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An End-Use Analysis

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I. Introduction: Scope of the Study

There has been much attention drawn to plans for reductions or restraint in future CO_2 emissions, yet little analysis of the recent history of those emissions by end use or economic activity. Understanding the components of CO_2 emissions, particularly those related to combustion of fossil fuels, is important for judging the likely success of plans for dealing with future emissions. Knowing how fuel switching, changes in economic activity and its structure, or changes in energy-use efficiency affected emissions in the past, we can better judge both the realism of national proposals to restrain future emissions and the outcome as well. This study presents a first step in that analysis.

We examine the long-term evolution of carbon dioxide emissions from energy use from 1973 through 1991 in ten OECD countries (Japan, the U.S., the Federal Republic of Germany, Norway, Finland, Sweden, Denmark, France, Britain, and Italy). These countries account for nearly 80% of commercial primary energy use in the OECD, and over 35% of worldwide energy use. We break down the analysis into six sectors of the economy: residential, services, manufacturing, travel, and freight. Calculations for "other industry" (construction, agriculture, and mining) are presented only for a few countries for which energy consumption data were available. We use a factorial analysis based on a fixed base-year Laspeyres index decomposition to analyze historical changes in emissions by sector and subsector. From this analysis we draw conclusions about past causes of changes in emissions and discuss the implications for future emissions. Subsequent analyses will develop the factorial analyses further using other index methods.

Our results are somewhat surprising to many observers. Aggregate CO_2 emissions from the sectors we have studied (including emissions from producing electricity and district heat) fell or barely rose in all but one country between 1973 and 1991. Relative to GDP, emissions fell strongly everywhere. The main elements of this decline were improvements in energy efficiency, fuel switching, and, in a few countries, shifts away from production of raw materials. In many countries, emissions from consumer activities (households, personal transportation, and portions of the service sector) fell less than emissions from manufacturing and freight. But by the late 1980s, the rate of decline in emissions relative to GDP slowed, both because improvements in efficiency and fuel switching slowed.

The organization of this paper is as follows. We present a brief background and summarize previous work analyzing changes in energy use using the factorial method. We then describe our data sources and method. We then present a series of summary results, including a comparison of CO_2 emissions in 1991 by end use or sector. We show both aggregate change and change broken down by factor, highlighting briefly the main components of change. We then present detailed results, sector by sector. Next we highlight recent trends. Finally, we integrate our results, discussing the most important factors driving change — evolution in economic structure, changes in energy intensities, and shifts in the fuel mix. We discuss briefly some of the likely causes of these changes — long-term technological changes, effects of rising incomes, the impact of overall changes in energy prices, as well as changes in the relative prices of energy forms.

II. Background

Figure 2.1 shows world CO_2 emissions in 1973 and 1991 by region. Clearly the growth is occuring outside the OECD. But the OECD leads as the predominant source of current emissions. This study focuses on countries in the OECD that account for about 80% of the OECD emissions shown in Figure 2.1.

Although emissions grew in most regions, gross domestic product (GDP) grew even more in most countries. Indeed, there is no question that relative to GDP, world energy use has evolved towards lower carbon emissions for many decades (Nakicenovic, 1993). The issue for many is whether the recent rate of this decline can be maintained or accelerated so as to reverse the increase in the *absolute* level of emissions.

Current trends in emissions from the industrialized countries do not suggest such dramatic changes are about to occur without changes in current policies. Fossil fuels are inexpensive compared to the late 1970s and early 1980s, economies are growing, and the transportation sector, which is almost completely reliant upon petroleum, is growing strongly. Although this study will make no predictions about the future, we will discuss the underlying components of current changes in CO_2 emissions and what they imply about likely trends in the near future, i.e., to the year 2000.

Figure 2.2 presents a view of energy use, the principal driver of CO_2 emissions, for the industrialized countries of the OECD studied here. Based on a fifteen-year research program summarized by Schipper *et al.* (1992a), this view was assembled "bottom up" by studying the use of each fuel for each major end use (heating, cars, trucks, etc.) or subsector (steel, paper and pulp, etc.). The bottom-up, end-use analysis is important for several reasons. First, CO_2 emissions arise from the use of fuels and electricity for various activities. To understand the trends in emissions, one must understand the trends in these activities: they happen largely, but not completely, independently of one another. Second, both technology and behavior influence energy use for each activity. To understand the complementary role of each in shaping trends in activities, one is also forced to look at energy use in detail. Finally, policies – be they broad taxes or more focused schemes (such as efficiency standards for certain devices) – affect small parts of energy use that in turn affect overall CO_2 emissions. Understanding how these policies affect emissions requires the ability to analyze the components of each aspect of energy use subject to policies. Thus, any sound analysis of CO_2 emissions and their restraint must confront energy uses at a detailed level. In practice, of course, a few key uses in households (space heating, water heating, six major appliances, lighting), automobile and air travel, truck freight, and five or six branches of manufacturing account for most of the final energy demand. Energy use data for these applications are included in this study. Unfortunately, detailed time series for uses of fuels and electricity in the service sector and most of remaining industry (agriculture, mining, construction) are not available, so these sectors are treated in much less detail.

A good example of the futility of trying to understand changes in aggregate emissions arises when one tries to understand the changes that occurred since 1990, the base year for many agreements over emissions restraint. Since that time (a year of record-warm winters, emerging recession in some countries, the reunification of Germany, and the collapse of the Soviet Union), emissions from fossil fuel use were subject to many forces beyond those normally credited with shaping energy use – namely incomes, prices, technological change, energy policies, and lifestyles. Will countries be able to return emissions in a future year to their 1990 levels? Certainly some of the aforementioned factors must be taken into account, but they affect emissions by fuel and sector unevenly. To be able to relate 1990 emissions to those in any future year thus requires at least a rudimentary map of energy use, emissions, and economic and human activity so that authorities can at least argue, if not agree, over how to take these different factors into account.

This study will focus on a decomposition of the underlying components of changes in carbon emissions. As such, this approach is not new. Torvanger (1991) carried out such a decomposition of emissions from manufacturing in several industrialized countries. More recently, Liu et al., (1992), Ang and Lee (1994), and Ang (1994) decomposed manufacturing energy use in Singapore and Taiwan. The interest in decomposing carbon emissions received new impetus from a recent paper by Matsuo (1996). This paper exploits the so-called "Kaya Identity", whereby emissions are written as the product of (population)*(GDP/capita)*(energy use/GDP)*(carbon emissions/unit of energy). But Matsuo and his coworkers address only the algebra of the aggregate measures in this relation. Clearly the variation in the carbon emissions per unit of activity over time depends on the type of activity and the fuels used. Moreover, the relative importance of emissions from each activity varies over time. And, as we shall see, the role of each of these components (or the separate elements of emissions from each use) varies strongly between countries. Economies do not emit carbon – firms and individuals engaged in production and consumption do so. Therefore, policies desiged to address emissions must aim at the points of production and consumption where emissions take place, at the manufacturers of technologies used by producers and consumers, or both. Hence the importance of a disaggregate approach to analyzing both the historical and future path of emissions is clear. We present this approach below.

III. Method

Our basic method revolves around previous efforts to use bottom-up analysis of the structure of energy use (Schipper *et al.*, 1992a). We extend this work by calculating the CO_2 emissions from more than 25 energy uses or outputs in economies – uses that account for 80-85% of all primary energy consumption. We use a fixed base-year Laspeyres index to analyze the components of changes in emissions between 1973 and 1991. Key elements of the index decomposition method are outlined here.

A. Definitions

There are six sectors of final demand we consider: households, services, manufacturing, other industry (in some contexts), travel, and freight. Within the household sector we will define six end uses, within manufacturing six individual branches (and a residual branch), and within travel and freight up to five modes of transport depending on the country. Typically absent are some parts of transportation not measured (such as consumption of natural gas in pipelines, use of fuels for private boats, use in military vehicles), energy use and losses in refining, some additional energy transformations. Complete data for "other industry", which is made up of agriculture, mining, and construction, are only available for four countries so are omitted in most contexts. The main reason for these omissions is the lack of precise data on energy use, or output or activity, or both.

We do account for all energy consumption in the production of electricity and district heat, however, since these two are the ones with the largest losses. This permits us to measure energy consumption in two ways. *Delivered energy* is what final consumers actually purchase (or collect, as in the case of wood or some renewables) and convert to work, light, and heat. *Primary energy*, in this study, is delivered energy plus the *losses* incurred in producing and distributing electricity and district heat, with the losses allocated to the sector or end use in question. These losses are allocated using the yearly average conversion ratios and primary fuel mixes of electricity and heat production.

Output or Activity. We measure this in several ways. In manufacturing and other industry, output is production measured as real value added, a component of the GDP. Using this definition is somewhat problematic, as there are other economic and physical measures of output available. One advantage of value added, however, is that it is a component of GDP. In the household sector, overall output or activity is really the number of people housed. The individual end-uses (counted below under "structure") include heating, water heating, cooking, lighting, and electric appliances. For the services sector, we use GDP arising in that sector as a measure of activity, although floor area is in some ways a more appropriate measure of how energy is used. Unfortunately, services floor area data is not available for all countries. For the travel and freight sectors, activity is measured as the passenger-kilometers travelled or tonne-kilometers hauled by each mode.

Structure. The structure of each sector measures the mix of output or activities. For manufacturing and other industry (where known), the shares of value added in seven and three subsectors, respectively, measure structure. For travel and freight, the shares of domestic passenger-km and tonne-km by mode represent structure. For households, the "output" of heating is the number of square meters of home area per capita with homes heated by central heating (or fixed electric systems) counted at twice the weight of those heated by room stoves (Sheinbaum and Schipper, 1993). Structure for appliances is just the number of major appliances, per capita. Structure for lighting is floor area. And structure for cooking and water heating is an index of the square root of the number of people in an average household compared with its

1973 value, as it has been observed (Schipper *et al.*, 1989) that all else equal, energy uses for these two purposes vary with household size in that way. For the service sector we have no single measure of structure available for all our study countries. There are, however, several different measures of structure for the service sector which could fit this analysis pending their availability such as floor area per employee and end-use saturations.

Intensity and Efficiency. Intensity is energy use per unit of activity. Efficiency has many definitions; here we connote the ratio of output or activity to energy as efficiency, hence efficiency is related to the inverse of intensity. This broad measure of efficiency captures both technical or process-level efficiency as well as (on the producer side) improvements in other production factors such as labor and capital inputs and (on the consumer side) changes in consumer behaviour such as lowering water temperatures and driving smaller cars. For each household energy use, mode of transportation, or subsector of manufacturing or other industry, we form an energy intensity. The indices representing central heating and household size are only used in the actual index number comparisons.

The five sectors and their primary losses covered in this report account for roughly 80% of all energy use and around the same share of CO_2 in the countries studied. "Other industry", where quantified, adds about 5% to the total. We include wood and other renewables (including wastes used in the paper and pulp sector) in the analysis, but we do not burden these energy sources with CO_2 emissions. We do not include CO_2 released in benefaction, transportation, refining, and distribution of fossil fuels. Because of data problems, we have also been forced to ignore the losses incurred in the refining of petroleum, as these are not usually counted as fuels under the manufacturing sectors of European countries.

Variations in yearly average winter temperatures can have significant influences on space heating demands, particularly in the household sector (Schipper *et al.,* 1985). The usual measure of the severity of the winter is degree-days, measured most simply as the difference between the daily average temperature and 18°C. By this standard, Japan has less than 2000 degree-days for heating, France 2200, and the U.S. 2700, while Finland has over 4600 degree-days. These differences alone may be important reasons why CO_2 emissions differ, since space heating can account for as much as 15% of a country's primary energy use. Equally as important, the number of degree-days in a heating season has varied from as little as 85% of its long-term average to as much as 117% of that average, depending on country and year. The years 1970, 1978-1981, and 1985-7 were the coldest recorded in European countries for the period we studied, while 1989-1992 the warmest. In order to study long term trends, then, we have adjusted the residential component of space heating by the inverse of the percentage difference between actual degree-days and the long-term average. *For this study, the main variation in energy use caused by variations in winter temperatures has thus been removed to first order.*

We have not treated the service sector this way, both because the data on the space heating share are less well understood and because the actual variation in energy use with outdoor temperature is much more complicated. Had we done this, energy use in the service sectors of most countries in 1989-91 might be adjusted upward by as much as 3%. Finally, we do not adjust the residential or service sectors for variations in cooling demand caused by warmer or cooler summers. Space cooling is significant in the U.S., Japan, and increasingly so in Italy and France, but, again, consistent data on the share of energy, usually electricity, for space cooling in the service sector over time are difficult to find. In future work we hope to correct these omissions, but their impact on the present work should be small.

B. Data

The LBNL database on energy use draws from a wide variety of *national* sources from each country. We use international data for energy consumption only as a last resort, except for the energy sectors, where we found the data from the International Energy Agency of high quality and uniform across all countries. We use international data for aggregate economic indicators, but rely primarily on country data for the components of GDP, data on housing and household equipment, and virtually all data on transportation activity. Many of our sources are discussed in Schipper *et al.* (1992a).

With this start, we have made our analyses of energy use by sector, end use, and in certain instances, technology for ten OECD countries. Based on this database, a series of papers have been published that analyze energy use and identify data sources by sector: (Residential) Schipper *et al.*, 1985; and Schipper *et al.*, 1996; (Services) Schipper *et al.*, 1986; and Sezgen and Schipper, 1995; (Transportation) Schipper *et al.*, 1992b; Schipper *et al.*, 1992c; Schipper *et al.*, 1993d; Schipper, 1995; Kiang and Schipper, 1996; and Schipper and Scholl, 1996; and (Manufacturing) Howarth *et al.*, 1990; and Howarth and Schipper, 1991. Complementing these reports are published studies of the four Nordic countries: Schipper *et al.*, 1990 (for Norway); Schipper *et al.*, 1993b (for Denmark); Schipper and Price, 1994 (for Sweden); and Schipper *et al.*, 1995b (for Finland). These reports have been followed more recently with analyses of carbon dioxide emissions from the manufacturing sector (Torvanger, 1991 – updated for this project as Greening *et al.*, 1995), the residential sector (Sheinbaum and Schipper, 1993 – also updated for this project), the travel sector (Scholl *et al.*, 1995), and the freight sector (Schipper and Scholl, 1996). Finally, certain special studies focused on the problem of measuring automobile fuel use (Schipper *et al.*, 1993a) and transportation energy use in Japan (Kiang and Schipper, 1995). The factorial approach was first applied by Howarth *et al.* (1993) and Schipper *et al.* (1993c), and further amplified in Schipper *et al.*, (1992a). Greening *et al.*, (1996) provided a comparison of several index methods.

Not every year from 1970 is included in our analysis. For Sweden, Finland, Japan, Germany, and the U.S., the analysis begins in 1970 (earlier for the last three), for France 1973, and for Britain, Italy, and Denmark 1972. But there are important holes in these time series occasioned by either a lack of detailed energy consumption data or economic and structural data or both. Thus Finland is "empty" for 1971-2 and 1974, Italy is missing for 1974 and only partially complete for 1976-78, Denmark is missing for 1973 and 1974, Sweden, France, and Britain are missing for 1974 (fuel hoarding and other uncertainties make analysis of 1974 very problematic). The household sectors of most countries are interpolated for 1976 or 1977 from partial data and sound analyses of 1975 and 1978. Manufacturing, by contrast, is complete for every country (although British and Italian data lack some subsectoral resolution affecting metals and paper/printing). Problems with data from the United States is the major factor limiting our analysis to five sectors and the year 1991, while problems with Italy force us to treat it in less detail than the other countries.[2]

International sea bunkers are omitted from our analysis because of a lack of data on freight carried in international traffic. Moreover, there is no clear scheme to allocate the corresponding emissions by country. International air traffic is more problematic. The International Energy Agency collects data on fuel consumed for "domestic" and "international" air traffic. Our inspection of their time series, however, revealed that for the majority of countries, "domestic" means fuel supplied to domestically owned airlines for both domestic and international departures. How else could "domestic" fuel use in Austria account for nearly 50% of all fuel supplied? On the other hand, our contacts with five major airlines suggest that the airlines themselves know full well which routes used which fuel and may report such information to air authorities. With this in mind, we can say that Japanese, U.S., British, Danish, Finnish, and Swedish data for fuel for airlines reflect very closely fuel used for domestic flights. France is a close approximation while Germany, Italy, and Norway represent very rough approximations. Since national data on air travel reflect domestic travel of residents, it would be impossible to try to match fuels for all flights with travel. And since national data on "domestic air fuel" do not in general include fuel used by domestic carriers to fly back, it is not possible to capture the international fuels either.

2 As explained in a companion report (Schipper and Golove, 1995), a full description of the structure and energy use of manufacturing, services, or the household sector appears only every third year (one sector per year in rotation), and then only after a two year delay. Detailed national income and product accounts for the U.S. in real dollars are also released more than three years after the close of a calendar year. No detailed data exist for energy use in mining, construction, or agriculture after 1985. For Italy, problems resolving energy use in manufacturing at a sufficient level of disaggregation, difficulties separating the residential and service sectors, and problems with transportation leave disaggregated analysis of that country with the greatest uncertainties of all the countries we studied.

C. Factorial Approach to the Decomposition Analysis of Energy Use and CO_2 Emissions

We can decompose energy use E in any year as follows:

$$E = Y\sum_{i}\left(\frac{E_i}{Y_i}\right)\left(\frac{Y_i}{Y}\right)R$$

where Y, (E_i/Y_i), and (Y_i/Y) represent output (or activity), energy intensity, and structure, respectively, for each end use, mode, or subsector i in a given sector. Energy intensity can represent either final energy per unit of activity or primary energy per unit of activity. R represents a residual term which captures cross-term effects not isolated by our definitions of output, intensity, or structure.

Previous LBNL studies on energy use have used this identity to measure the impact of changes in activity, structure, and intensity on energy use, i.e., what would have occurred in response to changes in each factor alone if the other two had remained constant at the base year (1973 in all countries except Denmark, for which the base year was 1972). In this study, we apply a similar methodology in our analysis of carbon emissions in the residential, services, manufacturing, freight, and passenger travel sectors.[3] The energy use profile for each sector and then the entire economy is disaggregated into activity, structure, and energy intensity changes.

In extending our energy analysis to CO_2 emissions, activity, structure, and energy intensity still represent the same indicators. The indices we develop capture changes in CO_2 emissions resulting from changes in these components alone. Because the base year weights are now emissions, rather than energy, the impact of any one of these factors on emissions will not, in general be the same as the impact of the same factor was on energy use, either at the sectoral level or economy wide.

To these three components we add three more. *Final fuel mix* represents the share of each final energy carrier for each activity or end-use, counting both electricity and district heat at their final values. *Utility mix* represents the primary fuel mix required to provide 1 kWh of electricity or one unit of district heat to final users, with the final user's fuel mix held constant. Holding all other factors constant and allowing the *final fuel mix* per unit activity or service to vary illustrates the effect of fuel-switching alone on carbon emissions in a sector or across the entire economy. Allowing *utility mix* to vary measures the impact on emissions of changes in the mix of primary fuels used to make electricity and district heat. Separating these two effects permits us to distinguish between the substitution of one fuel for another by the end-user and the larger-scale shift of fuels for power or heat production carried out by a utility. *Carbon intensity* measures the ratio of carbon emitted to output or activity. This last new term is a function of *energy intensity*, *final fuel mix*, and *utility mix* changing simultaneously.

We can now recast the previous identity. If emissions in any one year across all sectors are denoted by C, then the general equation[4] relating total carbon emissions to activity, structure and the components of carbon intensity is given by

$$C = Y\sum_{ij}\left(\frac{C_{ij}}{E_{ij}}\right)\left(\frac{E_{ij}}{E_i}\right)\left(\frac{E_i}{Y_i}\right)\left(\frac{Y_i}{Y}\right)R$$

where the final fuel mix, E_{ij}/E_i, varies over each subsector or end use i and fuel j, and Y, Y_i/Y, and E_i/Y_i connote activity, structure, energy intensity, and a residual, respectively, as before. The summation is

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[3] Other industrial sectors (i.e., construction, agriculture/forestry/fishing, and mining) are not included in the overall comparative decomposition analysis because of severe data problems affecting both energy use figures and those measuring output; fortunately, emissions from these sectors tend to be relatively small.

[4] This general equation is applied slightly differently in each sector (see definitions box in section IIIA). The residential sector in particular varies from the others in terms of the specific definitions of carbon intensity, energy intensity, structure, and activity. The formulas for fuel mix and utility are the same for all sectors.

across i and j. The coefficients for the average release of CO_2 per unit of energy consumed, C_j/E_j, are given in the *Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, Volume 3 – Greenhouse Gas Inventory Reference Manual* (1995). We assume that these C_j/E_j are constant over time for fuels, except those for purchased district heat (3-8% of final consumption in Germany and the Nordic countries) and electricity which are evaluated by taking into account the average primary fuel mix used to produce a unit of final heat or electricity in each year (discussed in section IIID). The variation of these two C_j/E_j coefficients, then, models the utility mix effect. Taking the ratio of the above identity to itself while allowing only one term to vary over time in the numerator and holding all terms in the denominator at their base year values gives the following index terms:

Activity Effect:

$$\Delta\%_{activity} = \frac{Y_t}{Y_0}\frac{\sum_{ij}\left(\frac{C_{ij0}}{E_{ij0}}\right)\left(\frac{E_{ij0}}{E_{i0}}\right)\left(\frac{E_{i0}}{Y_{i0}}\right)\left(\frac{Y_{i0}}{Y_0}\right)}{\sum_{ij}\left(\frac{C_{ij0}}{E_{ij0}}\right)\left(\frac{E_{ij0}}{E_{i0}}\right)\left(\frac{E_{i0}}{Y_{i0}}\right)\left(\frac{Y_{i0}}{Y_0}\right)} = \frac{Y_t}{Y_0}$$

Structure Effect:

$$\Delta\%_{structure} = \frac{Y_0}{Y_0}\frac{\sum_{ij}\left(\frac{C_{ij0}}{E_{ij0}}\right)\left(\frac{E_{ij0}}{E_{i0}}\right)\left(\frac{E_{i0}}{Y_{i0}}\right)\left(\frac{Y_{it}}{Y_t}\right)}{\sum_{ij}\left(\frac{C_{ij0}}{E_{ij0}}\right)\left(\frac{E_{ij0}}{E_{i0}}\right)\left(\frac{E_{i0}}{Y_{i0}}\right)\left(\frac{Y_{i0}}{Y_0}\right)} = \frac{Y_0\sum_i\left(\frac{C_{i0}}{Y_{i0}}\right)\left(\frac{Y_{it}}{Y_t}\right)}{C_0} = \sum_i\frac{C_{i0}}{C_0}\left(\frac{\frac{Y_{it}}{Y_t}}{\frac{Y_{i0}}{Y_o}}\right)$$

Energy Intensity Effect:

$$\Delta\%_{energy\_intensity} = \frac{Y_0}{Y_0}\frac{\sum_{ij}\left(\frac{C_{ij0}}{E_{ij0}}\right)\left(\frac{E_{ij0}}{E_{i0}}\right)\left(\frac{E_{it}}{Y_{it}}\right)\left(\frac{Y_{i0}}{Y_0}\right)}{\sum_{ij}\left(\frac{C_{ij0}}{E_{ij0}}\right)\left(\frac{E_{ij0}}{E_{i0}}\right)\left(\frac{E_{i0}}{Y_{i0}}\right)\left(\frac{Y_{i0}}{Y_0}\right)} = \sum_{ij}\frac{C_{ij0}}{C_0}\left(\frac{\frac{E_{it}}{Y_{it}}}{\frac{E_{i0}}{Y_{i0}}}\right)$$

Final Fuel Mix Effect:

$$\Delta\%_{fuel\_mix} = \frac{Y_0}{Y_0}\frac{\sum_{ij}\left(\frac{C_{ij0}}{E_{ij0}}\right)\left(\frac{E_{ijt}}{E_{it}}\right)\left(\frac{E_{i0}}{Y_{i0}}\right)\left(\frac{Y_{i0}}{Y_0}\right)}{\sum_{ij}\left(\frac{C_{ij0}}{E_{ij0}}\right)\left(\frac{E_{ij0}}{E_{i0}}\right)\left(\frac{E_{i0}}{Y_{i0}}\right)\left(\frac{Y_{i0}}{Y_0}\right)} = \sum_j\frac{C_{j0}}{C_0}\left(\frac{\frac{E_{jt}}{E_t}}{\frac{E_{j0}}{E_0}}\right)$$

Utility Mix Effect:

$$\Delta\%_{primary\_utility} = \frac{Y_0}{Y_0}\frac{\sum_{ij}\left(\frac{C_{ijt}}{E_{ijt}}\right)\left(\frac{E_{ij0}}{E_{i0}}\right)\left(\frac{E_{i0}}{Y_{i0}}\right)\left(\frac{Y_{i0}}{Y_0}\right)}{\sum_{ij}\left(\frac{C_{ij0}}{E_{ij0}}\right)\left(\frac{E_{ij0}}{E_{i0}}\right)\left(\frac{E_{i0}}{Y_{i0}}\right)\left(\frac{Y_{i0}}{Y_0}\right)} = \sum_{ij}\frac{\left(\frac{C_{ijt}}{E_{ijt}}\right)E_{ij0}}{C_0}$$

where Δ% is the percent change in carbon emissions in year t relative to the base year 0 (1973), if only one component (i.e., final fuel mix) had changed.

From this decomposition we see that changes in activity, structure, energy intensity, final fuel mix, and the mix of fuels used to produce heat or electricity all influence CO_2 emissions. It is useful to separate the utility mix since this is, in general, not under the control of the firms or subsectors we are studying.

These terms are not all independent in a dynamic sense. Over time, reductions in energy intensities mean the cost of using energy – and releasing carbon – for a particular activity falls, which leads one to expect some increase in that activity. For example, Greene (1992) found that a reduction in fuel intensity of driving of 10% would lead to an increase in distance driven of 1.3% (at constant fuel price), for an elasticity of -0.13. Similarly, a reduction in the cost of space heating may lead consumers to increase indoor temperatures. Exactly how much of this "bounce back" occurs is controversial, although most believe the overall effect in high-income countries is small, i.e. the net impact of lower energy intensities is less energy use *than otherwise*. For CO_2, the picture is more complicated since it is possible to substitute a low-CO_2 fuel (natural gas) for a high-CO_2 fuel (coal). At this juncture we cannot model this interaction explicitly, but hope to do so in future work.

D. Carbon Emission Coefficients

A carbon coefficient is the amount of carbon released per unit final energy consumed of a particular fuel. Carbon emissions can be released directly through the combustion of fossil fuels at the point of end use or indirectly through the consumption of electricity or district heat. Each fossil fuel has a different carbon coefficient, and even for the same fossil fuel, emission coefficients will vary according to assumptions about the mix of properties of the fuel stock.

The carbon coefficients for primary fossil fuels used in this analysis are taken from the IPCC (1995).[5] The coefficients for biomass, solar, wind, hydro, and nuclear power are assumed for practical purposes to be zero. The coefficients for electricity and heat[6] have been developed on a country-by-country, time series basis. Given information on inputs and outputs[7], the annual average carbon coefficient for electricity and heat production is determined by

$$(C/E)_{elec} = \sum_j \left[E_j * \left(C_j / E_j \right) \right] / P_{elec}$$

where E_j is the amount of primary fuel j consumed, C_j/E_j equals the carbon released per unit of primary fuel j consumed, and P_{elec} is final electricity produced after losses in transmission and distribution are also excluded. (The equation for heat would be the same.) To simplify the analysis, we assume that any electricity imported is burdened with the same primary energy and fuel requirements as electricity produced domestically. The same holds for exported electricity. Ultimately the "burden" a country or sector bears, then, is equal to the carbon released by the final energy consumed as well as that implied by the losses of fuels transformed to electricity and heat. No attempt is made to account for eventual differences in the actual mix of electricity consumed in different sectors as a function of time of day or season, although we acknowledge that there may be significant differences when certain industries have

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5 IPCC's carbon coefficients are as follows: coal (25.8 ktC/PJ); oil (21.1 ktC/PJ); natural gas (15.3 ktC/PJ). These coefficients were compiled from several studies (notably Grubb [1989] and Marland and Rotty [1984]) and are based on full combustion. Therefore, they do not include emissions from the upstream processing (e.g., mining and extraction) of the primary inputs. In this study we do not distinguish between grades of coal or gas or different oil products, but in our studies of travel and freight we do find a slight contribution to changes in emission from variations in the share of diesel, gasoline, or other liquid fuels.

6 The carbon coefficient for electricity and heat refers to the amount of carbon emitted per unit final energy *produced*, adjusted to reflect losses in transmission and distribution. In other words, we examine only the structure of domestic production, and do not analyze the structure of imports or exports. While this is appropriate for heat production (since there is no significant international trade in heat), electricity production presents special problems. Ideally, electricity that is traded should carry the same carbon coefficient as the producing country or even the electricity-producing facility. Should an international market in low carbon electricity develop, a rigorous tracking of the flow of electricity and its corresponding carbon coefficient would be necessary. For our work, imports of electricity carry the same carbon coefficient as domestic production. Since imports of electricity are generally a small proportion of the total, overall carbon emissions are not significantly affected by this assumption.

7 Unless otherwise specified, raw data on primary fuel inputs and outputs of electricity and heat are from the International Energy Agency, based on their balances running from 1960 to 1992. For Western Germany, data for 1988-1992 are from national sources; heat coefficients for the 1990-92 period are held at the 1989 level. The Sweden CHP and district heat data for the period 1973-1992 were provided by Statistiska Meddelanden, Sveriges Officiella Statistik; the heat coefficient for 1970-1972 is held at the 1973 level. In Denmark, the heat coefficient for 1973 and 1974 is held at the 1975 level, and for the period 1970-1971, the heat coefficient for 1972 is applied.

access to captive hydro-power (Japan National Railways), run-of-the-river excess hydro (in Norway or Sweden), or where certain industries or other customers take particular advantage of off-peak electricity. Particularly important is night-time electric space heating, which may be nuclear-based as in France or Sweden (no carbon) or coal-based as in Germany or the U.K. (high carbon).

