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Publication Date
1999-09-01

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**Environmental Energy
Technologies Division**

September 1999

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Abstract. Disaggregation of sectoral energy use and greenhouse gas emissions trends reveals striking differences between sectors and regions of the world. Understanding key driving forces in the energy end-use sectors provides insights for development of projections of future greenhouse gas emissions. This report examines global and regional historical trends in energy use and carbon emissions in the industrial, buildings, transport, and agriculture sectors, with a more detailed focus on industry and buildings. Activity and economic drivers as well as trends in energy and carbon intensity are evaluated. We show that macro-economic indicators, such as GDP, are insufficient for comprehending trends and driving forces at the sectoral level. These indicators need to be supplemented with sector-specific information for a more complete understanding of future energy use and greenhouse gas emissions.

1. Introduction[1]

Future projections of greenhouse gas emissions rely on a number of variables for predicting trends in energy use, including both the level of energy demand and the various sources used to provide this energy. Macro-economic models use historical data as well as estimates of future population, gross domestic product (GDP), autonomous energy efficiency improvement rates, elasticities, and energy prices to determine energy demand levels. These variables, however, do not clearly explain all of the driving forces behind historical or future energy use patterns. As such, more detailed socio-economic and technical information is needed by policy analysts and policymakers. Only with such information can they identify greenhouse gas mitigation measures and formulate policies to implement these measures.

Greenhouse gas emissions from energy use, predominately in the form of carbon emissions, are the result of burning carboniferous fossil fuels. This paper reviews historical trends in energy use and carbon emissions and provides insights on driving forces such as economics, activity levels, and energy and carbon intensity trends. To improve our understanding of global energy use and carbon emissions trends and relationships, we focus on the key sectors of the economy that use energy: industry, buildings, transport, and agriculture. To gain insight on regional trends, we divide the world into four categories based on similar economic development characteristics: industrialized countries, economies in transition in Eastern Europe and the former Soviet Union (EITs), developing countries in Asia/Pacific (DC-AP), and the rest of the world (ROW).[2]

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[1] Much of this material has been published in Price et al., 1998.

[2] We recognize that the countries of the EIT region are also industrialized, but have separated them from the other industrialized countries due to their distinct situation as a group of countries undergoing similar economic transitions from centrally-planned economies to market-based economies. A list of the countries included in each region is provided in Appendix A.

The industrial sector is extremely diverse, encompassing the extraction of natural resources, conversion into raw materials, and manufacture of finished products. Five energy-intensive industrial sub-sectors account for roughly 45% of all industrial energy consumption (iron and steel, chemicals, petroleum refining, pulp and paper, and cement). These industries are generally engaged in the transformation of raw material inputs (e.g. iron ore, crude oil, wood) into usable materials and products for an economy. Throughout this paper, we focus on the iron and steel industry when discussing energy-intensive industry.

Energy use in residential and commercial buildings varies throughout the world, reflecting differing climatic conditions, building construction practices, appliance and equipment penetrations, and overall levels of energy demand. Residential buildings range from single-family, detached dwellings to multi-family apartment complexes. Energy consumption levels depend on building shell features such as insulation levels and the energy-efficiency of windows as well as the number of energy-using appliances, how these appliances are used, and their energy-efficiency. Energy use in commercial buildings is also related to features of the building shell and appliance and equipment penetration levels; analysts have shown a strong relationship between commercial building type and energy use.

Transport sector development is easy to quantify; world vehicle stocks, fuel consumption and fuel prices are well known. In addition, there has been considerable modeling in the transport sector, probably because of the high degree of government involvement in transport infrastructure planning. Transport energy use can be disaggregated into passenger and freight transport, and by modes such as automobile, truck, rail, ship, or air. Road transport, both passenger and commercial, accounts for the vast majority of total transport energy use.

Commercial energy is used in the agriculture sector for equipment, irrigation, drying, horticulture, and raising livestock. Energy use for production of fertilizers and pesticides is not included in this sector bur rather is accounted for in the industrial sector. Non-commercial energy, an important element of traditional agriculture, is also not included in this discussion. Due to a lack of detailed information on this sector, we do not include it in our discussion of sectoral driving forces.

The goal of this report is to provide historical sectoral-level energy and carbon emissions data as well as an understanding of the key underlying drivers of energy use and carbon emissions in two of the end-use sectors: industry and buildings. Such information is helpful for the development of energy use and carbon emissions scenarios because it provides modelers with a historical basis from which to extrapolate trends as well as information on how various factors such as population, energy intensity, and structural trends affect energy use and associated greenhouse gas emissions.

We first discuss historical trends in energy use and greenhouse gas emissions by end-use sector for four world regions. After that, we examine activity and economic drivers of energy use and greenhouse gas emissions in the industrial, buildings, and transport sector. Next we discuss energy and carbon intensity trends by sector. We conclude by commenting on how these historical trends and drivers can be used in the development of greenhouse gas emissions scenarios.

2. Data and Methodology

2.1 Data

This report presents energy use and carbon emissions data for the industrial, buildings (both commercial and residential), transport, and agriculture sectors. The end-use breakdown was made using IEA (International Energy Agency) statistics (IEA, 1997a; IEA 1997b; IEA, 1997c), British Petroleum (BP) data for energy trends in the EIT region (BP, 1997), and expert judgment of the authors.[3] The IEA statistics, on which most of the data in this paper are based, include all "commercial" sources of energy, defined as hard coal, brown coal/lignite, natural gas, crude oil, natural gas liquids, hydro, geothermal/solar, wind, tide, and nuclear power as well as coal products, manufactured gases, petroleum products and electricity. Data on biomass ("combustible renewable and waste") energy sources are included, although there are uncertainties regarding the quality of these data (IEA, 1994; IEA, 1997a; IEA 1997b). IEA data are available beginning in 1960 for industrialized countries and beginning in 1971 for all other countries. Primary energy was calculated assuming an electricity generation efficiency of 33%. Following IEA convention, we do not include the energy used for conversion of primary fuels in the end-use sector totals. If petroleum refining and coke oven gas were added to the industrial sector values, global industrial sector energy use would increase by roughly 12%.

The energy use and carbon emissions data presented in this paper are based on a reallocation of IEA end-use data for all regions except the EIT region. The IEA energy statistics report final energy and electricity use for end-use sectors defined as industry (TOTIND), transport (TOTTRANS), and other (TOTOTHER). The other category is further divided into agriculture (AGRICULT), commercial and public services (COMMPUB), residential (RESIDENT), and non-specified other (ONONSPEC). This last category includes energy use in the agriculture, commercial and public services, and residential sectors that has not been allocated to these end-use sectors by the submitting countries. In some cases, there is no entry for the non-specific other category, indicating that all end-use energy consumption has been allocated to the other end-use sectors. However, some countries require the reallocation of the non-specified other category to the end-use sectors. This is especially important for those years in which a particular country reports all of the other energy use as non-specified. To perform this reallocation, the non-specified other category was allocated to the other end-use sectors (agriculture, commercial and public services, residential) based on the share of allocated energy in each of these sub-sectors for each of the industrialized countries and the IEA groupings of Asia excluding Japan, Africa, Latin America, and the Middle East.[4]

Carbon embodied in electricity and heat consumption was calculated by multiplying the amount of electricity and heat used by average yearly carbon factors for electricity and heat produced. Carbon factors were derived as the ratio of carbon emissions from all fuel inputs at power plants to electricity or

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[3] The authors worked with a number of staff members at the IEA to both understand the IEA end-use sector allocations and to use their knowledge to assist in the reallocation.

[4] The results of this allocation scheme were compared to LBNL sectoral energy data for a number of industrialized countries. In general, the sectoral energy consumption values based on allocated IEA data compared favorably to LBNL data for total buildings and agriculture for most countries. Larger discrepancies were seen between the LBNL data and the allocated IEA data at the level of commercial and residential buildings. Further analysis of the differences between the allocated IEA data and LBNL data is required to fully understand energy use trends at the commercial and residential buildings level.

3

heat delivered.[5] Fuel inputs for electricity production were separated from inputs to heat production. Fuel inputs to electricity production contain fuels that are used in electricity plants (both public and autoproducer plants) and fuels that are used for electricity production in combined heat and power plants. Fuel inputs into heat production combine fuels used in heat plants (both public and autoproducer plants) and fuels that are used for heat production in combined heat and power plants.[6] Fuel inputs in combined heat and power plants are separated into fuel inputs for electricity and heat production according to the shares of electricity and heat produced in these plants. The data for fuel inputs in all power plants, as well as for electricity and heat output from each type of plant, were taken from the IEA Extended Energy Balances Database. The fuel inputs were multiplied by the respective carbon emission factors for each fuel. We calculated carbon emissions by sector for industrialized countries and selected EIT, DC-AP, and ROW countries. When aggregated, our total carbon emissions for a country or region differ from IEA values because we only include emissions from fuel combustion, electricity, and heat consumption. IEA CO_2 statistics include a number of other categories, such as unallocated non-energy use, that we did not include.

We used BP data for energy use trends in the EIT region because IEA data show growth in buildings sector energy use between 1990 and 1995 in this region, despite the serious economic difficulties experienced during this period. In contrast, BP statistics show a decline in overall buildings energy use at this time. EIT data were provided in primary units by BP. We converted these primary values to fuel and electricity values based on their shares as reported in IEA statistics for this region. Sectoral energy use shares were calculated based on a previous analysis (WEC, 1995a). Carbon emissions for the former Soviet Union were carefully derived following a fuel-by-fuel review of IEA data that included reallocations to attempt to correct for missing or obviously erroneous data. Carbon emissions for the other EIT countries included in Table 4 were calculated using IEA data. We strongly caution the reader to recognize the uncertainty in the values presented for this region; however, we believe that these are the best sectoral level estimates of energy use and carbon emissions currently available for the EIT countries.

Additional difficulties were encountered with the data for China for 1971 and 1975, years for which official data are scarce for that country. For final energy, the reported values for industry for these years (0.96 and 1.3 EJ, respectively) represented significantly lower shares of total final energy (12% and 13%, respectively) than the 61% to 66% shares seen in 1980-1995. Thus, total industry values for 1971 and 1975 were adjusted to 60% of total final energy for 1971 and 1975. Similar adjustments were made in the transport sector, where the 1971 and 1975 values were 3% and 4% of total final energy, respectively. These values were adjusted to be 6% of total final energy which is more closely aligned with the 8 to 9% experienced in later years. No values were reported for the categories of agriculture, commercial buildings, and residential buildings for China for 1971 and 1975 (except residential in 1975). A non-specified other value was reported for both of these years. However, adding the non-specified other (plus residential in 1975), industry, and transport values does not result in the reported total final consumption value for these sectors. To resolve this discrepancy, the reported values for non-specified other for 1971 and 1975 were not used; instead non-specified other was calculated as the difference between the adjusted industry and transport values and total final consumption. This non-specified other category was then allocated to agriculture, commercial buildings, and residential buildings based on the 1980 shares of

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[5] Delivered electricity or heat is primary (gross) electricity or heat produced excluding distribution losses.

[6] This excludes heat pumps and electric boilers since fuel inputs for those energy producers are electricity and heat, respectively.

these end-use sectors. Similar adjustments and reallocations were made to the electricity values for 1971 and 1975 for China.

We compared the IEA data for China to Chinese national statistics for the years 1980 to 1990 (Sinton, 1996). Final energy use was virtually the same in all sectors for all years, except for the residential sector in 1990 (national statistics were 1.4 EJ higher than IEA statistics) and the industrial sector for all three years (national statistics were 2.6 EJ, 3.4 EJ, and 5.1 EJ higher that IEA statistics in 1980, 1985, and 1990, respectively). We use IEA statistics in this paper, but caution the reader that more research is needed to understand the differences between IEA statistics and Chinese national statistics.

2.2 Methodology

This report presents historical energy use and carbon emissions trends and discusses the underlying drivers of these trends. The main factors affecting growth of carbon emissions in an economy include the rate of population growth, the size and structure of the economy (depending on consumption patterns and stage of development), the amount of energy consumed per unit of activity, and the specific carbon emissions of the fuel mix used. Our discussion of the drivers is guided by the terms of the so-called Kaya identity (Kaya, 1989) as outlined by equation 1.

$$\text{CO}_2 \text{ Emissions} = \text{Population} \times \frac{\text{GDP}}{\text{Person}} \times \frac{\text{Energy}}{\text{GDP}} \times \frac{\text{CO}_2}{\text{Energy}} \qquad (1)$$

We have redefined the terms slightly to more closely match the available data and the characteristics of the end-use sectors that we focus on in this paper. Thus, our discussion is structured as given by equation 2.

$$\text{CO}_2 \text{ Emission} = \text{Activity Drivers} \times \text{Economic Drivers} \times \text{Energy Intensity} \times \text{Carbon Intensity} \qquad (2)$$

The various terms are defined differently in each end-use sector. For example, while activity is generally linked to population in all sectors, it also includes commodity production levels in the industrial sector, number of persons per household in the residential sector and cubic meters of building space in the commercial sector.

We begin with a discussion of historical energy use and carbon emissions trends in Section 3. This is followed in Section 4 with a more detailed discussion of the energy use and carbon emissions drivers and terms in equation 2 for the industrial and buildings sectors. We discuss the main drivers for these sectors and explain trends and regional variations. Understanding these factors enables calibration of models to trends observed in the past.

3. Historical Trends in Energy Use and Carbon Emissions

3.1 Primary Energy Demand

Global primary energy use grew from 191 EJ in 1971 to 307 EJ in 1990 at an average annual growth rate (AAGR) of 2.5% per year. This growth tapered off in all sectors after 1990, with total global primary energy increasing to only 319 EJ by 1995 (see Table 1), mainly due to the large declines experienced in the EIT region because of the political and economic restructuring in many of those countries.

Figure 1 shows that the industrial sector clearly dominates total primary energy use, followed by the buildings sector (commercial and residential buildings combined), the transport sector, and the agriculture sector. Figure 2 shows that between 1971 and 1990, the largest annual growth was experienced in the commercial buildings and agriculture sectors. After 1990, these trends shifted, with transport experiencing the fastest growth, while very little growth was seen in the industrial sector. Industrialized countries consumed about 160 EJ (52%) in 1990 compared to 74 EJ (24%) in the EIT, 45 EJ (14%) in the DC-AP, and 30 EJ (10%) in the ROW regions. Growth in primary energy use between 1971 and 1990 was highest in the DC-AP and ROW regions, which grew at average annual rates of 5.8% and 5.4%, respectively. Table 2 provides detailed information on primary energy use by sector by region.

Table 1. Global Primary Energy Use by Sector, 1971-1995 (EJ). Reference: IEA, 1997a; IEA, 1997b; BP, 1997.

