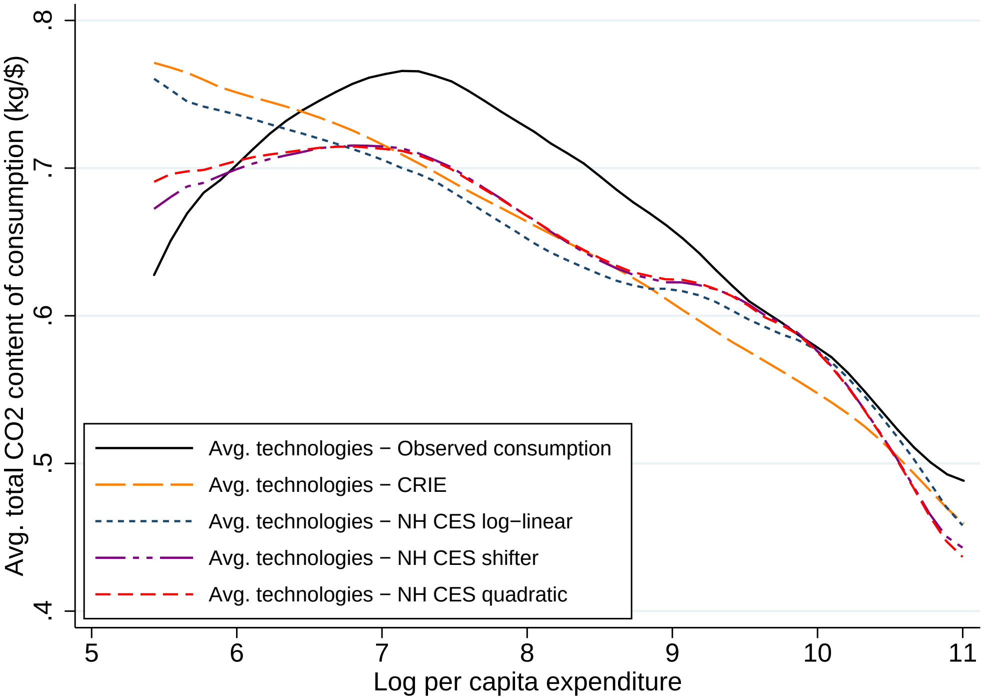
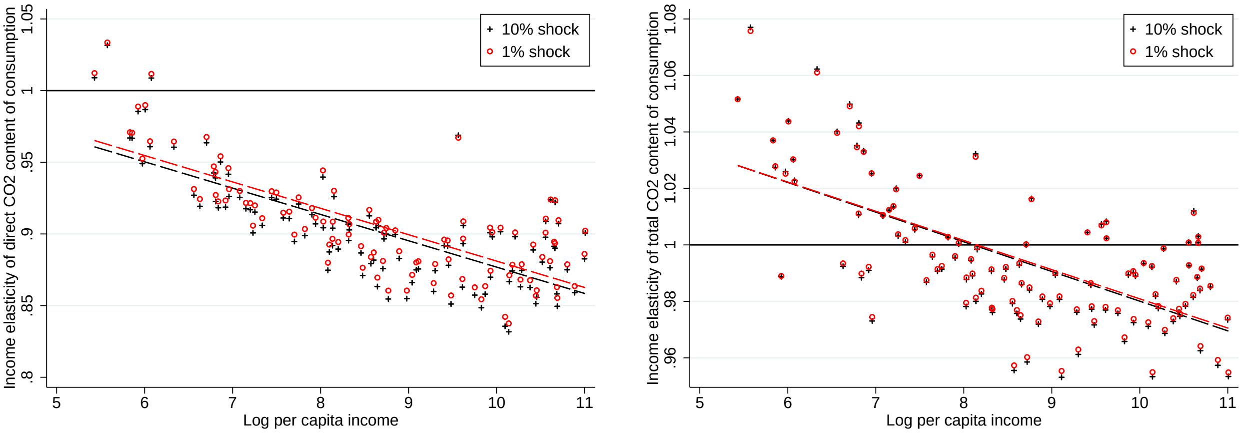
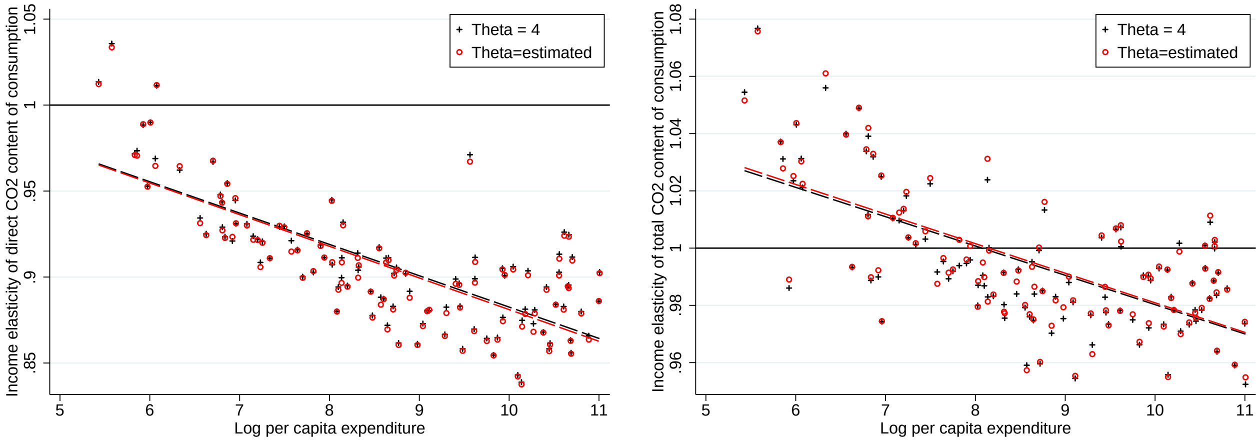


