Residential sector carbon dioxide emissions in OECD countries, 1973-1989: A comparative analysis

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1. SYNOPSIS

Better efficiency and fuel-switching reduced end use emissions in OECD 9. Increased appliances use contributed rapidly to residential emissions, but again was mitigated by fuel-switching.

2. ABSTRACT

The evolution of carbon emissions from energy use in the residential sector for nine OECD countries for 1973-1989 is analyzed. Results are presented both at an aggregate level and by end use, using carbon emission coefficients for primary energy use. Following the methodology of previous studies by Schipper and Meyers, we also review how changes in activity, structure, and intensity had affected both primary energy use and the resulting carbon dioxide emissions on each country. We find that the level of household energy services (home size, numbers of appliances, etc.), energy efficiency, fuel mix, and power generation fuels all play an important role in determining the level of per capita CO_2 emissions. We note that space heating is the most important source of CO_2 emissions, but that the increased importance of electricity use for appliances and lighting as well. To control emissions, improved end-use efficiency, improved efficiency in power generation, and substitutions for carbon-intensive fuels can plan important roles.

3. INTRODUCTION

Near consensus in the scientific community admits that anthropogenic additions of carbon dioxide (CO_2) and other greenhouse gases (GHG) to the natural flux will warm the atmosphere. CO_2 is deemed responsible for 61% of the current radiative forcing[1] and is the primary GHG released from energy combustion. Energy use, the primary source of GHG, is responsible for nearly 57% of all anthropogenic emissions (EPA 1990a), and, consequently, energy choices made today will have implications for the future climate. If lifestyles and energy-use patterns continue in the same energy-consuming manner they follow, "there will be substantial increases in the greenhouse properties of the Earth's atmosphere, which are virtually certain to create environmental change" (Schneider 1989, p. 23).

Energy data can be examined from three levels: final, primary, and emissions. Each level offers a different insight into the patterns of energy use. Final energy data provide information on how much energy is used directly to complete a task or provide a service. However, examining final energy use can obfuscate the losses incurred in the process of transforming and delivering energy.

Primary energy, the next level of analysis, is the sum of final energy and losses incurred from energy transformation (electricity production) and delivery (electricity transmission and distribution losses). Because of an increased penetration of electricity in the residential sector, primary energy data offer a different picture of energy use than final energy accounts.

Lastly, emissions-level energy data are examined to evaluate climate implications. This third level of analysis provides insight by linking energy uses with their environmental effects. Since each fossil fuel (coal, oil, and natural gas) has a different carbon emission coefficient, a changing fuel mix will have implications for future climate.

This paper looks at energy use and associated carbon emissions in the residential sector of nine OECD countries (the U.S., Japan, the former West Germany (FRG), France, Italy, the U.K., Denmark, Sweden, and Norway) in the period 1973-1989. We examine general trends from all three levels of analysis, but our primary emphasis is carbon emissions. We then disaggregate the results and illustrate how end-use emissions are affected by changes in population, structure, and intensity.

1.1. An overview of residential energy use

Residential energy use rose sharply in the 1960s in the OECD countries. Demand for the services and amenities that electrification provided led to this rise. At that time utility companies promoted increased energy use, encouraging ratepayers to take advantage of the reliable and inexpensive supplies of fossil fuels. This trend slowed during the 1970s, when the oil crisis kindled a new sense about the limits of energy supplies, fostered conservation efforts, and spurred some governments to impose efficiency standards on residential appliances and building codes. By the 1980s, the combination of enhanced efficiency and household saturation stabilized and even depressed demand in some OECD countries.

Three phenomena shape the patterns of energy use in the residential sector: population, structure, and intensity. The residential sector is unique because there is no output (as in manufacturing and services) or physical level of activity (as in transportation) associated with it. While we can measure the activity level of the industrial sector in terms of widgets per Kwh or the transportation sector in terms of kilometers traveled per gallon, there is no ready counterpart in the residential sector. The underlying purpose of residential energy use is to enhance the comfort and well-being of people. But evaluating how efficiently energy use provides this service relative to other sectors is difficult. Because nothing is "produced" in the residential sector, activity levels are the only indicator.

Population is an indicator of the amount of energy a country will require, but not of the amount of services *rendered*. Changes in population reflect the macro forces — migration, birth rates, death rates — that affect energy usage.

Structure refers to physical and behavioral forces, often in response to social phenomena, that affect demand. For example, all else being equal, larger homes will have greater energy requirements than smaller homes. Structure may be further broken into three key factors: home area per capita, type of heating equipment, and appliance ownership rates. The amount of dwelling area per person will influence lighting and space-conditioning requirements and may also affect the number and size of appliances. Since heating consumes the largest share of residential energy, changes in the type of heating equipment will have implications for the sector as a whole. Finally, structural change will be affected by appliance ownership rates.

The third key factor, energy intensity, is the amount of energy used per unit of service for a given year. *Space-heating energy intensity* is expressed as useful energy per m^2 of area and is affected by indoor temperature, thermal integrity, heating equipment efficiencies, and the use of secondary heating fuels. *Appliance energy intensity* refers to changes in unit energy consumption for a given appliance and is affected by the efficiencies of new and old appliances, stock-turnover time, and household usage characteristics.

