## Diverging Developments in Residential Space Heating and Electric Appliances: The Impact on CO<sub>2</sub> Emissions Evidence from Ten OECD-Countries

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ABSTRACT While energy use for residential space heating in OECD countries increased considerably over the period from 1970–1995, CO<sub>2</sub> emissions from space heating nearly remained stable. A reason for this phenomenon involves changes in fuel shares. Since natural gas contains much less carbon per unit of energy than oil or coal, fuel switching clearly reduced the carbon intensity of space heating. In addition, the transition from old coal stoves to modern boilers furnished a significant increase in energy efficiency. Energy use for electric appliances and lighting rose dramatically from 1970-1995. Although OECD countries made remarkable progress in improving appliance and lighting efficiency as well as reducing the amount of carbon dioxide released per unit of electricity, this progress did not stabilize CO<sub>2</sub> emissions from these electric enduses. Because the carbon content released per unit of delivered electricity significantly exceeds that of fossil fuels for every observed country except Norway, Sweden and France, further increases in appliance use and lighting will tend to bolster carbon emissions in the OECD. This study investigates carbon emissions from space heating and appliances and lighting in ten OECD-countries (Austria, Denmark, France, Germany, Italy, Japan, Norway, Sweden, UK, and the USA). Our major finding is that, in the absence of policy interventions, residential carbon emissions will begin to accelerate in the near future.

#### Introduction

Households contribute as much as one-third of national  $CO_2$  emissions among OECD countries. Within the residential sector, space heating accounts for the highest proportion of energy demand and is the major force behind  $CO_2$  emissions. The second largest amount energy is consumed by water heating. Because neither end-use experienced overwhelming growth in energy use, and both shifted towards lower carbon fuels, their  $CO_2$  emissions remained relatively stable or even diminished slightly from 1970-1995 for most countries. On the other hand, electricity consumption for appliances and lighting rose over that period (see Figure 1), and will continue to bolster residential carbon emissions in the near future. This is a threatening development if policymakers intend to restrain future  $CO_2$  emissions. The carbon content per unit of final electricity is higher than that of oil or gas for every country except Norway, Sweden, and France. Thus, increases in electricity consumption, driven by continuing increases in appliance saturation, will lead to very high carbon emissions in 7 of the 10 countries we investigated. Considering the high costs and obstacles involved with building hydro- or nuclear power plants, the carbon content (see Fig. 2a) and the carbon content of electricity (see Fig. 2b) is not likely to decline dramatically in the future.

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Figure 1. Shares of final energy for residential end uses in ten OECD countries from 1970 to 1995







Fig. 2b Carbon content of final electricity in 1995 in 10 OECD countries

In order to better understand the development of residential  $CO_2$  emissions in the observed countries, we investigate: (1) space heating; and (2) electric appliances and lighting. We begin with a STRINT (STRucture and INTensity) approach, extend it to decompose  $CO_2$  emissions, and then provide some projections for the near future.

## The Historical Development of Space Heating and CO<sub>2</sub> Emissions

In the last two decades energy demand for space heating in OECD countries underwent significant changes. Figure 3 presents the evolution of  $CO_2$  emissions per capita from space heating in 10 OECD countries from 1970 to 1995. Only Sweden, France and Denmark experience a significant decrease in carbon emissions per capita. In 7 out of 10 countries we notice an essentially flat emissions trajectory.

The nearly stable carbon emissions levels among the investigated countries result from a combination of factors. The expansion of structural parameters (i.e. square meters of floor area per capita) pushed space heating energy use and carbon emissions upward, while energy efficiency increases countered these structural effects. A very detailed description of these forces in the residential sector can be found in (Schipper et al. 1985; Schipper et al. 1992; Schipper et al. 1993; Schipper et al. 1996; Sheinbaum, Schipper 1993). Fuel switching was a third effect that played a very important role in restraining emissions levels. In the late 1970's and for most of the 1980's, household fuel shares for space heating experienced a major transition. While oil and solids were the primary energy source for space heating in the 1970's, they were largely displaced by natural gas, and for some countries district heat or electricity, over the following decade. There are two main reasons for this transformation. First, individuals replaced coal- and oil-fired heating systems due to the comfort, cleanliness, and the ease of operation that natural gas provided. Second, increases in petroleum prices influenced people to substitute other fuels for heating oil. As shown in (Haas et al. 1998), individuals reacted very strongly to high energy prices after the oil shocks of the 1970's.