	1971	1975	1980	1985	1990	1995	AAGR 1971-90	AAGR 1990-95
Industrial	88.0	98.5	113.5	119.8	129.4	130.8	2.1%	0.2%
Buildings	61.5	70.3	81.3	92.6	105.6	109.8	2.9%	0.8%
Residential	41.7	47.1	54.5	60.6	67.4	69.4	2.6%	0.6%
Commercial	19.8	23.2	26.8	31.9	38.2	40.3	3.5%	1.1%
Transport	37.5	43.6	50.1	54.4	63.3	69.0	2.8%	1.7%
Agriculture	4.4	5.1	6.1	7.5	8.9	9.3	3.8%	0.8%
Total 4 sectors	191.4	217.5	251.0	274.2	307.2	318.8	2.5%	0.7%

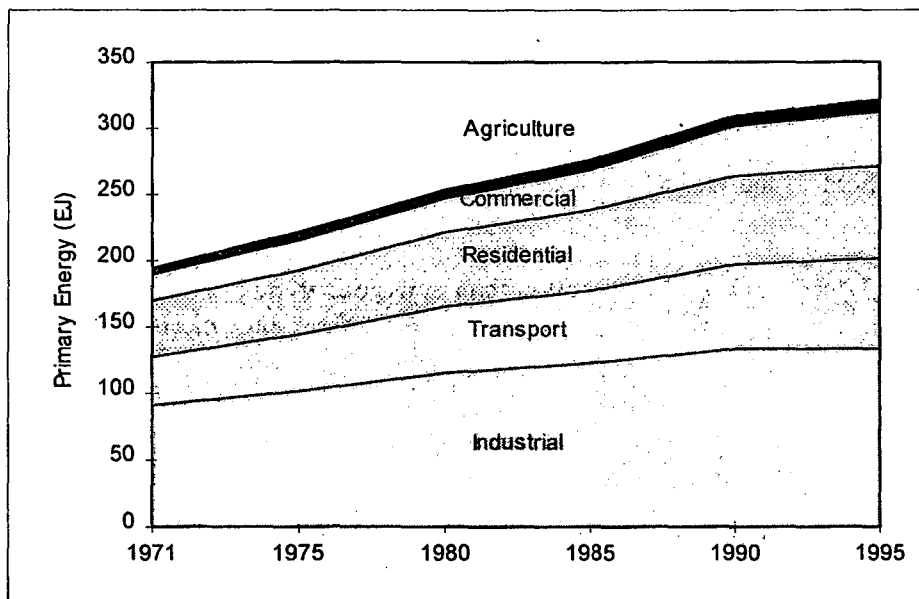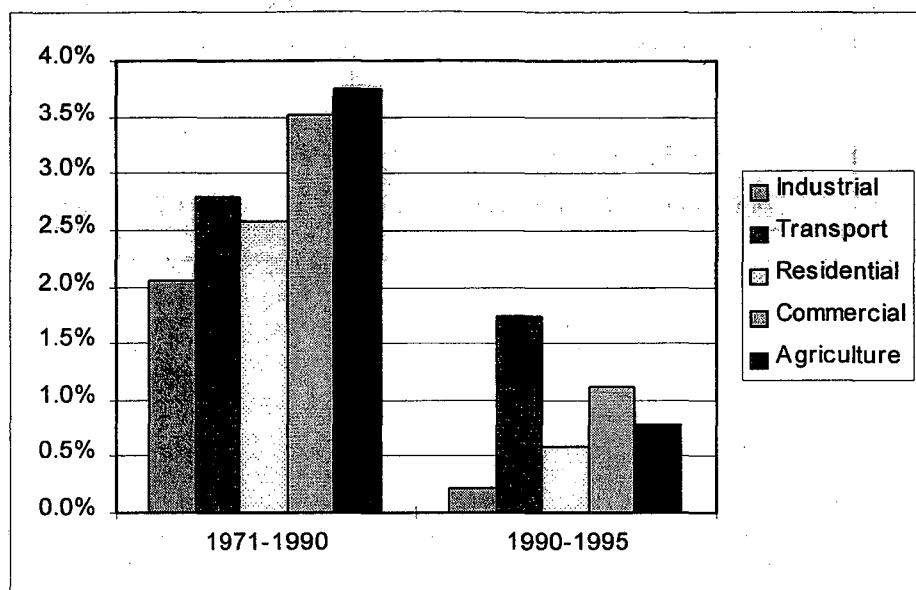*Figure 1.* Global Primary Energy Use by Sector, 1971 to 1995.

Figure 2. Average Annual Growth in Global Primary Energy Use by Sector.

3.1.1 Primary Energy Demand: Industry

In 1990, industry accounted for 42% (129 EJ) of global energy use. Between 1971 and 1990, industrial energy use grew at a rate of 2.1% per year, slightly less than the world total energy demand growth of 2.5% per year. This growth rate has slowed in recent years, and was virtually flat between 1990 and 1995, primarily because of declines in industrial output in the EIT region. Energy use in the industrial sector is dominated by the industrialized countries, which accounted for 42% of world industrial energy use in 1990. Countries in the EIT, DC-AP, and ROW regions used 29%, 20%, and 9% of world industrial energy use, respectively, that year (see Table 2).

Industrial energy consumption in the industrialized countries increased at an average rate of 0.6% per year between 1971 and 1990, from 49 EJ to 54 EJ. The share of industrial sector energy consumption within the industrialized countries declined from 40% in 1971 to 33% in 1995. This decline partly reflects the transition toward a less energy-intensive manufacturing base, as well as the continued growth in transportation demand, resulting in large part from the rising importance of personal mobility in passenger transport use. The industrial sector dominates in the EIT, accounting for more than 50% of total primary energy demand, the result of the long-term policy emphasizing materials production that was promoted under years of central planning. Average annual growth in industrial energy use in this region was 2.0% between 1971 and 1990 (from 26 EJ to 38 EJ), but dropped by an average of −7.3% per year between 1990 and 1995.

In the DC-AP region, the industrial sector accounted for between 57% and 60% of primary energy consumption during the period 1971 to 1995. Industrial energy use grew rapidly between 1971 and 1995, with an annual average growth rate of 5.9%, jumping from 9 EJ to 35 EJ. The fastest growth in this sector was seen in China and in other rapidly-developing Asian countries.

Table 2. Primary Energy Use by Sector and Region, 1971-1995 (EJ). Reference: IEA, 1997a; IEA, 1997b; BP, 1997.

	1960	1971	1975	1980	1985	1990	1995	AAGR 1960-1990	AAGR 1971-1990	AAGR 1990-1995
Industrial Sector										
Industrialized Countries	27.7	48.6	49.3	55.0	52.3	54.3	56.8	2.3%	0.6%	0.9%
Economies in Transition		26.0	31.6	34.0	36.9	38.0	26.0		2.0%	-7.3%
Developing Cos. in Asia-Pacific		8.8	11.5	15.5	20.0	26.1	34.8		5.9%	5.9%
Rest of World		4.6	6.2	8.9	10.5	11.0	13.0		4.7%	3.5%
World		88.0	98.5	113.5	119.8	129.4	130.8		2.1%	0.2%
Buildings Sector										
Industrialized Countries	28.3	44.4	48.9	52.3	56.8	62.3	68.5	2.7%	1.8%	1.9%
Residential	*16.6*	*28.3*	*30.5*	*33.0*	*34.6*	*36.7*	*40.6*	*2.7%*	*1.4%*	*2.0%*
Commercial	*11.7*	*16.1*	*18.4*	*19.3*	*22.2*	*25.6*	*27.9*	*2.6%*	*2.5%*	*1.7%*
Economies in Transition		10.7	13.0	18.2	21.0	23.0	16.2		4.1%	-6.8%
Residential		*8.1*	*9.8*	*12.9*	*14.3*	*15.1*	*10.4*		*3.3%*	*-7.2%*
Commercial		*2.6*	*3.2*	*5.3*	*6.7*	*7.9*	*5.8*		*6.0%*	*-6.1%*
Developing Cos. in Asia-Pacific		3.6	4.6	5.6	7.9	10.2	12.9		5.7%	4.8%
Residential		*3.0*	*3.9*	*4.6*	*6.3*	*7.9*	*9.3*		*5.2%*	*3.4%*
Commercial		*0.6*	*0.8*	*1.0*	*1.6*	*2.3*	*3.6*		*7.8%*	*8.9%*
Rest of World		2.7	3.7	5.1	6.9	10.1	12.1		7.1%	3.8%
Residential		*2.2*	*2.8*	*3.9*	*5.4*	*7.8*	*9.1*		*6.8%*	*3.2%*
Commercial		*0.5*	*0.8*	*1.2*	*1.5*	*2.3*	*3.0*		*8.5%*	*5.7%*
World		61.5	70.3	81.3	92.6	105.6	109.8		2.9%	0.8%
Residential		*41.7*	*47.1*	*54.5*	*60.6*	*67.4*	*69.4*		*2.6%*	*0.6%*
Commercial		*19.8*	*23.2*	*26.8*	*31.9*	*38.2*	*40.3*		*3.5%*	*1.1%*
Transport Sector										
Industrialized Countries	14.7	26.2	29.4	32.5	33.8	39.4	43.3	3.3%	2.2%	1.9%
Economies in Transition		6.0	7.3	8.0	9.2	10.0	7.3		2.7%	-6.0%
Developing Cos. in Asia-Pacific		2.0	2.4	3.3	4.3	6.0	8.7		5.9%	7.6%
Rest of World		3.3	4.6	6.3	7.2	7.8	9.6		4.6%	4.2%
World		37.5	43.6	50.1	54.4	63.3	69.0		2.8%	1.7%
Agriculture Sector										
Industrialized Countries	1.2	1.8	1.8	2.1	2.6	2.7	3.0	2.9%	2.2%	1.6%
Economies in Transition		1.3	1.6	1.8	2.4	3.0	1.7		4.5%	-10.6%
Developing Cos. in Asia-Pacific		0.9	1.3	1.6	1.7	2.3	3.0		4.8%	5.6%
Rest of World		0.4	0.5	0.7	0.8	0.9	1.6		4.7%	12.6%
World		4.4	5.1	6.1	7.5	8.9	9.3		3.8%	0.8%
All Sectors										
Industrialized Countries	71.8	121.0	129.3	141.8	145.5	158.8	171.7	2.7%	1.4%	1.6%
Economies in Transition		44.0	53.5	62.0	69.5	74.0	51.3		2.8%	-7.1%
Developing Cos. in Asia-Pacific		15.4	19.7	26.0	33.9	44.7	59.5		5.8%	5.9%
Rest of World		11.0	14.9	21.1	25.4	29.8	36.4		5.4%	4.1%
World		191.4	217.5	251.0	274.2	307.2	318.8		2.5%	0.7%

Growth in the ROW region was slightly lower, averaging 4.7% per year between 1971 and 1990 and 3.5% per year between 1990 and 1995. The nature and evolution of the industrial sector varies considerably among developing countries. Some economies that are experiencing continued expansion in energy-intensive industry, such as China and India, show relatively unchanging shares of industrial energy use. In other countries, such as Thailand and Mexico, the share and/or growth of the transportation sector dominate. Many smaller countries have remained primarily agrarian societies with modest manufacturing infrastructure.

3.1.2 Primary Energy Demand: Buildings

In 1990, residential and commercial buildings consumed slightly over 100 EJ of primary energy, about one-third of total global primary energy. Table 2 shows that primary energy use in the buildings sector worldwide grew at an average annual rate of 2.9% between 1971 and 1990. Over the period, growth in buildings energy use varied widely by region, ranging from 1.8% per year in industrialized countries to 7.1% per year in the ROW region. Growth in commercial buildings was higher than growth in residential buildings in all regions of the world, averaging 3.5% per year globally. In 1990, industrialized countries used about 60% of global buildings energy, followed by the EIT (22%), DC-AP (10%), and ROW (9%) countries, respectively.

Between 1990 and 1995, growth in the use of primary energy in buildings slowed in all regions except the industrialized countries where buildings primary energy use climbed at an average of 1.9% per year. The greatest decline occurred in the EIT region due to the economic and political restructuring that began in the late 1980s. As a result, buildings energy use in this region declined an average of 6.8% annually between 1990 and 1995, dominated by a 7.2% per year average drop in residential primary energy use. Growth in buildings energy use in the other two regions – DC-AP and ROW – slowed during this period, but growth rates were still high, averaging 4.8% and 3.8%, respectively.

3.1.3 Primary Energy Demand: Transport

The transport sector consumed slightly over 63 EJ, or about 20% of global primary energy in 1990. Transport sector primary energy use grew at a relatively rapid average annual rate of 2.8% between 1971 and 1990, slowing to 1.7% per year between 1990 and 1995 (see Table 2). Industrialized countries clearly dominate energy consumption in this sector, using 62% of the world's transport energy in 1990, followed by the EIT (16%), the ROW region (12%), and the DC-AP region (10%). The most rapid growth was seen in the DC-AP countries (5.9% per year) and the ROW region (4.6% per year). Transport energy use dropped dramatically in the EIT region after 1990; by 1995 this region only consumed 11% of global transport energy use. Growth in transport primary energy use also declined slightly in the industrialized countries, dropping from an average of 2.2% per year between 1971 and 1990 to 1.9% per year between 1990 and 1995. High growth continued in the DC-AP and ROW regions, with the DC-AP countries increasing to an average of 7.6% per year between 1990 and 1995.

3.1.4 Primary Energy Demand: Agriculture

The agriculture sector used only 3% of global primary commercial energy in 1990. Unlike the other sectors, the EIT region dominated agricultural energy use in 1990, using 34% of the total, followed by the industrialized countries (30%), DC-AP (26%) and the ROW (10%) regions (see Table 2). Between 1971 and 1990, average annual growth in primary energy used for agriculture was slower in the industrialized countries (2.2% per year) than in the three other regions which ranged between 4.5% and 4.8% per year. Trends in agricultural primary energy use changed significantly in the EIT and ROW regions after 1990, with EIT consumption dropping an average of 10.6% per year and ROW consumption increasing an average of 12.6% per year through 1995.

3.2 Final Energy Demand: Fuels and Electricity

Final energy use grew more slowly than primary energy use in all regions between 1971 and 1995. Fuels dominate final energy use, but the share of fuels dropped from 90% in 1971 to 83% in 1995, reflecting an increased growth in electricity associated with growing urbanization and electrification in many areas of the world. Figure 3 shows that the share of electricity in final energy grew in all regions, although this growth slowed in the EIT region after 1985.