4. METHODOLOGY

This work is carried out in stages. First, we analyze the use of energy by fuel and end use, as described in Schipper, Ketoff, and Kahane (1985) and Schipper, Meyers et al. (1992). Next, we decompose changes in energy use over time into population and structural and intensity components, as described in Schipper, Steiner, et al. (1992) or Schipper, Meyers et al. (1992). We then calculate the carbon emissions from each energy use and apply the same decomposition to estimate the magnitude of changes in emissions from each of these factors alone. Lastly, we calculate changes in emissions arising from changes in the mix of primarily fuels used by households and then from the change in the mix of fuels used for electricity generation.

Changes in the level of CO_2 emissions in the residential sector may be attributed to five factors:

- aggregate population,
- structural change,
- energy intensity,
- mix of gas, oil, solids, electricity, and district heating consumed directly in the home, and
- primary fuel mix used to produce electricity and district heating.

In formal terms, the CO_2 emissions from all residential activities will be described by:

$$CO_{2_{(t_f)}}=[\sum_j \sum_k F_{kj(t_f)} C_{k(t_f)} P_{(t_f)} S_{j(t_f)} I_{j(t_f)})] \tag{1}$$

where:

t_f	=	current year of analysis,
F_{kj}	=	dimensionless ratio of fuel k to residential energy used for activity j, e.g., (GJ gas)/(GJ energy) used for stoves,
C_k	=	CO_2 coefficient of fuel k, e.g., (tons CO_2)/(GJ gas),
P	=	population,
S_j	=	ratio of activity j per capita, e.g., stoves/capita, and
I_j	=	energy intensity of specific activity j, e.g., (GJ gas)/(stove).

The *ceteris paribus* assumption allows us to conject how a single variable, say population, could be expected to impact carbon emissions. By allowing a single variable to fluctuate while all other conditions are fixed, a simplified model can evaluate the impact of this changing variable on emissions. Where there are measured improvements to energy intensity, carbon emissions will decrease using *ceteris paribus* assumptions; where there is population growth, emissions will increase. This assumption permits examination of the reasons for changes in carbon emissions and indirectly assists us in forecasting future emissions of CO_2.

The population effect evaluates changes in energy use that would be expected by population growth or shrinkage, and is determined by

$$\%\Delta CO_{2_{(t_f)}}=[(\sum_j \sum_k F_{kj(t_0)} C_{k(t_0)} P_{(t_f)} S_{j(t_0)} I_{j(t_0)}) - CO_{2(t_0)}]/CO_{2(t_0)} \tag{2}$$

where:

t_0	=	base year of analysis

Similarly the structure effect, which reflects changes in dwelling area, central heating saturation, family size, and appliance ownership is depicted as:

$$\%\Delta CO_{2_{(t_f)}}=[(\sum_j \sum_k F_{kj(t_0)} C_{k(t_0)} P_{(t_0)} S_{j(t_f)} I_{j(t_0)}) - CO_{2(t_0)}]/CO_{2(t_0)} \tag{3}$$

The energy intensity effect:

$$\%\Delta CO_{2_{(t_f)}}=[(\sum_j \sum_k F_{kj(t_0)} C_{k(t_0)} P_{(t_0)} S_{j(t_0)} I_{j(t_f)}) - CO_{2(t_0)}]/CO_{2(t_0)} \tag{4}$$

The primary fuel mix effect (with electricity and district heating production):

$$\%\Delta CO_{2_{(t_f)}} = [(\sum_j \sum_k F_{kj(t_0)} C_{k(t_f)} P_{(t_0)} S_{j(t_0)} I_{j(t_0)}) - CO_{2(t_0)}] / CO_{2(t_0)} \qquad (5)$$

And the fuel share effect alone:

$$\%\Delta CO_{2_{(t_f)}} = [(\sum_j \sum_k F_{kj(t_f)} C_{k(t_0)} P_{(t_0)} S_{j(t_0)} I_{j(t_0)}) - CO_{2(t_0)}] / CO_{2(t_0)} \qquad (6)$$

2.1. Calculation of CO_2 emissions

CO_2 emission coefficients estimate the amount of carbon released when a unit of fuel is burned. Coefficients will vary with the type, quality, and combustion characteristics of the fuel.

CO_2 emissions from wood are considered zero as long as replanting occurs. The amount of carbon sequestered by trees during maturation will equal the amount released during the combustion process, with a net result of zero emissions.

An emission coefficient index is calculated from the shares of fossil fuels used to generate electricity and district heating. Energy losses occur through the transmission and distribution of district heating and electricity, and the amount of energy delivered to homes will thus be a fraction of the primary energy used to generate it. We examine primary rather than end-use energy to capture emissions from the point of generation.

However, we do not conduct a full-cycle analysis of energy use. "Embedded" energy, the energy used to extract, convert, and transport fuels, is not included in these calculations. Most of the studies on embedded energy were conducted in the late 1970s, and their accuracy, current applicability, and relevance are uncertain. The amount of energy embedded in a unit of fuel is non-zero, and, as the recent Gulf War indicates, securing fuel supplies can carry social and economic costs in addition to the embedded fuel costs. Chapman (19XX) estimated the efficiency of energy industries, where:

$$\textit{Efficiency} = (\textit{Output})/(\textit{Energy Cost}) \qquad (7)$$

and

$$\textit{Energy Cost} = (\textit{Calorific Value of Fuel}) + (\textit{Energy Expended Producing Fuel}) \qquad (8)$$

as coal, 96%, gas, 72%, oil, 88%, and nuclear, 93%.

