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INDICATORS OF ENERGY USE AND CARBON EMISSIONS: Explaining the Energy Economy Link

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■ **Abstract** This article reviews energy indicators, which are developed to describe the links between energy use and human activity in a disaggregated manner. After briefly reviewing a number of early and current efforts to develop indicators, we discuss the basic concepts of various indicators and the methodologies used to derive them. We also review the use of decomposition

methods to aid in the analysis of trends in energy use and comparisons of uses between countries. Findings from our comparative and time-series analyses of several industrialized countries illustrate the application of these methods. Using simplified methods for estimating the carbon released in direct combustion of fossil fuels, and in electricity and heat production, energy indicators can be extended to carbon emissions. These carbon indicators can play an important role in aiding negotiations over carbon reduction targets and evaluating progress toward meeting abatement goals.

INTRODUCTION: WHAT ARE ENERGY INDICATORS?

Energy indicators describe the links between energy use and human activity in a disaggregated framework. They are essentially measures of energy consumption and the underlying factors driving that consumption. Using these data, analysts commonly construct ratios of the energy consumed per unit of a given activity (energy intensities) in order to calculate changes in energy efficiency. The calculation of energy intensities at a meaningfully disaggregated level requires detailed data on economic and human activity, for example value added by manufacturing branch or passenger kilometers by transportation mode, as well as measurements of the energy used for those activities.\footnote{Unfortunately, outside the manufacturing sector, few energy uses are really measured in detailed surveys. So analyses rely on indirect measurements, estimates, and regression analysis. For the analyst, the distinction between data and indicators, as well as the strengths and weaknesses of the data themselves, must be kept clearly in mind.}

Careful examination of energy indicators helps to extract key trends from a large amount of disaggregated data. Using index-number methodologies, the indicators can be used to measure the impact of changes in energy intensities or changes in the mix of activities on total energy use. The indicators are not meant to be normative; they are descriptive and analytical. Indicators help to show how energy use is shaped by economic and technical factors, such as energy prices, economic growth, and new technologies.

Disaggregated measures of energy intensities are necessary to determine what impact prices, policies, or other factors have had on reducing energy consumption. Energy intensity measurements at higher levels of aggregation can often lead to misleading conclusions. One of the most widespread indicators---the ratio of energy use to gross domestic product (GDP)---does not measure much. Little can be said, on the basis of that ratio, about why energy use for any sector has reached a certain level, how efficient that use is, or why use varies so much between otherwise similar countries.

The problem with using the ratio of energy to GDP is that the denominator, GDP, represents many diverse activities. Since the energy intensities of these activities differ widely, changes in the mix of activities can cause significant variations in the ratio of energy to GDP over time, regardless of changes in specific intensities. Thus, it is hard to take seriously an aggregate ratio of energy use to GDP as an indicator for measuring energy efficiency.

In order to better understand factors affecting energy use, many kinds of energy indicators have been developed, each highlighting a different dimension or issue related to energy consumption.

1. "Snapshots" provide a single year's shares of fuels or other simple quantities. Time series display these quantities over time. Cross-sectional or comparative indicators highlight differences between countries either in snapshot or over time.
2. Aggregate indicators show total energy by fuel, by main sector, or by total GDP, whereas disaggregated indicators give details of end uses, subsectors, or components of GDP. The level of disaggregation is usually determined by a compromise between the need for detailed information and the availability of data. Index number and decomposition techniques are used to reaggregate detailed information in meaningful ways.
3. Extensive quantities like total energy or total emissions can be contrasted with intensive quantities normalized to GDP, population, or other activity terms.

4. Structural indicators give measures of activity (from aggregates like GDP to output in each industry or activity in each transport mode), usually presented as intensive quantities, such as shares or per capita values.
5. Intensity indicators [such as gigajoules (GJ)] per tonne of steel produced, fuel use per vehicle kilometers driven, or heat use per square meter of floor area) relate energy use to activity measures in matching categories at matching levels of disaggregation. These are the indicators most closely related to energy efficiencies.
6. Causal indicators point to how driving forces, such as energy prices or personal incomes, are related to such energy uses as per capita fuel use for cars or home area, respectively.
7. Consequential indicators relate emissions of CO_2 or other pollutants to activities, such as emissions per kilometer of car use or emissions per tonne of steel produced.
8. Physical indicators of new equipment efficiencies, or surrogates such as quantities of energy-saving materials sold, show how efficiencies or intensities are changing.

This review focuses on disaggregated structural and intensity indicators, causal indicators, consequential indicators related to carbon emissions, and reaggregation using indices. The scope is international and historical, with comparisons of both time-series analyses and single-year cross-sectional differences. Examples are drawn from a sample of 14 International Energy Agency (IEA) member countries. We consciously try to show not the same countries every time but only those that illustrate the extremes or the most important trends. Section 2 provides a brief overview of the development of current national- and international-level energy indicator efforts. We discuss various approaches to indicators work and the methodologies used in Section 3. Illustrative examples of findings from our analyses of three energy-using sectors are provided in Section 4. In Section 5, we show how the sector-level decompositions of the factors affecting energy consumption can be aggregated across the entire economy, and we discuss some key findings of this analysis. The use of causal indicators to help illustrate what factors have had the most impact on driving the demand for energy are reviewed in Section 6. Finally, we conclude in Section 7 by showing where the use of indicators have been important for policy makers and by discussing the future of indicators work in light of the need to monitor progress in restraining carbon emissions.

REVIEW OF MAJOR ENERGY INDICATOR DEVELOPMENTS

The extent of analysis devoted to energy indicators has risen sharply in the past decade. Current IEA indicators effort began with a workshop held at Lawrence Berkeley National Laboratory in 1994 (1), which reviewed and synthesized earlier work at the laboratory based both on country studies (2--6) and on an overview of all sectors from a selection of IEA countries (7). Since 1994, a number of national (8--18) and international efforts (19, 20) have led to fruitful discussions, publications, and official statistics covering dozens of countries. This suggests that many national authorities support the disaggregated approach offered by indicators. The IEA officially undertook international indicators analysis beginning in 1995. An extensive review of this work appeared in 1997 (21) as well as a shorter companion volume providing the major highlights (22).\footnote{Since 1995, analytical work has been carried out in the IEA's Energy Efficiency, Technology and R&D Directorate, which has access to rich data and estimates from more than a dozen IEA countries. The results have been transferred to the Agency's Energy Statistics Division, which has more aggregate data for all 25 IEA member countries. The Statistics Division, as part of its responsibility for official data collection, will send the data collected by the Energy Technology Policy Division to country authorities for verification and will then develop questionnaires with which to collect the required data regularly. The data used in this report are taken predominantly from official national sources but are not yet "official" within the IEA data. Schipper et al. (21) contains an extensive bibliography.} Work so far has focused on the time period from the early 1970s to the mid-1990s in 14 IEA member countries: Australia, Canada, Denmark, Finland, France, western Germany, Italy, Japan, the

Netherlands, New Zealand, Norway, Sweden, the United Kingdom, and the United States. In addition to the comparative analyses performed at the IEA, five member countries have commissioned detailed national studies of their energy use (23--27). Individual workshops have also been dedicated to understanding the particular issues surrounding energy consumption in each sector of the economy\footnote{The IEA workhops are summarized at http://www.iea.org/acti.htm. A similar series of workshops organized by the US Energy Information Administration are summarized in http://www.eia.doe.gov/emeu/efficiency/contents.html}.

APPROACH AND METHODOLOGY

The methodology for energy indicators depends in part on the policy questions being addressed. Such questions define the kinds of indicators needed, the level of disaggregation, and, consequently, the data required. For example, if a policy is designed to save energy in household space heating by promoting more efficient equipment and insulation, useful indicators would provide estimates of the amounts of energy used for heating, the home area heated, indoor and outdoor temperatures during the heating season, the efficiency of various heating systems, and other parameters, such as household occupancy. As the next section argues, however, indicators need not be limited to intensities. Structural data can often reveal important characteristics even when detailed data on energy use are not known.

The Structure of Economic and Human Activities

Measuring the underlying structure and magnitude of activities for which energy is used is an essential step to developing disaggregated energy indicators. This entails measuring the output levels (activity) of various energy-consuming end uses. These activities are generally measured in physical terms, but for many end uses in the productive sectors of the economy they can also be measured in economic terms. Although the activity indicator measures the total output for each sector, the structural indicator tracks how shares of output have changed among each sector’s end uses. Examples of activity indicators include total tonne kilometers hauled or total manufacturing value added. The respective structural indicators would be the shares of tonne kilometers hauled by each freight mode or shares of manufacturing value added by each industry. Taken together the two terms measure "energy services." Using indices, we can measure the total impact on energy use from changes in the overall mix and magnitude of energy-consuming activities, i.e., a structure-weighted measure of the activities that consume energy that we refer to as the energy services effect.

Farla & Blok (29) argue for the use of physical indicators to model economic activity, but they fall short of measuring output in service industries or household sectors. Indeed, in the household sector, there are few data to measure production of such household activities as heating, cooking, or washing. One can, however, find physical surrogates, such as home area heated or the rates of ownership of certain kinds of cooking or washing equipment, appliances, and heating systems. Family size, which is a surrogate for such activities as the number of meals eaten at home or consumption of hot water, is another structural indicator (30). For the household sector, the "structure" of energy use is thus complex. In the end, both Farla & Blok (29) and Schipper et al. (22) settled on a hybrid approach, using a mix of physical and monetary indicators for manufacturing, other industries, and the service sector but relying on physical indicators for transport, freight, and households.\footnote{Note that the basic energy services in these sectors are not represented in national accounts, except for turnover or value added in transport for hire (air travel, public transport, for-hire trucking, and other collective freight modes).}

The structural evolution of economies and human activities can cause changes in energy consumption that enhance or offset shifts caused by changes in energy intensities. Increases in appliance or automobile ownership may be so rapid as to raise energy use much faster than GDP, as was the case in western Germany and Japan in the 1960s. Alternatively, saturation of ownership and use can occur. In these cases, GDP rises faster than energy use for certain energy-related services.

Measuring the impact of these "structural" changes is therefore crucial to understanding how the ratio of energy use to GDP changes over time.

Energy Intensities

The other component of energy indicators is energy intensities, which measure the energy consumed per unit of activity. Energy intensities are related, but not equivalent, to the inverse of energy efficiencies (a measure of output per unit energy consumed) because an increase in energy efficiency helps reduce energy intensity. Although improving efficiency is a policy goal in many countries, measuring the energy efficiency of thousands of economic activities, most of which require multiple transformations of energy, is difficult.

We can define "process efficiencies" as measures of how much physical output (or converted energy) is provided for a given amount of energy "consumed," i.e., converted from fuel or electricity to low-grade heat, in each process. Even if the processes are understood, there are different ways of analyzing efficiency using different thermodynamic concepts (31). Whatever the definition, the details from each process and product must be reassembled into an economy-wide picture. If technical data for each process were available, as well as data on process-level utilization, the thermodynamic efficiency of each energy conversion in a given technology could be described in physical terms. They could then be transformed, using the various measures of utilization, into meaningful energy intensities for key end uses. However, as Farla and colleagues (32) have shown, because of the multiplicity of products and processes, describing the real efficiency of industrial production processes is a daunting task.

