The CO_2 Content of Consumption across US Regions: A Multi-Regional Input-Output (MRIO) Approach

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Abstract

We improve on existing estimates of the carbon dioxide (CO_2) content of consumption across regions of the United States. Using a multi-regional input-output framework which tracks both interstate and international trade, we estimate the direct and indirect CO_2 emissions attributable to domestically and internationally imported goods. We find that on average indirect emissions embodied in non-energy consumption goods and services account for 55% of total consumption-related emissions.

In contrast to previous analyses using an input-output approach to track emissions from production to consumption, we find substantial heterogeneity in the indirect CO_2 intensity of consumption across regions. Importantly, this heterogeneity is quantitatively similar to the more easily observable heterogeneity in the CO_2 emissions attributable to direct fossil fuel and electricity consumption.

These findings have important implications for the regional distributional impacts of a national climate policy as well as for understanding differing incentives to implement state-level or regional policies.

Keywords: CO_2 content of consumption; CO_2 accounting; multi-regional input-output
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I. Introduction

An extensive literature attempts to trace the full effect of consumption of particular products or patterns of consumption on carbon dioxide (CO_2) emissions throughout the economy. The motivation for these studies ranges from attributing responsibility for emissions, to guiding producers, consumers, or public policy to favor products and processes with lower emissions, to understanding how emissions pricing might affect households with different consumption patterns. One strand of the literature relies on an engineering-based life-cycle approach that identifies emissions related to a particular production process, and emissions related to the production of inputs into the production process, and so forth, with the goal of identifying all of the emissions associated with a product through its full life cycle (e.g. ISO, 2006; Liamsanguan and Gheewala, 2009: US EPA, 2010a, b; Jones and Kammen, 2011). Engineering-based analysis typically stops somewhere along the production chain: Counting the direct emissions used to produce chemicals used to produce the product of interest, but maybe not the emissions associated with building the plant that produced the chemical, or the emissions related to the cement that was used to build the plant that produced the chemicals. A second common approach relies on input-output (I-O) tables which describe the entire production chain. Linear algebra manipulation of the matrix structure of I-O tables is ideally suited to attributing emissions throughout the economy to individual consumption goods.[1]

While these two approaches are similar in some respects and at some levels have the same general goal, in application they generally have different purposes. Engineering life-cycle analysis is best suited to answering the question of which product to buy or which production process to use. Is cola A less CO_2 intensive than cola B, or fuel produced using process X better than that using process Y. These calculations thus answer the question, if I as a producer of some good want to reduce my emissions, which supplier of inputs should I go with or what production process should I use. The I-O approach is difficult to resolve at the level of different brands of the same product or different processes used to produce what otherwise is a homogeneous product because of the aggregation in I-O tables. It is better suited to indicate the full CO_2 implications of the patterns of consumption of different regions or large groups of consumers, such as, for example, different income classes. As such it can potentially be used to understand whether, for example, per capita emissions in California are low because Californians consume different products or products produced differently than, for example, Texans. Or whether they are low because the emissions-intensive activities related to their consumption patterns are embodied in goods imported into the state. In that case, the full emissions effect of Californians' consumption patterns may, in fact, be no different than that of Texans. One might attribute emissions from chemical and fuels production in Texas to Texans while those from the film and television industry in California leads to little emissions but maybe both Texans and Californians consume chemicals, fuels, and films at similar rates and with similar indirect emissions.

Apart from simply assigning responsibility, I-O analysis has also been used to assess the potential burden of emissions pricing on different consumers (e.g. Metcalf (1999)). Here the idea is that a CO_2 emissions price will be reflected in the cost of products throughout the economy in proportion to the emissions incurred during production or consumption. The price of final goods

[1] Albeit, this is still a slightly different concept than "cradle to grave" accounting that would go on to consider emissions associated with the disposal of the product.

in the economy will thus reflect the CO_2 cost of their production and use, carrying along the cost of all the CO_2 emissions associated with intermediate and primary production. While widely used for such purposes, such an assessment is at best an approximation to a partial answer to the question of who bears the burden of emissions pricing. It assumes that all industries have constant cost production functions so that all emissions costs are passed forward to consumers rather than backwards to owners of factors, which in general equilibrium is not the case. Wages and returns to assets will be affected by carbon pricing, and most likely differentially. Some households will derive more of their income from wages than capital, and among capital owners some may be invested in fossil fuels while others are invested in renewable energy sources. It further assumes that there are no options to abate emissions, the point of carbon pricing in the first place. A product whose production can be switched to a lower emitting process at minimal cost will do so and thus will not pass through much of the carbon price, while a product with no reasonable low-carbon production options will pass it through completely. Even assuming all of these effects are neutral across households, the answer is partial in that it does not address what happens with the revenue from, or allowance value inherent in, a carbon pricing system. How the revenue is used to maintain government programs, transfer payments or pay down the government debt, or who gets the allowances and hence reaps their value, is often more important in determining the final distributional effects of a carbon pricing policy than the effects that occur through differential patterns of consumption (see e.g. Rausch et al. 2010 and Rausch et al. 2011).

Never-the-less, current consumption patterns are one of the ingredients that determine relative burden in more complete analyses. Hence, to understand how burdens may differ across states and regions, the current CO_2 intensity of consumption of different states and regions is important. The existing literature, in making such calculations for US states, has made the simplifying assumption that indirect emissions associated with the consumption of different imported products is uniform among different regional sources of those products because they have lacked the full bi-lateral trade data necessary to track the domestic or international source of imports. Hence, they assume, for example, that a dollar's worth of vehicle produced in Michigan has the same emissions as a dollar's worth of vehicle produced in Tennessee, Germany, or Japan (e.g. Metcalf (1999), Dinan and Rogers (2002), Hassett, Mathur and Metcalf (2009), and Mathur and Morris (2012)). Input-output modeling has been used to track carbon dioxide emissions through the economy across countries because international trade data sets provide information on bilateral trade flows (See Wiedmann et al. (2007) or Winchester, others on the China work, Winchester on trade story). Thus, our contribution is to improve on empirical estimates for states or regions within the US. This has become an important issue in Congressional efforts to craft legislation as they look for mechanisms that "fairly" distribute the cost of the policy among states and regions.

In previous work for the US, Hassett et al. (2009) find that roughly half of CO_2 emissions related to final consumption are indirect emissions – emissions that occur in the production of the non-energy goods consumed by households. That indirect emissions are such a large share of overall emissions follows from the fact that most consumer expenditures are on non-energy goods and services. Direct consumer expenditures on energy (fuel oil, natural gas, electricity, and gasoline) accounted for only 9 percent of household expenditures in 2011-2012.[2] Thus while emissions associated with most non-energy goods and services are fairly low, a large share of household emissions result from these goods and services given that the vast bulk of spending is

[2] Data are from the Consumer Expenditure Survey Midyear Tables at http://www.bls.gov/cex/tables.htm accessed on Aug. 5, 2013.

on these items. We use the same terminology as Hassett et al. (2009) where direct emissions are defined as those related to fuel use by households and emissions related to the production of electricity used in the household and all other emissions are indirect emissions. We define this more precisely in Section II.

To undertake this analysis, we develop a multi-regional input-output model with over 100 countries and the United States disaggregated to the state level. This allows us to track carbon embodied in products both domestically produced and consumed as well as imports and exports. We advance previous work by using available data for the US on interstate and international trade flows to estimate a full matrix of inter-state bilateral trade flows and bilateral trade flows between US states and foreign countries. While the full bi-lateral trade flows are in part estimated and the available data on which they are based is incomplete, the results are a "good faith" estimate using the data that are available. Given the data issues, we are cautious about claiming our new estimates of carbon emission implications of consumptions patterns of different states and regions are precise. However, we believe the data we have developed are at least sufficient to test a critical assumption of previous work: i.e. that the emissions intensities of imports of similar types of goods from different regions are identical. If, given our good faith estimates, the difference in carbon intensity does not much depend on the origin of imports into a state then this simplifying assumption may be reasonable. However, if there are substantial differences among different sources of imports then, while our estimates may not be correct, we can at least conclude that further data collection and/or effort to estimate bilateral trade flows is needed to develop better estimates or to make a compelling case that assuming the origin of imports is not important. In Section II we describe the model and data development. In Section III we discuss our findings. We offer some final thoughts in Section IV.

II. Estimating the CO_2 Content of Consumption in a Multi-Regional Input-Output Model

We develop a multi-regional input-output (MRIO) model and use it to estimate the CO_2 content of consumption across US regions. Input-Output models can track flows of inputs through the economy assuming Leontief production. MRIO modeling has been widely used to track carbon dioxide emissions through the economy across countries. Wiedmann, Lenzen, Turner and Barrett (2007) provide a recent survey of that literature. It has not, to our knowledge been used to estimate differences in the CO_2 content of consumption across regions of the US. In particular, the existing literature on regional incidence of U.S. carbon pricing policy has not until now used MRIO.

The MRIO approach allows us to track emissions through to final consumption regardless of the origin of emissions or the number of intermediate production layers.[4] For example, consider glass produced in Ohio that is exported to Michigan for assembly into automobiles, which in turn are exported to New York for sale. The MRIO approach allocates the emissions associated with the glass production to New York for consumption-based emissions accounting while it would allocate the emissions to Ohio under a production based emissions framework. In neither case are emissions allocated to Michigan.

[4] Peters (2008) compares and contrasts production and consumption based emission methodologies based on an emissions embodied in bilateral trade (EEBT) approach and the MRIO approach. While the latter approach is more complicated and less transparent, it is more accurate in allocating emissions to final consumption.

Our input-output framework also differs from what is found in the existing literature on regional incidence of U.S. carbon pricing policy in that it combines country-level data outside of the US with sub-national (regional) data within the US. These two types of regions are conceptually similar, however, and we denote them with the same index r. The model tracks flows for n sectors of the economy. We follow the usual notation from the literature, in particular Peters (2008). Output in region r (x^r) is used in intermediate production, consumption, and exports:

(1) $$x^r = A^r x^r + y^r + e^r - m^r$$

where the n by n matrix A^r tracks the use of output as an intermediate input in region r, y^r is an n by 1 vector of final consumption in the region, e^r is a vector of exports from region r, and m^r is a vector of imports to region r.

This equation can be decomposed according to the origin of intermediate and final demand. The input-output matrix A^r can be decomposed into a matrix of industry requirements for domestic output (A^{rr}) and matrices of industry requirements for production of domestic output from imports from region s (A^{sr}). Exports to region s (e^{rs}) can be decomposed into exports for final consumption elsewhere (y^{rs}) and exports for use as intermediate inputs in region s (z^{rs}):

(2) $$e^{rs} = z^{rs} + y^{rs}$$

where

(3) $$z^{rs} = A^{rs} x^s$$

Letting y^{rr} represent the final consumption in region r that is produced domestically, and noting that imports need not be tracked explicitly since imports to region r from s are exports from region s to r, equation (1) can be rewritten as:

(4) $$x^r = A^{rr} x^r + y^{rr} + \sum_{s \neq r} A^{rs} x^s + \sum_{s \neq r} y^{rs}$$

This system of equations can be stacked over the R regions:

(5) $$\begin{bmatrix} x^1 \\ \vdots \\ x^R \end{bmatrix} = \begin{bmatrix} A^{11} & \cdots & A^{1R} \\ \vdots & \ddots & \vdots \\ A^{R1} & \cdots & A^{RR} \end{bmatrix} \begin{bmatrix} x^1 \\ \vdots \\ x^R \end{bmatrix} + \begin{bmatrix} \sum_s y^{1s} \\ \vdots \\ \sum_s y^{Rs} \end{bmatrix}$$

or

(6) $$X = AX + Y$$

where X is an nr by 1 vector and so on. The Y vector is the vector of consumption both consumed domestically and imported.

