One Man's Carbon is Another Man's Bread:
Further Understanding Differences in the Structure of Carbon Emissions

Lee Schipper and Fridtjof Unander
International Energy Agency

Scott Murtishaw
Lawrence Berkeley International Laboratory

In previous work, we summarized a new method for comparing carbon emissions from various countries. We call this the "mine-yours" comparison. In this paper, we provide details of the comparisons methodology, and carry out the comparison on a number of IEA countries. We calculate the average energy intensities **I** for a sample of countries ("yours") and multiply them by structural parameters **S** for a particular country ("mine"). Comparing the results with the vector **IS** product for the country in question gives us an estimate of how much energy that country would use with its own intensities but with average structural conditions. The converse can be calculated as well, that is, own structure and average intensities. Emissions can be introduced through the **F** term. The entire exercise can be carried out bilaterally as well. Results can be expressed on a per capita basis, or per unit of GDP. These calculations show where differences in the components of emissions lead to large gaps among countries, and where those differences are not important. These differences are important for negotiating changes in emissions.

We show which components cause the largest variance in emissions by sector. In households, home size, average winter climate, and space heating energy intensity appear to be the most important differentiating characteristics for space heating. For other residential energy uses the mix of fuels used to generate electricity (utility mix) is most important. In the service sector, value added per capita, built area per services value added and the utility mix are the most important factors. In manufacturing, output per capita, fuel mix, and the energy intensities of individual branches are the key differentiating factors. In personal and freight transportation, total activity per capita (in passenger- or tonne-km) is by far the most important distinguishing feature, but the energy intensity of travel or freight, particularly that of automobiles, and the share of modes used to haul freight are also important.

Interestingly, in the freight, manufacturing, and residential sectors, some important features appear to interact and offset each other. Several countries with very energy-intensive manufacturing output mix (Sweden, Norway, and Canada) also rely heavily on hydro or nuclear power, which significantly lowers emissions per unit of output. Similarly, the largest countries (Canada, U.S., Australia) have the highest levels of freight activity per unit of GDP, but these also have the smallest shares of carbon-intensive trucking, which offsets somewhat the influence of the geographical feature. Finally, the coldest countries tend to have the most efficient space heating. Thus careful analysis of emissions by sector reveals many characteristics that offset each other.

Overall, GDP differences account for the largest part of differences in per capita emissions among IEA countries. If we normalize emissions to GDP, then energy intensities, structural differences (including winter temperatures), and utility fuel mix share about equally in explaining the differences in the carbon/GDP ratios among countries. Individual binary comparisons can show extremes, however. Norway, with more than 40% of its primary energy in the form of hydroelectricity and most of the rest in the form of oil, is far less carbon-intensive (with average or even above-average energy intensities) than w. Germany[1], which has lower energy intensities but much more carbon-intensive fuels. Because some of the differences are "built in" – geography, climate, natural resources endowment – we conclude by questioning whether uniform emissions reductions targets make sense. Indeed, the "mine-yours" tool provides a valuable guide to important ways in which emissions may or may not be flexible. The tool does not prove that Country "A" can copy Country "B", but it does provide insights as to where to look for carbon reductions based on international comparisons.

Please address all correspondence to Lee Schipper, ljschipper@lbl.gov,
International Energy Agency, 9 rue de la Federation, 75739 Paris 15, France
phone 33 1 40576714, fax 33 1 40576749

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[1] For this study, we use only economic and energy data for western Germany, i.e. the territory of the former Federal Republic of Germany.

I. Broad Purpose

Since the 1992 Earth Summit at Rio de Janeiro, attention has focused on reduction of emissions of carbon dioxide and other greenhouse gases (GHG). With the signing of the Kyoto Protocol and adoption of goals or targets for GHG reduction, interest has grown to understand how each country's economic and human activity is linked to emissions (Schipper 1997). More important for international agreements, questions arise concerning what components underlie differences in emissions, and how and why the differences occur. This paper will chart out preliminary findings from detailed studies of 14 IEA member countries (which as a group we refer to as the IEA-14) energy-related carbon emissions covering (for most countries) the period from the early 1970s to the mid 1990s.

Exploring differences in the underlying factors that differentiate CO2 emissions is important for several reasons. First, some differences may be irreducible and consequently, some features of a country's economy may always lead to high (or low) emissions. Some of these "irreducible features" of an economy, such as its winter climate, its size and other geographical features, or its natural resource endowment, may force key parts of the emissions pattern away from the negotiating table. Second, differences in emissions patterns may indicate differences in the rates at which emissions can be lowered or at least restrained. Third, some of the variations in emissions will arise because of differences in energy supply or energy-use technologies, two aspects of the energy-economy link that may be changed. Finally, some parts of the differences in emissions among countries arise because of differences in policies, be they energy policies, fiscal policies, or other policies. By understanding how underlying components of emissions differ among countries, these policies, some of which are hidden far from the energy sector, might be unveiled to suggest useful ways of reducing or avoiding emissions.

Among the issues that will be confronted in ongoing GHG policy debates is the extent to which future emissions targets will be set on a per capita basis or pegged to economic performance. The choice of metric can have a dramatic effect on relative rankings for certain countries. Thus, the implications for the necessary reductions in carbon emissions will be quite different. As an example, the relative rankings of emissions from heavy manufacturing normalized to both total GDP[2] and population are given in Figure 1. The shaded portion of each bar represents per capita emissions while the outline represents the emissions scaled to GDP. Canada and Japan, which both have about average emissions per capita, are both higher than average when emissions per GDP are considered. Normalization to GDP would also imply that Finland, the Netherlands, and Australia would have to meet more stringent reduction targets in order to come more into line with the other IEA-14 countries. Findings in this paper are expressed primarily in terms of emissions per capita, but for some sectors we contrast these figures with actual emissions normalized to GDP.

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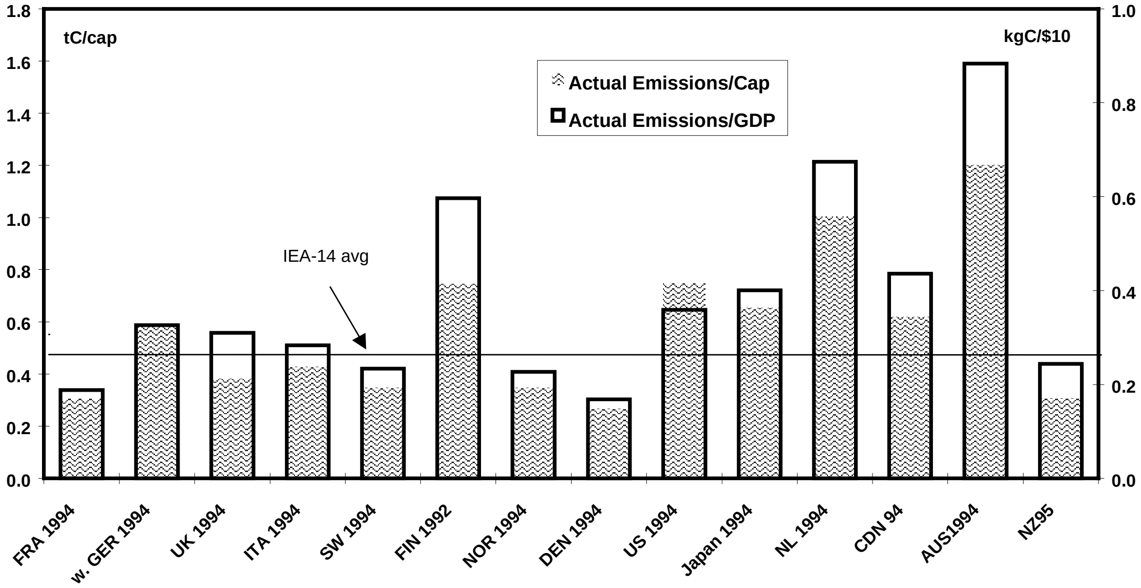
[2] All GDP and value added figures used in this report are given in 1990 U.S. dollars, adjusted for purchasing power parity.

Figure 1. Emissions from Heavy Manufacturing, per Capita and per GDP



The data used for this study are drawn from an International Energy Studies database of international energy and economic statistics at the Lawrence Berkeley National Laboratory. This database relies on raw data from official national energy balances where possible. For economic indicators OECD accounts are used.

II. Background: Decomposition and STRINT

The mine-yours method grew out of our work using decomposition methods to examine changes in energy use and carbon emissions over time (Greening et al. 1996; Schipper et al. 1997; Greening et al. 1997). In these decompositions, changes in total energy use for each sector are disaggregated into activity, structure, and intensity terms (hence "STRINT"). Depending on the sector activity is measured either as value added, passenger-kilometers (pkm), tonne-kilometers (tkm), population, or built area. Intensity is simply a measure of how much energy is consumed per unit of activity. Generally, structure is defined as the composition of subsectoral shares of sectoral activity. In the manufacturing sector, for example, structure is defined as the relative shares of each industry branch in total manufacturing value added. For carbon emissions decompositions we include two additional terms: one to account for changes in end-user fuel mix (fuel mix) and another for changes in the utility fuel mix (utility mix). Changes in energy use or carbon emissions are attributed to the underlying decomposition factors to determine the direction and magnitude that these effects have had over time.

Mine-yours analysis uses the same decomposition terms[3] but rather than tracking changes over time they are used to compare values across countries for a single year. We calculate an average substitution factor for each term and that value is substituted for each country's own value while holding the other terms constant. When a comparison is made between one country and the group average, that country's own share in the average is left out. This approach prevents large countries like the U.S. and Japan from exerting a strong pull on the averages to which they are compared.

Since the mine-yours carbon emissions calculations are largely based on mine-yours energy results, it is important to understand how the latter are performed. To demonstrate how the activity per capita, intensity, and structure terms are calculated, we take examples from the manufacturing sector. More detailed descriptions of these substitutions for each sector are given below.

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[3] The activity term, per se, is not used. It would not be helpful to ask, "How much carbon would Norway have emitted if it had the same manufacturing output as w. Germany?" Instead each country's activity is scaled to its population and differences in the ratios of activity per capita are used to calculate mine-yours results.

The mine-yours intensity result illuminates the impact of differences in subsectoral energy intensity on total sectoral energy use. To determine the intensity effect's part in explaining differences in manufacturing energy consumption we calculate an average intensity for each branch. The average intensity for each branch is multiplied by the actual national output for that branch. To illustrate how this substitution works we use an example from the iron and steel industry. In 1994 U.S. iron and steel makers consumed 1,946 petajoules (PJ) of energy, but at 47 megajoules (MJ) per dollar (the average intensity of the thirteen other IEA countries used in our study) the U.S. would have consumed 1,384 PJ. Similar calculations are performed for the other industry branches and summed to give the intensity substitution effect for the manufacturing sector. No affirmation that the U.S. could produce iron and steel with this intensity is implied; what is meant is that the calculation shows how large or small the difference in one component is relative to the same component in other countries.

The activity per capita substitution simply adjusts the total sectoral energy consumption to reflect the differences in aggregate output. For manufacturing this entails multiplying each country's own manufacturing energy consumption by the ratio of average manufacturing value added per capita to own value added per capita. Japanese manufacturers consumed 4,633 PJ of energy in 1994, but the average manufacturing value added per capita is less than 80% of Japan's. Thus, at average per capita output they would have consumed about 3,600 PJ.

For the structural substitution each branch's contribution to total manufacturing value added is adjusted to reflect its average share of total manufacturing value added. The structure-adjusted energy consumption for each industry branch equals the average share of that branch in total sector value added times own sectoral value added times own branch energy intensity. In other words this method sets the output shares of the country's industries equal to the average output shares and adjusts each branch's energy consumption proportionally.

The freight and passenger transport calculations are most similar to those in the manufacturing sector. The various modes of transport are analogous to the industry branches and distance that people or goods are moved provides a common metric of activity. Instead of industry shares of manufacturing output, the structural term for passenger and freight transport is defined as the modal shares of total pkm or tkm. Structural substitutions are performed by adjusting each mode's level of activity to reflect the average shares. For example, automobiles in Japan consumed 1,681 PJ of energy in 1994, but they carry a much lower share of total pkm than in the other IEA-14 countries (58% vs. 84%). At the average modal share Japanese automobiles would have consumed 2,434 PJ. The activity per capita substitution changes total travel or freight energy use by the ratio of average pkm/cap to own pkm/cap. The modal intensities equal energy consumed by each mode divided by the number of pkm or tkm carried by that mode. For each mode the intensity substitution is calculated by multiplying own pkm by the average energy use per pkm. These results are summed across the modes to arrive at the total sectoral level.

The residential sector is in some ways the most complicated for mine-yours analysis. Unlike the manufacturing sector where all subsectors can be compared using value added as a common metric, all of the residential end-uses have more distinct characteristics. For this reason, structural calculations are not performed for this sector. Moreover, due to definitional differences in the measure of activity, separate activity per capita terms are determined for each major end-use. Energy use is adjusted according to floor area per capita for space heating, air conditioning, and lighting; number of occupants per household (i.e. dwellings per capita) for water heating and cooking; and ownership per capita for appliances. More specifically, the activity-adjusted level of energy consumption for space heating and lighting equals own energy consumption times the average area per capita times own population. The space heating calculation is further modified to adjust for climate by multiplying the ratio of average degree-days to own degree-days. We would also like to adjust for the percent of dwellings with central heating since central heating systems use more energy for comparable heating requirements, but meaningful data are not available for two countries. The activity substitution for cooking and water heating is performed by multiplying own energy use by the square root of the ratio of own number of occupants per dwelling to average number of occupants per dwelling. This is based on observed trends in per household energy consumption for these end-uses. For appliances the own unit energy consumption (UEC) per appliance is multiplied by the number of appliances the country would have at average ownership rates. This can only be calculated for the major appliances[4] for which there are disaggregated UEC and ownership data. To estimate the activity effect for all appliances the ratio of the average total appliance energy consumption to average major appliance energy consumption is multiplied by the country's activity-adjusted major appliance energy consumption.

Average intensity substitutions for space heating and lighting are based on the energy consumption per unit of floor area. To determine the hypothetical energy consumed, the average energy per floor area is multiplied by own floor area. Cooking and water heating terms are found by multiplying the average energy per capita by own population. Note that these figures are structure-corrected by multiplying the results by the square root of the inverse of the occupants per dwelling ratio described above. For the mine-yours appliance substitution, we sum the products of the average UECs for each appliance and the own number of appliances. Similar to the structure substitution, total intensity-adjusted appliance energy demand is estimated by multiplying the major appliance intensity result times the country's own ratio of total appliance demand to major appliance demand.