Because of the difficulty of measuring disaggregated process efficiencies, we fall back on energy intensities and related quantities, such as fuel per kilometer, therms of heat per square meter of floor area, gigajoules per tonne of steel, or kilowatt hours per year for major appliances.\footnote{When intensities refer to physical processes, they are often called "specific energy requirements" (such as gigajoules per tonne of steel). When they refer to the yearly use for an appliance or end use, they are labeled "unit consumption" (such as kilowatt hours per year for a refrigerator).} This compromise has trade-offs in terms of measuring energy efficiency. Intensities reflect behavior, choice, capacity or system utilization, and other factors besides just process efficiencies. These factors overlap with structural characteristics because they describe the amount of service. For example, a heavy car will usually be more energy intensive than a light one, but is it less “efficient”? In general, a heavy car requires less energy per unit of mass per kilometer of travel than does a light one (32a). It may also be providing more service (comfort and power) to satisfy the driver. The distinction can be important if a policy goal is narrowly defined, such as improving the thermodynamic efficiency of heaters or the efficiency of automobiles as defined above. Few national leaders advocate reducing heating comfort or driving smaller cars, except in times of shortage or perceived crisis. Therefore, it is important to distinguish what is meant or implied by “energy intensities.”

Usually data are only sufficient to construct estimates of energy intensities, using surrogates for physical characteristics and utilization such as the number of refrigerators in the economy. These estimates of subsectoral activities and intensities can be aggregated to yield energy intensities for a large number of activities by using index-number techniques described below.\footnote{In economics, intensities are often used to measure how much of one or many resources is used to produce a given output.}

Index-Number Decomposition

Separating the effects of structural and intensity changes on energy use is critical for policy analysis because most energy-related policies target energy intensities and efficiencies, often by promoting new technologies. Accurately tracking changes in intensities helps measure the effects of these new technologies. Indexing, or “factoral decomposition,” has become a popular technique for separating different components of changes in resource use over time, such as for food, water, or materials (33). Ang & Zhang (34) reviewed more than 50 studies of indexing of energy use. That review provided convincing evidence of the important role index decomposition has taken on in the disaggregated analysis of energy use. Indices can also be used to reaggregate information from more-detailed indicators to reveal information that the ratio of energy use to population or GDP cannot.

The arithmetic falls back on the "*IPAT*" equation set out by Ehrlich & Holdren in the early 1970s (35). Those authors symbolically related an environmental impact *I* to the product of population *P*, per capita activity *A* related to that impact (say car driving), and the characteristics of technology *T* that consumes the energy and materials to provide the services described in *A*. An important characteristic of this formulation is that the factors multiply to give the result, so relative changes are as important as absolute size. This has been applied to carbon emissions under the name Kaya identity (36, 37).

In the current analysis, decomposition of changes in energy use *E* can described by the relation that has come to be known as "***ASI***", shown in Equation 1 below:

$$E = \Sigma \boldsymbol{A}_i * \boldsymbol{S}_{i,j} * \boldsymbol{I}_{i,j}, \qquad 1.$$

where ***A*** represents overall sectoral activity in each sector *i*, say value added in manufacturing, ***S*** represents sectoral structure expressed as share of subsector *j* in each sector *i* (in the residential sector, *j* indicates per capita home size and equipment ownership), and ***I*** represents the energy intensity of each subsector *j* shown in *S* (in energy use per unit of output). The indicators effort was the first to disaggregate ***A***, ***S***, and ***I*** into subsectoral components (*j*), finding that such a disaggregation yielded important new information.

If the dimension of fuel mix is introduced (with fuel shares of final users distinguished from those used in electricity or heat production), the equation can be extended easily to carbon dioxide emissions. In this case, we decompose changes in carbon emissions *G* using Equation 2:

$$G = \Sigma \boldsymbol{A}_{\mathrm{i}} * \boldsymbol{S}_{i,i,} * \boldsymbol{I}_{i,j} * \boldsymbol{F}_{i,j,k}, \qquad 2.$$

where ***F*** stands for the carbon content of each fuel *k* used in branch *j* of sector *i*. The *k* index represents two factors: the utility carbon intensity (electricity and district heat generation fuel mix and efficiency) and final fuel mix within each end use sector. The product of the two components of the equation representing changes in the energy system (***I*** and ***F***) is denoted carbon intensity" whereas "energy (or carbon) services" is defined as the product of ***A*** and ***S***.

Index-number techniques permit us to analyze how this relationship changes over time. Greening et al. (38) compared six methods applied to the same data on manufacturing energy use to examine the differences in the size of residuals. The simplest indices are the Laspeyres or Paasche indices applied to discrete data, usually over time. The former approach holds all but one of the members of the right-hand side of Equations 1 and 2 constant in a starting base year and measures the impact of the third member changing. The latter holds quantities constant in final year values. A problem with either of these forms is the presence of residual quantities. Divisia indices present a more sophisticated form, using logarithms of differences and generating less residual problems, particularly adaptive weighting Divisia (AWD) indices, which have virtually no residuals. Whatever the method, indexing provides a powerful tool for understanding how multiplicative factors of energy use affect the total.

Indexing has been applied to energy use decompositions in transportation (39), manufacturing (40--43), and households (44). With suitable assumptions, individual sector results can be combined to give economy-wide measures of changes in energy use with either Laspeyres (24) or AWD indices (26). Torvanger (45) carried out an early decomposition of carbon emissions from manufacturing with Divisia indices, whereas Greening et al. (43) used AWD indices. Schipper et al. (46) used Laspeyres indices for decomposing carbon emissions both sectorally and economy-wide. One particular extension of indexing methodology, known as the mine/yours method, allows for comparison of two countries or of one country against a number of others. In this approach, the ***A***, ***S***, or ***I*** of one country (or an average of other countries) is substituted for the ***A***, ***S***, or ***I*** of another country, and the resulting hypothetical energy use is compared with actual energy use. The result shows how important a single component is in differentiating emissions between one country and any other(s) (47). Thus, the approach has both time-series and cross-sectional applications.

EXAMPLES OF INDICATORS: THE MAIN SECTORS OF ENERGY USE

Our approach defines six "sectors" of energy use: personal travel, freight, manufacturing industries, nonmanufacturing industries, services, and households. This section reviews key structural and intensity indicators in personal travel, manufacturing, and households, based on Schipper (22) and a number of national studies carried out at the IEA. In the illustrations that follow, the countries shown are drawn from the 14 the IEA has studied thoroughly, with regard in each case for illustrating important extremes or trends that can isolated from aggregate data using indicators. Table 1 displays the measures of activity, structure, and intensity and subsectoral disaggregations that are applied in our analyses. The reader is referred to Schipper (22) and other studies for the services or commercial sector (48--50; see also Footnote 3), freight (51), and "other industry," which includes mining, construction, and agriculture (52).

Table 1 Measures of activity, structure, and energy intensities applied to International Energy Agency member countries[a]

Sector (i)/ subsector (j)	**Activity (A_i)**	**Structure (S_{ij})**	**Intensity ($I_{ij} = E_{ij}/A_{ij}$)**
Residential			
Space heat	Population	Floor area/capita	Heat[b]/floor area
Water heat	Population	Persons/household	Energy/capita[c]
Cooking	Population	Persons/household	Energy/capita[c]
Lighting	Population	Floor area/capita	Electricity/floor area
Appliances	Population	Ownership/capita	Energy/appliance[d]
Passenger transport			
Cars & light trucks	P-kms	Share of total P-km	Energy/P-km
Bus	P-kms	Share of total P-km	Energy/P-km

Rail	P-kms	Share of total P-km	Energy/P-km
Domestic air	P-kms	Share of total P-km	Energy/P-km
Manufacturing			
Paper & pulp	VA	Share of total VA	Energy/VA
Chemicals	VA	Share of total VA	Energy/VA
Nonmetallic minerals	VA	Share of total VA	Energy/VA
Ferrous metals	VA	Share of total VA	Energy/VA
Nonferrous metals	VA	Share of total VA	Energy/VA
Food & beverages	VA	Share of total VA	Energy/VA
Other manufacturing	VA	Share of total VA	Energy/VA

[a]P-km, passenger kilometers; VA, value added.
[b]Adjusted for climate variations and for changes in the share of homes with central heating systems.
[c]Adjusted for home occupancy (persons/household).[d]Includes ownership and electricity use for six major appliances.

Travel

The output of vehicle use is travel activity, expressed in passenger kilometers per capita. This is calculated as the number of kilometers moved by each vehicle type times the average number of people per vehicle (load factor). For automobiles, load factors were close to two in 1970 but dropped to 1.5 by the late 1990s. Per capita travel by mode (**Figure 1**) reveals wide variations in values for each mode. With the exception of high shares of bus travel in Japan and domestic air travel in the United States, there is relatively little variation in the modal shares of travel activity. Fuel use per capita therefore depends primarily on the total automobile travel per capita and the intensity of automobile travel.

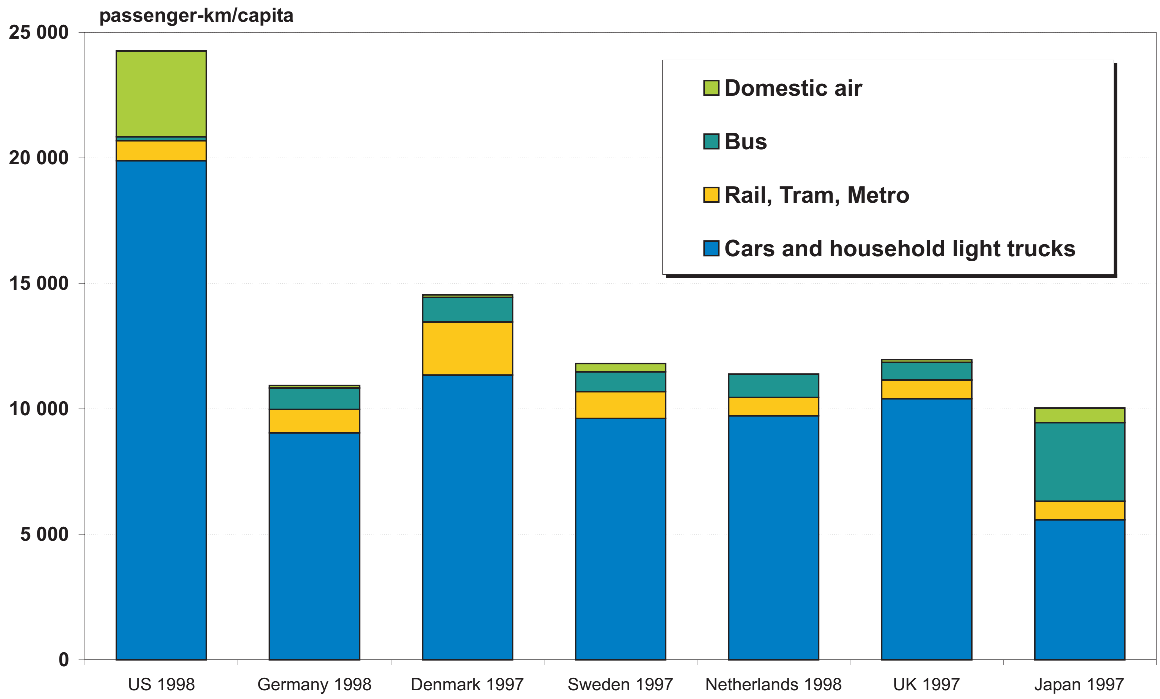

Figure 1. Domestic travel activity per capita by mode, 1997/8

Because so many national and international policies are aimed at improving auto fuel economy, one of the most closely watched indicators is the on-road fuel economy, expressed in energy per kilometer, of cars and private light trucks, including sports utility vehicles (**Figure 2**). European governments have obtained a voluntary agreement from the auto industry to reduce fuel CO_2 emissions per kilometer (related to fuel intensity) in new cars as measured by tests. Both the fuel intensities of new cars in tests and actual fuel intensity on the road must be monitored to measure the impact of this policy. However, calculating this quantity and measuring it from detailed surveys is difficult (51, 53).