Figure 3.1 shows the average ratio of carbon to primary energy use (for the five sectors counted in this study and electric and heating utilities, all aggregated) for each country over time. This ratio has fallen. Since the ratio of energy use to GDP has fallen in every country, the graph confirms what was asserted in the introduction, namely that for every country the carbon intensity of energy use has decreased.

A large part of the relationship depicted in Figure 3.1 depends on the fuel mix used in the power sector. For electricity plants, national statistics provide accurate accounts of primary energy inputs and electricity outputs, and developing carbon coefficients is thus a straightforward process.[8] Figure 3.2 shows the carbon releases per PJ of all final electricity generated. The amount and carbon content of primary fuel inputs and the efficiency of fossil fuel-based electricity production determines the size of the coefficient. Denmark's electricity production is coal-intensive and it thus has the highest carbon coefficient of countries, trailed closely by the U.S. (46 ktC/PJ). The coefficient for Japan is about 30 ktC/PJ, with nuclear power contributing 34% of the fuel share. Sweden's coefficient dropped from 18 to 0.1 ktC/PJ, with hydro and nuclear power providing over 98% of the fuel share, while Norway's was always close to zero because of almost full reliance on hydro power there.

For international comparison, it is important that there be a consistent framework for analyzing inputs, outputs, and associated emissions from CHP and AHP (see box). We assume the efficiency of heat production is fixed between 90% and 100%, which is a slightly higher level than is technologically achievable from the production of heat alone.[9] This also results in somewhat higher efficiencies of electricity production than can be achieved in electric power facilities. In Denmark, the efficiency of heat production from CHP is fixed at 90%, and the remaining inputs are allocated to electricity. In Sweden and Germany, the national data sources we used set the efficiency of heat production between 90% and slightly better than 100%.

CHP and AHP. Evaluating emissions from combined heat and power (CHP) and auto-produced heat and power (AHP) facilities is a more complicated issue. CHP plants generate heat and electricity for sale, while auto-producers generate heat and electricity wholly or partly for their own use. Where both electricity and heat are produced, there is neither hard engineering guidance nor an internationally accepted formula for distributing inputs between the two outputs (for a detailed technical discussion of this issue, see Krause *et al.*, 1994). Oftentimes, the issue is confounded by country-specific reporting requirements that do not require accounting of certain inputs and outputs, which make international comparison difficult. For example, industries are not always required to report energy balance data for CHP and AHP; waste heat may not be reported as an input; and electricity output that is not delivered to the grid but used within the plant itself may not be reported at all.

In Denmark, Sweden, Finland, and Germany, CHP and AHP contribute significantly to the electricity or heat output totals. Denmark relies particularly heavily on CHP, which provided nearly 80% of total electricity and 50% of heat production in 1991. In countries like Denmark, how the inputs to CHP are distributed between electricity and heat is instrumental in determining the carbon coefficient. Because

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[8] It is also possible to develop carbon coefficients based on time of day purchase of electricity, which takes into account the different fuel mixes during peak and off-peak times. For example, many industrial facilities in Sweden purchase off-peak electricity, generated primarily from nuclear and hydro. Applying the average carbon coefficient for electricity will thus overestimate emissions for these off-peak electricity purchases. As industrial facilities seek greenhouse gas reduction strategies, the timing of electricity purchase may prove an important component.

[9] We considered several other allocation mechanisms. One is to attribute fuel consumption on the basis of heat content output. In other words, electricity and heat production would have the same input/output ratio. The main objection to this method is that the separate production of electricity requires at least twice as much primary fuel as the production of heat. Another method is to allocate inputs based on CHP plant technology. For every one unit of heat, 0.15 units of electricity are lost. However, if all the savings are attributed to heat, unrealistically high conversion efficiencies for heat production result. Further, it is not clear why heat should receive all of the "savings" from CHP processes. We decided to hold heat production constant at about 100%, which gives modest benefit to the conversion efficiencies of both electricity and heat.

there are no international protocols, each country is at liberty to distribute CHP inputs differently. In their national accounts, the Danes assume 200% efficiency of heat production from CHP, such that the heat released in conjunction with electricity generation is essentially waste or "free". Applying a 200% efficiency, the carbon coefficient for electricity in Denmark would be 64 ktC/PJ and the heat coefficient would be 14 ktC/PJ. A 90% efficiency would lower the electricity coefficient by 16% (to 54 ktC/PJ) and increase the heat coefficient by nearly 50% (to 25 ktC/PJ).

As countries search for mechanisms to achieve carbon reduction targets, these emission coefficients may assume strategic and economic importance. The purchase of low carbon electricity from countries like Sweden and Norway[10] will affect electricity price and distribution, with the purchaser of the low-carbon electricity receiving the carbon benefit. Norway is surrounded by relatively energy-poor nations that are currently willing to pay much higher prices for electricity. For example, Danes spend twice the amount per unit of electricity than Norwegians. Coupled with the incentive to lower their carbon balance, nations like Denmark may push up the price of imported low-carbon electricity and affect the structure of demand and supply.

IV. Aggregate Results over Time: CO_2 Emissions by End Use or Final Demand at the National Level

Reviewing just aggregate changes in CO_2 emissions by sector reveals many important facets of the dynamics of CO_2 emissions. The emissions profiles of each of the study countries by end use are presented in Figure 4.1. Manufacturing dominates, with the next most important sector in general being households, and in a few cases travel. The impact of the 1973 oil embargo on emissions is readily apparent by the emissions downfall in the subsequent years. The peak for most countries was hit in 1979, falling thereafter when the second oil crisis occurred. Overall, emissions since 1973 have increased in Japan (+44% by 1991); rose and then fell back (and in some cases rose again) close to 1973 levels in the U.S., W. Germany, Finland, the U.K., France, and Denmark; and dropped significantly in Sweden and Norway. In all countries, there was an increase in emissions from freight and travel, while in most countries emissions from services increased while those from manufacturing fell. Below we review briefly what happened in each country.

Emissions rose in Japan throughout the study period. Manufacturing emissions had changed little by 1991 relative to 1973, releasing 50% of total emissions. The shares of 1991 emissions from services, residences, freight, and travel are similar (between 11% and 15%), and emissions in all sectors have been steadily growing at the expense of manufacturing. "Other industry" emissions remain a small proportion of the total (6%). Oil dominates the fuel mix in Japan, although coal, nuclear power, and natural gas from imported liquids made inroads after 1973. Overall there was no change in emissions per capita by 1991, but emissions per unit of GDP have fallen 44%.

By 1991, U.S. emissions lay at about their 1973 level, having risen from a low in 1982 to a high in 1989 and then fallen with the 1990-91 recession. In the U.S., travel, households, and manufacturing release nearly equal amounts of carbon. Manufacturing emissions have dropped slightly over time, while emissions in the other sectors have grown. The share of total emissions from freight and travel are high relative to the other countries, with the exception of Sweden. Combined, freight and travel release about one third of all emissions. Coal dominates power generation; natural gas is most important in the residential, service, and manufacturing sectors; and oil is concentrated into transportation and manufacturing. In 1991, the U.S. still had the highest ratio of emissions to GDP among the countries studied, mainly because the U.S. had a high ratio of energy use to GDP and to some extent because coal is the most important fuel in the power sector. The decline in emissions per capita was 10%, and the drop in emissions per unit of GDP was 33% – about average for all the countries studied.

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[10] For practical purposes, Norway's electricity coefficient is zero due to its virtually exclusive reliance on hydro resources for electricity generation.

West Germany's emissions profile in 1991 is similar to that of the U.S., though the transportation sectors in W. Germany release a smaller share of total emissions. Between 1970 and 1991, emissions from services and residences have been stable. Manufacturing emissions have dropped but have been more than offset by an increase in transportation emissions, particularly passenger transport. Coal dominates power generation and some industrial and household consumption, while oil and gas vie for consumption in buildings. Total emissions in 1991 were about 10% below their 1973 level, having peaked in 1979. Per capita emissions fell 10% in all; emissions per unit of GDP fell 38%.

In Denmark, the residential sector releases 36% of total emissions, a noticeably higher share than any other country. Services and residences together release over 50% of total emissions. Conversely, the share of emissions arising from Denmark's manufacturing sector, which is marked by few energy-intensive industries, is very low. Emissions from manufacturing, services, and residences have held fairly steady between 1970 and 1991, with changes in the emissions profile caused primarily by the travel and freight sectors. While the power and heat sectors converted rapidly to coal starting in the late 1970s, they are moving towards gas. Oil dominates direct fuel use in buildings, but is gradually losing share to natural gas. Overall emissions in 1991 were about the same as in 1972, the base year for Denmark. Per capita emissions fell 5%; emissions per unit of GDP fell 32%.

Emissions in Sweden were initially dominated by the household and manufacturing sectors. The combination of increased electrification in these sectors, based on hydro and nuclear electricity, however, helped spur a dramatic drop in emissions in Sweden. Emissions from the residential, services, and manufacturing sectors have shrunk by more than 50% in the 21-year period. Growing, however, were emissions from both travel and freight. Sweden suffered a severe recession from 1990 to 1993, which cut emissions somewhat. Oil was the main fuel in all sectors in 1973, when Sweden was the highest per capita importer of oil. Since 1973, oil has been displaced by direct uses of electricity, wood/biomass, and more recently by some coal and natural gas. Overall, Sweden had the largest decline in emissions per capita of any country and the greatest decline in absolute emissions.

Norway, with its enormous reliance on hydro-electricity and wood/biomass both in manufacturing and in buildings, had the lowest carbon emissions in 1973 per capita and the lowest relative to GDP. These figures fell steadily through the 1990s, and Norway remains the least carbon-intensive economy, whether measured on per capita or per GDP basis.[11] As with Sweden, however, emissions for travel and freight have grown. The activity in the offshore sector is excluded, which underestimates emissions in Norway significantly. This accounts for some of the decline in carbon emissions, since growth in offshore-sector GDP was boosted in large part by oil revenues, although direct energy use in this sector is still relatively small. In 1991, around 50% of final energy in Norway was electricity or wood, with no CO_2 released. Overall emissions per capita fell 30%; emissions per unit of GDP fell by 54%, the most of all the countries studied here.

Finland was an energy- and CO_2-intensive country in 1973, relative to GDP. From 1973 to 1989, Finland had the highest GDP growth of any country except Japan and also experienced the greatest changes in housing and transportation towards more energy-intensive activities. The manufacturing sector dominated emissions throughout the period, but emissions from travel and freight grew, while those from homes fell somewhat. Emissions in 1991 were about the same as those in 1973, having peaked in 1979, dropped to a low in 1983, and then risen slowly until 1990. Like the U.S. and Sweden, Finland entered into a recession in 1990 that continued for much longer, depressing activity and emissions. In 1991, Finland had the second highest ratio of CO_2 emissions to GDP, reflecting the high energy intensity of the economy. Per capita emissions declined less than 10% by 1991, but emissions per unit of GDP fell 36%.

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[11] Norway's offshore oil production and on-shore refining sector has significant CO_2 emissions not studied here.

Emissions in France were dominated initially by manufacturing, followed by households. Originally an economy dominated by oil use, the 1970s and 1980s saw the rise of nuclear electricity, a switch from coal or oil to gas and electric heating, and some efficiency improvements. Total emissions dropped dramatically in both manufacturing and households. Emissions for travel and freight, on the other hand, rose steadily. Total emissions peaked in 1979, bottomed in 1986, and have grown since then as the impact of nuclear electricity has steadied. After Sweden and Norway, France had the third lowest ratio of emissions to GDP, a ratio that had fallen 45%, the third largest decline we measured.

In primary energy terms, Italy has been the least energy-intensive economy of the countries studied. In CO_2 terms, Italy has also continually ranked as the least carbon-intensive economy of the non-nuclear countries. Manufacturing accounts for the largest share of emissions but has lost share to the transportation sectors which have seen very strong growth in activity and emissions. Initially a country heavily dependent on oil, Italy's manufacturing, household, and service sectors have seen significant fuel-switching away from oil to electricity and natural gas. The power sector has seen a similar diversification of its primary fuels used for electricity generation, yet the carbon intensity of this sector has been slowly growing due to its continued reliance on oil (>50% share), the termination of Italy's nuclear program in 1987, and the significant use of coal since 1980. In balance, Italian carbon emissions have grown in both absolute and per capita terms since 1973 – 19% and 13%, respectively – the highest levels of growth measured of the countries studied here.

Emissions in the U.K. in 1973 were high relative to GDP because of the high dependence of the economy on coal. Manufacturing and households were the most important sectors. Since that time, emissions from these sectors declined while services, travel, and freight increased in absolute terms. As in other countries, emissions peaked in 1979, bottomed in 1986, and have grown slowly since. The role of coal fell continually as natural gas became the most important fuel in all but the transportation sectors. Still, the U.K. has the second highest level of emissions relative to GDP. The predominant use of coal in the power sector and its continued importance in manufacturing and even households is one reason for this high position. A 16% drop in emissions per capita, made possible both by modest reductions in energy intensities and the drop in the final use of coal, led to a 33% decline in emissions per unit of GDP.

The pattern is clear: CO_2 emissions fell in per capita terms for most countries and fell, for some, in absolute terms as well. Emissions fell the most (or grew the least) in manufacturing. The residential sector saw only modest growth or decline as well. Emissions for services increased as well in some countries. But the most uniform increase in emissions was in travel and freight. Only in the U.S. did emissions in travel stay level, while emissions in freight increased everywhere.

Since GDP per capita increased, emissions per unit of GDP declined strongly (even in Japan, where emissions per capita grew). Emissions relative to GDP declined both because the final fuel mix evolved away from high-carbon sources and because the ratio of energy use to GDP fell. This decline resulted both because energy uses became more efficient and, for every country except Finland, the mix of activities evolved away from energy-intensive production. At the same time, the rate of decline has slowed in almost every country after 1986. But before we examine the trends more closely, we compare all the countries in a recent year.

V. Brief Comparison of Emissions

In the following section we omit "other industry" from the comparisons. As in the previous section, the emissions from power and heat generation are distributed to the sectors where these energy forms are consumed.

A. Emissions in 1991: Components of Differences

Because of the enormous variation in the size of economies (as measured by GDP) or populations, it is important to address the issue of normalization of emissions for purposes of comparisons. Figure 5.1 presents one such normalization, CO_2 emissions per capita from 10 sectors or end uses (excluding other industry) for 1991. Fig. 2.2 showed a similar pattern for primary energy use per capita for the main sectors. The differences in rankings of energy use are explained in part by differences in GDP per capita, but even if we normalize energy to GDP, differences in the structure of economies and differences in the efficiency of energy uses can account for a nearly two-to-one spread in the ratio of energy use to GDP (Schipper, Meyers, *et al.*, 1992). The differences in CO_2 emissions are explained by these factors as well as by the relative amount of fossil fuel use in different economies, the mix of these fuels (i.e., coal, oil, and natural gas – in descending order of CO_2 content), as well as the differences in energy use hidden in Figure 2.2. We review the emissions comparisons here based on these two sets of indicators.

In general, the most important factor explaining overall differences in CO_2 emissions is income: wealthier countries produce more and consume more, all of which tends to raise CO_2 emissions. If we normalize emissions to the GDP of each country (in real, 1980 currency converted to U.S. dollars at purchasing power parity), we eliminate this term. This is clear from Figure 5.2, which shows less variation in the ratio of emissions per GDP than Figure 5.1 shows for emissions per capita. However, significant differences in emissions remain. For the sample of high-income countries studied here, emissions vary by more than ±25% around a mean in 1991. The remaining differences, which are still large, are then explained by fuel mix, the structure of the economy, and the efficiency of energy uses, in roughly that order. Here, the structure of the economy refers to the mix of goods produced, the size of homes (or conditioned space in the service sector), total travel (and the mix of modes), and total freight (and modal mix) as well.[12]

This comparison, based on energy uses, was illustrated vividly for the U.S. and Japan (Schipper *et al.*, 1992a). Americans have more space per capita and move farther per capita than the Japanese. These are the most important components of the close to two-to-one difference in per capita energy use or ratio of energy use to GDP. Collectively, such *structural* differences are more important to the U.S.–Japan comparison of emissions than energy intensity (or efficiency) differences.

If we compare the U.S. with Europe or European countries among themselves, the differences arising from each component become smaller. First, Sweden, Norway, and Finland have more energy-intensive manufacturing than other countries in Europe, a colder climate, and, for Sweden and Norway (along with Denmark), the largest homes and greatest extent of built space. These countries also have the highest mobility in Europe, measured as travel (in passenger-km) per capita, and relatively high levels of freight per capita as well. Not surprisingly, their per capita energy uses are closest to (but still below) that of the U.S. Italy, France, the U.K., and above all Japan have milder climates, lower mobility, and smaller homes, which are important reasons why these countries have somewhat lower emissions. Germany is intermediate: relatively small homes but a cold climate, high mobility, and energy-intensive industries.

Final fuel mix also influences the level of CO_2 emissions. Norway's electricity production is virtually 100% hydro, and electricity provides more than half of the final energy in homes and services, with wood a distant second for households. For Sweden, nuclear and hydro provide the bulk of electricity, which has high penetration in end-use markets, and wood again has a prominent place in home heating. This explains why Sweden's emissions are so much less than those in Denmark, a country with a slightly milder climate, less heavy industry, and somewhat less automobile travel. For other countries in Europe, the climate is less severe, homes are smaller, and total mobility is slightly less than in the Nordic countries, thus reducing energy use relative to the U.S. But these countries (and Denmark) are far more dependent upon coal than the Nordic countries, which significantly boosts their CO_2.

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12 Of course there are important interaction terms ignored here. These will be studied in future reports.

After the U.S., Sweden, Norway, and Finland have the most energy-intensive economies in the sample: the coldest climates (high space heating), highest personal mobility, high freight haulage relative to GDP, and, for Sweden and Norway, large per capita area in homes and services. But the energy mix in these two countries is less reliant on fossil fuels than in Finland or the U.S. France owes its position with the third lowest emissions relative to GDP in part to its mild climate (third-mildest among the countries studied) and in part to its high reliance on nuclear power – a result driven by policy. Thus both structural factors and fuel mix factors affect emissions. These often offset each other, but significant differences in emissions per GDP remain.

Energy Intensities. How do energy intensities figure into these comparisons? Overall, most energy intensities in the U.S. are still above those in Western Europe, but the gap in 1991 was much smaller than in 1973. Branch by branch, U.S. manufacturing requires more energy (and CO_2) per unit of output than do most industries in Europe or Japan (Figure 5.3), with Finnish industries in the next position. U.S. space heating requires less energy than space heating in Western Europe, but more than in the Nordic countries (Figure 5.4). The American service sector requires slightly more fuel per square meter than buildings in Europe and considerably more electricity, some of which difference is related to less efficient usage in the U.S. Overall, the ratio of energy use to service sector GDP in the U.S. is high (Figure 5.5). U.S. automobiles and household light trucks require 25%–35% more energy (and emit that much more CO_2) per vehicle-km than those in Europe (but only 15% more than in Japan), which is the most important component of CO_2 emissions per passenger-km travelled (Figure 5.6). U.S. air travel (included in Figure 5.6) now has below-average CO_2 intensity and fell dramatically over time. U.S. trucking energy intensity is about average for all the countries examined (Figure 5.7). Interestingly, trucks carry a smaller share of freight in the U.S. than do trucks in other countries. As a result, U.S. freight has a very low aggregate energy intensity, and, since virtually all freight movements depend on oil products (i.e., fuel mix differences have very little importance). U.S. freight CO_2 intensity is one of the lowest among all countries. After the U.S., Sweden has the highest energy intensities (for car travel and manufacturing), followed by Finland (for manufacturing). Among other countries, differences are smaller but still significant. Interestingly, key energy intensities (manufacturing, automobiles, space heating) converged, with the U.S. intensities generally among the highest in 1973 but much closer towards the average by the early 1990s.

In general, we can say:

- Differences in GDP per capita explain some of the differences in per capita energy use and per capita CO_2 emissions over a wide range of incomes, but are less important among the countries considered here;

- Differences in the structure of economies, including the differences in lifestyles (as reflected in home sizes and travel, for example), are the most important reasons why there are differences among countries in CO_2 emissions relative to GDP arising from energy use;

- Differences in final fuel mix are about equally as important as differences in economic structure in accounting for differences in CO_2 emissions per unit of GDP;

- Differences in energy efficiency rank after these factors in contributing to differences in per capita CO_2 emissions;

- Differences in the severity of the climate also contribute to differences in CO_2 emissions because climate is a strong determinant of energy use for space heating and, to a lesser degree, space cooling.

Since 1973, structural differences among countries have become smaller. Key elements of lifestyles in Europe – car ownership, mobility, appliance ownership, and living space – have increased more rapidly than in the U.S., although the European (and Japanese) values in general still lie well below those for the U.S. On the other hand, U.S. manufacturing, whose structure was somewhat less energy-intensive than that in Europe or Japan in 1973, shifted away from energy-intensive output, while little shift occurred elsewhere except in Germany and Japan. Intensity differences have also become smaller since 1973 as the U.S. closed about half of the gap between its intensities and respective intensities in Europe.

By illustrating which factors account most for the variations in CO_2 emissions among industrialized countries, these comparisons suggest which factors might lie behind potential for future restraint in CO_2. Certainly GDP is not. If anything, developed countries foresee increases in that term and developing countries count on much more. Economic structure will probably not be considered explicitly either but could evolve in ways important to future CO_2 emissions. One aspect of structure, the local climate and resulting needs for heating and cooling, is not likely to change except from climate change itself. Thus fuel mix and efficiency are the two "free parameters" that authorities are likely consider, and we shall pay particular attention to the historical evolution of these parameters in our analysis.

Are high emissions "bad"? We cannot judge that here. For one thing, the issue of how to measure "high" (i.e., whether emissions should be normalized by GDP or population) is not at all clear. Should there be an adjustment for the influence of the cold climate in the Nordic countries? Does the U.S. get a geography adjustment? The fact that Americans travel twice as far per capita by car as Europeans is the single most important component of U.S.–Europe emissions difference. Is this because the U.S. is a big country? Comparison shows that the average trip in a car in the U.S. is barely longer than car trips in Europe (Schipper, 1995; Schipper *et al.,* 1995a). Instead, it is the much higher *number* of car trips in the U.S., not distance per trip, that boosts total car travel. So, it is unclear whether the U.S. emissions figures should be adjusted similarly because of geography.

B. Comparison of Changes in Aggregate CO_2 Emissions Patterns

Figure 5.8 shows three measures of the change in CO_2 emissions for each country – absolute emissions, emissions per capita, and emissions per unit of GDP. Measured either way, Sweden and Norway had the largest reductions in emissions. France had the next greatest reduction in emissions per capita, while Japan had the third largest reduction in emissions per unit of GDP but the second largest increase in total emissions. Finland and Denmark had almost no reductions in emissions per capita but significant reductions in emissions per unit of GDP. Italy had the largest increase in both absolute and per capita emissions, yet still decreased the amount of emissions per unit of GDP by 13%. The U.S., France, and the U.K. had 10-20% reductions in per capita emissions and 30-35% reductions in emissions relative to GDP. Thus relative to GDP – the primary factor driving energy use and therefore emissions – all countries showed significant reductions in emissions, and in almost every case during the period 1973 to 1991, this reduction was greater than the increase in GDP. To see whether this might be true in the future, however, we have to decompose changes more carefully, examine sectoral trends, and pay particular attention to the most recent years.

In these figures, several factors leading to emissions reductions stand out. Manufacturing, and then households, contributed the most to emissions restraint. Where electricity was generated with low-carbon sources (France, Sweden, Norway, and Finland from the early 1980s onward), the increased use of electricity for heating in the residential and service sectors also contributed to emissions restraint. Within transportation, only the U.S. experienced a significant restraint in emissions from travel, albeit from what was a very high level in 1973. In general, travel, freight, and services increased their relative (and absolute) importance, accounting for most of the growth in emissions across this sample of countries.

VI. Results of Sectoral Decomposition Analyses

To summarize the changes in emissions by country using our factorial decomposition, we use the following procedure. First, we calculate an index for each effect in each sector, starting in the base year of 1973 and then in each subsequent year t. Using the indices we obtain, we calculate emissions (in MtC) by sector arising because of a change in a particular factor. To measure the overall impact of a given factor on the whole economy in year t, we first note the calculated carbon emissions[13] from each sector i in 1973, $C_{i,73}$, and sum these to get total emissions, C_{73}. This gives us the absolute effect of this factor on total carbon emissions. By comparing $C_{i,t}$ with C_{73} we have an index of carbon emissions arising from changes in that particular factor. This permits us to compare the importance of that factor across countries and time. We can then compare each of these sectoral results with actual emissions for that sector in any year. Indexing the results to actual base year emissions (1973) permits a comparison of changes among countries. For each country we show a "spider diagram", where each line represents the impact of the factor labeled on carbon emissions relative to those in 1973. Careful examination of this diagram, as well as those for each sector, identifies which components of which sectors have led to reduced CO_2 emissions and, conversely, which lie behind increased emissions. Since "activity" is measured in various ways, the overall changes caused by "activity" can be compared with changes in overall GDP to gauge the components of the reduction in the ratio of emissions to GDP.

Figure 6.1 presents the results of the decomposition analysis as these "spider" diagrams over time. Table 6.1 summarizes the percentage impacts on total emissions from changes in each factor both across countries and across factors in 1991 relative to 1973. We show the residuals as well.

Table 6.1 1991 results of Laspeyres index decomposition of total carbon emissions from the OECD-10 (1973=100%).

	Actual Emissions	Activity Effect	Structure Effect	Carbon Intensity Effect	Energy Intensity Effect	Final Fuel Mix Effect	Utility Mix Effect	Residual
Denmark	97%	121%	117%	73%	68%	107%	98%	-5.3%
Norway	82%	122%	100%	68%	88%	77%	100%	-0.5%
Sweden	56%	119%	109%	45%	75%	81%	89%	-20.8%
Finland	104%	147%	140%	74%	79%	88%	85%	-14.3%
W. Germany	93%	135%	114%	64%	70%	109%	88%	-10.6%
Japan	117%	171%	101%	71%	77%	109%	89%	-10.0%
USA	97%	141%	103%	69%	70%	109%	93%	-5.8%
France	79%	128%	114%	58%	78%	93%	84%	-10.7%
UK	91%	114%	104%	75%	76%	110%	93%	-0.1%
Italy	119%	150%	114%	78%	70%	110%	102%	-11.3%

Figure 6.2 presents the results in a different light, showing how each country's CO_2 emissions in 1991 were related to 1973 emissions through each effect. Here, however, we show how each sector's changes contributed to the overall change in emissions from each effect. Travel and freight show the smallest contributions to declining emissions from any factor because energy intensities changed so little, activity and structure acted to raise emissions, and fuel mix was virtually unchanged. By contrast, the shrinking of the carbon intensity terms for residences and manufacturing is clear in almost every country. Figure 6.2 also shows how both activity and structure lead to more emissions. This reminds policy-makers that they are working against these two factors (which tend not to be targets of CO_2 restraint policies) by seeking ways to reduce the components of carbon intensity.

[13] where we have calculated the changes in carbon emissions in year t caused by a particular factor as the index value in year t multiplied by actual base year emissions.

Examining the impacts of each factor shown in Figures 6.1 and 6.2, we can see that increased activity – population growth, economic growth in both the service and manufacturing sectors, and increased mobility of people and goods – led to emissions increases in all countries (Figure 6.3 and Table 6.1). The growth in emissions from increased activity ranged from 15% (the U.K.) to 70% (Japan). In general, none of these individual sectoral factors grew more rapidly than GDP, nor did the aggregate presented in Table 6.1. As a result, the ratio of CO_2 to GDP fell "without anyone trying". That is, growth in the economy itself led to lower CO_2 intensity of the GDP.

A small part of this effect lies in the nature of services, which have lower primary energy requirements per unit of GDP generated than manufacturing. And while services rely more on electricity than manufacturing, they rely less on oil and coal, in general. Hence the small shift in the origin of GDP, from manufacturing to services, had in turn a small downward effect on CO_2 emissions. Cyclical changes in GDP also reduced emissions, such as in the 1974-5 period, the 1981-2 period, and for Sweden and Finland, after 1989, but we do not count these in long-range studies. By the same token, however, recovery from recession should not lead to alarm over a rapid rise in emissions. This in and of itself leads to another important policy question: how shall "baselines" and "targets" for CO_2 emissions be adjusted for swings in the business cycle or weather?

Changes in the structure within individual sectors increased CO_2 emissions, ranging from 40% in Finland and 17% in Denmark to only 3% in the U.S. and 0% in Norway (Figure 6.4 and Table 6.1). In general, structural changes in manufacturing had only small effects, except in W. Germany, the U.S., and Japan where such changes alone reduced emissions by more than 10%. In Finland, structural change increased emissions from manufacturing. However, in almost every country, the manufacturing subsectors where coal typically plays a large role (e.g., ferrous metals and nonmetallic minerals) lost importance in total manufacturing output which helped to restrain *growth* in overall emissions. Structural changes within freight – the shift to trucks – raised emissions in almost every country. In all countries, strong structural changes in the household sector and modest ones in travel increased CO_2 emissions significantly. These types of structural effects arising from changes in consumer behavior - greater floor area per home, more home appliances, greater travel in cars and airplanes - grew roughly with GDP.

Lower final energy intensities reduced emissions in every country (Figure 6.5 and Table 6.1). The greatest declines occurred in the U.S., W. Germany, the U.K., Denmark, and Italy, where emissions fell around 30% because of the drop in final energy intensities. Similar declines occurred in Norway and Sweden, but these were permitted by a switch from oil to electricity. This marked fuel-switching would appear to show a decline in primary energy if hydro-power is counted at 85% efficiency and a big decline in CO_2 emissions no matter how hydro-power is counted.

