

The supply chain of CO₂ emissions

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CO₂ emissions from the burning of fossil fuels are conventionally attributed to the country where the emissions are produced (i.e., where the fuels are burned). However, these production-based accounts represent a single point in the value chain of fossil fuels, which may have been extracted elsewhere and may be used to provide goods or services to consumers elsewhere. We present a consistent set of carbon inventories that spans the full supply chain of global CO₂ emissions, finding that 10.2 billion tons CO₂ or 37% of global emissions are from fossil fuels traded internationally and an additional 6.4 billion tons CO₂ or 23% of global emissions are embodied in traded goods. Our results reveal vulnerabilities and benefits related to current patterns of energy use that are relevant to climate and energy policy. In particular, if a consistent and unavoidable price were imposed on CO₂ emissions somewhere along the supply chain, then all of the parties along the supply chain would seek to impose that price to generate revenue from taxes collected or permits sold. The geographical concentration of carbon-based fuels and relatively small number of parties involved in extracting and refining those fuels suggest that regulation at the wellhead, mine mouth, or refinery might minimize transaction costs as well as opportunities for leakage.

carbon intensity of economy | emissions embodied in trade | emissions from traded fuels | international incidence of carbon price

Anthropogenic climate change is driven by CO₂ emissions from the burning of fossil fuels (1, 2), which are generally attributed to the country where the emissions are produced (i.e., where the fuels are burned) (3). However, these production-based accounts differ substantially and increasingly from consumption-based accounts of where goods associated with emissions are ultimately consumed, primarily because of exports from China and other emerging markets to consumers in developed countries (4–8). In addition, fossil fuel resources are more geographically concentrated than energy demand, and therefore, fuels burned to generate energy have, in many cases, been extracted far from the point of combustion and resulting CO₂ emissions (9). As a result, goods and services consumed in one country are commonly produced in another country using fossil fuels extracted in a third country. Understanding the distribution of interests along this supply chain may facilitate international efforts to limit CO₂ emissions from the burning of fossil fuels. The distribution of emissions along the supply chain also has important implications for the international incidence of the economic burden of a given climate policy. Given these implications, we present results from a model that tracks global CO₂ emissions from the source of extracted fossil fuels through the production of emissions during combustion of those fuels to the consumption of goods and services related to those emissions to generate a consistent set of accounts that span the global supply chain of CO₂ emissions. Thus, for every category of goods and services consumed in a country, our results indicate the source and type of fossil fuel that these products required as well as where the fuels were burned and the quantity of associated emissions.

Details of our analytic approach and the underlying data are described in *Materials and Methods*. In summary, the analysis is based on fossil energy resources of coal, oil, natural gas, and secondary fuels traded among 57 industrial sectors and 112

countries in 2004 (10). We use the term countries to describe the spatial disaggregation of this data, although in some cases, we intend collections of related countries. CO₂ emissions produced in each country (production emissions) are calculated using country-, sector-, and fuel-specific data of CO₂ emissions per unit of energy. Using trade data, these emissions are traced back to the point of extraction, even if the extracted fuels were processed in and reexported from an intermediate country (extraction emissions). The forward link from production emissions to where goods are consumed (consumption emissions) is based on a global multiregional model that ties sector-level economic data with trade data (4).

The difference between production emissions (F_{Pr}) and extraction emissions (F_{Er}) represents the net difference in emissions related to traded fuels ($F_{Pr} - F_{Er}$) and therefore, equals emissions from imported fuels less emissions from exported fuels. Emissions from burning of traded fuels are distinct from emissions embodied in traded goods, which are the emissions produced during manufacture of the goods. The net of emissions embodied in trade represents the difference between production emissions and consumption emissions ($F_{Pr} - F_{Cr}$). By combining emissions related to trade in fuels and goods, it is possible to examine the difference between extraction emissions (F_{Er}) and consumption emissions (F_{Cr}) and follow the supply chain of emissions from where fuels are extracted to where dependent goods or services are ultimately consumed.