Since energy data by end-use for the services sector are not as complete as they are for the residential sector, mine-yours calculations are not performed by end-use as they are for the residential sector. Instead, the intensity and structural substitution terms are determined at a higher level of aggregation. The structural term for the services sector is derived from the average ratio of services floor area to services value added. The structural substitution equals the average floor area to value added ratio times own services value added times own ratio of energy to floor area. We calculate the mine-yours intensity figure by multiplying the average energy consumption per floor area by own floor area.

In addition to providing insight into the underlying reasons for differences in aggregate energy intensities, the mine-yours method is also applied to carbon emissions. Mine-yours intensity and structure carbon substitutions for the services, freight, and passenger transportation sectors are based on the aggregate mine-yours energy results. The ratio of the mine-yours result to the actual energy consumed is multiplied by the actual carbon emissions. However, the aggregate structure and intensity carbon results for the manufacturing and residential sectors must be compiled by subsector since fuel mix (and hence the carbon released per unit of energy consumed) varies by subsector or end-use. The intrasectoral differences in fuel mix can significantly affect the aggregate results. To understand why, imagine a country with two industries, chemicals and iron and steel, which both generate the same value added and consume the same amount of energy. The chemicals industry uses mostly natural gas for its energy needs, while iron and steel relies predominantly on coal, which emits much more carbon per unit of energy. A given percent energy intensity reduction in either branch would have the same impact on aggregate energy intensity. However, the energy intensity reduction in iron and steel would yield a larger decrease in carbon emissions than the same reduction in the chemicals industry. To account for these intrasectoral differences, the actual carbon emissions of each branch (or end-use) are multiplied by that branch's ratio of the mine-yours energy result to the actual energy consumption. The resulting subsectoral mine-yours carbon emissions are summed to find the aggregate sectoral result.

As mentioned above, we add two additional terms to the mine-yours variables to analyze differences in aggregate carbon intensities. These terms account for differences in emissions owing to variations in fuel mix, one term for fuel mix at the end-user level and another for the fuel mix at the utility level. The fuel mix and utility mix calculations are the same for all sectors. The fuel mix method adjusts the country's own fuel mix to reflect the average shares of fuels in the sector. The formula for each fuel is the average share of fuel times own final energy times that fuel's carbon coefficient (a measure of carbon released per unit of fuel consumed).[5] The carbon coefficients for coal, oil, and gas are constant, but district heat and electricity coefficients must be determined for each country based on that country's inputs into the generation mix. Each country's own district heat and electricity carbon coefficients are used for the fuel mix calculation.

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[4] The major appliances include freezers, refrigerators, washers, dryers, dishwashers, and air conditioners.

[5] We use the simplified carbon coefficients for fossil fuels recommended by the Intergovernmental Panel on Climate Change (IPCC 1996). The IPCC carbon factors are 21.1 ktC/PJ for petroleum products, 15.3 ktC/PJ for natural gas, and 25.8 ktC/PJ for coal.

We use average utility coefficients in the utility mix formula. The mine-yours utility mix substitution equals own emissions from oil, gas, and coal plus own district heat energy times average district heat carbon coefficient, plus own electricity energy times average electricity carbon coefficient.

To gauge the magnitude of each effect we measure the factor of change from actual carbon emissions that each substitution yields. For an increase from actual, this is simply the ratio of the mine-yours result to the actual figure. If the substitution results in a decrease, the inverse of this ratio is used. Thus a substitution that would double emissions carries the same weight as a substitution that would cut them in half. In order to rank each substitution across all countries, we weight these ratios by the sectoral carbon emissions from each country and calculate the variance of these data points. Weighting the ratios in this manner gives a sense of the importance of each factor in terms of total carbon emitted and helps to prevent small outlier countries from skewing the results. A summary of the variances for all sectors is given in the appendix in Table A1.

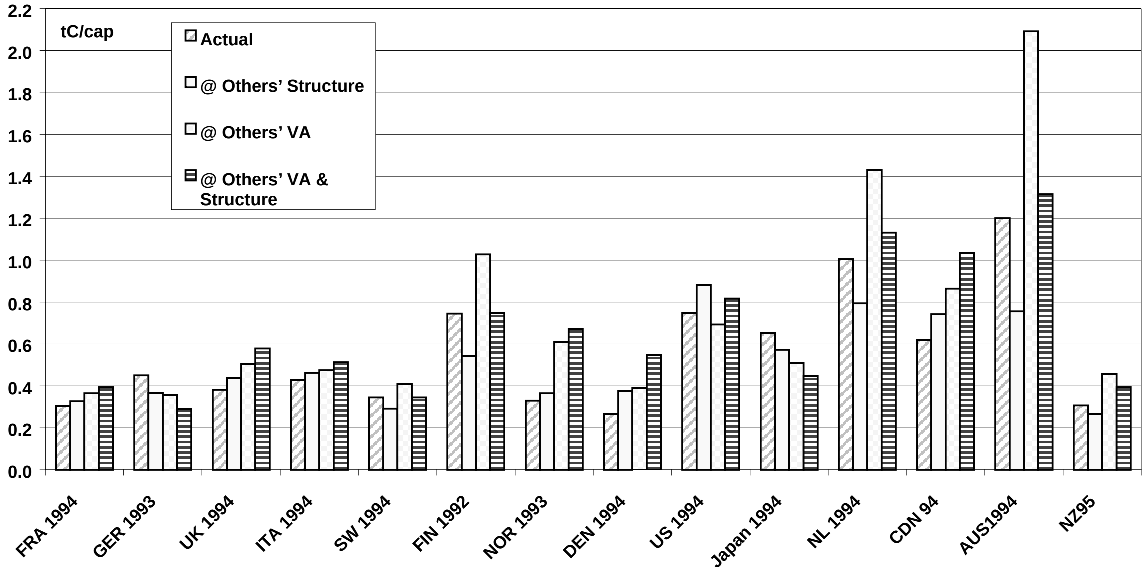
One final caveat must be added. The substitutions in this calculation assume that all of the mine-yours terms are separable. In reality they are not entirely separable, as we note in certain cases. Above all, low energy intensities, which may be associated with low energy costs, may stimulate activity levels, while high intensities may inhibit growth in activity levels. This kind of "rebound effect" is probably small for most sectors, but could be large for energy-intensive sectors like non-ferrous metals, heavy chemicals, or air travel, (Schipper and Grubb 2000). Thus it is important not to assume that the substitutions implied by the calculations, even if carried out, would give the resulting energy use implied by multiplying one country's intensities by another's activities. For carbon, however, the matter is more complex, since carbon does not have any real value (Birol and Keppler 2000). Since the carbon emissions here are tied to energy use, however, it is better not to assume that such a substitution would automatically give the emissions level implied by no interaction.

III. Mine-Yours Results by Sector

A. Manufacturing

The manufacturing sector is the largest emitting sector for energy-related carbon emissions in most of the IEA-14 countries. It is also a sector with an astonishing range of aggregate carbon intensities. While comparisons can be made at this aggregated level (Unander et al. 1999), they reveal little about the underlying causes for the differences among countries. Our mine-yours analysis is intended to help illuminate the underlying causes behind the aggregate differences.

Figure 2. Heavy Manufacturing Emissions, with Others' Structure, Value Added, and Structure/Value Added Combined



For this sector we separate heavy manufacturing (i.e. raw materials processing industries such as pulp and paper or ferrous metals) from light manufacturing (food processing and all remaining manufacturing industries) since the characteristics of these industries are quite different. Figure 2 depicts the actual metric tonnes of carbon emitted per capita from the heavy manufacturing industries as well as emissions at average structures and value added per capita. While structure substitutions generally induce only modest changes in emissions, they do play a large role in boosting or restraining emissions in certain countries. Australia in particular has an extremely carbon-intensive manufacturing mix compared to the other IEA-14 countries. Australia, Finland, and the Netherlands would have all emitted 20% or less carbon if they had the average manufacturing mix of the other countries. At the other extreme, Denmark would have emitted considerably more carbon at average structure.

Table 1. Heavy Manufacturing Energy Intensities and Value Added Shares by Branch

	Shares of Manufacturing Value Added						Energy Intensities in MJ/$				
Country	**Pulp & Paper**	**Chemicals**	**Minerals**	**Iron & Steel**	**Nonfer-rous**	**Light Manf**	**Pulp & Paper**	**Chemicals**	**Minerals**	**Iron & Steel**	**Nonfer-rous**
FRA	3%	11%	4%	3%	2%	77%	20.2	15.1	22.5	53.7	16.4
GER	3%	11%	4%	5%	2%	74%	13.2	12.3	19.3	31.4	12.9
UK	3%	13%	4%	3%	1%	76%	17.3	8.8	19.1	58.2	29.5
ITA	3%	8%	7%	4%	1%	78%	17.5	18.7	20.8	40.7	17.2
SW	10%	9%	2%	4%	2%	73%	76.5	9.3	31.3	57.9	26.5
FIN	14%	7%	4%	4%	1%	69%	104.7	32.8	24.3	97.9	31.1
NOR	6%	9%	3%	3%	6%	74%	73.9	44.2	54.0	161.3	128.8
DEN	3%	10%	4%	1%	0%	82%	14.4	7.3	43.7	28.0	12.6
US	5%	12%	2%	3%	2%	77%	48.4	25.4	36.3	66.3	33.1
JPN	2%	9%	4%	6%	2%	77%	26.9	9.9	22.5	43.6	16.8
NL	4%	17%	4%	3%	1%	72%	20.8	40.8	24.1	81.5	40.2
CDN	8%	3%	2%	3%	4%	79%	116.5	82.9	29.1	86.0	71.3
AUS	3%	8%	5%	4%	7%	73%	41.5	35.2	39.5	99.9	97.9
NZ	7%	12%	3%	4%	0%	74%	61.4	5.2	26.5	91.8	N/A*
Average	4%	11%	3%	4%	2%	77%	43.7	19.3	26.0	52.1	32.5

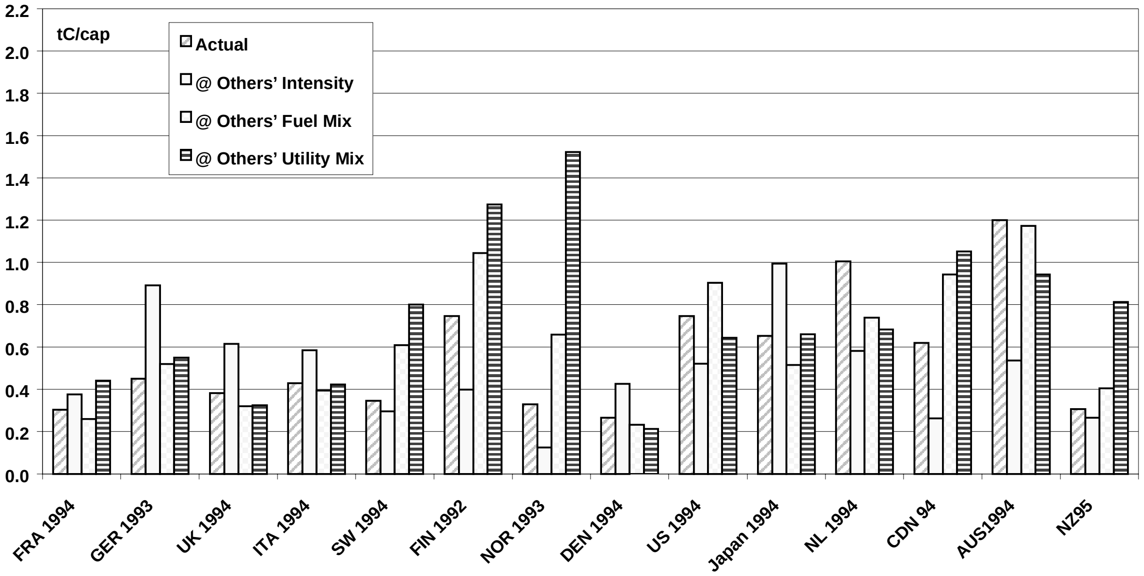
* Since New Zealand only provides aggregated data for "primary metals," data for nonferrous metals could not be disaggregated from the data given for iron and steel.

Table 1 illustrates in more detail how the structure results were derived. As value added shares are adjusted to reflect the averages, a given country's emissions will increase as output from light manufacturing is shifted to heavy manufacturing or as output within heavy manufacturing is shifted from a less carbon-intensive industry like chemicals, to a more carbon-intensive industry such as ferrous metals. Australia, which has a relatively large and carbon-intensive nonferrous metals industry would emit 37% less carbon at average structure. Set to average shares of manufacturing value, Australia's nonferrous metals industry would be reduced to about a quarter of its actual size while chemical industries, which are much less carbon-intensive, would increase about 40%. In contrast, Denmark, which has the largest share of light manufacturing in the IEA-14, experiences the largest increase in emissions from the structure substitution. At average shares, the pulp and paper, nonmetallic minerals, and nonferrous metals industries would all be larger while chemicals and ferrous metals would remain approximately the same.

Figure 2 also shows that differences in per capita manufacturing value added are a significant source of variation in per capita carbon emissions. Emissions decline from this substitution only in the U.S., w. Germany, and Japan. The final column for each country represents the combined effect of activity and structural differences in order to give a sense of the effect of differences in total demand for energy services. At the average demand for energy services, the emissions from Denmark and Norway would double while those from w. Germany would fall by over a third. Interestingly, the variance from the combined effects of structure and per capita value added is not much greater than either effect alone. This is due to the fact that in the U.S. and several other countries these effects offset each other.

The substitution of energy intensities yields significantly more variance than any of the other terms. The high degree of variance in the intensity substitutions results from a pronounced polarization of energy intensities among these countries, with countries such as the U.S., Australia, New Zealand, and Finland being much more energy-intensive than countries like Japan, west Germany, and Denmark. The results of the intensity and fuel mix substitutions are depicted in Figure 3.