Globally, electricity use grew at an average rate of 4.3% between 1971 and 1990 (see Table 3), significantly higher than the 2.5% and 2.1% per year growth seen in global primary and final energy use, respectively. The highest annual growth rates in electricity use were in the DC-AP and ROW regions, which averaged 8.6% and 7.2% per year, respectively, between 1971 and 1990. Total electricity use was highest in the industrialized countries, which used 60% of global electricity in 1990. Figure 4 shows that commercial buildings had both the largest growth and highest total electricity consumption, followed by residential buildings, industry, and agricultural. Transport consumes very little electricity; electricity's share in final energy in this sector remained virtually unchanged throughout the period. Both commercial and residential buildings showed the largest growth in electricity, averaging about 5.3% per year between 1971 and 1990. Growth in industrial sector electricity averaged 3.5% per year.

Figure 3. Share of Electricity in Final Energy Consumption in Final Energy Consumption by Region, 1971 to 1995.
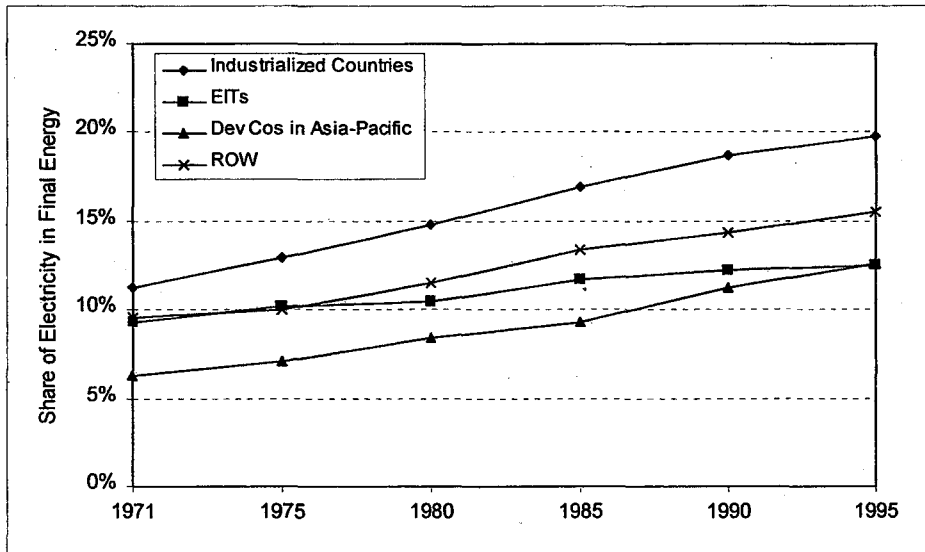

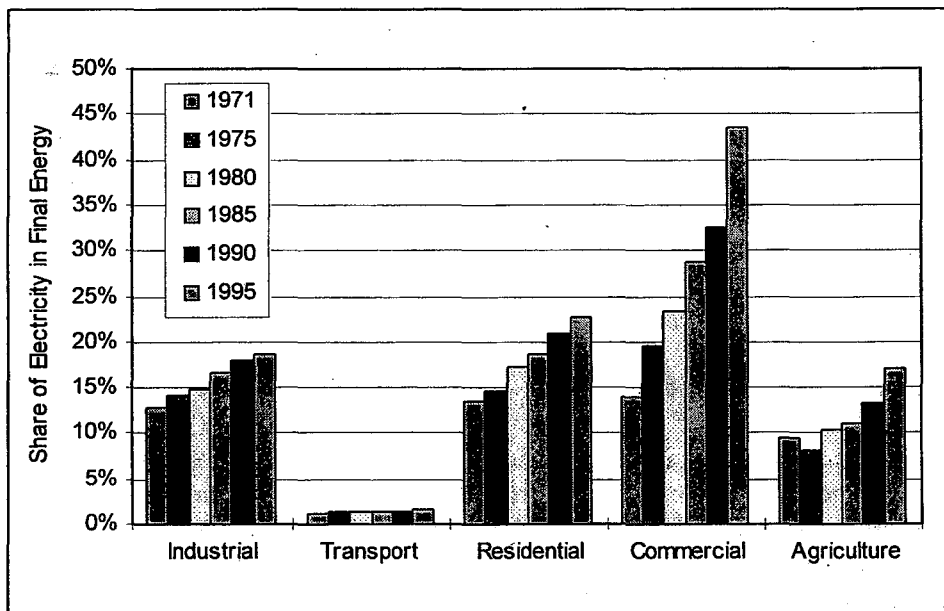*Figure 4.* Share of Electricity by Sector, 1971 to 1995.

Table 3. Electricity Use by Sector and Region, 1971-1995 (EJ). Reference: IEA, 1997a; IEA, 1997b; BP, 1997.

	1960	1971	1975	1980	1985	1990	1995	AAGR 1960-1990	AAGR 1971-1990	AAGR 1990-1995
Industrial Sector										
Industrialized Countries	2.72	5.43	6.13	7.22	7.54	8.60	9.47	3.9%	2.4%	2.0%
Economies in Transition		2.48	3.17	3.45	4.28	4.44	2.92		3.1%	-8.0%
Developing Cos. in Asia-Pacific		0.58	0.83	1.24	1.71	2.51	3.43		8.0%	6.4%
Rest of World		0.46	0.66	1.00	1.32	1.51	1.78		6.4%	3.4%
World		8.96	10.78	12.91	14.84	17.06	17.60		3.5%	0.4%
Buildings Sector										
Industrialized Countries	1.94	5.39	6.86	8.57	10.38	12.46	14.21	6.4%	4.5%	2.7%
Residential	*1.19*	*3.25*	*4.04*	*5.05*	*5.86*	*6.81*	*7.63*	*6.0%*	*4.0%*	*2.3%*
Commercial	*0.74*	*2.14*	*2.82*	*3.51*	*4.52*	*5.65*	*6.58*	*7.0%*	*5.3%*	*3.1%*
Economies in Transition		0.62	0.95	1.38	1.68	2.10	1.39		6.6%	-7.9%
Residential		*0.41*	*0.50*	*0.84*	*1.00*	*1.27*	*1.18*		*6.1%*	*-1.4%*
Commercial		*0.21*	*0.45*	*0.54*	*0.68*	*0.82*	*0.20*		*7.5%*	*-24.3%*
Developing Cos. in Asia-Pacific		0.17	0.24	0.40	0.66	1.12	1.85		10.4%	10.5%
Residential		*0.09*	*0.14*	*0.23*	*0.39*	*0.65*	*1.08*		*10.7%*	*10.7%*
Commercial		*0.08*	*0.11*	*0.18*	*0.28*	*0.47*	*0.77*		*9.9%*	*10.2%*
Rest of World		0.38	0.54	0.89	1.26	1.67	2.31		8.2%	6.7%
Residential		*0.26*	*0.33*	*0.57*	*0.85*	*1.13*	*1.52*		*8.1%*	*6.1%*
Commercial		*0.12*	*0.21*	*0.32*	*0.41*	*0.54*	*0.79*		*8.2%*	*7.9%*
World		6.56	8.59	11.24	13.98	17.35	19.76		5.2%	2.9%
Residential		*4.01*	*5.01*	*6.69*	*8.09*	*9.86*	*11.41*		*4.8%*	*3.0%*
Commercial		*2.54*	*3.58*	*4.55*	*5.89*	*7.49*	*8.34*		*5.7%*	*2.6%*
Transport Sector										
Industrialized Countries	0.11	0.18	0.20	0.22	0.24	0.29	0.33	3.1%	2.5%	2.6%
Economies in Transition		0.24	0.32	0.38	0.44	0.48	0.57		3.7%	3.6%
Developing Cos. in Asia-Pacific		0.01	0.01	0.02	0.04	0.06	0.10		9.7%	10.2%
Rest of World		0.02	0.02	0.02	0.03	0.03	0.03		2.7%	1.5%
World		0.45	0.55	0.64	0.75	0.85	1.03		3.5%	3.6%
Agriculture Sector										
Industrialized Countries	0.13	0.13	0.10	0.13	0.16	0.18	0.20	1.0%	1.8%	2.3%
Economies in Transition		0.10	0.08	0.13	0.19	0.25	0.22		4.7%	-2.7%
Developing Cos. in Asia-Pacific		0.09	0.13	0.21	0.25	0.40	0.59		7.9%	8.2%
Rest of World		0.02	0.03	0.06	0.08	0.10	0.17		8.2%	11.6%
World		0.35	0.35	0.53	0.67	0.93	1.18		5.1%	5.1%
All Sectors										
Industrialized Countries	4.91	11.13	13.29	16.14	18.32	21.53	24.21	5.1%	3.5%	2.4%
Economies in Transition		3.44	4.52	5.34	6.59	7.27	5.10		4.0%	-6.8%
Developing Cos. in Asia-Pacific		0.86	1.22	1.87	2.66	4.08	5.96		8.6%	7.8%
Rest of World		0.88	1.24	1.97	2.68	3.31	4.30		7.2%	5.3%
World		16.31	20.27	25.31	30.24	36.20	39.57		4.3%	1.8%

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3.3 Carbon Dioxide Emissions

Total global carbon dioxide emissions from fuel combustion grew from 3.6 GtC in 1971 to 5.4 GtC in 1990 at an average of 2.0% per year. Growth slowed to 1.0% per year between 1990 and 1995; carbon dioxide emissions in 1995 reached 5.6 GtC.[7]

Industrialized countries were responsible for almost half of the world's carbon dioxide emissions (see Table 4). In these countries, the buildings sector had the largest emissions in 1990 (915 MtC), followed by the industrial sector (887 MtC), transport (743 MtC), and agriculture (48 MtC). Industrial sector carbon dioxide emissions dropped between 1971 and 1990, at an average annual rate of -0.3% per year, while all other emissions grew.

Carbon dioxide emissions grew from 741 MtC to 1131 MtC between 1971 and 1990 in the EIT countries, declining to 892 MtC by 1995 as energy use dropped significantly as a result of the economic crisis in this region. In the former Soviet Union[8], total carbon dioxide emissions grew from 561 MtC in 1971 to 948 MtC in 1990, at an average rate of 2.8% per year. Following the start of economic restructuring, carbon dioxide emissions in the former Soviet Union dropped to 733 MtC in 1995. In 1990, the industrial sector was responsible for 53% of carbon dioxide emissions in the former Soviet Union, followed by the buildings sector (31%), agriculture (9%), and transport (7%).

Energy-related carbon dioxide emissions grew from 358 MtC to 1036 MtC in the DC-AP region between 1971 and 1990, and then jumped to 1392 MtC in 1995. Growth in emissions averaged 5.8% per year between 1971 and 1990, increasing slightly to 6.1% per year between 1990 and 1995. China dominates the DC-AP region, with 1990 emissions of 613 MtC and 1995 emissions of 814 MtC. The industrial sector was responsible for 66%, 58%, and 37% of emissions in China, India, and Indonesia, respectively. Energy-related carbon dioxide emissions continued to grow at high rates in all three countries between 1990 and 1995.

Between 1971 and 1990, carbon dioxide emissions grew from 281 MtC to 533 MtC in the ROW region at a average rate of 3.4% per year. The industrial sector clearly dominated carbon emissions in Brazil (36%), Mexico (42%), and South Africa (63%) in 1990. Carbon dioxide emissions increased in both Brazil and Mexico between 1990 and 1995; only South Africa experienced a decline in carbon emissions during this period, mostly due to decreased emissions in the industrial and buildings sectors. Overall emissions, which reached 615 MtC in 1995, grew a little slower between 1990 and 1995, averaging 2.9% per year.

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[7] Our carbon dioxide emissions for a country or region differ from IEA values reported in Ellis and Tréanton, (1998) because we only include emissions from fuel combustion, electricity, and heat consumption. IEA CO2 statistics include a number of other categories, such as unallocated non-energy use, that we did not include.

[8] As discussed in section 2.1, we estimated historical sectoral CO2 emissions for the former Soviet Union based on IEA data which have many data gaps and uncertainties.

Table 4. Carbon Dioxide Emissions by Sector for Industrialized Countries and Selected EIT, DC-AP, and ROW Countries (MtC). Reference: IEA, 1997a; IEA, 1997b; IEA, 1997c.

	1960	1971	1975	1980	1985	1990	1995	AAGR 1960-1990	AAGR 1971-1990	AAGR 1990-1995
Industrial Sector										
Industrialized Countries	622	932	911	970	859	887	852	1.2%	-0.3%	-0.8%
Economies in Transition		404	474	570	585	602	445		2.1%	-5.9%
Developing Cos. in Asia-Pacific		223	287	384	483	632	859		5.6%	6.3%
Rest of World		126	158	209	218	199	214		2.4%	1.4%
World		1684	1830	2133	2145	2319	2370		1.7%	0.4%
Buildings Sector										
Industrialized Countries	434	790	836	886	887	915	958	2.5%	0.8%	0.9%
Residential	323	522	543	549	537	539	560	1.7%	0.2%	0.8%
Commercial	111	268	293	336	350	377	398	4.2%	1.8%	1.1%
Economies in Transition		229	280	341	355	350	307		2.3%	-2.6%
Residential		155	200	248	266	258	244		2.7%	-1.1%
Commercial		74	80	94	89	92	62		1.2%	-7.5%
Developing Cos. in Asia-Pacific		67	88	131	179	232	292		6.7%	4.7%
Residential		57	75	110	145	180	210		6.2%	3.1%
Commercial		10	14	21	33	51	81		9.0%	9.7%
Rest of World		80	97	126	157	171	200		4.1%	3.1%
Residential		62	77	102	128	136	157		4.2%	2.9%
Commercial		17	20	24	29	35	42		3.8%	3.6%
World		1166	1302	1484	1578	1668	1756		1.9%	1.0%
Residential		797	895	1009	1076	1113	1172		1.8%	1.0%
Commercial		369	408	476	502	555	584		2.2%	1.0%
Transport Sector										
Industrialized Countries	287	494	554	612	636	743	816	3.2%	2.2%	1.9%
Economies in Transition		65	75	77	83	87	67		1.6%	-5.0%
Developing Cos. in Asia-Pacific		51	54	69	87	122	173		4.7%	7.3%
Rest of World		65	87	116	131	139	170		4.1%	4.1%
World		676	770	874	937	1091	1227		2.6%	2.4%
Agriculture Sector										
Industrialized Countries	22	35	33	38	45	48	51	2.7%	1.7%	1.3%
Economies in Transition		43	52	69	85	93	73		4.1%	-4.7%
Developing Cos. in Asia-Pacific		17	23	36	38	51	68		5.9%	6.0%
Rest of World		10	14	19	21	23	31		4.6%	5.9%
World		105	122	162	189	215	223		3.8%	0.8%
All Sectors										
Industrialized Countries	1365	2252	2334	2506	2426	2593	2678	2.2%	0.7%	0.6%
Economies in Transition		741	880	1057	1108	1131	892		2.3%	-4.6%
Developing Cos. in Asia-Pacific		358	453	620	787	1036	1392		5.8%	6.1%
Rest of World		281	356	470	528	533	615		3.4%	2.9%
World		3632	4024	4653	4848	5293	5577		2.0%	1.0%

4. Drivers of Energy Use and Greenhouse Gas Emissions in Industry and Buildings

Key drivers of energy use and carbon emissions include activity drivers (total population growth, urbanization, building and vehicle stock, commodity production), economic drivers (total GDP, income and price elasticities), energy intensity trends (energy intensity of energy-using equipment and appliances), and carbon intensity trends. These factors are in turn driven by changes in consumer preferences, energy and technology costs, settlement and infrastructure patterns, technical change, and overall economic conditions. This section focuses on key drivers in the industrial and buildings sectors.[9] In the industrial sector, energy-intensive industries account for approximately 50% of industrial energy use worldwide and we focus on a specific energy-intensive sub-sector, the iron and steel industry. Buildings trends and drivers are discussed for the entire buildings sector as well as for commercial and residential buildings separately when possible.