Results

Fig. 1 highlights the largest net exporters (blue) and importers (red) of emissions related to traded fuels (Fig. 1 *Top*), emissions embodied in consumer goods (Fig. 1 *Middle*), and the two combined (Fig. 1 *Bottom*). Exports of fossil resources are highly concentrated; of the 10.2 billion tons (Gt) CO₂ from traded fuels, the 11 largest fuel exporters make up 7.8 Gt (77%) of these emissions, primarily destined for combustion in developed countries and large developing economies. The Middle East region, the European Union, the United States, Russia, China, and Japan together account for 59% of the total difference between regional extraction and production emissions ($F_{Er} - F_{Pr}$) (Fig. 1 *Top*) and 64% of the total difference between regional extraction and consumption emissions ($F_{Er} - F_{Cr}$) (Fig. 1 *Bottom*). In most countries, either imported fuels represent a substantial proportion (>25%) of F_{Pr} or exported fuels are a similarly large proportion of F_{Er} . In almost all cases, the emissions related to traded fuels and embodied in traded goods are aligned, such that combining the two (Fig. 1 *Bottom*) reinforces the trade imbalance.

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Fuels imported to the European Union derive primarily from Russia, Norway, and North Africa. Fuels imported to the United States are more commonly sourced from Canada, Venezuela, and Mexico. Japan imports large amounts of coal from Australia. However, the most developed countries all import oil from the Middle East. Fuels exported from the Middle East alone were associated with 2.3 Gt CO₂ emissions produced in other countries, representing 8.3% of global emissions.

Fig. 2 depicts the supply chain of selected countries at different points. Fig. 2 *Left* shows the original source of fuels burned in the countries, Fig. 2 *Center* reveals where the goods and services consumed in the countries are actually produced (i.e., where the required fuels are burned), and Fig. 2 *Right* shows the original sources of fuels that are required to produce all of the goods and services consumed in the countries. The countries in Fig. 2 include the largest extractor of fuels (China), the largest producer of emissions (United States), the largest consumer of embodied emissions (United States), and the four countries with the largest trade in emissions (United States, the Middle East, Japan, and Germany).

Fig. 3 shows the balance of gross trade in emissions from extraction of fuels to consumption of goods and services, such that exports and imports represent combined emissions from traded fuels and embodied in goods and services.

Unlike consumption-based accounts, the size of a country's economy is decoupled from its extraction-based emissions, which instead, depend on the fossil resources available and the extent to which those resources have been exploited. In affluent but resource-poor countries of Asia and Western Europe, emissions from net import of fuels are 55–99% of production emissions (Fig. 4 *Left*), with the proportion decreasing to 30% (1.9 Gt CO₂) in the United States and further still to 7% (0.4 Gt CO₂) and 4% (0.2 Gt CO₂) in the United Kingdom and China, respectively. With the exception of emerging economies like China, Brazil, and India, even larger proportions of consumption emissions are made up of combined net imports of fuels and goods (Fig. 4 *Center*). These percentages are an indicator of energy security, reflecting the extent to which these countries depend on foreign sources of fossil fuels. In contrast, net export of fuels from countries with abundant fossil resources is 57–92% extraction emissions (Fig. 4 *Right*).

Assessing the carbon intensity of gross domestic product (GDP) in terms of extraction (F_{Er}/G_r) also reveals economies reliant on domestic fossil resources: former Soviet republics, North Africa, Nigeria, southeast Asia, and the Middle East. In these countries, energy consumed per unit GDP (energy intensity of GDP or E_r/G_r) is high, because extracted fuels are often either exported raw or used domestically by heavy industry and manufacturing sectors that are recovering or still developing (Fig. S1 *Center*, row 3). Similarly, normalizing the difference between extraction emissions (F_{Er}) and production emissions (F_{Pr}) by GDP (G_r) highlights those economies most dependent on trade in fossil fuels. Again, net exporters of extracted fuels are often developing or recovering economies (e.g., Russia, former Soviet states, the Middle East, and areas of Africa and South America). However, net exports of emissions are also large relative to GDP in some wealthy but smaller economies where fossil energy resources are especially plentiful (e.g., Norway). Net imports of emissions are largest relative to GDP in several Eastern European countries (e.g., Ukraine, Belarus, Bulgaria, and Armenia) with recovering, industrial economies and few domestic resources (Figs. S1 *Center*, row 1 and S2 *Lower*).

Discussion

Our results are relevant to both crafting of new climate policies and ex post evaluations of enacted policies. Carbon pricing mechanisms intended to regulate emissions may be imposed at any point in the supply chain of emissions. The economic burden of such regulation will ultimately be distributed among producers

and consumers according to the relative price elasticities of supply and demand—regardless of where taxes are remitted or permits are required (11, 12), but the overall efficiency of the policy may depend on the point of regulation and the countries and sectors implementing the pricing mechanism (13).