Technological changes, like advances in pipeline efficiency, will affect such calculations. The process of calculating embedded energy is laden with difficulties and is not particularly necessary for the purpose of evaluating CO_2 emissions from the residential sector. Emissions from fuel extraction and processing are in effect "charged" to the country where these processes took place, while the country that uses the fuel is charged only with the emissions released from combustion of that unit of fuel. We recognize the analytical limitations of this approach, but given the uncertain nature of embedded energy study results, we find it to be the most tenable.

2.2. CO_2 Intensities

Our energy data are disaggregated by end use and fuel using a bottom-up approach (Schipper et al. 1985) that allows us to calculate CO_2 intensities by end use. The end uses are space heating, water heating, cooking, lighting, and electric appliances. For each end use, we multiply the energy intensity by the amount of CO_2 emitted by a unit of energy that reflects the actual fuel mix. For example, space heating CO_2 intensity is measured as kg of carbon/m^2/degree day.

For water heating, cooking, lighting, and electric appliances, CO_2 intensity is reported as kilograms of carbon per capita. With these figures we can estimate the impact of changing energy intensities alone on CO_2 emissions by multiplying the 1973 CO_2 emissions intensity by the change in energy intensity for each end use. Similarly, we also estimate the effects of population and structural changes on CO_2 emissions by multiplying 1973 CO_2 emissions by an index that represents the impact of each of these changes on the given energy use, as calculated in Schipper, Meyers, et al. (1992).[2]

Next, we can estimate the impact of changes in the fuel mix for each end use by multiplying 1973 CO_2 intensity by an index representing changes in emissions caused only by the evolution of the final energy demand fuel mix, holding the fuel mix used to produce district heating and electricity constant at 1973 values.

Finally, we measure the impact of changes in the mix of fuels used to generate electricity on CO_2 emissions by holding all components of household CO_2 emissions constant at 1973 levels (including the share of electricity in 1973 household energy use) except the electric power generation mix.

Table 1. *CO_2 as Thousands of Tons of Carbon per PJ*

Oil	20.8
Natural Gas	14.42
Solids	25.16
Wood	0

Source: Torvanger 1991

2.3. The Data

Using energy and structural data from the International Energy Studies Group at the Lawrence Berkeley Laboratory (Schipper, Meyers, et al. 1992; Schipper, Ketoff, and Kahane 1985), we analyzed the U.S., Japan, West Germany, France, Italy, United Kingdom, Denmark, Sweden, and Norway. The data for electricity-generation fuel shares are from the *OECD Energy Balances* 1970 and 1990 (IEA). District heating generation fuel shares for Denmark, West Germany, and Sweden (1990) are from each country's energy balances. District heating in other countries is less than 3% of delivered household energy, and, consequently these data are ignored.

The CO_2 emission coefficients are from Torvanger (1991) and Marland (1990). Table 1 shows the emission coefficients used for gas, carbon, and oil. These coefficients, as Torvanger reports, estimate how much carbon is released in the production of a given amount of energy. They do not account for the efficiency of combustion, which may overestimate emissions, given the likelihood of incomplete combustion. These coefficients are held constant for the period of study.

2.4. Electricity and district heating CO_2 emission coefficients

Electricity and district heating are special cases, since fuel shares and corresponding CO_2 coefficients will vary between countries and over time. For the electricity emissions coefficient, the fuel share and efficiency of power production are determined by the aggregate data. It is thus assumed that oil-, coal-, and gas-fired ele ctricity plants will operate at the same efficiency.

As the fuel mix for producing electricity fluctuates, the corresponding emission coefficient will likewise change. As shown in Figure 1, the electricity emission coefficient index in Italy and Denmark grew because of increased use of coal in electricity generation.[3] For the other seven countries, the coefficient decreased, most often because of an increase in nuclear power generation.

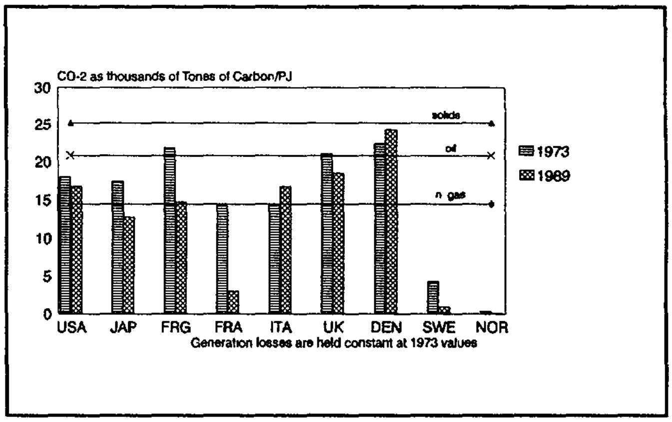

Figure 1. ***Electricity emission coefficient***

For Norway the electricity index is almost zero due to the dominance of hydropower to the virtual exclusion of other sources of electricity.

For district heating, correspondence is also assumed between the residential and the total share of district heating production. The district heating emission coefficient (CO_2 per unit of delivered district heating) decreased in Sweden by 28%, in West Germany by 19%, and in Denmark by 27%, due to the replacement of oil products with biomass.

3. RESULTS

3.1. Final and primary energy use: The importance of electricity for CO_2 emissions

The residential sector accounts for nearly 25% of final energy use in most OECD countries (Schipper, Meyers et al. 1992). Space heating is the largest component of final household energy use followed by water heating, cooking, appliances, and lighting (Schipper, Ketoff, and Kahane, 1985; Ketoff and Schipper, 1990).