4.1 Activity Drivers of Energy Use and Greenhouse Gas Emissions

Population is the fundamental activity driver and all sectoral-level activity drivers are influenced by trends in population growth. Between 1970 and 1990, world population increased 30%, with the bulk of growth in the DC-AP and ROW regions (UN, 1996). Globally, this increase averaged 1.8% per year, led by 2.6% average annual growth in the ROW region and 2.0% average annual growth in the DC-AP region. Industrialized countries and the EIT both had moderate population growth, averaging 0.8% per year. World population growth slowed between 1990 and 1995, averaging only 1.5% per year.

Sectoral-level activity, while driven by trends in population growth, is measured differently in each of the end use sectors; in industry activity is based on commodities produced and in buildings it is based on number of households or square meters of living or commercial space. Regardless of how activity is measured, though, there are factors specific to each sub-sector that drive activity levels, which in turn are related to energy use and greenhouse gas emissions.

4.1.1 Industrial Sector Activity Drivers

Generally, industrial production has been growing in most economies. Industrial production can be measured using either economic or physical indices. At an aggregate level, monetary values such as value added, value of shipments, and production value are the most commonly used terms for describing production, although various physical production indices are available to measure production of specific commodities. Manufacturing value added per capita has been growing in most regions, except there has been a decline recently in the EIT region and in most African countries over the past 15 years. The share of manufacturing value added of GDP is around 30% for most regions in the world, as shown in Figure 5. The only exception is the EIT region which has a very large share of industrial production in the economy.[10] The economic transition process occurring in these countries has led to a severe reduction of industrial production in recent years.

Figure 5 also shows that the share of manufacturing value added is increasing in countries such as those in the DC-AP region, while showing a small decline in the economies of industrialized countries due to continuous restructuring away from industrial activities and toward more service activities. For example,

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[9] The transport and agriculture sectors are not included in this discussion; readers are directed to Cole et al., 1996; Michaelis et al., 1996; WEC, 1995b; and Worrell et al., 1997a for further information on trends in these sectors.

[10] Note that the concept of GDP may not be fully compatible with other means to express the production volume used in the former centrally planned economies.

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the industrial sector share dropped from 42% in 1970 to 35% in 1990 in the Western Europe region, while increasing from 24% to 33% and from 27% to 40% in China and Eastern Asia, respectively. In the former Soviet Union, the manufacturing share dropped from 60% to 55% during this period (RIVM, 1998).

Figure 5. Historical Trends in Manufacturing Value Added, Expressed as Share of GDP (in 1990 US$) for 13 Regions, 1970-1990. Reference: RIVM, 1998.
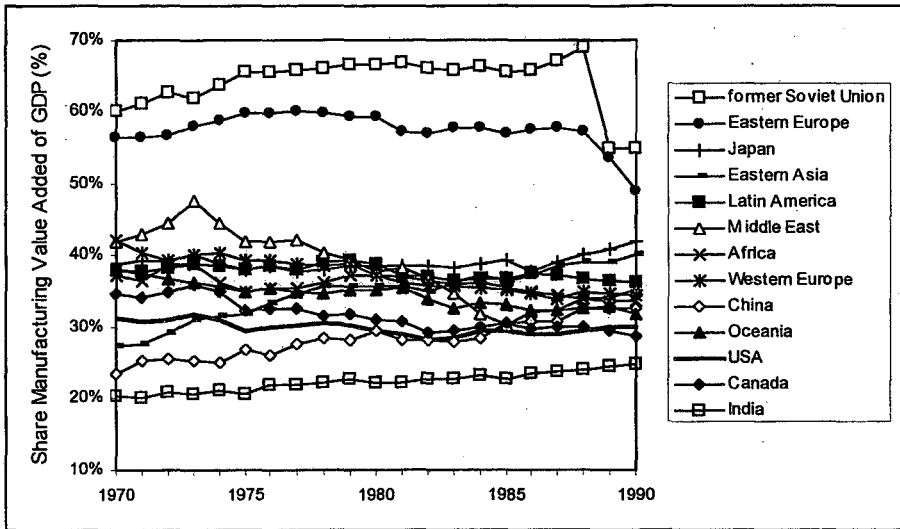
The industrial sector is dominated by the production of a few major energy-intensive commodities such as steel, paper, cement, and chemicals. In any given country or region, production of these basic commodities follows the general development of the overall economy. Rapidly industrializing countries will have higher demands for infrastructure materials and more mature markets will have declining or stable consumption levels. Global steel production increased from 28 Mtonnes in 1900 to 730 Mtonnes in 1994 (IISI, 1996), at an average growth of 3.4% per year (see Figure 6). In the industrialized countries, steel production is growing slowly, at a rate of just over 1% per year, and is expected to level off in the near future (Wödlinger et al., 1997). Steel production in the EIT region declined in recent years due to the economic restructuring process.

Figure 6. Global Steel Production from 1900 to 1994 With Regional Distribution of Production for 1982 to 1994. References: IISI, 1996; Wödlinger et al., 1997.
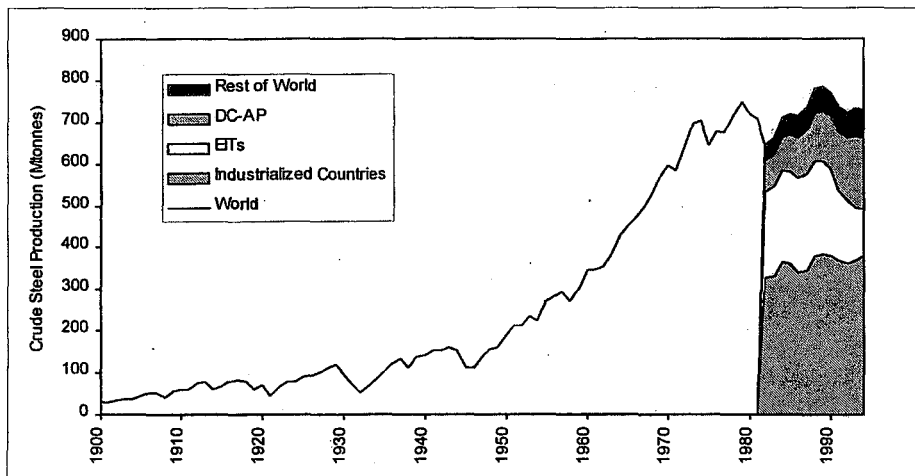
In contrast, production of steel in developing countries has been 6.6% per year on average (IISI, 1996), and is expected to be the main driver for continued growth in global steel production. Recently, the Asian region experienced high average annual growth in steel production of about 7.5% per year. In the medium term Asia is expected to be main growing consumer of steel. The low per capita consumption of steel in developing countries (51 kg/capita in 1991) compared to the high levels in industrialized countries of over 300 kg/capita (IISI, 1996), shows that there is still a large potential for growth in production in these countries.

The regional differences in consumption patterns (expressed as consumption per capita) will fuel a further growth of consumption in developing countries. Many commodities, including steel, are traded globally and regional differences in supply and demand may remain in the future. Trends also depend on regionally availability of resources (e.g. scrap) and capital. Therefore, a link between consumption and production by region is not easy to estimate or to model. Table 5 presents an overview of regional growth of steel production showing that production in industrialized countries and the EIT region, while strong in the 1950 to 1990 period, dropped considerably between 1990 and 1995. As expected, growth in production was large in both the DC-AP and ROW regions for the entire period (Wödlinger et al., 1997).

Table 5. Historical Growth of Steel Production in Various Regions and the World. References: IISI, 1996; Van Vuren, 1995; Wödlinger et al., 1997.

Region	Growth 1950-1990 (% per year)	Growth 1985-1995 (% per year)
Industrialized Countries		
Western Europe	3.0%	0.5%
North America	0.3%	1.1%
Japan	8.1%	-0.7%
Oceania	4.5%	3.0%
EITs		
Eastern Europe & former Soviet Union	4.4%	-6.4%
DC-AP		
China	16.6%	7.1%
Other Asia	9.5%	7.0%
Rest of World		
Latin America	8.7%	2.4%
Middle East	11.1%	11.0%
Africa	6.6%	1.0%
World	3.6%	0.2%

4.1.2 Buildings Sector Activity Drivers

Along with population size, key activity drivers of energy demand in buildings are rate of urbanization, number of households, per capita living area, persons per residence, and commercial floor space. As populations become more urbanized and areas become electrified, the demand for energy services such as refrigeration, lighting, heating, and cooling increases. In the residential buildings sector, the level of energy demand is further influenced by population age distribution, household income, number of households, size of households, and the number of people per household. In the commercial buildings sector, demographic factors that influence energy demand include the overall population level (i.e., the number of people desiring commercial services) and the size of the labor force.

The number of people living in urban areas increased between 1970 and 1990, growing from 1.35 billion, or 37% of total, in 1970 to 2.27 billion, or 43% of total, in 1990. Growth in urbanization was strongest in the DC-AP and ROW regions, where the average annual increase in urban population was nearly 4.0%

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per year (see Figure 7). Much slower growth was seen in the already relatively urbanized industrialized and EIT regions. Increasing urbanization in the DC-AP and ROW regions leads to the increased use of commercial fuels, such as kerosene and liquified petroleum gas, for cooking instead of traditional biomass fuels. Additional increases in energy use come with electrification, when appliances and lighting are adopted. In general, higher levels of urbanization are associated with higher incomes and increased household energy use (Sathaye et al., 1989; Nadel et al., 1997).

Globally, the number of people living together in a household (defined as a separate living unit) tends to decline with increasing income and urbanization of the population. In industrialized countries, household size dropped from an average of 3.5 persons per household in 1970 to 2.8 persons per household in 1990. This decline in household size lead to an increase in the total number of households in the region, where households grew 1.5% per year faster than population between 1970 and 1991 (Schipper and Meyers, 1992). Energy use per household declined as household size dropped; however, residential energy use per capita increased during this period (IEA, 1997d).

In the EIT region, the number of persons per household has also declined recently, dropping from 3.7 to 3.5 between 1978 and 1988 in Poland and 3.0 to 2.8 between 1980 and 1991 in the Czech Republic (Meyers et al., 1995). In 1989, Russia and Ukraine each had an average of 3.2 persons per household (World Bank, 1995). Much larger household sizes are common in the DC-AP and ROW regions. For example, average household size in China dropped from 5.2 persons per household in 1981 to 4.0 persons per household in 1995 (World Bank, 1995; Turiel et al. 1998). Between 1970 and 1995, average household size dropped from 5.9 to 5.4 in the Philippines, from 5.5 to 4.0 in S. Korea, from 6.5 to 4.8 in Thailand, and from 5.4 to 4.2 in Brazil (LBNL 1998b; Turiel et al., 1998).

Either commercial sector GDP or commercial sector floor space can be used to measure activity in commercial buildings. The commercial sector share of GDP is high in industrialized countries and has been growing rapidly in recent years. A survey of ten industrialized countries showed that commercial sector GDP grew an average of 3.3% per year from 1970 to 1995, with even higher rates experienced in some countries like Japan and Finland (Schipper and Meyers, 1992). In 1995, the overall GDP commercial sector share was 66% in thirteen industrialized countries (Krackeler et al., 1998). Although some industrialized countries collected detailed data on commercial floor area, this is a more difficult measure of activity due to lack of data for many regions of the world.

Figure 7. Percentage of Population Living in Urban Areas by Region, 1960, 1970, 1990, 1995. Reference: U.N. 1996.
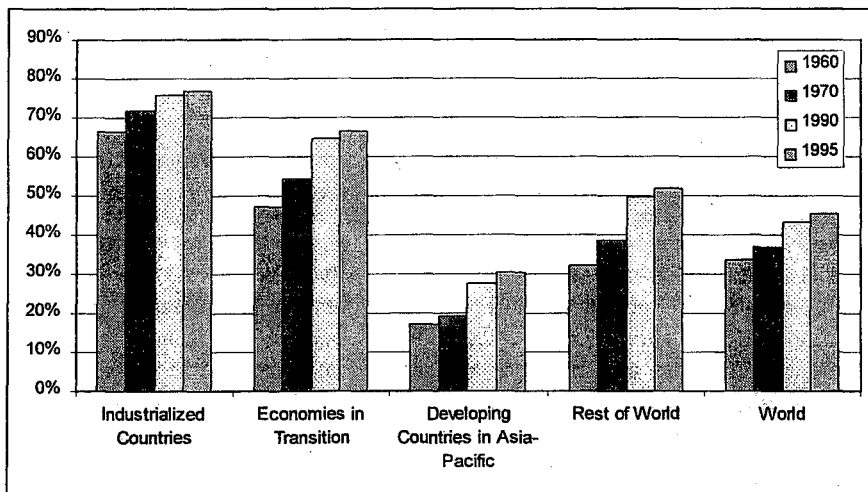
4.2 Economic Drivers of Energy Use and Greenhouse Gas Emissions

Many macroeconomic projections of energy use and greenhouse gas emissions rely on historical data to estimate price and income elasticities for energy demand and then use projections of GDP and energy prices to generate energy and emissions projections. The relationship between total final sector energy use and economic drivers such as GDP per capita varies across countries depending upon the sector. We found a relatively strong relationship in the buildings sector and a moderate relationship in the industrial sector. Other economic indicators, such as level of economic development in the industrial sector and personal consumption expenditures in residential buildings, are more closely correlated with energy use in these sectors.

Income elasticities vary widely among different types of energy services and the country or region under consideration. For example, the income elasticity of refrigerator ownership in most industrialized countries is extremely low, as most households already own a refrigerator. The elasticity is much higher in medium-income countries with low refrigerator ownership. In general, income elasticities for ownership or use of appliances are lowest for very low income countries, highest for medium income countries where a substantial portion but not the majority of the population can afford the appliance, and intermediate for high income countries where the vast majority of the population already have access to the appliances.