Production-related Emissions

Emissions of carbon dioxide per unit of output associated with production in region r is denoted by the row vector f^r of dimension n. These vectors can be stacked next to each other in the row vector F of dimension 1 by nr:

$$F = [f^1 \dots f^R]$$

so that domestic (production) emissions in region r are given by:

(7) $$E_P^r = f^r x^r$$

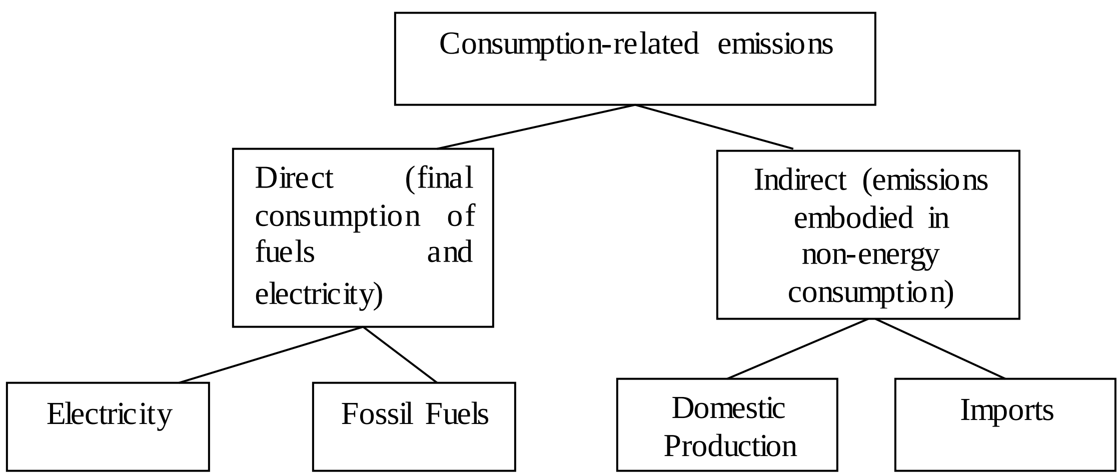
The emissions embodied in r's output (including those embodied in domestic and imported intermediates) can be computed as:

(8) $$E_X^r = F\ (I - A)^{-1} X^r$$

where X^r is an nr by 1 vector of r's consumption by source region:

(9) $$X^r = \begin{bmatrix} 0 \\ x^r \\ 0 \end{bmatrix}$$

Consumption-related Emissions



We distinguish two types of emissions related to household consumption: **direct** emissions that are defined as those emitted when households consume fossil fuels and **indirect** emissions that result from the production of all other consumption goods. For consistency with Hastert et al. (2009) and most of the literature, we consider the emissions associated with the production of electricity consumed by households to be **direct** emissions. Emissions caused directly by the burning of fossil fuels by households (gas and oil for heating, oil for transport, mainly), are given by:

(10) $$\tilde{E}_D^r = B^r\ C^r$$

Where B^r is a *1* by *nr* vector of CO_2 emissions coefficients for the combustion of fossil fuels, representing the quantity of CO_2 emitted per dollar of fossil fuel use by households in region r and C^r is the *nr* by *1* vector of *r*'s consumption by source region:

(11) $$C^r = \begin{bmatrix} y^{1r} \\ \vdots \\ y^{Rr} \end{bmatrix}$$

Indirect emissions embodied in region *r'*s consumption ($\tilde{E}_C^r$) are given by

(12) $$\tilde{E}_C^r = F\ (I - A)^{-1} C^r$$

and

(13) $$E_D^r = B^r\ C^r$$

For consistency with the Hassett, et al. (2009) definitions, indirect emissions as generally calculated in equation (12) can be decomposed into an **electricity** component (E^r_{ele}), and an **indirect non-energy** (E^r_{ne}) component by reconstructing C^r to include only electricity or only non-electricity goods. Total direct emissions are then defined as $E_D^r = B^r\ C^r + E_{ele}^r$, and indirect emissions are defined as $E_C^r = \tilde{E}_C^r - E_{ele}^r$.

Emissions Intensity

The E_X vector allocates emissions to regions based on production while E_C allocates emissions to regions based on consumption. Total emissions for region *r* are given by summing the elements of the relevant emissions vector. Each region's production and consumption based emissions intensities are then given by:

(10) $$\boldsymbol{k_X^r = \frac{1' E_X^r}{1' x^r}}$$

(11) $$\boldsymbol{k_C^r = \frac{E_C^r + E_D^r}{1' C^r}}$$

Where k^r_X is the emissions intensity (or average CO_2 content per dollar) of production and k^r_C is the emissions intensity of consumption. The measure of CO_2 intensity is closely related to the notion of carbon tax incidence computed in Hassett, et al. (2009). Indeed, if the price shock caused by a tax on CO_2 emissions is assumed to completely pass through to consumers, the two metrics can be shown to be equivalent.

Here, we estimate the carbon content of consumption using multi-regional input/ouptut (MRIO), providing two improvements on their methodology. First, we account for differences in the CO_2 intensity of foreign imports and trace these to different parts of the United States and whether they are then consumed in that region or traded to other parts of the Country. Second, intra-national trade patterns are based on U.S. interstate trade data rather than an assumption of homogeneity of the dispersion of products within the United States.

Construction of the A, D, and F matrices is discussed in Section B of the appendix and more detail is available in Caron and Rausch (2013). Our dataset describes the full matrix of bilateral trade between all regions of the US and their international trading partners as well as input-output tables and CO_2 emission coefficients for all regions. Our bilateral trade matrix does not, however, distinguish between trade in intermediate and final goods. These are, as often done in MRIO analysis, shared out according to bilateral trade shares. This implies, for example, that the bilateral sourcing of glass for final consumption to Michigan is assumed to follow the same patterns as the total sourcing of glass to Michigan. There is, to our knowledge, no data describing these shares at the state-level.

The dataset used for the analysis includes input-output tables, final demand data and bilateral trade data for all 50 US states as well as 113 countries and regions outside of the US (a list of which can be found in Table 8 in the appendix). By covering the whole world economy, this dataset can be used to compute the total CO_2 intensity of both internationally and domestically traded goods. Within states and countries, we track 52 sectors (see Table 7 in the appendix). While we also compute results at the state-level, we simplify exposition in the main body of the text and aggregate states to 11 sub-regions of the US, as shown in Figure 1.

Figure 1 Regional aggregation of states

III. Results

We begin in Table 1 by reporting the average amount of carbon dioxide (in kg) embedded in each dollar of gross output (the CO_2 intensity of output) across regions of the U.S. for the 24 highest emitting sectors in the dataset (representing over 90 percent of U.S. emissions). The intensity measure is based on the MRIO computations and, as such, represents the total amount of CO_2 required for the production of goods in each sector divided by the value of gross output in that sector. It shows, for example, that a dollar's worth of output in the "Motor vehicles and parts" sector in the Midwest contains an average of 0.58 kg of CO_2. This number takes into account the use of intermediate inputs purchased both domestically and internationally.

Table 1 reveals the large heterogeneity in carbon intensities both across regions and across sectors. For example, it shows that New England and New York have less than half the carbon content per dollar of electricity output than the South East and Central regions of the country. The distribution of intensities is more homogenous in other sectors but large differences exist in almost all goods and services. These can reflect differences in the within-sector composition of production, in technology, in prices (these intensity measures use value as a denominator) or in the CO_2 intensity of the intermediate inputs, in particular electricity.

Despite the many limitations inherent to the use of IO for tax incidence analysis which were described in the introduction, these sector-level estimates can be used to investigate the distribution of impacts which would be caused by potential carbon taxation policies. For example, if emissions were to be subject to a uniform tax t everywhere in the world (measured in terms of $ per kg), one could use this intensity measure to compute a crude approximation of the incidence of such a tax on the price of each of these goods by multiplying their CO_2 intensity by t. Focusing on the electricity sector to illustrate, the table shows that the electricity produced in New England contains an average of 4.59 kg of CO_2 per dollar of output. A crude approximation of the incidence of a carbon tax of t=$0.02/kg ($20/metric ton) is thus that it will increase the price of electricity by $4.59 * t = 0.09$ -- 9 cents for every dollar of output.

Because these intensity indices capture the CO_2 emitted in all upstream sectors, multiplying them by the value of output and summing across regions and sectors would lead to double-counting emissions (and any associated tax revenue). Intensity measures reflect the average amount of CO_2 embedded in each sector and they do not inform us about the amount of CO_2 emitted directly in that sector (the amount which determines the tax paid by producers in that sector). In order to determine their total contribution to nation-wide emissions, the final three columns of Table 1 display the national total CO_2 emissions directly and indirectly embodied in the production of each sector, directly emitted in the production of each sector, and embodied in the final demand for each of these goods.

Table 1 Carbon intensity (direct and indirect) of production by region and sector

	NENG	NY	MATL	SEAS	FL	MWES	NCEN	SCEN	TX	MOUN	PACI	CA	**Direct and indirect emissions**	**Direct emissions**	**Emissions in final demand**
	CO_2 intensity, direct and indirect (Kg CO_2/$)												Total US CO_2 (Mt)		
Electricity	4.59	2.70	9.56	9.57	9.61	9.56	9.62	9.58	6.82	6.48	6.44	6.60	2364	2305	809
Recreational and other services	0.11	0.16	0.22	0.23	0.31	0.22	0.22	0.34	0.26	0.23	0.18	0.18	1028	77	275
Trade	0.13	0.15	0.22	0.24	0.27	0.21	0.21	0.30	0.25	0.17	0.14	0.14	459	36	268
Transport nec	2.08	1.27	2.01	2.21	1.70	1.97	2.29	3.08	2.65	1.99	1.74	1.83	1240	899	202
Chemical, rubber, plastic products	0.22	0.28	0.53	0.67	0.45	0.62	0.52	2.26	1.95	0.44	0.25	0.31	948	294	162
Petroleum, coal products	0.47	0.46	0.64	0.76	0.50	0.95	1.00	1.00	1.48	0.91	0.67	0.67	600	287	152
Public Admin., Defense, Education, Health	0.07	0.07	0.09	0.10	0.11	0.11	0.11	0.15	0.11	0.08	0.07	0.06	305	22	147
Air transport	2.53	2.85	3.85	3.43	3.86	3.36	2.73	3.86	4.46	3.31	4.44	3.28	436	336	145
Motor vehicles and parts	0.07	0.18	0.21	0.48	0.12	0.58	0.39	0.45	0.23	0.14	0.15	0.24	287	11	90
Food products nec	0.15	0.17	0.31	0.52	0.19	0.88	1.43	0.92	0.60	0.43	0.48	0.46	187	44	84
Manufactures nec	0.20	0.10	0.20	0.38	0.18	0.31	0.32	0.44	0.17	0.19	0.16	0.25	75	3	80
Wearing apparel	0.14	0.19	0.19	0.61	0.22	0.19	0.23	0.90	0.14	0.17	0.32	0.32	13	2	60
Electronic equipment	0.22	0.15	0.21	0.25	0.29	0.17	0.28	0.24	0.44	0.46	0.47	0.32	248	10	56
Beverages and tobacco products	0.15	0.10	0.37	0.54	0.36	0.35	0.38	0.63	0.50	0.69	0.20	0.35	68	13	54
Financial services nec	0.09	0.11	0.15	0.12	0.17	0.12	0.12	0.11	0.13	0.09	0.09	0.07	112	1	45
Communication	0.09	0.10	0.12	0.17	0.16	0.12	0.16	0.19	0.20	0.21	0.17	0.16	138	12	45
Bovine meat products	0.07	0.11	0.24	0.47	0.16	0.67	2.65	1.62	1.18	0.53	0.38	0.38	89	13	39
Gas manufacture, distribution	0.44	0.93	0.56	0.20	0.31	0.63	2.23	0.15	0.17	0.41	0.65	1.51	54	32	27
Meat products nec	0.09	0.02	0.27	1.71	0.21	0.21	0.78	2.38	1.01	0.05	0.59	0.35	64	14	27
Leather products	0.18	0.19	0.10	0.25	0.13	0.19	0.25	1.37	0.08	0.15	0.10	0.18	2	0	22
Business services nec	0.15	0.17	0.18	0.22	0.23	0.19	0.25	0.35	0.22	0.17	0.13	0.16	134	21	21
Water transport	0.96	0.70	0.89	0.95	3.79	0.57	0.43	5.64	0.47	0.52	3.67	0.84	52	24	21
Sugar	0.14	0.09	0.48	0.30	0.40	0.70	5.24	4.88	1.05	1.54	0.36	0.40	30	16	20
Textiles	0.23	0.10	0.22	1.17	0.13	0.19	0.21	0.74	0.06	0.06	0.12	0.37	48	4	19
..															
Average CO_2 intensity of gross output	0.20	0.18	0.33	0.53	0.33	0.54	0.59	0.86	0.68	0.51	0.33	0.23			
Average CO_2 intensity of value added	0.13	0.13	0.24	0.41	0.25	0.42	0.46	0.74	0.59	0.45	0.18	0.15			
Avg. CO_2 intensity of final good production	0.15	0.14	0.24	0.40	0.29	0.37	0.44	0.57	0.45	0.38	0.23	0.17			

Regional Cells report carbon intensity measured as tons of CO_2 per dollar of output in each region. The final columns report total national emissions (millions of metric tons of CO_2) embodied in production (directly and total) and embodied in final consumption. States within each region: NENG: ME,NH,VT,MA,CT,RI; SEAS: KY,NC,TN,SC,GA,AL,MS; MATL: DE,MD,PA,NJ,DC,VA; MWES: WV,WI,IL,MI,IN,OH; SCEN: OK,AR,LA; NCEN: MO,ND,SD,NE,KS,MN,IA; MOUN: MT,ID,WY,NV,UT,CO,AZ,NM; PACI: OR,WA,HI

The last three rows of Table 1 reveal how differences in intensities within sectors and differences in the sectorial composition of production in each region filter to differences in the average CO_2 content (or CO_2 intensity) of production in each of the regions. The first of these rows displays the CO_2 intensity of gross output, and corresponds to the average of the sector-level intensities above it, weighted by gross output. It reveals very large differences between regions, ranging from 0.18 kg of CO_2 per dollar of output, on average, for New York, to 0.86 for the South Central region. The second of these lines shows the CO_2 intensity of value added in each region defined as the amount of CO_2 emitted directly in the production of all sectors divided by value added (or GDP) in that region. These values vary even more across regions, as the traded intermediates included in the gross output measure mitigate differences in direct CO_2 intensity between regions. Finally, the last line displays the CO_2 intensity of the final goods -- goods that will be consumed by household without further transformation -- produced in each region (again, including the CO_2 emitted in the production of the necessary intermediate inputs). These intensities are on average lower than the gross output intensities, and also vary less across regions.