Figure 3. Heavy Manufacturing Emissions, with Others' Intensity, Fuel Mix, and Utility Mix



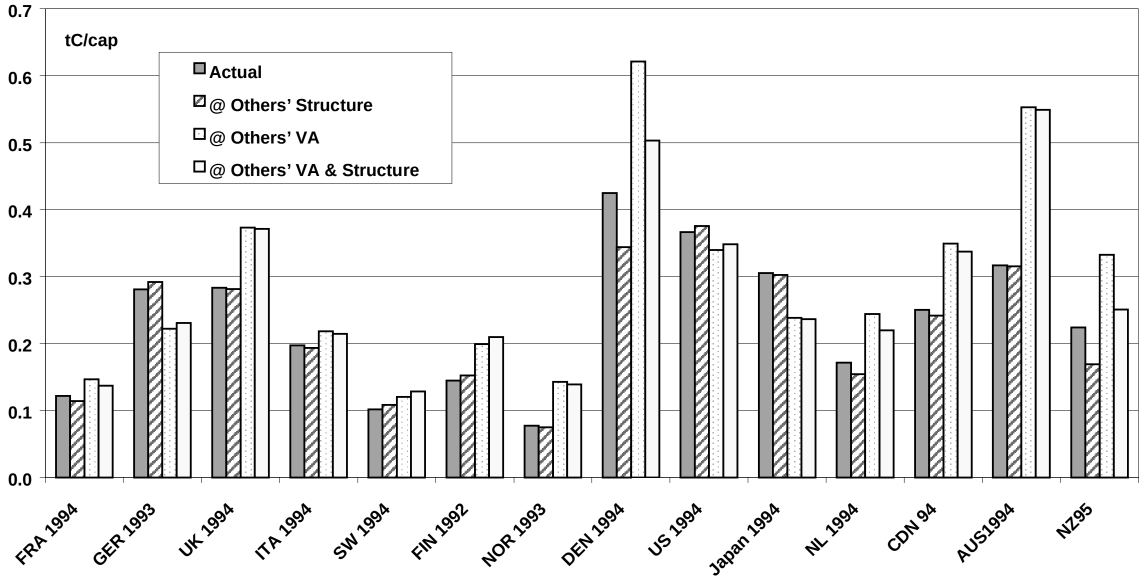
The information in Table 1 also helps to illustrate the derivation of the intensity substitution. For example, the pulp and paper industries in Canada and Finland are much more energy-intensive than the average. Thus, substituting the average energy intensity of the other countries for this industry will pull total emissions down. Keep in mind that as each country is compared to the average, its own energy consumption and value added are removed the average. When mine-yours results are calculated for large countries like the U.S. and Japan, their exclusion from the totals can dramatically change the averages from what is given in Table 1. For example, recall that when the mine-yours energy intensities are calculated for the U.S., the iron and steel intensity falls to 47 MJ/$.

Utility mix substitutions obviously have a profound effect on countries such as France, Sweden, Canada, Norway, Finland, and New Zealand that have high shares of nuclear and hydropower in their generation mix. With the exception of France, all of these countries would also experience an increase of 30% or more in emissions at average fuel mix. To some extent this is because the fuel mix substitution results in decreased shares of electricity in favor of fossil fuels, particularly for Norway, Sweden, and New Zealand. For Sweden and New Zealand the increase in emissions due to the fuel mix substitution is also enhanced by the large share of biomass in final energy, and this is principally responsible for the large fuel mix effects in Finland and Canada.

Light manufacturing, which consists of food processing and all remaining manufacturing industries, accounts for about three-fourths of manufacturing value-added in the IEA-14. However, these industries are on average much less energy- and carbon-intensive than the heavy manufacturing industries. Despite their share of value added they represent only about a third of manufacturing emissions.

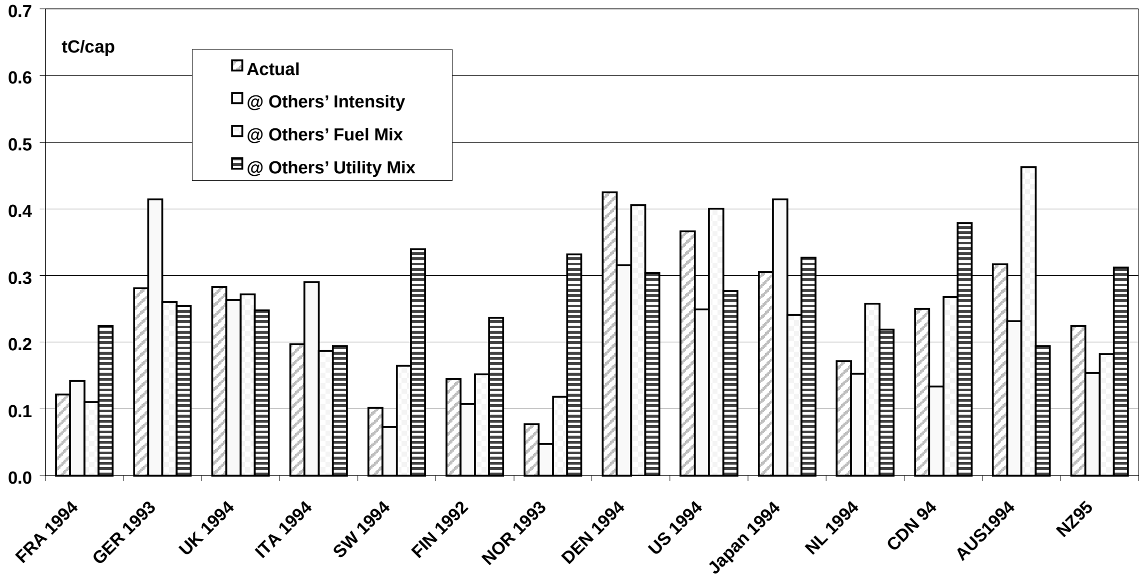
Among the light manufacturing industries, structural differences appear to be the least important factor differentiating carbon emissions. The only countries to experience a significant effect from this substitution are New Zealand and Denmark (see Figure 4). In New Zealand food processing constitutes a much larger than average share of value added among the light industries. Therefore, at average shares other manufacturing industries, which are significantly less energy-intensive than food processing, would increase. Since Denmark's light industries have the largest share of national manufacturing value added, the structure substitution leads to a shift of emissions from light to heavy industries. The per capita differences in value added generate more variance in the results. Since our computation of this effect is based on total manufacturing value added per capita, the changes are of the same magnitude for each country as they are for the heavy industries.

Figure 4. Light Manufacturing Emissions per Capita, with Others' Structure, Value Added, and Structure/Value Added Combined



For light manufacturing, as for the heavy industries, energy intensities play the largest role in differentiating carbon intensities. This is due to the sharp bifurcation of energy intensities between the high- and low-intensity countries. With the exception of the U.K. and Denmark, the groupings of more- and less-than-average intensity countries are the same as in the heavy industries.

Figure 5. Light Manufacturing Emissions, with Others' Intensity, Fuel Mix, and Utility Mix



Electricity constitutes a much larger share of final energy in the light industries than in the heavy industries (34% vs. 21% for the IEA-14). This is because heavy industries rely on so much high- and medium-temperature process heat, almost always supplied by direct combustion of fuel. Thus, utility mix has a relatively larger impact on differentiating emissions levels in light industry and generates the most variance after the intensity substitution. Differences in emissions owing to the fuel mix and per capita value added effects are approximately equal and significantly less important that intensity and utility mix. Norway and Sweden both experience increases from the fuel mix effect as shares of low-carbon electricity are reallocated to fossil fuels, primarily natural gas. Additionally, Sweden uses a high share of biomass, as does Australia. In the Netherlands an extremely large share of natural gas is apportioned to every other fuel source. Japan, the only country to experience a significant decrease from this effect, uses very large shares of oil in these industries, which at average fuel mix would lead to substantially more use of gas and some biomass.

B. Households

The residential sector is an important source of energy-related carbon emissions, consuming about one-fifth of the delivered energy in the IEA-14 countries. Emissions from the residential sector have been divided into two separate operations for the mine-yours analysis. We analyze space heating separately since it is such a large component of residential energy use and emissions (accounting for one quarter to three-quarters of sectoral emissions in most countries).

Actual per capita carbon emissions from space heating vary widely with a factor fifteen difference between the highest and lowest countries. Figure 6 depicts both the actual per capita emissions and the hypothetical mine-yours emissions. Activity per capita is the most important factor differentiating emissions among these countries. This is mostly due to the fact that this term has the largest impact on U.S. emissions. At the others' per capita floor area U.S. emissions would fall by approximately 20%.

Figure 6. Mine-Yours Analysis of Home Heating Emissions

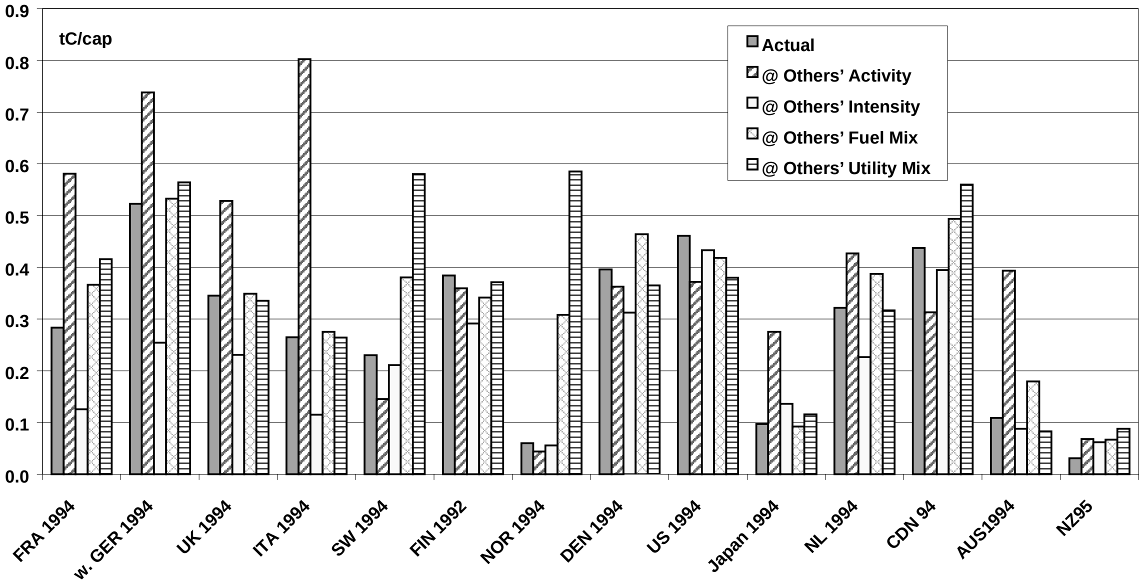
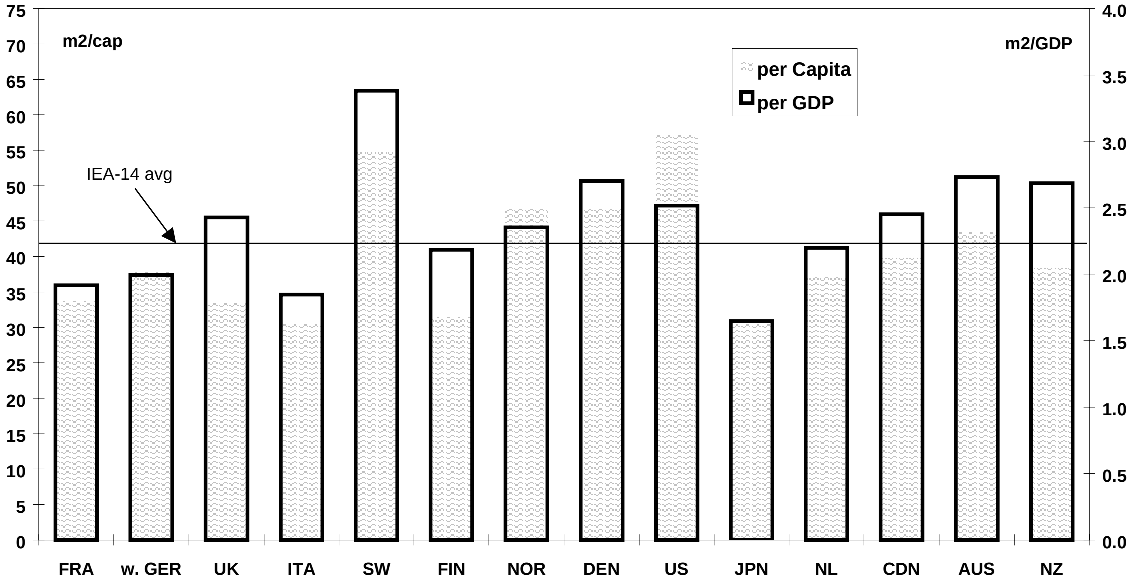


Figure 7 gives an idea how much of the activity variation is due to home sizes. The shaded area compares the IEA-14 countries when area is measured per capita, the metric used for the calculations represented in Figure 6. From this chart it becomes apparent that very little of the large activity difference attributed to Canada and Australia is due to the dwelling size, but is rather a reflection of their climates. For countries at the extremes such as the U.S. or Sweden, the differences in home size have a tremendous effect on space heating energy use. On the other hand, the climate in Italy or Japan is relatively mild, so a larger home than otherwise means less to emissions.

Figure 7. Residential Heated Area per Capita, and per GDP



Energy intensity is the second most important factor in terms of variance in the results, and it is the predominant term for France, w. Germany, Denmark, and the Netherlands. The remaining three terms all yield approximately equal levels of variance in their results and have considerably less impact. Utility-mix, however, had substantial effects on certain countries, particularly Norway, whose emissions would increase nearly ten-fold. This is due both to the high share of electricity used for home heating (65% of delivered energy) and the almost negligible carbon coefficient associated with electricity production there. Sweden and New Zealand also would experience more than a doubling of emissions at the average utility mixes for similar reasons. In these three countries, electricity use is high in part because electricity is inexpensive due to the low-carbon nature of hydropower, or in the case of Sweden, nuclear power. Were these countries to generate electricity from the thermal mixes of the others', costs would doubtless be higher, and thus usage lower. This is an example of how two terms, in this case fuel mix and intensity, interact.