4.2.1 Industrial Sector Economic Drivers

In the industrial sector, empirical studies have shown that economic development rather than price elasticity may be the major factor explaining trends in material intensity because elasticity of industrial demand for resources (including energy) varies widely due to the diverse activities, production cost breakdowns, and technologies used in industrial production (Evans, 1996). Figure 8 shows that the correlation between industrial final energy use and GDP[11] is moderate ($R^2 = 0.6$). This measure, which includes the energy intensity of industrial production, the structure of the industrial sector, and the demand for industrial production illustrates that modeling trends in industrial energy consumption is not straightforward.

Greenhouse gas emissions and energy use by industry are still dominated by a relatively small number of basic energy-intensive industries (WEC, 1995a). These industries are primarily involved in upgrading natural resources to materials used in society and are relatively large emitters of pollutants and greenhouse gases (Jänicke et al., 1997). Material consumption is still increasing and this growth is apparent for "classic" materials (e.g. cement, steel) and for the "new" materials (e.g. plastics, aluminium). Studies of material consumption in industrialized countries have shown that consumption (expressed as apparent consumption per capita or unit GDP[12]) increases in the initial development of society to a maximum, and eventually saturates or even declines. Trends in materials use in industrialized countries show saturation on a per capita

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[11] GDP values are presented in terms of purchasing power parity (PPP) rather than market exchange rates because it has been shown that there is a stronger correlation between energy use and GDP when this value is calculated using PPP rather than market exchange rates (Siddiqi, 1994).

[12] International statistical data give the apparent consumption of materials, i.e. the intermediate consumption of materials in industry. Due to increasing import and export streams of products (containing the materials) the figures represent the consumption by the economic production sectors, rather than the end-use of the society. The first detailed analyses of end-use in some countries are available but not yet as time series. The availability and comparability of GDP data is often difficult, as we know from energy intensity analyses, see e.g. (Schipper and Meyers, 1992; Martin et al., 1995). Comparisons of the material intensity, expressed as material use per unit GDP, should be interpreted carefully.

basis. Expressed as function of unit GDP, material intensity declines after reaching a maximum (Williams et al., 1987).

In Figure 9 the historical trends in apparent consumption of steel are depicted for the U.S. and Germany expressed as consumption of steel per capita and per unit GDP. The initial increase is caused by large investments required in building an industrial infrastructure. In later stages, material substitution and competition between materials as well as a shift to a more service-oriented economy contribute to a decrease in the material intensity of societies (Malenbaum, 1975; Williams et al., 1987; Bernardini and Galli,1993). For example, the substitution of classical steels by aluminium in transport applications led to the development of high strength steels that can compete with aluminium. Because of improved properties, less material is needed to fulfill the service, leading to declining material intensities. The inverse U-shaped curve as developed by Malenbaum (1975) cannot always explain irregular developments in material intensity trends (Evans, 1996). Recycling appears to increase with development (Bernardini and Galli, 1993), as can be seen from the increasing post-consumer recycling rates in the industrialized world. The development curves seem not only to be valid for construction materials but also for other commodities like food (Bernardini and Galli, 1993), fertilizers (Williams et al., 1987), and pesticides. In addition, Bernardini and Galli (1993) suggested that the maximum intensity declines if reached later in time by a given economy or society. However, most analyses have been performed only for industrialized countries. The need for further analysis is stressed by the current situation in rapidly-industrializing countries like South Korea that have a very high per capita apparent consumption of steel which is used in large exporting industries like car manufacture and ship building.[13] The industry in South Korea is heavily dependent on exports of these material-intensive products, determining the material intensity of the economic activities, rather than the intensity of society. Although the use of all materials in developing countries will certainly grow, per capita consumption may not be as high as in the industrialized countries. The level of saturation depends on many factors, including technology transfer but also infra-structural (including economic structure) policy choices (Jänicke et al, 1997).

Figure 8. Relationship Between 1995 Industrial Final Energy Use per Capita and GDP in 122 Countries. Reference: IEA 1997a; IEA 1997b.
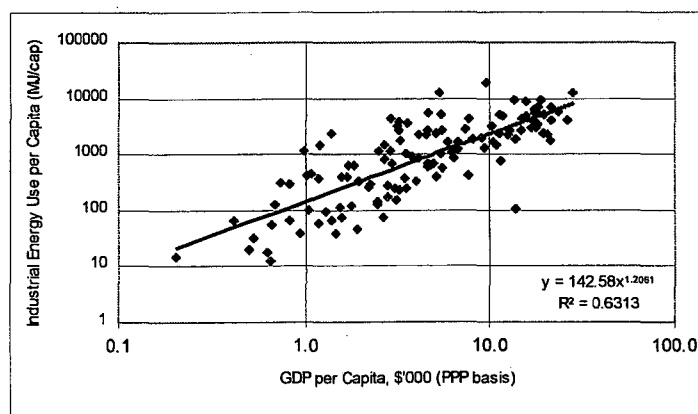

Various economic indicators are commonly used at the level of individual industrial sub-sectors, e.g. value added, production value, value of shipments, while physical indicators are under the development for a wide range of industrial sub-sectors (Phylipsen et al., 1997). Physical indicators are more closely

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[13] This case shows that the available statistics are not yet suited to prove that countries developing later in time will reach a lower saturation level, as stated by Bernardini and Galli (1993).

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linked to technical efficiency, but can only be used for relatively homogeneous activities (Schipper and Meyers, 1992). Where energy services are explicitly modeled, they are usually assumed to be dependent on GDP or per-capita income, and price or cost. The link might be made through constant income and price elasticities of absolute demand for a service, through a logistic curve, or through income elasticities that fall with increasing income. In general equilibrium models, energy services demand may be estimated using a system of nested production functions ultimately delivering final consumption.

Figure 9. Apparent Steel Consumption in the U.S. and Germany, 1940-1990 (depicted as function of GDP and per capita). Reference: Worrell et al., 1997a.
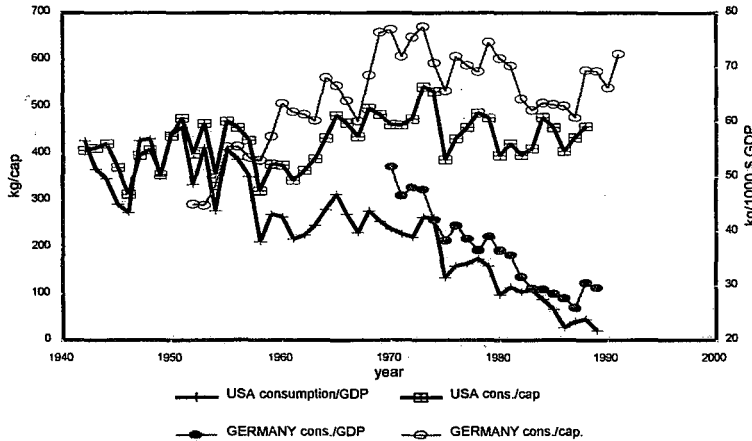
An historical analysis of the European steel market showed that steel demand has also been reduced in periods of low economic growth, and showed that diffusion of new technology is mostly responsible for reduced material intensity, rather than income growth (Mannearts, 1997). Steel production and industrial production can be modeled using growth in population, income, and developments in materials intensity (or intensity of use). Figure 10 depicts the relatively weak link between income per capita and apparent steel consumption.

Figure 10. National Per Capita Apparent Consumption of Crude Steel as a Function of GDP per Capita in 1994. References: IEA 1997a; IEA, 1997b; IISI, 1996.
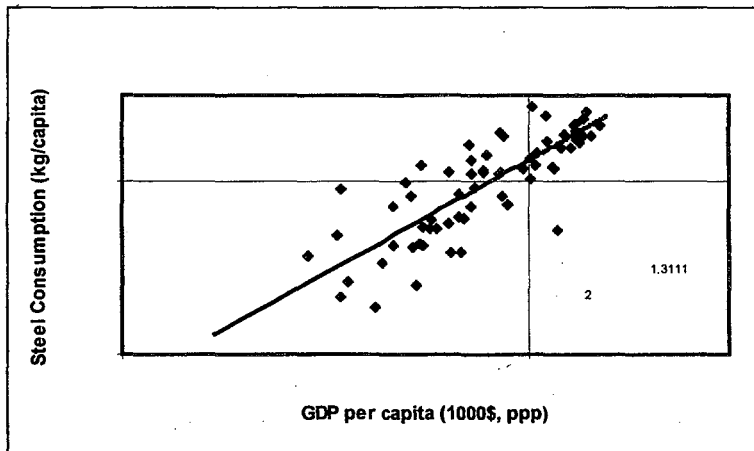
4.2.2 Buildings Sector Economic Drivers

In the buildings sector, we found a relatively strong relationship across countries between GDP per capita and final energy use in residential (R^2=0.77) and commercial buildings (R^2 = 0.78) using data for 25 industrialized countries, China, and the regions of Asia, Africa, Latin America, and Middle East (see Figures 11 and 12). Energy use in buildings is not only influenced by economic variables, but also by climate, energy-related policies, house size or commercial building floor area, and consumer energy-using behavior patterns.

Energy consumption in residential buildings is strongly correlated with household income levels. Between 1973 and 1993, increases in total private consumption translated into larger homes, more appliances, and an increased use of energy services (water heating, space heating) in most industrialized countries (IEA, 1997d). In general, countries with colder climates have higher incomes as well as higher heating levels. Household size, a key determinant of residential energy use, has grown with personal consumption expenditures in most industrialized countries, led by the United States where economic policies granting tax reductions on home loan interest have contributed to that country having the largest average home sizes in the world.

In developing countries, urban areas are generally associated with higher average incomes (Sathaye and Ketoff, 1991). Wealthier populaces in developing countries exhibit consumption patterns similar to those in industrialized countries, where purchases of appliances and other energy-using equipment increase with gains in disposable income (WEC, 1995a). Modern fuels such as kerosene, LPG, and electricity account for more than 90% of household energy consumption in high income homes in India, while lower income homes consume less than 50% of these commercial fuels (IEA, 1995). An important finding, though, is that purchased household energy use rises less rapidly than income, suggesting that there is a level of saturation of energy-using equipment. In industrialized countries, household energy consumption has slowed as equipment penetration rates reach saturation (IEA, 1997d).

In the commercial sector, the ratio of primary energy use to total GDP as well as commercial sector GDP fell in a number of industrialized countries between 1970 and the early 1990s. This decrease occurred despite large growth in energy-using equipment in commercial buildings, almost certainly the result of improved equipment efficiencies. Electricity use in the commercial sector shows a relatively strong correlation with commercial sector GDP, although there is a wide gap in electricity use at any given level of commercial sector GDP (IEA, 1997d).

Figure 11. Relationship Between 1995 Residential Buildings Final Energy Use per Capita and GDP per Capita in 25 Industrialized Countries, China, and the Regions of Asia, Africa, Latin America, and Middle East. References: IEA, 1997a; IEA, 1997b.
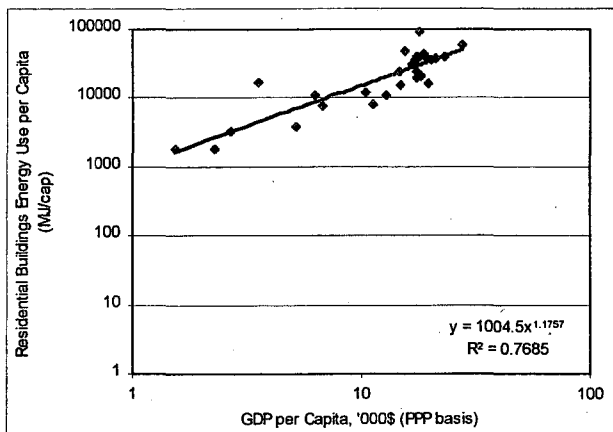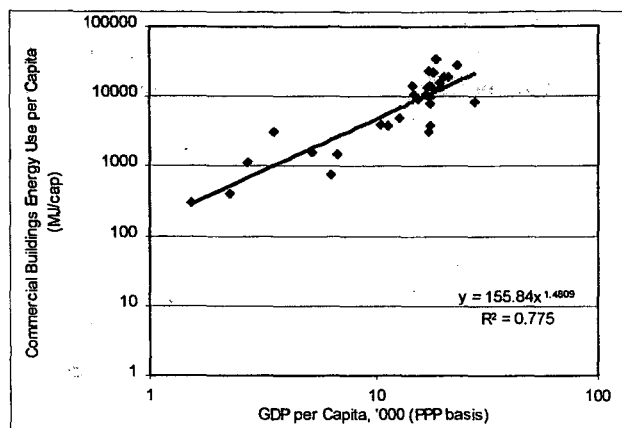
Figure 12. Relationship Between 1995 Commercial Buildings Final Energy Use per Capita and GDP per Capita in 25 Industrialized Countries, China, and the Regions of Asia, Africa, Latin America, and Middle East. References: IEA, 1997a; IEA, 1997b.

4.3 Energy Intensity Trends

Energy intensity is the amount of energy used to perform a particular service such as producing a tonne of steel or powering a refrigerator. Technical progress generally leads to improved energy efficiency in technologies such as lights, vehicles, refrigerators, and manufacturing processes. In theory there are large potentials for energy savings. Using the thermodynamic concept of exergy, Ayres (1989) estimates that the U.S. uses its primary energy sources with only a 2.5% efficiency when fulfilling its energy services illustrating that there is a substantial theoretical potential for energy intensity improvement. Jochem (1989) has stated that a 50% reduction in energy demand in industrialized countries is technologically feasible, and in the long term even an 80% reduction of the current primary energy consumption is possible. For industrial processes thermodynamic principles are used to calculate the theoretical efficiency and hence the maximum potential for energy savings. Several authors have assessed the minimum energy requirements of an activity, e.g. (Szargut and Morris,1987; Wall, 1988). Other studies have shown that considerable energy efficiency improvement can be realized (technically and economically) in the short term (10 to 15 years) with available technologies (Nakicenovic, 1993; Lovins and Lovins, 1991; WEC, 1995a; Worrell et al., 1997b).

4.3.1 Industrial Sector Energy Intensity Trends

Energy intensity in the industrial sector can be measured using both economic and physical indices. Economic energy intensity measurements (e.g. energy use/economic output) are useful for characterizing the entire industrial sector or for those portions of the industrial sector that are not easily measured in physical terms. Physical energy intensity measurements (e.g. energy use/tonne of product), also called specific energy consumption, more accurately reflect trends in energy efficiency, but are typically limited to use in the energy-intensive industrial sub-sectors. Evaluations of these two means of measuring energy intensity have shown that economic energy intensity values do not always accurately reflect physical energy intensity trends, making physical energy intensity measurements the preferred metric where possible (Worrell et al., 1997b; Freeman et al., 1996).