Consumption: Household, Government and Investment Final Demand

Before switching our focus to measures of the CO_2 intensity of consumption, we find it informative to construct regional CO_2 balances. We will compute these both from a production and a consumption perspective, allowing for a differential attribution of responsibility for emissions across regions. In order to do so, we decide to take a broad definition of consumption and include not only the final use of goods and services by private households but also public or government final demand. Goods and services purchased by governmental entities can indeed be assumed to mostly benefit households within the same region. We also include the share of final investment used to purchase capital which will be used to produce domestic consumption in the future. This share is not observed in the data so we assume it to be proportional, in each sector, to the share of that sector's output which is used in domestic final demand. Although this share is 41% on average across sectors, investment flows over-proportionally to sectors with high export shares, so the share of investment attributable to domestic final demand in each region is only 14% on average.

Figure 2 displays the CO_2 embedded in each region's consumption and decomposes it into household, government and domestic investment demand. For each element it displays direct emissions, stemming from the consumption of fossil fuels and electricity, and the indirect emissions embedded in the consumption of non-energy goods. Household demand dominates, but government and investment demand account for non-negligible shares of the CO_2 emissions. In the remainder of the paper, we refer to "consumption" as the sum of these three elements.

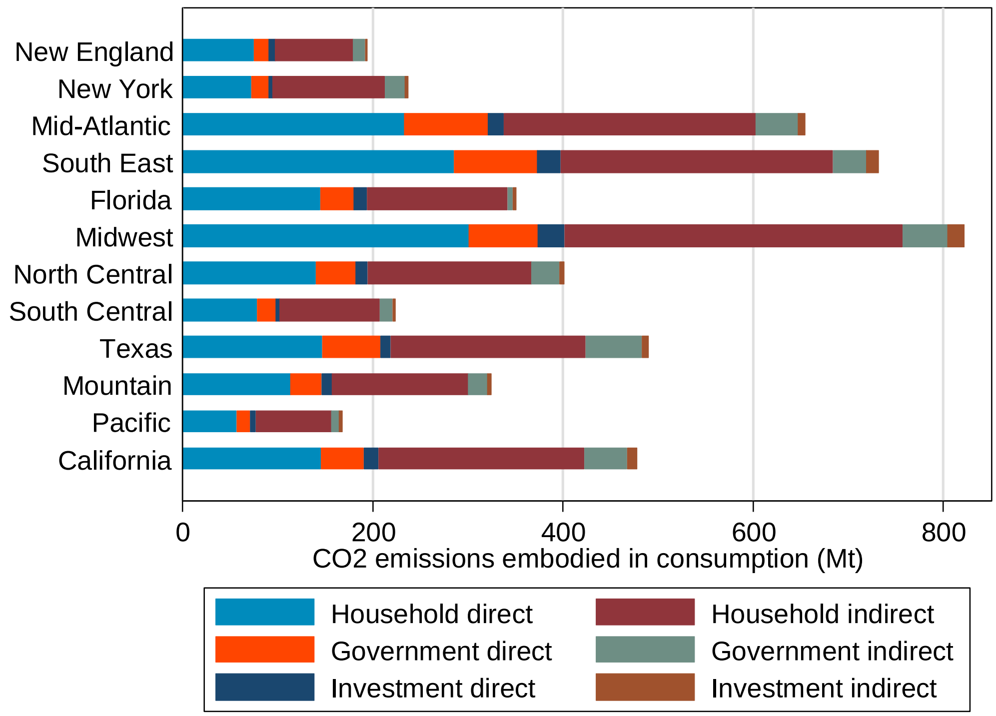


Figure 2 CO_2 emissions embodied in consumption: decomposition by final demand type

Regional Emissions on a Production versus a Consumption Basis

We now use our MRIO framework to compute regional CO_2 balances. Figure 3 displays, for every region, both a production-based (the top bars) and a consumption-based estimate of CO_2 emissions (the bottom bars). In order to make their total length comparable, we include direct consumption emissions (the first segment) in both bars.

The amount of CO_2 emitted in the production of goods and services which are ultimately consumed locally (second segment, in orange) is of course identical in the top and bottom bars. These emissions are computed using the MRIO framework which tracks emissions through the production chain to final consumption. They therefore include not only the carbon emitted in the production of final goods which are directly consumed in the region, but the CO_2 emitted to produce goods that are used as intermediates for all goods which are ultimately consumed within the region. For example, they include both the CO_2 emitted for the production of cars consumed in the Midwest that where produced in the Midwest and the CO_2 emitted in the Midwest for the manufacturing of glass used in the production of these cars.

A production-based estimate of regional emissions adds to that the emissions incurred in the production of goods and services which are ultimately consumed out of the region (the third segment in dark blue). This would include, for example, the CO_2 emitted in the Midwest to produce glass for cars produced in the Midwest but purchased in New York. The first three segments of the top production bar correspond to the total CO_2 emitted within each region.

On the other hand, a consumption-based estimate includes the CO_2 embodied in consumption which was emitted out of the region and imported either as a final good or further up the production chain (third element of the bottom bars, in dark red). The carbon emitted for the production of glass in the Midwest for cars produced in the Midwest but sold in New York would be attributed to New York in this case. The first three elements of the bottom consumption bar correspond to the total CO_2 attributable to each region's consumption.

Finally, in order to complete the CO_2 accounting for each region, the last segment of both bars (in silver) indicates the amount of "re-exports" of CO_2. These correspond to the CO_2 which is imported to the region embodied in goods which are transformed and ultimately re-exported and consumed out of the region. These emissions should obviously not be attributed either to domestic consumption nor production. Adding these re-exports to the amount of CO_2 which is emitted locally but exported (the last two segments of the top bars) indicates the amount of CO_2 embedded in the region's exports. Adding these re-exports to the amount of CO_2 which is emitted out of the region but consumed locally (the last two segments of the bottom bars) indicates the amount of CO_2 embedded in the region's imports.

Comparing the top and bottom bars in Figure 3 reveals whether a region is a net importer or exporter of CO_2. We find that New England, New York, the Mid Atlantic, Florida and California are all significant net importers of embodied carbon. The Southeast, Midwest, North Central, and Pacific are nearly balanced with imports of carbon very close to exports. The South Central, Mountain states, and Texas are exporters of carbon. These statistics include carbon imported or exported abroad and so do not net to zero for the US as a whole.

To illustrate the role of bilateral trade flows in generating these estimates, Table 9 in Section D of the appendix displays the CO_2 embodied in bilateral trade flows (in Mt CO_2) between the US regions as well as with their major international trading partners.

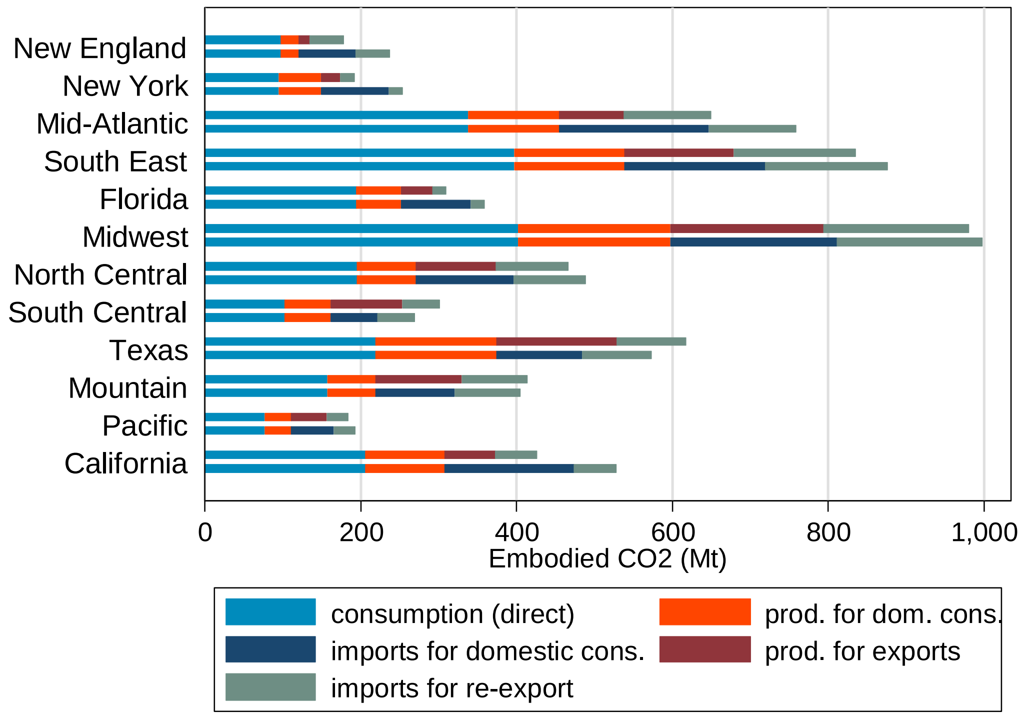


Figure 3 Embodied CO_2 on a consumption production and consumption basis, by region

Figure 3 highlights the respect to which measures of CO_2 can differ when computed on consumption rather than a production basis. Consider California, for example: its emissions on a consumption basis are about 100Mt larger than when measured on a production basis. It imports 1.85 times more embodied CO_2 that it exports. While we do not trace emissions over time in this analysis, the difference in emissions on a consumption versus a production basis suggests reason for caution about drawing policy conclusions from curves such as the "Rosenfeld Curve" which shows a marked decline in per capita energy consumption in California between 1963 and 2009 (Rosenfeld and Poskanzer (2009)). In assessing what has happened to emissions within the state, it largely underestimates the amount of emissions for which the state is responsible (for a detailed analysis of the California experience, see Levinson (2013)). The decline of emissions observed over time in California may be due in part because the state has been importing more of the emissions embodied in its consumption. Without estimates such as ours that go back over time, one cannot conclude whether California has done better than other parts of the country or that emissions have simply shifted out of the state for various economic or regulatory reasons. New England and New York similarly import large shares of the emissions for which they are responsible. Overall, Figure 3 highlights the importance of tracking trade flows: almost all regions consume more imported than domestically emitted CO_2, and most regions export a majority of the CO_2 they emit in the production of goods.

Whether measured on consumption or a production basis, emissions are highest in the Midwest, but the emissions accounting shown in Figure 3 does not control differences in the regions' sizes. To do so, Figure 4 normalizes the values by each region's population. Shifting to per capita emissions, two things stand out.

First, the ranking of regions changes significantly. The South Central region moves from the middle of the pack to become the region with the highest per capita emissions on a production basis, whereas Texas has the largest emissions on a consumption basis. New York has both the lowest production-based and consumption-based emissions. California, even with its substantial imported emissions, remains among the lower emitting regions on a per capita basis.

Second, although the variation in emissions drops significantly (part of the variation in Figure 3 reflected the fact that the regions differ in size), it is still quite large, particularly when measured on a production basis. The ratio of highest to lowest emissions is still roughly two to one. This variation is large, especially considering the fact that we display results at a relatively high level of aggregation. The variation is lower in a consumption-based accounting of emissions, as trade between regions partially equalizes emission rates. This equalization is far from complete, however, and there are large differences in the per capita *consumption* of CO_2. Figure 5 shows that results are not appreciably different if emissions are scaled by GDP rather than population. We now focus on this variability by computing and decomposing the CO_2 intensity of consumption in each region.