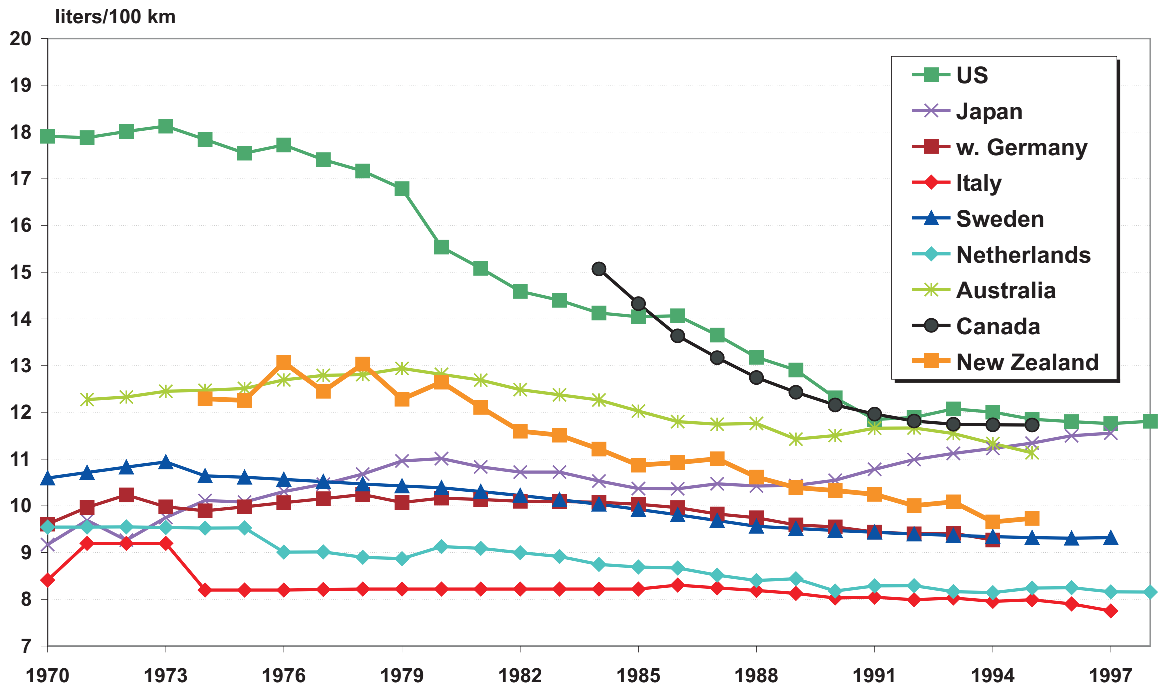

Figure 2. On-road fuel economy (fuel intensity) for cars and light trucks, 1970-1998

Figure 3 provides an example of a causal indicator, which compares automobile use (in vehicle kilometers per capita), against GDP per capita. In this figure, lowest GDP per capita corresponds to the earliest year in the sample, here 1970.\footnote{Note that in this and subsequent figures with per capita GDP on the *X*-axis, the left-most point generally represents the earliest year covered. Points are plotted in chronological order. Time generally progresses with higher GDP per capita, except when a severe recession temporarily reverses GDP, as can be seen in the plot for Canada.} The upward march of vehicle kilometers along with higher GDP is caused mainly by increased automobile ownership, rather than greater use per car. This demonstrates both the level of automobile use and its relationship to a strong driving force, GDP per capita.

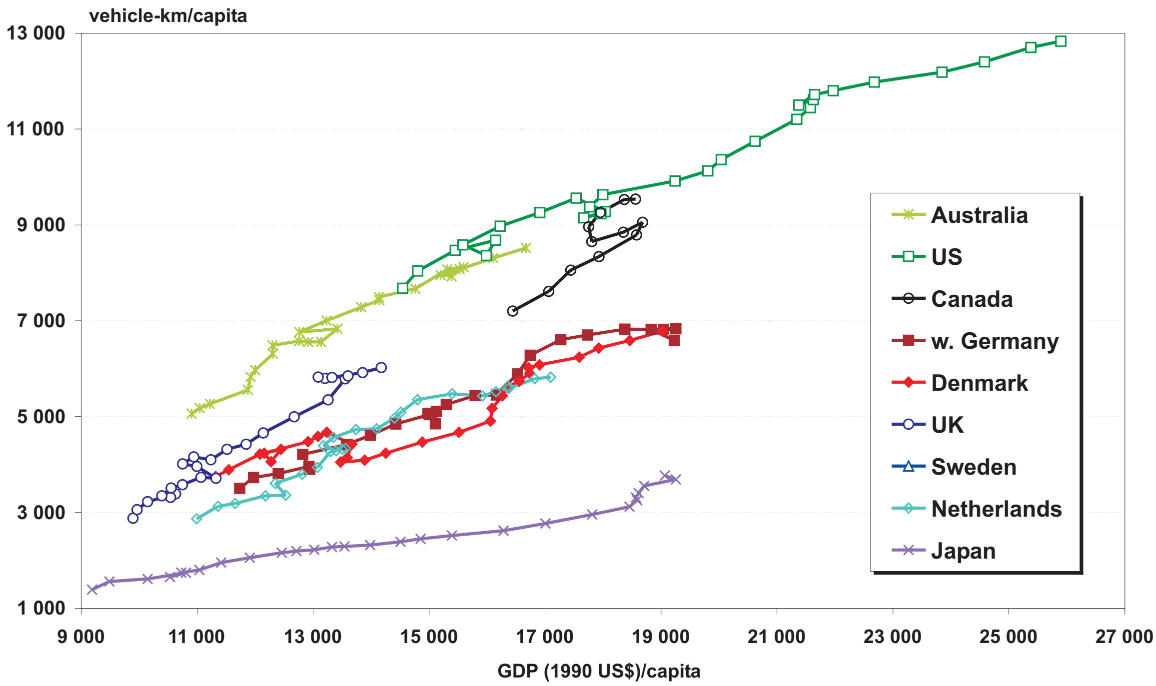

Figure 3. Car and light truck use per capita vs. GDP per capita, 1970-1998

The product of the indicators in **Figure 2** and **Figure 3** is per capita fuel use for cars and private light trucks. By estimating both the kilometer driven per capita and the fuel per kilometer, we can "explain" per capita fuel use for these personal vehicles. Differences between countries or changes over time arise because of variations in both of these components, but it is fuel intensity that is most often the object of government action. Hence changes in the energy intensity must be identified separately from other driving forces. Note that the spread in fuel intensities in **Figure 2** is about as large as the spread in car use per capita or total travel per capita, underlining the importance of both in analyzing the evolution of overall fuel use.

Indicators will play an important role in measuring the achievement of policy goals in this sector. Because automobiles are by far the predominate travel mode in most IEA countries, the total activity and energy intensities of automobiles (***A*** and ***I***) are the key components to understanding differences in energy use, and carbon emissions. The fuel mix (***F***) term has been much less important because the petroleum products used for travel differ relatively little in their carbon content. In the future, as alternative fuel vehicles are commercialized, this could change.

Households

The residential sector is an important source of energy demand in IEA countries, accounting for 12%--20% of total delivered energy consumption. Among the residential end uses, space heating consumes the most energy, followed by electric appliances. Observations of actual end uses are difficult to develop, but surveys can be combined with regression techniques to estimate the relative importance of each end use, as Latta did for the United States (54).

Population---the number of people housed---is the activity indicator for this sector. Therefore, international comparisons based on the activity term are inapplicable. Structural characteristics and intensities (***S*** and ***I***), as we define them, account for all the differences in energy use between countries. Moreover, since population has grown slowly in IEA countries in recent decades, most of the changes in energy use over time are also functions of these terms. We begin with an analysis of structural effects on residential space heating, the largest household end use in most IEA countries.

Because space heating energy consumption is roughly proportional to outdoor temperature for a given set of dwelling characteristics, differences in average winter temperature are significant determinants of variation in household energy use. The impact of average temperature on heating demand is measured by degree-days, the difference between outdoor temperature and an indoor reference temperature (typically 18°C) integrated through the heating season. These figures can be estimated for different regions of a country, then added up and weighted by population, number of housing units, or area heated (25). The 14 countries studied vary from under 1000 degree-days (Australia) to over 4500 degree-days (Finland and Canada) during an average heating season.

The other key structural feature in residential space heating is dwelling area per capita, which depends on both average dwelling area and occupancy. **Figure 4** shows how dwelling area has varied with private consumption per capita in a number of countries. The continued growth, even when consumption fell during recessions, is striking. Note again the significant dispersion in this indicator at a given level of private consumption per capita. Although the variation is not as large as that for degree-days, it is still large enough to cause significant differences in household energy use among countries. Because the size of households fell from over 3.2 persons per household in 1970 to between 2.3 and 2.6 in 1999, area per dwelling has risen less rapidly than dwelling area per capita, as portrayed in **Figure 4**. The same demographic trend, although leading to slight decreases in energy consumption per household, tends to increase household energy use per capita because a larger number of dwellings is needed to house a given population (55). It is interesting that such a simple indicator has a profound impact on residential energy use.

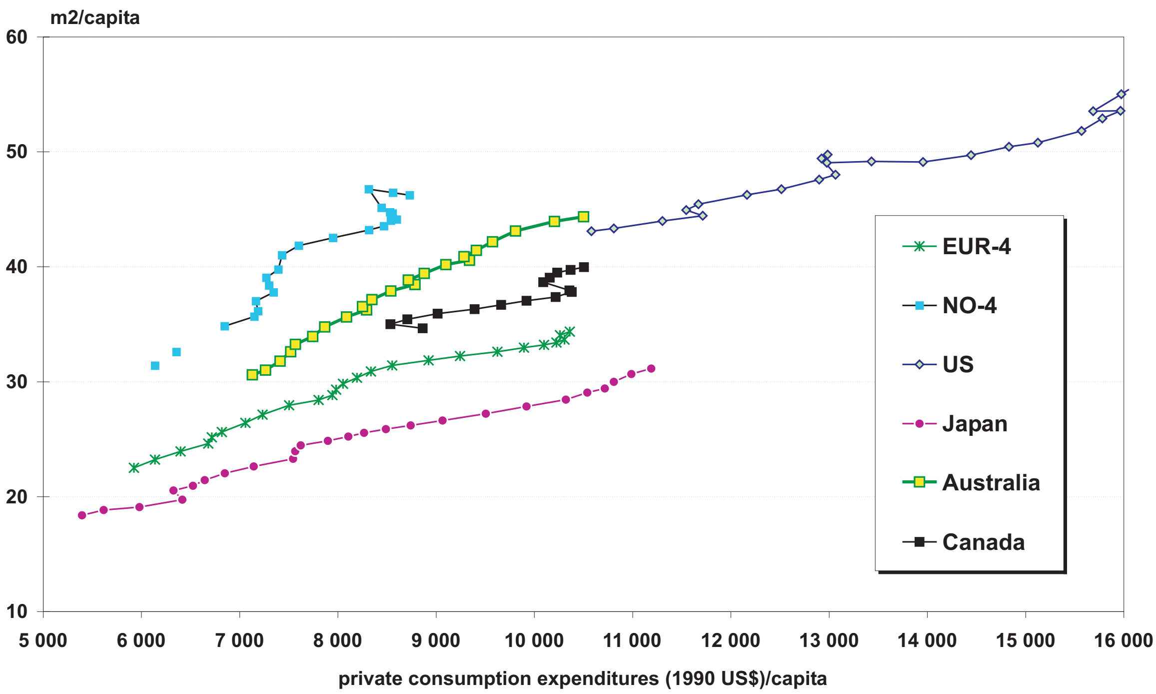

Figure 4. House area per capita vs. private consumption expenditures per capita, 1970-1997

Figure 5 summarizes all the main household end uses, aggregating fuels and purchased heat, but keeping electricity separated. The space heating figures are also scaled to 2800 annual degree-days, the approximate average for all 14 countries included in this survey. The thin bar shows the unscaled value, which for Canada is significantly higher than the actual and for Australia is significantly lower. Since Canada and Australia have very large homes, the differences in winter climate have an enormous impact as compared with others in Western Europe or the United States, which happens to have nearly the same number of degree-days as Western Europe on average.