For instance, transaction costs might be greatly reduced by regulating carbon at the point of extraction, because there are far fewer parties extracting fossil fuels than there are either burning the fuels or consuming goods and services derived from fossil energy (14, 15). Furthermore, fossil fuel resources are sufficiently concentrated such that, if the relatively few countries that extract the most fuels imposed a price on carbon at the point of extraction, the economic burden of that regulation would be shared among all of the beneficiaries of those fuels, with very little opportunity for carbon leakage (13, 16). Manufacture of goods may shift from one country to another, but fossil resources are geographically fixed. Regulating the fossil fuels extracted in China, the United States, the Middle East (a region comprised of 13 countries in our analysis), Russia, Canada, Australia, India, and Norway would cover 67% of global CO₂ emissions.

Although there might seem to be few incentives for countries to impose a price on the carbon in their own fossil fuels for the explicit purpose of reducing consumption, the incidence of a price on carbon imposed elsewhere along the supply chain could create strong incentives. For example, if the only alternative to regulation at the point of extraction was regulation farther downstream (e.g., carbon-linked tariffs) (<http://krugman.blogs.nytimes.com/2009/06/29/climate-trade-obama/>), extracting countries might lose not just the value of their fossil resources but also the revenues that could be generated from taxes collected or permits sold (17). Indeed, at least one study has concluded that substantial reductions in emissions could be realized with near term gains in the GDP of oil-producing countries in the Middle East (18). Emissions instead regulated at the point of import, combustion, or consumption of goods would generate revenues in the country where the fuels are burned or goods are consumed. This difference is small in countries like the United States and China, which burn most of the fuels that they extract, but the present value of such revenue could be important for countries with less diverse economies where fuels are mostly exported (e.g., in the Middle East) (14).

Parties that extract fossil fuels, parties that burn the fuels to produce goods and services, and parties that consume those goods and services all benefit in some way from the current fossil fuel-driven economy, just as they are all vulnerable in some way to the climate change that results. Understanding how to resolve this dilemma is likely to depend on fully understanding the interests that all these parties have both in maintaining current patterns of energy use and effectively transitioning to new patterns of energy use.

Materials and Methods

Sources of Data. Data on international trade, economic input–output by sector, GDP, population, energy use, and combustion-based CO₂ emissions of each region sector are all taken from Version 7.1 of the Global Trade Analysis Project (GTAP), which compiles the primary data from voluntary contributions of each region and harmonizes them to remove conflicts and inconsistencies (10). Population data (P_r in Table S1) are derived from the World Bank and the Central Intelligence Agency (CIA) World Factbook by the GTAP. CO₂ emissions (F_{Pr}) from each region sector were calculated according to fossil fuel inputs using the method described in the work by Lee (19), which uses standard assumptions for carbon content and the fraction of carbon oxidized during combustion of the different fuels as well as sector-specific ratios of fuels combusted and used as feedstocks. Emissions from the oxidation of nonfuel hydrocarbons (e.g., feedstocks to the chemical industry) and non-CO₂ greenhouse gases are omitted from the analysis. Total global CO₂ emissions estimated by this method represent 103% and 101% of the total reported by the Carbon Dioxide Information Analysis Center (CDIAC) and Energy Information Administration (EIA), respectively, in 2004 (20, 21).