Figure 3. Carbon emissions from space heating per capita in 10 OECD countries from 1970 to 1995

Figure 4 shows the development of fuel shares for space heating in 10 OECD countries since 1970 (for France and Norway we have reliable data only from 1973). We observe a dramatic reduction of oil use in countries that initially had a high initial penetration of oil-fired heating equipment, such as Denmark, Norway, Sweden, Italy, France and Western Germany. Only in Japan did the share of oil for space heating remain nearly constant, due to its geographic characteristics and its lack of national energy resources. Norway and Sweden attained a very high proportion of electric heated homes, largely due to their extensive flow of inexpensive hydro-power. For Austria, Norway and France, we observe a high share of solid fuels, consisting mostly of wood.



Figure 4. Fuel shares for space heating in the residential sector

# The Historical Development of Electric Appliances and Lighting and CO<sub>2</sub> Emissions

In the last two decades the penetration of electric appliances grew in all investigated countries. Table 1 lists the saturation of five major appliances (based on consumption per unit). During the last twenty years, ownership levels of each appliance grew by 20-30% on average. In addition, minor electric appliances (e.g. TV, VCR, PC's, kitchen appliances, etc.) have often experienced even more dramatic saturation increases.

Table 1. Saturation percentage (penetration) of five major appliances in 1975, 1985, and 1995

country	USA			W-GER			Α			DK			JAP		
	75	85	95	75	85	95	75	85	95²	75	85	95	75	85	95
Refr & Combis	102	116	121	102	118	132	88	95	99	99	94	104	109	116	121
Freezers	35	36	33	39	51	66	35	57	67	48	63	64	N.A.	N.A.	N.A.
Clothes Wash.	70	77	85	82	89	94	65	81	85	44	58	70	96	98	98
Dryer	39	49	55	4	14	28	3	9	23	3	12	27	0	5	20
Dish Washer	30	46	48	11	29	40	5	20	40	10	21	33	N.A.	N.A.	N.A.

country	N			S			UK			I			F		
	75	85	951	75	85	95	75	85	95	75	85	95	75	85	95
Refr & Combis	93	100	106	100	109	114	83	98	104	92	96	.1 99	84	97	98
Freezers	64	78	79	65	75	86	15	36	38	2	15	22	13	35	46
Clothes Wash.	73	85	92	62	78	86	71	84	90	71	77	83	69	84	90
Dryer	17	22	36	15	38	42	8	28	40	N.A.	N.A.	N.A.	0	4	13
Dish Washer	5	30	38	17	28	47	2	6	18	8	10	14	7	25	34



Figure 5. Carbon emissions from appliances and lighting per capita in 10 OECD countries between 1970 to 1995

<sup>&</sup>lt;sup>2</sup> Note that for Norway and France 1995 values were estimated from 1993 and 1994 values

Due to the fact that electricity is produced (at least partly) in many countries by thermal power plants, electric appliances and lighting account for a relatively large release of  $CO_2$  per unit of delivered energy.

Figure 5 shows the development of carbon emissions from appliances and lighting per capita in the investigated countries. We observe an increase of about 100% in Western Germany, Italy, Japan and Austria and a growth of about 50 % in the United States and in Denmark. Due to major changes in the primary fuel mix of utilities, France and the U.K. experienced almost flat emissions path from 1970-1995. Since electricity is generated mostly by hydro-power in Norway and Sweden, carbon emissions from appliances and lighting are basically insignificant in those countries.