Between 1973 and 1988 final energy use per capita in the U.S. decreased by 18.4%, in Denmark by 24.6%, Sweden, 7.8%, and UK, 1.8%. This reduction in energy intensity is primarily the result of improvements in space heating efficiency. However, it is also attributed to an increase in the market share of electricity for space heating, water heating, and cooking (Schipper, Meyers, et al. 1992). Electricity is often more efficient than direct combustion at converting *final* energy to its end-use purpose. Nevertheless, electricity is much less efficient than direct combustion at converting *primary* energy to its end-use purpose, with around two-thirds of primary energy lost in the conversion to electricity. Most of this energy degradation occurs in the transmission and distribution of electricity, losses which are small compared with those that arise in generation. The impact of differences in the

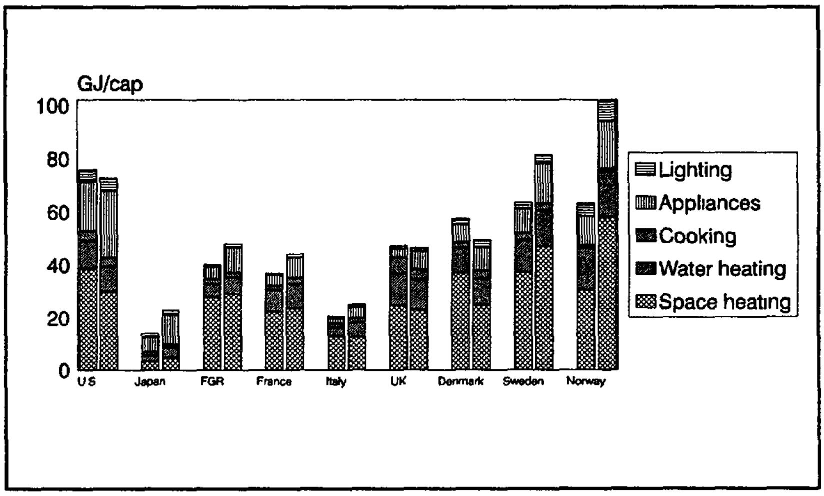

Figure 2. ***Residential primary energy use by end uses, 1973 and 1989***

rate of loss over time or among countries in our comparison is very small compared with the other factors we analyze here.

Primary energy use per capita grew 28% in Sweden and decreased by 1% in the UK, 13% in Denmark, and 4% in the U.S. In Sweden, Norway, and France, heating through direct combustion of fossil fuels was largely replaced by electricity. In the other countries, higher ownership of larger appliances and more use of electricity for cooking led to growth in electricity use.

In most countries, space heating has remained the largest component of primary energy use. However, the shares of energy use for lighting and appliances increased, surpassing energy use for cooking and water heating in most of the countries (Figure 2). This is why the fuel mix utilized for electricity generation has played an increasingly more decisive role in determining the CO_2 emissions by country and by fuel.

3.2. The aggregate picture

Figure 3 shows the total CO_2 emissions per capita by end use for each country in 1973 and 1989. Americans have by far the highest per capita CO_2 emissions. In 1989 the U.S. emitted 1158.6 kilograms of carbon per capita. This is principally because Americans have the largest homes and the most appliances, and only secondarily because American appliances use somewhat more electricity per unit of service than those in Europe. But notice that the emissions from all but two countries were lower in 1989 than in 1973. We discuss the reasons below.

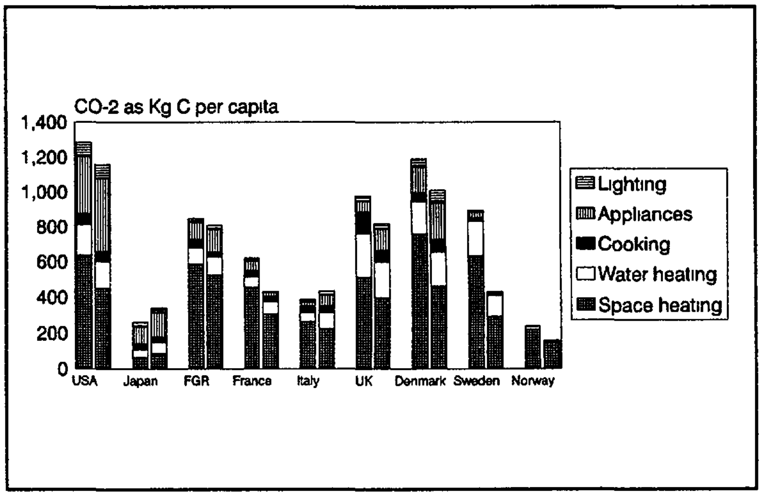

Figure 3. ***Residential carbon dioxide emissions by end use, 1973 and 1989***

The second largest per capita emitter from household energy use is Denmark, which in 1989 emitted 1007.8 kilograms of carbon. Like the Americans, the Danes have large homes and many appliances, though their equipment has higher efficiencies and their per capita emissions are thus lower. Denmark is followed by the U.K. with 817.2 and West Germany with 806.7 kilograms of carbon per capita; though homes in these two countries are heated less efficiently than in the U.S. or Denmark, they are smaller and sometimes heated directly with coal.

CO_2 emissions per capita decreased in all but two of the studied countries due, in varying extents, to changes in the fuel mix, increases in end-use efficiency, and appliance saturation. In France, Britain, and Germany, this decrease of per capita emissions occurred despite increased penetration of central heating and household appliances. A reduction in key energy intensities in the U.S., Denmark, and Germany, and a significant reduction in coal use in Germany and Britain permitted a modest overall reduction in CO_2 emissions from residential energy uses in these countries. Sweden and France reduced their CO_2 emissions per capita through wide penetration of hydro- and nuclear-based electricity for space- and water-heating as well as cooking.