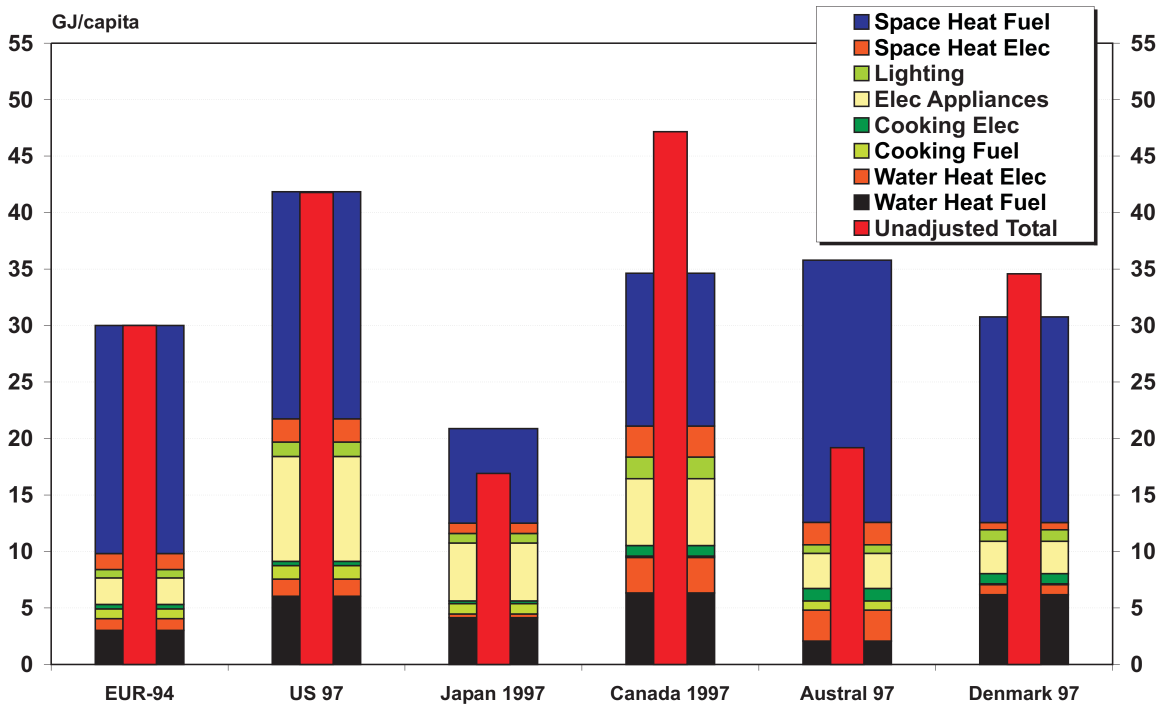

Figure 5. Household energy use per capita by end use and main fuel choice, 1997 (1994 for Eur-4).

Many IEA member countries have promulgated policies to reduce energy use for heating. A number of countries [France (56), the Netherlands (56a), Sweden (56b), the United States (56c)] have instituted detailed household heating surveys to follow the progress of efforts to save energy from space heating. **Figure 6** portrays the trends in space heating useful energy intensities for several countries. Useful energy, a measure of the energy content actually applied to the energy service rendered, is used to correct for the effect of fuel switching on final energy intensities because the average combustion losses for fuels vary. The intensity shown is also normalized to house size and degree-days, so that figures are comparable year-to-year within a country and among countries.

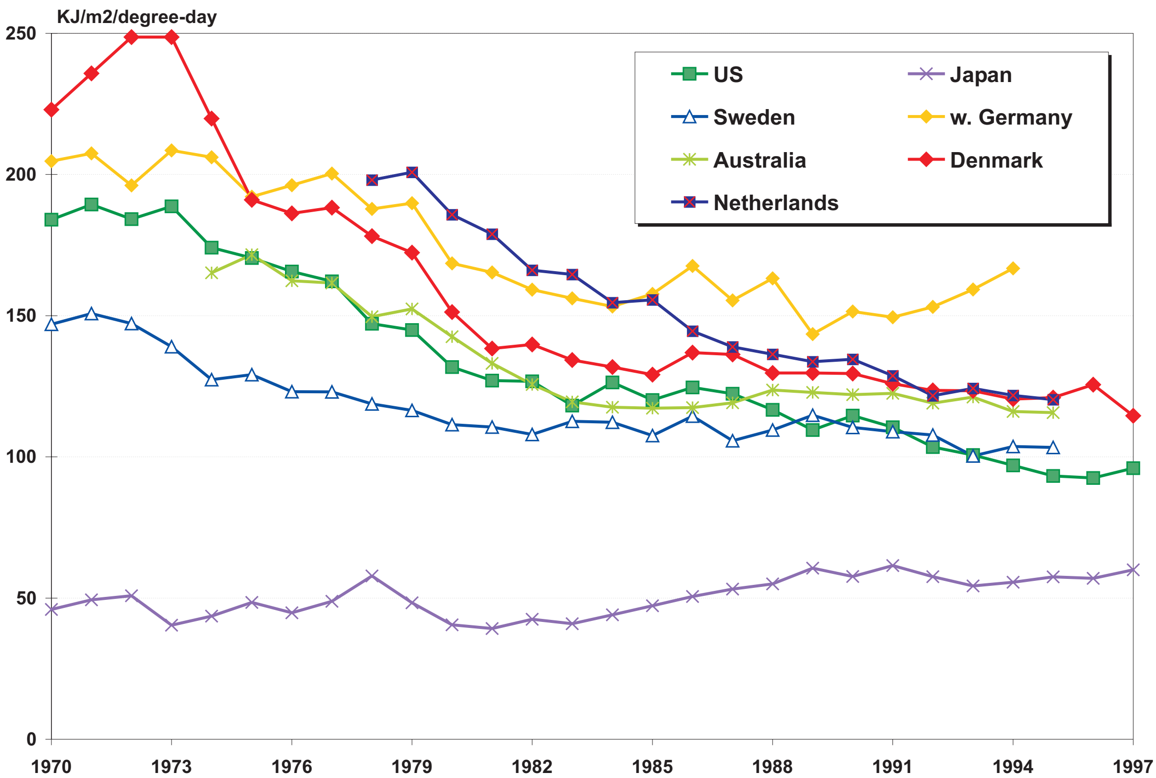

Figure 6. Useful space heating energy per unit floor area and per degree-day, 1970-1997

The data suggest that many countries have met their goals to reduce space heating intensity, although they do not indicate to what extent government policies may have been responsible. However, with higher area to heat per capita and higher population, it is no surprise that household energy use in some countries in 2000 was higher than in the early 1970s, in spite of important energy-saving efforts. The flat line for Japan reflects increases in the standard of indoor comfort during this period (greater area heated, longer heating hours, higher indoor temperatures) as standards approached those in the other IEA countries. This does not imply that energy efficiency was not improved, only that other factors were driving heating comfort up.

Unlike transportation services, households rely on a wide mix of fuels, with separate choices for available for space heating, water heating, and cooking. The Netherlands and the United Kingdom rely on natural gas for heating in over 80% of households, the United States in about half, whereas in the Nordic countries outside of certain regions of Denmark this source of fuel is uncommon. Residential coal use is almost nonexistent in the 1990s but was once the dominant heating fuel. District heating is common in Denmark, Sweden, and Finland (more than a third of households). Electric space heating has high penetration in Canada, Sweden, France, and above all Norway, where it is present in about 90% of homes. It is not surprising that each heating fuel is most used where it is least costly.

These variations in final fuel mix have significant implications for carbon emissions from home space heating, as shown in **Figure 7** (see also 44). Space heating of homes accounted for 10%--15% of all carbon emissions in the IEA in the mid-1990s. Because the fuel mix generally moved from coal and oil to gas and in some countries to low-carbon electricity, carbon intensities per square meter fell even more than energy intensities. In this comparison, Norway lies under Japan, but it lies well above Japan in **Figure 6**. This is because Norway's space heating relies almost entirely on hydroelectricity. In recent years, the decline in importance of carbon-intensive coal used directly for space heating and the rising share of end use electricity boosts the importance of utility mix in this sector. Indeed, for most countries, the utility portion of the fuel mix term differentiates household carbon emissions much more than does the choice of final fuels used. Because of differences in the carbon content of electricity and fuels used in this sector, as well as in the services and manufacturing sectors, carbon trends may be considerably different from those for energy.

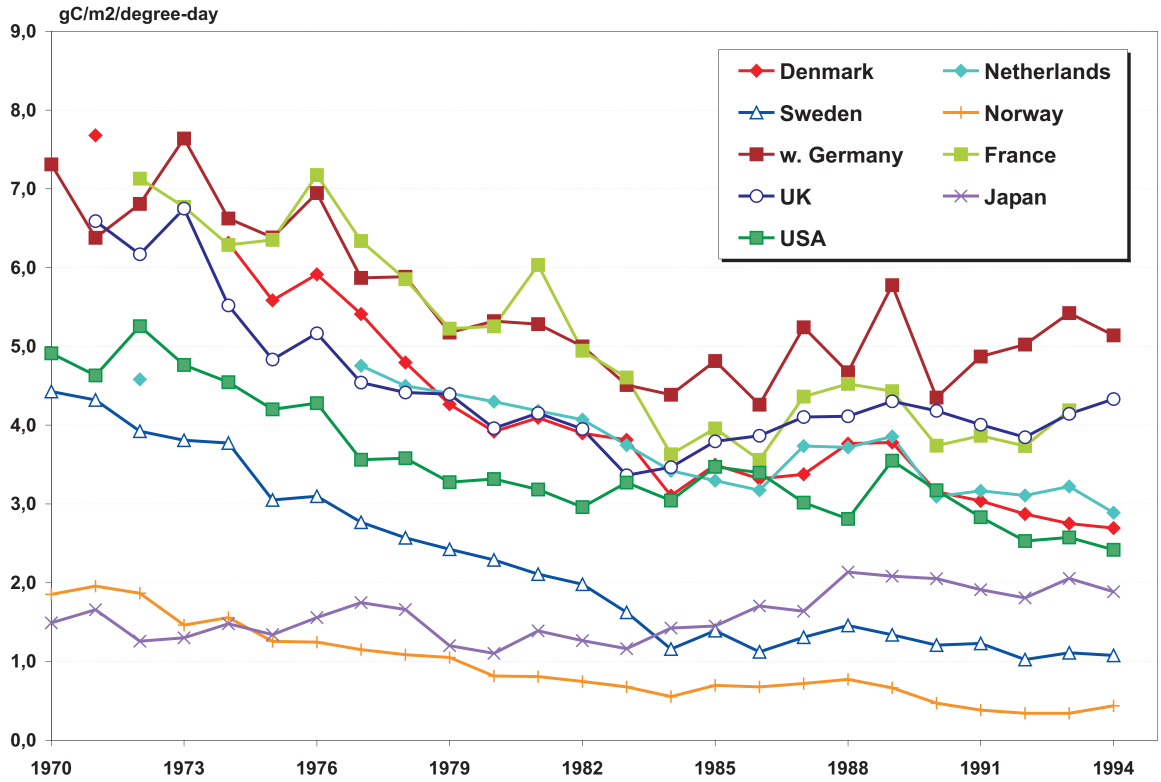

Figure 7. Space heating carbon emissions per unit floor area and per degree-day, 1970-1994

Manufacturing

Because of a rich data set, energy use and intensities in the manufacturing sector have been the subject of many important studies. One of the early pioneering analyses examined energy intensities in the 1950s and 1960s and found that both improved technologies and fuel mix changes contributed to the decline in intensities that occurred despite falling real energy prices (57). Many efforts to study manufacturing energy use have been based on relatively aggregated data, often using data disaggregated down to only the two-digit level of the International Standard Industrial Classification. At this level, some key energy-intensive industry branches are combined under one heading, such as "iron and steel" and "nonferrous metals" into "primary metals." This has significant consequences for the analysis because indicators based on higher levels of aggregation can yield misleading results. However, the availability of internationally consistent disaggregated data is limited.