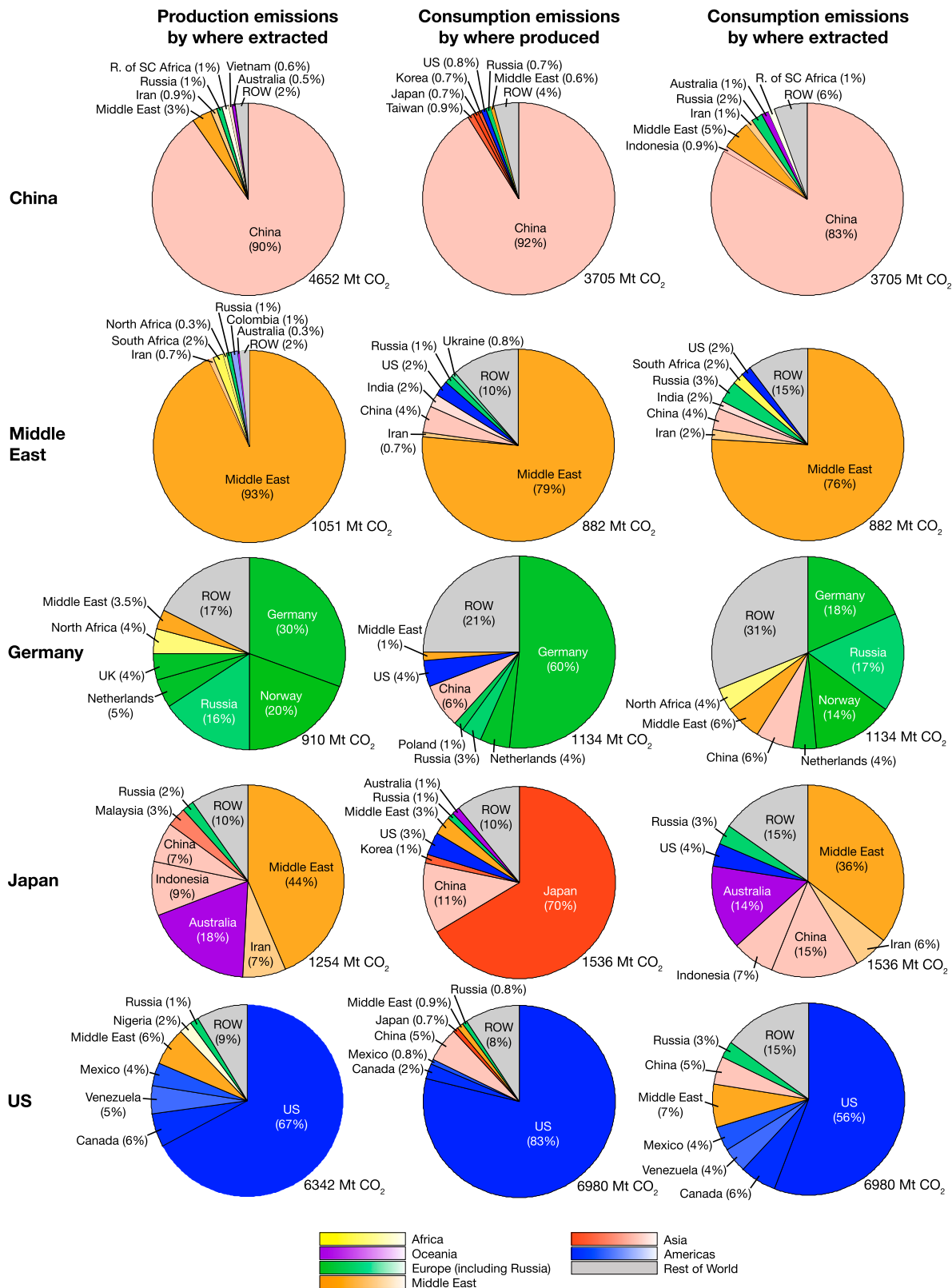


Fig. 2. Geographical sources of CO₂ emissions for selected countries. For CO₂ emissions produced by burning fossil fuels in the country/region, the pies in *Left* show where the burned fuels were extracted. For all goods and services consumed in the country/region, the pies in *Center* show where fossil fuels were burned to produce the goods and services, and the pies in *Right* show where the fuels required to produce those goods and services were extracted. Source countries are colored according to world region and shaded according to GDP per capita from the most affluent countries in the darkest shades to the least developed countries in the lightest shades. Each pie shows the top seven sources; rest of world (ROW) includes all other sources. The Middle East region aggregates Bahrain, Iraq, Israel, Jordan, Kuwait, Lebanon, Occupied Palestinian Territory, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, the United Arab Emirates, and Yemen. The rest of South Central Africa (R. of SC Africa) region aggregates Angola and the Democratic Republic of the Congo. The North Africa region aggregates Algeria and Libya.