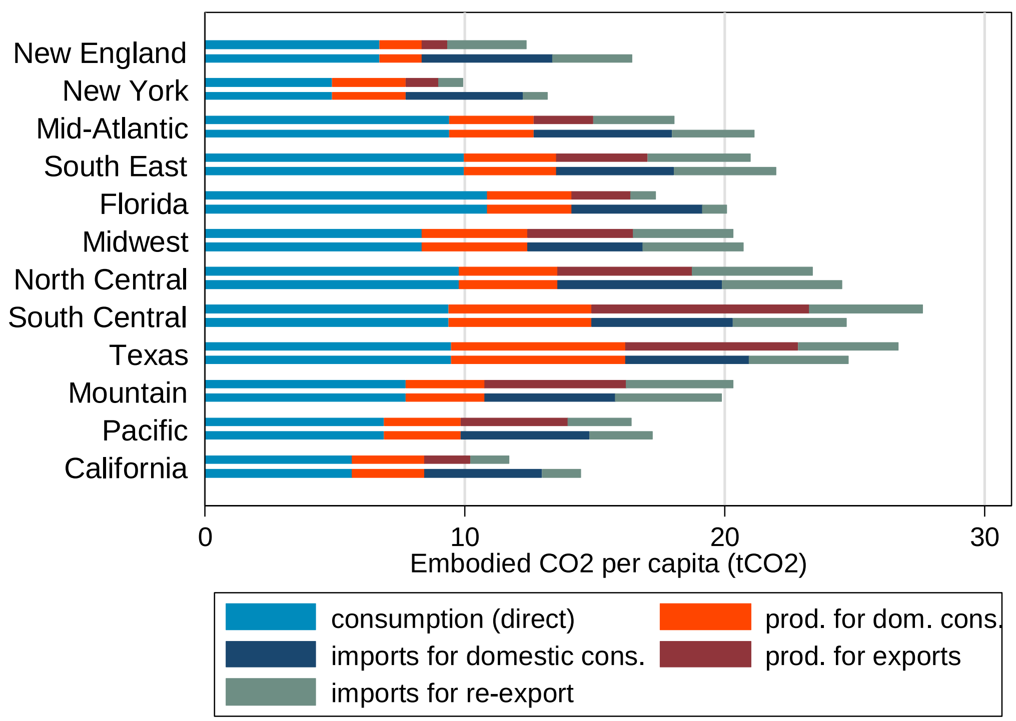


Figure 4 Embodied CO_2 per capita

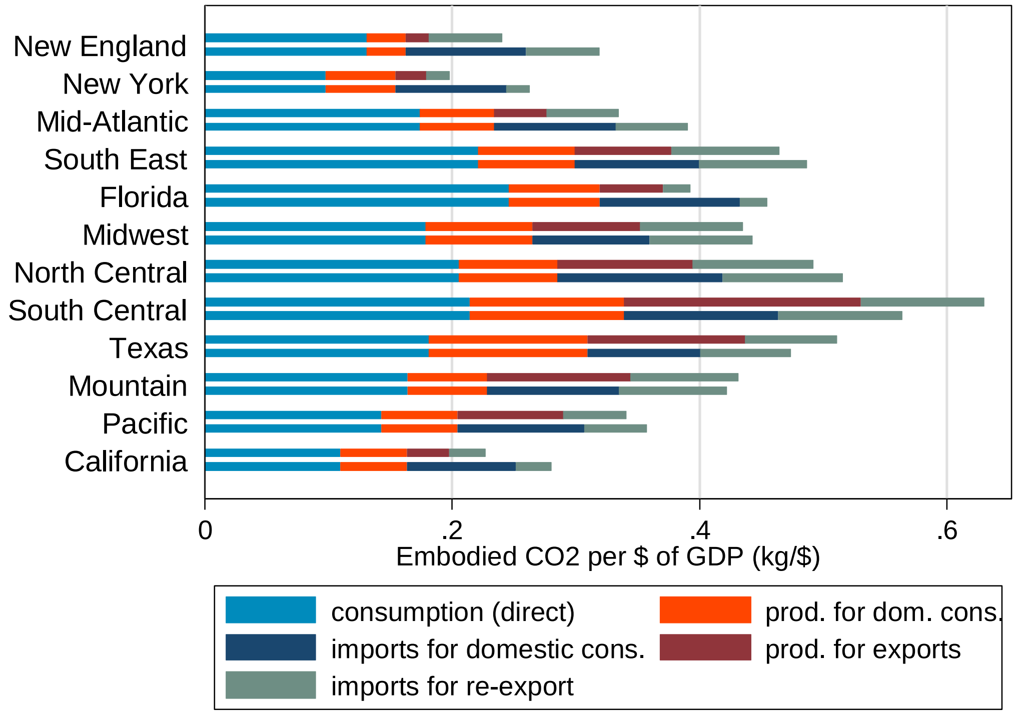


Figure 5 Embodied CO_2 per Dollar of GDP

The Direct and Indirect CO_2 Intensity of Consumption

Figure 6 displays the average CO_2 content per dollar (or CO_2 intensity) of consumption for each region. It distinguishes the emissions stemming from the combustion of fossil fuels by households, the government and investing firms in final demand (*direct – fossil fuels*), the emissions due to final demand for electricity (*direct – electricity*), and emissions embodied in all other consumption goods (*indirect non-energy*).

Table 2 provides summary statistics on these intensity measures, weighted by total consumption in each region such that the mean value corresponds to the US mean value. Table 5 in Section A of the appendix displays estimates of this intensity for all 50 states.

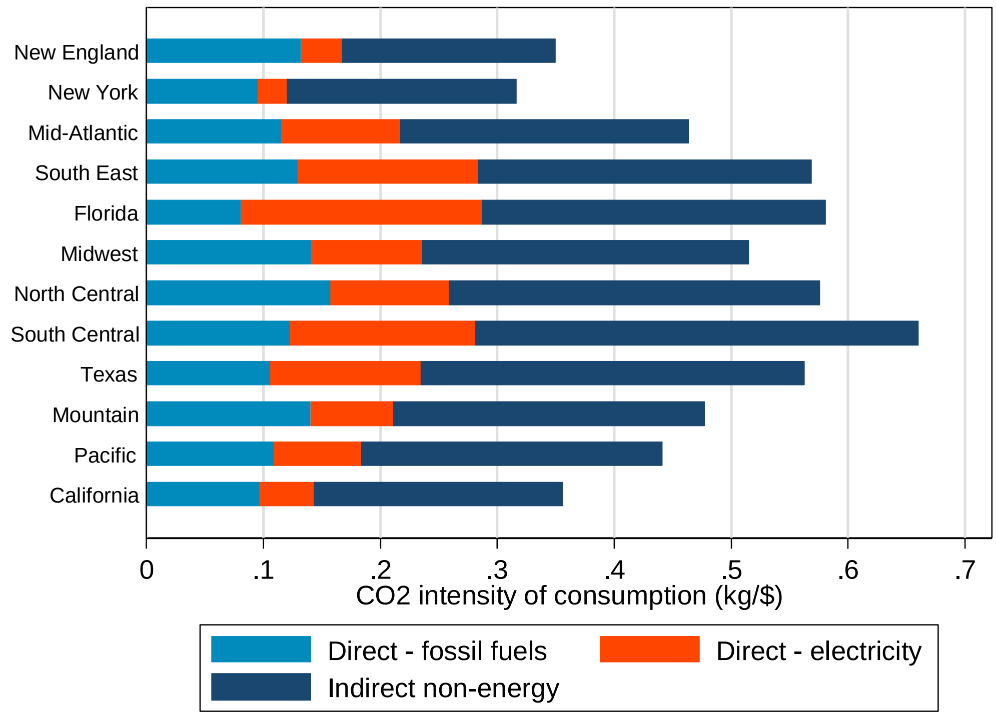


Figure 6 CO_2 intensity of consumption

Table 2 CO_2 intensity of consumption -- Summary statistics

CO_2 intensity of consumption (kg/$)	Mean	Std. dev.	Var. coeff.	Min	Max
Total	0.484	0.098	0.202	0.317	0.661
Direct	0.218	0.054	0.248	0.120	0.287
Fossil fuel	0.120	0.022	0.180	0.081	0.157
Electricity	0.099	0.050	0.505	0.024	0.207
Indirect	0.265	0.048	0.182	0.182	0.380
Emitted domestically	0.125	0.043	0.340	0.049	0.213
Emitted in other US regions	0.076	0.014	0.192	0.050	0.105
Emitted internationally	0.064	0.010	0.157	0.048	0.079

Notes: CO_2 intensity defined as the physical quantity of CO_2 in kg per dollar value of consumption; all values weighted by total regional consumption; Variation coefficient corresponds to the standard deviation divided by the mean.

The first thing to note from Figure 6 is that the indirect component of consumption accounts for more than half the emission intensity. On average over the whole country, a dollar of consumption contains 0.218 kg of direct emissions and 0.265 kg of indirect emissions. While policy makers tend to focus on the impact of carbon pricing on energy goods that cause emissions directly (gasoline, home heating fuels and electricity for the most part), most consumer spending is on non-energy goods in which the embodied emissions occurred during their production. The indirect emissions intensity of non-energy goods and services is quite low relative to that of energy goods, but it adds up to a large share of consumption-related emissions because so much more of the household budget is spent on these goods. One implication, then, is that while the impact of carbon pricing might be most obviously seen in the price of energy goods, other things equal one-half of the budget impact may come through very small, almost unnoticeable, increases in the cost of all other goods.

The second thing to note is that both the direct and indirect elements vary considerably across regions. The direct emissions intensity across the regions ranges from 0.12 to 0.29 kg per dollar of consumption. The big trends here are broadly that northern states have higher fossil fuel intensity (partially from higher heating requirements), whereas southern states have higher electricity intensity (partially from higher air conditioning requirements). Overall, the range of direct intensities is roughly consistent with that found by Hassett, et al. (2009) and Mathur and Morris (2012). The picture changes, however, when we look at indirect emissions. These are found to vary considerably more than estimated by the previous literature, which argued that the geographic distribution of indirect carbon emissions has much lower variance than direct emissions do. The indirect carbon intensity varies from a low of 0.18 in New England to 0.33 kg/$ in South Central, a ratio of almost two to one. This leads to large differences in the overall carbon intensity of consumption. In contrast, Mathur and Morris (2012) find that the CO_2 intensity of the most emissions-intense region is less than 25% higher than that of the least intense region and that direct emissions vary twice as much between regions as indirect emissions. While the regions in the two analyses are constructed slightly differently making direct comparison difficult[6], it is clear that there is considerably more variation in the indirect emissions statistic computed using MRIO. There are also differences in the relative magnitudes of the measures across regions but given the different composition of regions in the two papers, it is difficult to draw substantive conclusions from the different patterns.

The cross-regional variability in indirect intensities can be better visualized in Figure 7, which also further decomposes estimates according to the locus of emission for the carbon embodied in non-energy consumption: emissions which occurred within region (*domestic indirect*), in other regions of the US (*Other US indirect*) or internationally (*International indirect*). Interestingly, our estimates suggest that, on average, most of the emissions occur out of region: the indirect emissions embodied in consumption that are emitted domestically correspond to 0.13 kg per dollar of consumption on average. Imported emissions account for 0.14 kg per dollar of consumption on average, with almost half of that (0.06 kg/$) coming from international sources. There is slightly less variation in the international intensity than in the "Other US" intensity, indicating that the importance and composition of international imports varies less from region to region than domestic imports.

[6] Figure 11 in Section A of the appendix reproduces the direct and indirect burdens of a carbon tax estimated in Table 7 of Mathur and Morris (2012). These are theoretically equivalent to the CO_2 content of consumption.

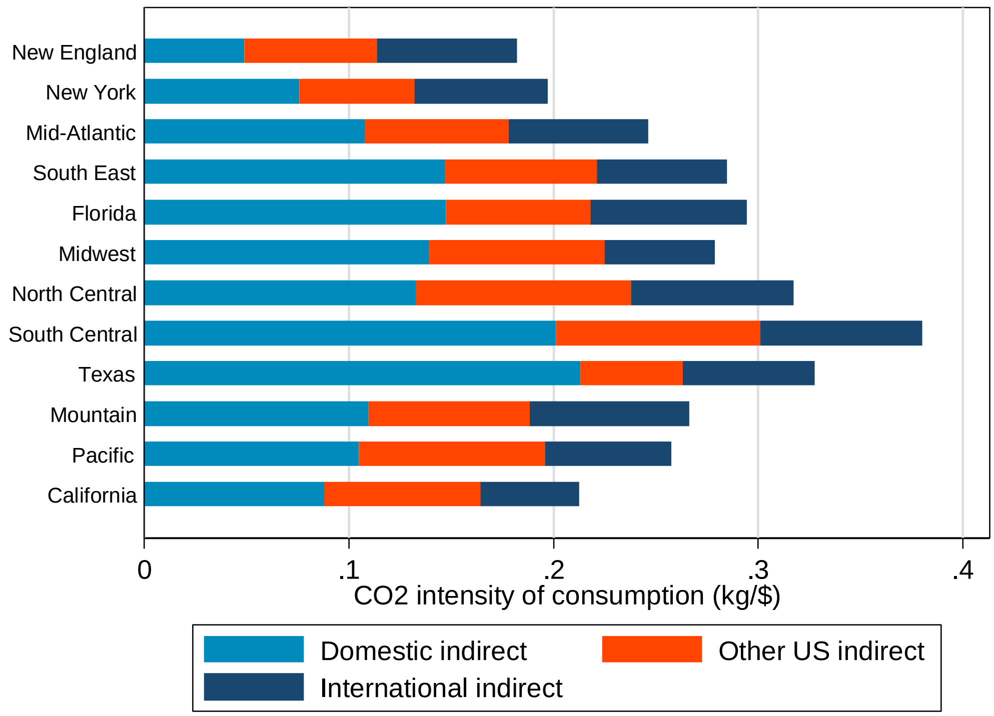


Figure 7 Indirect CO_2 intensity of consumption

The large differences in the indirect CO_2 intensity of consumption revealed by Figure 7 have important implications regarding the incidence of carbon taxation across regions. The extent to which households will be affected across regions will vary not only because of differences in the consumption of fossil fuels and electricity, but through differences in non-energy consumption as well. These differences in the CO_2 intensity of consumption across regions may be caused by differences in consumption patterns, or alternatively, households might consume similar sets of goods but purchase them from different sources and may thus embody different amounts of carbon. We now provide a decomposition of results to better understand the source of this variability. Among other things, we want to compare the carbon content of consumption computed using a full multi-regional (MRIO) decomposition to that computed using average US intensities for non-energy goods as for instance in Hassett, et al. (2009).

Understanding the Source of the Differences in the CO_2 Intensity of Consumption

As noted earlier, a key assumption made by Hassett, et al. (2009) and other recent papers is that commodities produced in any given state and exported out of state have an equal probability of being consumed in any other state. Our results suggest that this homogeneity assumption may drive the result that indirect emissions are nearly constant (as a share of income) in those papers. The data, however, do not support this assumption. To illustrate this, Figure 8 indicates the proportion of exports from Ohio that go to each state. It displays both actual shares from the 2007 Commodity Flow Survey, the source of bilateral trade data in our dataset, and the share that would be implied by uniform sourcing (based solely on the importing state's share of GDP). The pattern found in the data reflects what would be predicted by a gravity model: trade is not only larger with larger states but also nearby states. Exports to neighboring Michigan are much larger than its GDP would suggest whereas exports to California are much lower. Although the Commodity Flow Survey may be capturing flows of goods which are further transported without transformation (because of warehousing, for example) and may thus exaggerate the effect of distance on trade, it clearly suggests that trade shares depend on geographical patterns and that trade costs (transport costs, transaction costs, etc..) play a role in limiting trade. This explains how the regional differences in production CO_2 intensities that we identified in Table 1 can lead to differences in the overall CO_2 intensity of consumed good across states. To quantify the effect of these differences, and make a direct comparison with the approach used in Mathur and Morris and Hassett, et al. (2009), which we will refer to as the HMM method, we use our data and regional aggregation and apply their simplifying assumptions while estimating CO_2 intensities.