Changes in the final fuel mixes for final energy uses has strongly affected emissions (Figure 6.6 and Table 6.1). Final fuel mix worked towards lower emissions where final consumers moved away from coal to gas (the U.K., France, and to some extent W. Germany). Increased use of low-carbon electricity in place of fossil fuels (Norway, Sweden, and Finland) also reduced emissions significantly[14]. But the increased share of electricity in the final fuel mix of the residential, manufacturing, and services sectors lead to increased emissions in Denmark, Japan, W. Germany, the U.K. (for services and manufacturing), Italy, and the U.S. since the 1973 carbon coefficient for electricity and district heat in these countries was greater than the coefficients for the fossil fuels replaced. However, in these countries, most of the increased electricity use was simply to provide more energy services (motors, lighting, appliances), not to substitute directly for fossil fuels.

The utility mix effect lead to lower emissions in all countries but Italy because of the falling carbon coefficients for electricity and district heat (Figure 6.7 and Table 6.1). That is, electricity and district heat

[14] The dramatic behaviour of Finland's fuel mix term between 1974-1978 is mainly due to data problems. The large drop after this period is believed to be real and attributable to the influx of nuclear power (and marketing of electricity) in the early 1980s.

production became less CO_2-intensive, even in Norway where fossil fuels played a small role in 1973. In Denmark, this effect was almost negligible, as the impact of more efficient generation (largely through the expanded role of CHP) was almost offset by a major switch from heavy oil to coal as a primary fuel. In the Italian power sector, the diversification of its primary fuel mix (from nearly 70% oil in 1973 to 50% oil and approximately equal shares of natural gas, coal, hydro-power, and renewables in 1991) was not enough to offset the absolute growth in electricity production which, despite obvious efforts, was met mainly by the increased use of oil. Conversely, the rising use of nuclear fuels and natural gas for power generation reduced CO_2 emissions from this sector in several of the study countries[15].

The carbon intensity effect measures the overall intensity of carbon released per unit of activity. As such, this combines the effects of final fuel mix, primary utility mix, and energy intensity changing simultaneously. This measure has fallen in all of the study countries, often quite dramatically, leading to significant restraint in carbon emissions (Figure 6.8). In Sweden, the decline was more than 50%; in France, Norway, the U.S., and W. Germany the decline was around 30-40%; and in the remaining countries the decline was 22-29%. Changes in carbon intensity thus have had a downward effect on emissions. If we ignore changes in energy intensities but consider only the combined effect of utility mix and final fuel mix, emissions fell in Norway, Sweden, Finland, and France but were essentially unchanged in the other countries. Thus for five countries (the U.S., W. Germany, Japan, Denmark, and the U.K.), lower energy intensities led to more reductions in CO_2 emissions than did changes in the overall final fuel mix; while for two countries (Norway and Finland), final fuel mix contributed more to reduced emissions than did lower energy intensities; and in two countries (Sweden and France), lower energy intensities and the overall final fuel mix contributed equally to reducing emissions.

Thus we can now "explain" the drop in the value of CO_2 per capita or CO_2 per GDP in each country as a multiplicative result of each of the changes we have measured. GDP per capita grew, raising CO_2 emissions in every country. Although basic sectoral activity grew in each country, the overall growth was less than GDP. When structural change within sectors are considered, CO_2 emissions in general were boosted. The impact of changes in energy intensities was downward, and these three effects alone were sufficient to limit the net rise in CO_2 emissions per capita to less than half the rate of GDP growth. Additionally, however, final fuel mix and utility mix acted together to reduce the carbon intensity of each economy, although in some countries final fuel mix alone raised CO_2 emissions.

VII. Key Developments in Each Sector

We can summarize the findings of our sectoral studies here. We show per capita emissions over time, carbon emissions per unit of primary energy consumed in each sector, emissions by end use or final demand, and aggregate emissions per unit of output for each sector. Figures 5.1 and 5.2 showed sectoral and subsectoral emissions normalized first to population and then to GDP in 1973 and 1991. Figure 7.1 shows the *relative* amounts of CO_2 emissions from primary energy use in each sector in 1973 and 1991 with some key sectors split into two or more subsectors. After describing each sector, we note how each sector's emissions behaved relative to those from other sectors.

A. Manufacturing

Emissions for all manufacturing were shown in Figures 5.1 and 5.2. Since the emission of carbon dioxide from the use of fossil fuels was not the subject for much debate until the 1980s, we can consider the evolution of emissions from manufacturing strictly as a consequence of changes in energy use. Torvanger (1991) analyzed our earlier data to show how emissions had fallen from manufacturing in seven of the present countries. Using this information, expanded to all countries and extended to 1991, we display CO_2 emissions from manufacturing in each country by subsector in Figure 7.2. For comparison, we have

[15] Recall that the values in Table 6.1 reflect how changing utility mix affected overall emissions, so even a dramatic drop in emissions from power generation (as shown in Figure 3.2) must be weighted by the share of electricity in the economy in 1973.

scaled each country's emissions to population. Emissions per capita fell in every country, but the decline was such that the absolute level of emissions also declined.

It may come as a surprise that CO_2 emissions from manufacturing fell in all countries. But final energy use itself for manufacturing fell in almost every country shown, which reduced CO_2 emissions. This occurred even though output increased and structural change itself only reduced energy demand significantly in three countries. Thus, the factors considered in our *energy* analysis above served to reduce CO_2 emissions. Additionally, however, the final fuel mix in manufacturing moved towards more natural gas and less coal or oil or both, reducing CO_2 emissions further. Also recall that the CO_2 intensity of electricity production fell in nearly every country (Figure 3.1). If we combine the utility mix, final fuel mix, and energy intensity effects, we find that the resulting carbon intensity, or emissions per unit of manufacturing value added, fell markedly in every country (with activity and structure held constant, Figure 7.3). Thus it is no surprise that aggregate CO_2 emissions per unit of real output from manufacturing fell everywhere, as Figure 7.4 shows.

Figure 7.4 also shows that there are significant *differences* in manufacturing carbon intensity among our study countries. The most important reasons behind these differences are the different mix of primary fuels, split roughly between different utility fuel mixes and different final fuel mixes. Countries where coal still plays a prominent role in manufacturing (Germany, the U.S., or the U.K.) tend to have higher emissions per unit of output and saw less of a decline in carbon intensity than countries where coal was more rapidly displaced by other fuels. Differences in manufacturing energy intensities (Figure 5.3) lie close behind in importance to differences in overall carbon intensity. Differences in the structure of manufacturing have a mixed effect. On the one hand, the energy-intensive nature of manufacturing in Sweden, Norway, and Finland might be associated with high emissions, but the important role of biomass and hydro or nuclear electricity in those countries mitigate this structural effect.

The changes between 1973 and 1991 can be seen better in Figure 7.5. There we show 1991 CO_2 emissions from all manufacturing relative to 1973 emissions in several ways. First we display actual 1991 manufacturing emissions over all subsectors. Then we show the calculated impact of changes in structure on 1991 emissions relative to 1973. Next we show the impact of changing energy intensities alone, again relative to 1973 values. We then vary only the final fuel mix, then only the emissions per unit of electricity production, and show the calculated impacts on 1991 manufacturing emissions relative to 1973. It turns out that this decomposition shows greater CO_2-reduction within the manufacturing sector than in travel or freight in each respective country, and, in most cases, more CO_2-reduction than in households or services as well. In otherwords, manufacturing showed the greatest reduction in CO_2 emissions of any sector in the countries we studied.

These findings are significant for two reasons. First, they show that, in general, CO_2 emissions from manufacturing fell principally because of energy saving in that sector, to some extent because of structural changes, and to a lesser extent because of changes in final fuel mix and utility fuel mix as well. These substitutions within the final fuel mix occurred as a result of longer-term trends away from solid fuels to oil and natural gas, the latter of which was only introduced in Sweden and Denmark in the 1980s. Since manufacturing energy intensity seems to decline the more output grows, the wedge between CO_2 emissions and output is large, leading to restraint in emissions relative to output. This means that if trends continue, CO_2 emissions from manufacturing should continue to lag significantly behind output, particularly if the substitution of gas for oil and coal and reduction in CO_2 intensity of electricity production continues.

The range of per capita emissions from manufacturing across countries is large relative to the range of overall per capita emissions. The reasons for this difference are mainly that per capita output varies by nearly two to one across the countries, energy intensities vary by nearly as much, and the carbon intensities of primary energy use in manufacturing varies by more than a factor of two to one from highest to lowest. Thus the high *ranking* of U.S. per capita manufacturing emissions is explained by its high output, relatively high emissions per unit of energy, and its relatively high energy intensities.

Overall, manufacturing emissions dropped the most consistently across countries, and manufacturing lost share dramatically in the emissions profile of almost every country (Figure 7.1). The primary reason was lower energy intensities, but final fuel mix and utility mix contributed. On the other hand, structural changes were only significant (in the downward sense) in W. Germany, Japan, and the U.S.

B. Residences

Emissions in this sector were analyzed by Sheinbaum and Schipper (1993) and by Schipper, Haas, and Sheinbaum (1996). Their evolution is characterized by similar trends across all countries. Activity (i.e., population) grew very slowly, but structure (floor area and appliance ownership per capita) grew rapidly in Japan and Europe and modestly (from high levels) in the U.S. These changes alone raised energy use and emissions by 50-80%. Energy intensities for almost all end uses in all countries fell, from 10-20% for water heating and cooking to 15-25% for electric appliances (through stock turnover) to 25-50% for space heating (see Figure 5.4). As a result of these changes alone, emissions in the residential sector grew very little or fell in absolute terms except in Japan and Finland. Figure 7.6 shows residential CO_2 emissions per capita from 1970 to 1991 which declined in most countries.

Final fuel mix had varied effects on residential emissions. Space heating fuels evolved from a mix of coal, oil, and gas to one of very little coal, some continued reliance on oil, and a significant increase in the use of gas, district heat (increasingly fueled by biomass or natural gas), and electricity (in countries with relatively low-cost nuclear or hydro resources). Electric heating has grabbed a large share of new homes in the U.S., France, Norway, Finland, and Sweden and a smaller, but significant, share of existing heating systems in Norway and Sweden. Increased ownership of electric appliances also boosted the use of electricity, indirectly leading to higher emissions wherever electricity systems were based principally on fossil fuels (i.e., all countries except France, Norway, and Sweden). Thus, even though the emissions of most electricity systems decreased, the increased use of electricity can still boost emissions significantly, since a unit of electricity is, on average, still more CO_2-intensive than a unit of natural gas or oil – the two most common fossil fuels used in households. Overall however, as Figure 7.7 shows, the residential final fuel mix did indeed become less CO_2-intensive.

Residential energy intensities fell, particularly for space heating (see Figure 5.4). The intensities of electric appliances fell slowly as less energy-intensive models replaced older ones. On an absolute level, space heating CO_2 emissions increased because of the near doubling in the number of homes with central heating in Western Europe and the large increase in the number of electric appliances in all countries. However, space heating CO_2 intensity (Figure 7.8) fell, principally because of falling energy intensity and then because of changing fuel mix. Overall, the role of space heating in the total profile of residential emissions declined as that of electric appliances increased.

The overall effect of all of these changes was to reduce CO_2 emissions per capita in the household sector, particularly in the countries where significant amounts of low-carbon electricity were used (France, Sweden, and Norway) or where energy intensities fell strongly (Denmark, W. Germany, and the U.S.). In Finland and Japan, final fuel mix, utility mix, and intensity changes did not offset the strong impacts of structural change towards more heated area and equipment per capita. Figure 7.9 compares the different effects by country. The prominence of the structural effect is clear, as is the opposite (but in general somewhat weaker) effect of energy intensities as well as the modest effect of final fuel mix and utility mix.

The wide range of per capita emissions from households, like the ranges in manufacturing, arises because of wide differences in floor area and other elements of structure, energy intensities, and fuel mix. High emissions in the U.S., for example, stem from the largest per capita floor area, higher than average energy intensities, average winter climate, and a primary fuel mix that is slightly more CO_2-intensive than average. Japan's emissions are very low because homes are small, the climate is mild, and space heating energy intensity itself is low. Norway's emissions are low in spite of large, well-heated, well-lit homes in a cold climate because so much of the primary energy comes from hydropower.

Compared with emissions from other sectors, residential sector emissions in general decreased less than those of manufacturing (see Figure 7.1), thus *gaining* a share of total emissions in those countries where structural change was important (Finland and Japan). Indeed for those countries, the structural effect was greater in this sector than in any other sector. Emissions from households lost share otherwise, particularly where travel and freight grew rapidly or where significant quantities of low-CO_2 electricity were introduced. On the sectoral level, the reductions in residential energy intensities were the second largest measured after those in manufacturing. The impacts of changing final fuel mix and utility mix restrained residential emissions somewhat, to the same approximate degree as in manufacturing.

C. Services

Sezgen and Schipper (1995) recently analyzed changes in energy use in the service sector. Unfortunately, there is no good measure of the "structure" of that sector because there are no data relating either floor area or services GDP by subsector to energy use by subsector over any significant historical period. Additionally, there are no consistent estimates of the use of energy for various end uses (heating, lighting, etc.) by country over time either. Consequently, we follow only total output (in real services GDP) and energy use per unit of output. (We also studied floor area for those countries where such a measure existed.) Figure 5.5 showed aggregate primary energy use per unit of services GDP for each country. The fuels component (most of which is used for space heating) dominated the 1973 picture but has since decline dramatically. The electricity component of total primary energy per GDP ratio increased in all countries, except where electricity generation itself was not CO_2-intensive (Norway, Sweden) or moved significantly away from CO_2-intensive sources (W. Germany and Finland). The results are shown in Figure 7.10 as the ratio of CO_2 emissions to services GDP.

In simple terms, activity (services GDP) increased by 40% to 110% across our study countries, boosting energy use and emissions. Decreases in primary energy intensity lowered emissions 5% to 35%, except in Norway, where primary energy intensity increased because of increased penetration of low-cost electricity into the heating markets. However, in all countries but Italy, CO_2 emissions per unit of services GDP decreased significantly, and only in Denmark, Italy, the U.K., Japan, and the U.S. did per capita services emissions in 1991 exceed 1973 levels. The main reason for these increases was the strong growth in those respective service sectors as well as the increase of coal-fired electricity production in Denmark and the greatly increased use of high-carbon electricty in Italian services. When all factors are combined, the resulting per capita emissions (Figure 7.11) shows modest declines in most countries, increases in a few, and significant declines in only two countries. Because the share of electricity in services final energy across countries is the highest of all the sectors examined, this sector's emissions are very sensitive to the evolution of the utility fuel mix. This explains why only a few countries showed such a strong decline in per capita emissions (Sweden, France, and Norway) while most showed a small decline or even an increase.

The range of per capita carbon emissions from the service sector arises principally from the range in per capita services output, with the U.S. having the highest output. Additionally, however, the carbon intensity of this sector's primary energy mix plays a large role in Italy and the U.S. where high-carbon electricity accounts for 60% and 40% of final use, respectively. Similarly in Denmark and the U.K., the primary energy mix plays a significant role in determining services emissions since there is still substantial fuel oil use in their respective service sectors. The U.S. also has high energy intensity, even compared with its large built area. Finland has a high energy intensity in this sector (but low carbon intensity for electricity), while Germany has high output, low energy intensity, and average carbon intensity of its primary fuel mix. The lowest per capita emitter from services, Norway, enjoys a final fuel mix that is almost 80% hydroelectricity or wood.

Compared with other sectors, emissions in services increased their share except in the countries with relatively low-CO_2 electricity (Figure 7.1). While the overall decline in emissions per unit of activity was significant, the overall effect of activity growth, the strongest of all the sectors studied, dominated. Again, the high dependence of this sector on electricity couples services emissions tightly to utilities.

D. Travel

Scholl *et al.*, (1995) analyzed changes in carbon emissions from transportation. Simplifying this work is the fact that travel depends almost wholly on oil products, for which emissions vary little from one fuel to the next. As a result, changes in emissions depend principally on changes in energy use. Figure 7.12 shows per capita emissions for travel by mode in 1973 and 1992 for Japan, the U.S., and eight European countries aggregated. Because the differences among European countries and the changes in Europe over time were relatively uniform, we have aggregated these countries (into the EU-8) to simplify the description. Figure 7.13 shows the behavior of per capita aggregate emissions over time. The declining trends in aggregate emissions were caused principally by declines in activity during periods of recession and higher fuel prices. However, note that the predominant trend was towards *greater* per capita emissions (principally from automobiles) in all countries except in the U.S. Not surprisingly, aggregate carbon intensity (Figure 7.14), measured as the ratio of emissions to aggregate activity in passenger-km, increased over time as well, decreasing only in the U.S. (and marginally in Denmark and Italy relative to 1973).[16] In all but a few countries, it took more energy (with more CO_2 released) to transport a person one kilometer in 1992 than in 1973.

Figure 7.15 compares the different effects. In all countries, activity boosted emissions relative to 1973 levels - 31% in the U.S., 65% in Japan and Norway, and 71% in Europe as a whole. Structural shifts towards cars and air travel increased emissions almost everywhere, above all in Japan where automobiles passed the 50% share of total travel only in the late 1980s. Intensity changes (see Figure 5.6) reduced emissions by nearly 20% in the U.S. but had little effect elsewhere. Air travel energy intensity fell significantly in every country, but the intensity of automobile travel fell significantly only in the U.S. (by 20%) and barely fell or even increased in other countries. This surprising result occurred because the load factors of automobile travel fell by about 25% in every country, while the energy intensities of car use, in MJ/vehicle-km, fell by less than 15% except in the U.S.

The U.S. per capita emissions from travel dwarf those from the other study countries. Since fuel mix is virtually the same everywhere, the reasons why U.S. emissions stand out are principally the fact that Americans travel twice as far (or more) as Europeans by car and five times farther by air. Moreover, the energy intensity of travel in the U.S. is about 30% higher than in Europe or Japan. Note, however, that over the 1970s and 1980s, the overall carbon intensity of travel in the U.S. has declined to be fairly close to that of Europe through 1991, before turning around and increasing slightly.

As figure 7.1 shows, emissions from travel represented the second-smallest share of the five sectors studied here in 1973. However, travel emissions grew in all countries over the study period (although emissions in the U.S. fell in per capita terms). Activity changes contributed strongly to this growth, as much as in any other sector. Structural changes contributed marginally to increased emissions, less than in the residential or freight sectors. Changing energy intensities reduced travel emissions significantly in only one country (the U.S.) and marginally in two others, in contrast to the impact of intensities in services, manufacturing, households, and even freight. Changes in final fuel mixes had very little effect since the main transportation fuels (gasoline, diesel, and jet fuel) release nearly the same amount of CO_2 per unit of energy. Because of electricity's relative unimportance in the travel sector, utility fuel mix had virtually no effect in this sector.

E. Freight

Total and per capita U.S. energy use and carbon emissions from freight transportation were as much as three times higher than those in Europe or Japan in 1992, as Figure 7.16 shows. Figure 7.17 shows the evolution of freight emissions over time, which generally follows GDP and is sensitive to business cycles.

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[16] In this analysis the unit of activity, passenger-km, is calculated for automobiles as vehicle-km times load factor, or people/car.

Whereas autos dominate the travel picture, trucks predominate in the freight picture. Because of the differences in size, geography and production characteristics between the U.S. and Western Europe, the modal structures and energy intensities of their respective freight systems differ significantly, considerably more than is the case for travel. The U.S., where total freight haulage is dominated rail and barge systems carrying bulk materials over long distances, contrasts with Western Europe and Japan, where all payloads are hauled much shorter distances. As a result, Europe relies more on trucking than the U.S., although the U.S. ships far more domestic freight, per capita or per dollar of GDP, than do the other countries. Consequently, the U.S. freight sector, in contrast to its travel sector, is on average less energy-intensive than that in Europe or Japan but uses more energy and emits more CO_2 on an absolute basis because of higher levels of tonnage hauled. Consequently, the U.S. has one of the lowest ratios of emissions to freight hauled (Figure 7.18). Since trucking dominates energy use and emissions, the characteristics of trucking are key to the overall picture. Figure 5.7 showed how the energy intensity of trucking varied over time for these countries; trucking CO_2 intensities followed these trends closely. The total U.S. freight sector then – with the lowest share of trucking in total freight and relatively low CO_2 intensities of trucking – winds up with only three times the emissions even though the volume of freight, relative to Europe or Japan, is so much higher (by a factor of approximately 15).

CO_2 emissions from freight grew significantly in all ten countries studied, 49% in the U.S., 63% in Japan, and 51% in the EU-8 between 1973-1992. Of the European countries, growth in CO_2 from freight was the highest in Italy (122%) and the lowest in Finland and the U.K. (31%). Although emissions grew less in the U.S. than in Europe, per capita freight emissions there are still almost twice as high. The trends in CO_2 emissions closely mirrored those in energy use since there was no significant fuel-switching that affected freight's overall carbon intensity. Growth in emissions was not steady throughout the period. From 1979 to 1985, growth in emissions slowed or, in several cases, reversed. This period was followed by a sudden surge in emissions after 1985. For example, average annual growth in emissions was -2.0%/yr from 1979-1985 and then +5.5%/yr from 1985-1992. This is most likely related to changes in industrial output during the recessions after the oil shocks, during which freight haulage declined.

From the decomposition indices for freight (Figure 7.19), we see that increasing freight activity (tonne-km's) has been the primary driver behind increasing CO_2 emissions since 1973. Growing activity levels alone (holding other factors constant) pushed up emissions 41% in the U.S., 37% in Japan, and 38% in the EU-8. Structural changes, specifically modal shifts towards trucking and away from rail and ship, also had a significant upward impact on emissions in every country except U.K., Norway, Sweden, and Denmark. Structural shifts considered alone would have increased emissions 14% in the U.S., 30% in Japan, and 15% in the EU-8. The effect of modal energy intensity on emissions, holding mode shares and activity levels constant, had a varied affect among the countries studied. In France, Italy, Sweden, and Denmark, changes in modal energy intensity increased emissions while in all the other countries except Finland the effect was a decrease in emissions. Although the share of diesel fuel has increased in many countries, changes in final fuel mix had little effect on total freight emissions. However, in France, a substantial shift to nuclear power decreased the carbon intensity of electric rail by 76% and suppressed emissions somewhat.

The main reason for the large gap between U.S. per capita freight emissions and per capita freight emissions from the other countries is the larger volume of freight shipped in the U.S. In fact, the U.S. freight system has a considerably lower carbon intensity than most other countries, because of both low modal energy intensities and the relatively low reliance on trucking. Still, this low carbon intensity is not low enough to offset the huge difference in freight volume.

As Figure 7.1 shows, freight emissions represented the smallest share of the five sectors studied here. However, these emissions grew uniformly in all countries. Structure and activity changes contributed strongly to this growth, and intensity reduced emissions only in half of the countries while fuel mix had very little effect. Because of electricity's relative unimportance, utility fuel mix had virtually no effect on emissions in this sector.

F. Summary of Sectoral Trends

Figure 7.20 shows the overall summary of changes in per capita emissions by sector, as well as the change for the country as a whole. We compare all values with their 1973 emissions. The contrast between manufacturing emissions (declines in all countries) and travel and freight emissions (increases in all countries but one for travel) is clear, with the other sectors varying but generally showing declines. From a perspective of individual countries, only Japan showed emissions growth in four of five sectors, whereas Finland and Italy (and Denmark and the U.K. to a much lesser degree) showed growth in three sectors. Only the U.S. showed a decline in travel, which offset the total increase in freight there. Structural change boosted emissions in the travel, freight, and residential sectors and was a key determinant of the increase in emissions.

Figure 7.21 normalizes each sector's change to activity, showing which sectors have become more or less CO_2-intensive. The latter picture may be more valuable for policy, since few advocate restraining activity per se, except perhaps in the travel or freight sectors. This picture contrasts considerably with that in Figure 7.20. Relative to sectoral activity (in the case of households, relative to one measure of sectoral activity – floor area), emissions fell relatively strongly in every sector except freight and travel. Emissions from travel fell strongly in the U.S., declined weakly in a few countries, but otherwise increased. Again, manufacturing showed the most consistent performance among countries, freight and travel the most variability.

Figure 7.22 summarizes all of changes in the sectoral components of CO_2 emissions, comparing 1991 with 1973 using fixed base-year Laspeyres indices. Activity changes increased emissions across the board. Intensity changes decreased emissions. Stuctural changes generally increased emissions; the one exception was Japan where the shifts away from energy-intensive manufacturing outweighed other structural changes, largely because of the manufacturing sectors dominance over all energy uses in 1973. Utility mix led away from carbon emissions, while final fuel mix led to increases in emissions in five countries (as much as 10%) and decreases in four (those with important non-fossil sources of electricity in 1973). The overall carbon intensity of the economy, holding activity and structure constant, decreased in every country.

Figure 7.22 suggests an important goal for CO_2-related public policy – to try to reduce the CO_2 intensity of travel and freight, the sectors that consistently showed the least decline in CO_2 intensity, and, as Figure 7.21 reminds us, also grew strongly from both activity and structural effects. If policies and taxes encourage the use of less carbon-intensive but more expensive fuel sources, these sectors might show restraint both from lower carbon intensity and from slight reductions in the importance of the activity effect. Additionally, since in most countries automobiles are more energy- or carbon-intensive than bus or rail, higher fuel costs (in the name of a low-carbon fuel) could lead to slight shifts in modes towards less energy-intensive modes.

VIII. Recent Trends by Sector and Country

The foregoing analysis was based on the 1991 emissions profiles and economic structures of each country. As we noted above, however, emissions peaked in most countries, then fell, but began upward again in many countries. We review the most recent trends here, which for travel, freight, and households (and for other sectors in some countries) can be analyzed through 1992 or 1993. *We repeat that the reason why the country-wide analyses end in 1991 is largely the limitations of structural data, particularly for the U.S., but we hope to update the figures to 1992 and even 1993 very soon.* Figure 8.1 gives the rates of change of each factor by country for 1973-1985, 1985-1989, and 1989-1991; changes at the sectoral level should be clear from figures presented in the previous sections.

A. Recent Trends in Emissions by Sector

By far the most important growth in emissions after 1986 occurred in freight, travel, and to some extent in services. This is in part because higher output in manufacturing seems to lead away from carbon-intensive coal and toward lower energy intensities, as well as declining the importance of the most energy-intensive industries in some countries. Higher personal incomes in the household sector do not appear to lead to proportional increases in residential energy use, mainly because of equipment saturation. But in travel, higher incomes mean bigger cars and more travel by car and air, as well as more freight shipped by truck. This is confirmed by the trends we can observe beyond 1991 in the transport, household, and service sectors to 1992 or 1993.

In travel, the energy intensities of car travel have ceased to fall in the U.S. and are falling only very slowly in Europe. The energy intensities of freight fell in only half the countries, while levels of activity (and the continued shift to trucks) raised emissions. Thus in the early 1990s, transportation was the most important end-use sector driving emissions upward. In the service sector, intensities for space heating fell markedly in almost every country. Since heating everywhere but in Sweden and Norway was dominated by fossil fuels, this decline was an important source of emissions reduction, but the rate of decline slowed after 1986. Meanwhile electricity use continues to grow, driven by new electrical end uses but restrained somewhat by higher efficiency of each use. By contrast, emissions growth from manufacturing remains slow because energy intensities continue to fall. Growth in residential emissions remains slow because intensities are falling slowly, household formation itself has slowed, and actual energy services are saturating.

Thus since 1986, emissions from transportation have been growing because activity and structural change boost emissions while intensity is relatively flat and fuel mix is relatively constant. Emissions from services are growing because activity is growing, intensity is flat, and electricity use for many purposes is still increasing per unit of output (a hidden structural change). Emissions from manufacturing are only growing feebly because activity is growing slowly, structural change is roughly neutral in its impact on emissions, and intensities and fuel mix are still moving towards lower emissions. Emissions from households are also only growing weakly as equipment-saturation effects coupled with a weak but continuing decline in intensities and slow activity growth (population) lead to very little change. Concerned authorities should thus examine the transportation sector most closely.

B. Trends in Emissions by Component

We noted that higher activity in each sector drove emissions upward, boosted in turn by structural changes. Figure 6.3 showed the activity effect alone for each country, and Figure 6.4 showed the structural effect. In households, the saturation of energy services (a structural effect) becomes perceptible as the number of homes (and ownership of equipment per home) now grows more slowly with income. Travel activity is still growing strongly in Europe and Japan – almost as rapidly as GDP. The modal mix has shifted increasingly towards cars and air travel. (If we could include international air travel this effect probably would be even more marked, because international air travel appears to be growing more rapidly than domestic travel.) Freight activity is not growing as much relative to GDP, but shifts towards trucks continue to raise energy use and emissions. The effects of these structural changes are included in the figures.

The impact of falling energy intensities was shown in Figure 6.5. This decline was strongest before 1985. While it is still occurring in households and manufacturing, the rate has itself abated. As for the transportation sectors, the rate of decline of automobile energy intensity is almost nil in most countries, while that for truck freight is still falling in a few. Overall, energy intensities in each economy fell less rapidly in recent years than in the period before 1985. Recession in Finland amplified this effect, but a similar slowdown appeared in other countries between 1989 and 1991.

Nevertheless, aggregate carbon intensity, or CO_2 emissions per unit of GDP, is still falling. Some of this decline occurs because GDP is growing faster than energy consumption (and hence carbon emissons), which is driven by increases in *sectoral* activity and/or structural change rather than by trends in GDP itself. Most of the ongoing decline in carbon intensity, however, is rooted in the continual, slow decline of certain end-use energy intensities and the pervasive move away from coal and oil towards gas in manufacturing, homes, and services. Seen against a background of rising GDP, these intensity and fuel mix trends alone would still permit CO_2 emissions to fall relative to GDP and provide some possible absolute restraint in emissions. However, despite the fact that the final fuel mixes in manufacturing, households, and services are moving slowly towards more gas and more electricity, differences in utility fuel mix trends across countries show that the latter move restrains emissions only in about half the study countries. Combined, these trends mean that emissions are rising again, in an absolute sense, in about half the study countries if one discounts for the effect of recession in the U.S., Finland, and Sweden.