In aggregate terms, studies have shown that technical efficiency improvement of 1 to 2% per year is possible in the industrial sector and has occurred in the past (Ross and Steinmeyer, 1990). Energy

requirements can be cut by new process development. In addition, the amount of raw materials demand by a society tends to decline as countries reach certain stages of industrial development which leads to a decrease in industrial energy use. The accounting of trends in structural shift, material intensity and technical energy efficiency and their interactions can be extremely difficult. To understand trends in energy intensity, as shown in Figure 13, it is important to analyze the structure of the industrial sector. Industrial energy use can be broken down into that of the energy-intensive industries (e.g. primary metals, pulp and paper, primary chemicals, oil refining, building materials) and the non-energy intensive industries (e.g. electronics and food).

Reduction of energy intensity is closely linked to the definition of structure, structural change, and efficiency improvement. Decomposition analysis is used to distinguish the effects of structural change and efficiency improvement. Structural change can be broken down into intra-sectoral (e.g. a shift towards more recycled steel), inter-sectoral (e.g. a shift from steel to aluminium within the basic metals industry). A wide body of literature describes decomposition analyses (see e.g. Schipper and Meyers, 1992; Ang, 1995), and explains the trends in energy intensities, CO_2 intensities, and efficiency improvement. Decomposition analyses of the aggregate manufacturing sector exist mainly for industrialized countries (IEA, 1997d), but also for China (Sinton and Levine, 1994), Taiwan (Ang and Pandiyan, 1997; Li et al., 1990) and selected countries including Eastern Europe (Park et al., 1993). Table 6 summarizes the results of selected decomposition analyses.

The annual change in energy intensity in the industrial sector in the studies summarized in Table 9 varied between −0.1% and −6.6% per year. Generally, electricity intensity has remained constant, while fuel intensity has declined, reflecting the increasing importance of electricity (IEA, 1997d). The results also clearly show that different patterns exist for various countries, which may be due to specific conditions as well as differences in driving forces such as energy prices and other policies in these countries (IEA, 1997d). More detailed analyses on the sub-sector level are needed to understand these trends better, as well as their implications for bottom-up modeling.

Figure 13. Industrial Sector Economic Energy Intensity Trends in Selected Industrialized Countries, 1970-1995. Reference: LBNL, 1998a.
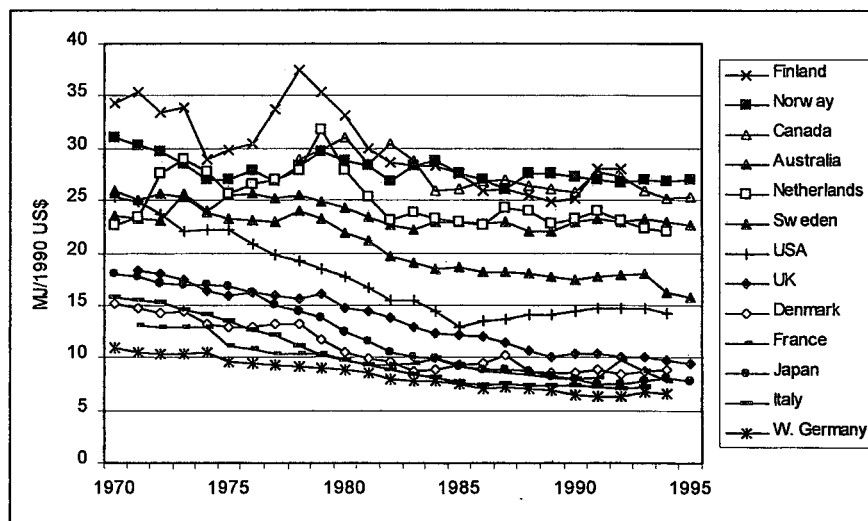
Table 6. Overview of the Results of Selected Decomposition Analyses of Manufacturing Energy Use.

Country (and period of analysis)	Annual change in aggregate energy intensity (% per year)	Contribution of structural change (% per year)	Contribution of energy intensity improvement (% per year)	References
Brazil (1973-80)	1.4%			1
Brazil (1980-88)	4.0%			1
China (1981-84)	-3.7%	-0.6%	-3.1%	2
China (1985-90)	-5.6%	-0.6%	-4.8%	2
China (1980-91)	-7.2%	-0.5%	-6.6%	3
France (1973-87)	-3.1%	-0.5%	-2.5%	4
West Germany (1973-87)	-2.6%	-0.4%	-2.2%	4
Japan (1973-87)	-4.2%	-0.9%	-3.2%	4
South Korea (1981-93)	-2.7%	-0.6%	-2.1%	3
Sweden (1973-87)	-2.2%	-0.5%	-1.7%	4
Taiwan (1980-93)	-1.4%	0.0%	-1.3%	3
Taiwan (1971-85)	-1.5%	-1.4%	-0.1%	5
United Kingdom (1973-87)	-2.4%	-0.1%	-2.3%	4
United States (1973-87)	-4.0%	-1.1%	-2.9%	4
USSR (1973-80)	-1.4%			1
USSR (1980-87)	-1.4%			1

Note: Annual trends in aggregate energy intensity are decomposed into structural change (change in the activity mix of the manufacturing sector) and energy intensity (change in energy input per unit of output for each of the sub-sectors). Note that different methodologies, analysis periods, and aggregation levels have been used, which leads to different results.

References: 1. Park et al., 1993. 2. Sinton and Levine, 1994. 3. Ang and Pandiyan, 1997. 4. Howarth et al., 1991. 5. Li et al., 1990.

Changes in energy intensities can also be disaggregated into structural changes and efficiency improvements at the sub-sector level. In the iron and steel industry, energy intensity is influenced by the raw materials used (i.e. iron ore, scrap) and the products produced (e.g. slabs, or thin rolled sheets). A recent study on the iron and steel industry used physical indicators for production, distinguished six products to describe structure, and decomposed trends in seven countries which together produced almost half of the world's steel (Worrell et al., 1997b). Figure 14 shows the trends in physical energy intensity in these countries, expressed as primary energy used per tonne of crude steel. The large differences in intensity among the countries are clearly shown, as well as the trends towards reduced intensity in most countries.

Table 7 shows the results of the decomposition analysis for the seven countries for the period 1980 to 1991. Although the analysis covered only a relatively short period, it clearly shows the differences in processes (structural changes, efficiency improvement) underlying the energy intensity trend. Actual rates of energy efficiency improvement varied between 0.0% and 1.8% per year, while in the case of the restructuring economy of Poland the energy efficiency was reduced.

Figure 14. Trends in Physical Energy Intensity (GJ/tonne crude steel) in Seven Countries Between 1971 and 1994. Reference: Worrell et al., 1997b.
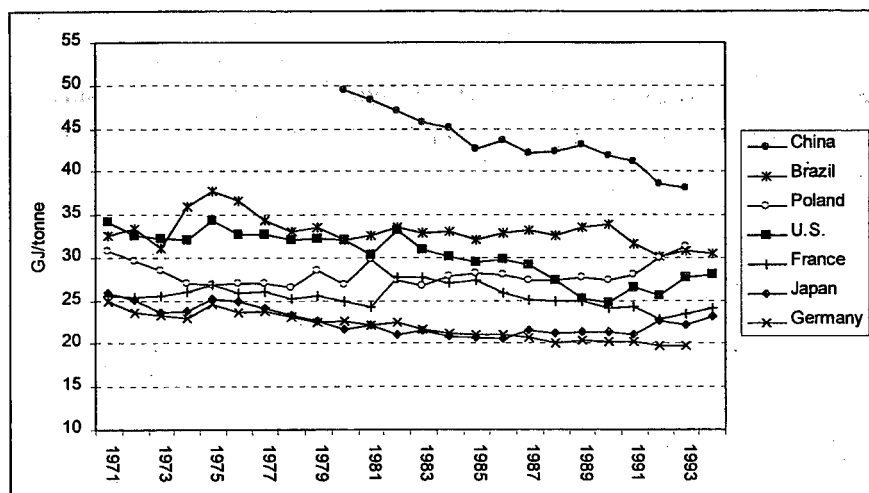

Table 7. Changes in Physical Energy Intensity (GJ/tonne of crude steel) in Seven Countries Between 1980 and 1991 and Breakdown of Structure and Efficiency Contributions to the Changes (relative changes in %). Source: Worrell et al., 1997b.

	Physical Energy Intensity 1980 (GJ/tonne)	Structure (GJ/tonne)	Efficiency (GJ/tonne)	Physical Energy Intensity 1991 (GJ/tonne)
Brazil	31.2	0.1 (+0%)	-1.6 (-5%)	29.7 (-5%)
China	51.3	0.2 (+0%)	-9.0 (-18%)	42.4 (-17%)
France	24.9	-1.8 (-7%)	1.1 (4%)	24.2 (-3%)
Germany	22.6	-0.3 (-1%)	-4.0 (-18%)	18.3 (-19%)
Japan	21.7	-0.6 (-3%)	-0.1 (-0%)	21.0 (-3%)
Poland	26.9	-0.7 (-3%)	1.8 (7%)	28.0 (4%)
U.S.	32.0	-2.1 (-6%)	-3.4 (-11%)	26.5 (-17%)

Note: The figures are based on an electricity generation efficiency of 33% across countries for all years.

4.3.2 Buildings Sector Energy Intensity Trends

Energy is used in buildings to provide many different services, which vary widely across regions and climates. Space heating accounts for a significant share of residential buildings energy use (see Figure 15 for the U.S.), while water heating, refrigeration, space cooling, and lighting are also important. In commercial buildings, other end-uses such as office equipment and lighting dominate. The amount of energy consumed in buildings is dependent on climate, building construction, appliances and equipment within the buildings, and energy use patterns of building occupants.

Overall energy intensity in the buildings sector can be measured using energy consumption per capita values. Between 1971 and 1990, global primary energy use per capita in the buildings sector grew from 16.5 GJ/capita to 20 GJ/capita. Figure 16 shows that buildings per capita energy use varied widely by region, with the industrialized and EIT regions dominating globally. Energy use per capita is higher in the residential sector than in the commercial sector in all regions, although average annual growth in commercial energy use per capita was higher during the period, averaging 1.7% per year globally compared to 0.6% per year for the residential sector.

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While informative for making general comparisons, energy consumption per capita values do not adequately describe the actual energy intensity trends within buildings. Another means of measuring these trends is to calculate energy use per unit of building floor area. This measurement, however, best reflects space heating and cooling intensities, but does not provide adequate information regarding the energy use of equipment and appliances within the buildings. Thus, a meaningful understanding of buildings energy use trends requires disaggregation of this sector into residential and commercial buildings intensity trends in space conditioning as well as in equipment and appliances within the buildings.

Figure 15. Buildings Primary Energy End-Uses in the United States. References: U.S. Congress, OTA, 1992; IPCC, 1995.
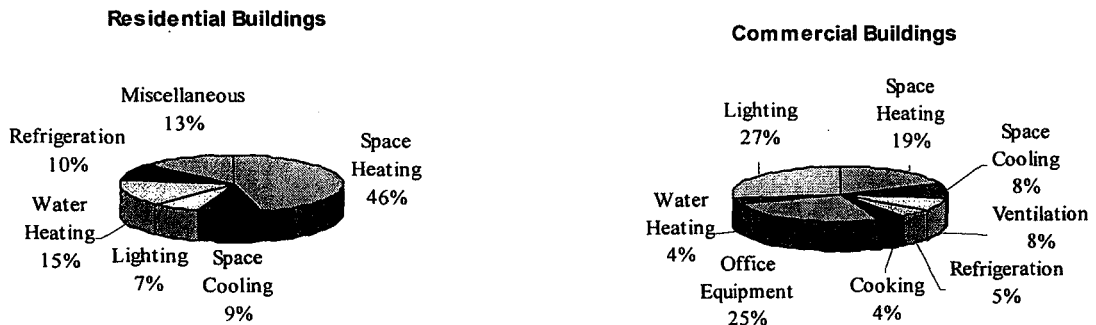
4.3.2.1 Residential Buildings

Energy intensity trends in residential space conditioning are affected by climate, building thermal integrity, and the heating and cooling equipment used. Space heating is an important end-use in the industrialized countries, the EIT region and in some developing countries, including half of China's residential and commercial buildings (Nadel et al., 1997). Buildings that are centrally heated consume almost twice as much energy as those that are heated by small room heaters. The penetration of central heating doubled from about 40% of dwellings to almost 80% of dwellings in many industrialized countries between 1970 and 1992 (IEA, 1997d). District heating systems are common in some areas of Europe and in the EIT region. In the former Soviet Union, district heating provides about 40% of residential space heating, with the remainder of the demand met through the use of small coal-fired boilers (U.S. Congress, OTA, 1993). Energy use for residential space heating is estimated to be about 80% of final energy use in Poland and about 75% of final energy use in the Czech Republic and the former Soviet Union (Meyers et al., 1995). Space heating is not common in most developing countries, with the exception of China, Korea, Argentina, and a few other South American countries (Sathaye et al., 1989). In China, 75% of the residential buildings that require heating use coal-fired stoves to burn raw coal, coal cakes, briquettes, or biomass (Nadel et al., 1997). Figure 17 shows that residential space heating energy intensities[14] declined in most industrialized countries (except Japan) between 1970 and 1992. Most of the decline was due to reduced heat losses in buildings, while a small portion of the savings were due to lowered indoor temperatures, more careful heating practices, and improvements in efficiency of heating equipment (IEA, 1997d; Schipper et al., 1996).

[14] Space heating energy intensities are measured as useful energy per square meter, climate corrected. Useful energy is based on the aggregates of various energy carriers, assuming that liquids and gases are converted to heat, hot water, or cooking services at 66% efficiency and solids at 55% (IEA, 1997d). Japan's space heating intensity is low due to a combination of low heating temperatures, fewer heating hours than the number of degree days implies, and a lower degree day base.