In Italy and Japan, increased penetration of central heating and household appliances and continued reliance on coal and other fossil fuels for power generation led to a growth in per capita emissions.

Thus we see that even in the aggregate, the changes in per capita CO_2 emissions in each country arise from a variety of factors that often offset each other. We examine these changes further below.

3.3. Fuel mix

Figure 4 shows the share of CO_2 from each fuel use for 1973 and 1989. Between these years, the share of CO_2 emissions from electricity production and use increased in all countries except France and the U.K. In France, the decrease is attributed to an increase in the share of nuclear energy for electricity generation; in the U.K., the decrease in emissions from electricity was due to the substitution of gas for space and water heating.

CO_2 emissions from coal for direct use decreased by 32.5% in Japan and by more than 50% in the remaining countries due to the substitution of other fuels. In the former West Germany, for instance, the numbers of homes heated mainly by coal decreased by 64% between 1973 and 1989.

The share of CO_2 emissions due to oil use (including LPG) has declined in all nine countries; however, total oil emissions increased in Japan by 23%. As in the case of coal, the decline in oil emissions is primarily the result of fuel-switching. In most of the study countries, oil was replaced by gas, electricity, or district heating. Between 1973 and 1989, oil CO_2 emissions decreased 82% in Denmark, 66% in Sweden, 52% in the U.S., 34% in Norway, and around 30% in the other four European countries (West Germany, U.K., France, Italy).

The share of gas grew in Japan, the four European countries just mentioned, and Denmark. Total emissions from gas increased by 69% in Japan, 199% in West Germany, 103% in France, 250% in Italy, 115% in the U.K., and 244% in Denmark. But this gas reduced the use of oil and coal; hence the net effect was a reduction in emissions.[4]

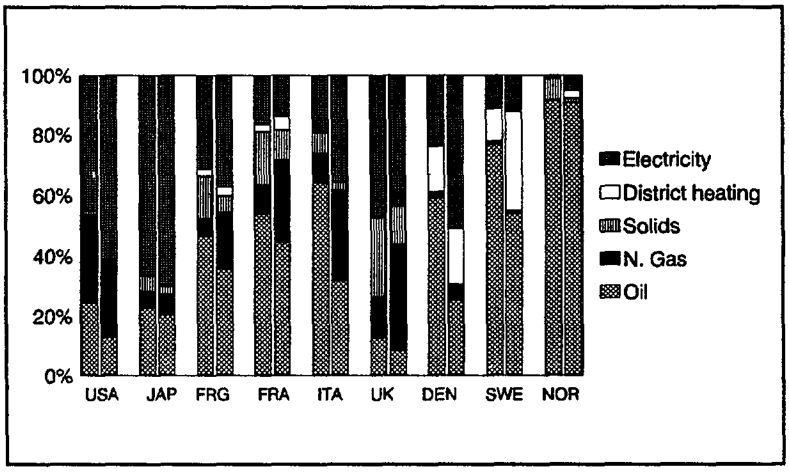

Figure 4. ***Residential carbon dioxide emissions by fuel, 1973 and 1989***

CO_2 emissions from district heating increased in France (25%), the former West Germany (27%), Denmark (3%), and Sweden (43%), where this energy source is important. In all cases the emissions growth was due to an increased use of district heating and was offset significantly by changes in the fuel mix for district heating generation.

3.4. Space heating CO_2 emissions

Space heating is the largest component of household CO_2 emissions in every country except Japan. However, for the nine OECD countries as a whole, the share of space heating in total residential energy use decreased from 61% to 51% (Figure 5).[5] Excluding the increased share of other end uses, this important change was due to a decrease in primary energy use for space heating (i.e., increased efficiency), as well as a decline in the share of fossil fuels for generating electricity used for space heating.

These factors affect CO_2 emissions in different ways in each country. In the U.S., for instance, both changes affect the 29% decrease on CO_2 emissions since space heating primary energy use per capita decreased by 9.1% and the electricity emission coefficient, per unit of energy, fell by 6.8%.

In the case of France, CO_2 emissions decreased by 33% even though space heating primary energy use grew by 12.9%. In this country as well as the former West Germany, Norway, and Italy, the most important factor that pushed down CO_2 emissions was the decrease in the share of fossil fuels in power generation.

In Denmark, despite an increase in the electricity coefficient of 8.6%, CO_2 emissions decreased by 39.6%. A switch away from space heating led to a 31% reduction in space heating energy demand.

For Japan, the increase in space heating CO_2 emissions was related to the 72% increase in primary energy use, both as direct energy (kerosene and gas) and as electricity for foot-heaters, electric blankets, and heat pumps, for this end use alone.