Bear in mind, though, that the wholesale decline in emissions permitted by a rapid rise in the role of nuclear power (France and Sweden), the substitution of electricity for oil (Sweden and Norway), or the rapid declines in energy intensities is probably over barring significant changes in policies. The main reservoirs of potential for low-carbon utility emissions are in the U.S., W. Germany, Denmark, Italy, and the U.K. where coal (or oil in the case of Italy) has been king but where gas is now moving into the power sector. Gas is also gradually gaining share in space heating markets of France, W. Germany, Denmark, and Italy. There are great reserves of potential energy efficiency improvements in all sectors, but these are only occurring significantly in manufacturing and slowly in households and services. The decline in emissions in many countries after 1989 was principally caused by a drop in the carbon intensity of electricity production. No one can deny that there exists a great potential to reduce the ratio of carbon emissions to GDP rapidly, but few can claim that potential is being harvested rapidly today.

C. Countries with Recent Growth in Emissions

With this background in mind, in which countries can we expect the most rapid rise in the absolute level of emissions? Economic growth itself (which drives the activity index term via services and manufacturing GDP and the rather direct couplings of travel and freight activity to GDP trends) behaved irregularly after 1989. The respective GDPs of Japan, W. Germany, France, and the U.K. surged through 1991, then slowed with recession. Those of the U.S. and the Nordic countries fell sooner into recession. Judging long-term trends by the data from 1989 to 1991 or 1992, therefore, would be fraught with uncertainty. Nevertheless we can make some generalizations.

To do this, we show each country's factorialization in terms of rates of change for three periods 1973-1985, 1985-1989, and 1989-1991 (Figure 8.1). Even though this display of the Laspeyres indices lacks the residual terms (which accumulate over the time period shown), this presentation still suggests that with some exceptions, CO_2 intensity and energy intensities fell less rapidly after 1985 than before, or even increased. Some of the recent fall in total emissions, particularly in the U.S., was clearly related to recessions which, as noted above, hit some countries after the study period. However, note that Denmark had an increase in emissions (following decreases in previous periods) even though it has experienced the slowest economic growth in the most recent period. Carbon intensity in the U.S. continued to fall, driven downward by both energy intensity and the utility fuel mix. But in general, the rate of decarbonization has slowed. The complex interaction of all of these factors suggests that simple measures like total CO_2 emissions or even the ratio of CO_2 to GDP are insufficient to understand short-term trends in emissions. And it is clear that overall, actual emissions are rising in Denmark, Finland, W. Germany, Japan, France, Italy, and the U.K.

Early in 1996, economies in crisis in the early 1990s (Sweden, Finland, France, W. Germany, and Japan) look to recover while those that recovered earlier, like the U.S., are still growing. Certainly when Japan's economic growth picks up we expect a continued rise in travel and indoor living standards – both strongly based on oil and electricity – which will boost emissions. The same is likely true of Denmark, Finland, and the U.K., the three European countries in our sample with the fewest autos. Additionally, the U.K., France, and Finland have relatively less residential floor area per person than other countries in Western Europe. Overall, however, it is continued economic growth that would drive emissions upward, through increased mobility and home comfort in all of these countries except Denmark.

Opposing this trend is the significant potential for fuel switching away from coal (power sectors of U.K., Denmark, W. Germany, and the U.S.). While nuclear power expansion may be effectively blocked in most countries, much of the growth in power generation could be from gas rather than coal. And few doubt that more efficient energy use will continue to chip away at CO_2 emissions, albeit at a slower rate than before 1985. Ironically, one of the most important stimuli leading to greater efficiency is the turnover of equipment in all sectors. This turnover, however, is fostered by higher economic growth. The result is rarely an absolute decline in CO_2 emissions from turnover alone, but rather an increase in the size of the wedge between emissions and activity, an effect first noted by Schurr (1982) for energy as a whole.

IX. Most Important Factors that Influenced Emissions

With these historical observations in mind, we can ask which components of the economy and energy use hold the most weight over emissions, particularly in the future. Understanding the role of these components in carbon restraint plans is important if we are to understand which elements of a plan are occurring anyway, which represent acceleration of trends, which represent breaks in trends, and which represent unique opportunities to reduce emissions, such as the inclusion of Eastern Germany in the overall carbon accounts of a united Germany.

A. Income and Economic Structure

Economic structure (by which we mean both sectoral activity and sectoral structure) has evolved to boost emissions of CO_2, although in most cases the *overall* measure of economic output, GDP, has grown faster than our measures of economic structure. Income and to some extent population are important driving factors that boost emissions – the former in per capita terms and the latter as a multiplier. However, we noted at the outset that no country aims to restrain economic growth or population as a greenhouse gas-restraint measure.

Economic structure is another matter, however. It is hard for the U.S. government to discourage the rise in the share of manufacturing output from the production of energy-intensive raw materials which have driven emissions up after 1988. Similarly, industrial policies of the Swedish, Norwegian, and Finnish governments have arguably favored raw-materials development. But these three countries are also blessed with reserves of hydro-power and biomass, which significantly mitigates emissions from heavy industry. Were all three countries to develop or increase the use of natural gas in place of imported coal, CO_2 emissions from heavy industry could fall significantly. On the other hand, it may be politically opportune for some governments to reduce dependence on coal use, if that dependency has meant costly subsidies, complicated schemes to shore up the share of coal in some sectors, and environmental damage from high coal use.

At the same time, it has been documented how policies *not* related to energy or CO_2 in some countries have affected economic development and in turn boosted CO_2 emissions. While controversial, fuel and vehicle taxation that undercharges for externalities may contribute more generally to greater use of road vehicles, less use of other, less energy-intensive modes, and more movement of people or goods (Kaageson, 1993). (Recall from Figure 7.14 that the ratio of carbon emissions to domestic travel dropped only in the U.S. but is now constant there, as it has been in all the other countries we studied.) But the Swedish "Traffic and CO_2 Delegation" (1994) recognized these vital links, links that have been weakened recently in the U.K. (OECD, 1995). Tax treatment of company cars is light in many European countries, encouraging more, larger cars and more travel (Schipper *et al.,* 1993d; OECD, 1995). Similarly, tax deductions for mortgage interest in the U.S. and some European countries promotes larger homes that are often more dispersed as well (Schipper *et al.*, 1989; Gentry, 1994). It does not appear that any country will easily promote changes in some of these policies to reduce future carbon emissions. The political debate that has erupted in Sweden over company car priviledges and the inability of most tax-reform advocates in the U.S. to address the mortgage interest income-tax deduction suggest that such changes will be a long time in coming.

In the final analysis, the shift from "production to pleasure" (Schipper *et al.*, 1989) – by which energy uses are growing in a relative sense for consumer needs (transportation, households, personal services) while shrinking for production (manufacturing, freight, and business services) – itself signals an important transformation of economies. It is arguable that energy use is not a factor of production for consumers in a competitive economy in the same sense that energy is an input to production processes for competitive firms. This large-scale shift in where energy is used, and therefore where CO_2 is ultimately emitted, means that restraint must be practiced directly or indirectly by large numbers of small consumers, rather than just a relatively few number of utilities and large manufacturing and transportation firms. Note that it was manufacturing where CO_2 emissions fell the most on an absolute level *and* the most consistently across countries. Freight behaved in the opposite sense, but taken together, these two "production" sectors still showed great CO_2 restraint.

B. Fuel Mix

In the rush away from oil after 1973 and 1979, most countries promoted substitution of other fuels for oil in power generation, and, to a limited extent, in other industries. Coal emerged in the power sector (along with nuclear power) and its final fuel share in manufacturing increased somewhat (or declined less rapidly) in the 1980s. Energy policies of W. Germany and the U.K., for example, locked coal into and gas out of power production for many years (Hawk and Schipper, 1988). This raised CO_2 emissions, all else equal. More recently, the spread of natural gas for home heat in Europe to industrial boilers and power generation in both Europe and N. America has restrained growth in emissions. A carbon tax probably would accelerate this trend by raising the price of coal relative to that of gas (or oil), although some of the theoretical differential could disappear as supply and demand balance under such a tax. As noted above, the countries with heavy reliance on coal for power generation (W. Germany, Denmark, the U.K., and the U.S.) could encourage switching to gas, but for all but Denmark (which imports its coal), this implies a significant transformation of coal-mining regions, and the removal of some regulatory barriers in the U.K. and Germany.

C. Energy Intensities

More efficient energy use acted more than any other factor to restrain CO_2 emissions. At present, however, efficiencies are improving more slowly than in the 1980s. One reason is that energy prices have fallen or at least stabilized from their 1980s levels. Another reason is that some energy efficiency programs have simply expired or run their courses. While there are many electric utility programs in place in the U.S. their combined effects are still limited in nature relative to total electricity use or total energy use. The point is that while there is still an enormous resource of energy efficiency to be harvested, the actual rate of improvement is now slow. There are many reasons: stagnant energy prices, consumer resistance, true market failures in some sectors, and risks inherent in bringing out any new technology that might radically lower fuel intensity or carbon emissions but have other, uncertain effects on its producers or users. As one of us argued recently (Schipper, 1993), the issue is not whether there is a continued (or even growing) potential for reducing energy use per unit of activity or CO_2 emissions per unit of energy but why the rates of reduction are slower now than in the 1980s.

D. Other Driving Forces

What other factors could drive CO_2 upwards or in some cases downward? Income growth means more activity and emissions, but less carbon-intensive electricity and fuels, and more efficiency. The main reason for this is because economic growth is tied to technological progress – this progress means both greater efficiency in end uses and power generation but also more wealth and demand for energy services. On balance, we have seen that economic growth means a lower CO_2/GDP ratio but higher CO_2 emissions in a absolute sense.

Energy prices are recognized as a major factor in determining both energy intensities as well as fuel mix and, in some cases, even the overall level of activity (where energy-intensive activities like cement manufacturing, heating, or driving are concerned). But energy prices are flat, in some cases falling in real terms. For half of the countries studied, for example, real prices for automobile fuel in 1992 were equal to or less than their 1973 levels.

Conversely, some factors noted in passing might lead to unexpected restraint. One is the possibility of continued structural changes in manufacturing away from raw materials and towards goods with less materials but higher information content. Related to this information revolution is the possibility (but by no means certainty) that more people will substitute telecommunications for travel and even freight shipments.

On the other hand, we noted the importance of the shift from "production to pleasure". Right now, information as a commodity is creating the wealth that is helping to drive this change on the production side, with increases in the incomes of large portions of society driving this change on the consumption side. This means that even though energy use for home comfort and convenience may be saturating, higher incomes lead to more mobility of people and goods, with no saturation yet in sight. This trend may or may not continue, but it would be foolish to expect only a reduction in mobility because of an increase in communications capability without also considering an increase in mobility via higher incomes.

X. Conclusions

This review has shown that between 1973 and the early 1990s, CO_2 emissions from the major energy-using sectors in ten OECD economies have declined or not increased as rapidly as overall economic output. Falling energy intensities, shifts away from coal and oil, and in some countries a marked reduction in the role of energy-intensive manufacturing all contributed to this restraint. In all countries, however, greater consumer household comforts, personal mobility, and increased reliance on trucks all led to oppose this general trend. Relative to GDP growth, the evolution of sectoral activity and sectoral structure since the early 1970s undermined the restraint of CO_2 emissions in all but one country. Recent trends, combining renewed economic growth with a slowdown in the decline in energy intensities and growth in the size and power of personal vehicles, portend to reverse the decline in emissions or accelerate the recent increases seen in some countries.

What caused the restraint in per capita CO_2 emissions? Since there was no premium on low-CO_2 energy sources over the study period, changes in CO_2 emissions followed changes in fuel mix and energy use patterns. Schipper *et al.*, (1992a) argued that generally higher prices for energy, long-term technological progress, and in some cases energy efficiency policies "caused" energy efficiencies to increase. Furthermore, the relative prices of fuels, the increased availability of natural gas, and policies favoring (or in some cases discouraging) the use of nuclear fuels or natural gas in the power sector certainly affected the primary fuel mix. By the early 1990s, for example, the ratio of the price of natural gas to that of oil as a boiler fuel had fallen in every country (except the U.S.) from its pre-1973 level. While the period of high oil prices favored coal to some extent as a boiler fuel, the price ratio moved back towards its historic levels after that time. Local environmental concerns also add a hidden cost to coal more than to oil as well. Thus the fuel mix, which was moving towards less carbon per unit of energy anyway in the early 1970s, continued to accelerate in that direction. Only countries with initially low average emissions per unit of primary energy (Norway and Sweden) faced pressures in the other direction, as the rise of oil use for transportation raised the CO_2 intensity of their primary fuel mixes. Finally, most of the economies we studied have undergone an evolution whereby the growth in energy services has been less rapid than growth in GDP. Even without any concern for energy or CO_2, emissions relative to GDP have decreased.

This analysis has revealed how CO_2 emissions arise from energy use in several key economic sectors and end uses. In spite of great concerns voiced at international meetings over CO_2 emissions, however, few countries have been able to relate emissions to these end uses in their national communications on CO_2 restraint. Consequently, it is not clear how well authorities understand the implications of their pledges for CO_2 emissions. The complex interaction of all of the factors affecting CO_2 emissions suggests that simple measures like total CO_2 emissions or even the ratio of CO_2 to GDP are insufficient to understand short-term trends in emissions. The importance of structural and activity components of emissions growth, as well as the slow down in both the rate of decline in energy intensities and in some countries the rate of decline of the ratio of emissions to primary energy does not bode well for *significant* reductions in absolute CO_2 emissions in the near future, or even for restraint in emissions relative to GDP and other measures of activity.

Over a longer period of time, our trends cannot say much. We emphasize that over much longer periods of time (20-40 years), the enormous changes in emissions that some feel are necessary for restraining climate change seem possible. However, there do not appear to be any forces in the industrialized countries studied here that seem able to stop the present rise in CO_2 emissions and return them to 1990 levels by the year 2000 without changes in government policies. What the present analysis shows is only that present trends, if not modified to roughly the level of change that occurred in the 1973-1985 period, will <u>not</u> lead to absolute emissions reductions. And while we have not undertaken detailed analyses of the climate strategies of all of the countries we studied, our readings of such plans for Japan, the U.S., France, and Italy do not suggest emissions will be reduced in the near future. The U.K. could well achieve reductions because of its combined strategies to shift to natural gas from coal and to impose considerable taxes on fuels for transportation. Denmark faces many of the same options. W. Germany will not see emissions reduction, but the combined Germany will -- principally because of the restructuring of the new Laender (which are counted in the 1990 comparison), but with some contribution from mitigation measures in the former W. Germany as well. Finland has made marked strides to reduce the carbon content of its primary energy mix but still has high energy intensities in some sectors.

The real dilemmas are those facing Norway and Sweden, with very high consumption of non-carbon resources (hydro and nuclear), and France, with an enormous component of nuclear power in its electricity supply. For Norway and Sweden, the only significant sources of emissions are travel and freight (as well as fuel in agriculture), which we showed were problematic. For France, there remains significant use of oil in manufacturing, homes, and buildings that will gradually yield to natural gas (at least in built-up areas where there is gas), but like Norway and Sweden, transport remains an important source of emissions. To what extent should any agreements to reduce emissions take into acount the past performance of these countries, if for no other reason than to reduce oil use in the 1970s and 1980s?

The future may be different. Current trends in fuel mix and energy intensities point to continued restraint in CO_2 emissions from energy use relative to GDP growth. This may be heartening. But current emissions targets, expressed as a return to the 1990 level of emissions for most countries, will be hard to meet unless the rate of intensity decline approaches that of early 1980s, which is not likely. Another alternative – significant increases in the use of nuclear power – is also unlikely in most countries. Increased use of gas for space heating and in the power sector will likely contribute to added restraint in the U.S., Germany, Italy, and the U.K. Will the rise in freight and travel activity saturate relative to GDP or population? This is another key factor that we cannot address here. How these forces will interact, and how the trends compare with current expectations as expressed in each country's climate plan, is a subject for further study.

What our analysis shows is that it is almost impossible to understand trends in past emissions at the aggregate level. This implies that it is futile to understand them this way in the future. But there is a more subtle message here. The differences in starting points in 1973 and 1990, the dramatic reductions in emissions made in some countries that appear to be transient, and the uneven persistence of coal utilization in some countries suggest that it is also futile for every country to share a common, aggregate goal for restraint or reduction. What was already achieved in any one country – big savings in space heating, substitution of gas for coal in final demand sectors or nuclear and hydro for fossil fuels in power generation – cannot be "achieved" again in the same manner, although attention to other energy uses may yield meaningful restraint. What was not achieved, or indeed worsened, through increases in coal use for power generation or higher volumes of travel and freight oil use without any declines in intensities, might be easy to achieve in the medium term at modest or even low cost. The enormous diversity of emissions profiles argues for a diversity of targets (and a similar diversity of mitigation policies and measures) if the goal is overall emissions restraint or reduction at least cost. Can the industrialized countries implement the measures and policies that will turn around the trends we have presented? That is also a subject for another study, but also, like the previously suggested topic, must await the passage of several years until we can observe what the present set of intentions actually accomplishes.

What occurs to us in the end, however, is how strange it is that this study is effectively the first international comparison of the links between economic activity and carbon emissions. Few of the national communications even show the kind of detail necessary to evaluate this link for a single country. Perhaps a key item on the international agenda is mutual exposure to these profiles, followed by the expected disagreements on accounting, followed by even more complex discussions on interpreting differences and past trends. After all, if those discussions do not take place, what will be the basis for meeting the future as it unfolds?

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Global Carbon Emissions from Energy Use by Region