The IEA/Organization for Economic Co-operation and Development (OECD) effort to establish an international database, with energy and activity data down to four digits of International Standard Industrial Classification disaggregation, is now expanding as more countries supply data to the IEA (58).

A STATIC PICTURE OF MANUFACTURING ENERGY USE The disaggregation of manufacturing energy use is important to allow for separating out the few energy-intensive branches that account for most of the sector's energy use. These branches are typically only responsible for a small fraction of total value added (see **Figure 8**). The most energy-intensive branch based on data for 13 IEA countries is the production of ferrous metals. The energy intensity in this branch was about 16 times higher than the category "other manufacturing" in 1994. The output from the branch, however, constituted only 4% of total manufacturing value added, compared with more than 65% from "other manufacturing." In fact, these two subsectors each accounted for about 21% of 1994 manufacturing energy use.

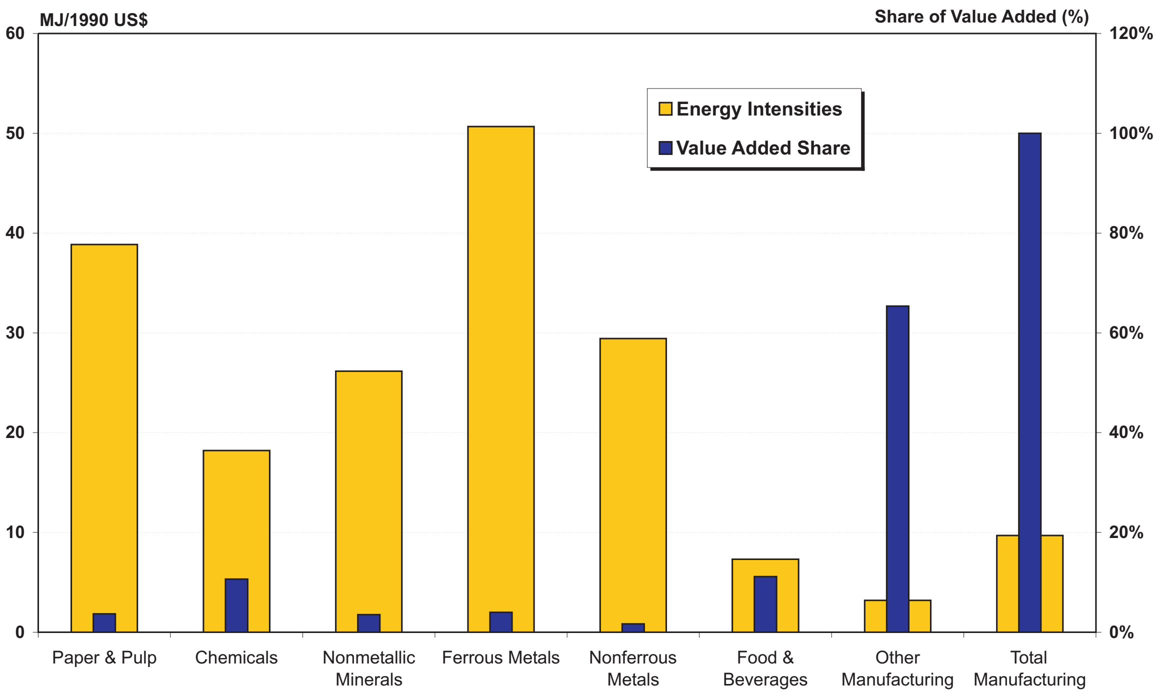

Figure 8. Average manufacturing energy intensity and value added share by branch in the IEA-13, 1994

It can thus be expected that countries with high energy intensities in energy-intensive subsectors and/or higher shares of manufacturing production arising from these subsectors will have higher than average total manufacturing energy use per unit of output. Indeed, total manufacturing energy use per unit of output varies by a factor of almost four among IEA countries (see **Figure 9**). How much of these variations arise from differences in the structure, or output mix from various branches, and how much arise from differences in energy intensities at individual branch levels?

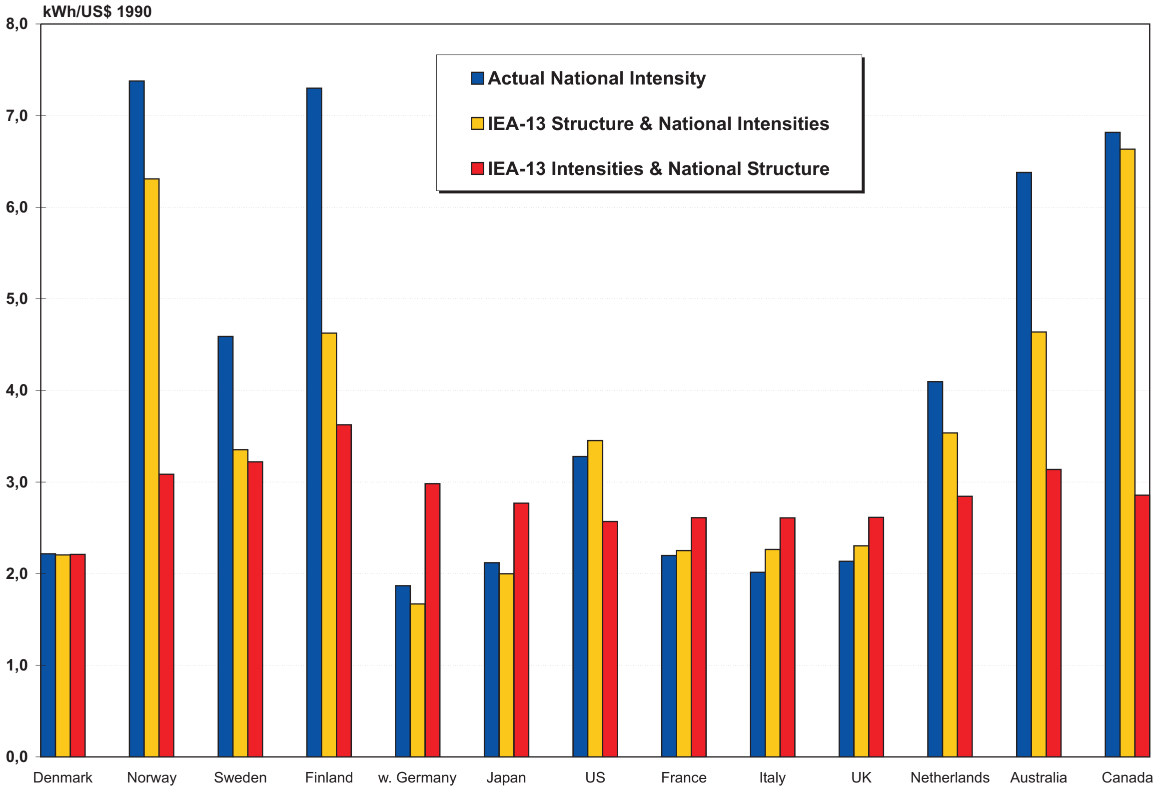

Figure 9. Manufacturing energy intensities in 1994: actual, using IEA-13 structure, and using IEA-13 intensities

A way to adjust for the differences in the mix of output across a set of countries is to calculate the energy intensity that would have occurred if each country had the same shares of subsectoral output as the average for the whole group. This adjustment equalizes the structure of manufacturing across countries by multiplying each country's subsectoral intensity by the respective subsectoral output shares given by the group average. This adjusted intensity is shown in **Figure 9** (IEA-13 structure and national intensities) for a group of 13 IEA countries. Where the intensity increases in the adjusted version, e.g., United States, United Kingdom, and Italy, the country in question had an output structure less energy-intensive than the average of all countries; where a decline occurred, the structure was more energy-intensive than the average. For Finland, Sweden, Norway, and Australia, the decline is large, indicating the importance of the high shares of energy-intensive products.

After this adjustment there are still wide variations across countries. These variations indicate that the levels of subsectoral intensities differ from country to country. To investigate the impact of differences in these intensities, we calculate the aggregate energy intensity that would have occurred if each country had the average IEA-13 energy intensity in every manufacturing subsector but its own sectoral output mix. The results are displayed in **Figure 9** (IEA-13 intensities and national structure). In this case, increasing energy intensity (e.g., Denmark, western Germany, Japan, France, Italy, and United Kingdom) compared with the actual value means that a country’s energy intensities are lower than the IEA-13 average; a decline indicates that the intensities are higher than average. The latter is particularly the case for big producers of raw materials: Norway, Finland, Australia, and Canada, where the intensities within the paper/pulp and metals subsectors are high. These subsectors are more energy intensive than in the other countries in part because of the high proportion of pulp, steel, and aluminum produced from virgin lumber and ores as opposed to secondary production from recycled stocks. Adjusting for the structural differences at this level would require data disaggregated below what is available in an internationally consistent format.

MANUFACTURING ENERGY USE OVER TIME Just as structural differences explain much of the variation in aggregate manufacturing intensities, shifts in output shares over time can have large impacts on manufacturing energy use, even if energy intensities remain unchanged. The larger the gap in energy intensities between different branches, the greater the impact of shifts in output on energy use. Consider what happens when a country's "other manufacturing" value added grows faster than its ferrous metals value added. Because each dollar generated in the former sector requires one tenth or less of the energy input required for iron and steel (see **Figure 8**), a small reduction in the share of ferrous metals will yield a significant reduction in the aggregate manufacturing energy intensity.

Figure 10 illustrates the effect of structural changes in selected IEA countries, including the average percentage changes in actual energy use and real value added between 1981 and 1994. All countries show increased value added in this period. Except for western Germany, all countries also saw increased energy use in manufacturing, although less than the rise in output. This means that aggregate energy use per real manufacturing value added declined in every country.

Figure 10 also illustrates the effects of structural changes on manufacturing energy use, expressed as annual percentage change. To calculate this effect, energy intensities for each subsector as shown in **Figure 8** are held constant and only the shares of value added among subsectors are varied. Similarly, the effect of changes in energy intensities, adjusted for these structural changes, can be calculated by holding the subsectoral shares of output constant and while varying the subsectoral intensities (**Figure 10**).