Figure 16. Primary Energy Use per Capita in Residential and Commercial Buildings by Region, 1971 and 1990. References: IEA, 1997a; IEA, 1997b, UN, 1996.
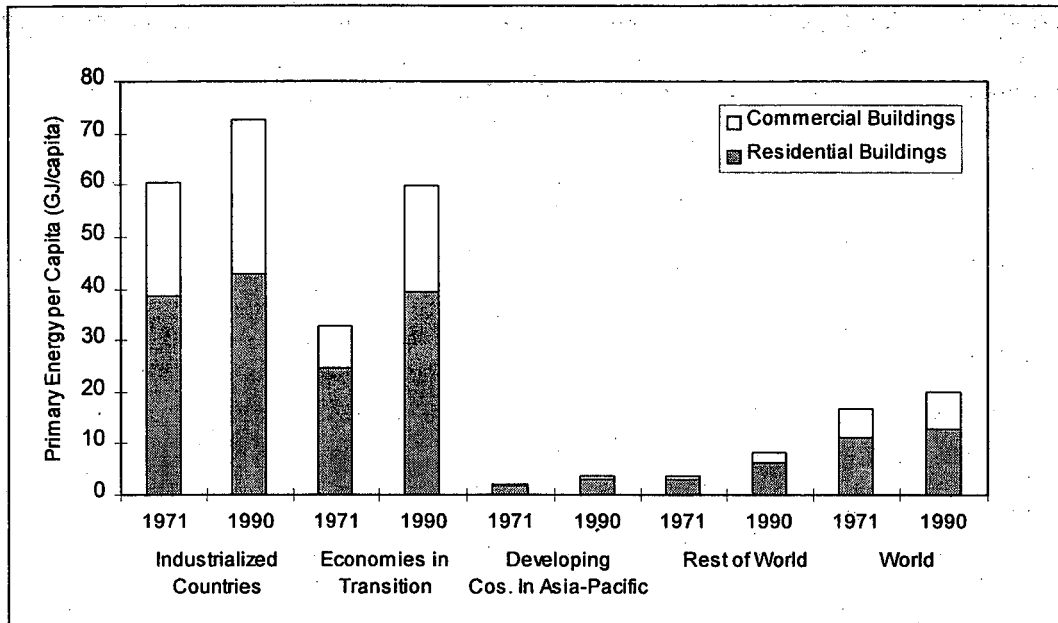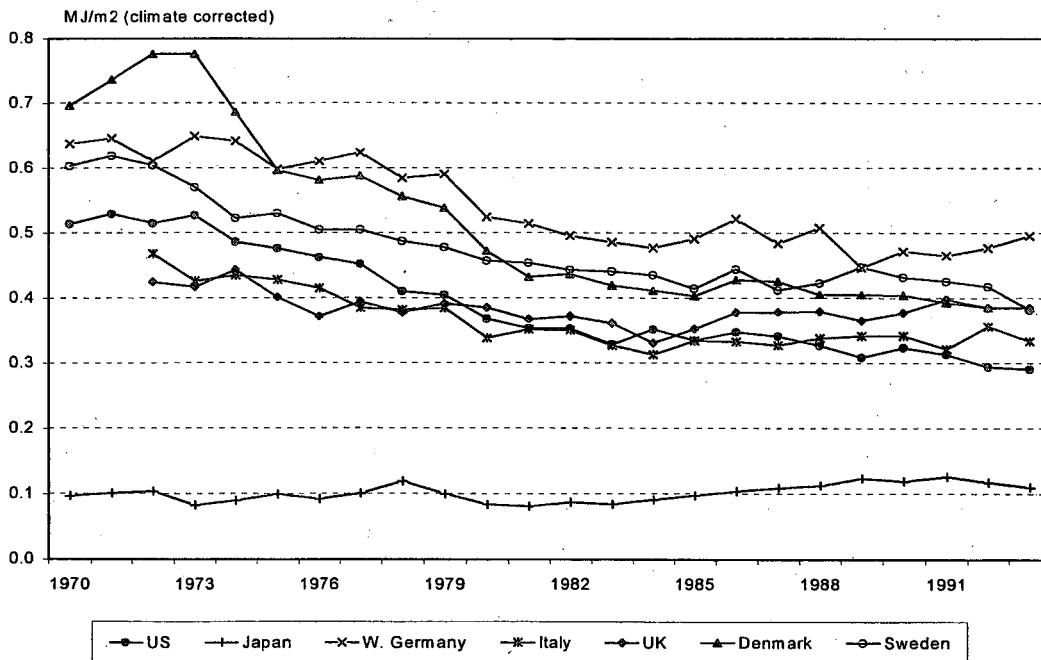

Figure 17. Residential Space Heating Energy Intensity for Selected Industrialized Countries, 1970-1993. Reference: IEA, 1997d.

Water heating, refrigeration, space cooling, and lighting, are the next largest residential energy uses, respectively, in most industrialized countries (IEA, 1997d). In developing countries, cooking and water heating dominate, followed by lighting, small appliances, and refrigerators (Sathaye and Ketoff, 1991). Appliance penetration rates increased in all regions between 1970 and 1990. Table 8 shows the growth in refrigerator and air conditioning equipment penetration rates for a number of industrialized countries during this period. In 1990, refrigerators were found in almost all households in France, Germany, Italy, Japan, and the U.S. (LBNL, 1998a). (Penetration rates over 100% indicate that more than one unit is owned per household.) Refrigerators were found in 22% of urban residences in India (1993), 66% of urban residences in China (1995), and 87% of urban residences in Thailand (1993). Air conditioners were found in 8% and 58% of urban households in China and Thailand, respectively, those years (Turiel et al., 1998). Figure 18 shows historical appliance penetration rates in urban and rural China for 1981 to 1996 (State Statistical Bureau of China, 1996).

The energy intensity of new appliances has declined over the past two decades; new refrigerators in the U.S. were 65% less energy-intensive in 1993 than in 1972. Table 9 shows energy intensity reductions in new refrigerators, freezers, clothes washers, dishwashers, and air conditioners in Denmark, former West Germany, and the U.S. (IEA, 1997d). The decline in new appliance intensities does not always mean a reduction of the average energy intensity of the appliance stock in a given country due to other factors such as stock turnover rates, appliance lifetimes, and consumer choice. Table 10 gives unit energy consumption values for selected appliance stocks in 1970 and 1990 for France, Germany, Japan, and the U.S. The increase in refrigerator intensities seen in France, Germany, and Japan was due to purchases of larger refrigerators with more features (e.g. ice makers) during this period. The average volume of refrigerators in Japan more than doubled between 1973 and 1990, offsetting reductions in energy intensity (Schipper et al., 1996).

Table 8. Refrigerator and Air Conditioner Penetration Rates in Selected Industrialized Countries, 1970 and 1990. Reference: LBNL, 1998a (France is 1972).

Refrigerator Penetration (%)	France	Germany	Italy	Japan	U.S.
1970	80	85	79	95	93
1990	98	127	96	116	118
Air Conditioner Penetration (%)					
1970	n.a.	n.a.	40	7	40
1990	n.a.	n.a.	140	114	69

Table 9. Reduction in Energy Intensity of New Appliances in Selected Countries.* Reference: IEA, 1997d.

	Refrigerator	Freezer	Clothes Washer	Dish Washer	Base Year, Final Year
Denmark	29/51	40	35	55	1970, 1994
former W. Germany	21	37	18	29	1978,1985
U.S.	65	58	38	36	1972, 1993

*measured as the ratio of new appliance electricity use in a recent year to that of an earlier base year.
Note: Second value for refrigerator in Denmark is for a combined refrigerator/freezer; value for refrigerator in U.S. is for a combined refrigerator/freezer.

Table 10. Unit Energy Consumption (kWh/year) for Selected Appliances in 1970 and 1990 in France, Germany, Japan, and U.S. Reference: LBNL, 1998a.

	France			Germany			Japan			U.S.		
	1970	1990	AAGR	1970	1990	AAGR	1970	1990	AAGR	1970	1990	AAGR
Refrigerators	494	630	1.2%	300	398	1.4%	283	715	4.7%	1316	1115	-0.6%
Freezer	739	690	-0.3%	700	540	-1.3%	na	na	na	1430	1039	-1.6%
Clothes Washer	366	305	-0.9%	60	51	-0.8%	28	44	2.3%	102	103	0.0%
Clothes Dryer	na	na	na	400	330	-1.0%	na	459	na	1006	952	-0.3%
Dishwasher	385	324	-0.9%	100	62	-2.4%	na	na	na	346	116	-3.6%
Air Conditioner	na	na	na	na	na	na	338	243	-1.6%	1924	1748	-0.5%

Figure 18. Appliance Penetration Rates in China, 1981 to 1996. Reference: State Statistical Bureau of China, 1996.
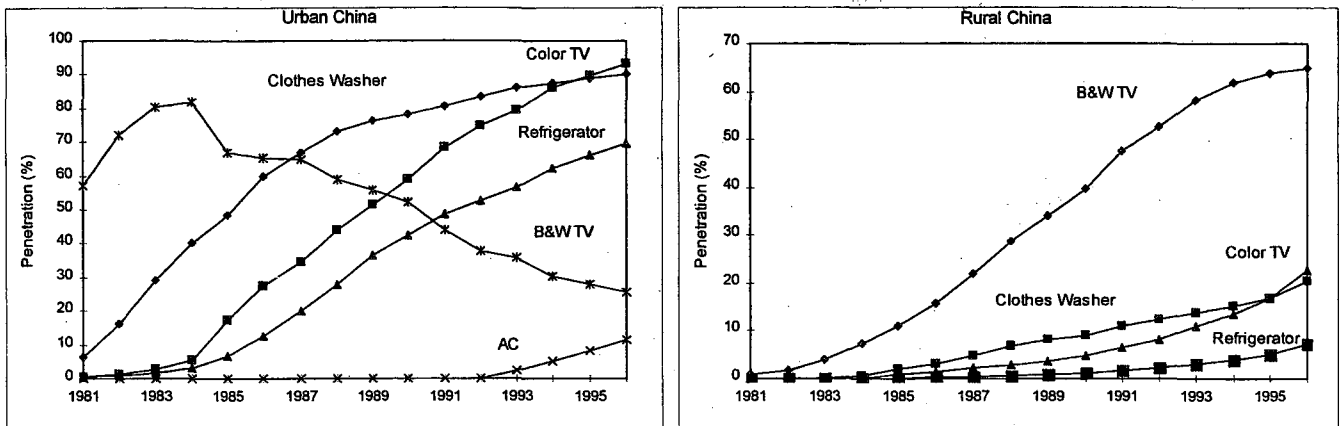
4.3.2.2 Commercial Buildings

Like residential buildings, energy intensity of commercial buildings is dependent upon both the building construction as well as the energy-using activities within the building. The type of building occupant clearly influences commercial buildings energy use because some buildings, such as hospitals and hotels, use energy continuously while others range from sporatic use (sports and entertainment facilities) to steady weekly use (office buildings) (IEA, 1997d). In the U.S. 15% of commercial floor space is used continuously and slightly over 35% is used less than 50 hours per week (U.S. DOE, EIA, 1992; U.S. DOE, EIA, 1994).

Primary energy use per square meter of commercial sector floor area has gradually declined in most industrialized countries despite two countervailing trends: growth in the share of electricity and increases in electricity intensity (see Figure 19) and reduction in fuel use and fuel intensity (see Figure 21). Electricity use and intensity (MJ/m^2) increased rapidly in the commercial buildings sector as penetration of computers, other office equipment, air conditioning, and lighting has grown. Fuel intensity (PJ/m^2) declined rapidly in industrialized countries as the share of energy used for space heating in commercial buildings dropped due to thermal improvements in buildings (Krackeler et al., 1998).

Figure 19. Electricity Use per Commercial Buildings Floor Area in Selected Industrialized Countries, 1970-1995. Reference: Krackeler et al., 1998.
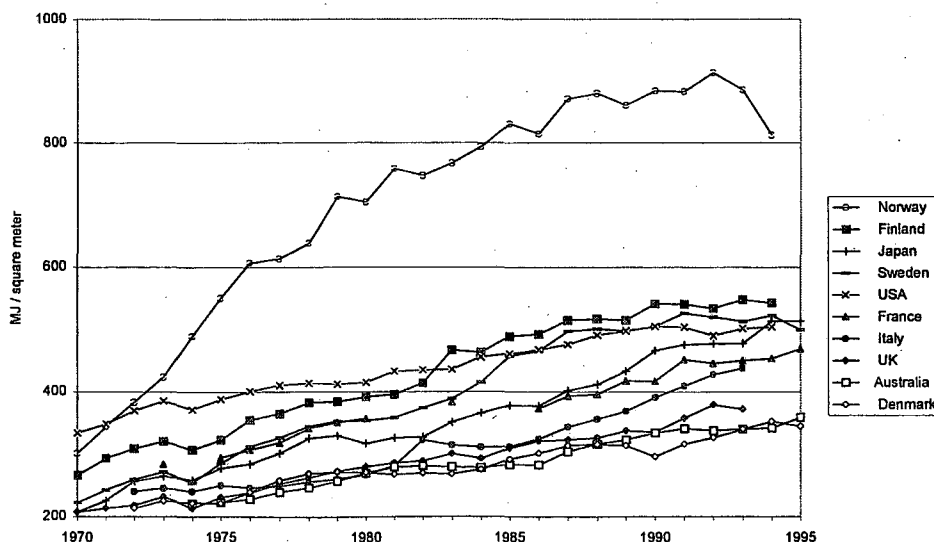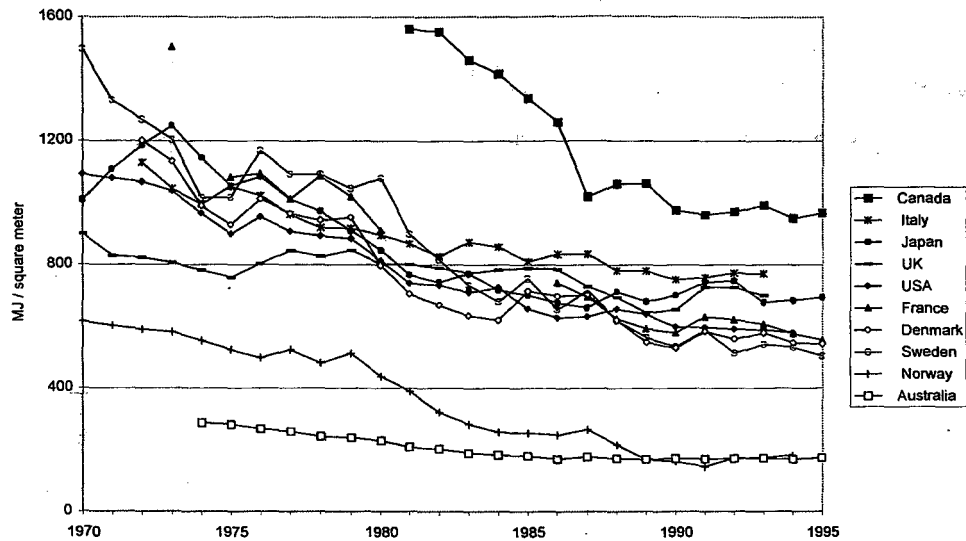

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Figure 20. Fuel Use per Commercial Buildings Floor Area in Selected Industrialized Countries, 1970-1995. Reference: Krackeler et al., 1998.

4.4 Carbon Intensity Trends

Carbon intensity changes mainly as a result of fuel substitution, but also as a result of changes in technology or process in the energy supply chain. Thus, the largest shifts in carbon intensity have been associated with changes in the energy sources used for power generation (Nakicenovic and Grübler, 1996). Smaller shifts have resulted from fuel switching in industrial, commercial and residential energy consumption.