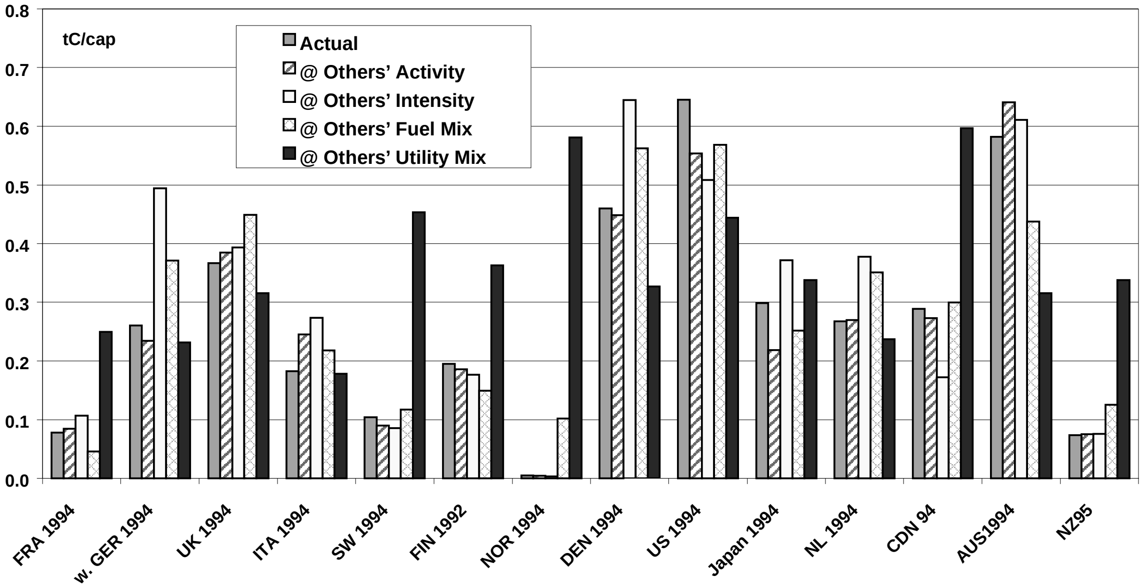
A little consideration (see Schipper, Haas, and Sheinbaum 1996) shows why electricity use is also important in Japan. Space heating is predominantly the domain of fossil fuels. The lack of a strong demand for space heating in Japan, and therefore low fossil fuel demand, combined with the popularity of heat pumps to provide heat in the mild climate, explains the large share of electricity used for space heating there. Australia, with an even warmer climate than Japan, is in a similar situation (Schipper et al. 2000). Oil and gas dominate space heating outside of the Nordic countries, which is why their emissions tend to be important in colder countries. But while electricity supply in Norway, Sweden, and to some extent Finland is not very carbon-intensive, it is much more carbon-intensive in Japan or Australia, giving the electricity part of household energy-related emissions in these two countries greater weight.

It is interesting to note the distinct regional trends that seem to offset each other. Italy, France, w. Germany, and the U.K. all have smaller than average per capita floor space. At the others' home sizes, all of their emissions would increase considerably. On the other hand, they are all more energy-intensive in terms of the energy used to heat a unit of floor space. In the Nordic countries, the opposite is true. Sweden, for example, has much larger home sizes per capita than every country but the U.S. and is one of the least energy-intensive.

Other home emissions arise mostly through the consumption of electricity for cooking, water heating, and running other appliances. Electricity accounts for about 60% of the delivered energy for these end-uses in the IEA-14. However, natural gas for cooking and water heating is a significant fuel source in some countries, and it accounts for most of the remaining energy demand.

Since electricity comprises such a large share of the total energy for these end uses, the utility mix is by far the predominant effect. The hypothetical per capita emissions from substitution of this term generate about three times the variance of any of the other factors. From Figure 8 it is apparent that Norway is an extreme outlier for this substitution. With Norway removed, the variance falls by more than half. Nonetheless, utility mix remains the most important effect. Utility mix is the most important effect in eight of the IEA-14 countries and equals the intensity effect in Denmark. The other terms are approximately equal in their impacts.

Figure 8. Mine-Yours Analysis of Other Home Emissions



Intensity is the next most important factor and is the predominant effect in w. Germany, Italy, and the Netherlands. The largest variations in end-use efficiencies are in water heating and cooking. We would expect more variation in these end-uses than in lighting or appliances because delivered energy demand is also partly a function of fuel mix. Much of the delivered energy content of natural gas and oil is lost through waste heat and incomplete combustion.[6] Thus, it requires more delivered energy to get a unit of "useful" energy from these fuels than it does from electricity. Lighting, not surprisingly, shows little variation in energy use per floor area, while appliance intensities fall somewhere in between.

Activity differences have the greatest impact only in Japan. Saturation adjustment for the major appliances accounts for some of this, since Japan has relatively high saturation levels for these products. However, the large drop stems mostly from the high share of electricity not accounted for by the major appliances. Recall that in our activity calculation, the sum of the saturation-adjusted consumption for the major appliances is multiplied by the ratio of the others' total appliance energy to major appliance energy to estimate the effect for all appliances. Since this ratio is much lower for the other countries this calculation significantly diminishes Japan's total appliance energy consumption.

The U.K. is the only country for which the fuel mix effect is predominant. This is due to the large share of natural gas used for water heating and cooking. Other than the Netherlands, the U.K. is the only country that provides more than half of its non-space heating home energy from gas.

The comparison suggests where carbon emissions might be reduced in this sector. First, substitution of gas for oil or coal in space and water heating and cooking is one avenue. Second, reduction in the carbon emissions from utilities would have an important impact on the household sector because of the high electricity share. Finally, improvements in end-use efficiency, particularly for electric appliances, would have an important impact in most, but not all, of the countries studied.

C. Services

The services sector accounts for energy used in most buildings not represented in the manufacturing and residential sectors (see Krackeler and Schipper 1999 for a review). Internationally compatible data for the services sector by main end use or by subsector do not exist; hence it is difficult to study the details of this sector. Instead, "structure" in this study is defined as the amount of floor space used per unit of services

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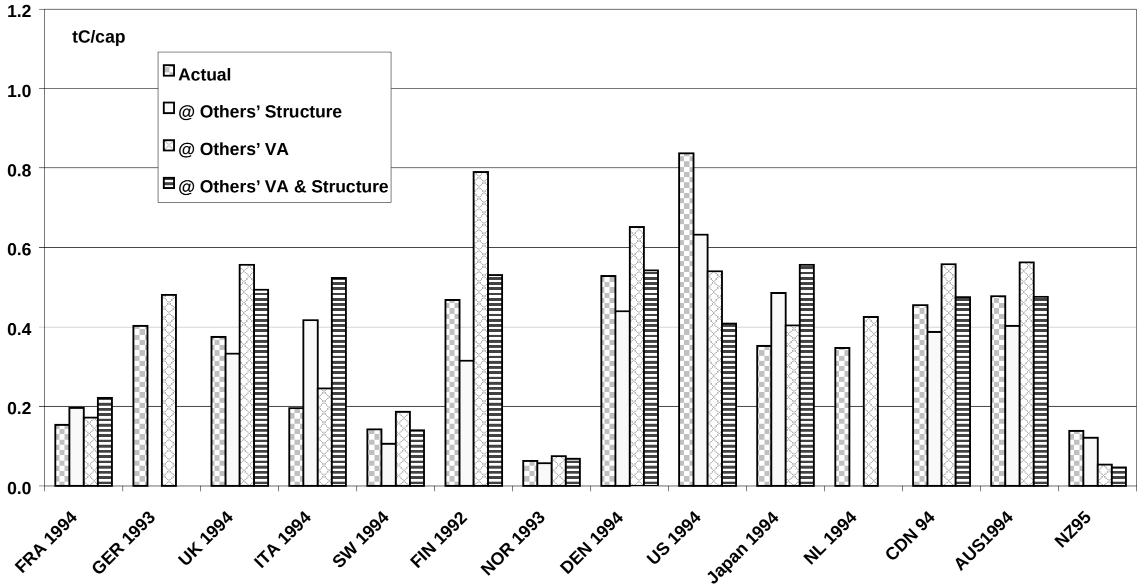
[6] To calculate the useful energy we multiply the delivered energy from fuels by the following coefficients: oil and gas (0.66), coal (0.55), and wood (0.55).

value added, which is the main difference between countries we can measure. Intensity is defined in terms of energy per unit of floor area. (The exceptions are w. Germany and the Netherlands, for which the floor space data are not available: for these two countries we have to assume that the ratio of floor area to service sector GDP is the average of all countries.) Intensity is defined as energy used per unit of sectoral value added.

In the mine-yours comparisons for this sector, the structural and per capita value added components emerge as the most important of the terms. Although half of the IEA-14 countries' services area per services value added are clustered around 1.5 to 1.6 m^2/\$1000 the spread among the remaining countries is quite large. Finland and Sweden top the list with 2.0 and 1.8 m^2/\$1000 respectively, while Italy, France, and Japan have ratios ranging from 0.7 to 1.1 m^2/\$1000. One likely explanation for this range is climate: the cold northern climate means there is little outdoor space that can be used in this sector compared with what is done in the aforementioned warmer countries.

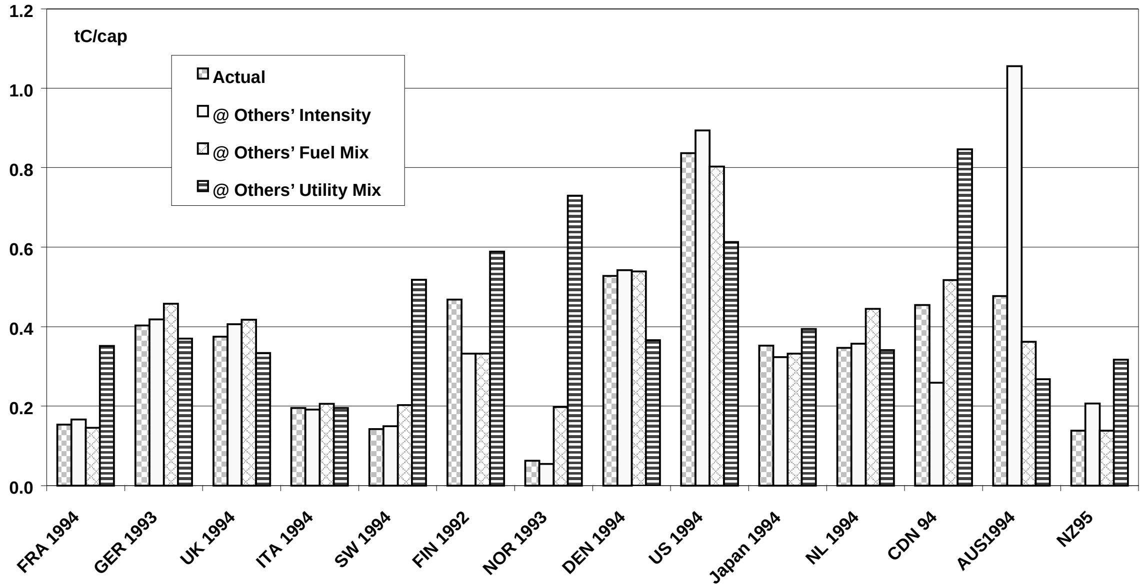
Figure 9. Service Sector Emissions, with Others' Structure, Value Added, and Structure/Value Added Combined



Given the high share of electricity used in the services sector, the utility mix substitution is, not surprisingly, a close third in terms of the variance generated. The pattern is the same here as it is in the other sectors: emissions in Australia, Denmark and the U.S. would fall, while those of Norway, France, Sweden, and New Zealand would increase substantially. The utility mix effect is most pronounced in those sectors having the highest shares of electricity, namely, services and other home emissions.

Intensity and fuel mix effects are relatively less important in differentiating emissions in this sector. The intensity substitution is only significant in reducing emissions in Finland and Canada and only significantly increases them Australia and New Zealand. Without reliably disaggregated data, it is not possible to say with certainty what end-uses are responsible. But it is likely that these countries are the most and least intensive due to space heating requirements, considering that these are the coldest and warmest countries respectively. Fuel mix effects decreased emissions for Finland and Australia. For Finland this is a result of oil and high-carbon district heat being shifted to gas and low-carbon electricity. Australia's services, which utilize an unusually large share of (high-carbon) electricity would consume relatively more gas and oil. Norway, the Netherlands, and Sweden all experience increases from this substitution. The Netherlands, with the highest share of natural gas would consume much more oil and electricity at average fuel shares. In Sweden emissions increase primarily because low-carbon district heat would be replaced mostly by gas. As in other sectors, Norway relies on a very large share of electricity that would at average shares be replaced by gas.

Figure 10. Service Sector Emissions, with Others' Intensity, Fuel Mix, and Utility Mix



D. Transportation

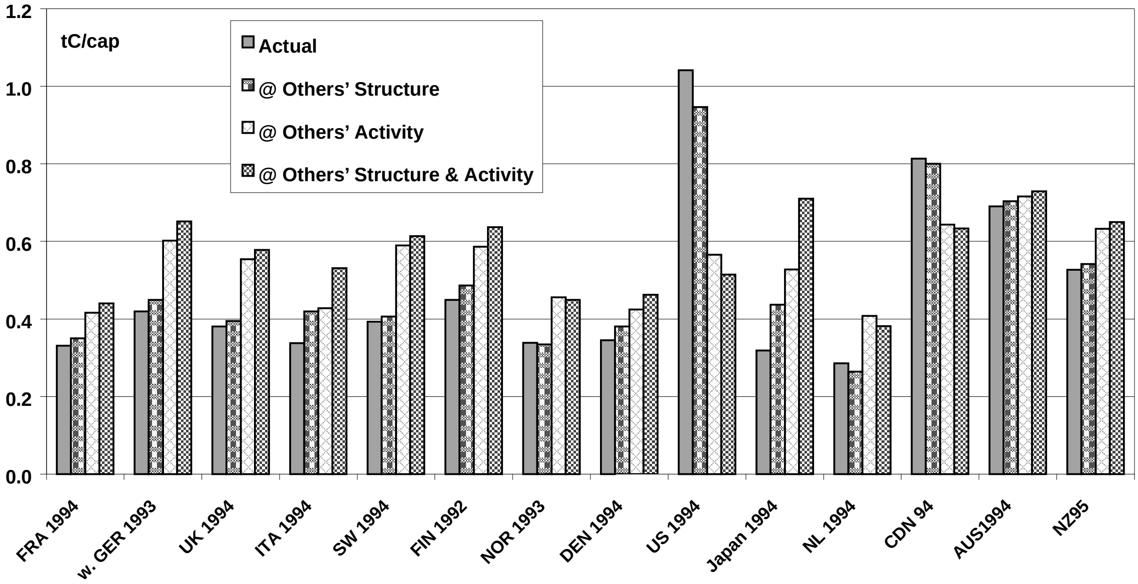
Transportation consists of two subsectors, domestic personal transport (travel) and goods transport (freight). These typically account for 90% of all energy use classified as "transportation" in energy statistics. The remaining fuel use may be off-road vehicles, small boats, civil aviation, military uses, and even some uses in the agriculture sector.

D.1. TRAVEL

The main activity indicator in the travel sector is passenger-km, the measure of how far people move. The structural parameter is the modal mix, usually described by the share of travel in each mode. For this study we consider only motorized modes, although non-motorized modes provide as much as 10% of all travel in Denmark and the Netherlands.