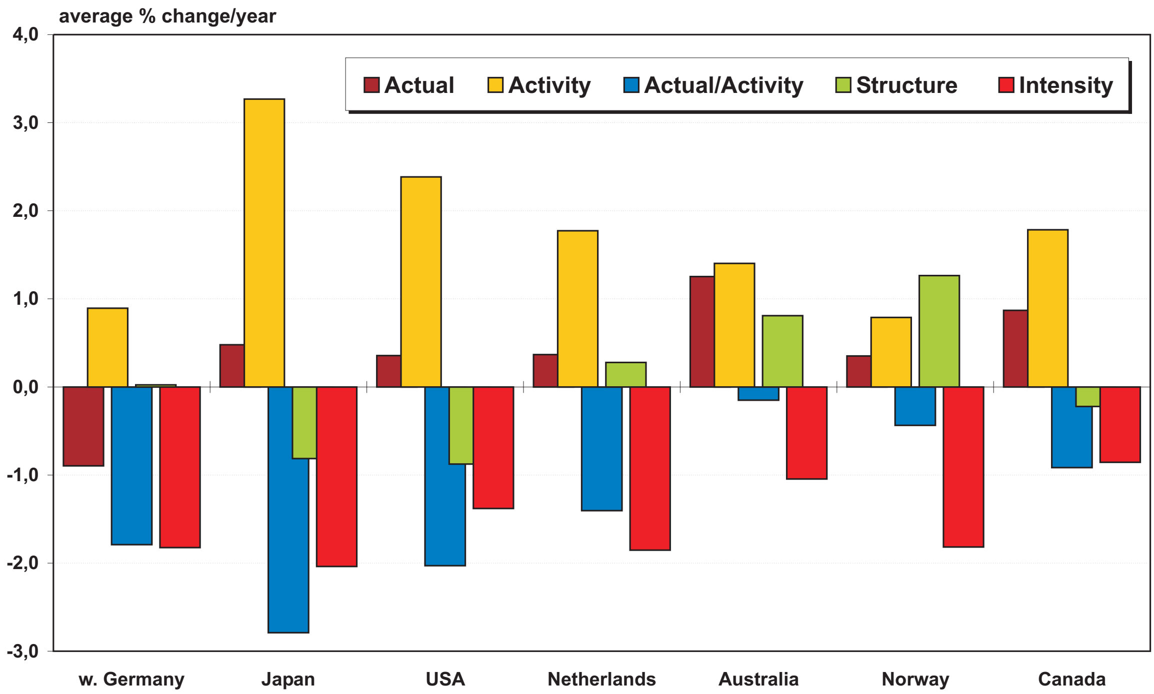

Figure 10. Impact of changes in structure and energy intensities on manufacturing energy use, 1981-1994

The wide variations shown in **Figure 10** imply that country comparisons based on the aggregate intensity can be misleading. Consider the United States and Norway as an example. Both countries had about the same growth in actual energy use (approximately 0.3% per year), but whereas value added grew by almost 2.5% per year in the United States, the growth rate in Norway was only 0.8%. Hence aggregate energy intensity fell much more in the United States than in Norway---2.1% per year and 0.4% per year, respectively. During the same period, the US manufacturing output moved toward less energy-intensive branches. This effect alone reduced energy use by almost 1% per year. At the same time, the structure of Norwegian manufacturing became more energy intensive, driving up energy demand by about 1.3% per year. Taking structural changes into account, US intensities fell by only 1.3% per year while falling intensities reduced Norwegian manufacturing energy use by 1.7%. Aggregate intensity calculations underestimate savings in countries like Norway, Australia, and the Netherlands, where the manufacturing structure became more energy intensive, and overestimate savings in countries like Japan and the United States, where the converse was true.

Structure-adjusted manufacturing energy intensities have fallen by 21%--58% between 1973 and 1994 among the countries we have studied (59). However, long-term data show that the downward trend was also present before the sharp rise in world oil prices in the 1970s (**Figure 11**). These savings were largely the result of improvements in technology and increases in the scale of production. In most cases, energy intensities continued to decline after oil prices collapsed in 1986, but more slowly than during the 1970s and early 1980s. Some of this change is a consequence of the recession in the early 1990s; this is especially the case for Japan.

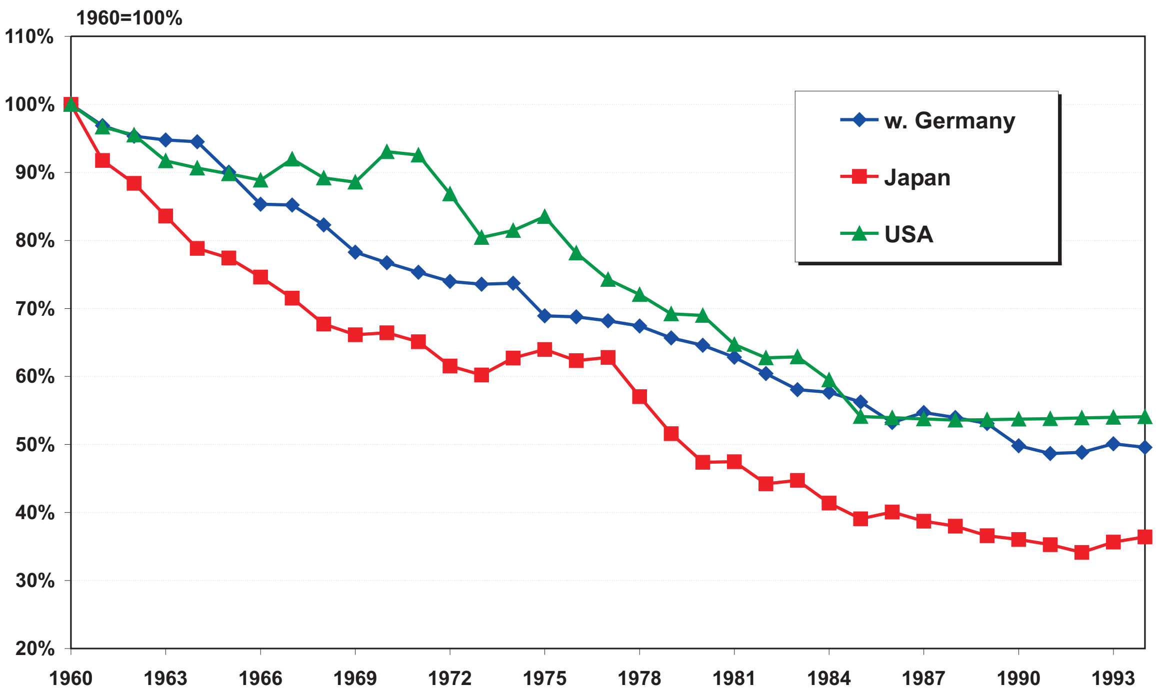

Figure 11. Long-term impact of changes in energy intensities on manufacturing energy use, 1960-1994

As discussed in the previous section there are also important structural differences between countries at more disaggregated levels of detail than we have studied. Changes in this "microstructure" of manufacturing within one country may also affect manufacturing energy use over time. Data limitations make assessment of these small-scale structural changes difficult. Phylipsen (60) uses a methodology to evaluate the effect of microstructural changes in such branches as iron and steel, aluminum, cement, and the chemical and petrochemical industries. She also points out, however, that the application of this methodology for cross-country comparison is limited by the availability of consistent data.

Phylipsen's work and other efforts define energy intensity as energy use per ton of physical product. This indicator, also known as specific energy requirements (SER), comes closer to measuring energy efficiency (expressed by a decrease in the SER) than an intensity calculated in terms of monetary output (61). Unfortunately, long-term data for such indicators are difficult to find, except for a handful of products---namely primary materials such as steel. The advantage of the SER indicators is that they permit a physical explanation of changes both in intensities over time and in differences between countries. These explanations are rooted in the use different processes to produce a given product. Farla (62) shows how physical indicators can be developed for cross-country comparisons of energy-intensity developments in the paper and pulp and iron and steel industries, but because of data problems, comparison of these indicators is limited to a few countries.

Comparing absolute values of physical indicators or SER among countries or companies may reveal considerable differences in practices that can save energy. The most effective of these are often called "best practices." Although it is important to understand the technologies behind best practices, it should also be borne in mind that "best" is a function not only of energy intensities but also of the cost of other resources, such as capital and labor. The indicators do just what their name implies: They indicate important areas for further investigation. They do not prove that a particular technology is "good" or "best," only that it is higher or lower in energy intensity for a particular application.

CHANGES IN MANUFACTURING CARBON EMISSIONS **Figure 12** shows changes in manufacturing carbon emissions between 1973 and 1994 for selected IEA countries, decomposed according to Equation 2. It illustrates how all the ***ASIF*** components are important in explaining the decline in manufacturing carbon emissions that occurred in all the countries shown. Decreasing energy intensities had the largest downward effect on emissions everywhere, whereas increasing output (activity) pushed up emissions, but to a varying degree. Structural change reduced emissions in all countries included in **Figure 12**, most notably in the United States and Japan, as countries shifted away from energy-intensive raw materials production. For the selected group of countries shown here the decarbonization was augmented by significant fuel switching away from oil and coal in the power sector, reducing the utility carbon intensity. End-use fuel mix changes drove up emissions everywhere as the share of electricity in the end-use fuel mix raised. In countries where electricity is predominantly based on fossil fuels, average emissions per unit of final energy from electricity will typically be higher than end-use of oil, or even coal.

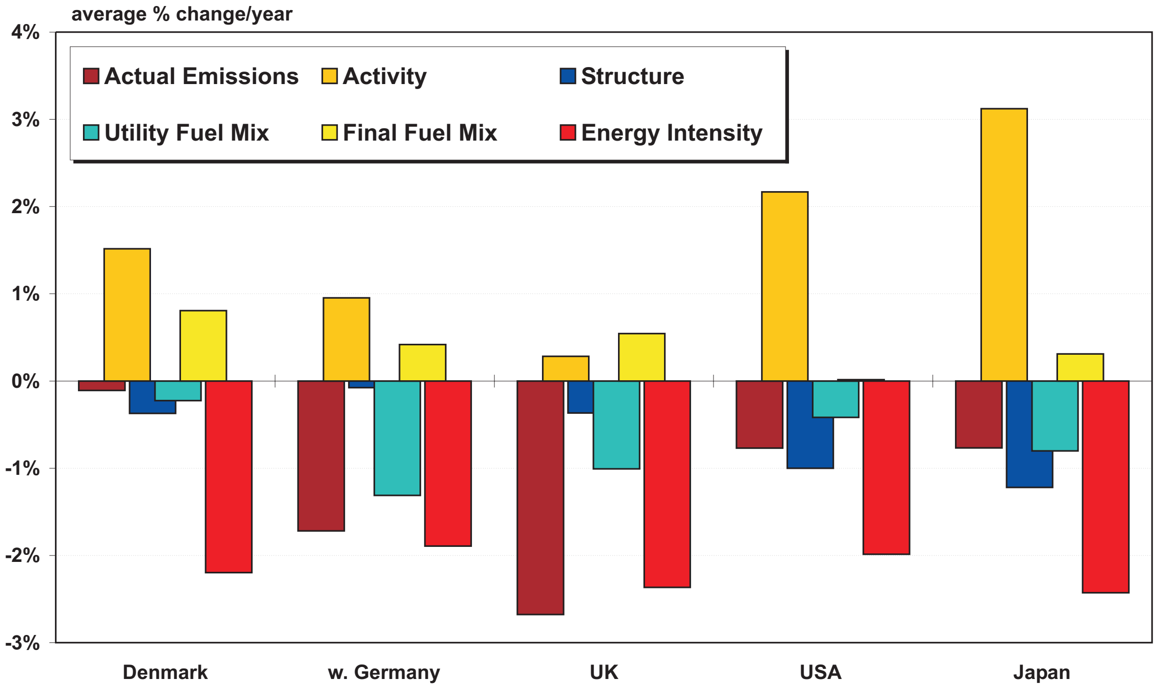

Figure 12. Impacts of changes in carbon intensity on manufacturing carbon emissions, 1973-1994

ECONOMY-WIDE INDICATORS OF ENERGY INTENSITIES AND ENERGY SERVICES

Time-Series Decomposition of Energy Services and Intensities

We have shown how disaggregated indicators reveal the importance of structural effects at finer levels of detail for each sector of energy use. At some point, however, the details need to be boiled down to a few simple figures for capturing behavior over time or making international comparisons. This section presents such indicators. The indicators for individual end uses within a sector can be combined to synthesize an aggregate energy-intensity index for that sector, as was shown for the sectors presented above. The resulting indices from each sector can be combined further, weighted at base-year values of energy use, to measure the impact of changes in either energy intensities or economy-wide energy services on overall energy use. The same approach can be applied to carbon emissions.