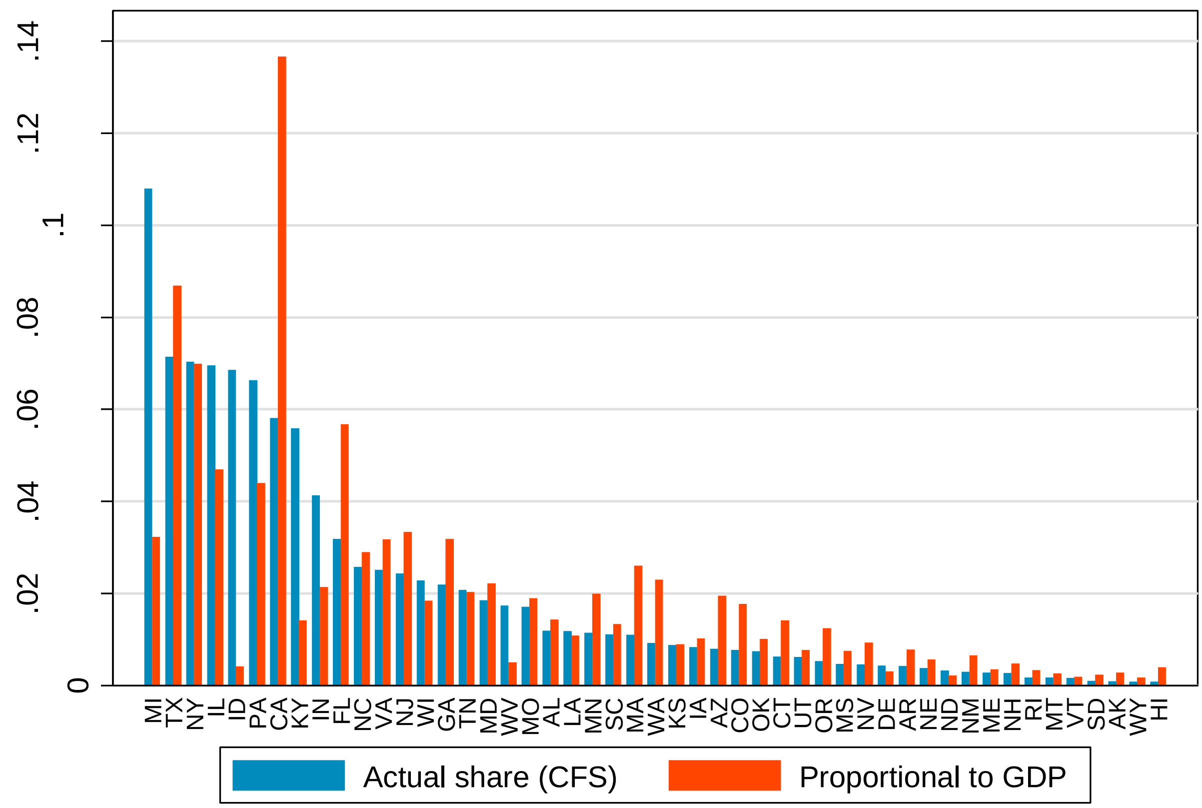


Figure 8 Share of exports from Ohio, by destination state (2007 Commodity Flow Survey)

Recall that we have region specific estimates of the input-output matrices A^r and CO_2 intensity vectors F^r. To decompose the sources of variability, we re-compute estimates of the emissions embodied in consumption using average values of A and F and compare these to full MRIO estimates. In particular, we make 4 sets of assumptions for indirect emissions (including a set of assumptions which replicate the HMM approach):

- **US AVG** – This set of assumptions uses average US intensities for domestic production and imports in all regions. All cross-regional variation is explained by differences in consumption shares, as technological differences or differences in the within-sector composition of consumption are assumed away. These estimates would be obtained if only average US production intensity data (i.e. only a national IO table) was used, or if region-specific IO tables were available but we didn't know the intra-national bilateral trade matrix and thus couldn't compute region-specific indirect embodied emissions.

- **HMM (US AVG + ELE)** – As in HMM, we assume US average intensities except for the household consumption of electricity where region-specific coefficients are used. These estimates would be obtained if we knew cross-regional differences in electricity emissions-intensity only.

- **US AVG+ELE+INT IMP** – Domestic emissions are computed as above, but we use observed average US emission intensities for international imports. These estimates would be obtained if we also had access to a bilateral international trade dataset linked to foreign production intensity data, but didn't know the exact sourcing of imports by sub-national region.

- **AVG INT IMP** – This set of assumptions uses the intra-national bilateral trade data to compute indirect intensities of all goods taking differences in domestic sourcing into account, but uses US average intensities for international imports. These estimates would be obtained if we had all the data necessary for multi-regional input-output analysis within the US, but no information regarding international imports.

In all cases, the direct emissions from household fossil fuel use will be identical. A more detailed algebraic description of each of the 4 decompositions can be found in Appendix Section C. Table 3 displays, for all regions, the CO_2 intensity of consumption for each of the above set of assumptions and compares them to the full MRIO estimates. In the first block of 5 columns, it displays the total values encompassing both direct and indirect consumption of CO_2, whereas the second block of 5 columns displays values for the indirect intensity only (where we expect differences to be larger).

Table 3 CO_2 intensity of consumption: MRIO and decompositions

	MRIO	US AVG	HMM - US AVG+ELE	US AVG+ELE+INT IMP	AVG INT IMP	MRIO	US AVG	HMM - US AVG+ELE	US AVG+ELE+INT IMP	AVG INT IMP
Production intensities - non-electricity	data	US avg	US avg	US avg	data	data	US avg	US avg	US avg	data
Production intensities - electricity	data	US avg	data	data	data	data	US avg	data	data	data
International import intensities	data	US avg	US avg	data	US avg	data	US avg	US avg	data	US avg
CO_2 intensity (kg/$)	Total					Indirect only				
New England	0.350	0.444	0.410	0.444	0.322	0.182	0.243	0.243	0.277	0.155
New York	0.317	0.415	0.361	0.395	0.278	0.197	0.241	0.241	0.275	0.158
Mid-Atlantic	0.463	0.446	0.461	0.493	0.441	0.246	0.244	0.244	0.276	0.224
South East	0.569	0.507	0.531	0.564	0.546	0.285	0.247	0.247	0.280	0.263
Florida	0.581	0.495	0.528	0.561	0.544	0.294	0.241	0.241	0.274	0.257
Midwest	0.515	0.470	0.485	0.516	0.486	0.279	0.249	0.249	0.281	0.250
North Central	0.576	0.490	0.506	0.543	0.549	0.317	0.247	0.247	0.284	0.290
South Central	0.661	0.507	0.532	0.565	0.686	0.380	0.251	0.251	0.284	0.405
Texas	0.562	0.503	0.479	0.512	0.544	0.328	0.244	0.244	0.277	0.309
Mountain	0.477	0.477	0.459	0.494	0.439	0.267	0.248	0.248	0.283	0.228
Pacific	0.441	0.447	0.428	0.459	0.391	0.257	0.244	0.244	0.276	0.208
California	0.356	0.399	0.388	0.413	0.331	0.213	0.245	0.245	0.269	0.188
Mean	0.484	0.464	0.464	0.496	0.457	0.265	0.245	0.245	0.278	0.239
Standard deviation	0.098	0.038	0.055	0.057	0.104	0.048	0.003	0.003	0.005	0.055
Variation coefficient	0.202	0.082	0.119	0.115	0.227	0.182	0.011	0.011	0.017	0.232
Minimum	0.317	0.399	0.361	0.395	0.278	0.182	0.241	0.241	0.269	0.155
Maximum	0.661	0.507	0.532	0.565	0.686	0.380	0.251	0.251	0.284	0.405

Notes: CO_2 intensity measured in kg per $ of consumption; for indirect only, USAVG and USAVG+ELE generate the same estimates

The last 5 rows of Table 3 describe the distribution of intensities under each set of assumptions. The restrictive assumptions of **US AVG** lead to estimates which are on average lower than the MRIO estimates (average of 0.46 instead of 0.48 kg/$). This difference indicates that internationally imported goods are on average more CO_2 intensive than domestic goods. More importantly, they also have dramatically lower variance. The coefficient of variation (standard deviation standardized by the mean) of *indirect* emissions in this case is only 0.01 – much less than the 0.18 found using MRIO. For overall consumption-based emissions, this translates to a variation coefficient of less than half of what is found under MRIO. These numbers indicate that differences in consumption patterns explain only a small part of the regional disparities in the average CO_2 content of consumption, most of which is explained by differences in technology and production intensities.

Differences in the CO_2 intensity of electricity explain part of this variability. Taking them into account in the set of assumptions which replicate HMM (**HMM - US AVG + ELE**) increases the coefficient of variation slightly, from 0.08 to 0.12, but it remains much lower than under MRIO.

Figure 9 compares MRIO estimates of the indirect CO_2 intensity of consumption to that found under the **HMM - US AVG + ELE** assumptions. It is clear from the figure that variation across regions is considerably smaller under those assumptions..

With **US AVG+ELE+INT IMP**, we identify the importance of accounting for the CO_2 intensity of international imports. Doing so increases the mean intensity of US consumption, as goods imported from foreign sources have higher intensities on average but doesn't affect the variability across regions. Finally, **AVG INT IMP** illustrates what would be obtained if domestic bilateral trade flows and regional production intensities were taken into account, but not international trade flows. In this case, the variation well replicates that of the MRIO estimates, but the mean is lower.

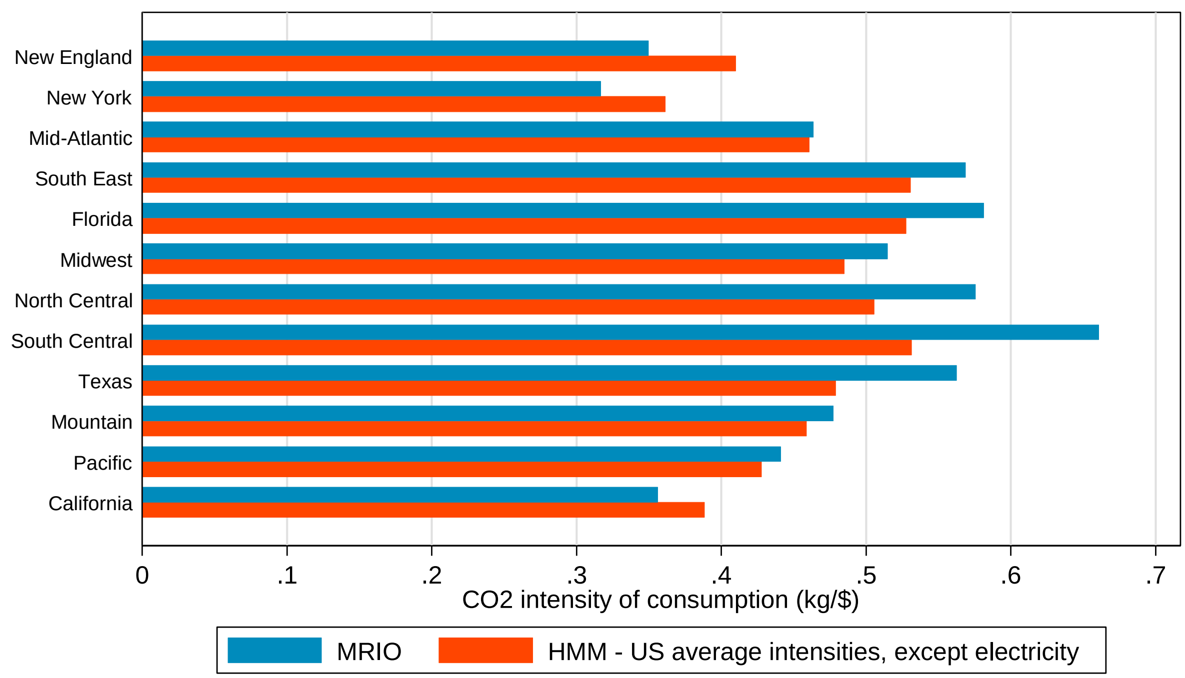


Figure 9 Indirect CO_2 intensity of consumption computed under MRIO, compared to HMM

Biases

From a practical standpoint, the most important aspect to consider when comparing methodologies might be the precision of estimates for particular regions which policy makers may care about. To investigate this, we also express differences in methodologies by computing the bias relative to full MRIO estimates. The biases are measured as 100*(counterfactual estimate/ MRIO estimate -1). The bias caused by using the assumptions in **HMM - US AVG + ELE** are shown in Figure 10 for both total and indirect emissions. The interested reader can find estimates of these biases for all 50 states in Table 5. Over all states, the median absolute bias for indirect emissions is 17%, but the bias is much higher in particular states. In the more extreme cases, the assumptions in HMM would for example overestimate the indirect CO_2 intensity of consumption by more than 37% in Massachusetts, while they would underestimate that of households in North Dakota by about 70%. This translates to a median bias of 11% for the total CO_2 intensity of consumption, which can be as large as 53% for certain states.