## An Augmented STRINT Approach to Decomposing Carbon Emissions

By constructing a bottom-up analysis using a wide variety of national sources from each country, previous LBNL studies (e.g. see (Schipper et al. 1992; Howarth, Schipper 1993)) used the STRINT methodology to decompose energy consumption into three underlying components: activity, structure, and energy intensity. *Activity* ( $f_{A,t}$ ) simply counts the number of housed people. *Structure* ( $f_{S,t}$ ) divides energy demand into three major end-uses: (i) Structure for heating considers the number of heated square meters of home area per capita, with homes heated by central heating systems counted at twice the weight of those heated by room stoves; (ii) Structure for appliances reflects the number of major appliances per capita; (iii) Structure for lighting is set equal to residential floor area. Finally, *energy intensity* ( $f_{EI,t}$ ) is calculated as the ratio of energy use to activity. The residual term, ( $f_{R,t}$ ), comprises factors not captured by activity, structure or intensity. We cast each term as a ratio to its own value in 1990, in order to show its impact on energy use, normalized for climate variations by using annual heating degree days, as follows in Equation 1:

 $E_{\rm t} = f_{\rm A,t} f_{\rm S,t} f_{\rm EI,t} f_{\rm R,t} E_{90}$ 

 $E_t$  ..... Energy demand in year t

 $E_{90}$ .... Energy demand in 1990

In order to evaluate  $CO_2$  emissions ( $C_t$ ), we augment Equation 1 with a term that captures the carbon content per unit of final energy, ( $f_{FCC,t}$ ). This term considers six different kinds of fuels (oil, natural gas, coal, renewables, district heating, and electricity). The carbon release for oil, natural gas and coal are presumed to be constant over time. The carbon release factor for electricity and district heating vary from year to year, depending on primary fuel mix. Renewables are assumed to have zero net emissions, since we presume that biomass is harvested sustainably. With this in mind, Equation 1 can be modified as follows to include carbon emissions:

$$\mathbf{C}_{\mathsf{t}} = \boldsymbol{f}_{\mathsf{FCC},\mathsf{t}} \boldsymbol{E}_{\mathsf{t}} = \boldsymbol{f}_{\mathsf{A},\mathsf{t}} \boldsymbol{f}_{\mathsf{S},\mathsf{t}} \boldsymbol{f}_{\mathsf{EI},\mathsf{t}} \boldsymbol{f}_{\mathsf{FCC},\mathsf{t}} \boldsymbol{f}_{\mathsf{R},\mathsf{t}} \boldsymbol{E}_{90}$$

This decomposition yields a time series for each factor, whose product equals the emissions level in any year as a proportion 1990 emissions

For forecasting future aggregate carbon emissions in the ten investigated countries, the underlying effects (activity, structure, energy intensity and fuel carbon content) are calculated as follows:

$$C_{A,t} = \sum_{countries} f_{A,t} f_{FCC,90} E_{90}$$
(3)

(1)

$$C_{S,t} = \sum_{countries} f_{S,t} f_{FCC,90} E_{90}$$
(4)

$$C_{EI,i} = \sum_{countries} f_{EI,i} f_{FCC,90} E_{90}$$

$$C_{FCC,i} = \sum_{countries} f_{FCC,i} E_{90}$$
(6)

We measure the effect of each term by allowing it to vary over time, while holding all other factors at their 1990 value.  $C_{A,t}$  is the effect of population changes on emissions.  $C_{S,t}$  is the structure effect (measuring heated square meters, proportion of central heated dwellings to non- central heated dwellings, floor area, number of major appliances per capita).  $C_{EI,t}$  scales changes in the ratio of energy use to activity, and  $C_{FCC,t}$  accounts for shifts in the fuel carbon content.

#### **Results of the Augmented STRINT Approach for Space Heating**

As described above, we decompose CO<sub>2</sub> emissions for space heating into four underlying causes. We compare the annual rates of change for those determinants before and after 1990, in order to provide further insight into the trends over time for emissions in the observed countries. Figure 6 presents this analysis below. In **Western-Germany** we observe almost constant structural growth rates before and after 1990, with the number of heated square meters and the percentage of dwellings with central heated dwellings each following a smooth incline. This structural growth was balanced by an equally large decline in energy intensity up until 1990, which pointed to energy efficiency improvements in the 1970's and 1980's. After 1990, however, energy intensity began to rise, reinforcing the structure effect. Activity (the number of housed people) does not vary significantly in Western Germany, and thus has no effect on residential carbon emissions. Due to large shifts from oil and coal to gas in recent years, fuel carbon content declines strongly after 1990. However, the transition to lower carbon fuels does not compensate for the steady rates of structural growth, which will continue to bolster carbon emissions from space heating in Western Germany.