Figure 13 shows the average annual rate of change of these indices for a number of countries, this time normalized to GDP. "Energy intensities" (***I*** in Equation 1) measure the impact of changes in over 30 energy intensities on total energy. The average annual decline was more rapid from 1980 to the early 1990s than afterward, as the effects of lower oil prices reduced pressures to improve efficiencies. Indeed, Japanese intensities rose in the early 1990s, in part because of recession in manufacturing. For New Zealand, deep recession and economic restructuring in the late 1980s were accompanied by hefty increases in manufacturing intensities, but these began to fall in the early 1980s (25). Note that, for a majority of countries, the intensities index fell less than the ratio of final energy use to GDP, whereas in two countries it fell more rapidly. In New Zealand, the energy per GDP ratio increased despite falling energy intensities.

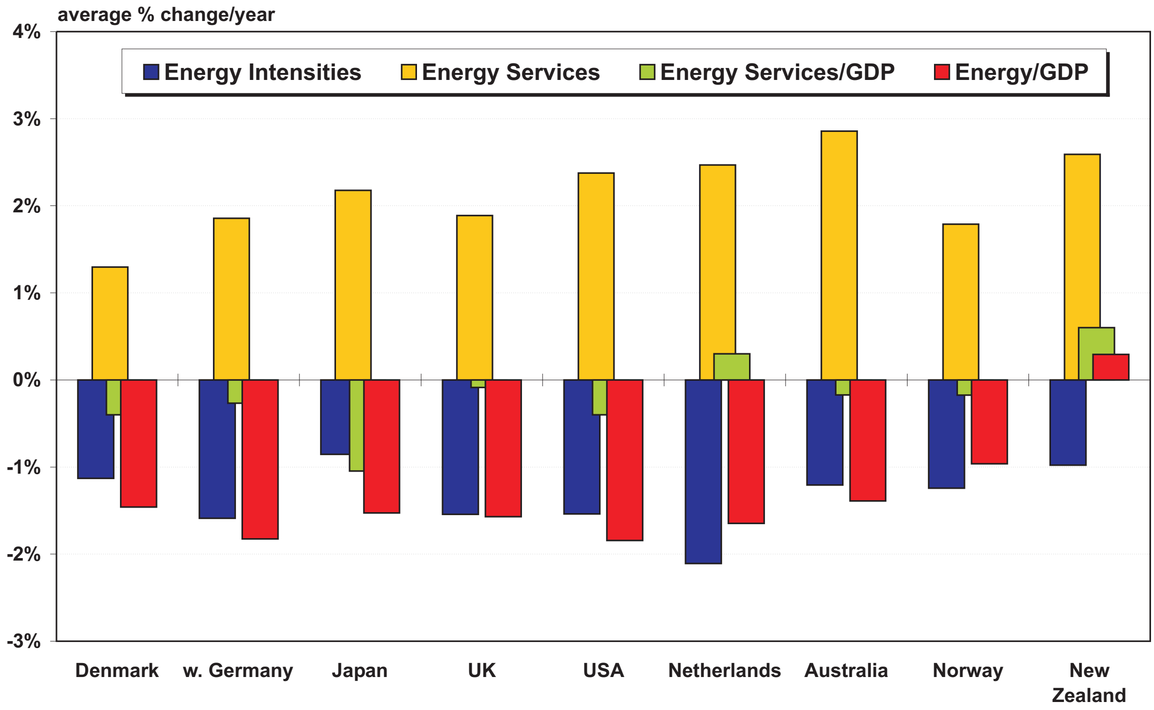

Figure 13. Impact of changes in energy intensities and energy services on total energy use (shown as average annual rate of change), 1980-1994

The evolution of energy services (cf. ***AS*** in Equation 1) explains much of the divergence between the rates of change for energy per GDP and intensities. Each component of activity and structure is indexed to the corresponding energy use in 1990, and the results are added across all energy uses. The results measure an "energy-intensity-weighted" GDP, which includes such physical components as passenger transport, freight, and residential energy use, together with GDP measures of output from the manufacturing and commercial sectors. The total can be compared with the 1990 total for energy use to obtain an overall index of how much energy use changed as a result of changes in energy services alone.

Figure 13 shows how energy services affected energy use. Most countries had relatively strong growth over this period, and in most cases, energy services grew more rapidly than energy intensities fell, leading to increases in energy use. Because GDP growth drives much of the change in energy services, it is interesting to see how the two growth rates compare. This development (energy services/GDP) explains the divergence between the energy intensity index and the ratio of energy use to GDP. In a few countries (the Netherlands and New Zealand), energy services expanded more rapidly than GDP for long periods. This effect alone raised energy use relative to GDP, even as individual energy intensities were falling. For New Zealand, the ratio of energy to GDP increased over time even though energy was saved. Other countries experienced less growth in energy services relative to GDP because, in some cases, the energy service component was already high and growing more slowly than GDP (the United States and Denmark). This accounts for the more rapid decline in energy/GDP than in intensities. This change reduced Japan's energy consumption per GDP more than intensity changes did. Yet, in none of these countries were changes in energy services even a minor component of energy policy goals, and few countries sought to offset the growth in the most energy-intensive activities. Thus the energy services per GDP indicator helps to show how much of the change in energy per GDP was not caused by changes in energy intensities.

These indexed aggregates can be extended to carbon emissions, as **Figure 14** shows. We expand the intensity term to include a separate term for final fuel mix as well as one for "utility carbon intensity," the ratio of carbon released to electricity (or heat) supplied to final energy users. With this addition, energy services have now become "energy/carbon" services because activities with greater carbon intensity (or a higher share of emissions in the base year) carry more weight than those with lower carbon intensity.

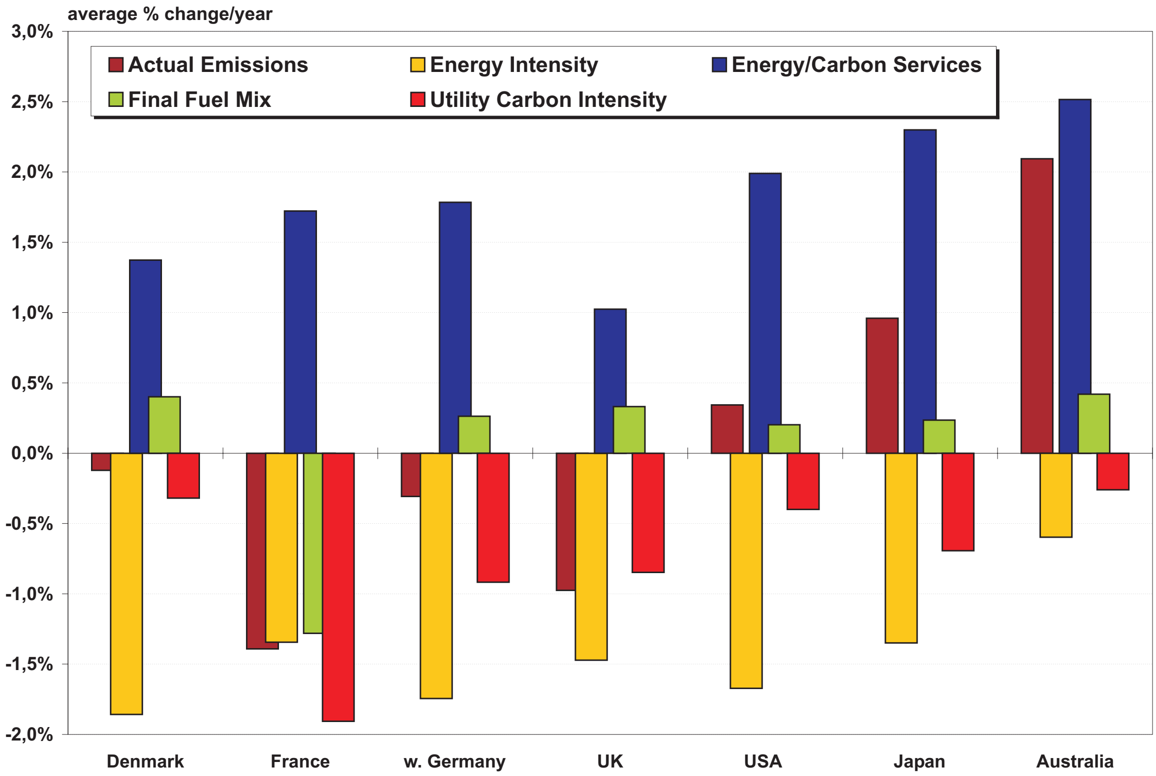

Figure 14. Impact of changes in energy intensities, energy services, and carbon intensities on total carbon emissions (shown as average annual rates of change), 1973-1994

It is not surprising that changes in energy services have raised emissions (*AS*). Changes in energy intensities, by contrast, restrained emissions considerably---in many countries enough to offset the impacts of energy services. Changes in utility carbon intensity have had a downward impact everywhere. Changes in the final fuel mix have had a small impact on emissions, often increasing them. Some countries used more carbon-intensive final fuels in manufacturing or more carbon-intensive electricity as a share of final fuel mix, particularly Australia. Still others, notably the United States, effected such deep savings of natural gas in home and service-sector heating that the overall final fuel mix appeared to become more carbon intensive. In many countries, a spurt in the use of oil for transport made the average fuel mix more carbon intensive as well.

Taken together, these summary indicators show how the underlying components raise carbon emissions or restrain them. By decomposing energy use or carbon emissions per unit of GDP into a structural/services component and an energy/carbon intensity component, and by further breaking these down by sector, we see precisely where the energy or emissions growth is strongest. We can also show to what extent intensity reductions are offsetting this growth. By including the structural component (the factor least affected by policies aimed directly at cutting carbon emissions), we can see whether this component is helping or hindering a country's effort to mitigate carbon emissions.

Static Comparative Indicators of Differences Between Countries

Figure 15 depicts carbon emissions per unit of GDP in a number of countries. Even after normalizing by GDP, differences remain in each sector. Although GDP accounts for the largest share of variation in emissions per capita, several factors affect the variation in emissions per unit of GDP.