4.4.1 Industrial Sector Carbon Intensity Trends

In industry, changes in carbon intensity and elasticity depend strongly on the sub-sector and its potential for fuel switching and efficiency improvement. For example, the use of biomass is historically connected with the forest products and food industries (e.g. bagasse in sugar making). New technologies and policies could make biomass use in other industrial sectors more economically attractive. Industries that use a large share of energy in biolers can convert to other fuels more easily than others. The growing market share of industrial cogeneration using relatively cheap gas turbine technologies is an example of a technology pushing the shift towards lower carbon fuels.

CO_2 emissions as a function of GDP of the industrial sector appear to stabilize in most countries, except for rapidly industrializing countries (IPCC, 1995). This trend is the result of changing economic structure, improved energy efficiency, and reduced carbon intensity of the fuel mix. A shift towards less carbon-intensive fuels took place between 1971 and 1992 in most industrialized countries as well as in S. Korea (Schipper et al., 1997; Ang and Pandiyan, 1997). The fuel mix has become more carbon-intensive in some developing countries such as China and Mexico (Ang and Pandiyan, 1997; Sheinbaum and Rodiguez, 1997), although a trend away from coal to other fuels has also been seen in some developing countries (Han and Chatterjee, 1997). The contribution of fuel mix changes to CO_2 emissions reduction has been small in most industrialized countries (Schipper et al., 1997; Golove and Schipper, 1997). Electrification has grown in all sectors in almost all countries (Han and Chatterjee, 1997). However, the

effect of increasing electrification on industrial emissions is unclear (IPCC, 1995). Price differences and elasticities, as well as lifetimes of existing process equipment, will influence future trends in fuel mix.

Various authors have studied the changes in fuel mix and effects on total CO_2 emissions of the manufacturing industry in industrialized countries (Torvanger, 1991; Schipper et al., 1997), China, South Korea, Taiwan (Ang and Pandiyan, 1997), and Mexico (Sheinbaum and Rodiquez, 1997). Although there has been a general overall trend towards lower carbon intensity (IPCC, 1992), Table 11 shows that fuel mix changes towards more carbon-intensive fuels occurred in industry in various countries. Such shifts may be related to availability of resources, policy measures, or change in the intra-sectoral structure.

Table 11. Annual Changes in Fuel Mix and Carbon Intensity in the Manufacturing Industry in Various Countries.

Country	Annual change in fuel mix (% per year)	Annual change in overall carbon intensity (% per year)	References
China (1980-91)	+0.4%	-0.2%	Ang & Pandiyan,1997
Denmark (1973-91)	+0.6%	-1.2%	Schipper et al., 1997
Finland (1973-91)	-2.1%	-3.9%	Schipper et al., 1997
France (1973-91)	+0.2%	-2.3%	Schipper et al., 1997
West Germany (1973-91)	+0.7%	-2.5%	Schipper et al., 1997
Italy (1973-91)	+0.2%	-3.1%	Schipper et al., 1997
Japan (1973-91)	+0.6%	-4.0%	Schipper et al., 1997
Japan (1979-87)	+0.3%	-0.8%	Torvanger, 1991
Mexico (1987-93)	+0.7%	-2.5%	Sheinbaum & Rodriquez, 1997
Norway (1973-91)	-2.8%	-3.9%	Schipper et al., 1997
South Korea (1981-93)	+0.2%	-0.9%	Ang & Pandiyan, 1997
Sweden (1973-91)	-1.7%	-6.3%	Schipper et al., 1997
Taiwan (1980-93)	+0.3%	-0.2%	Ang & Pandiyan, 1997
United Kingdom (1973-91)	+0.9%	-2.3%	Schipper et al., 1997
United States (1973-91)	+0.3%	-2.4%	Schipper et al., 1997
United States (1979-97)	+0.3%	-0.2%	Torvanger, 1991

Note: The changes in fuel mix represent the change in carbon emissions through a change in the final fuel mix of the power sector. The changes in carbon intensity represent the total changes in the energy consumed by industry, and is the product of changes in energy intensity, fuel mix, and fuel mix of the utilities.

In the iron and steel industry energy is used primarily for the reduction of iron oxides. The dominant process has been, and most likely will remain, the blast furnace, that uses coke as the primary reduction agent. Early blast furnaces, as well as some newly designed Brazilian blast furnaces, used charcoal as the reduction agent, requiring large quantities of wood. Later in the 19th century, coke (from coal) proved to be a much better reductant in British blast furnaces. Today, coke is the dominant fuel, partially replaced by injected fuels (coal, oil, gas). New technologies make it possible to replace coke completely by other fuels including coal and natural gas. These technologies currently have only a very small share of the global iron production.

Energy use for the production of steel is reduced by changes in efficiency and increased use of secondary materials. This trend, although not observed in all countries, also leads to a relatively small change in fuel-mix, away from coal towards more electricity and other (gaseous) fuels.[15] This leads to a reduction of the direct carbon emissions from the iron and steel industry. These may partly be offset by the emissions of the power sector, if fossil fuels are used for power generation. Figure 21 depicts the trends in specific carbon emissions for major steel producing countries around the world and shows a declining

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[15] Special circumstances, i.e. in Brazil, may lead to a different trend as non-fossil fuels are used in the reduction of iron oxides.

carbon intensity of steelmaking in nearly all countries. The countries with relative low carbon intensities are those countries with a high share of secondary steelmaking (e.g. Italy), energy efficient practices (e.g. West Germany) or use of low carbon energy sources in steelmaking (e.g. Brazil) or power production (e.g. Brazil, France).

Figure 21. Trends in Specific Carbon Emissions for the Production of Crude Steel in Major Steel Producing Countries, 1971-1994 (expressed in tonne C/tonne crude steel). References: Worrell et al., 1997b; Faaij et al., 1995.
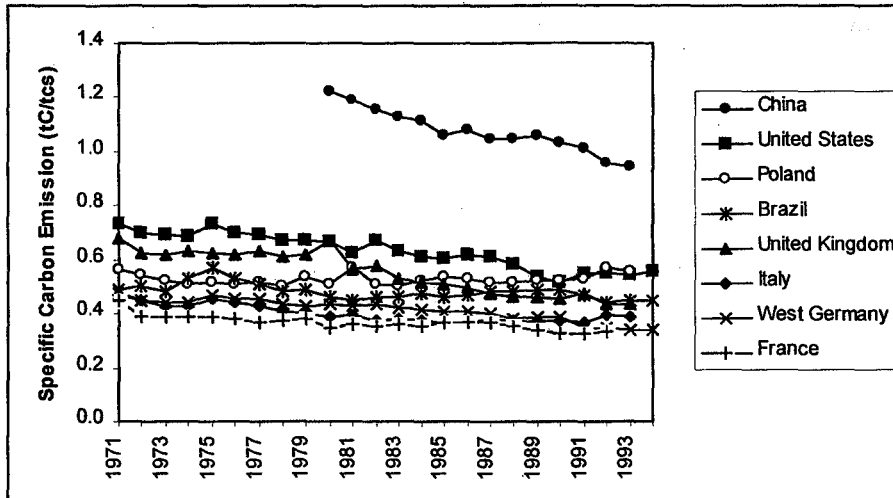
Note: carbon emissions from power production have been held constant at 1990 level for each country.

4.4.2 Buildings Sector Carbon Intensity Trends

Carbon intensity trends can be measured as either carbon emissions per unit of primary energy or per sectoral activity measurement (e.g. per capita and per square meter of floor area). Measuring carbon per unit of primary energy provides an indication of trends in the fuel mix, tracking whether more or less carbon-intensive fuels are being used to provide energy to buildings. Figure 22 shows that carbon intensity of the residential sector declined in most industrialized countries between 1970 and the early 1990s (LBNL, 1998a). In the commercial sector, carbon dioxide emissions per meter of commercial floor area also dropped in most industrialized countries during this period (see Figure 23) even though carbon intensity for electric end-uses (kgC from electricity/m^2) increased in most industrialized countries, dropping only in France, Sweden, and Norway, countries that moved away from fossil fuels (Krackeler et al., 1998).

In developing countries, biomass is often used in the residential sector, especially in rural areas. Increased urbanization, as well as increasing incomes and rural electrification, lead to rising carbon intensities in buildings because the mostly sustainable biomass is replaced with carbon-intensive fuels such as liquified petroleum gas (LPG), coal, and electricity generated by fossil fuels. In Brazil, the share of biomass energy used in the residential sector dropped from 90% in 1971 to just over 50% in 1992 as urban populations grew. In India, increasing incomes translated into replacement of biomass first with kerosene, then LPG, and finally electricity. This trend toward replacement of biomass fuels with commercial fuels in expected to continue in developing countries (IEA, 1995).

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Figure 22. Carbon Dioxide Emissions in the Residential Sector in Selected Industrialized Countries, 1970-1995. Reference: LBNL, 1998a.
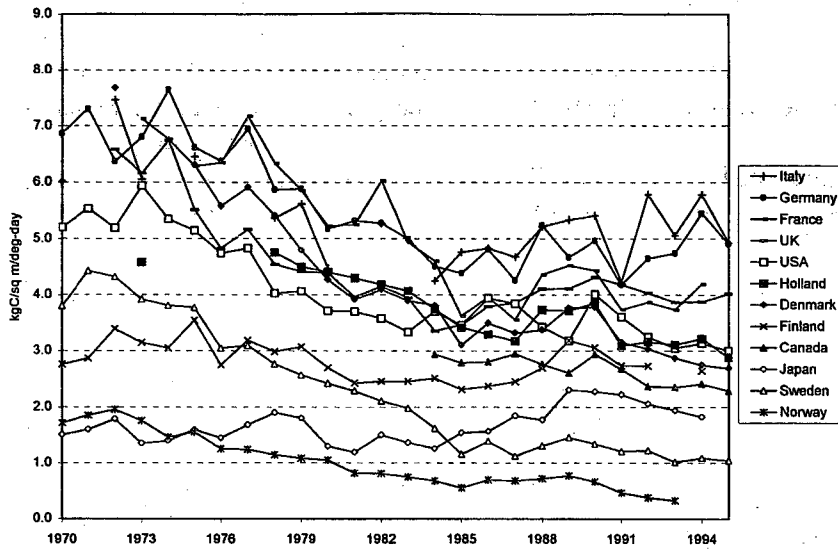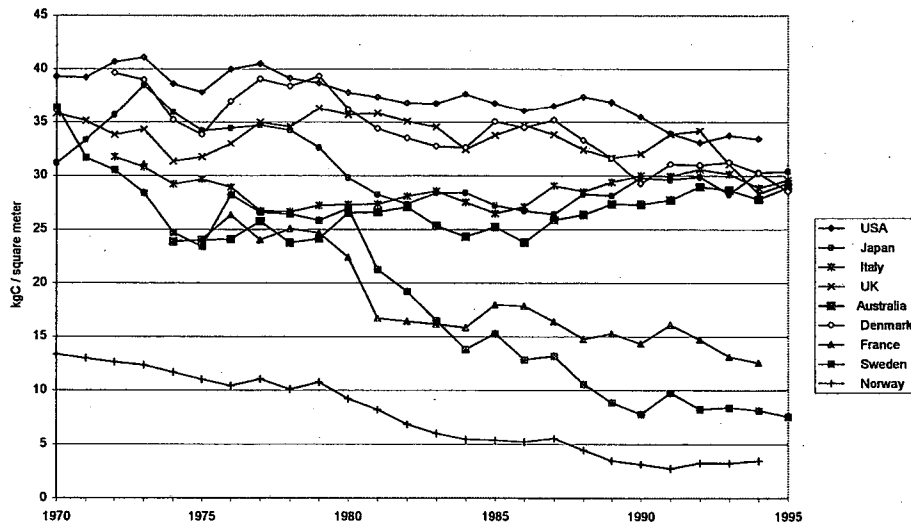

Figure 23. Carbon Emissions per Commercial Buildings Floor Area in Selected Industrialized Countries, 1970-1995. Reference: Krackeler et al., 1998.

5. Conclusions

While the industrialized countries clearly dominate current energy use and greenhouse gas emissions, the large recent population and energy use growth patterns in many developing countries, coupled with trends in sector-specific indicators such as lower number of people per household and increased per capita vehicle ownership in these countries, clearly illustrate the potential for significant increases in energy use and greenhouse gas emissions in these areas as these countries improve their welfare levels. Analysts and policymakers interested in understanding future trends and the potential to mitigate emissions require detailed sectoral and regional information to identify appropriate measures and formulate effective policies.

Energy use and greenhouse gas emissions trends vary widely by region of the world and end-use sectors. Using various data sources and reallocation methods to improve on the IEA Energy Balances, we were able to disaggregate energy use and CO_2 emissions into the key end-use sectors of industry, transport, buildings, and agriculture and to provide historical data for these sectors both globally and regionally. Using the key elements of the Kaya formula, we discussed the driving factors underlying these historical trends, showing that many factors influence energy consumption and CO_2 emissions. The varying contribution of the different drivers regionally and over time helps to explain global and regional CO_2 emission trends. Scenarios of future energy use and greenhouse gas emissions should reflect an understanding of these historical trends and their driving forces.

Driving forces behind energy use and carbon emissions in the industrial sector include the country's state of economic development, consumption and trade patterns, relative costs of energy, and availability of resources. In the buildings sector, household expenditure levels, appliance and equipment penetration levels, and the share of population living in urban areas all affect energy use. Settlement patterns, infrastructure and social factors affect vehicle choice and kilometers traveled as much as income levels and fuel prices.

In addition, the energy intensity and other characteristics of the technologies used in each of these sectors play a role in determining the amount of energy consumed. Fuel choice, which is a key factor in determining carbon emissions, is strongly affected by local availability and non-price factors, which are difficult to take into account in models. These many influences on energy use and greenhouse gas emissions vary widely by country and region of the world, but are essential to understand the model results, and the consequences for policy making.

Appendix A. Definition of Regions

Industrialized Countries: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, U.K., U.S.

Economies in Transition: Armenia, Azerbaijan, Belarus, Bulgaria, Czech Republic, Estonia, Georgia, Hungary, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldovia, Poland, Romania, Russian Federation, Slovakia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan

Developing Countries in Asia/Pacific: Afganistan, American Samoa, Bangladesh, Bhutan, Brunei, Cambodia, China, Fiji, French Polynesia, Hong Kong, India, Indonesia, Kiribati, Korea (N.), Korea (S.), Laos, Malaysia, Maldives, Mongolia, Myanmar, Nepal, New Caledonia, Pakistan, Papau New Guinea, Philippines, Solomon Islands, Singapore, Sri Lanka, Thailand, Vanuatu, Vietnam

Rest of World: all remaining countries

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