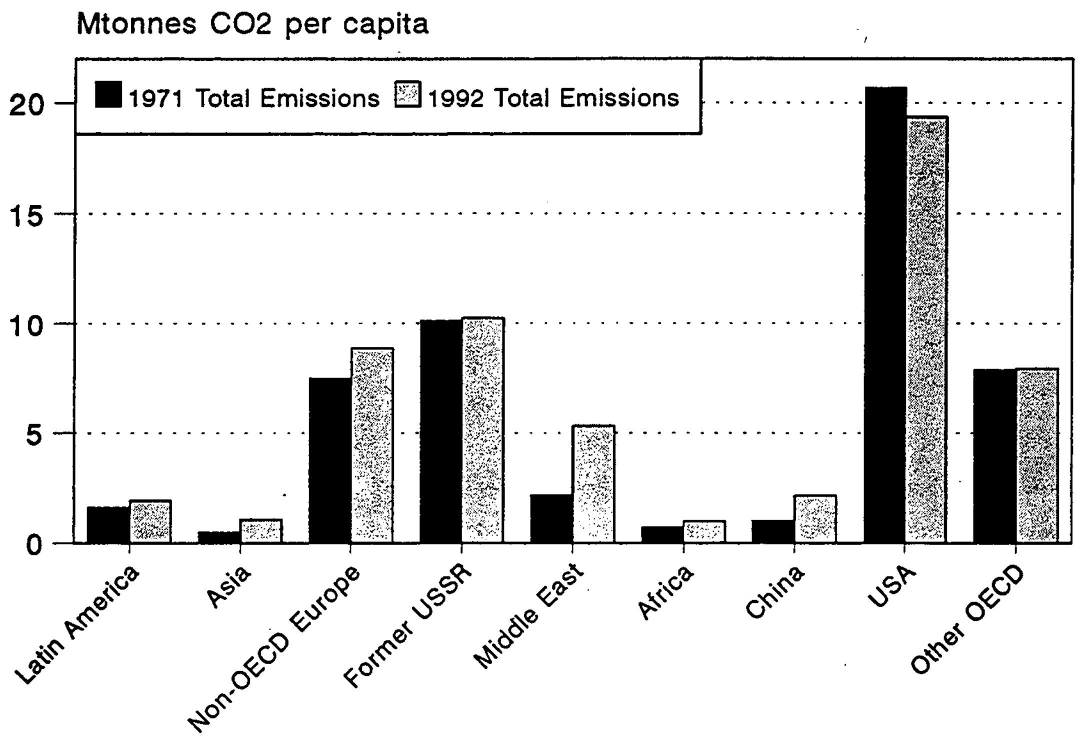

Figure 2.1

Primary Energy Use in the OECD-10

1973 vs. 1991 by Sector

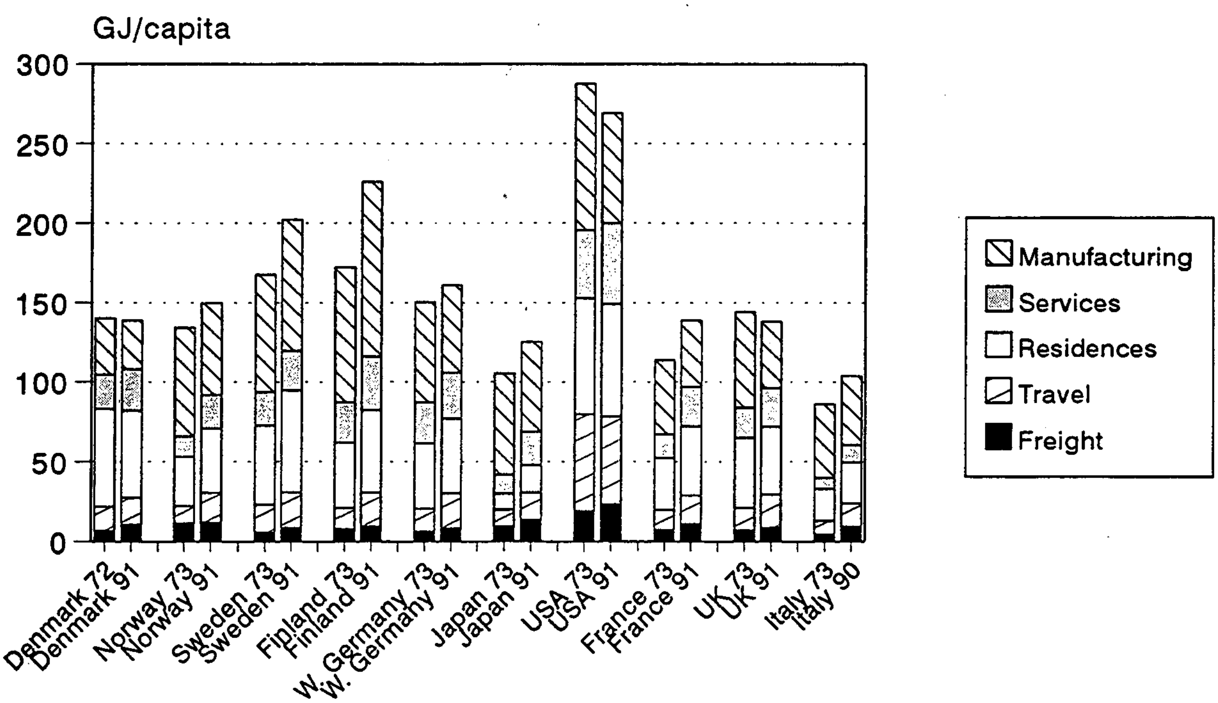

Figure 2.2

Carbon Emissions per Unit of Primary Energy Use in the OECD-10

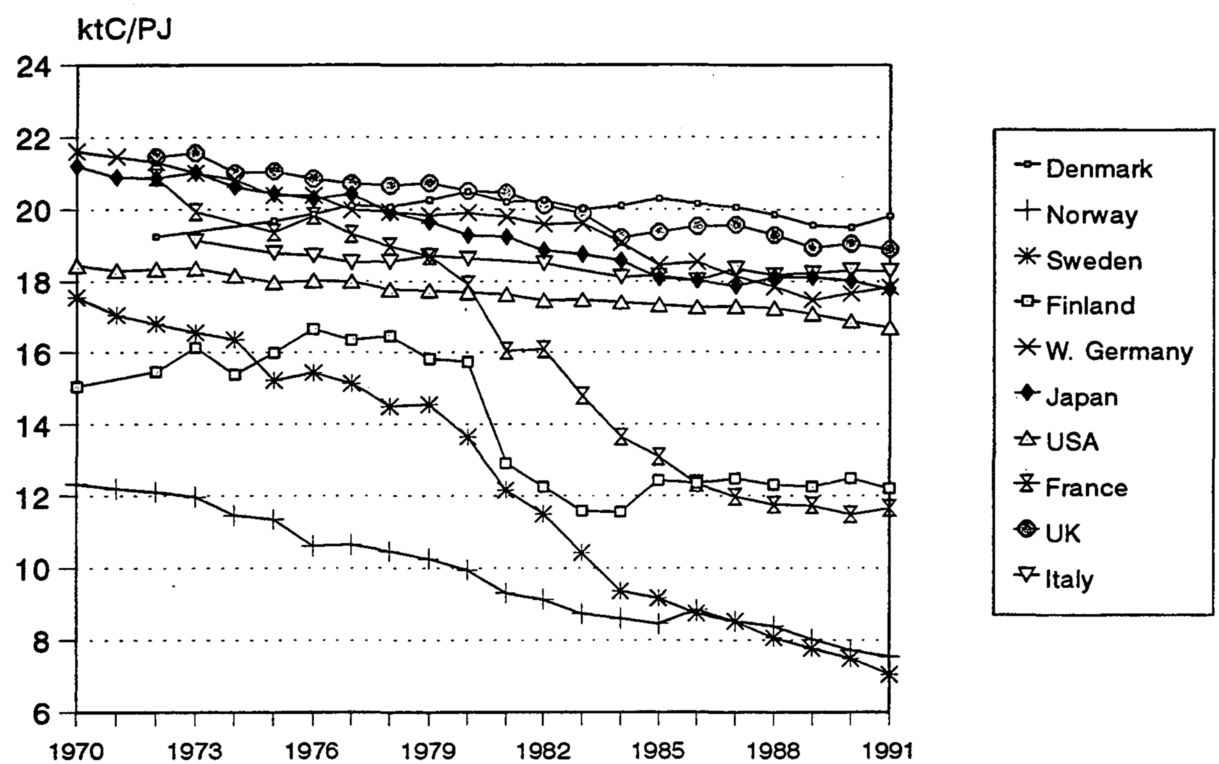

Figure 3.1

Carbon Coefficients for Electricity Production in the OECD-10

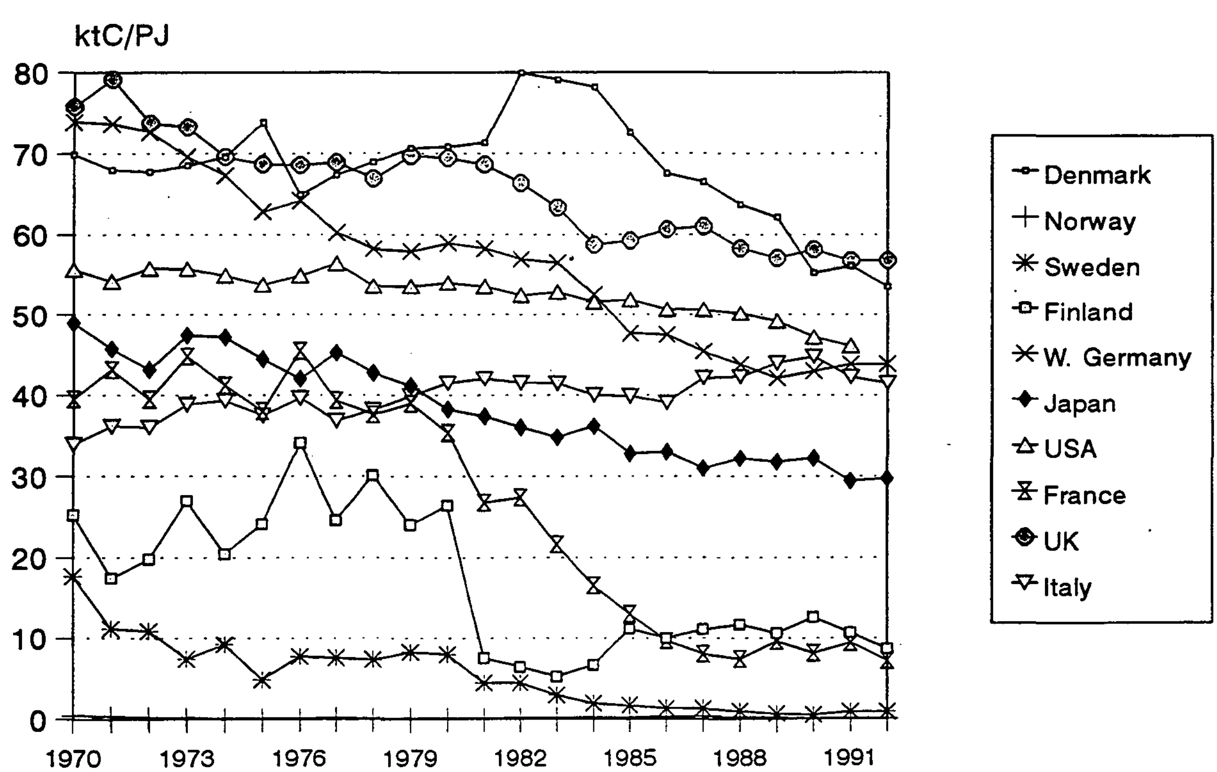

Figure 3.2

Carbon Emissions Profiles of OECD-10 Countries, 1970-1991

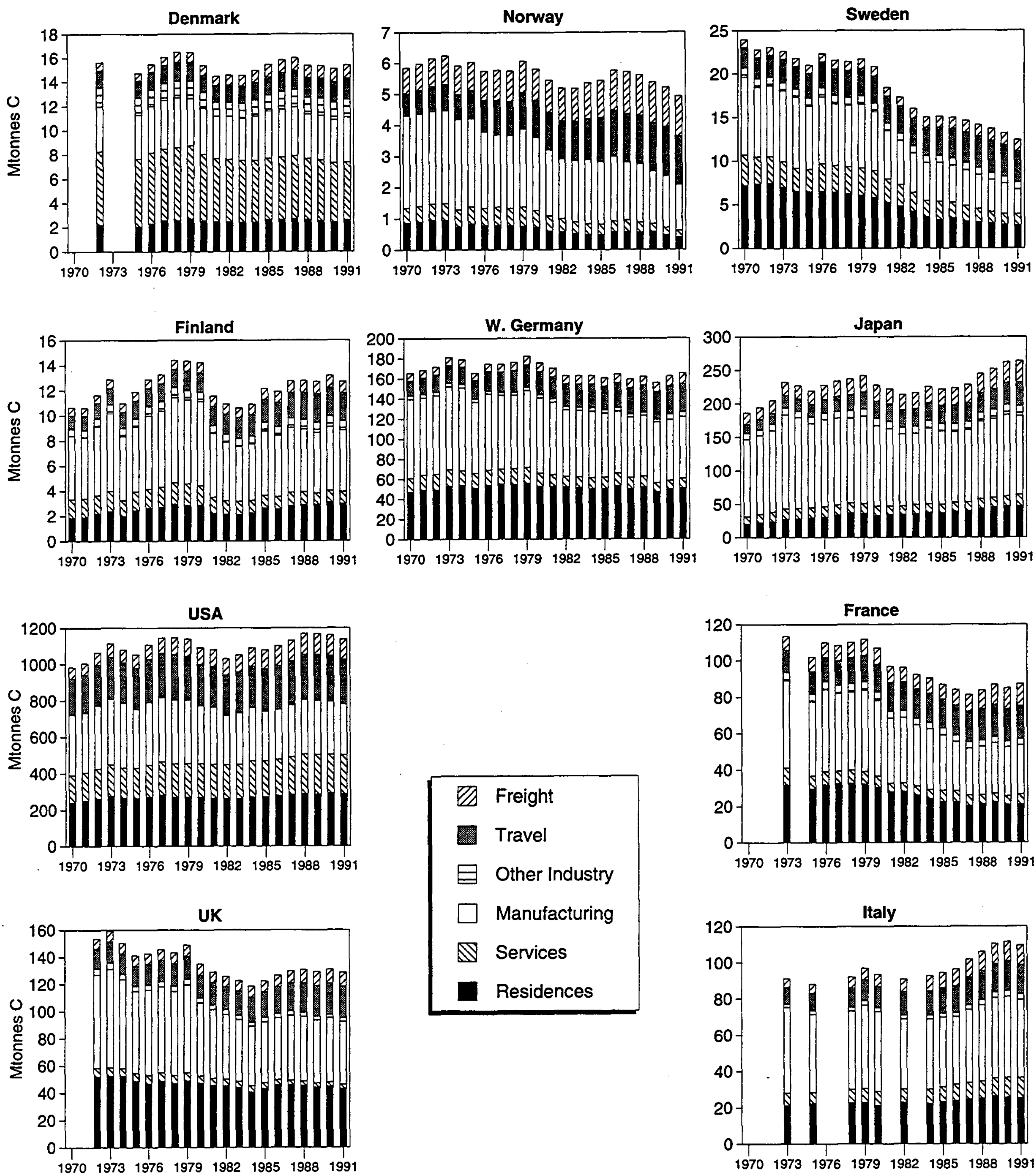

Figure 4.1

OECD-10 Carbon Emissions per Capita

1973 vs. 1991 by Major End Use

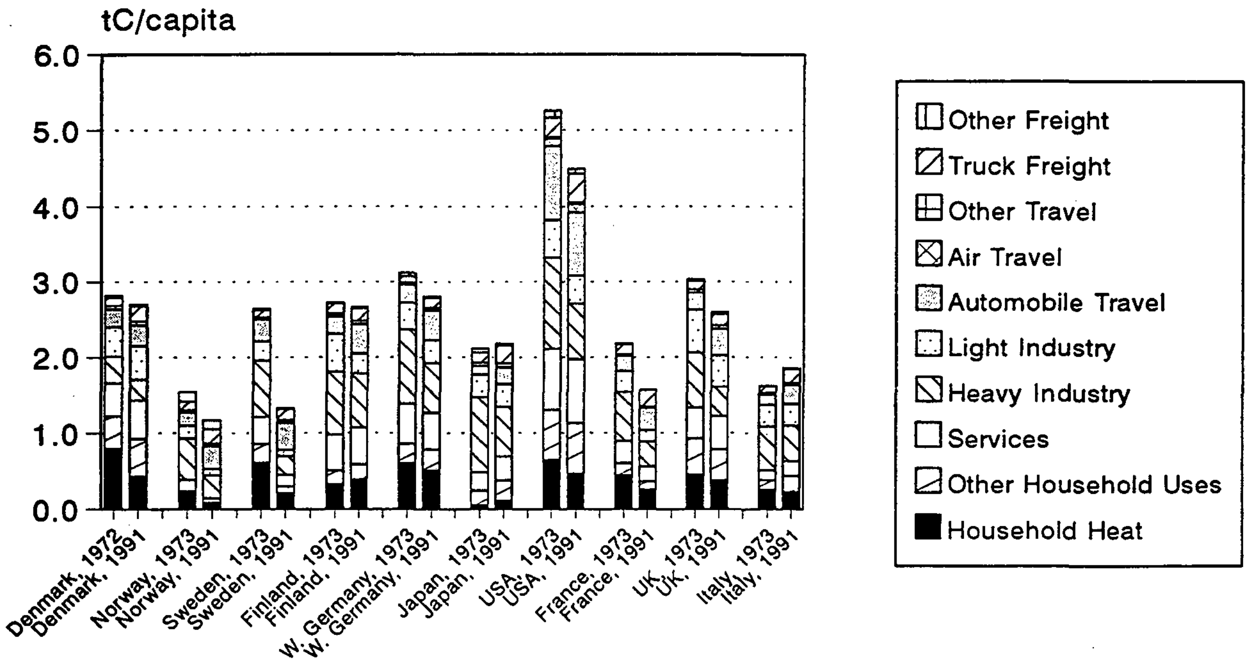

Figure 5.1

OECD-10 Carbon Emissions per GDP

1973 vs. 1991 by Major End Use

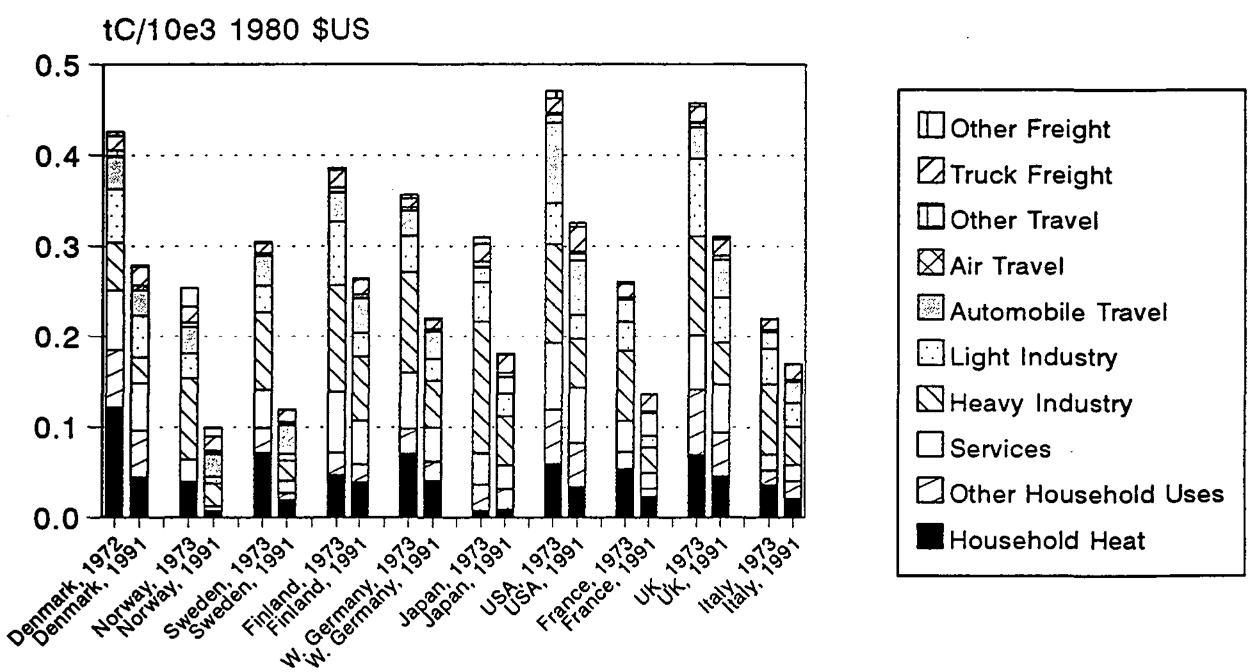

Figure 5.2

OECD-10 Manufacturing Energy Intensity

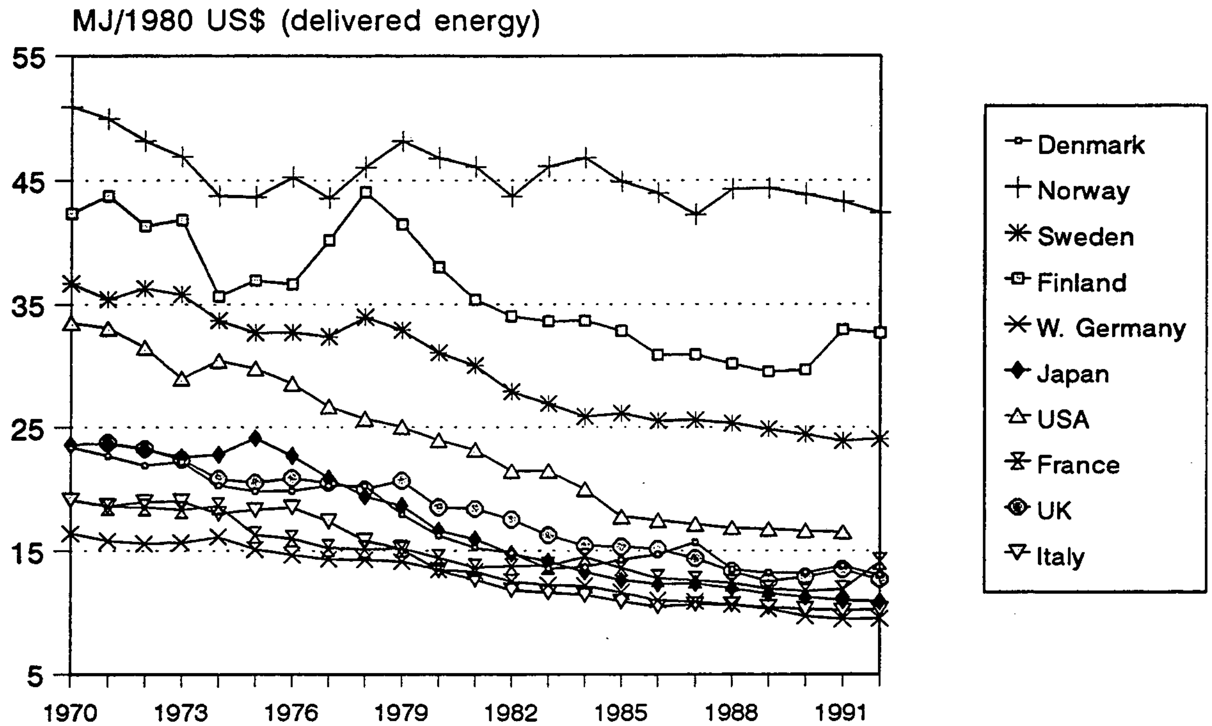

Figure 5.3

OECD-10 Household Space Heating Energy Intensity

Climate Corrected

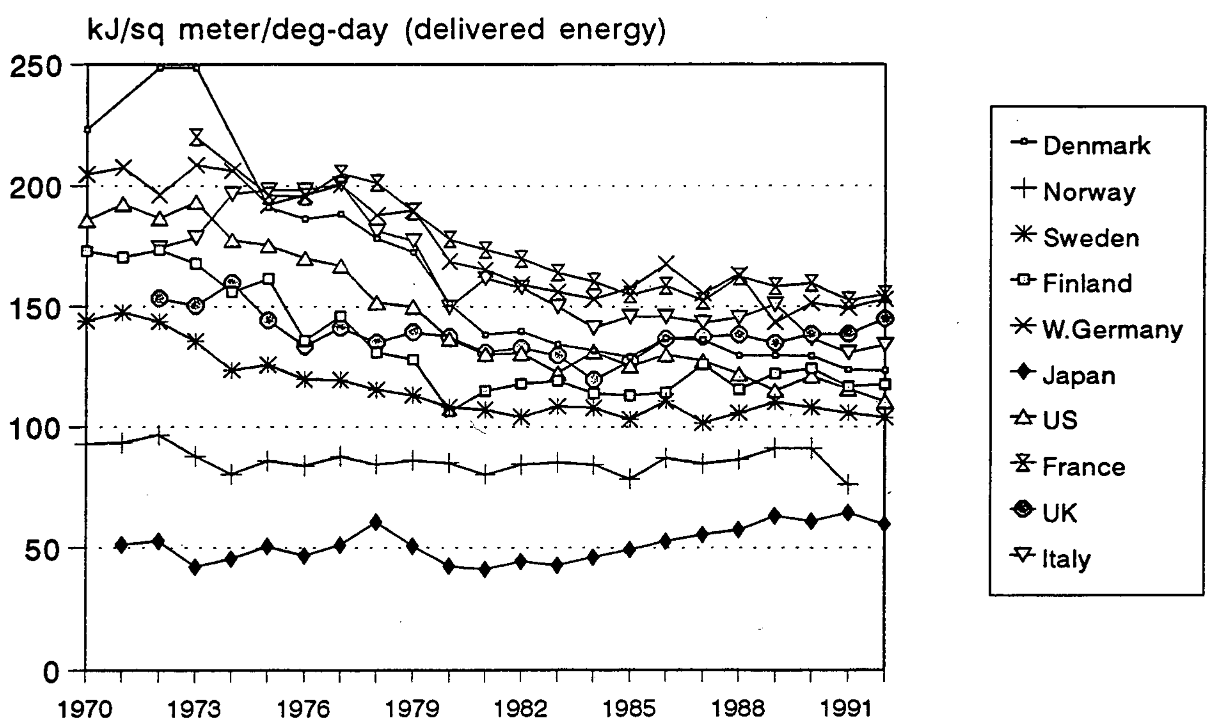

Figure 5.4

OECD-10 Service Sector Energy Intensity

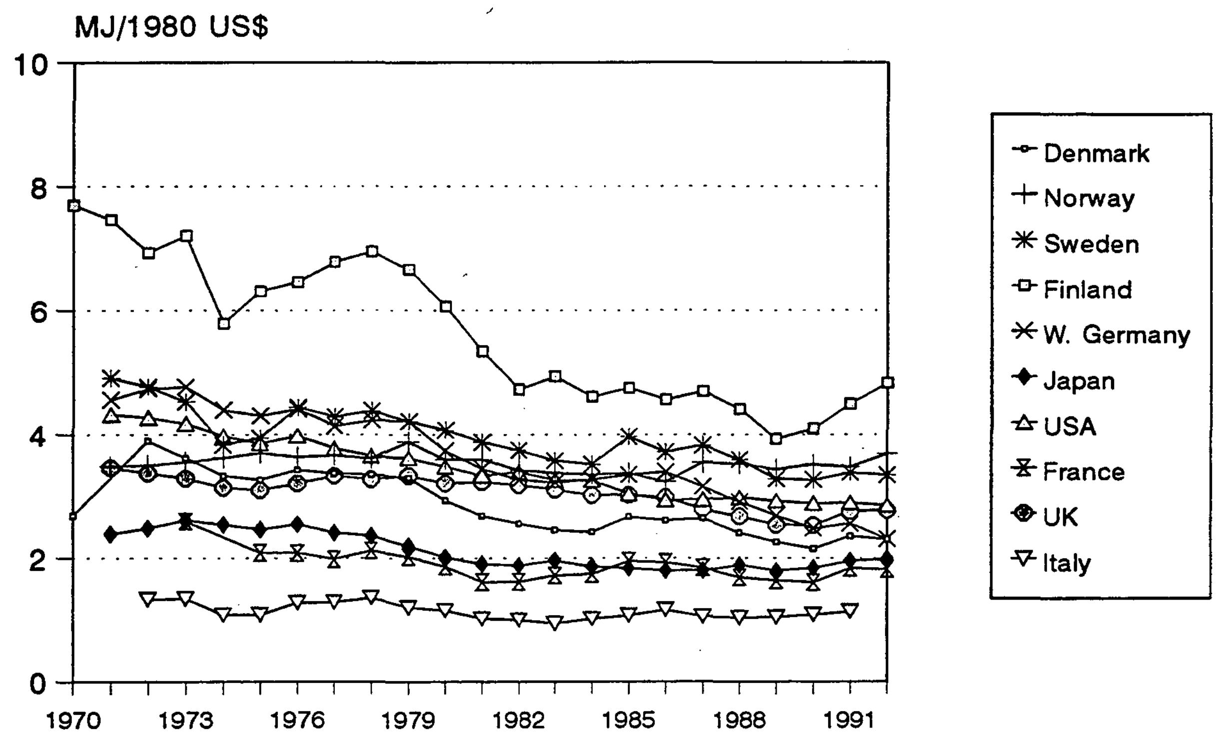

Figure 5.5

OECD-10 Travel Sector Energy Intensity

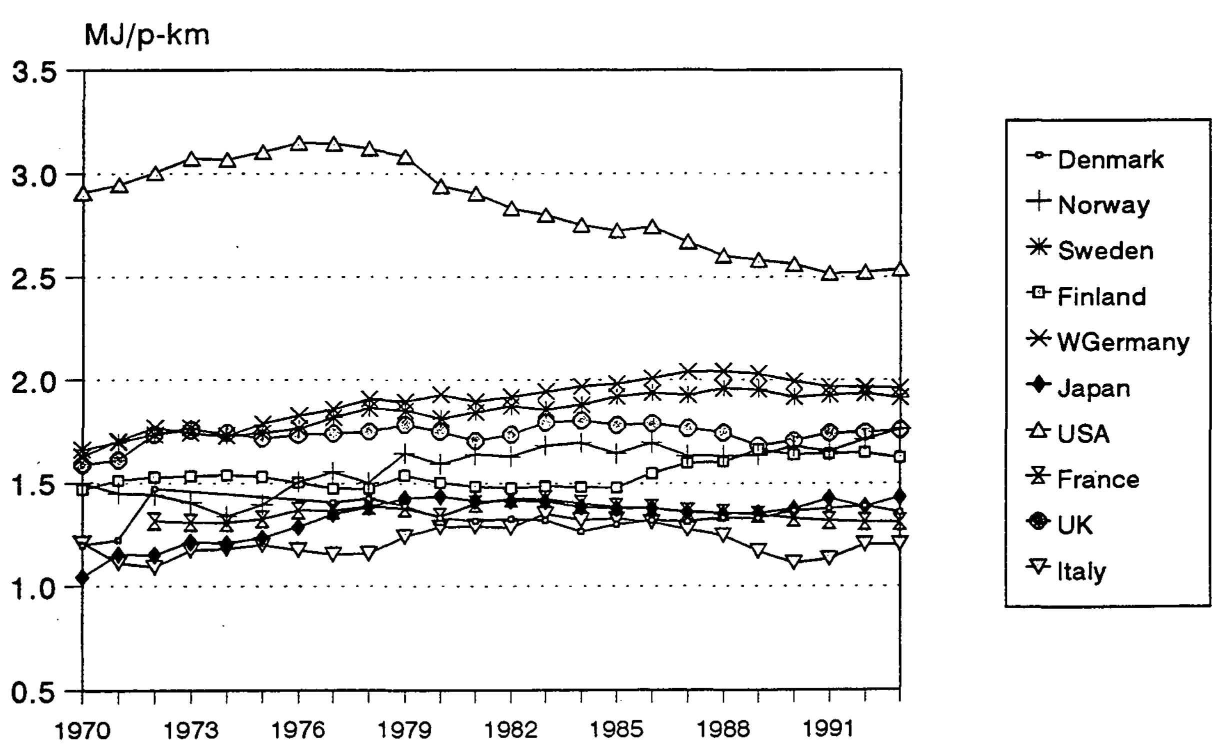

Figure 5.6

OECD-10 Truck Freight Energy Intensity

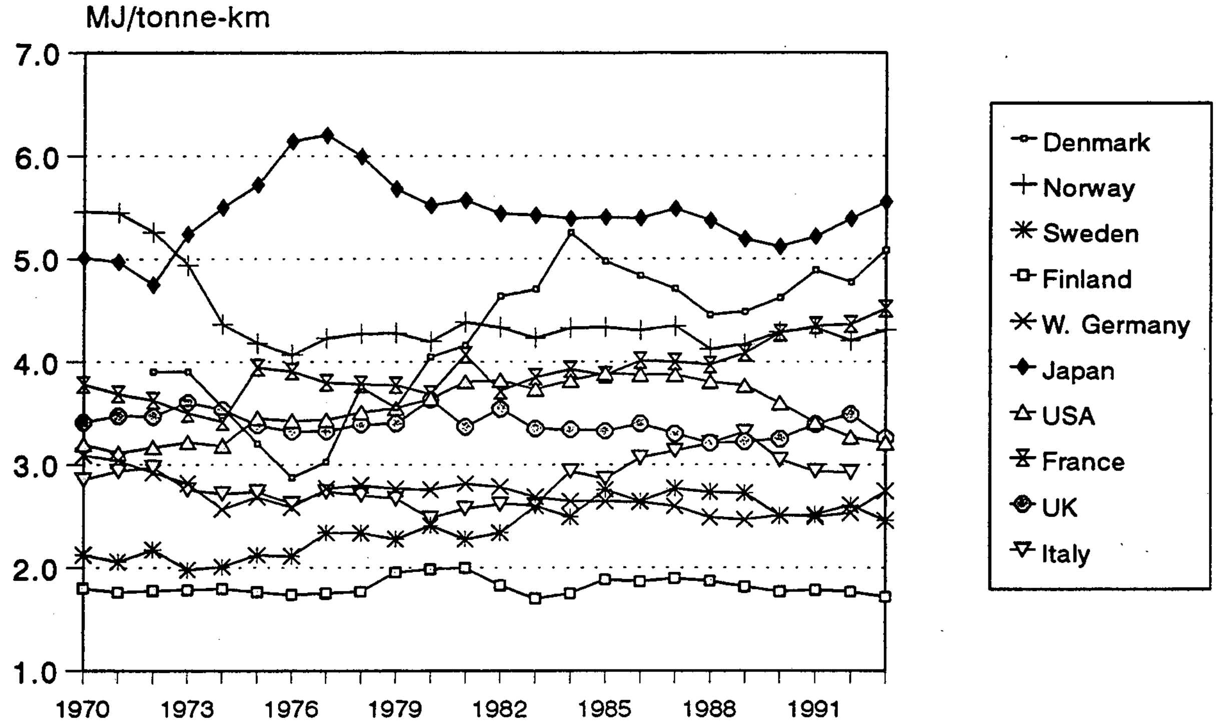

Figure 5.7

Changes in Carbon Emissions from the OECD-10
Three Measures

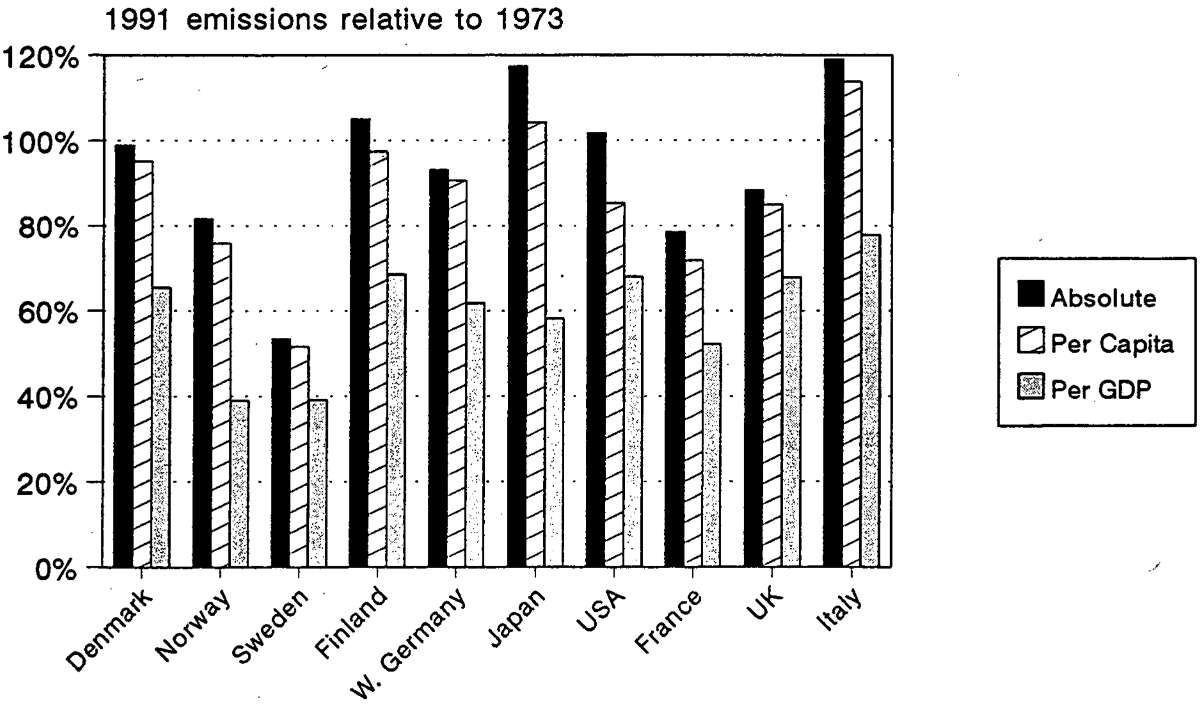

Figure 5.8

Results of Laspeyres Decomposition of Carbon Emissions from All Sectors
1970-1991 (1973=100%)

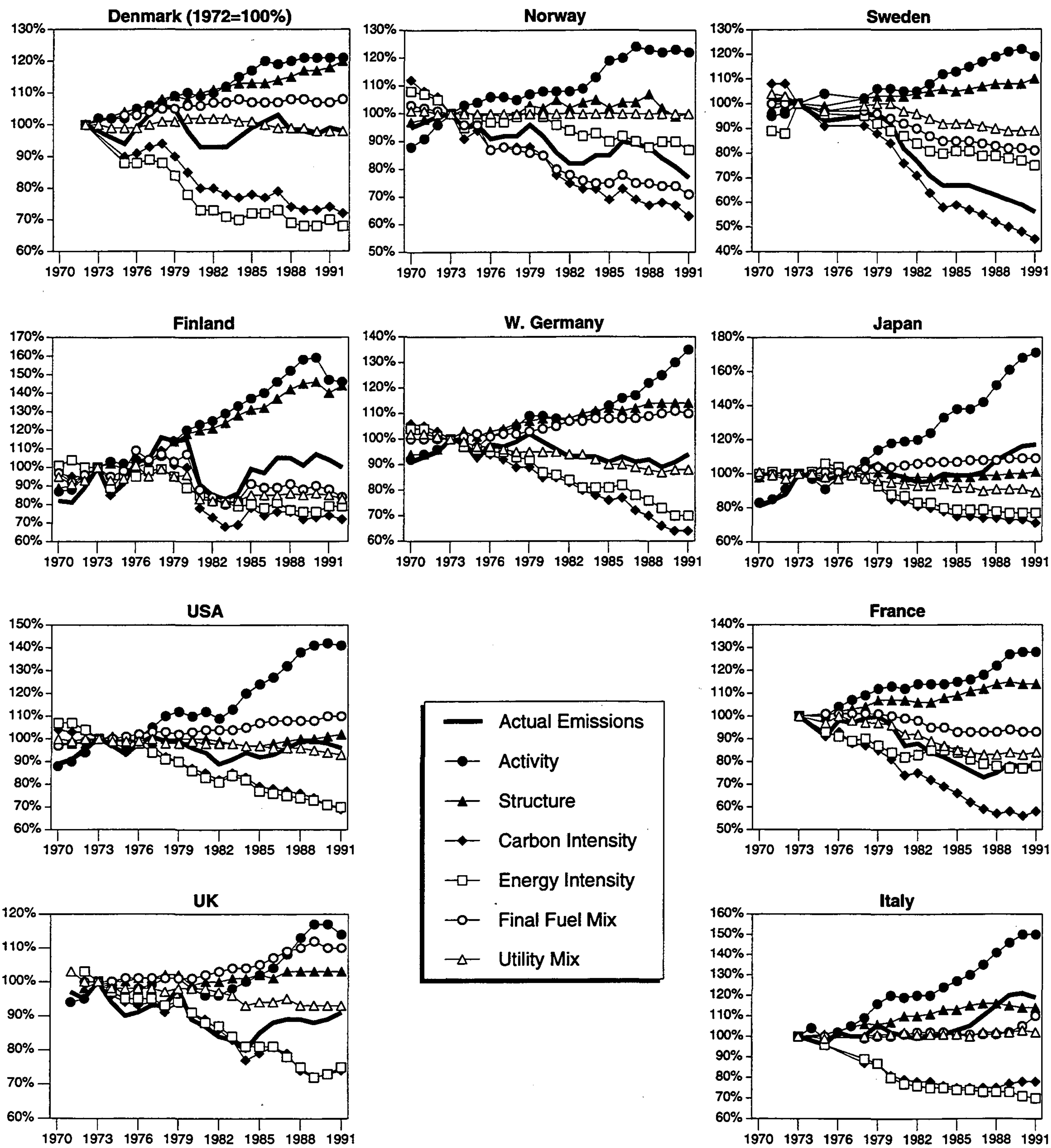

Figure 6.1

Results of Laspeyres Decomposition of Carbon Emissions from All Sectors
1973 vs. 1991 (1973=100%)