Table 4 summarizes the median and maximum biases found under all 4 sets of assumptions, computed overall states. It shows that, even using adding true international import intensities to the assumptions of HMM (**US AVG+ELE+INT IMP** assumption)**.** The median bias is still 14%, implying that the main source of bias is the assumption of homogeneous production patterns across regions of the U.S. Correct treatment of international import intensities does matter, though, and ignoring them (**AVG INT IMP** assumption) yields much smaller biases.

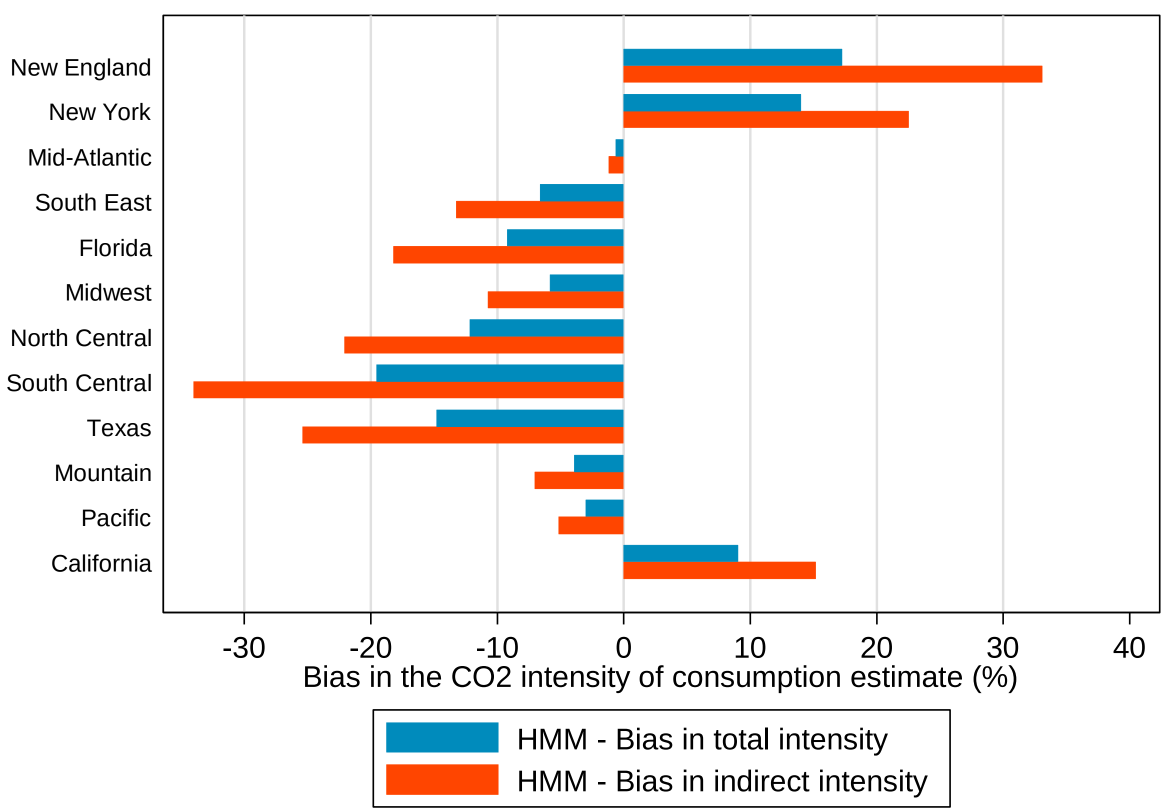


Figure 10 Bias estimates, HMM methodology relative to MRIO

Table 4 Median and maximum bias across assumptions (in %)

	Total		Indirect only	
	median	max	median	Max
US AVG	11.40	53.84	15.81	69.45
HMM - US AVG+ELE	8.53	51.43	15.81	69.45
US AVG+ELE+INT IMP	8.16	47.05	14.36	63.53
AVG INT IMP	6.31	24.39	11.75	32.93

IV. Conclusions

We have used a multi-regional input-output (MRIO) model to understand the production and consumption patterns for carbon dioxide in the United States. Our first significant finding is that state level "responsibility" for emissions differs substantially when emissions are allocated on a production versus a consumption basis. California's per capita emissions, for example, are much higher when allocated on a consumption basis given the large net inflow of emissions embodied in the goods it imports.

The second result in the paper is that there is significant regional heterogeneity in emissions per dollar of consumption, even when focused on the carbon embodied in non-energy consumption. This result contrasts sharply with previous literature. We find that differences in consumption patterns do not explain a large part of the heterogeneity and that it is rather explained by differences in production intensities and the sourcing of domestic and international imports. The patterns of bilateral trade between regions are such that differences in the CO_2 intensity of production across regions are reflected in CO_2 intensities of consumption. We thus conclude that the homogeneity assumption made by previous papers leads them to underestimate differences in the CO_2 intensity of consumption across states. We find good reason to believe that disparities in the impact of carbon pricing go well beyond direct energy consumption and should be taken into account.

Our results are important for understanding regional patterns of CO_2 intensity in consumption. They could, for example, help explain regional variation in support for climate policy in the United States. Our findings are also relevant for an analysis of state level carbon policy. Given the failure to enact carbon pricing at the national level, sub-national policy is becoming increasingly important. The carbon intensity of production and consumption in different sub-national regions could help explain the likelihood of enacting policy in those regions as well as the design of that policy (including, for example, whether they enact carbon pricing on a production or consumption basis).

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Appendix A - State-level Results

Table 5 The CO_2 intensity of consumption, by state (kg/$)

		CO_2 intensity of consumption (kg/$)				Bias in HMM (%)	
State		Direct - fossil fuels	Direct - electricity	Indirect non-energy	Total	Indirect non-energy	Total
Alaska	AK	0.168	0.065	0.646	0.880	-53.8	-39.5
Alabama	AL	0.117	0.163	0.356	0.636	-26.3	-14.7
Arkansas	AR	0.122	0.151	0.381	0.654	-31.4	-18.3
Arizona	AZ	0.098	0.104	0.227	0.429	7.5	4.0
California	CA	0.097	0.045	0.209	0.352	19.5	11.6
Colorado	CO	0.121	0.054	0.257	0.432	-2.3	-1.4
Connecticut	CT	0.117	0.038	0.180	0.334	35.4	19.1
Delaware	DE	0.104	0.129	0.275	0.507	-8.1	-4.4
Florida	FL	0.081	0.207	0.298	0.586	-17.9	-9.1
Georgia	GA	0.152	0.156	0.262	0.570	-5.1	-2.3
Hawaii	HI	0.074	0.116	0.406	0.596	-39.5	-26.9
Iowa	IA	0.183	0.102	0.300	0.584	-16.8	-8.6
Idaho	ID	0.477	0.076	0.302	0.855	-15.9	-5.6
Illinois	IL	0.126	0.078	0.248	0.452	0.6	0.3
Indiana	IN	0.138	0.112	0.285	0.535	-10.9	-5.8
Kansas	KS	0.115	0.107	0.333	0.555	-24.5	-14.7
Kentucky	KY	0.125	0.122	0.283	0.530	-9.5	-5.1
Louisiana	LA	0.126	0.180	0.460	0.765	-44.5	-26.7
Massachusetts	MA	0.128	0.024	0.180	0.332	37.8	20.5
Maryland	MD	0.102	0.122	0.249	0.472	-2.6	-1.4
Maine	ME	0.237	0.059	0.274	0.571	-7.0	-3.4
Michigan	MI	0.160	0.089	0.291	0.540	-9.6	-5.2
Minnesota	MN	0.193	0.088	0.275	0.556	-7.6	-3.8
Missouri	MO	0.146	0.120	0.299	0.565	-15.9	-8.4
Mississippi	MS	0.129	0.196	0.383	0.708	-32.8	-17.8
Montana	MT	0.179	0.071	0.561	0.811	-53.8	-37.3
North Carolina	NC	0.124	0.150	0.247	0.522	0.5	0.3
North Dakota	ND	0.192	0.106	0.852	1.150	-69.5	-51.4
Nebraska	NE	0.120	0.102	0.296	0.518	-15.7	-9.0
New Hampshire	NH	0.154	0.063	0.219	0.436	12.8	6.4
New Jersey	NJ	0.131	0.092	0.254	0.476	-2.1	-1.1
New Mexico	NM	0.128	0.052	0.330	0.509	-14.9	-9.7
Nevada	NV	0.089	0.067	0.209	0.364	20.0	11.4
New York	NY	0.096	0.024	0.198	0.318	24.0	14.9
Ohio	OH	0.135	0.109	0.276	0.520	-8.3	-4.4
Oklahoma	OK	0.120	0.142	0.346	0.608	-26.4	-15.0
Oregon	OR	0.099	0.071	0.215	0.386	15.0	8.4
Pennsylvania	PA	0.118	0.097	0.250	0.465	1.6	0.9
Rhode Island	RI	0.039	0.026	0.208	0.273	16.8	12.8
South Carolina	SC	0.137	0.165	0.276	0.578	-10.1	-4.8
South Dakota	SD	0.104	0.176	0.371	0.652	-32.8	-18.7
Tennessee	TN	0.112	0.153	0.303	0.569	-16.4	-8.8
Texas	TX	0.106	0.129	0.332	0.567	-24.8	-14.5
Utah	UT	0.143	0.050	0.247	0.440	2.7	1.5
Virginia	VA	0.112	0.114	0.253	0.480	-3.4	-1.8
Vermont	VT	0.194	0.053	0.247	0.493	2.2	1.1
Washington	WA	0.121	0.069	0.218	0.407	15.0	8.0
Wisconsin	WI	0.167	0.099	0.276	0.542	-7.8	-4.0
West Virginia	WV	0.114	0.111	0.314	0.539	-18.2	-10.6
Wyoming	WY	0.134	0.067	0.449	0.651	-42.7	-29.5

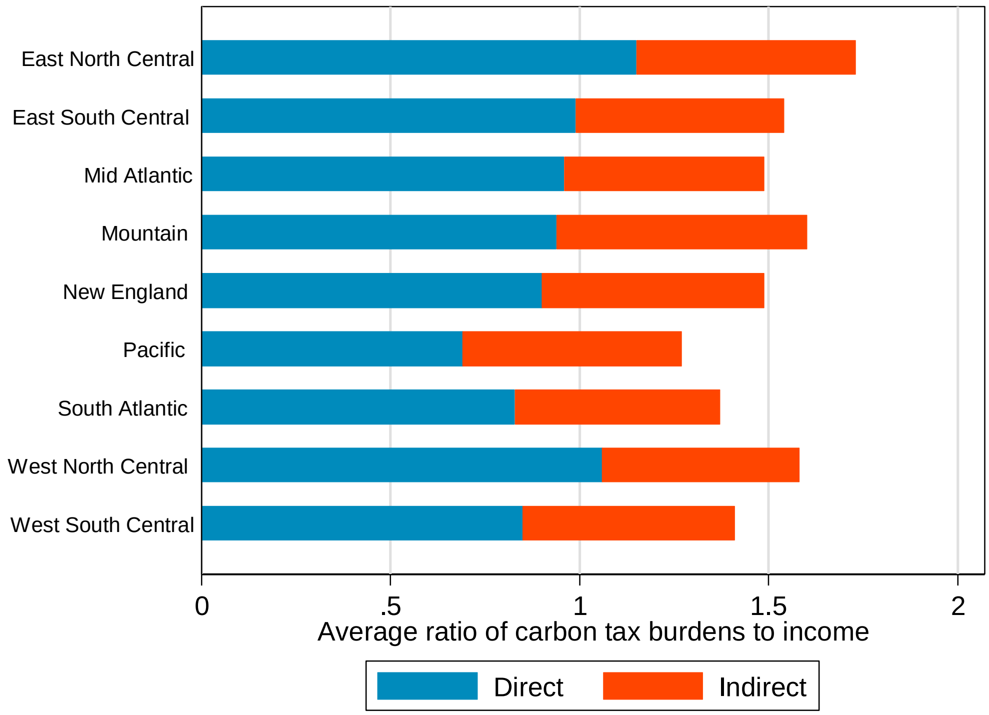

Figure 11 Regional Distribution of Burden. Source Table 7 of Mathur and Morris (2012)

Appendix B – Data Construction

Computing the matrices presented in section II requires the construction of the A, D and B matrices and vectors. For the input-output matrices of U.S. sub-national regions, A^r, we rely on data compiled by the IMPLAN group. IMPLAN constructs state-level input-output matrices from the national input-output table provided by the BEA as well as the National Income and Product Accounts (NIPA). Average (national) input coefficients are adjusted to match state-level output totals, which are themselves computed from both the BEA's output series and the U.S. Census Bureau's Annual Survey of Manufactures.[8] The input-matrices for other countries are taken from the Global Trade Analysis Project GTAP version 7 dataset as discussed in Caron and Rausch (2013).

The domestic final demand vectors for U.S. states are also taken from IMPLAN which compiles them from Household Personal Consumption Expenditures (PCE) of the BEA's National income and product accounts (NIPA) as well as the Consumer Expenditure Survey (CES).