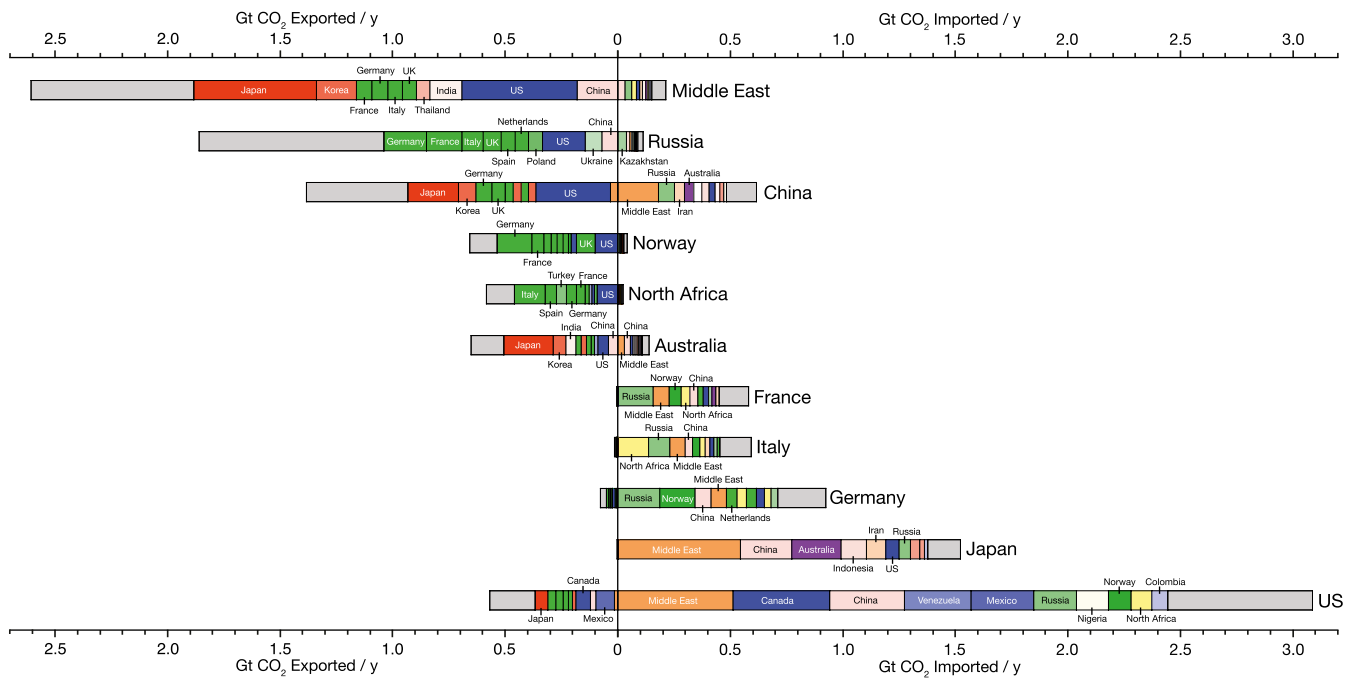


Fig. 3. Bars show the trade balance of CO₂ emissions in selected countries/regions between points of fossil fuel extraction and the final consumption of goods and services. Exports and imports shown represent a combination of emissions from traded fuels and emissions embodied in goods and services. Exports are emissions from fuels extracted in each country to make goods consumed elsewhere, and imports are emissions from fuels extracted elsewhere to make goods consumed in the country (or fuels that are burned directly by consumers in the country). As in Fig. 2, stacked bars of destination and source countries are colored according to world region and shaded according to deciles of GDP per capita. Fig. S3 shows the same balance of CO₂ emissions in trade but according to the industry sectors that consume the extracted fuels. Fig. 2 and SI Text have definitions of regions.

The production- and consumption-based emissions in Table S1 and Dataset S1 and flows of emissions embodied in trade in Fig. 1 differ slightly from the results of Davis and Caldeira (4) because of the updated version of the GTAP dataset used in this study. Also, F_{Pr} in the present study has not been scaled to match external data sources. Discussion of uncertainty is included in SI Text.

Extraction-Based Accounting. The analysis of extraction emissions is based on GTAP data of energy consumed and trade in each region by fuel type. The data includes both primary fuels (coal, crude oil, and gas) as well as secondary fuels (petroleum/coal products and electricity). We first derive production emissions (F_{Pr}) for each country sector according to energy use, fuel-specific carbon emission factors, and country- and sector-specific feedstock ratios (20). We then reallocate emissions from the combustion of all traded fuels back to where the fuels were extracted (F_{Er}) (Eqs. 1–3):

$$F_{Pr} = F_{Erd} + F_{Erm}, \quad [1]$$

$$F_{Er} = F_{Erd} + F_{ErX}, \text{ and} \quad [2]$$

$$F_{Er} = F_{Pr} + F_{ErX} - F_{Erm}, \quad [3]$$

where F_{Erd} is emissions contained in fuels extracted and combusted in country r , F_{ErX} is emissions contained in fuels that are extracted in country r and exported for combustion in another country, and F_{Erm} is emissions contained in fuels that are extracted in another country and imported for combustion in country r . Although not explicitly shown here, Eqs. 1–3 are performed for each fuel type, and the traded components of Eqs. 1–3 are bilateral. For example, exports from region r include trade to all other regions s (Eq. 4):