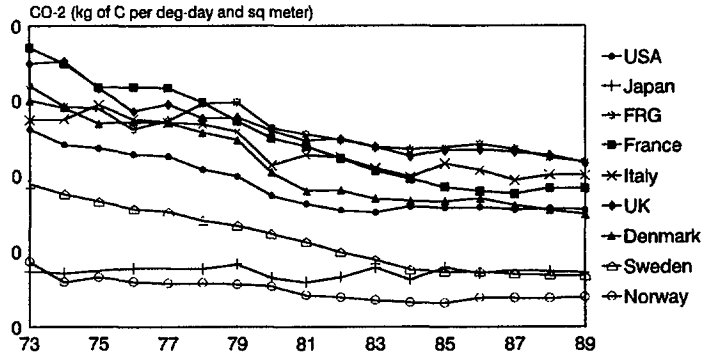

Figure 5. ***Space heating carbon dioxide emissions intensity (per degree day and floor area)***

The reduction in primary space heating intensity is basically a result of improvements in thermal integrity and heating equipment in new homes as well as behavioral changes such as reduction in average indoor temperature (Schipper 1992, Meyers 1987). This transformation happened in most of the nine countries. Further, increased penetration of central heating pushed down primary energy use (Schipper, Howarth, et al. 1992).

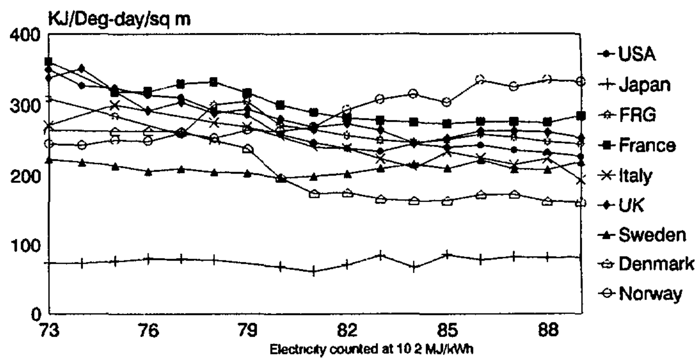

Figure 6. ***Space heating intensity, primary energy use by degree day/floor area***

Figure 6 shows space heating CO_2 emission intensity defined as (in parallel with space heating energy intensity) energy-related space heating CO_2 emissions per m^2 floor area and degree day. For the OECD 9, the intensity emissions fell between 1973 and 1989. The major decrease occurred in Scandinavia, where in Sweden, Denmark, and Norway the intensity declined by 63%, 52%, and 54% respectively. However, comparing CO_2 emission intensity with primary space heating intensity (Figure 6) shows that emissions per m^2 fell more than energy use per m^2 because of the reduction in fossil fuel use for electricity generation and reduced use of oil and coal for direct heating as well. Primary space heating intensity increased by 36% in Norway (a result of important increases in heating comfort and a switch to electricity), but decreased 39% in Denmark and 0.2% in Sweden.

3.5. Water heating and cooking

Water heating and cooking make up the second largest component of residential final energy use, but the third component of primary energy use. In Japan, however, these end uses represent around 50% of final energy use due to the low share of space heating (Schipper, Meyers, et al. 1992).

The difference between the share in final and primary energy use is due to the important share of fossil fuels in the energy supply for these end uses. With the exception of Norway, more than 50% of the households in the other countries heat their water with fossil fuels.

CO_2 emissions per capita from water heating and cooking decreased in the U.S. by 13%, the former West Germany by 10%, the U.K., 28%, Sweden, 43.7%, and Norway, 48.8% (Figure 7). By comparison, growth was 21% in Japan, 43% in Italy, 12.5% in Denmark, and 6.7% in France.

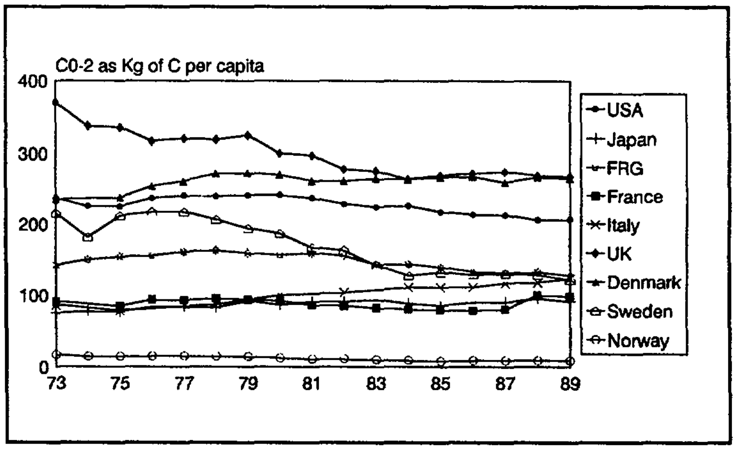

Figure 7. ***Carbon dioxide emissions, water heating and cooking***

The growth in water heating and cooking CO_2 intensity (emissions per capita) was brought about by the increased electrification in Japan and Italy and the increased share of coal in electricity generation in Denmark. Several factors affect the energy intensity of water heating: increased use of central heaters and ownership of appliances that use hot water (washers) push energy intensity upward. However, improvements in water heaters and lower temperature in water for washing push energy intensity down (Schipper, Meyers et al. 1992).

In the case of cooking, a decline in household size, greater participation of women in the labor force, the introduction of microwave ovens, and changes in eating habits pushed energy intensity downward.

3.6. Electric Appliances and Lighting

The largest growth in residential energy use in the OECD countries has been in electric appliances. After space heating, lighting and appliances now represent the second component of primary energy use and CO_2 emissions in the residential sector.

Since electricity is the only energy source for these end uses, isolating the causes of the changes in the CO_2 emissions is easy. Figure 8 shows the evolution of CO_2 emissions for these end uses. As shown, in all countries except Sweden and France, CO_2 emissions per capita grew between 1973 and 1989.