Over the whole period the **U.S.** experienced a large activity effect, but compared to other countries, a small structure effect. The structural impacts are relatively minor because the U.S. began with high initial levels of heated floor area and penetration of central heating systems. Its strong declines in energy intensity ease after 1990, implying a declining pace for efficiency gains. Space heating carbon emissions should remain almost stable in the U.S. in the near future, with the U.S. probably maintaining the highest level of per capita carbon emissions from residential space heating.

In Austria we recognize hearty structural growth, and almost no factors constraining carbon emissions. This suggests that emissions will continue to increase 2% per year in the near future. The high initial levels of carbon emissions in **Denmark** were reduced chiefly by efficiency improvements before 1990, and by reductions in the fuel carbon content after 1990. Minor upward pressure on  $CO_2$  from activity and structure effects will not prevent further reductions in carbon emissions. **Japan** experienced major structural growth from 1970 to 1995. Because an increasing share of dwellings are heated by electricity, Japan's fuel carbon content grew during the entire period. Although Japan achieves large reductions in energy intensity, future carbon emissions should continue to grow by almost 1.5% per year.

Norway<sup>3</sup> and Sweden attained the largest reductions in  $CO_2$  emissions from residential space heating. Declines in fuel carbon content, driven by transitions to hydro-power electricity, were the

<sup>&</sup>lt;sup>3</sup> For easier viewing of comparisons, we do not display the average annual change of fuel carbon content, which is 14%.

strongest factor. Remarkably, fuel carbon content for Norway decreased annually by 5.2% before 1990 and by 14.3% after 1990 (we did not included these values in Figure 7 due to scaling issues). Quite simply, carbon emissions from space heating were insignificant in these two Nordic countries.



Figure 6. Annual rates of change for activity, structure, energy intensity, and fuel carbon content for space heating before and after 1990

In the U.K. we observe an annual increase in structure of 1.3% before 1990, which was balanced by improvements in energy efficiency and fuel carbon content. After 1990 structural growth slowed slightly, while the carbon content of heating fuels declined at a faster rate. If this trend continues, carbon emissions from space heating will decline slightly in the near future. The structural growth in **France** was counterbalanced by steep reductions in fuel carbon content. These reductions stemmed from fuel switching to electricity, which was largely produced by nuclear power plants which release no  $CO_2$ . Ongoing energy intensity declines will contribute to further reductions in carbon emissions in the future. Finally, small structural increases in **Italy** were offset by minor reductions in energy intensity and fuel carbon content. In summary, we expect emissions in the near future to increase in three out of ten countries (Western-Germany, Austria and Japan), to remain stable in two counties (USA and Italy), and to decline in five countries (Denmark, Norway, France, Sweden, and U.K.).

Figure 7 illustrates an aggregate decomposition of all the observed countries. For the ten countries as a whole, the activity effect remained constant at 0.7% during the whole period of

investigation. Prior to 1990, increases in structure and activity were completely balanced by decreases in energy intensity, while fuel switching did not have an important impact on  $CO_2$  emissions. After 1990, the increase in structure slowed and was countered by small reductions in energy intensity and the fuel carbon content. Based on these developments, we project total carbon emissions from space heating in the ten observed countries to remain stable in coming years.



Figure 7 Aggregate effects of activity, structure, energy intensity, and fuel carbon content for space heating carbon emissions in 10 OECD countries

## **Results of the Augmented STRINT Approach for Electric Appliances and Lighting**

We also decomposed  $CO_2$  emissions for electric appliances and lighting into four underlying causes, and calculated their annual rates of change before and after 1990. Figure 8 shows the results of this decomposition technique.

In Western-Germany the structure effect strongly increases carbon emissions- the housing stock and appliance ownership levels are expanding quickly. Reductions in fuel carbon content (ktC per delivered PJ of electricity) and a small decrease in energy intensity failed to balance these structural increases. Thus,  $CO_2$  emissions from electric appliances and lighting should continue growing by about 2% per year.