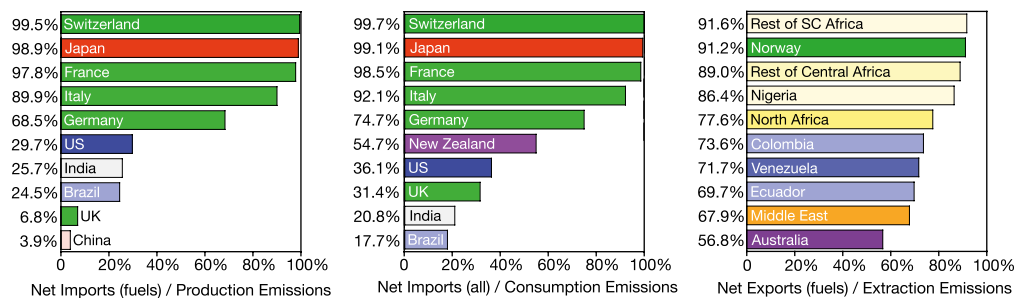


Fig. 4. Net trade of CO₂ emissions as a fraction of total regional emissions for selected countries. Panels show emissions from net imports of fossil fuels as a fraction of all emissions produced in the country (Left), net import of emissions both embodied in goods and services from traded fuels as a fraction of consumption emissions (i.e., the emissions related to goods and services consumed in the country; Center), and emissions from net export of fossil fuels as a fraction of extraction emissions (i.e., the emissions from burning of all fuels extracted in the country; Right). Bars are colored according to world region and shaded according to deciles of GDP per capita from the most affluent countries in the darkest shades to the least developed countries in the lightest shades (Fig. 2). The rest of Central Africa region aggregates the Central African Republic, Cameroon, Congo, Gabon, Equatorial Guinea, Sao Tome and Principe, and Chad. Fig. 2 and SI Text have definitions of regions.

$$F_{Erx} = \sum_s F_{Ers} \quad [4]$$

These calculations assume that primary fuels (i.e., coal, oil, and gas) that are imported and burned in a country were shipped directly from the country that extracted the fuels and not through another country. We believe this assumption is reasonable, because we know that these primary fuels undergo little or no refinement between extraction and combustion. However, our model distinguishes secondary fuels (e.g., diesel, gasoline, electricity, etc.), which frequently consist of primary fuels extracted in one country, refined or converted in a second country, and combusted or consumed in a third country. In the case of these secondary fuels, emissions are assigned to the source (i.e., feedstock) primary fuels as follows. Secondary fuels combusted in country r are refined in country r from primary fuels extracted in country r (Eq. 5),

$$F_{Erd}^s = F_{pr}^s \times (1 - P_{rm}^s) \times (1 - P_{rm}^p), \quad [5]$$

where F_{pr}^s is emissions from combustion of secondary fuels in country r , P_{rm}^s is the proportion of secondary fuels combusted in country r that is imported, and P_{rm}^p is the proportion of primary fuels combusted in country r that is imported. Secondary fuels exported from country r are refined in country r from primary fuels extracted in country r (Eq. 6),

$$F_{Erx}^s = F_{rx}^s \times (1 - P_{rm}^p), \quad [6]$$

where F_{rx}^s is emissions contained in all secondary fuels exported from country r . Secondary fuels exported from country r are produced in country r from primary fuels extracted in country q (Eq. 7),

$$F_{Eqx}^s = F_{rx}^s \times P_{rm}^p \times P_{r-q}^{p-s}, \quad [7]$$

where P_{r-q}^{p-s} is the proportion of primary fuels imported for the production of secondary fuels in country r that originate in country q . Last, secondary fuels combusted in country r are produced in country r from primary fuels extracted in country q (Eq. 8),

$$F_{Eqx}^s = F_{pr}^s \times P_{rm}^p \times P_{r-q}^{p-s}. \quad [8]$$

In each equation of Eqs. 5–8, emissions from secondary fuels are partitioned between primary inputs of coal and oil according to the ratio of each consumed during production of secondary fuels in country r .

Multiregional Input–Output Model. The multiregional input–output model used to calculate consumption-based accounts for each region (F_{Cr}) is identical to the model used by Davis and Caldeira (4), but the underlying data in this study have been updated from GTAP Version 7 to Version 7.1. The multiregional input–output model traces all emissions associated with consumed goods back to the original source that produced the emissions, even if products were transhipped through other countries/regions or were intermediate constituents in a multiregional supply chain. For example, it is not uncommon for an imported product to embody carbon emissions that were produced in the importing region itself. Our calculations take these complex relations into account. Additional details are in *SI Text*.

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