Figure 11 shows actual emissions per capita from travel, and emissions per capita with the average modal shares, level of travel (but own modal structure), and average travel and modal structure. It can be seen that there are three groups of countries: the U.S., with the highest emissions, 1.05 tC/capita; Australia, Canada and New Zealand with moderately high emissions of around 0.55 to 0.80 tC/capita, and the remaining countries, which lie between 0.30 and 0.45 tC/capita. If we excluded air travel, the U.S. figure would fall by over 10% and those for Australia and Canada by nearly as much, while the influence on the European countries' emissions is much smaller.

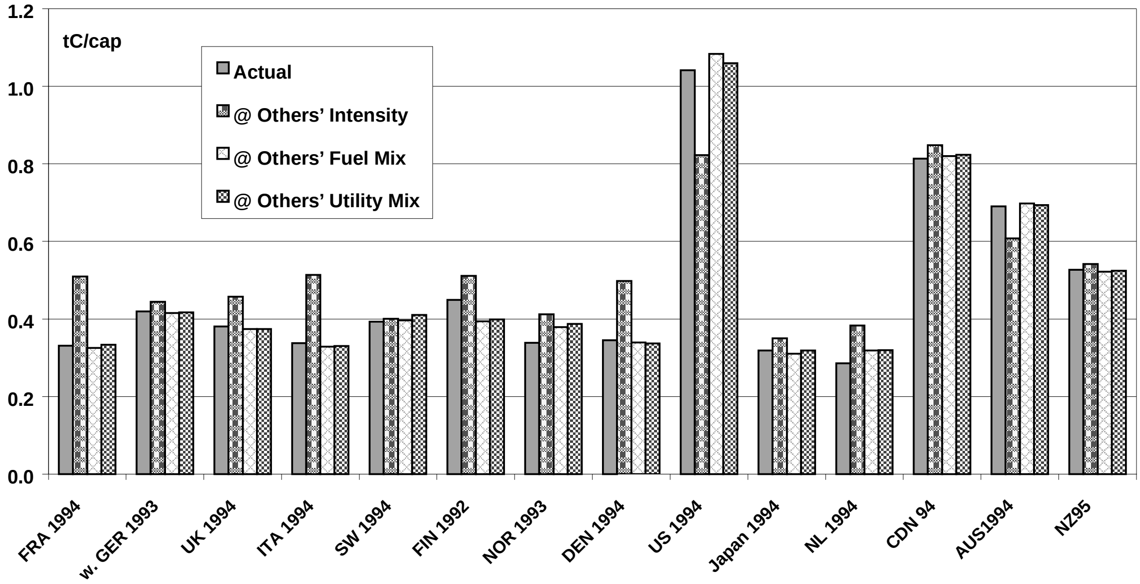
Figure 11. Personal Travel Emissions, with Others' Structure and Activity



If we impose the others' level of per capita travel on each country, the most noticeable changes occur in the U.S, where emissions drop by nearly 30% and Japan where they increase by almost 60%. The decline in the "medium" emissions countries is about 20%. For every other country the level of emissions rises by 10-25%, because "others" is dominated by the U.S. Similarly, if we impose only the others' modal shares on each country, the U.S. still shows a decline, this time about 10%. Canada, the Netherlands, and Norway show only a very slight decline, while all of the other countries show increased emissions, with Japan again having the largest gain. From these manipulations we conclude that total travel is considerably more important than modal mix to the total emissions from travel.

Examining the intensity terms, we find that when others' energy intensity is applied to each country, the U.S. again shows a decline of about 20% (see Figure 12). European countries typically show an increase, but Sweden shows almost no change, suggesting that country lies right on the average. By contrast, the fuel mix and utility terms have almost no influence. Imposing others' fuel mix on the U.S., and Canada actually increases emissions. These two countries use very little diesel fuel in travel, while Europe and Japan use considerably more. Because diesel has more carbon but is associated with little energy savings (Schipper, Lilliu-Marie and Fulton 2000), its presence in the fuel mix raises emissions slightly. Conversely, imposing this term on Europe or Japan leads to a reduction in emissions because the U.S. dominated average has less diesel fuel.

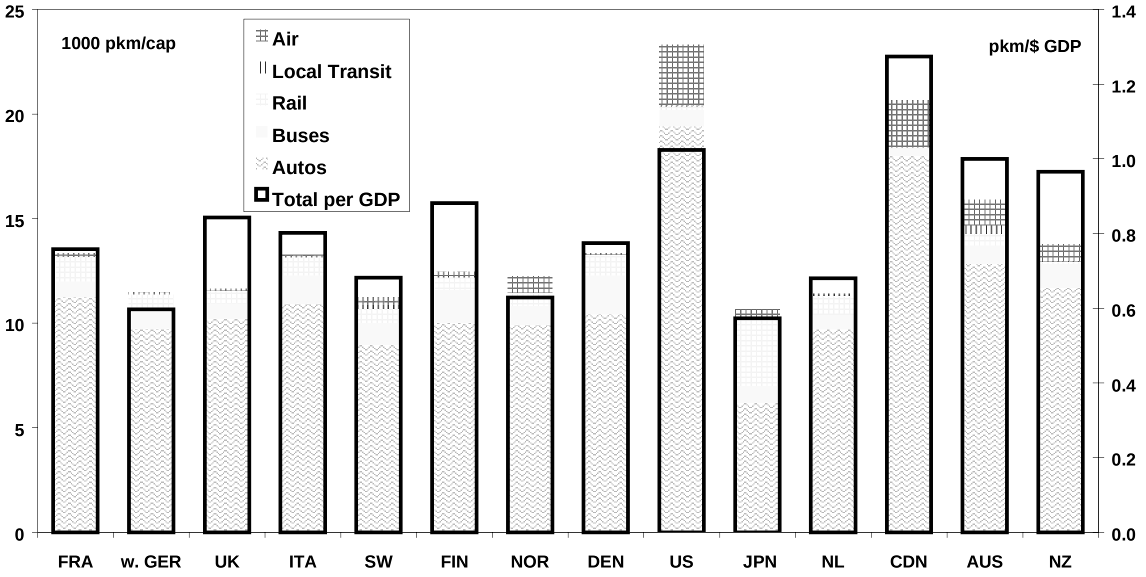
Figure 12. Personal Travel Emissions, with Others' Intensity, Fuel Mix, and Utility Mix



The U.S. emits the most carbon emissions per capita. The reason is that the U.S. has both the greatest level of travel and the highest combined share of car/air travel, the modes with the highest carbon intensities. Moreover, U.S. rail and bus travel are both considerably more carbon-intensive than the same modes elsewhere, because of the high energy intensities of these modes. Indeed, travel by city bus or commuter rail in the U.S. releases as much carbon per passenger km as travel by car or air, which are very close to each other (ORNL 1999). By contrast, Japan and the Netherlands have the lowest emissions per capita. Japan has the lowest level of total travel and the highest share of bus and rail, which also have very low energy intensities. The Netherlands has a higher share of car use than Japan, but its car fleet is less energy-intensive.

Figure 13 shows a key factor differentiating some of the countries: travel (in pkm) per capita by mode in 1994. The shaded areas represent the amount of travel per capita while the border depicts total travel per GDP. The three "large" countries lie at one extreme, while the rest tend to be at about 60% of the U.S. level. Since the average number of people in a car is between 1.5 and 1.6 in all the countries, the number of vehicle-km driven is 62-66% of the number of pkm indicated. As with other sectors, the GDP comparison differs from the per capita comparison because the ratio of travel/GDP differs significantly. Not surprisingly, the large countries have the highest levels of total domestic travel relative to GDP, crowded Japan the smallest.

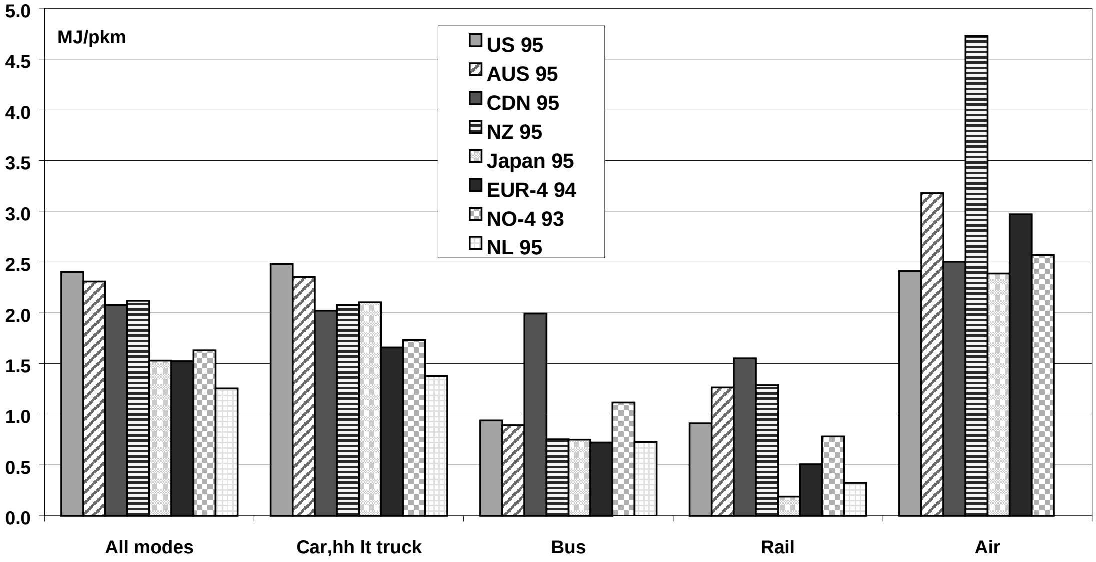
Figure 13. Passenger-km/Capita by Mode, with Total per GDP



Geography is one reason why the U.S. might have high emissions. Certainly the contribution of air travel is influenced by the sheer size of the U.S. But air travel per capita is much higher in the U.S. than in the other large countries. Whether the high level of car travel is "caused" by the large size of the U.S. is another question. For one thing, the average length of a car trip in the U.S. is around 15km, vs. 13-14 km in Europe (Schipper et al., 1995). But Americans make almost twice as many car trips per day as Europeans. It is this frequency that accounts for the difference in total travel, not the distance per trip. Thus, while geography plays some role in the overall totals, particularly for domestic air travel, it alone cannot explain the high levels of car travel in the large countries.

Fuel intensity of key modes is an important differentiating factor. Figure 14 shows total average fuel intensity and the fuel intensities of each key mode. In order to improve legibility of the chart, some countries with similar travel patterns have been grouped together. France, w. Germany, the U.K., and Italy are grouped into the EUR-4 while the Scandinavian countries are represented by the NO-4. Note that the level of car fuel intensity is by far the predominant component in average intensity since car use and car travel dominates passenger transport.

Figure 14. Travel Energy Intensities by Mode

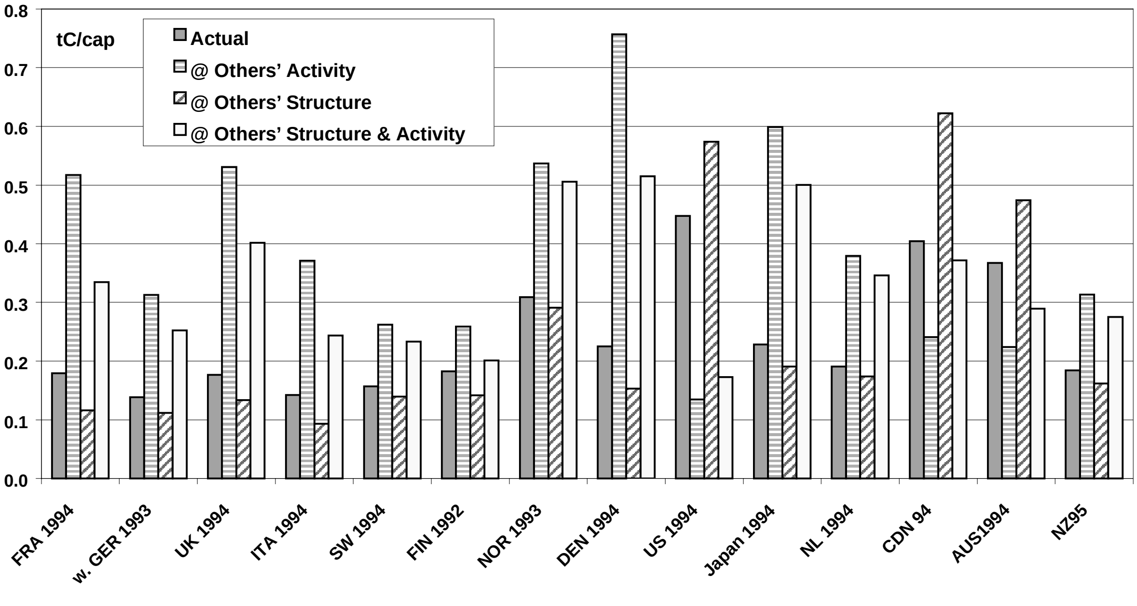


D.2. Freight Transport

Goods transportation has a different character than that of passenger transportation. In IEA countries, all freight haulage takes place in either commercial modes or by firms using their own vehicles, while passenger transport is dominated by the use of private individual modes. Second, while the average person-trip is typically 13-15 km in land transportation, the average distance a shipment moves is on the order of hundreds of kilometers, depending on both what is shipped and which modes are used.

Examining the first decomposition, we immediately see somewhat different groupings. The U.S. and Canada have very high levels of freight emissions, about 0.40 tC/capita, with Australia very close behind. Norway lies in the middle, at around 0.30 tC/capita while the remaining countries lie closely bunched between 0.14 and 0.23 tC/capita.

Figure 15. Freight Emissions, with Others' Activity, Structure, and Activity/Structure combined



When we substitute others' total activity, the drop in emissions for the large countries is dramatic, just as is the increase in emissions from all other countries. This suggests that size of a country is a very important determinant of emissions from freight. Indeed, the three large countries (i.e., the U.S., Canada, and Australia) shown have two to three times the level of domestic freight per capita of the majority of European countries, and 1.5 to two times the level of freight of Sweden or Norway. To some extent this comparison is unfair, however. For the European countries and Japan, a significant amount of freight (and implicitly, emissions) leaves or arrives by international sea (Krushch 1997). Much of this trade corresponds to the large volumes of domestic shipping and rail freight in the large countries. Hence the comparison of overall volumes of freight is somewhat misleading. For rail, no attempt is made to distinguish between "domestic" and "foreign" shipping, since railway cars are hauled by each nation's railway. A few countries (Denmark, for example) do give statistics on the volume of transit freight, but not on the energy for this freight. In general the total tkm hauled by a country's trucks outside of that country's borders is small compared with the same country's domestic tkm. But the total tkm by foreign trucks in some key transit countries like Germany can be large, as noted. In each case we use consistent freight and energy-use figures, but clearly the activity levels have to be examined more closely.[7]

Modal mix effects are also shown in the figure. Interestingly, all of the large countries would show greater emissions under the imposition of the others' modal mix, while the remaining countries would have higher emissions with others' modal mix. This is not surprising since in the three large countries carbon-intensive trucking carries less than 40% of the domestic freight. But this is because so much long-distance shipping of bulk materials (energy products, grain, ores, etc.) by rail or ship occurs. By contrast, in most of the other countries far less boat shipping is evident, with only Norway, Japan, the U.K., the Netherlands, and New Zealand having significant coastal shipping. Additionally, the smaller distances in Europe and Japan appear to favor trucking over rail for many products that might go by rail in the larger countries (Schipper, Scholl and Price 1997).