Figure A.10: Average total CO_2 content as a function of per capita total expenditures (local linear regression smoothing). Comparison between CRIE and NH CES specifications.



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

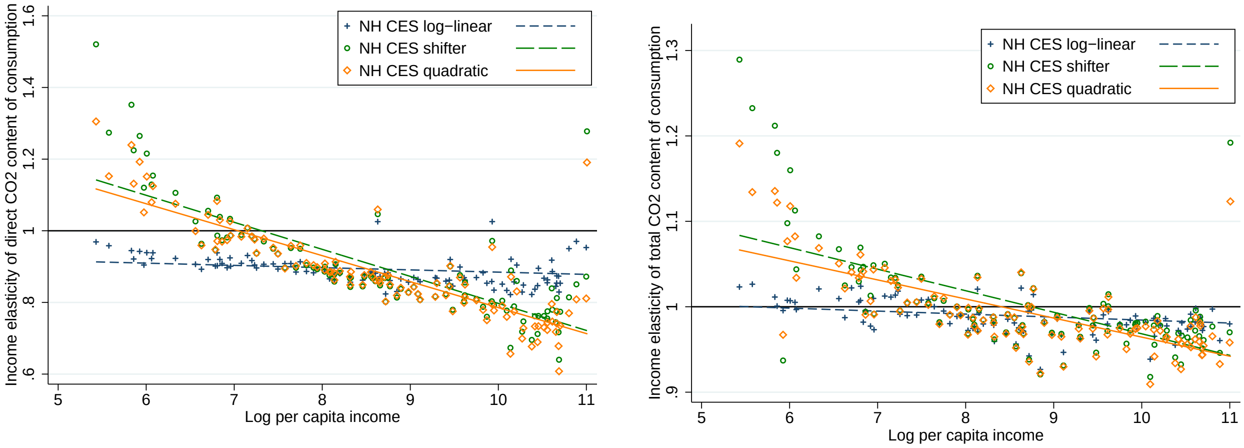
Figure A.11: Simulated elasticity of the total CO_2 content of consumption to per capita income. Comparing 1% and 10% simulated increases in TFP. CRIE preferences.