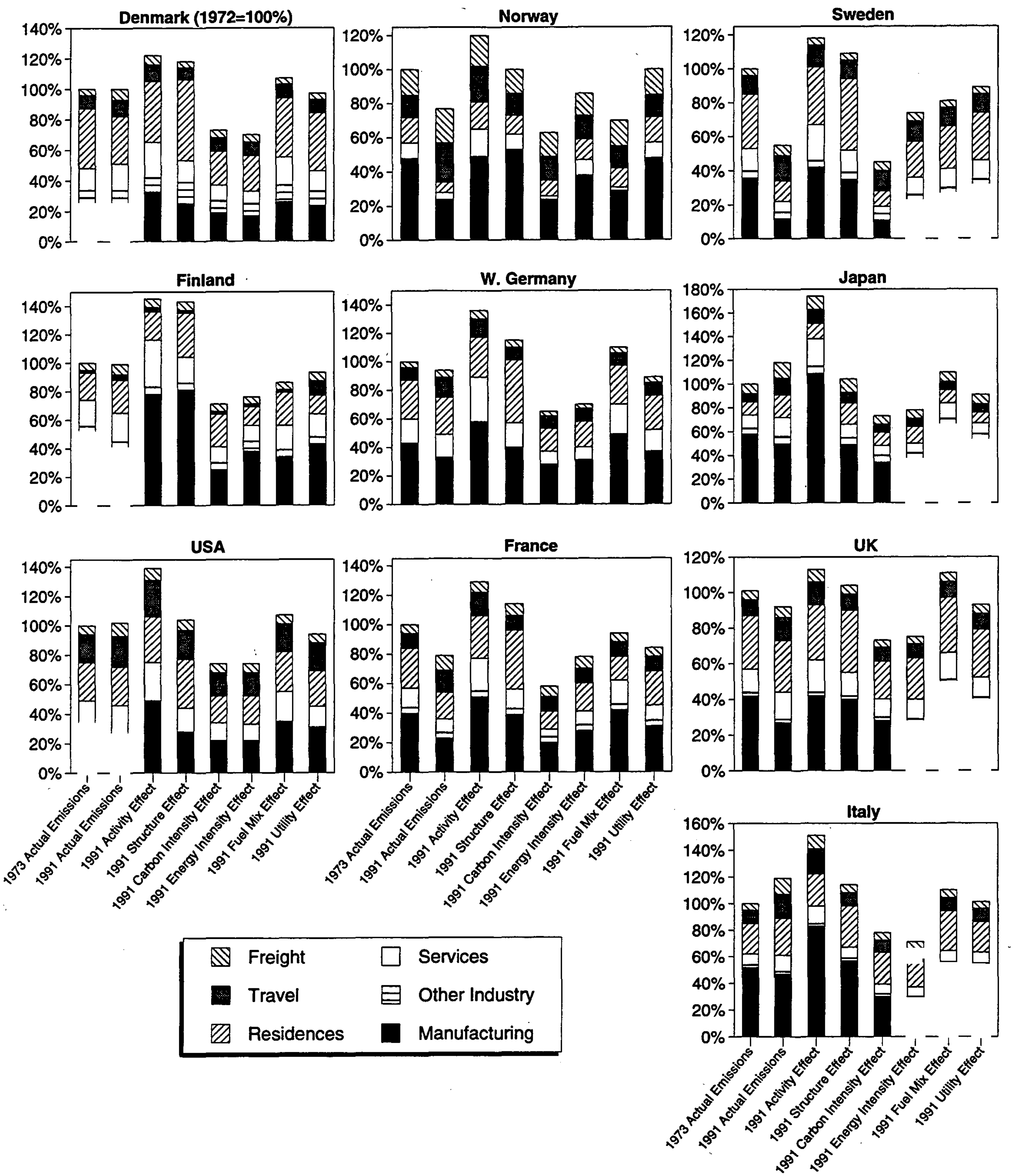

Figure 6.2

Results of Laspeyres Decomposition of Carbon Emissions from All Sectors

Activity Terms for the OECD-10

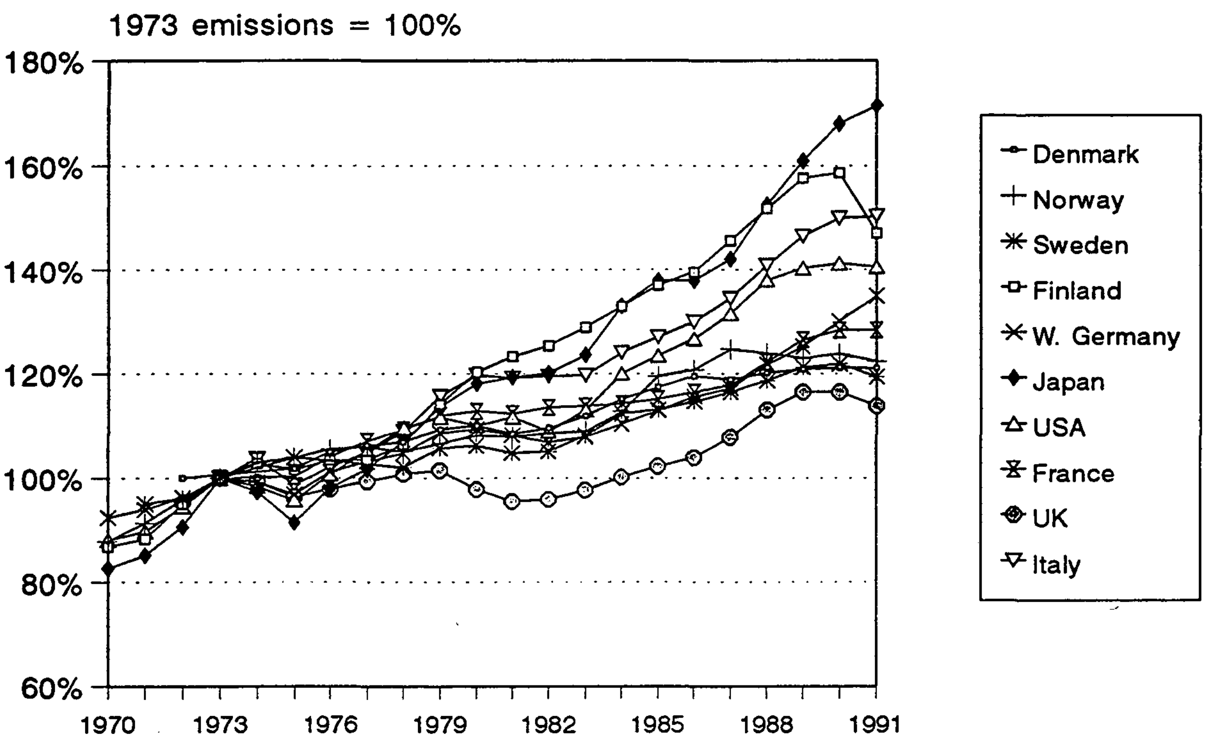

Figure 6.3

Results of Laspeyres Decomposition of Carbon Emissions from All Sectors

Structure Terms for the OECD-10

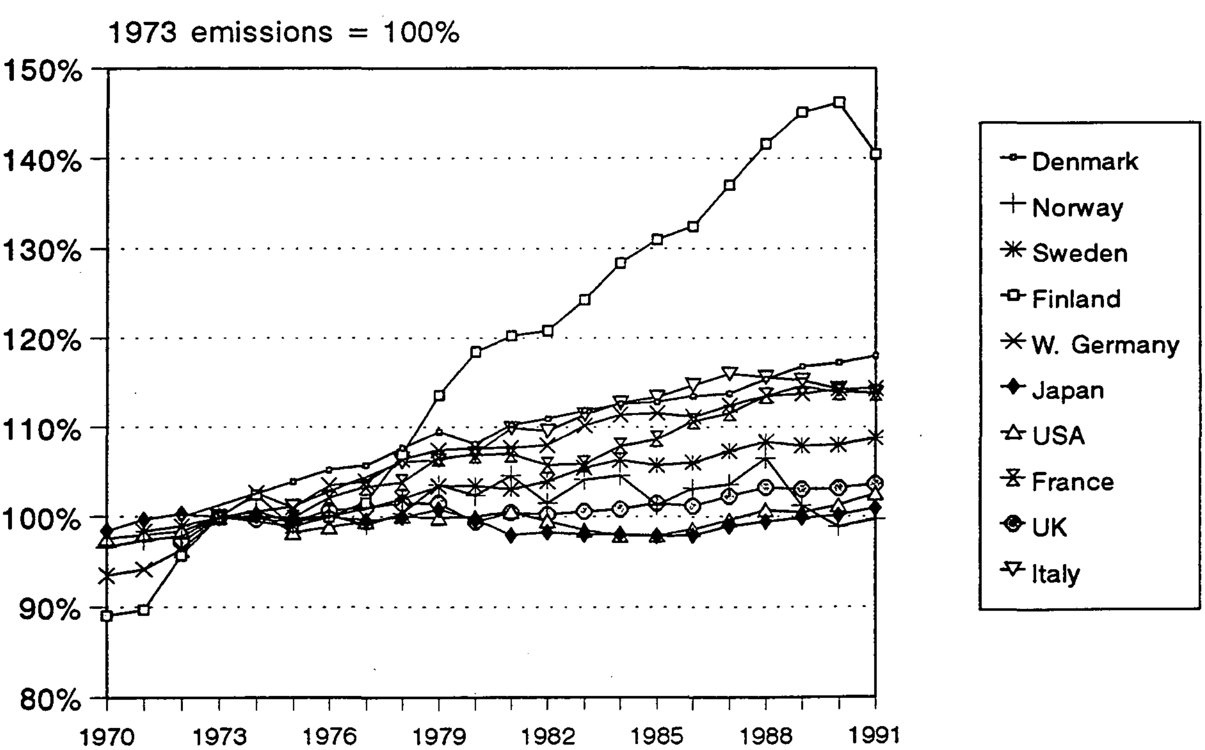

Figure 6.4

Results of Laspeyres Decomposition of Carbon Emissions from All Sectors

Energy Intensity Terms for the OECD-10

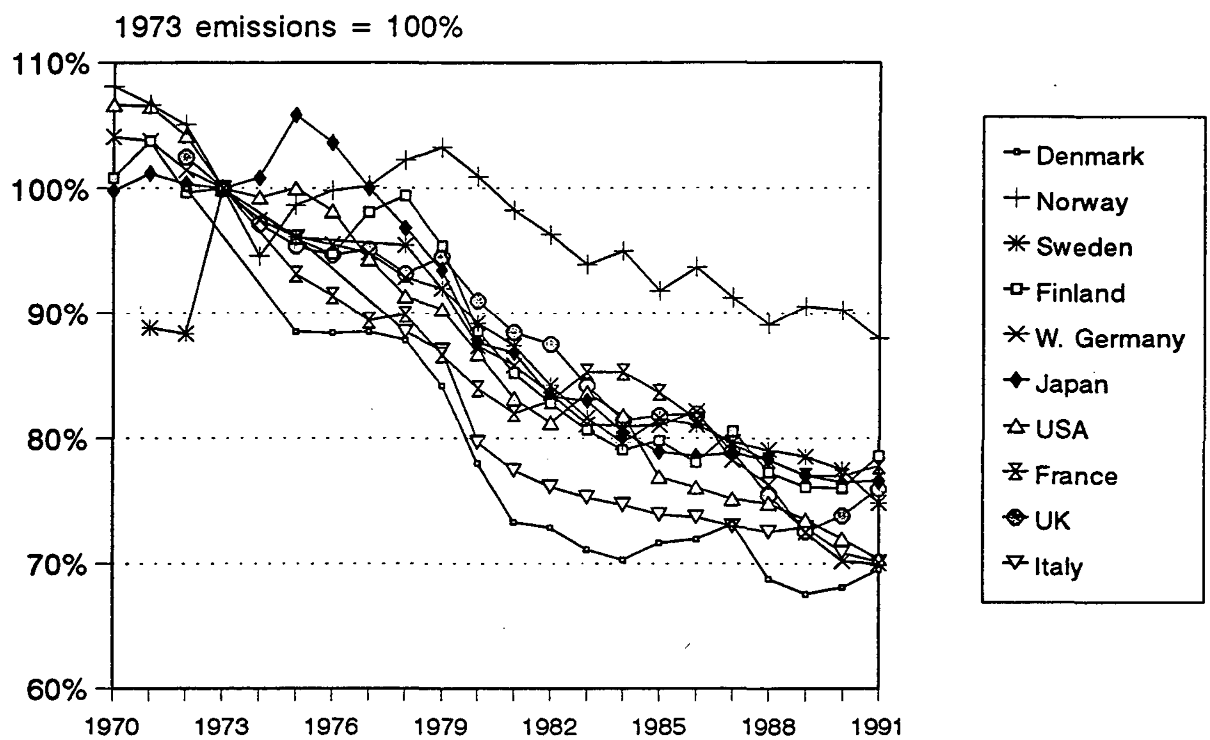

Figure 6.5

Results of Laspeyres Decomposition of Carbon Emissions from All Sectors

Final Fuel Mix Terms for the OECD-10

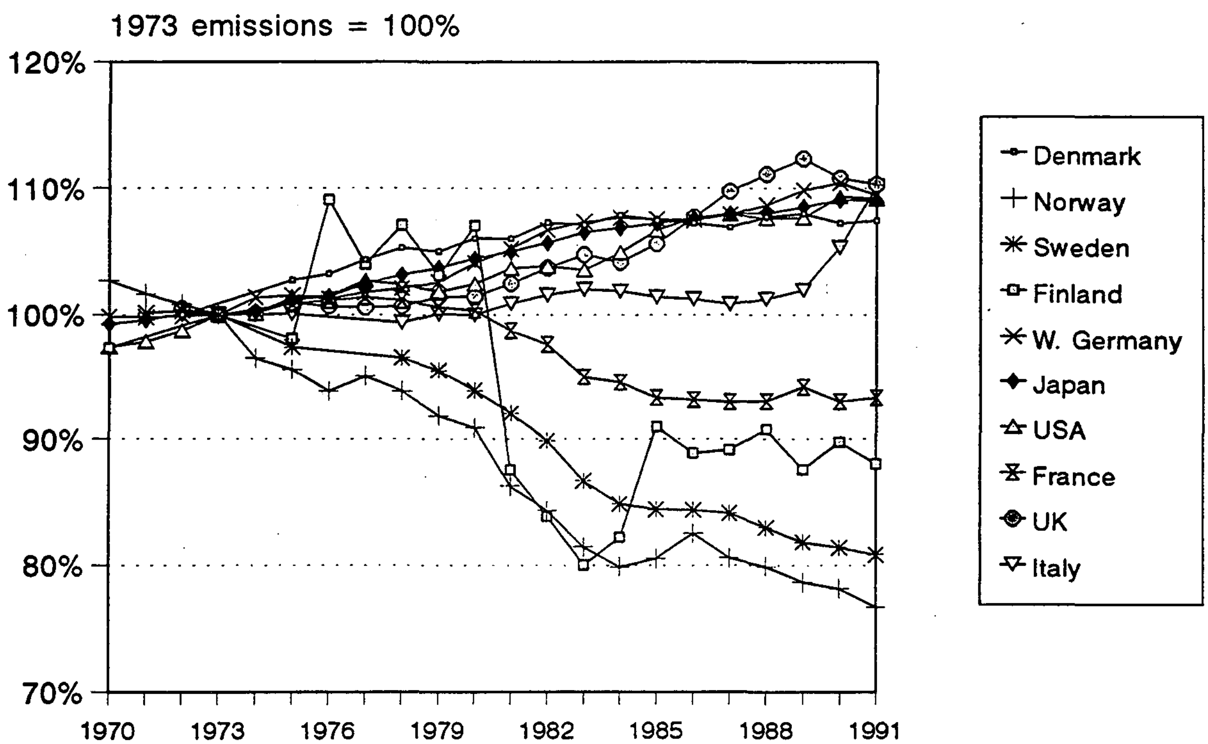

Figure 6.6

Results of Laspeyres Decomposition of Carbon Emissions from All Sectors

Utility Mix Terms for the OECD-10

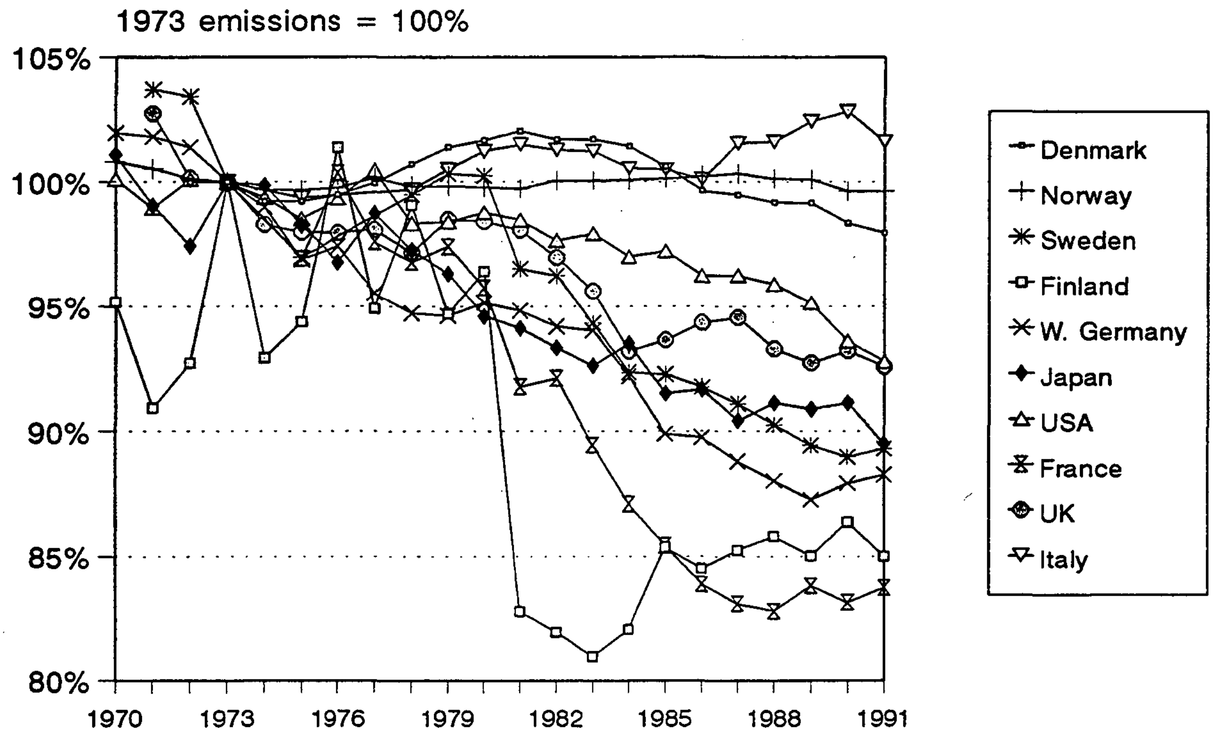

Figure 6.7

Results of Laspeyres Decomposition of Carbon Emissions from All Sectors

Carbon Intensity Terms for the OECD-10

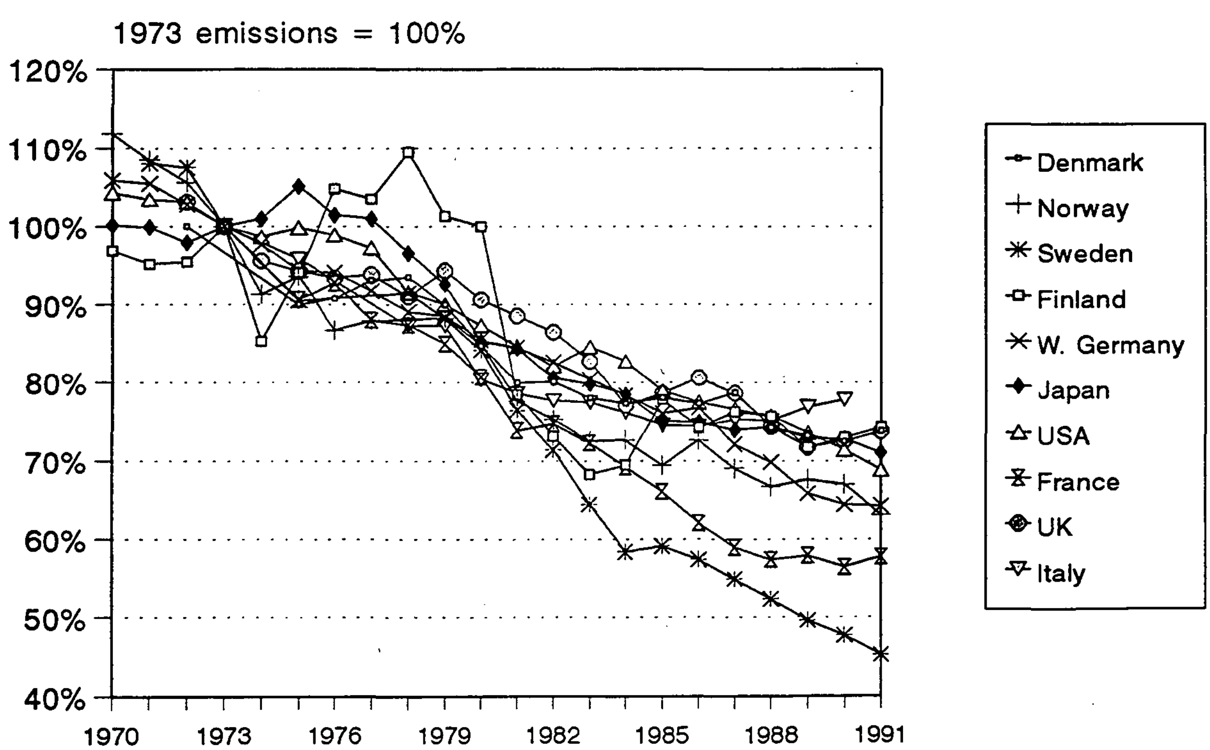

Figure 6.8

Shares of OECD-10 Carbon Emissions

1973 and 1991, by Major End Use

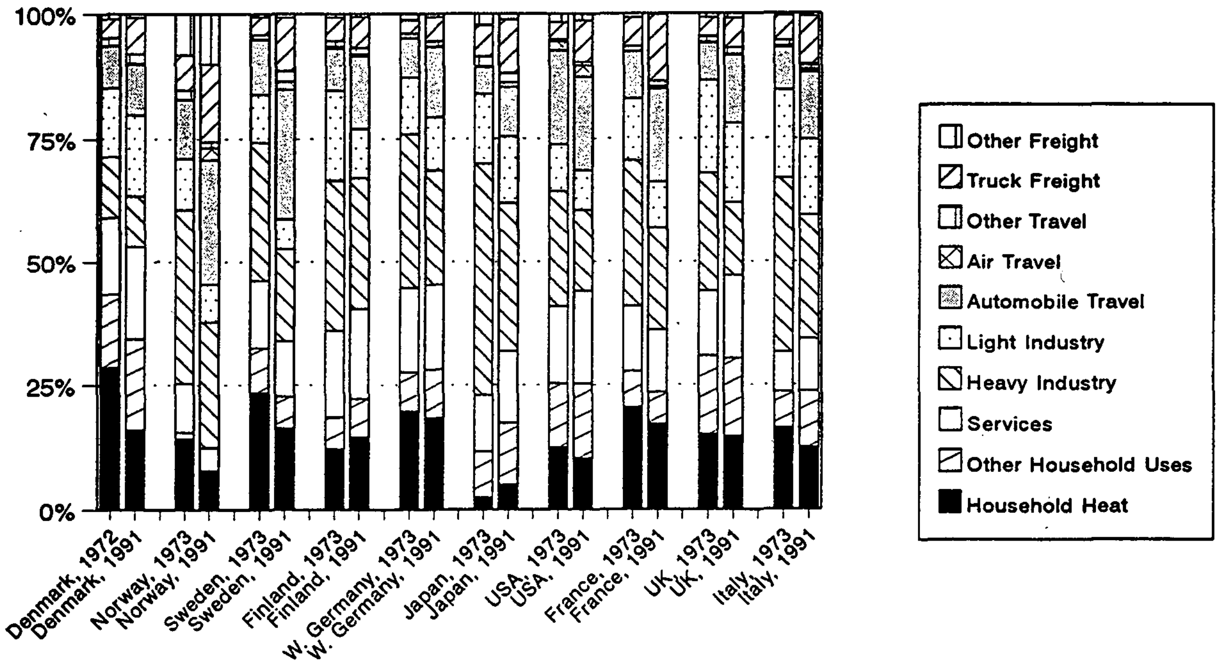

Figure 7.1

OECD-10 Carbon Emissions per Capita from Manufacturing

1973 vs. 1991 by Subsector