The overall levels of freight and modal mix play a very important role here, more so than they do for travel. This is both because there is more variation in total freight among the countries and because there is greater variation in the modal mix among the countries. Figure 16 shows the modal split for selected countries on a per capita basis, with the total per unit of GDP shown by the border of each column. Note that as with other sectors the freight/GDP ratios are ordered differently than the freight per capita ratios.

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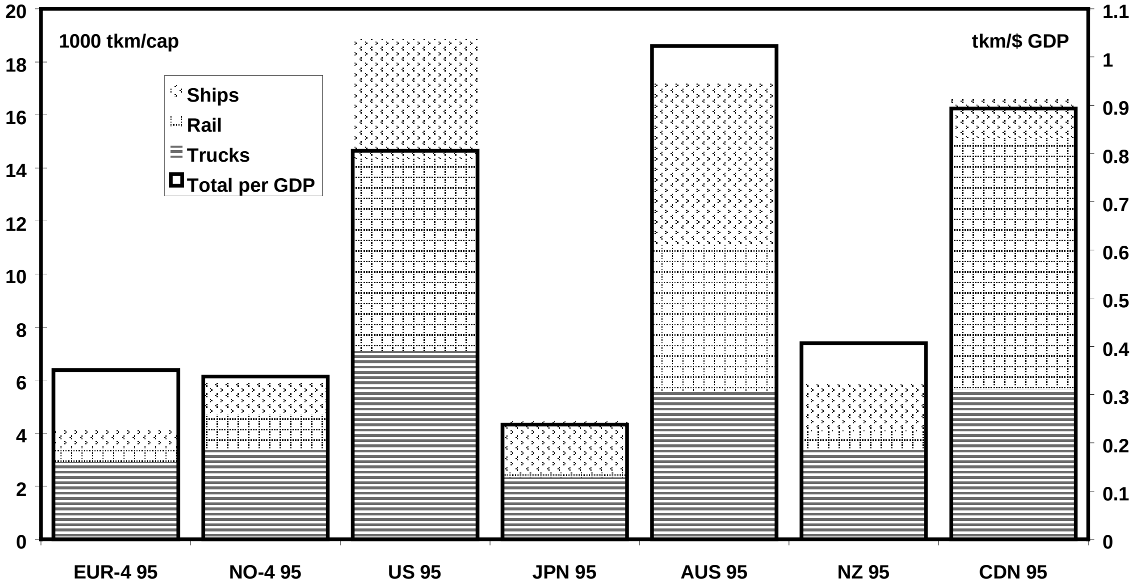
[7] For France, both foreign truck freight and foreign truck freight energy are excluded by the authority publishing the data (INSEE 1996). This excludes about 10-15% of the fuel and freight. For Germany, by contrast, about 20% of total truck freight carried in the country is by foreign trucks, whose energy use and freight have been counted in this analysis. For the Netherlands, there is a very large effect. Dutch trucks carrying freight from ports to other countries in similar transit situations is counted in Dutch statistics along with the energy use, which nearly doubles the volume of truck freight by Dutch trucks in the Netherlands.

Figure 16. Freight Activity per Capita by Mode, with Total Activity per GDP

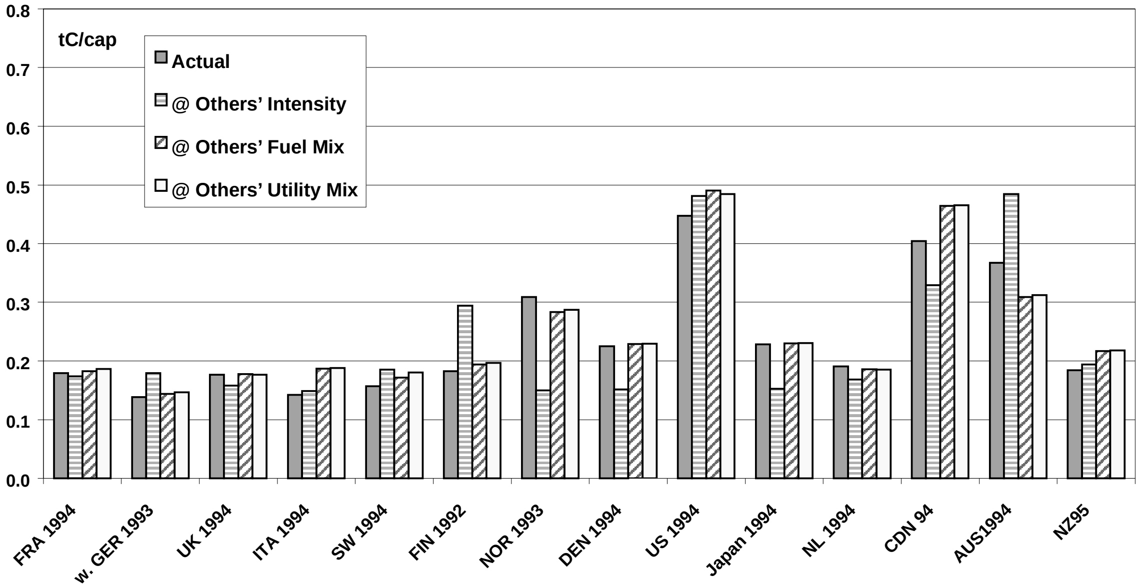


When we combine others' activity and modal mix, we find that the influence of the activity effect is generally greater than that of the modal mix, and as noted, these offset each other. Clearly, however, it is the volume of freight that has the largest influence on overall emissions from freight.

Figure 17 portrays the influence of various components of the carbon intensity of freight. Note almost immediately how little fuel mix or utility mix contributes to the variance among countries. This is because rail electricity has such a small role in total energy use, which is dominated by diesel and gasoline. Since these two fuels themselves have similar carbon content, the overall impact of either of these terms is small.

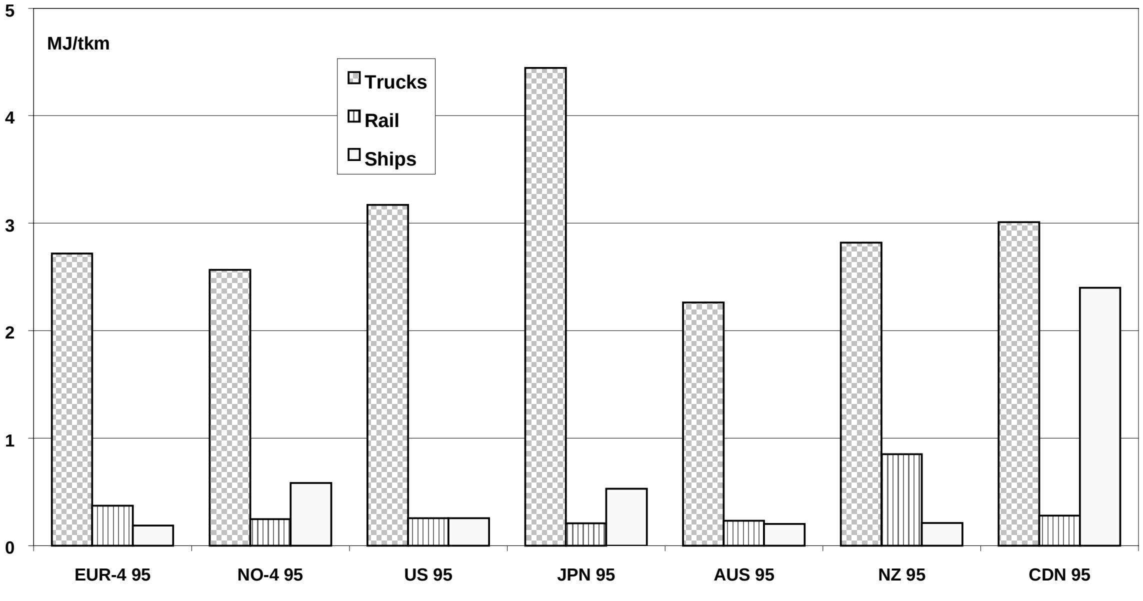
Intensity, however, has an important impact. Australia and Finland have very low intensities, hence imposing others' intensities raises overall emissions in these countries the most. For many other countries, notably Japan and Denmark, the energy intensity of trucking has a very high value and trucking has a high weight in total freight. Hence, imposing others' intensities in these two countries would lead to a great reduction in carbon emissions.

Figure 17. Freight Emissions, with Others' Intensity, Fuel Mix, and Utility Mix



The variation from the lowest intensities (for some domestic shipping) to the highest intensities (for trucking) can be as much as a factor of ten. Figure 18 shows intensities for the three most important freight modes: trucks, rail, and ships.

Figure 18. Freight Energy Intensities by Mode



There is a further factor that affects the intensities of both travel and, to an even greater extent, freight. That is capacity and its utilization. In general, the largest trucks, trains, ships, or aircraft have the lowest emissions per available unit of capacity (i.e., in seat-km or tkm). The mix of vehicles, which is in part determined by the kinds of passenger or freight loads hauled, will thus have an important influence on intensity. But the way the actual vehicles are utilized – empty back-hauls by trucks, buses running nearly empty during the return trips at rush hour, and aircraft load factors – is as important as the potential capacity, and together these factors are often more important than the actual energy efficiency in determining emissions per unit of output.

IV. Overall Emissions. Differences.

Figure 19a and Figure 19b show the actual emissions per capita from all sectors considered as well as the results of the structure and activity per capita effects. For each country the results are shown in order of actual emissions followed by the structure, activity, and combined effects. What emerges immediately from the figures is the predominance of the activity term over the structure term, although the fact that the structure results for the residential sector are set equal to the actual emissions partly explains this. Remember that activity in both manufacturing and services is driven by their respective value added components, while activity levels in freight, travel, residential buildings are measured by other indicators. However, these indicators are driven to some extent by GDP. Hence the importance of the activity term is predominantly, but not totally, a function of GDP.

In terms of the emissions-weighted variances, the activity term is the most important term differentiating emissions largely due to the impact of this term on the U.S. For the U.S. the activity adjustment yields major changes for the services, freight, and travel sectors. The activity substitution increases emissions for every European country, with increases for most countries coming in every sector. This is because the average for each sector is raised by the important U.S. term. The largest differences occur in the transportation sectors, particularly freight. This is mostly due to the large gaps in pkm and tkm per capita between the large and small countries.

Figure 19a. Actual per Capita All-Sector Carbon Emissions, with Structure, Activity and Combined Structure and Activity Effects – European Countries

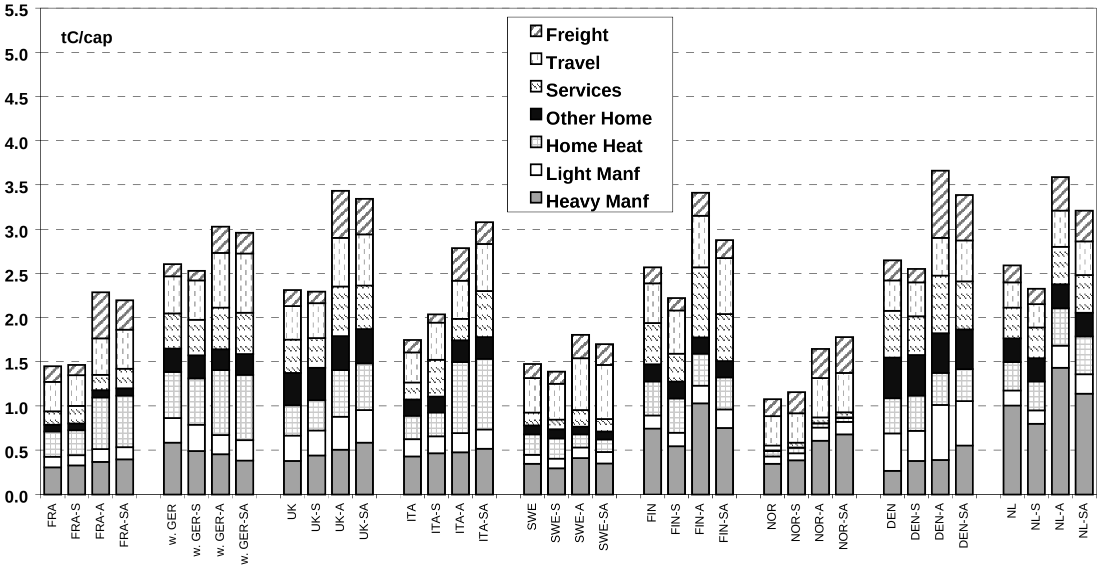
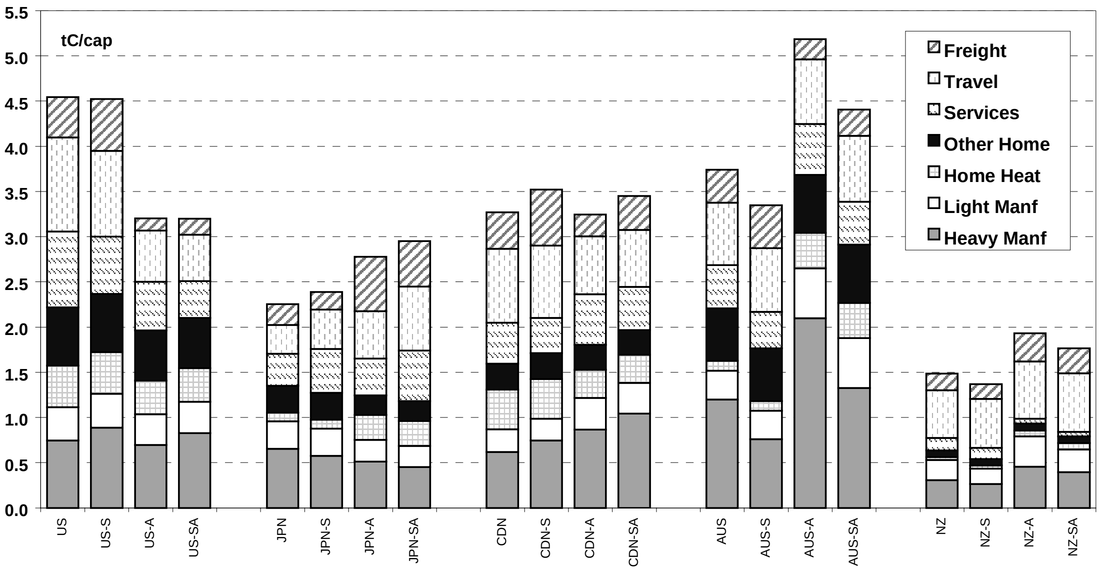


Figure 19b. Actual per Capita All-Sector Carbon Emissions, with Structure, Activity and Combined Structure and Activity Effects – North America and Pacific Countries



The intensity, fuel mix, and utility mix effects are depicted in Figure 20a and Figure 20b. Intensity plays a large role in differentiating emissions from manufacturing, for which it has the largest impact, but it is relatively unimportant in the other sectors. Among the European countries intensity has the most impact on w. Germany, principally by raising emissions from manufacturing industries there, which have very low energy intensities. The aggregate effect of the intensity substitutions raises emissions in Japan while lowering them in the U.S. and Canada, countries with high manufacturing energy intensities. In the case of Australia, the doubling of emissions from services offsets the big drop in emissions from the manufacturing intensity substitution. In other words, Australia's service sector intensities, in comparison with the other countries, are as low as its manufacturing intensities are high.