(a) Avg. direct CO_2 content of consumption

(b) Avg. total CO_2 content of consumption

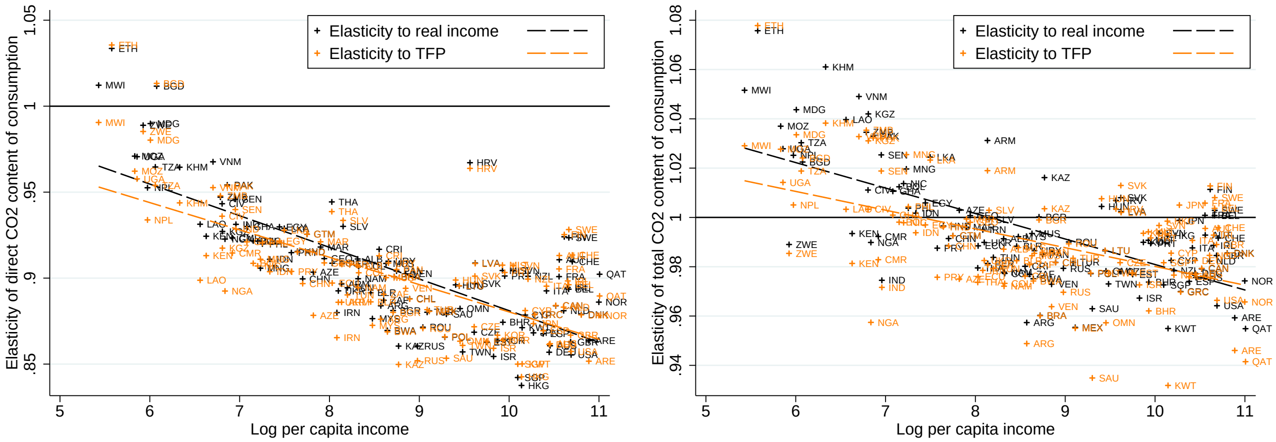
Figure A.12: Simulated elasticity of the total CO_2 content of consumption to per capita income. Sensitivity to the θ_k parameter describing the elasticity of trade to trade costs. Theta = 4: $\theta_k = 4$ for all sectors; Theta = estimated: estimated values of θ_k, rescaled such that their average = 4 (these are the benchmark values used in the rest of the paper). CRIE preferences.



(a) Avg. direct CO_2 content of consumption (includes electricity).

(b) Avg. total CO_2 content of consumption

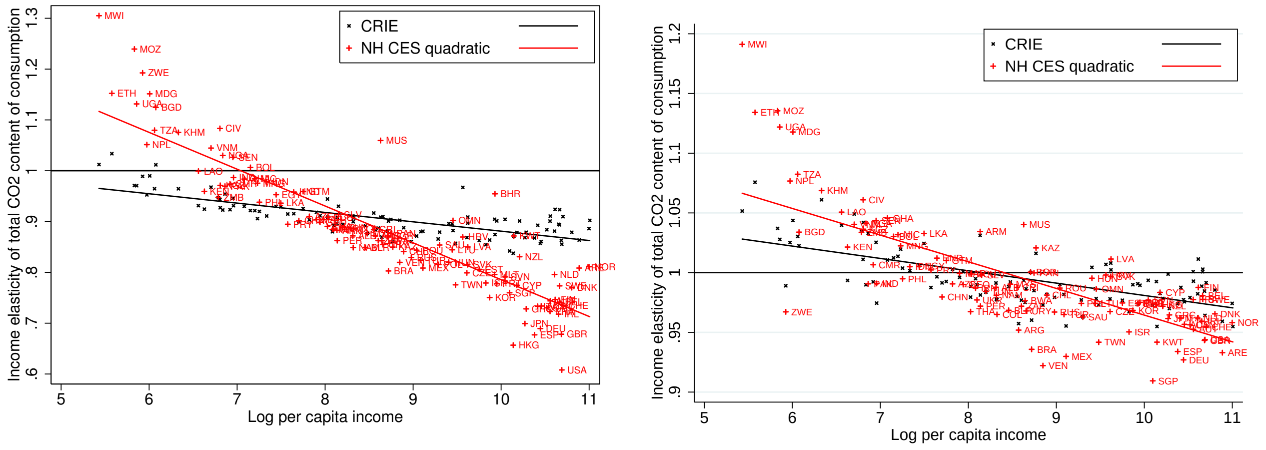
Figure A.13: Simulated elasticity of the total CO_2 content of consumption to per capita income. Comparison to alternative specifications of NH CES preferences.