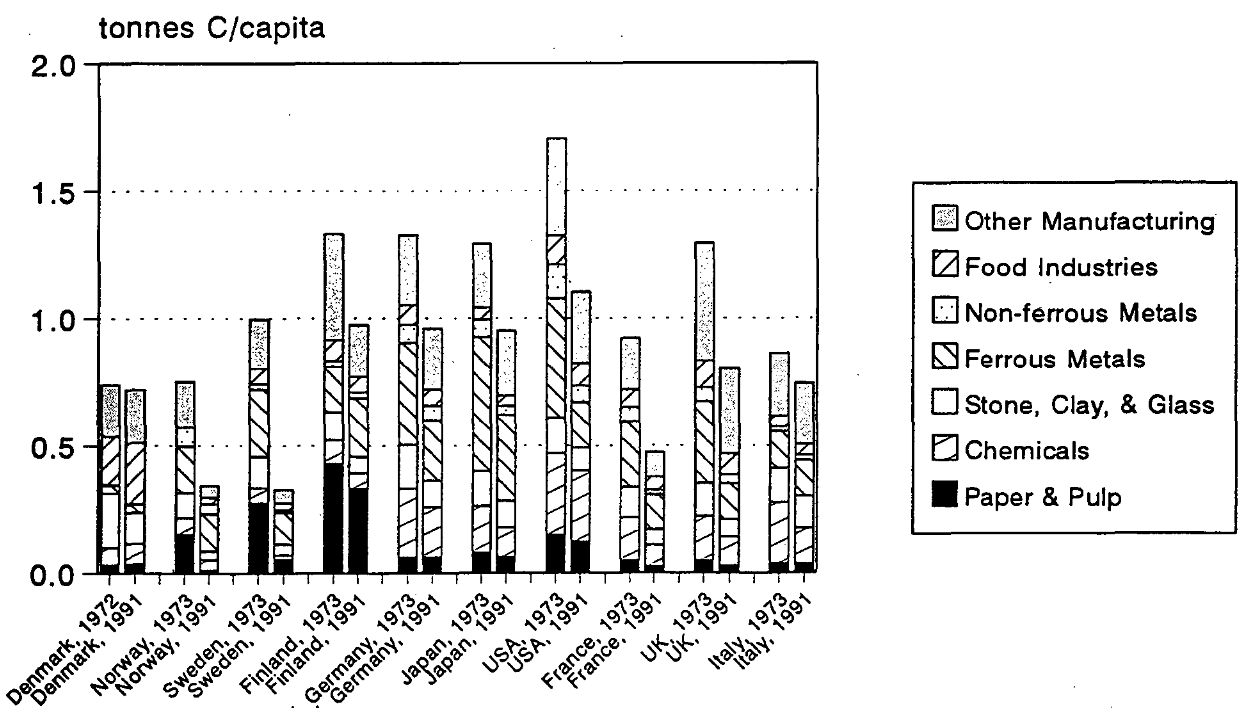

Figure 7.2

OECD-10 Manufacturing Carbon Intensity

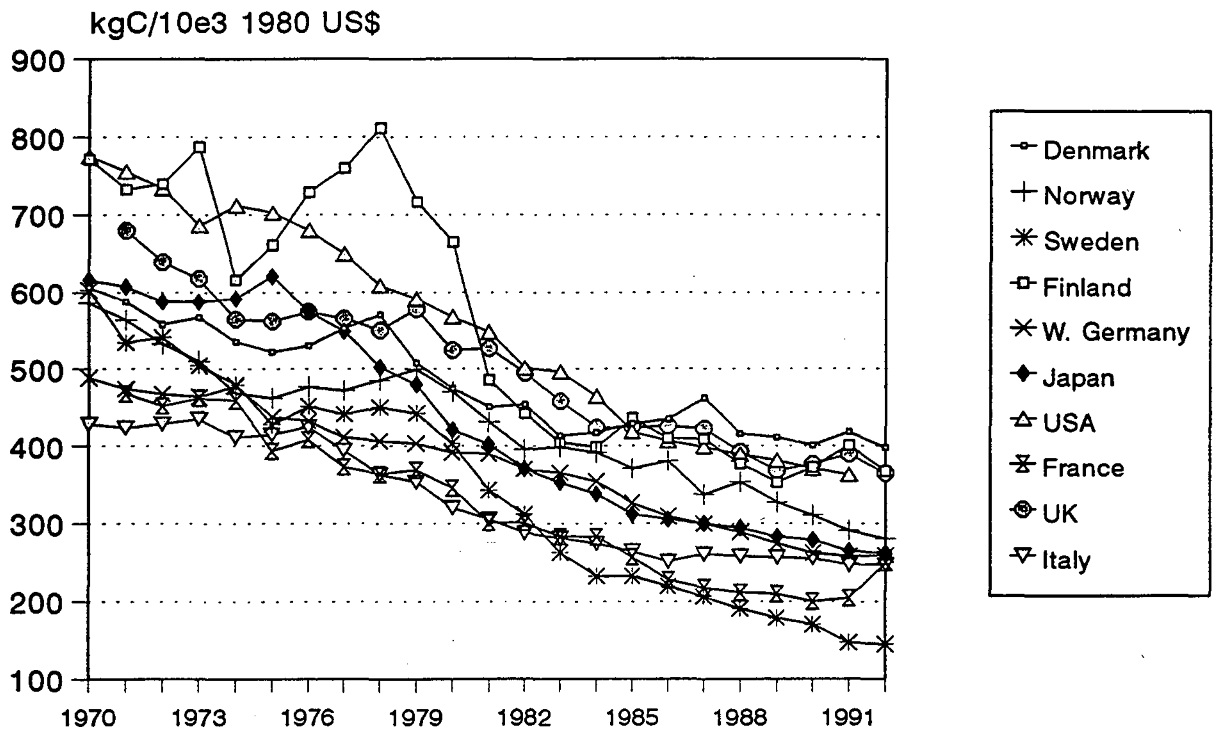

Figure 7.3

OECD-10 Manufacturing Carbon Emissions per Capita

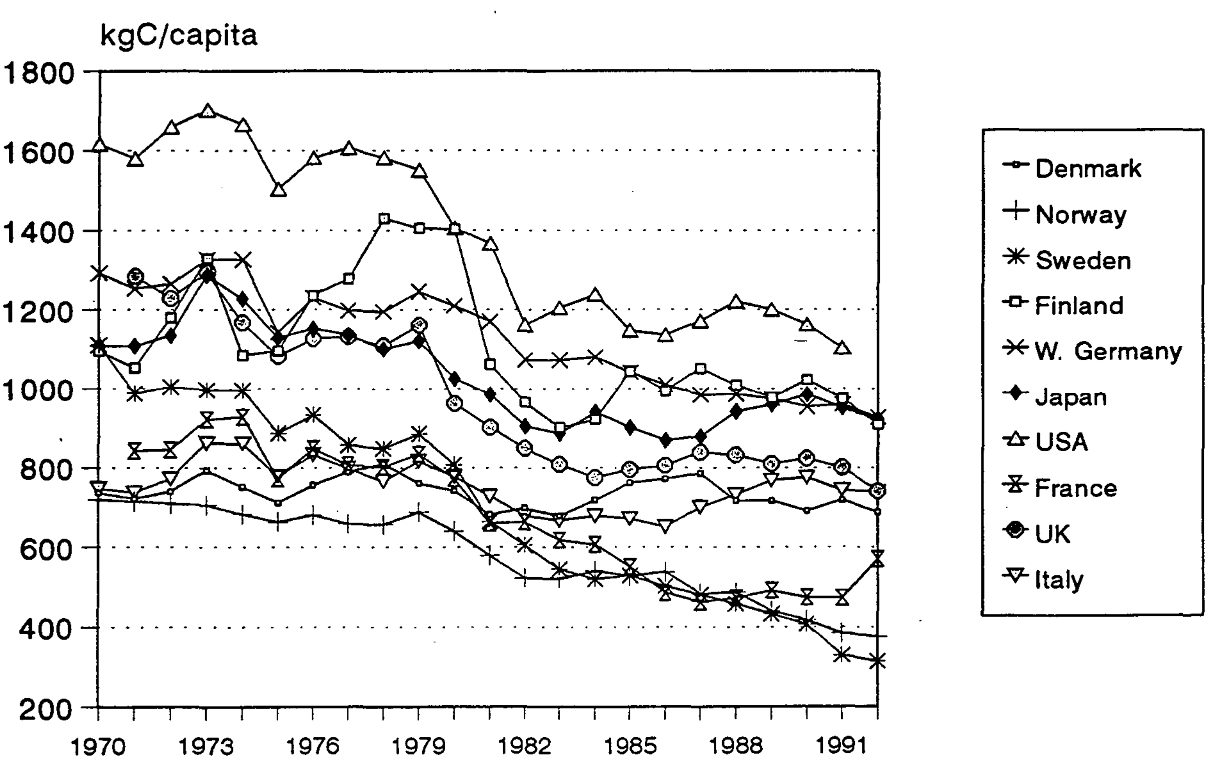

Figure 7.4

Sectoral Results of Laspeyres Decomposition
1991 Manufacturing Carbon Emissions

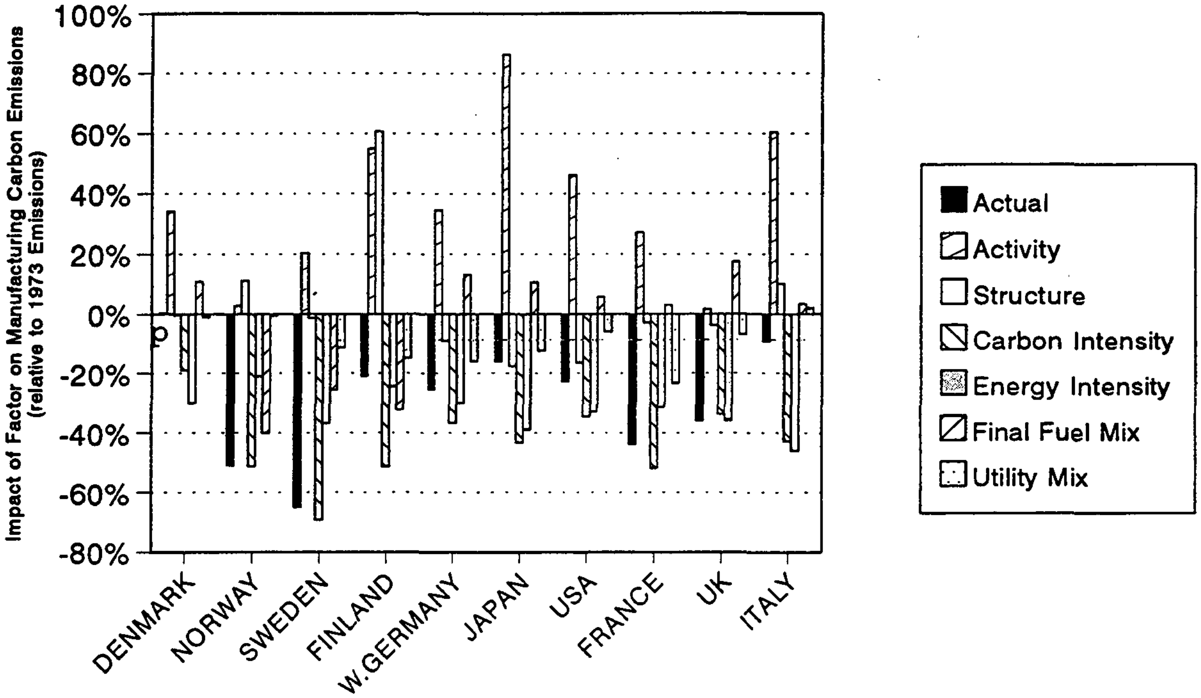

Figure 7.5

OECD-10 Residential Carbon Emissions per Capita
1973 vs. 1991 by End Use

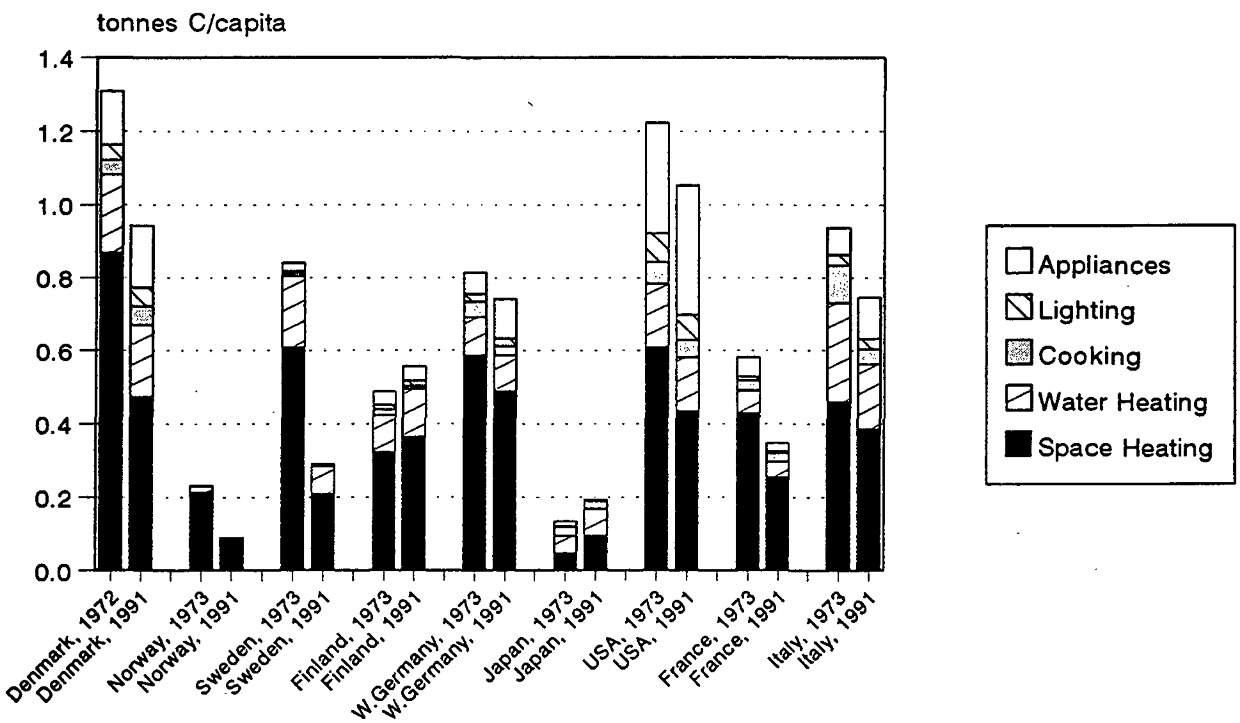

Figure 7.6

Carbon Emissions per Unit Residential Space Heating Primary Energy

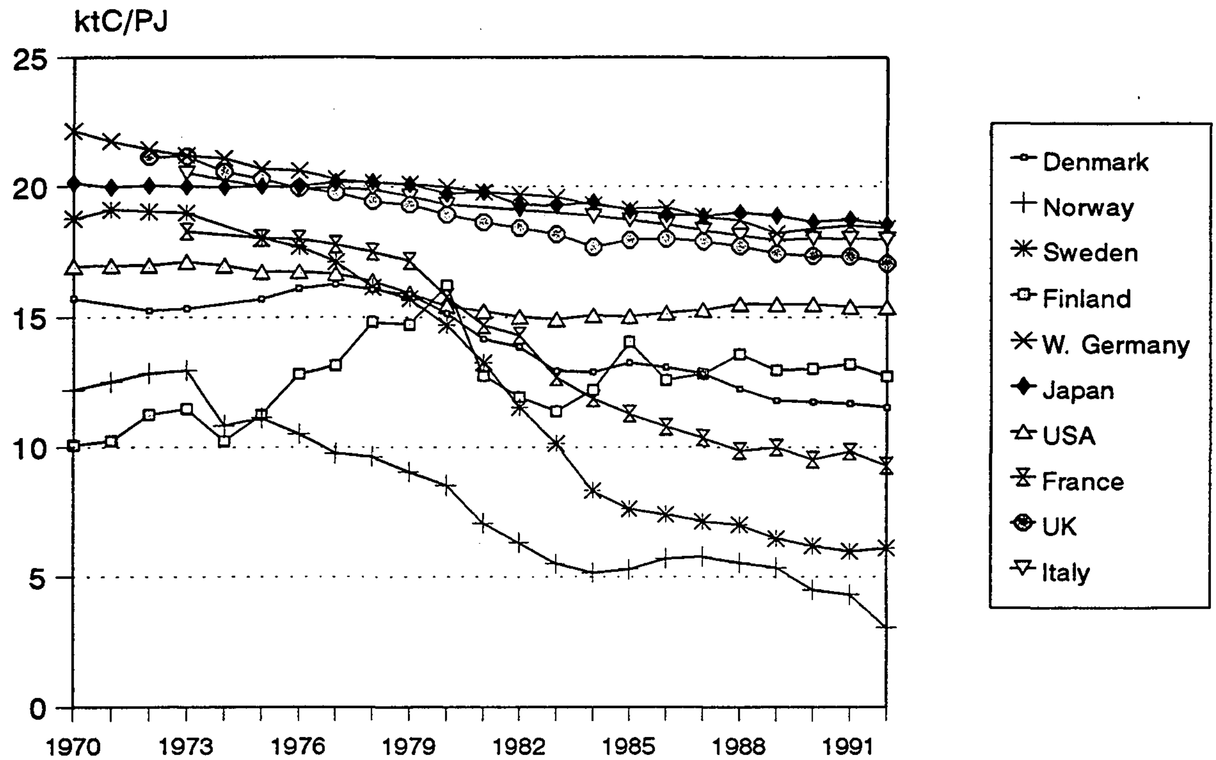

Figure 7.7

OECD-10 Residential Space Heating Carbon Intensity

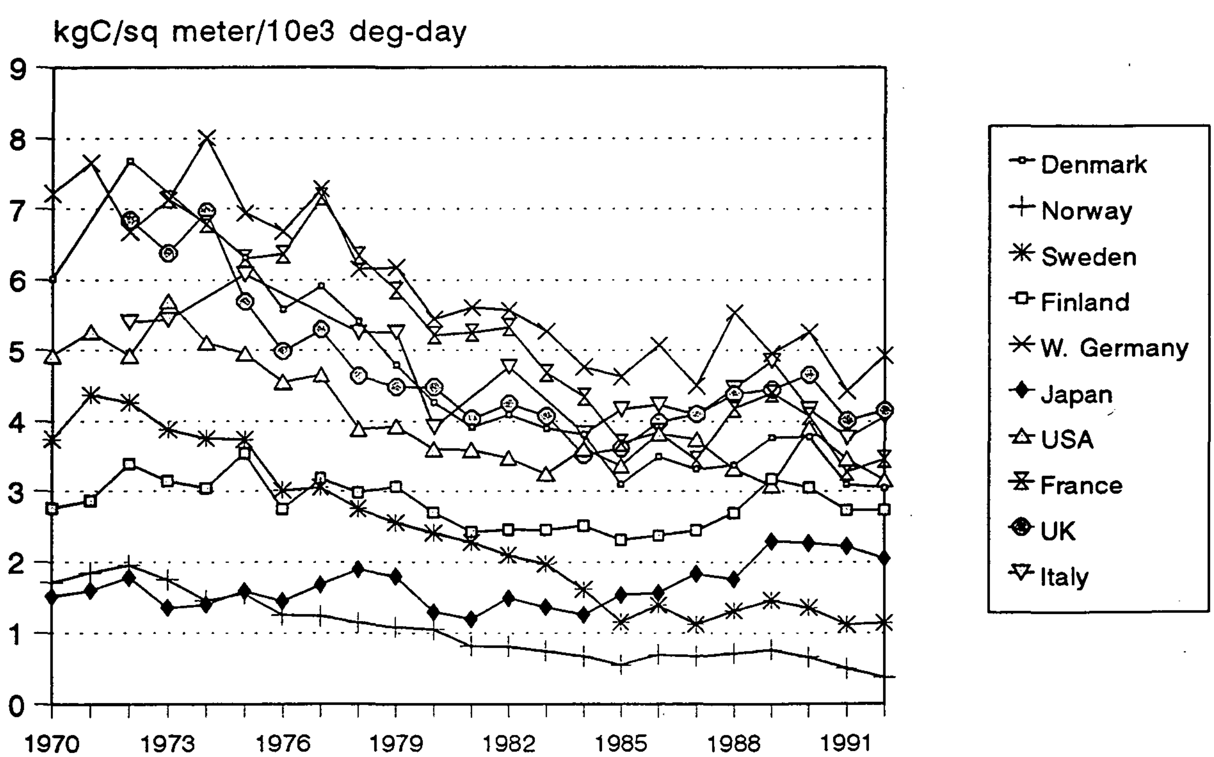

Figure 7.8

Sectoral Results of Laspeyres Decomposition

1991 Residential Carbon Emissions

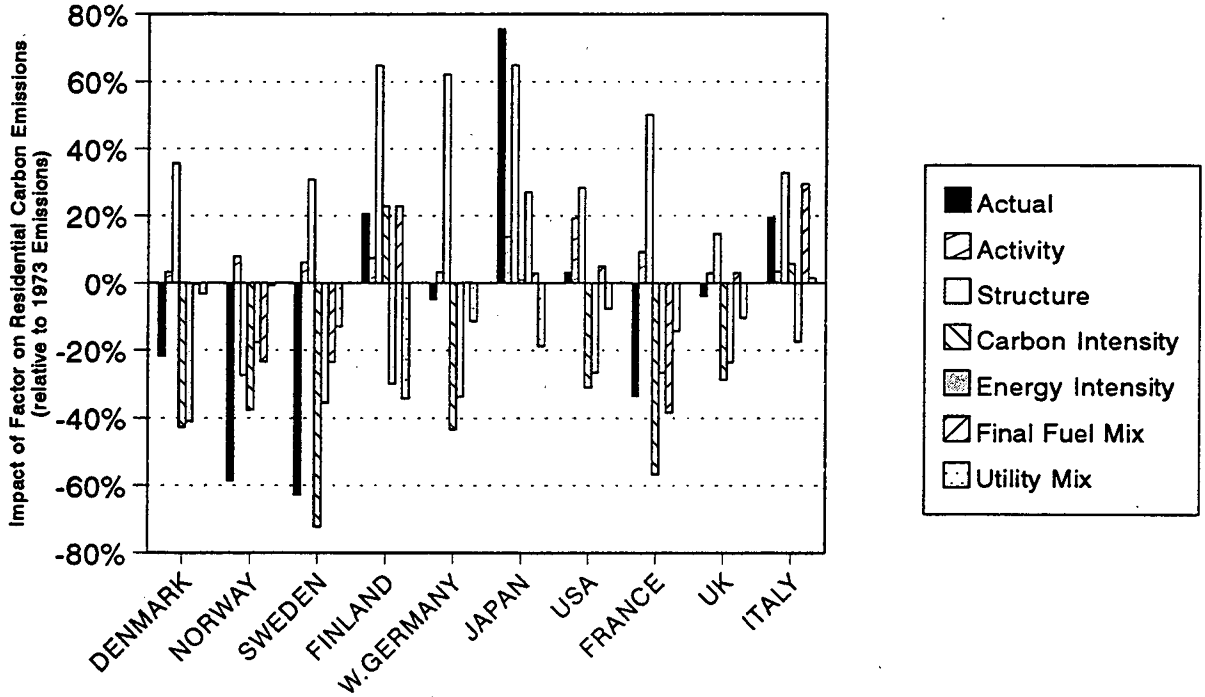

Figure 7.9

OECD-10 Services Carbon Intensity

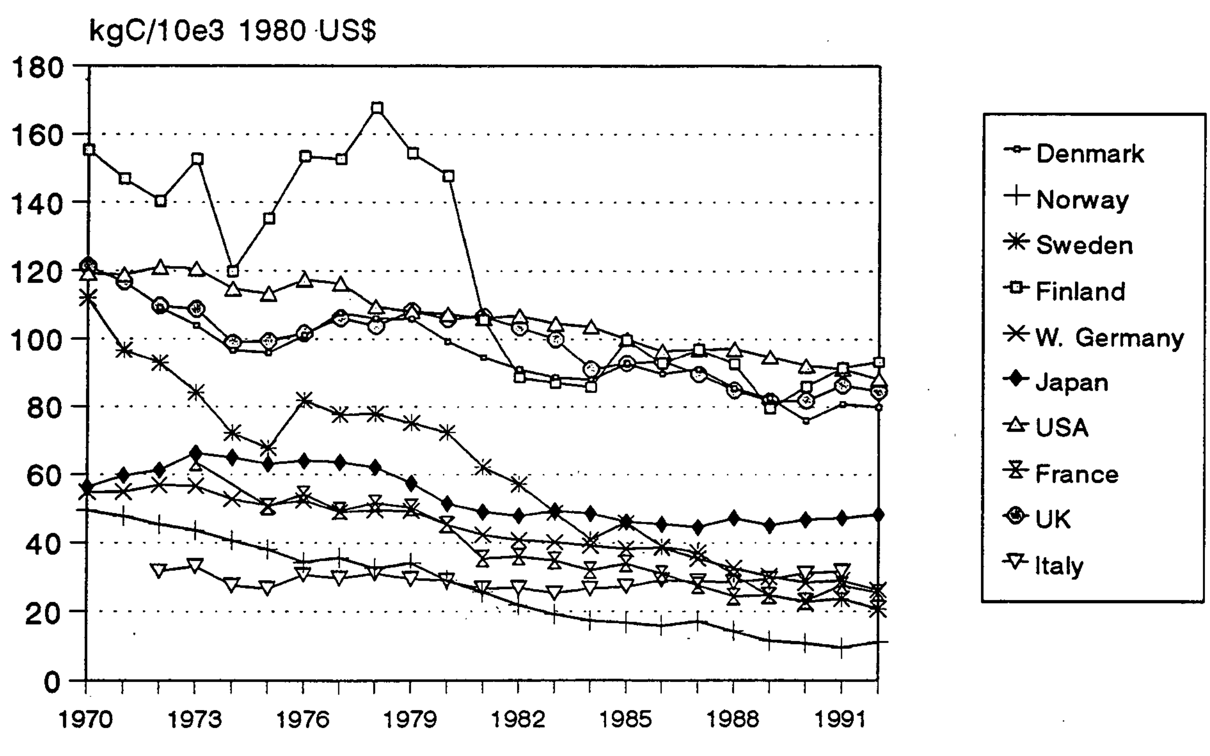

Figure 7.10

OECD-10 Services Carbon Emissions per Capita

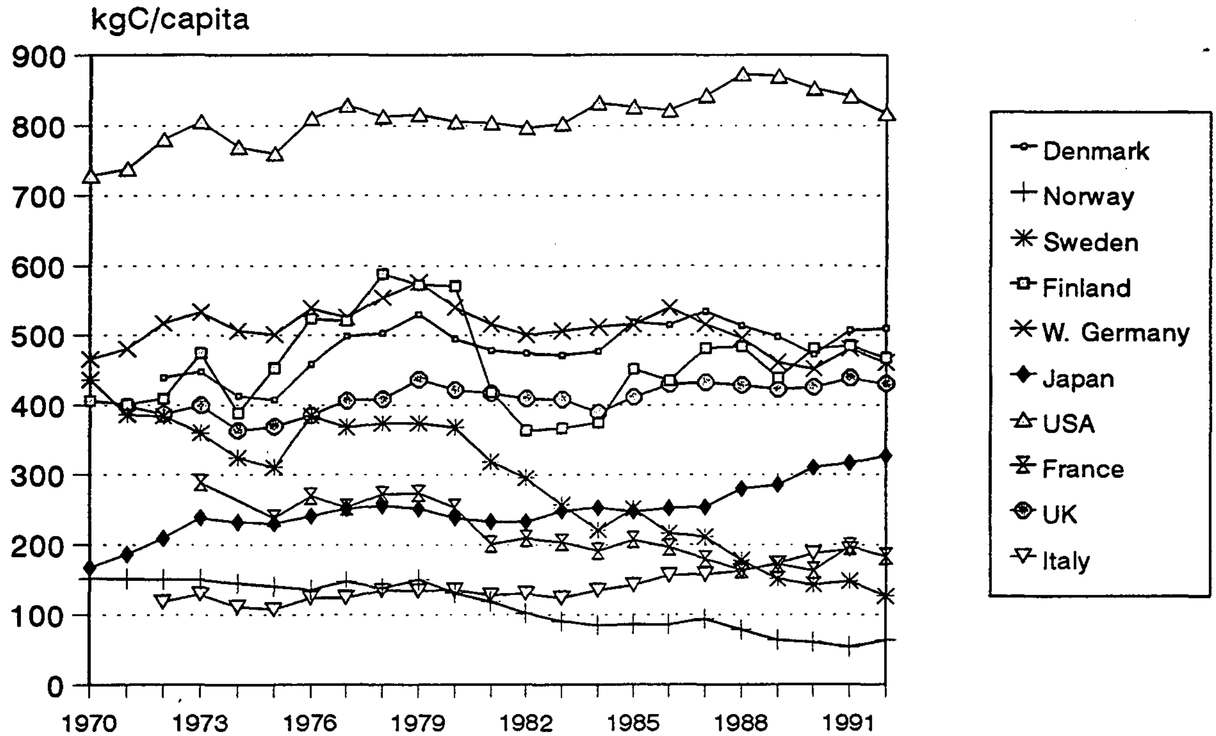

Figure 7.11

OECD-10 Travel Carbon Emissions per Capita

1973 vs. 1992 by Mode

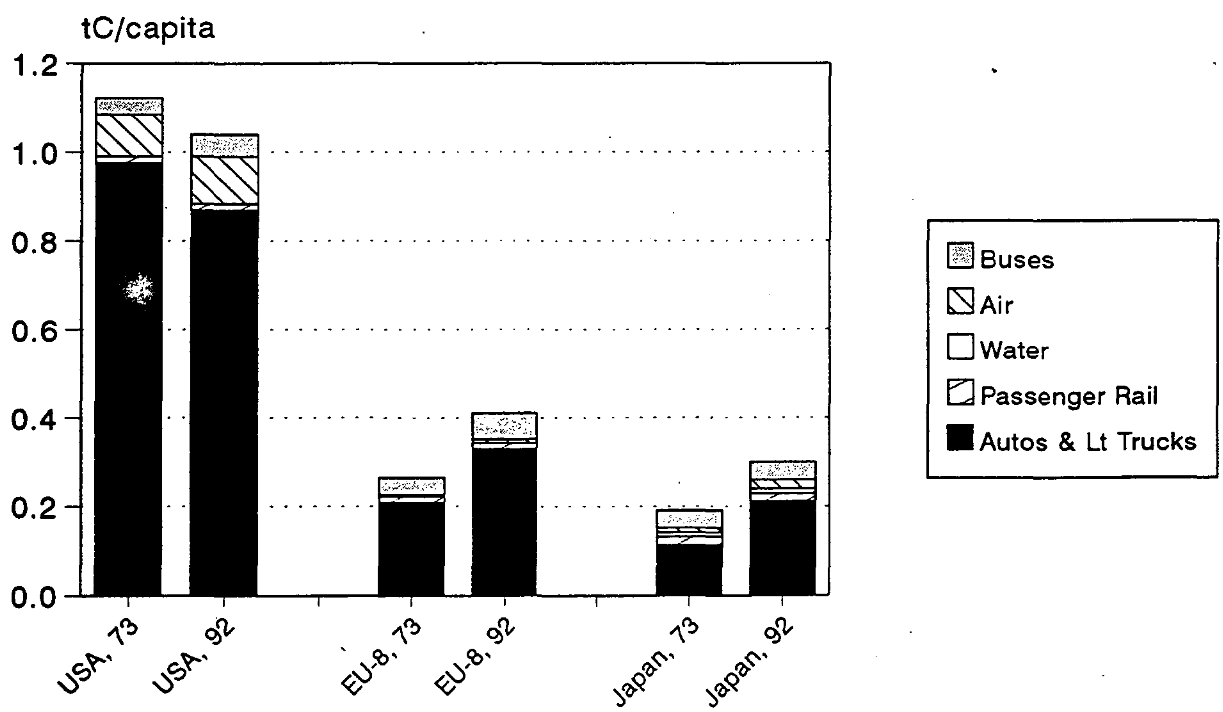

Figure 7.12

OECD-10 Travel Carbon Emissions per Capita

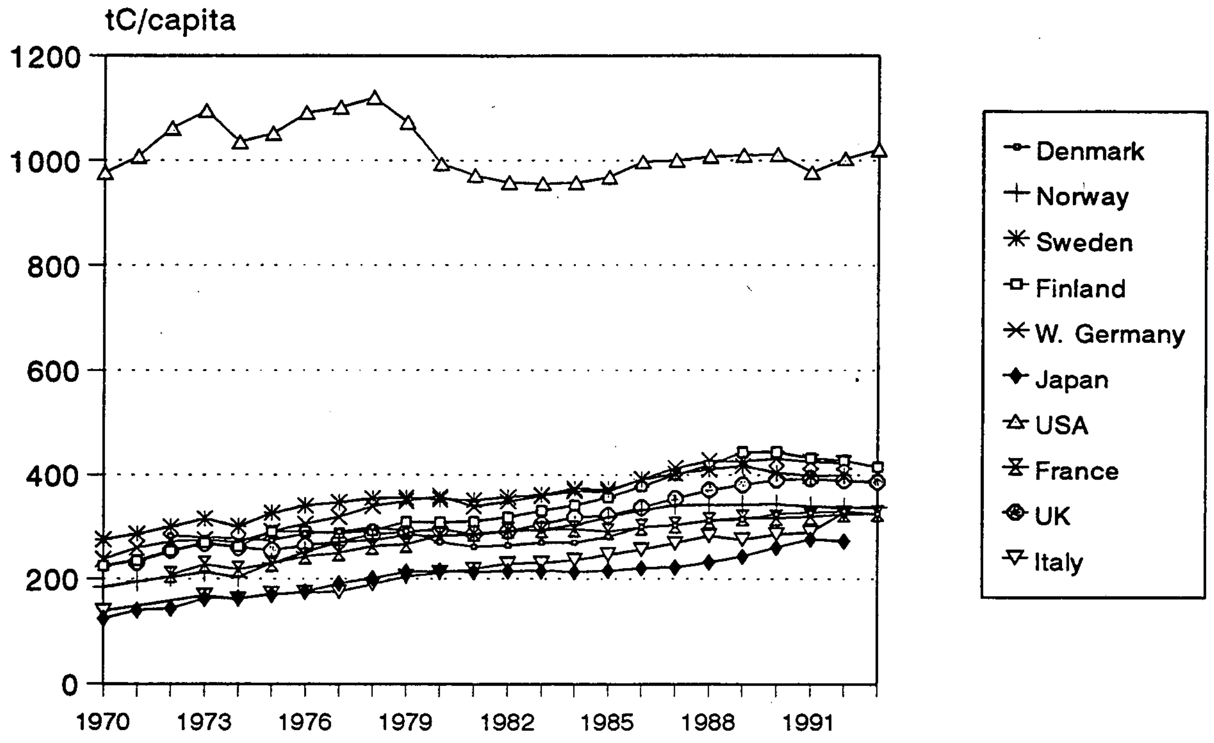