Figure 20a. Actual per Capita All-Sector Carbon Emissions, with Intensity, Fuel Mix, and Utility Mix Effects – European Countries

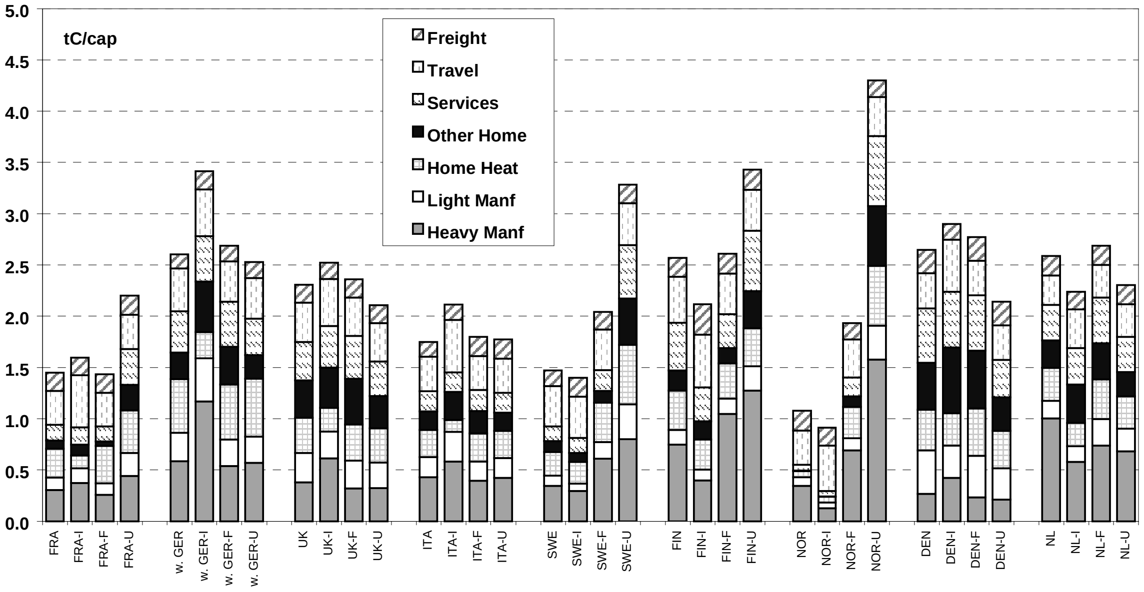
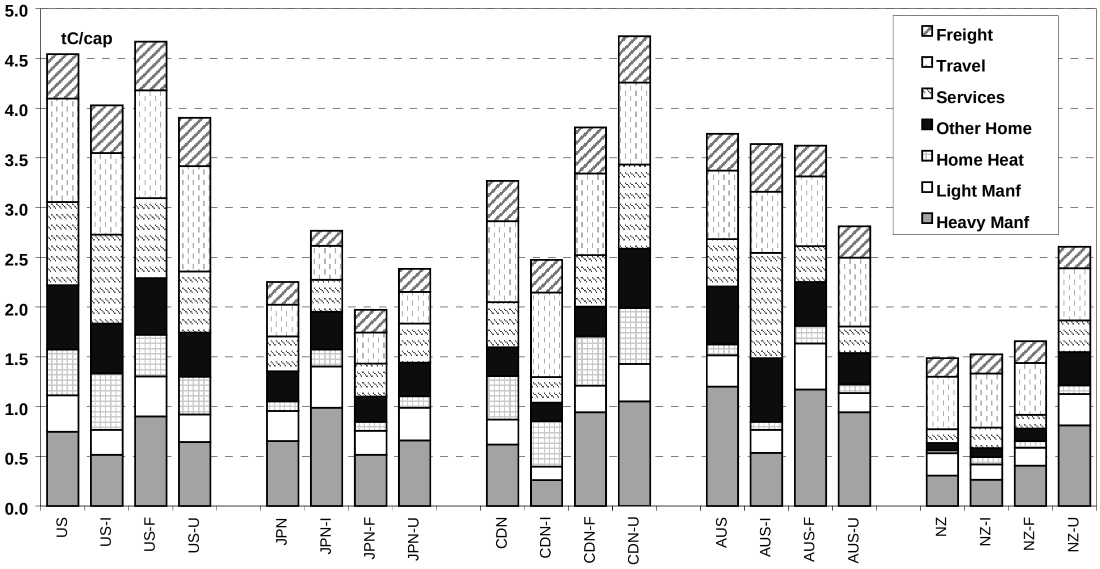


Figure 20b. Actual per Capita All-Sector Carbon Emissions, with Intensity, Fuel Mix, and Utility Mix Effects – North America and Pacific Countries



Fuel mix effects on a country's emissions are generally small. Important exceptions are Sweden and Norway, which both use large shares of low-carbon electricity. Fuel mix also has an appreciable effect on the emissions from Canada and New Zealand. Canada's emissions increase at others' fuel shares because Canada uses a relatively high share of natural gas and low-carbon electricity. Biomass and electricity shares in New Zealand would be shifted to more oil and natural gas. For Japan, emissions would increase as the high share of oil and coal is displaced to considerably more natural gas use.

In contrast to the fuel mix effect, utility mix has a profound impact on the carbon emissions of most of the IEA-14 countries. Total emissions from Norway would increase fourfold at the average utility mix while Sweden's would more than double. The large utility mix effects result from the tremendous range of carbon released per unit of delivered energy in electricity. Norway, with its hydropower resources emits 0.06 ktC/PJ compared to Australia, which emits 73 ktC/PJ.

V. Some Irreducible Structural Components and Their Importance

There are some components of a country's energy use that appear to be related to irreducible or nearly irreducible characteristics of that country. For example, the largest countries have by far the highest levels of domestic freight and generally the highest levels of domestic travel as well. Part of this is due to the fact that the country's large size captures as domestic some activity that would be international and not counted if it had occurred between two neighboring smaller countries. Not a coincidence perhaps, the largest countries (plus Sweden through the late 1980s, and New Zealand) have maintained lower prices on transport fuels than Japan or the rest of Europe. But U.S. road gasoline prices are still roughly 20% below those of Canada, Australia, or New Zealand, and roughly 1/3 of what they are in Sweden (Schipper and Marie-Lilliu 1999). One cannot ignore the role of low fuel prices in the U.S. in stimulating both acquisition of the most fuel-intensive car fleet of the countries studied and the greatest per capita use of those cars (and personal light trucks).

Industrial structure is to a great extent a function of industrial policy. Japan, with little energy or raw materials, built a large industrial base on both domestic demand and trade. But a country's natural resource endowment also plays a large role in shaping industrial structure. The countries with the most energy-intensive mix of output (i.e., highest shares in paper and pulp, non-metallic minerals, chemicals, iron and steel, and/or non-ferrous metals) are Norway, Sweden, Australia, Finland, the Netherlands, and, to some extent, Canada. Four of these countries are rich in hydropower and forest resources; Australia has bauxite, iron ores, and low-cost coal. The Netherlands has a huge chemicals industry built on its own natural gas resources and the refining complexes in Rotterdam. Norway, Australia, and Canada have significant non-metallic minerals sectors. Of these six countries, only the Netherlands and Australia consume principally fossil fuels to support their industries; Canada and the three Nordic countries have low-cost hydro, forest wastes, and in three cases relatively low-cost nuclear power. As our study of manufacturing carbon emissions shows (Schipper et al. 2000), the carbon intensity of Australia's manufacturing is by far the highest of all the countries we have studied, largely because of primary metals and their reliance on coal-fired electricity. But should Australia (or any other one of these countries) "give up" basic industry to save carbon? Would the same products be produced elsewhere on more or less carbon? Should the Dutch renounce their natural gas? Should the Nordic countries close their electric-intensive industries, particularly Norway's ferro-alloys and non-ferrous metals? That four of these countries have relatively carbon-free electricity and a relatively low-carbon overall manufacturing fuel mix might make them better suited than other countries for producing energy-intensive outputs.

Housing policy is another area of concern. Consider house size, which to first order drives emissions from space heating. Denmark, Norway, and Sweden have very high per capita living area in homes relative to GDP or personal consumption expenditures, as high or higher than the U.S. One reason is that these countries had very well developed housing loan systems with subsidies. Until recently these countries permitted unrestricted tax deductions of mortgage interest in some way or another. The U.S. still has full tax deduction, while neighboring Canada permits none at all. Gentry (1994) showed that part of the U.S. tax subsidy encourages greater investment in homes, including both larger homes and to some extent more energy saving features. Not surprisingly, Canadians have smaller homes, per capita, than Americans (see Figure 7), although per unit of GDP, house sizes for Canada and the U.S. are about the same. But while Sweden and Norway have extremely low levels of emissions because of both efficient heating and low-carbon heating sources, Denmark and the U.S. have "average" levels. Canada is intermediate because of low-carbon based electric heating. While this rough comparison is not exact, it serves to illustrate the importance of concerns and policies outside the energy sector that have large sway over carbon emissions. In no country is it easy to change housing policy, therefore the activity per capita component of CO2 emissions is not put on the table easily.

VI. Mutually Offsetting Factors

We noted some important mutually offsetting factors that mitigate emissions:

- High freight volumes relative to GDP but with low trucking shares, except for the Netherlands;

- A high share of raw materials in manufacturing is generally associated with a low share of manufacturing per unit of GDP or even a low manufacturing output per capita;

- High manufacturing energy intensities in countries with low-carbon electricity, in part because of very high production of certain raw materials, in part because of low energy efficiencies, but with only modest impacts on overall carbon emissions because the energy sources are low carbon, except for Australia;

- Low space-heating intensities in countries with cold climates, because of the extra economic value of adding more insulation in a cold climate.

Whether these effects are related to the Rebound Effect or other interactions is not clear. But they must be borne in mind when making comparisons among countries. Some facets of a country's structure that boost emissions acting through one component may also offer restraint through a complementary component.

VII. The Outliers: Extremes of Driving Factors, by Sector

We noted at the outset that it is dangerous to push the comparisons of energy intensities and carbon intensities too far. Still, the list below outlines some of the extremes of conditions among countries that affect emissions.

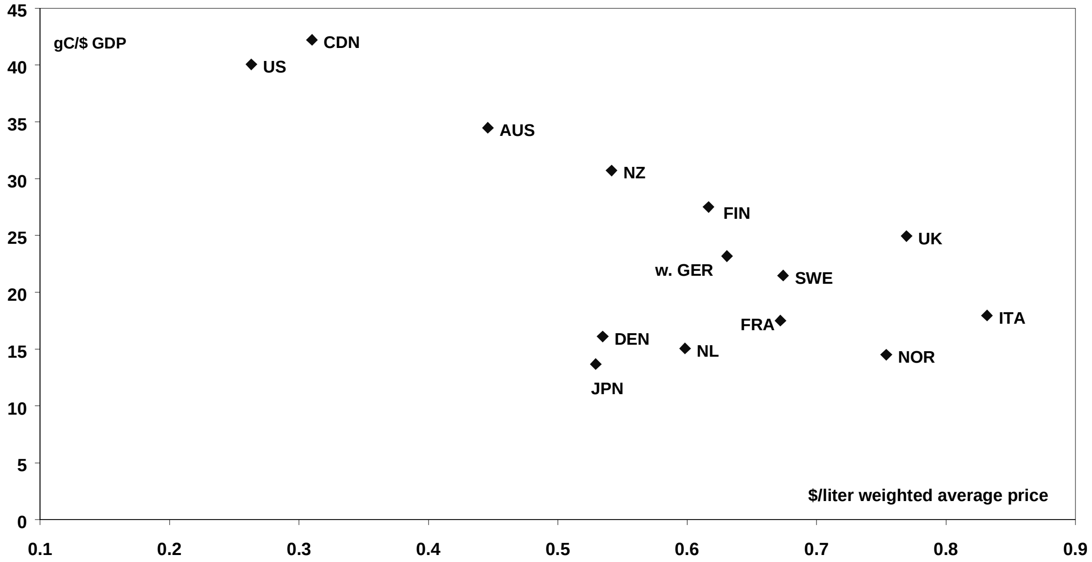
- Heating degree-days (base 18C) vary from 900 in Australia, 1,600 in New Zealand, and 1,800 in Japan to over 4,500 in Canada and Finland.
- Automobile use per capita varies from a high of 13,500 km/year in the U.S. to a low of 3,900 km in Japan.
- Freight tkm per capita varies by almost a factor of four between the ”large countries” and some European countries or Japan. The ratio of freight hauled to GDP varies by more than a factor of four among the same groups, clearly a function of geography as well as other considerations.
- Home size varies from over 155 square meters/home (or roughly 60 square meters/capita) in the U.S. to less than 90 square meters/home (closer to 30 square meters/capita) in Japan.
- Per capita manufacturing output (as 1994 value added compared at purchasing power parity) varies by over two to one, with Japan at the high end and New Zealand at the low end. The manufacturing share of GDP varies from under 20% in Australia or Denmark to nearly 30% in other countries, and the share of the energy-intensive raw materials sectors in manufacturing varies from over 30% in Australia, the Netherlands, Finland and Sweden, to only 15% in Denmark.
- Similar considerations in the service sector reveal an almost two-to-one ratio of built area to population or to service-sector GDP, with the U.S. having both the most space per capita and per unit of GDP, and Japan and Italy having the least.
- The average carbon content of a megajoule of primary energy varies from a low of 6.8 gC in Norway to a high of 20.3 gC in Australia.