(a) Avg. direct CO_2 content of consumption

(b) Avg. total CO_2 content of consumption

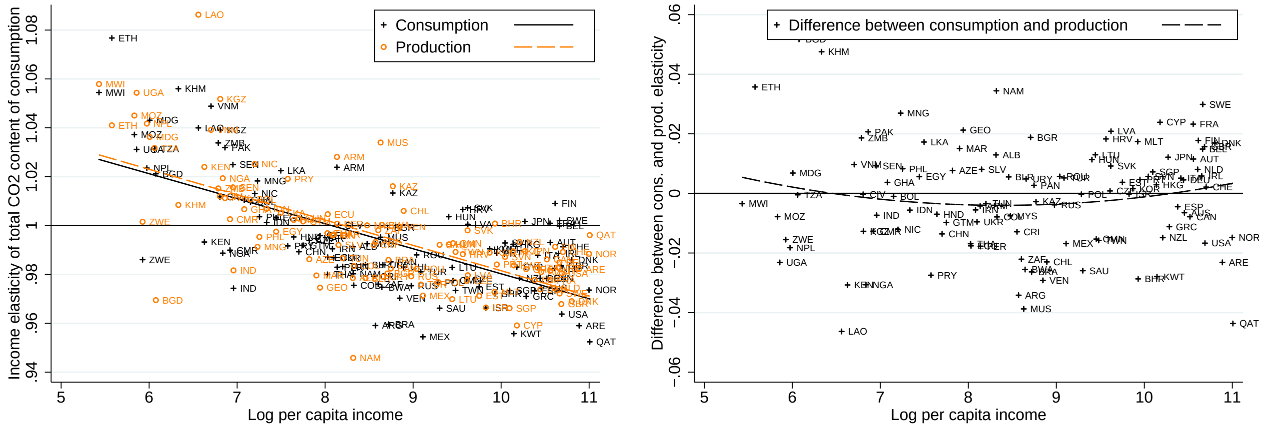
Figure A.14: Emissions elasticity to (real) income compared to elasticity to TFP. CRIE preferences.



(a) Avg. direct CO_2 content of consumption (includes electricity).