Figure 7.13

OECD-10 Travel Carbon Intensity

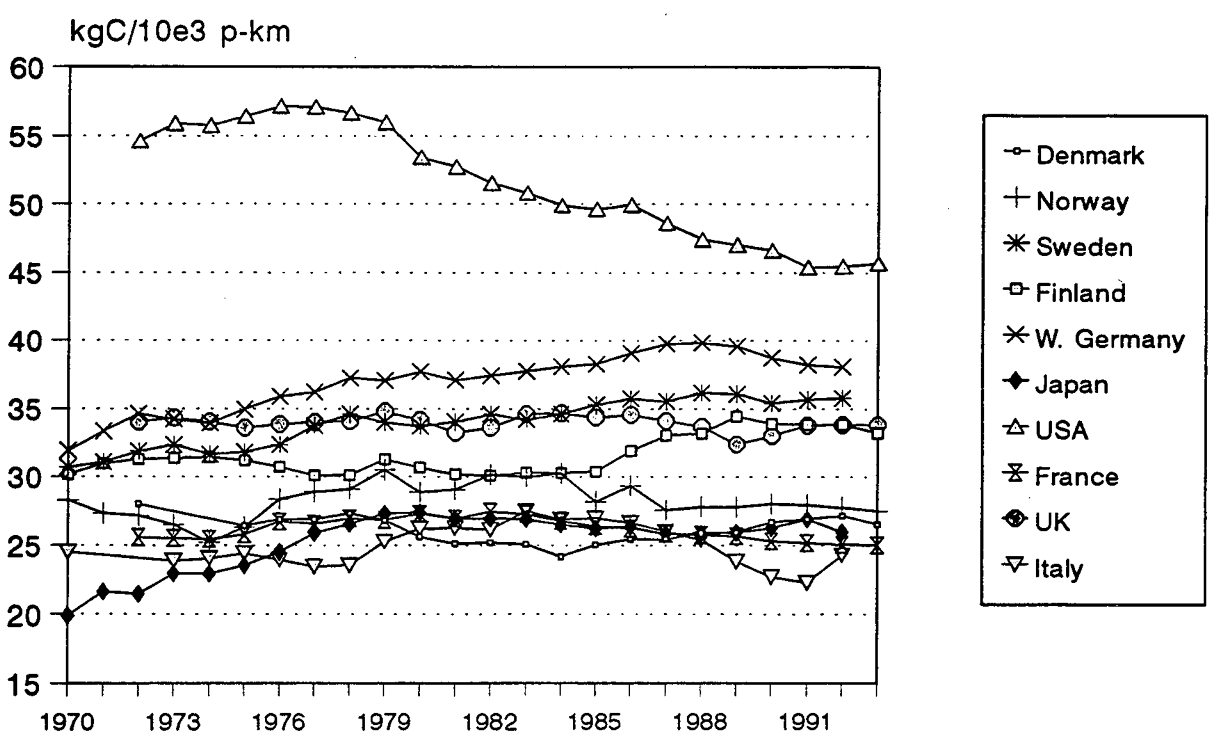

Figure 7.14

Sectoral Results of Laspeyres Decomposition

1991 Travel Carbon Emissions

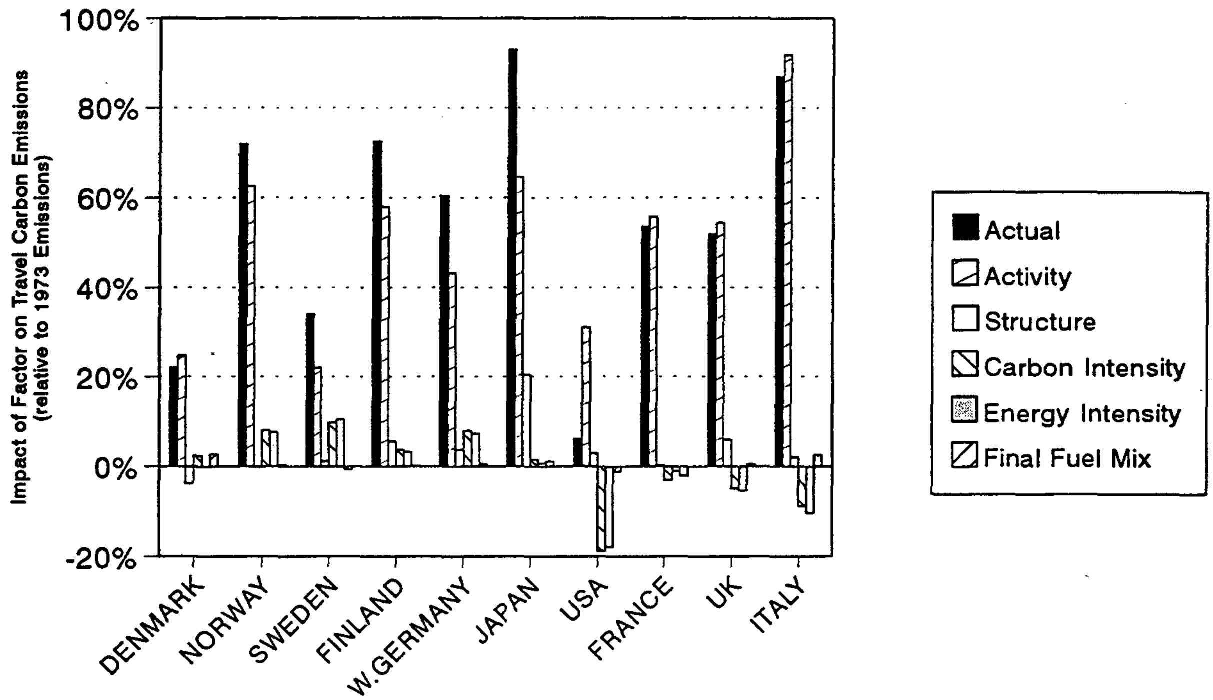

Figure 7.15

OECD-10 Freight Carbon Emissions per Capita

1973 vs. 1992 by Mode

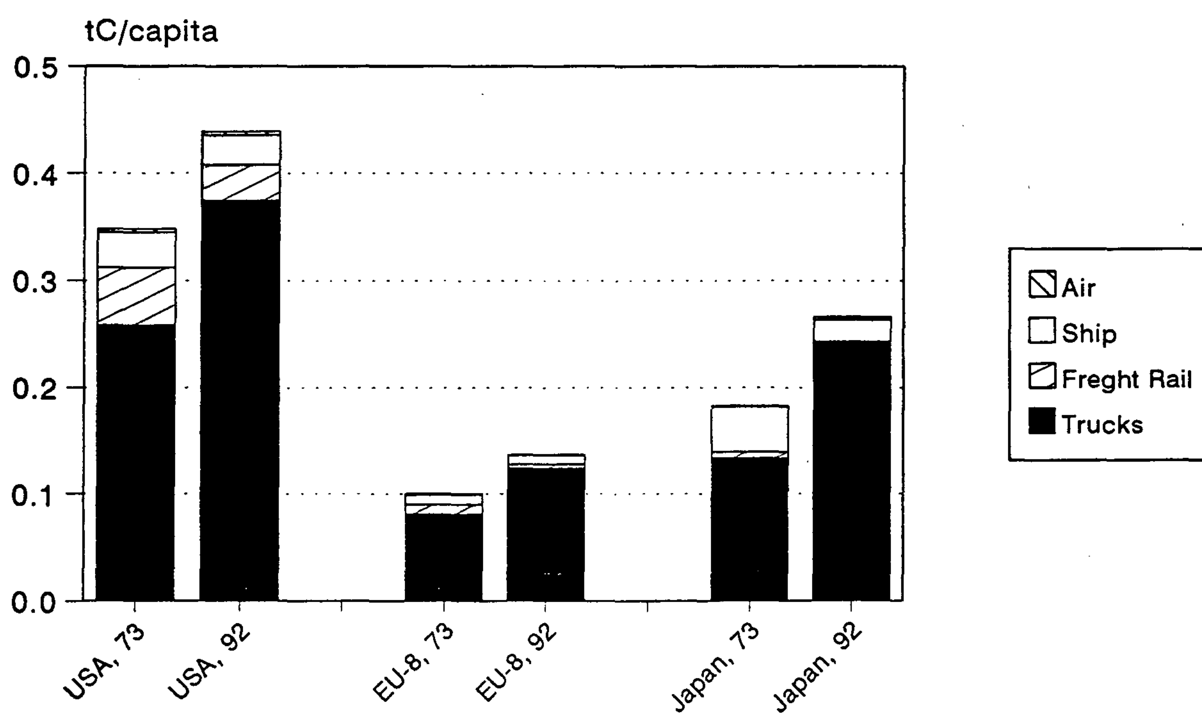

Figure 7.16

OECD-10 Freight Carbon Emissions per Capita

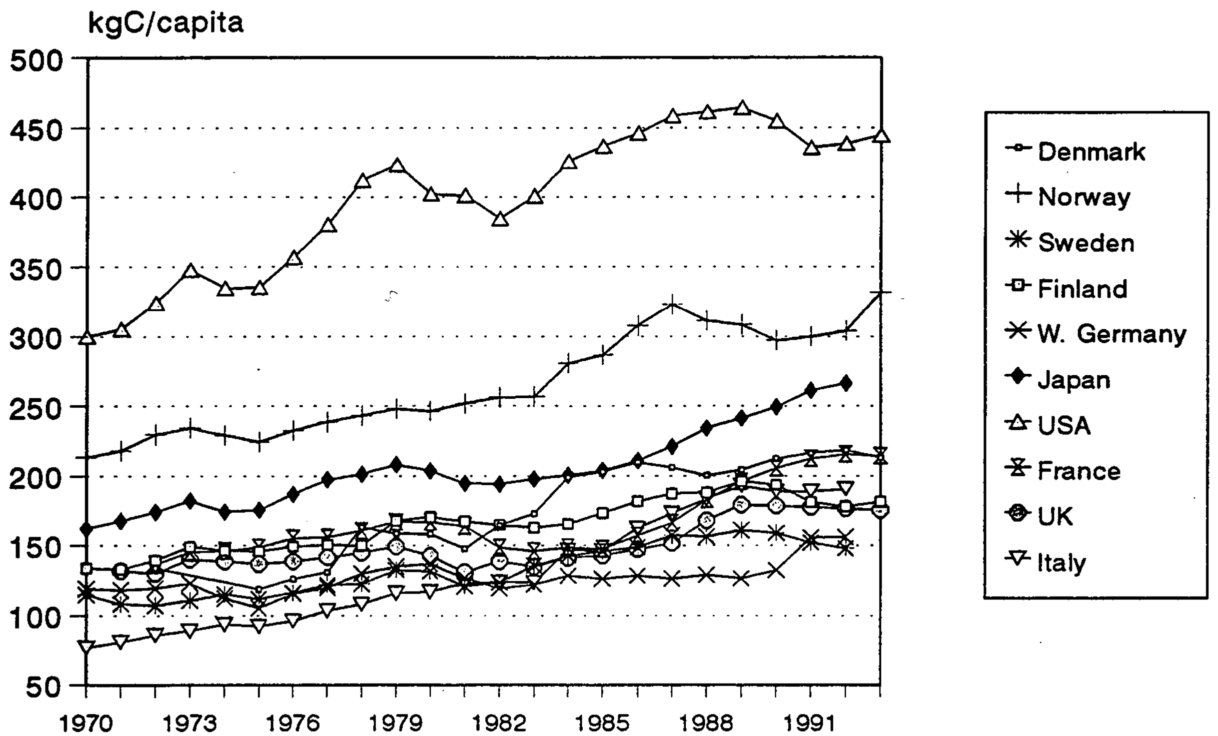

Figure 7.17

OECD-10 Freight Carbon Intensity

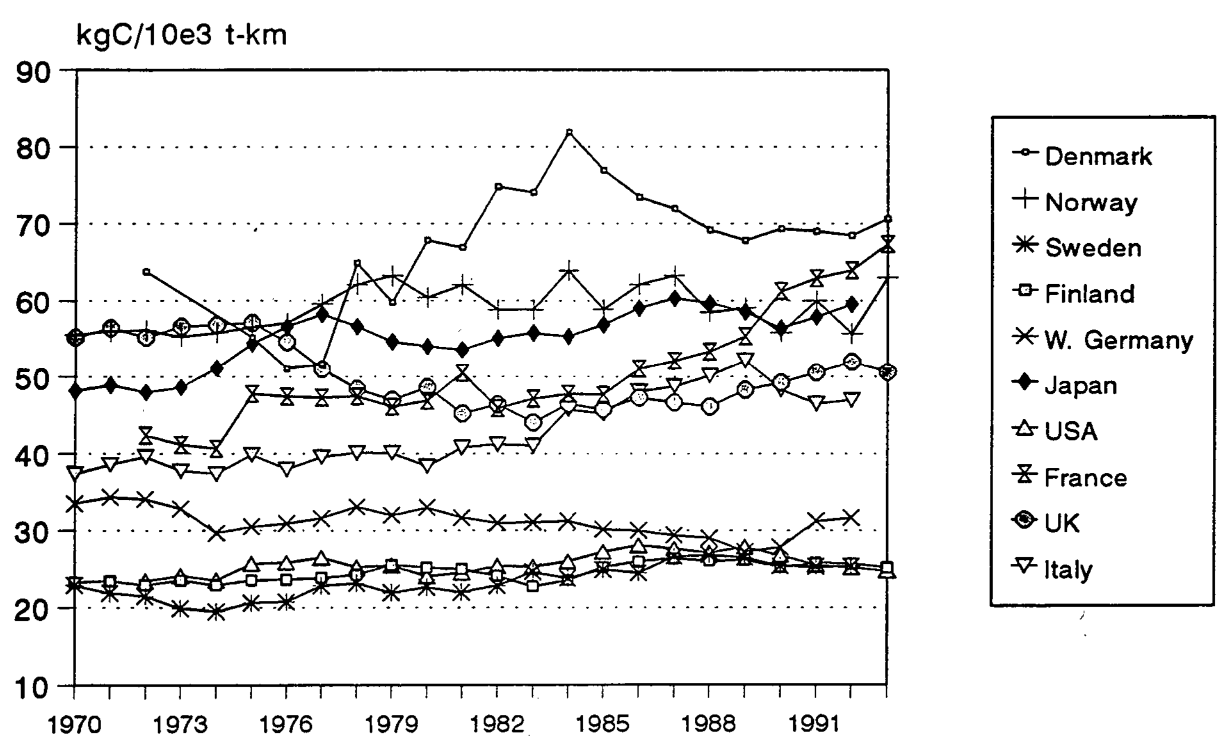

Figure 7.18

Sectoral Results of Laspeyres Decomposition

1991 Freight Carbon Emissions

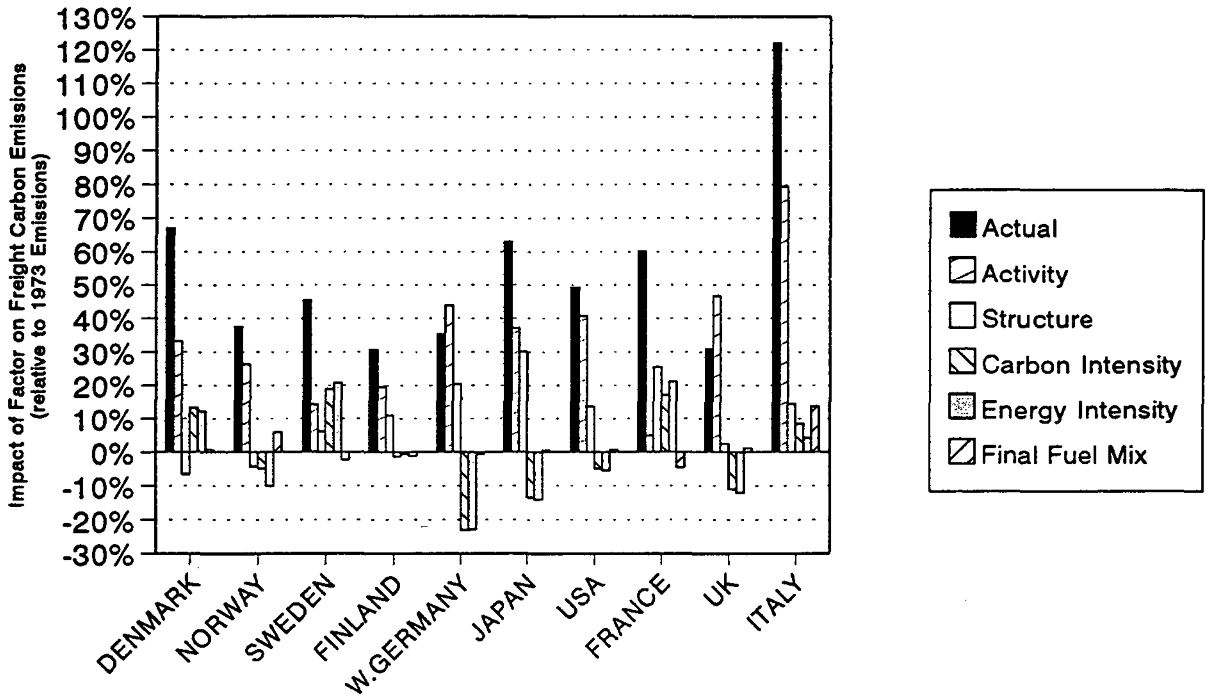

Figure 7.19

Changes in Carbon Emissions per Capita by Sector

1991 Relative to 1973

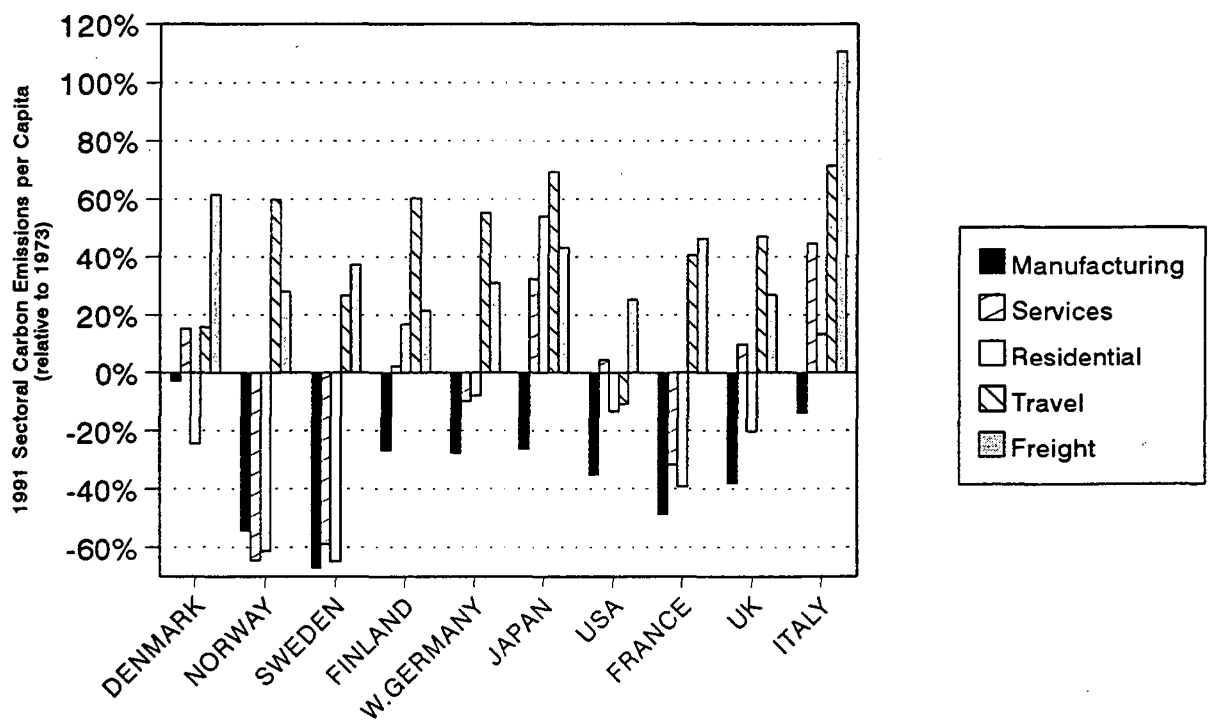

Figure 7.20

Changes in Carbon Emissions Intensity by Sector

1991 Relative to 1973

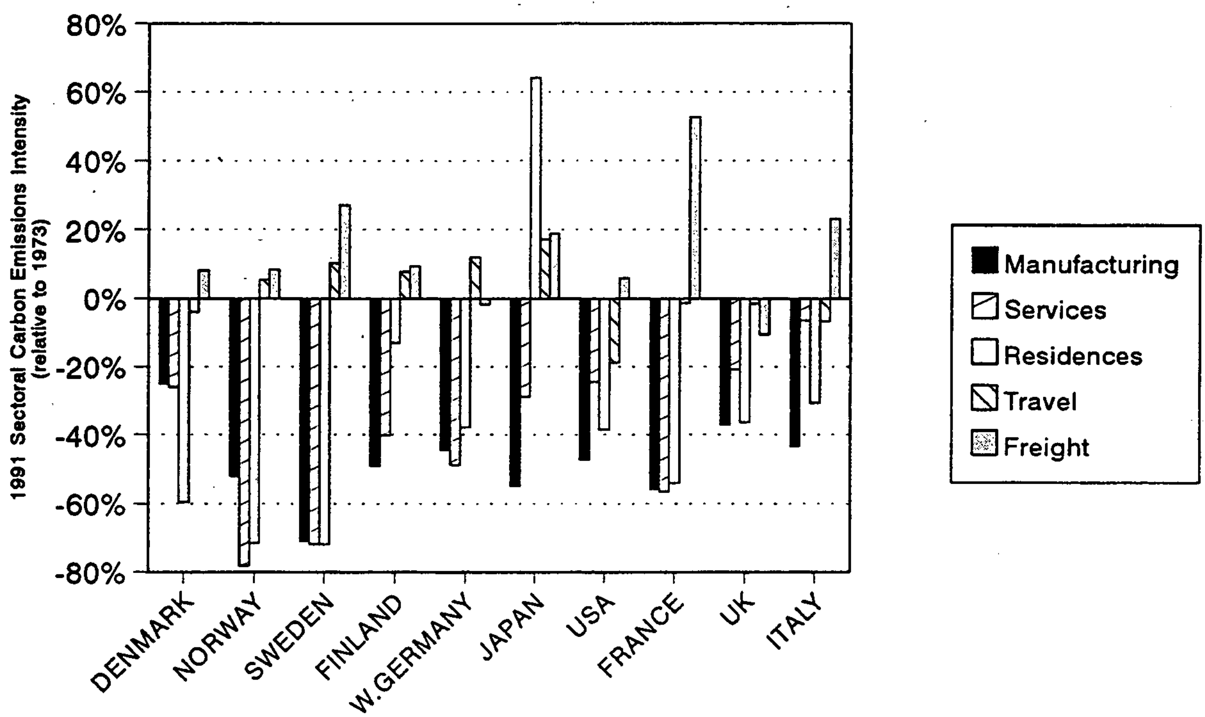

Figure 7.21

Results of Laspeyres Decomposition of Total Carbon Emissions

1991 Relative to 1973

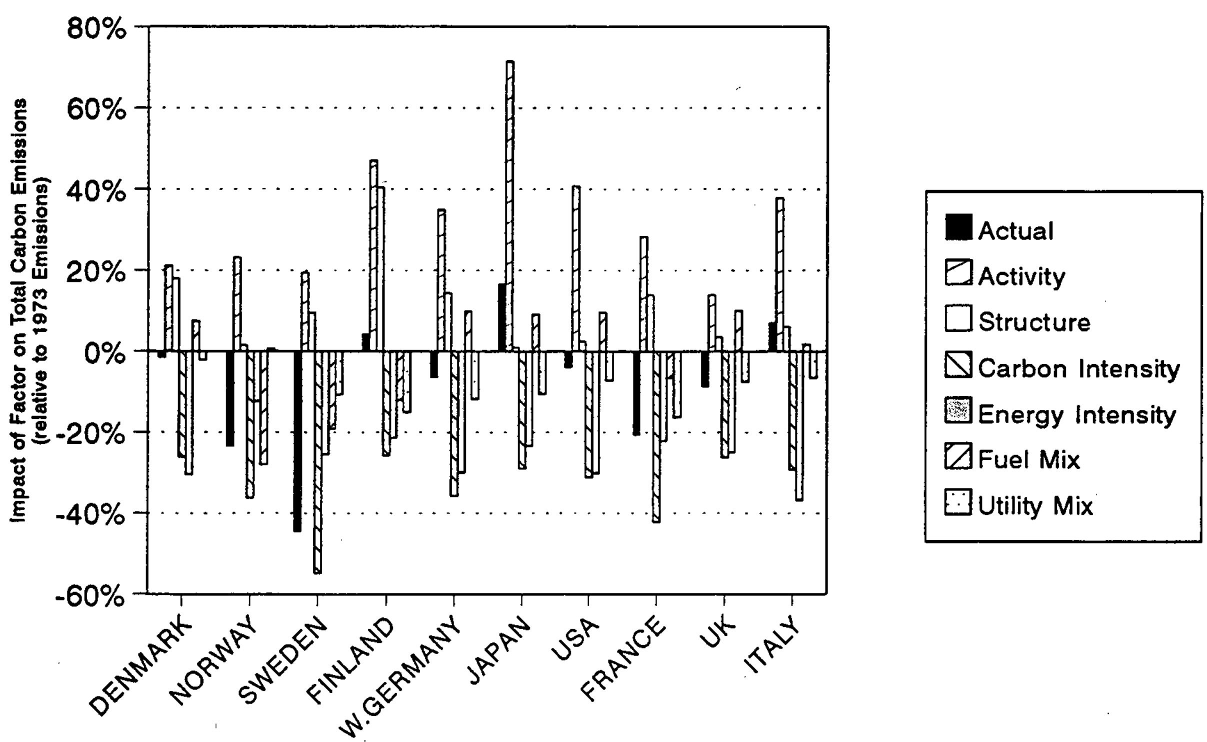

Figure 7.22

Annual Average Growth Rates of Laspeyres Index Terms

All Sectors Carbon Decompostion

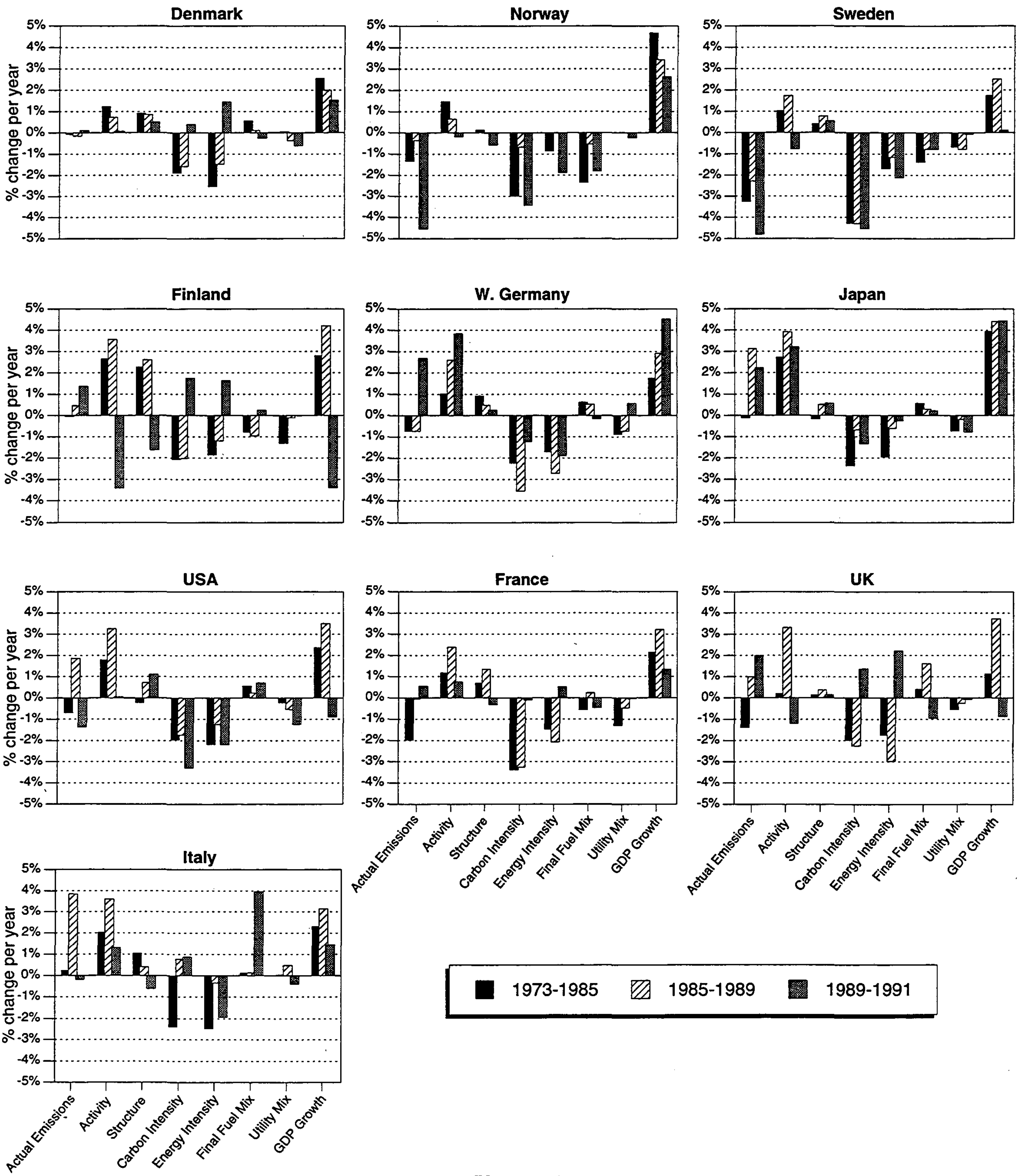

Figure 8.1

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