For energy goods (refined oil, coal, gas and electricity), we replace both the input requirement data in A and the final demand data in D with state-level data from the EIA's State Energy Data System (SEDS) dataset. This provides us with accurate final demand data for all energy goods, as well as aggregate energy input requirements for industry, agriculture and services at the state level.

MRIO analysis requires disaggregated estimates of input-output flows (A^{rs}) and demand flows (y^{sr}) on a bilateral basis. Such information is typically not available as bilateral trade flows do not distinguish between intermediate or final consumption trade. Instead, we use a bilateral trade matrix by sector and share out input requirements and final demand according to the aggregate shares. That is, we assume that the share of final goods purchased from a particular region equals the share of imports from this region. For example, this means that although we know the amount of clothing exported from Texas to California, we do not how much of it is purchased as final goods to households. This value is thus assumed to correspond to the value of all imported clothing consumed by households in California multiplied by Texas' share of imports of clothing to California. The same is done to infer the bilateral sourcing intermediate goods for each sector. The bilateral trade matrix, per sector, is built from four different sources. First, bilateral trade flows between states of the US are taken, for the sectors for which the data is available (mostly manufacturing and agricultural goods), from the Bureau of Transportation statistics' Commodity Flow Survey (CFS). For services, bilateral trade flows are built such as to match state-level import and export totals (which are backed out using production and consumption data), with bilateral shares generated by a gravity model. Second, Import and export totals for energy goods are taken from SEDS.

Third, bilateral U.S. state-to-country trade flows are based on the U.S. Census Bureau Foreign Trade Statistics State Data Series (U.S. Census Bureau, 2010). Bilateral exports and imports are taken from, respectively, the Origin of Movement (OM) and State of Destination (SD) data series. The OM and SD data sets are available at the detailed 6-digit HS classification

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[8] Information about IMPLAN data is available at http://implan.com/V4/index.php?option=com_multicategories&view=categories&cid=241:datainformation&Itemid=71 .

level, which permits aggregation to GTAP commodity categories. Finally, trade flows between countries outside of the US are taken from GTAP.

There is considerable heterogeneity in the carbon content of electricity within the United States. Given the pooled nature of electricity production and transmission, one cannot assume that electricity produced in a given state is consumed in that state. Following the approach taken in Rausch, Metcalf, Reilly and Paltsev (2010, 2011), we consider the carbon intensity of electricity to be constant within electricity pools. We define six regional electricity pools based on NERC regions and ISO's: Alaska, Western, ERCOT, Eastern with New England and NY broken out based on electricity flows within the interconnects. We broke NE and NY out of the Eastern Interconnect given the limited electricity trade flows between these two regions and the rest of the interconnect. So the Western region comprises CA, the MOUNT, and PACIF collection of states and the Eastern Interconnect comprises NEAST, SEAST, and FL. Note that electricity is a homogeneous commodity within each of the six pools and non-traded across the pools. Table 6 Geographic regions and electricity displays the mapping between U.S. regions and electricity pools.[9]

Table 6 Geographic regions and electricity pools

Geographic Region	**Electricity Pool**
California	West
Mountain	West
Pacific	West
Texas	Texas
Mid-Atlantic	East
Midwest	East
Southeast	East
Florida	East
New England	New England
New York	New York
South Central	East
North Central	East

The sectors included in the dataset are listed in Table 7 below.

[9] We have also modeled interstate electricity trade through a bilateral trade matrix extracted from the National Renewable Laboratory's ReEDS model. The ReEDS model describes electricity flows between 136 Power Control Areas (PCAs) and represents existing transmission constraints. The carbon content of consumption is substantially the same whether we use our approach or ReEDS modeling.

Table 7 Sectors in the dataset

Code	Description	Code	Description
ATP	Air transport	OAP	Animal products nec -- with raw milk, wool, silk-worm cocoons
B_T	Beverages and tobacco products	OBS	Business services nec
C_B	Sugar cane, sugar beet	OCR	Crops nec
CMN	Communication	OFD	Food products nec
CMT	Bovine meat products	OFI	Financial services nec
CNS	Construction	OIL	Petroleum, coal products
COL	Coal	OME	Machinery and equipment nec
CRP	Chemical, rubber, plastic products	OMF	Manufactures nec
CRU	Crude oil and natural gas	OMN	Minerals nec
CTL	Bovine cattle, sheep and goats, horses	OMT	Meat products nec
DWE	Dwellings	OSD	Oil seeds
EEQ	Electronic equipment	OSG	Public Administration, Defense, Education, Health
ELE	Electricity	OTN	Transport equipment nec
FMP	Metal products	OTP	Transport nec
FRS	Forestry	PCR	Processed rice
FSH	Fishing	PFB	Plant-based fibers
GAS	Gas manufacture, distribution	PPP	Paper products, publishing
GRN	Grains -- paddy rice, wheat, and cereal grains nec	ROS	Recreational and other services
I_S	Ferrous metals	SGR	Sugar
ISR	Insurance	TEX	Textiles
LEA	Leather products	TRD	Trade
LUM	Wood products	V_F	Vegetables, fruit, nuts
MIL	Dairy products	VOL	Vegetable oils and fats
MVH	Motor vehicles and parts	WAP	Wearing apparel
NFM	Metals nec	WTP	Water transport
NMM	Mineral products nec	WTR	Water

Table 8 Countries and international regions in dataset, sorted by share of US trade

	imports from US (bn$)	emb CO_2 in imports from US (Mt CO_2)	exports to US (bn$)	emb CO_2 in exports to US (Mt CO_2)	largest partner		imports from US (bn$)	emb CO_2 in imports from US (Mt CO_2)	exports to US (bn$)	emb CO_2 in exports to US (Mt CO_2)	largest partner
Canada	198.8	101.0	193.9	106.2	NEAS	Ukraine	1.6	0.8	2.0	5.4	NEAS
Mexico	113.7	72.8	123.8	56.7	TX	Rest of East Asia	0.7	0.4	2.4	3.9	NEAS
China	48.7	24.7	141.6	245.7	CA	Bangladesh	0.5	0.3	2.4	1.4	NEAS
Japan	84.8	35.3	110.8	36.4	CA	Czech Republic	2.3	0.9	1.7	1.7	NEAS
Germany	62.2	30.1	73.0	25.1	NEAS	Luxembourg	6.8	0.9	1.5	0.6	NEAS
United Kingdom	57.7	24.8	56.7	19.4	NEAS	Morocco	1.2	0.6	1.4	1.0	NEAS
Korea	40.2	21.1	41.4	26.3	CA	Sri Lanka	0.4	0.2	1.7	1.2	NEAS
Rest of Western Asia	36.7	13.3	49.2	49.3	TX	Cambodia	0.1	0.0	1.6	0.9	CA
France	33.5	16.0	30.3	9.4	NEAS	Slovakia	0.6	0.3	1.3	0.9	CA
Taiwan	25.1	11.8	29.8	24.7	CA	Croatia	0.7	0.4	1.1	0.7	NEAS
Italy	21.5	10.3	28.0	12.5	NEAS	Romania	1.1	0.5	0.8	1.5	NEAS
Belgium	19.0	13.4	16.4	8.0	NEAS	Slovenia	0.7	0.5	0.8	0.4	NEAS
Malaysia	13.1	5.3	23.2	16.2	CA	Rest of Eastern Africa	1.1	0.4	0.9	0.7	NEAS
Brazil	14.6	8.8	18.9	14.3	NEAS	Bulgaria	0.7	0.5	0.8	1.0	NEAS
Ireland	16.6	4.5	20.5	4.3	NEAS	Rest of Europe	1.0	0.6	0.6	0.9	NEAS
Singapore	20.8	9.5	13.0	6.5	CA	Rest of Oceania	0.8	0.4	0.8	0.8	CA
Venezuela	5.2	2.8	19.5	20.2	TX	Nicaragua	0.5	0.3	0.8	0.4	SEAS
Switzerland	14.0	7.4	14.9	5.0	NEAS	Rest of South African Customs Union	0.3	0.1	1.0	0.6	CA
Netherlands	18.7	10.1	11.5	7.5	NEAS	Lithuania	0.6	0.3	0.7	0.7	NEAS
Caribbean	13.1	9.9	10.4	9.9	FL	Kazakhstan	1.1	0.4	0.6	1.6	NEAS
Hong Kong	10.1	4.6	15.7	7.1	NEAS	Uruguay	0.5	0.3	0.6	0.3	NEAS
Thailand	8.5	4.0	15.0	16.9	CA	Malta	0.3	0.1	0.7	0.3	MOUN
Australia	18.9	9.2	9.4	7.6	NEAS	Cyprus	0.4	0.2	0.6	0.3	NEAS
India	8.8	4.2	14.0	24.6	NEAS	Tunisia	0.5	0.3	0.6	0.5	NEAS
Sweden	7.8	2.8	12.2	2.7	NEAS	Rest of Former Soviet Union	0.8	0.4	0.4	2.8	SEAS
Spain	10.6	5.8	8.5	4.4	NEAS	Rest of EFTA	0.7	0.3	0.5	0.3	NEAS
Russian Federation	7.8	3.2	9.6	30.8	NEAS	Estonia	0.4	0.2	0.4	0.4	NEAS
Nigeria	2.3	1.0	10.9	4.2	TX	Rest of South America	0.4	0.4	0.3	0.2	FL
Indonesia	5.3	2.4	9.4	11.3	SEAS	Mauritius	0.2	0.1	0.5	0.3	NEAS
Turkey	5.1	4.1	5.1	4.9	NEAS	Belarus	0.3	0.1	0.5	1.4	NEAS
Austria	6.8	2.6	6.6	2.2	NEAS	Rest of South Asia	0.4	0.2	0.4	0.3	NEAS
Colombia	5.1	3.3	5.7	3.1	FL	Rest of Southeast Asia	0.1	0.1	0.5	0.5	CA
Rest of Central America	4.8	4.5	4.5	1.8	SEAS	Madagascar	0.1	0.0	0.5	0.2	NEAS
Denmark	4.9	2.5	6.4	2.0	NEAS	Iran	0.7	0.1	0.3	1.1	SEAS
Norway	3.2	1.4	7.1	3.7	NEAS	Bolivia	0.3	0.2	0.3	0.4	FL
Philippines	4.4	1.9	6.3	4.3	CA	Panama	0.2	0.1	0.4	0.4	FL

South Africa	4.3	2.5	4.7	10.6	NEAS	Ethiopia	0.6	0.2	0.2	0.3	FL
Chile	4.1	2.7	4.2	3.1	NEAS	Rest of North America	0.5	0.3	0.1	0.1	NEAS
Rest of North Africa	2.6	1.2	5.5	5.6	TX	Latvia	0.3	0.2	0.2	0.2	NEAS
Vietnam	2.0	0.9	5.1	6.0	CA	Paraguay	0.6	0.2	0.1	0.1	FL
Argentina	4.1	2.6	3.2	4.4	TX	Azerbaijan	0.5	0.2	0.1	0.3	TX
Egypt	3.5	1.4	4.0	7.8	NEAS	Georgia	0.3	0.2	0.1	0.1	SEAS
Finland	2.9	1.5	3.6	2.5	NEAS	Tanzania	0.3	0.1	0.2	0.2	NEAS
Peru	2.4	1.8	3.2	1.1	NEAS	Uganda	0.1	0.1	0.2	0.1	NEAS
Ecuador	1.9	1.4	3.5	1.1	CA	Senegal	0.2	0.2	0.1	0.1	NEAS
Pakistan	2.7	1.4	3.2	2.7	NEAS	Botswana	0.1	0.0	0.2	0.2	NY
Greece	4.1	2.7	1.9	1.0	NEAS	Albania	0.2	0.1	0.1	0.1	NEAS
New Zealand	2.9	1.4	3.2	2.0	NEAS	Armenia	0.2	0.1	0.1	0.1	SEAS
Costa Rica	3.4	2.0	2.5	0.9	SEAS	Mozambique	0.2	0.1	0.1	0.1	NEAS
Rest of South Central Africa	1.4	0.5	3.8	0.8	TX	Zimbabwe	0.1	0.0	0.1	0.3	NEAS
Guatemala	2.8	2.5	1.6	0.7	TX	Malawi	0.1	0.0	0.1	0.1	SEAS
Rest of Central Africa	1.2	0.6	3.4	0.5	NEAS	Rest of Eastern Europe	0.1	0.1	0.1	0.1	NEAS
Poland	3.2	1.4	2.4	2.7	NEAS	Zambia	0.1	0.1	0.0	0.0	NEAS
Hungary	3.0	1.1	2.3	1.1	NEAS	Kyrgyzstan	0.1	0.0	0.0	0.1	NEAS
Portugal	1.6	0.7	2.4	1.2	NEAS	Laos	0.0	0.0	0.0	0.0	NEAS
Rest of Western Africa	1.9	1.4	1.6	0.7	TX	Myanmar	0.1	0.0	0.0	0.1	NEAS

Appendix C - Decomposition

This Appendix presents an algebraic description of the 4 set of assumptions in the decomposition presented in Section 4. In each case, we explain how E_C^r, the emissions embodied in consumption, is computed.