In the U.S., reductions in the carbon release from electricity use and lower energy intensities constrained some growth in  $CO_2$  emissions after 1990, but present trends suggest a 1% annual growth rate of carbon emissions. In Austria dramatic increases in appliance saturation and floor area outweigh improvements in energy intensities and fuel carbon content. These structural factors will drive future carbon emissions to increase 1% per year in coming years. Denmark experienced growth in carbon emissions before 1990 largely due to structural growth. After 1990, small reductions in energy intensities and a remarkable decline in electricity  $CO_2$  intensity helped balance continued structural growth, and should considerably reduce emissions in the future.

For Japan we observe the opposite phenomenon. Before 1990, activity and structure effects were offset by the impacts of energy intensity and fuel carbon content. After 1990, improvements in energy intensities and fuel carbon content nearly died out, which yielded increases in  $CO_2$  emissions of almost 3% per year. The carbon emissions from appliances and lighting in Italy and the U.K. should remain stable in the near future. For Norway<sup>4</sup>, Sweden<sup>4</sup> and France<sup>4</sup>, carbon emissions from appliances and lighting are essentially insignificant, due to low-carbon electricity.



Figure 8. Annual rates of change for activity, structure, energy intensity, and fuel carbon content for appliances and lighting before and after 1990

Figure 9 shows the results of combining the underlying determinants of  $CO_2$  emissions caused by electric appliances and lighting for all ten countries, using Equations 3 through Equation 6. Interestingly, the annual rate of  $CO_2$  emissions increased more quickly after 1990 (2.4%) than it did before 1990 (1.7%). As with space heating, activity rose 0.7% per year for the whole period. Structural changes increased carbon emissions 2.9% before 1990 and 3.4% afterwards. The impact of reductions in energy intensities declined from -0.9% to -0.6%. The major restraint on carbon emissions from appliances and lighting was a shift in the primary fuel mix for electricity. The carbon content of electricity declined 1.1% per year before 1990 and 1.3% afterwards.

<sup>&</sup>lt;sup>4</sup> For easier viewing of comparisons, we chose not to display the average annual change of fuel carbon content for Norway (-8%), Sweden (-13%) and France (-13%).



Figure 9. Aggregate effects of activity, structure, energy intensity, and fuel carbon content for electric appliances and lighting carbon emissions in 10 OECD countries

## **Conclusions and Future Emissions Trajectories**

Carbon emissions from space heating were virtually stable among the observed countries from 1970-1995. Other investigations of residential  $CO_2$  emissions (see e.g. Schipper et al 1996a and Schipper et al 1996b), found similar trends for water heating and cooking. Emissions from appliances and lighting, however, have grown considerably over the last quarter century, due mostly to increases in floor area and appliance ownership levels. This is a threatening development if policymakers intend to restrain future  $CO_2$  emissions.



Figure 10. Aggregated development and possible future developments of residential carbon emissions in ten OECD countries

Figure 10 shows possible future developments for residential carbon emissions from 1995 until 2005. The "Present trends continue" scenario was calculated with recent trends in activity, structure, energy intensity and fuel carbon content. Under this scenario,  $CO_2$  will increase 2.2% per year until 2005- an 8% emissions increase over 1995 levels and 10% growth from 1990 levels. The second scenario (worst case) assumes that energy intensity and fuel switching benefits die out after 1995. This produces 2005 carbon emission levels 16% higher than 1995 and 19% higher than 1990.

In sum, the structural growth of electric appliances and lighting has bolstered residential  $CO_2$  emissions, and has accelerated since 1990. We expect this development to continue in coming years, and for energy intensity declines to slow, especially in countries with lower per capita energy use. In the absence of serious policy intervention, residential carbon emissions will rise more quickly in coming years, and make it increasingly difficult for industrialized countries to meet emissions levels outlined in December 1997 at the Third Conference of Parties in Kyoto.

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### **Data Sources:**

The most recent listing of major data sources can be found in the appendix to Schipper, (1997) and in Haas et al, (1998).