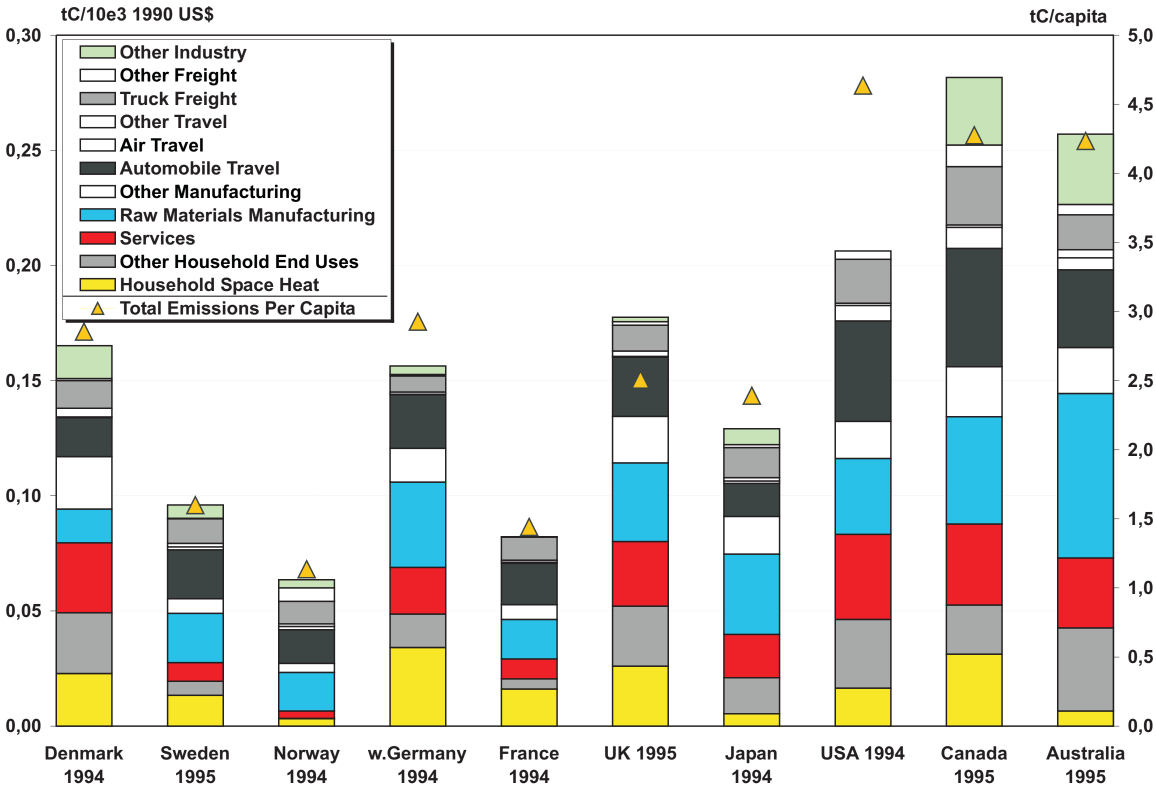

Figure 15. Total carbon emissions per unit GDP by major end use, 1994

To go deeper into differences in energy use or emissions, the **ASIF** decomposition can be used to measure how differences in sectoral components affect cross-country differences in emissions per capita or per unit of GDP. Although these comparisons reinforce some commonly held beliefs about differences in energy-related carbon emissions, they also reveal some surprises (63). We summarize our major findings from these mine/yours analyses as follows: (*a*) Subsectoral energy intensities and utility carbon intensities account for the next largest gaps in emissions; (*b*) differences in the ratios of energy services to GDP account for some of the emissions gaps; and (*c*) final fuel mix is the least important factor in creating differences in emissions, except for a few extreme examples, such as very high natural gas use in the Netherlands or very shares of low-carbon electricity in Norway.

In general, energy intensities for a given end use vary by more than a factor of two, as many of our earlier charts showed. What are less well appreciated are the variations in structural or energy-service parameters that also contribute. We have also shown how distance driven or traveled, home area, and winter climate vary by more than a factor of three among IEA countries and that the first two still vary considerably after normalization to GDP. These factors account for some of the enormous differences in emissions per unit of GDP, even between countries with roughly similar GDP and economic structure.

Some of these factors accounting for differences in emissions per GDP are natural, such as climate and geography. Although the former affects emissions from household and commercial buildings, the latter seems to have a profound effect on transportation patters. For example, Australia, the United States, and Sweden have more than two times the ratio of domestic freight tonne kilometers to GDP than that of most European countries and Japan. This leads to higher emissions from road, rail, and inland shipping. We estimate that such “natural” differences account for a third to half of the differences in the ratio of carbon emissions to GDP, with the utility carbon intensity, final fuel mix, and energy intensities contributing the rest. Others factors, such as the size of homes and buildings, can be affected by tax, housing, and urban policies. Americans have the largest homes, which increases emissions from space heating. Are these structural differences rigidly fixed in a way that will always make some countries high emitters?

Even the relatively more flexible factors, such as intensities and fuel mix, vary for complex reasons. Thus, a given country may not be able to achieve the carbon emissions reductions implied by the comparisons of energy intensity, final fuel mix, and utility carbon intensity shown throughout this article. However, identification and quantification of the impact of the factors associated with unusually high or low emissions in any country may be a useful step toward reducing high emissions, by learning what contributes most to lowering them.

DRIVING FORCES: POINTING THE WAY TO WHAT MATTERS

Indicators can reveal the importance of certain causal factors. **Figure 3** showed the use of cars in several IEA countries, displayed against each country's own GDP. The link between car use and output in each country---the income elasticity---is not rigid, but it is strong. Studies of income elasticity of car use give values from roughly 0.7 to over 1 (64). Except for the United States, fuel intensity, as shown in **Figure 2**, fell much less than car use rose during the 1970s and 1980s. Hence fuel use (and emissions) actually increased.

The other obvious factor affecting travel activity and intensity is the price of fuel. **Figure 16** displays the price of automobile fuel compared with emissions from automobiles per unit of GDP. The price is weighted using the shares of gasoline, diesel, and liquified petroleum gas actually consumed by cars. The points for a given country show a wide degree of scatter, but the cross-sectional comparison between countries suggests that prices play a strong role in shaping emissions from car use per unit of GDP, a point confirmed by many economic studies (64, 65). Normalizing emissions by GDP removes part of the influence of income in explaining differences in car use between countries. Although about one third of the differences in emissions/GDP are "explained" by variation in fuel use (or emissions) per kilometer, most are due to differences in kilometers driven per GDP (**Figure 3**).

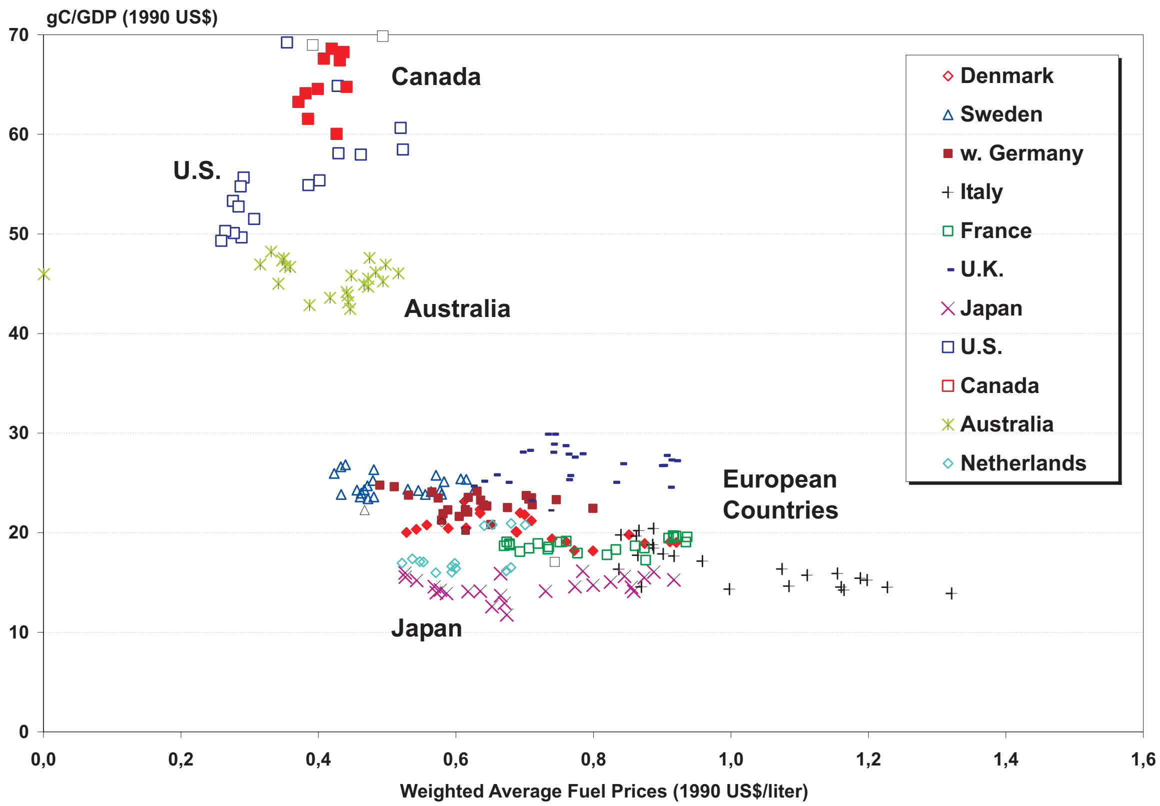

Figure 16. Cars and light truck carbon emissions per unit GDP vs. road fuel prices, 1970-1995

The indicators displayed here do not quantify causal relationships, but they highlight key links that point to causality and point analysts toward further investigation. What is novel about these illustrations is that they display a disaggregated component of structural indicators or energy use against a driving factor. Structural components are driven mainly by incomes and other forces not directly related to energy or energy policies. Intensity components, however, are related to energy-use technologies and efficiencies, which are often the object of government energy policies. To measure the impact of official policies or new technologies on energy uses, governments need to know with some degree of accuracy how the underlying forces have affected each component. This permits the analyst to isolate changes possibly driven by policies (or new technologies) from those driven by other factors, such as changes in prices, incomes, demographic structure, and so on. Energy policies may have affected how much energy is used to heat a square meter of an average home. Housing and fiscal policies, on the other hand, may explain why homes are of a given size.

CONCLUSION: WHAT ENERGY INDICATORS CAN DO

This article has shown that development of disaggregated energy indicators makes available a powerful set of analytical tools. Those tools reveal important trends in energy use that are obscured by traditional aggregate quantities like the ratio of energy use to GDP or sectoral energy use per capita. The same tools can be used to measure the effect of new technologies or policies on energy uses at a disaggregated level, as well as to probe the relationship between energy uses and their underlying driving factors. The use of decomposition techniques permits a large amount of information to be reaggregated into meaningful indices that untangle many of the knotty issues surrounding the evolution of energy use. The approach can be used to understand international differences in either energy use or carbon emissions. Decomposition quantifies the effects of economic structure (energy services), energy intensities, fuel mix, and utility carbon intensity on differentiating carbon emissions patterns for a given year or over time. The indicators approach offers the only way to explain large differences in aggregate energy use, energy to GDP ratios, or sectoral shares and is the only way to understand evolution of energy use over time. This approach is also the most thorough way of understanding differences in energy use among countries.

With examples from a sample of 14 IEA countries, we have shown that indicators can be developed that account for nearly 85% of all energy use in these countries. In noting the large number of countries that have official indicators publications and efforts under way, we underscore the status of the disaggregated approach in understanding trends in national energy use. That other international organizations in addition to the IEA have developed indicators for member countries validates the use of indicators in international discussions and analyses. The expanding number of books, peer-reviewed articles, data bases, symposia, and workshops on the subject continue to boost the substance of energy indicators in industrialized countries. A challenge remains to develop the same approach in the remaining IEA and OECD countries and to extend it to Eastern Europe and the major developing countries. It is in these nations where the greatest increases in energy use and emissions are foreseen.

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