- **US AVG – Average US intensities.**

$$E_C^r = \bar{F}^{US-avg} \left(I - \bar{A}^{US-avg}\right)^{-1} \bar{C}^r$$

In which $\bar{F}^{US-avg}$ is the 1 by n vector of average US CO_2 intensities of output, $\bar{A}^{US-avg}$ is the n by n average input-output matrix for the US and $\bar{C}^r$ is redefined as the n by 1 vector of consumption in r (not bilateral): $\bar{C}^r = \sum_s y^{sr}$.

- **HMM - US AVG + ELE - US average intensities, except for electricity.**

$$E_C^r = \bar{F}^{US} \left(I - \bar{A}^{US}\right)^{-1} \bar{C}^r_{non-ele} + f^r_{ele}\, c^r_{ele}$$

Where f^r_{ele} is the average CO_2 coefficient of output for all states within region r's electricity pool.

- **US AVG+ELE+INT IMP – Using data on the intensity of international imports.**

$$E_C^r = \bar{F}^{US-avg,W}\ (I - \bar{A}^{US-avg,W})^{-1}\ \overline{C^r_{w\,non-ele}} + f^r_{ele}\, c^r_{ele}$$

Where $\bar{F}^{US-avg,W} = [\,\bar{F}^{US}\ f^1\ \ldots\ f^{r \nexists US}]$ is the a vector of size 1 by (number of international regions +1) and

$$\bar{A}^{US-avg,W} = \begin{bmatrix} \bar{A}^{US} & \cdots & A^{US,R} \\ \vdots & \ddots & \vdots \\ A^{R,US} & \cdots & A^{RR} \end{bmatrix}$$

Is the input-output matrix that we would have (from GTAP for example) if the US was treated as a single unit. Finally, $\bar{C}^r_w$ would be an nR by 1 vector of r's consumption, where bilateral shares would simply correspond to US average bilateral shares $\propto^s_{US}$:

$$\bar{C}^r_w = \begin{bmatrix} \propto^1_{US}\ \bar{C}^r \\ \vdots \\ \propto^s_{US}\ \bar{C}^r \end{bmatrix}$$

- **AVG INT IMP – Using US average intensities for international imports.**

$$E_C^r = \bar{F}^{w-avg}\ (I - \bar{A}^{w-avg})^{-1}\ \overline{C^r_{w-avg}}$$

Where $\bar{F}^{w-avg} = [\,f^{state1} f^{state2}\ \ldots\ f^{stateS}\ \ \bar{F}^{US}]$ is the a vector of size 1 by (number of US regions regions +1) where international production is assumed to have the average US production intensity. And

$$\bar{A}^{w-avg} = \begin{bmatrix} A^{s1s1} & \cdots & A^{s1,US} \\ \vdots & \ddots & \vdots \\ A^{US,s1} & \cdots & \bar{A}^{US} \end{bmatrix}$$

is the input-output matrix that we obtain if the foreign imports where aggregated to a single unit and assumed to follow US intensities. Finally, $\bar{C}^r_{w-avg}$ would be a (number of US regions regions +1) by 1 vector of r's consumption, where all internationally sourced consumption is aggregated to into one element.

Appendix D – Trade flows

Table 9 CO_2 embodied in bilateral trade flows, including with the most important international trading partners (Mt CO_2)

	NENG	**NY**	**MATL**	**SEAS**	**FL**	**MWES**	**NCEN**	**SCEN**	**TX**	**MOUN**	**PACI**	**CA**	CHN	JPN	KOR	TWN	IND	CAN	MEX	VEN	FRA	DEU	ITA	GBR	RUS	XWS	Others	**Export**
NENG		5	3	2	1	3	1	1	1	1	0	1	1	1	1	0	0	3	0	0	1	2	0	1	0	0	4	**5**
NY	4		7	4	2	5	1	1	2	1	0	1	1	1	0	0	0	3	1	0	1	1	0	1	0	1	5	**4**
MATL	6	18		15	5	20	4	2	4	3	1	4	2	4	2	1	0	9	3	0	2	4	1	4	0	2	16	**1**
SEAS	5	8	19		28	32	10	12	13	7	3	11	4	6	2	1	0	15	7	0	2	6	2	4	1	2	24	**2**
FL	2	2	3	15		5	1	2	3	2	2	2	1	1	1	0	0	1	1	0	1	1	0	1	0	1	8	**5**
MWES	8	13	34	30	8		34	8	11	9	6	14	3	6	2	1	1	36	8	0	4	6	2	5	1	2	22	**3**
NCEN	2	3	5	9	4	36		8	9	9	3	10	2	3	2	1	0	10	4	0	1	3	1	2	0	1	11	**1**
SCEN	2	3	4	17	6	10	10		23	6	2	9	2	3	2	1	1	5	3	0	1	2	1	1	0	1	14	**1**
TX	4	5	6	16	8	13	11	22		14	3	11	6	6	6	4	1	14	35	1	3	5	2	4	1	4	40	**2**
MOUN	3	3	4	5	2	11	8	4	15		5	77	2	2	1	1	0	4	3	0	1	2	1	2	0	1	11	**1**
PACI	2	1	2	2	1	4	3	1	2	4		18	1	3	1	1	0	4	1	0	1	1	0	1	0	1	7	**7**
CA	5	3	4	6	3	9	5	3	9	13	6		3	6	3	2	0	6	5	0	2	3	1	3	0	1	15	**1**
CHN	8	14	26	36	8	35	12	4	22	6	9	66																
JPN	1	2	4	5	1	6	1	0	2	1	2	13																
KOR	1	1	2	4	0	5	1	0	3	1	1	8																
TWN	1	2	2	3	1	3	2	0	2	1	1	7																
IND	1	6	4	3	1	3	1	1	3	0	0	3																
CAN	10	10	11	10	2	33	8	2	4	4	5	8																
MEX	2	3	3	5	2	9	1	3	17	2	1	8																
VEN	0	0	4	1	2	1	0	4	7	0	0	0																
FRA	1	1	2	2	0	1	0	0	1	0	0	1																
DEU	2	1	6	5	1	4	1	1	1	1	0	2																
ITA	1	2	2	2	1	2	0	0	1	0	0	1																
GBR	1	1	4	4	1	2	1	1	2	1	0	2																
RUS	1	2	9	2	1	5	1	3	3	0	1	2																
XWS	1	6	9	3	1	3	1	6	10	1	1	7																
Others	14	22	43	36	13	25	7	9	24	8	6	35																
Import total	**113**	**139**	**284**	**314**	**104**	**395**	**183**	**107**	**194**	**122**	**81**	**325**																

Appendix E - Flow Charts

The following flow charts are meant to illustrate the various ways of accounting for flows of CO_2 emissions (represented as arrows). Full squares represent CO_2 emissions that are emitted at each point. Stripped squares represent embodied emissions. White squares mean that particular flow is not taken into account in that graph. The left hand side represents a generic "region" in the model, and the right-hand side represents an aggregation of its trading partners ("other regions"). The number of arrows illustrates the many types of CO_2 flows which are taken into account in MRIO analysis.

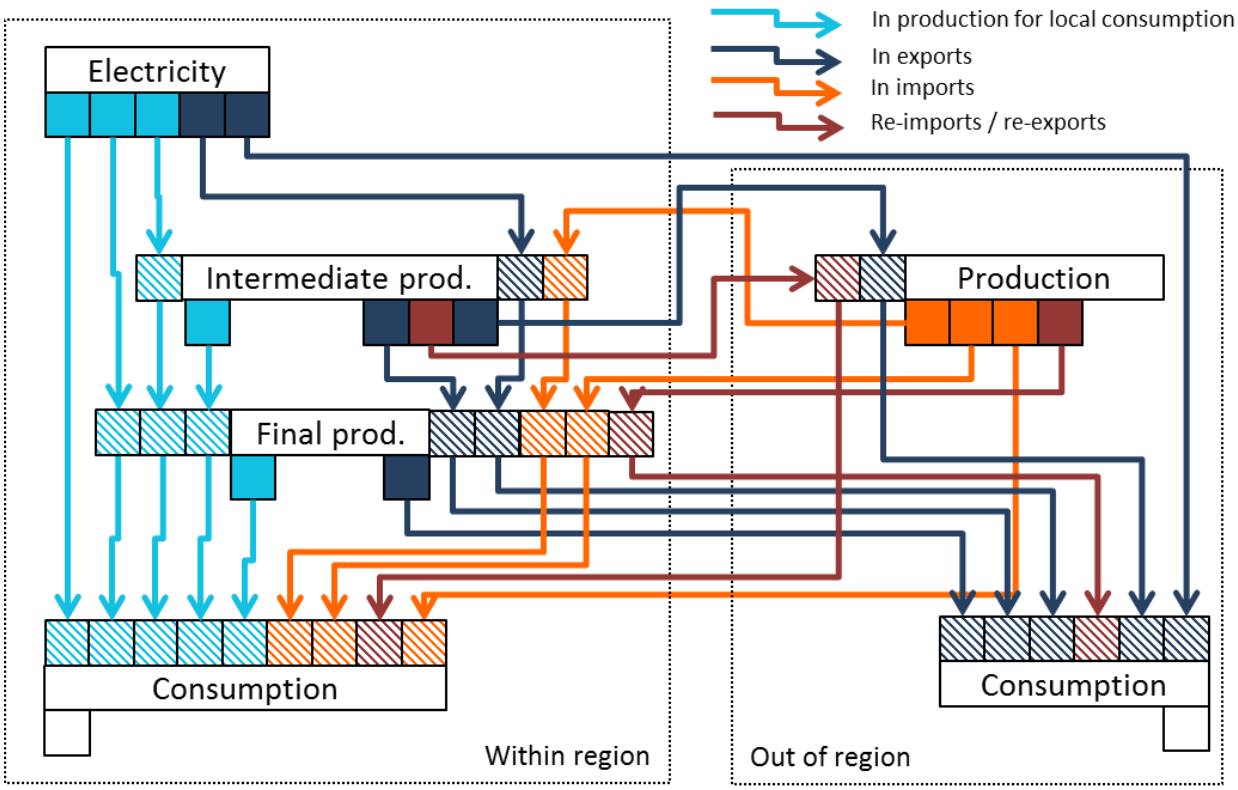

Figure 12 Flow chart describing CO_2 accounting of production, consumption and re-exports

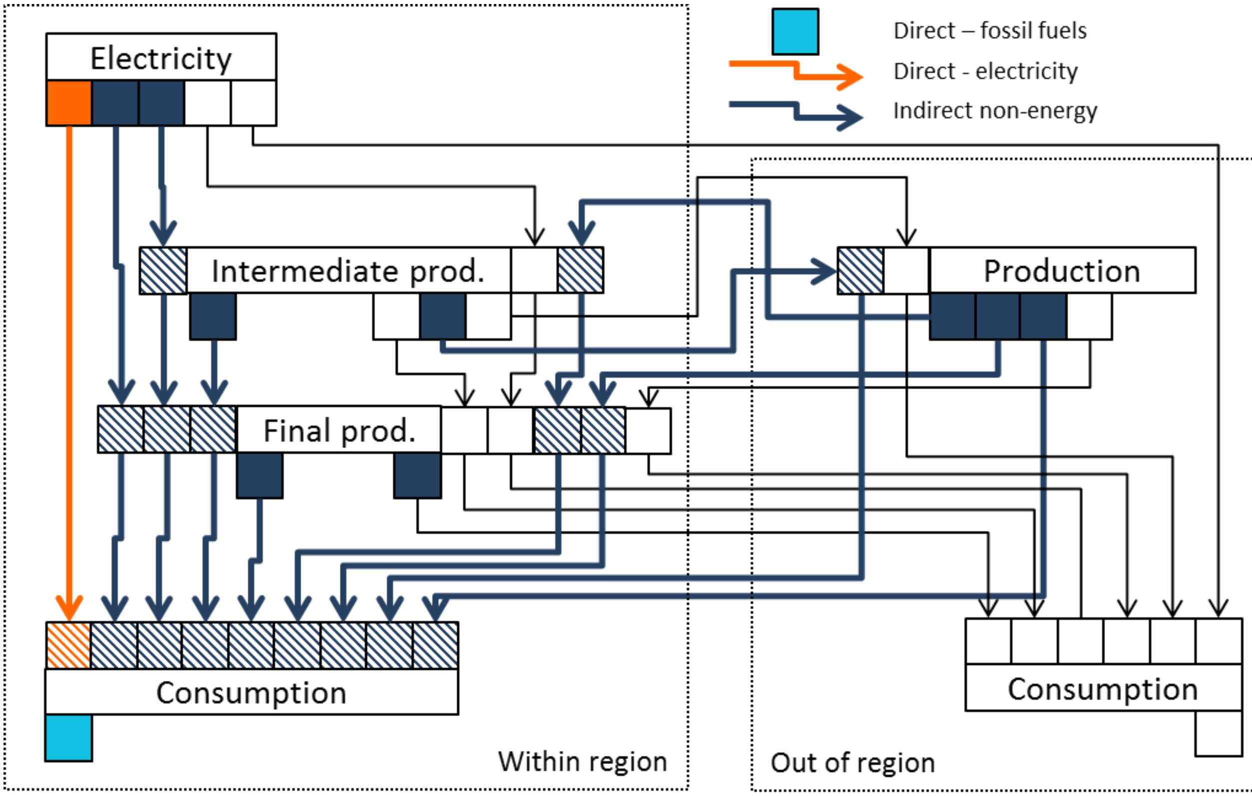

Figure 13 Flow chart describing the computation of the CO_2 content of consumption