According to Schipper and Meyers (1992), between 1973 and 1988 the final energy use for lighting and appliances increased in the nine countries. This large increase would have increased CO_2 emissions significantly in all countries (except Sweden and Norway) because of the prominent role of fossil fuels in electricity generation. However, reduced use of fossil fuels (in France and in Sweden), mostly because of the increased use of nuclear power, restrained emissions growth in France and Sweden. In Denmark, conversion of utilities from oil to coal had the opposite effect, while in the remaining countries the CO_2 emissions per kWh produced increased only slightly.

For the other countries where the fossil fuel share of electricity production also decreased, structural and population effects offset the impact of efficiency improvements and decreased use of fossil fuels in electricity generation. This is the case in the U.S., Japan, West Germany and U.K. where CO_2 appliances/lighting intensity decreased by 21.6%, 37.3%, 28.3%, and 68.6% respectively. For Denmark and Italy, where the share of fossil fuels in electricity generation increased, the emission intensity grew by 132% and 43.4% respectively. The high increase in Italy was due to increases in the key three factors: unit consumption per appliance, saturation (Schipper, Ketoff 1990) and share of fossil fuels in electricity generation.

In final energy use, structural effects such as the increase in appliance ownership and the size features

Table 2. ***Decomposition of Change in CO_2 Emissions related to Primary Energy Use per capita in the Residential Sector 1973-1989 (total % of change)***

	Actual	Pop. effect	Struct. effect	Inten. effect	Primary Fuel Mix	Share effect
USA	-9.8	17.5	13.2	-27.9	-5.9	-1.7
Japan	35.5	15.3	18.3	32.9	-16.2	-7.1
FRG	-4.6	1.0	41.8	-18.7	-19.4	-5.1
France	-39.8	7.2	35.0	-1.5	-50.2	-24.6
Italy	10.9	5.0	38.0	-12.3	-8.3	-12.9
UK	-16.1	1.7	69.3	-35.1	-15.0	-9.9
Denmark	-16.7	2.4	22.5	-31.1	-1.9	-0.9
Sweden	-52.0	4.5	22.8	-6.8	-62.6	-41.9
Norway	-33.6	6.1	30.0	-0.6	(1)	-58.2

(1) More than 99% of the electricity in Norway is produced by hydro power, thus this effect is minimum and therefore could be ignored.

(2) Actual total CO_2 emissions grew in all the countries except for Denmark.

pushed up appliance energy use even though an important decrease in unit consumption occurred (Schipper, Hawk 1991). The unit energy consumption for refrigerator-freezers, for example, decreased 10% in U.S. and 20% in West Germany. The increase in area per dwelling was the main factor causing energy use per capita for lighting to increase.

6. POPULATION, STRUCTURAL AND INTENSITY EFFECTS IN CO_2 EMISSIONS

Table 2 shows the decomposition of change in CO_2 emissions related to primary energy use per capita for the nine countries between 1973 and 1989. The changes are calculated by quantifying the structure and intensity effect on each end use and adding up to explain CO_2 emission at the aggregate level. In addition, primary fuel mix (accounting for both electricity and district heating fuel mix production) and fuel share effects are also shown in the table.

Actual emissions per capita decreased in all the countries except Japan and Italy, where structural factors led to an increase in per capita energy use.

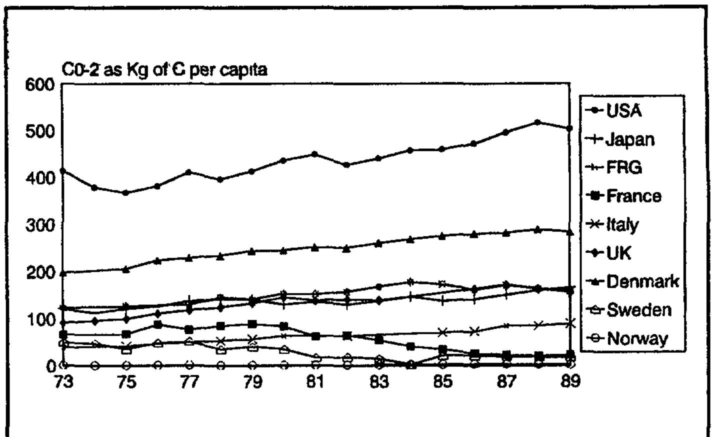

Figure 8. ***Carbon dioxide emissions, electric appliances and lighting***

An increase in *population*, principally in the U.S., Japan and France, pushes emissions upward in the nine countries. The *structure* effect, reflecting changes in dwelling area, central heating saturation, family size, and appliance ownership, also pushes up the CO_2 emissions. The former West Germany, U.K., Italy and, France are clearly the countries where the structural effect of CO_2 emissions pushes strongly upward.

The *intensity* effect pushes down CO_2 emissions except in Japan. The U.S., U.K., and Denmark were the countries where energy intensity was highly reduced. In the U.S. and Denmark, the reduction was due to improvements in energy efficiency (particularly in space heating) and in the U.K., the reduction was based on a lower share of electricity in primary energy use.

Table 3. ***Decomposition of Change in CO_2 Emissions Related to Electricity Use and Production in the Residential Sector 1973-1989 (total % of change)***

	Electricity production	Use of primary electricity
USA	-6.8	37.4
Japan	-26.7	32.4
FRG	-32.5	39.3
France	-78.5	96.7
Italy	16.2	47.7
UK	-12.1	-10.9
Denmark	8.6	93.4
Sweden	-77.8	84.9
Norway	97.6	11.2

The *primary fuel mix* effect, which accounts for changes both in the share of fuels used in households and in the share of fuels used to generate electricity and district heating, pushes emissions downward in the nine countries. In Sweden and France this effect is higher because of an increase in the share of nuclear and hydro power in electricity production.