(b) Avg. total CO_2 content of consumption

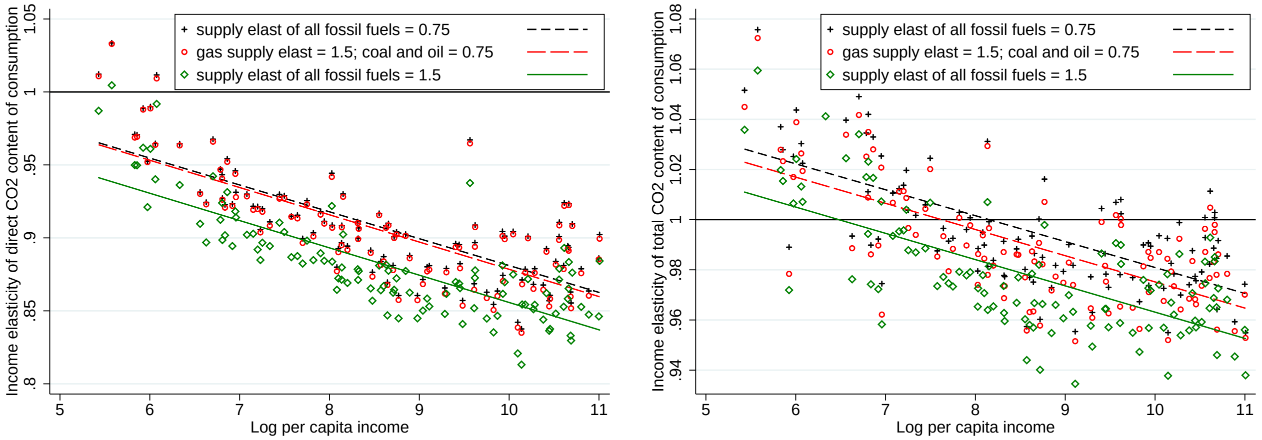
Figure A.15: Simulated elasticity of the total CO_2 content of consumption to per capita income. Comparison of direct and total CO_2 consumption.



(a) Consumption vs. production

(b) Difference between cons. and prod.

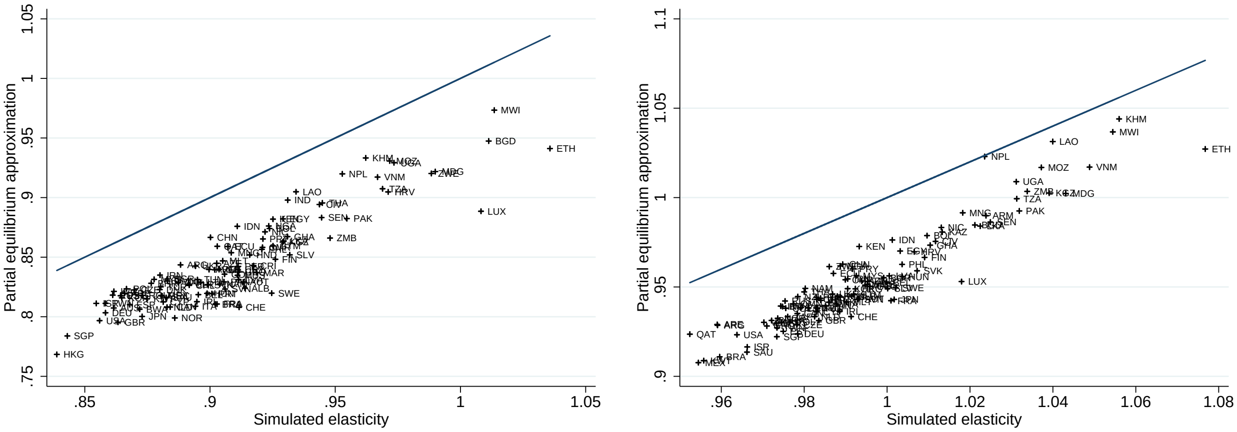
Figure A.16: Simulated elasticity of CO_2 contents to per capita income. Comparison of production and consumption emissions. CRIE preferences.



(a) Avg. direct CO_2 content of consumption

(b) Avg. total CO_2 content of consumption

Figure A.17: Simulated elasticity of the total CO_2 content of consumption to per capita income. Sensitivity to fossil fuel supply elasticity. CRIE preferences.



(a) Avg. direct CO_2 content of consumption

(b) Avg. total CO_2 content of consumption

Figure A.18: Approximated versus simulated income elasticity of the CO_2 content of consumption. CRIE preferences. The supply elasticity is calibrated at 0.75 in the general equilibrium simulations, so the approximated partial equilirbium estimates are further from unity, as they are computed assuming infinite supply elasticity ($\zeta = \infty$) to isolate the effect of shifting consumption patterns.