Key economic driving factors show important variations, too.

- Road-fuel prices vary by a factor of three (from the U.S. at the low end to Norway and Italy at the high end), home-heating fuel prices by a factor of two (for the U.S. at one end, and Denmark and Italy at the other), electricity prices in any sector by as much as a factor of three, with Norway and Sweden generally at the low end and Japan, Italy, and Denmark (for households) at the high end.
- People per dwelling varies from a low of approximately 2.25 in the Nordic countries to above 2.8 in Japan, which affects per capita residential energy use.
- Finally, GDP per capita varies by 1.75 to 1 across the countries considered, all compared using purchasing power parity, with the U.S. at the high end and New Zealand at the low end.

To show some of the influence of energy prices, we plot first emissions from cars and personal light trucks, per unit of GDP, as a function of weighted average fuel prices. These are constructed by taking the actual consumption of diesel, gasoline, and liquefied petroleum gas to calculate both emissions and the weighted prices. There is clearly a progression from the high price to the low price countries, although there is considerable scatter as well. By normalizing for GDP we remove some of the influence of income on both car size and on total travel.

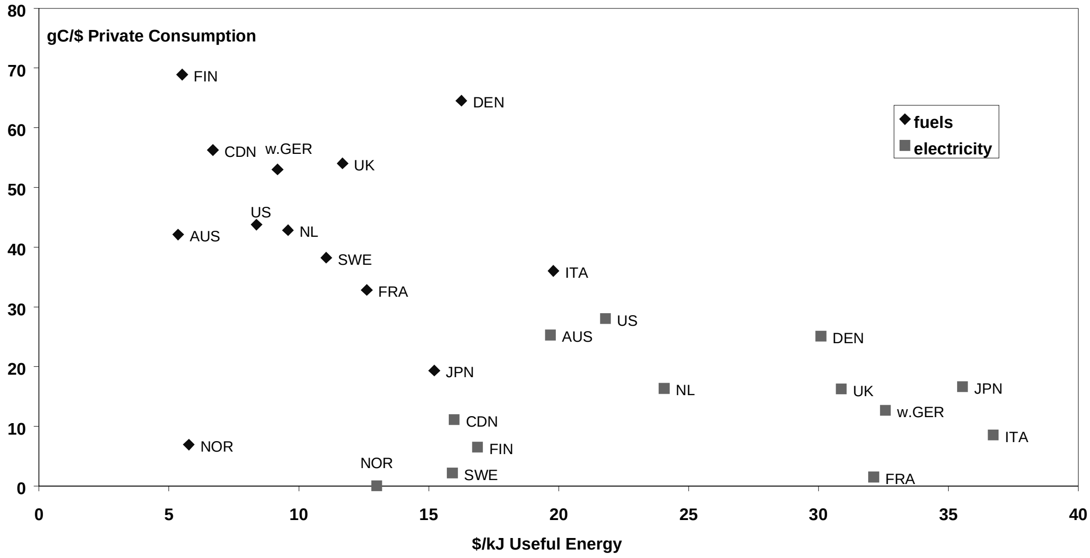
Figure 21. 1994 Carbon Emissions from Automobiles and Light Trucks per GDP vs. Weighted Average Fuel Price



Carbon emissions from cars and private light trucks/SUVs, per unit of GDP, vs. the weighted price of fuel show a strong inverse correlation. Japan, Denmark, and the Netherlands, which lie somewhat below the other countries, all have relatively high car ownership costs, use costs or significant restraints on use from city planning measures. We speculate that the low value for the Netherlands, relative to other countries, is a function both of low car ownership and the impact of town planning on both reducing car use and increasing the shares of non-motorized modes. Above, it was shown that travel distance per capita varies more than the carbon or energy intensity of travel. Some of this high level in the large countries is doubtlessly related to the relatively large sizes and low population densities of these countries. Driving distance is relatively inelastic to fuel price in the short term (Johansson and Schipper 1997), but with fuel prices varying by almost four to one, prices will affect overall distance driven. Fuel prices also affect new car fuel economy. However exact the relationships are, the two share in determining emissions per unit of GDP. Uncertainties notwithstanding, Figure 21 suggests that these emissions are affected by fuel price.

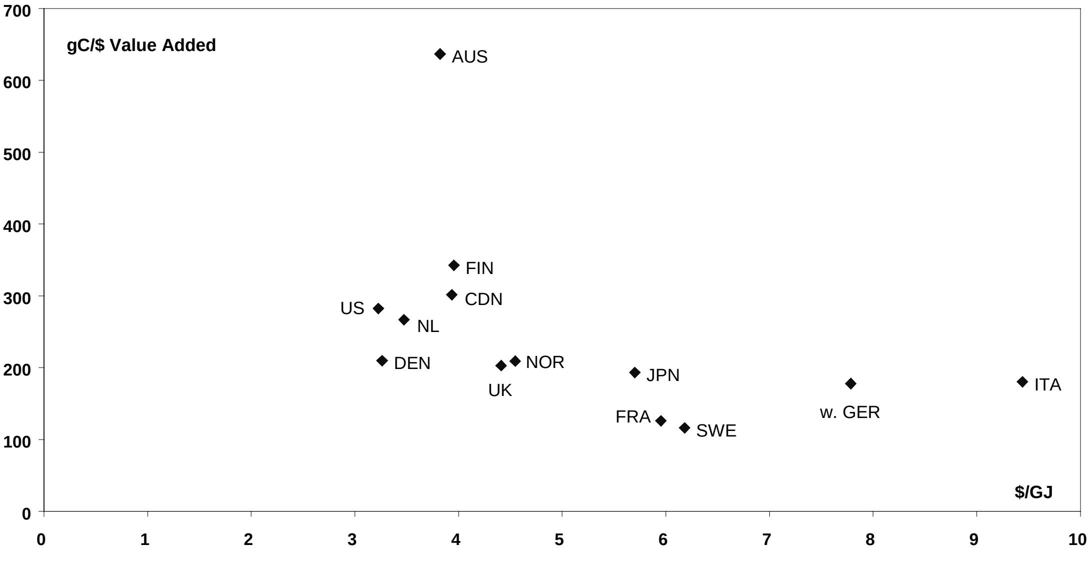
Next we show emissions per unit of private consumption expenditures from households for space and water heating and cooking from fuels and electricity (represented by the diamonds). Again there is a relatively good inverse correlation: lower prices are associated with higher use, but some of the colder countries with fossil fuel based heating (e.g. Denmark, Finland) have higher use in spite of higher prices. Since we have counted only electricity uses that compete with fossil fuels (heating, water heating, cooking), the two energy sources contribute inversely to emissions. The most extreme case is Norway, with very little oil used for heating. Wood and virtually carbon free electricity provide most of the energy. Sweden, Canada, and Finland represent three other colder countries where low-carbon electricity supplies a significant amount of energy to these uses, while France represents a warmer country with high electricity penetration – in spit of the relatively high price of electricity. This example illustrates how prices shape emissions in part through the interaction of fossil fuels and electricity for the same end-uses. The complexity here suggests that each country’s situation, i.e., climate, fuel mix, housing stock, must be examined carefully before judging how carbon emissions can be changed, and the role that energy prices might play. In the lower right portion of the diagram, the square data points depicting the nonsubstitutable uses of electricity (i.e. lights and electricity) per unit of expenditures vs. electricity prices show a similar inverse relationship.

Figure 22. Residential Emissions from Fuels and Electricity Used for Space Heating, Water Heating, and Cooking vs. Weighted Average Price of Useful Energy in Fuel and Emissions from Nonsubstitutable End-Uses of Electricity vs. Price of Electricity



Finally, we show manufacturing emissions per unit of GDP in manufacturing vs. the weighted average price of all fuels, including electricity, in 1994. Again there is a clear inverse relationship, but there are also some outliers, particularly Australia. It is noteworthy that over a range of average price of more than three to one, carbon intensity varies by more than two to one if we ignore Australia.

Figure 23. 1994 Manufacturing Carbon Emissions per Value Added vs. Weighted Average Price of Fuel



In all of these relationships we see the influence of price, but we also see outliers and exceptions. The figures do not quantify exactly the price relationships or elasticities. And our normalization by income assumes a linear relationship, i.e., an income elasticity of one. These are simplifications that can be addressed in further work. But the impression is clear that the intensity of carbon emissions depends on the price of fuels.

VIII. Broadest Conclusions: What Matters

The foregoing shows how key components underlying carbon emissions vary among wealthy countries. How much of this variation is natural versus how much is caused directly by differences in incomes and prices is a subject for debate. The same is true for energy intensities, which, as we have shown, also vary significantly. In broadest terms, per capita activity levels are the most important factors driving a wedge among countries' emissions per capita.

Manufacturing and services sector output make up typically 80% or more of any country's GDP, and these in turn drive emissions in each sector. To a certain extent GDP may be said to drive the other measures of activity, but as noted above, other factors are important as well. Travel and freight are proportional to GDP over time, but their levels seem to vary widely among countries according to both geography and fuel prices. Household heating depends on both climate and home area. While home area growth is coupled strongly to GDP, there is a wide range in area per capita at a given GDP per capita. Normalizing our results by a uniform division of GDP may add as much distortion as information. Thus we adhere to the per capita indicators but point out that GDP per capita has a strong influence on every sector and must be considered as key factor lying behind differences in per capita emissions.

For a few countries, a key structural feature (such as a few very carbon-intensive industries in the Netherlands or Australia) boosts emissions significantly, but in the main this is not an important effect. After activity, intensity is the most important factor. In a few countries, a particular set of energy or carbon intensities boosts emissions (high average carbon intensity of manufacturing branches in the U.S., Australia, or the Netherlands; high carbon intensity of automobile travel in the U.S. or Canada; high trucking carbon intensity in Japan or Denmark). And in some countries the presence of large hydro or nuclear resources, biomass, or absence of coal leads to a low-carbon fuel and utility mix. Conversely an electric power sector dominated by coal and a high dependence on coal and oil in industry (w. Germany, Denmark until recently) raises emissions.

IX. Conclusions for CO2 Policies

If we ascribe most of the variation in emissions per capita to activity levels, then we are forced to conclude that much of this variance is caused by differences in GDP per capita. Overall it appears that energy intensities drive the next greatest differences in carbon emissions, and therefore drive the largest differences in emissions per unit of GDP. Not all of these "intensities" are technological, as we noted, as many have behavioral components such as hours of heating, car size, load factors, etc. After that primary energy supply has the biggest influence on carbon emissions, and in a few countries (notably Sweden, Canada, and Norway) it is more important than energy intensities and may to some extent offset high intensities. Fortunately for policy makers, these are factors that can be influenced by technology and policy. But what drives these factors?

GDP itself is a driving factor, in the reverse sense, as higher incomes are clearly associated with lower carbon/GDP ratios (Schmalensee, Stoker and Judson 1998; Galeotti and Lanzo 1998). We freely admit that our linearization of the emissions picture with GDP in many examples is a simplification, but it is a necessary simplification as a first step towards an even deeper understanding.

It is hard not to give energy prices an important role in the answer to that question, as Figures 23-25 suggested. These shape fuel mix and make improved energy efficiencies and more efficient practices more – or less attractive. One must debate the strength of this role, i.e., the price elasticities, and the time lags before changes in energy prices affect both behavior and the choice of equipment. But it is difficult to deny that role and hard to foresee a successful carbon restraint program that does not somehow raise the price of carbon.

Finally, there are other factors as well. We pointed to the natural endowments and geography of a country, as well as some examples of the countless policies outside of the energy sector that influence activity and structure. Many of these endowments, such as the availability of raw materials for energy-intensive processing, raise carbon emissions, while others, such as the presence of hydro resources, lower them.

Given the wide variation in both “controlled” driving factors, e.g., incomes and prices, as well as “natural factors”, e.g., climate, geography, and natural resources, many countries want their special situations to be “differentiated”, so that their own carbon reduction targets take these natural factors into account. Which of the various components and factors we have isolated can be taken “off the table” as grounds for CO2 restraint? That is, could any one country with that component claim the right to decarbonize at a slower rate than others? Should the high emitters (Australia, Netherlands, U.S.) be given special dispensation, or should the low emitters (France, Sweden, Norway) get a better shake? The former could claim a certain dependency on carbon-intensive activity and high carbon intensities. The latter could either claim that they have little carbon to save (Norway) or that they already underwent significant decarbonization in the 1970s and 1980s (France, Sweden). What joins all of these countries, of course, is the relatively important role of transportation. Among the countries with higher carbon intensities, transportation is important and high except for the Netherlands. But among the less carbon-intensive countries, such as Sweden or Norway, transportation emits a greater than average share of all carbon, presenting a daunting target for policy-makers.

Next, there is the question of economic evolution. Space heating in Japan or New Zealand has not matured as far as it has in the colder countries. All other countries have passed the point where most homes are heated most of the time to 17-20 C during the winter, but not these countries (nor parts of Australia). This evolution will be carbon-intensive. Should it be put off?

Finally, there is an important issue we have had to ignore because of data problems, the carbon embodied in trade. Australia and the Netherlands export significant amounts of carbon in raw materials made from their own domestic energy resources and ores. Norway, Finland, and Sweden are in a similar position, but at lower carbon intensities. Denmark, by contrast, has very little heavy industry and imports much of its manufacturing carbon this way. Since the manufacturing share of emissions is shrinking in all but a few countries, typically to less than 1/3, this issue is less important as homes, services, and personal transportation lead the growth – or lack of restraint – in emissions. But this invisible carbon must be factored in to the overall balance.

Appendix

Table A1. Summary of Variances Due to Substitution Terms

	Heavy Manf	Light Manf	Home Heat	Other Home	Services	Travel	Freight
Structure	4783	892	N/A	N/A	7146	8246	1771
Activity/Cap	4239	1039	2178	2773	8534	20372	11089
Structure & Activity/Cap	4661	1000	N/A	N/A	16796	24527	6744
Intensity	7684	1753	1335	3526	4214	10265	1315
Fuel Mix	5104	1063	1456	2709	3881	6696	1006
Utility Mix	4338	1313	1704	4235	6418	5943	980

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