In Denmark and Italy, despite greater use of fossil fuels in electricity production, the fuel mix in the whole sector resulted in a decrease in CO_2 emissions per capita. In Italy, this decrease was basically due to increased use of natural gas in space heating. In the case of Denmark the fall was due to both increased use of district heating and a decrease in the share of fossil fuels in district heating production. In Norway, more than 99% of the electricity is generated by hydropower, so CO_2 emissions are small.

The *fuel share effect* (without electricity and district heating production effect) pushes emissions down in the nine countries, because the share of fossil fuels in final energy, and the share of oil and coal in particular, have decreased in all the countries. In this case, the U.S. and Denmark show the minimum effect due to small changes in the share of final energy use between 1973 and 1989. By contrast, France and Sweden exhibit the largest decreases in emissions because of the increased share of electricity in place of fossil fuels in final energy use. In both countries, the emissions from one unit of primary electricity in 1973 was lower than that from either oil or coal (Figure 1).

Tables 3 and 4 show the decomposition of change in CO_2 emissions related to electricity and district heating use and production. As Table 3 shows, the electricity share grew in all the countries except the in U.K. and the share of fossil fuels in electricity production fell in all the countries except Denmark and Italy. Table 4 shows how the district heating share in final energy use grew in the three countries where this energy source is important. It also shows that the share of fossil fuels in district heating production fell in the three countries.

7. CONCLUSIONS

The U.S., Denmark, the former West Germany, and the U.K. have the highest CO_2 emissions per capita of the nine OECD countries examined; significantly, coal dominates power production in these four countries.

Per capita CO_2 emissions from residential energy use were reduced in all countries except Japan and Italy. There were many reasons for this decline. In Sweden and France, where the largest drop in per capita emissions occurred, the increased share of nuclear in power generation and increased use of electricity for space and water heating were the largest contributors. In Norway, hydro-based electricity and wood drove emissions down in this sector. In Denmark and the U.S., improved energy efficiency was the main reason for the decline. In Great Britain and Germany, reduced use of coal in homes was the predominate reason for lower CO_2 emissions.

Table 4. ***Decomposition of change in carbon dioxide emissions related to district heating use and production in the residential sector 1973-1989 (total % of change)***

	District heat production	Use of district heat
FRG	-19.6	3.4
Denmark	-21.3	25.4
Sweden	-27.6	11.8

The main source of growth in emissions from residential energy use has been electric appliances, where, in spite of important improvements in energy efficiency, the number of appliances grew so rapidly that electricity use (and subsequent emissions) were increased for these end uses. For Norway, Sweden, and France, emissions from appliances were mitigated by the supply of nuclear and hydro-electric power. In the other countries, CO_2 emissions per capita from electric appliance use grew between 1973 and 1989.

The decomposition of change in CO_2 emissions related to primary energy use shows that population and structure effects push up the CO_2 emissions in the nine countries. The intensity effect pushes both energy use and CO_2 emissions down in all the countries except Japan.

The fuel mix effects, which account for both the changes in the share of fuels used in households and the share of fuels used to generate electricity and district heating, push emissions down in the nine countries. In Sweden and France, this effect was higher because of the increased share of nuclear and hydro power in electricity production. In Denmark and Italy, despite the increased use of fossil fuels in electricity production, the fuel mix in the whole sector led to a decrease in CO_2 emissions per capita.

This framework permits us to identify the structural changes that led to the increase of CO_2 emissions. The two primary structural changes were improvements in energy efficiency and a decrease in the share of fossil fuels in electricity and district heating production.

The results show that improving energy end-use efficiency, increasing the efficiency of power generation, and substituting away from carbon-intensive fuels are key to the control of CO_2 emissions.[6]

ENDNOTES

1. When the climate is in equilibrium, absorbed solar energy is balanced by radiation emitted from the Earth to space. Any factor that perturbs this balance is termed a radiative forcing agent. Radiative forcing refers to the anticipated share of global warming contributed by each gas. Thus, 61% of anticipated temperature change is attributed to CO_2 emissions currently in the atmosphere.

2. Recall that the activity effect estimates the change in energy use and thereby CO_2 emission changes due only to population increases, maintaining constant all the other variables at 1973 values. The structural effect accounts for the changes in energy use and emissions due only to variations in dwelling area per capita and growth in per capita ownership, as well as the per capita area of homes to measure lighting. The intensity effect isolates the effects of energy intensity changes only on the use of electricity and fuels for each end use.

3. The actual ratio of primary energy to electricity generated in Denmark fell by about 10% because of the spread of combined heat and power, but this effect is small compared to the virtually complete conversion of electric power production from oil to coal there. Variations in the thermal efficiency of power production in other countries were small compared to other factors influencing

CO_2 emissions.

4. Methane emissions related to natural gas use, mostly leakage in transmission and some production losses as well, have an important impact on the atmosphere. An incremental molecule of methane released to the atmosphere will result in a trapping of 20-30 times as much heat as an incremental CO_2 molecule (World Resources Institute 1990). However, for the countries studied here, these methane emissions are small enough such that it is the combustion that causes the greatest impact on the atmosphere.

5. The energy space heating data are climate-corrected.

6. It is important to take in consideration the environmental effects, as well as the economic problems, related to the nuclear power.

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