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Sectoral trends in global energy use and greenhouse gas emissions

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Abstract

Integrated assessment models have been used to project both baseline and mitigation greenhouse gas emissions scenarios. Results of these scenarios are typically presented for a number of world regions and end-use sectors, such as industry, transport, and buildings. Analysts interested in particular technologies and policies, however, require more detailed information to understand specific mitigation options in relation to business-as-usual trends. This paper presents sectoral trend for two of the scenarios produced by the Intergovernmental Panel on Climate Change's Special Report on Emissions Scenarios. Global and regional historical trends in energy use and carbon dioxide emissions over the past 30 years are examined and contrasted with projections over the next 30 years. Macro-activity indicators are analyzed as well as trends in sectoral energy and carbon demand. This paper also describes a methodology to calculate primary energy and carbon dioxide emissions at the sector level, accounting for the full energy and emissions due to sectoral activities.
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Keywords: Primary energy; Greenhouse gas emissions trends; Sectoral energy consumption

1. Introduction

This paper examines sectoral energy consumption trends for 10 world regions[1] using historical data for the period 1971–2000 and projected data for the period 2000–2030 based on the A1 and B2 scenarios of the Special Report on Emissions Scenarios (Nakićenović et al., 2000; Price et al., 2006). The data have been compiled to reflect the energy and energy-related carbon dioxide (CO_2) emissions related to three main end-use demand sectors: industry, buildings, and transportation. Our methodology re-allocates the indirect primary energy and CO_2 emissions due to the conversion of energy into electricity, petroleum products and coal products at the sectoral level.

We distinguish between final and primary energy consumption. Final energy consumption represents the direct amount of energy consumed by end user, while primary energy consumption includes final consumption plus the energy that was necessary to produce secondary energy, such as energy transformation loses. An alternative designation to primary energy consumption is the term source energy consumption as opposed to site energy consumption that refers to final consumption.

The purpose of showing primary energy and primary energy-related CO_2 emissions at the sectoral level is to fully represent the energy demand for each of the sectors. Consuming 1 terajoule of electricity is not equivalent to the consumption of 1 terajoule of natural gas or coal. The energy consumed represents additional energy consumption due to the amount of energy expended upstream in the production of the necessary electricity. Depending on countries and accounting methodologies, primary energy for one unit of electricity is between one and three times larger than its final energy value. This also applies to petroleum and coal secondary products. In terms of CO_2 emissions, a similar adjustment can be made. Even though electricity consumption does not result in direct CO_2 emissions, it results in considerable amount of indirect emissions, even more so if a large quantity of electricity is produced from coal. The introduction of primary factors and CO_2 factors is a mean of accounting for this indirect energy use and CO_2 emissions.

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[1]See Appendix A for a definition of these world regions.

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Table 1
World-average annual growth rates

	SRES A1 marker				SRES B2 marker			
	2002–2010	2010–2020	2020–2030	2002–2030	2002–2010	2010–2020	2020–2030	2002–2030
GDP	3.6	4.1	4.7	4.1	3.2	2.8	2.7	2.9
Population	1.1	1.0	0.9	1.0	1.2	1.1	0.9	1.1

The major driving forces of past and future energy demand and CO_2 emissions include demographic and economic variables, such as population and gross domestic product (GDP). The SRES scenarios provide information on their assumptions for these two variables with storylines describing the context of economic and social development. Table 1 shows these variables for the A1 and B2 scenario projections. The A1 scenario predicts very rapid economic growth and low population growth, while the B2 scenario foresees more moderate economic and population growth (Nakićenović et al., 2000). The A1 storyline sees a rapid introduction of new and more efficient technologies with increasing convergence among regions. The B2 storyline portrays an emphasis on sustainable development with less regional integration but more local development.

A frequently used approach to organize discussion of the drivers of emissions is through the Kaya identity (Kaya, 1989). The Kaya multiplicative identity can be broken down into further subcomponents. In this paper, the energy component is additionally decomposed into primary and final energy, to reflect conversion of primary energy sources to final energy. As explained in the SRES, the terms of the equation should be considered neither as fundamental driving forces in themselves, nor as generally independent from each other (Nakićenović et al., 2000).

End-use sector-level results for buildings, industry, or transportation or information regarding adoption of particular technologies and policies are not provided in the SRES. The goal of the work described in this article is to provide primary energy and CO_2 emissions at the sectoral level and analyze trends over 30 years of historical data and 30 years of projected data according to two SRES scenarios. Sectoral information is valuable for analysts and policy-makers who want to understand the implications of certain projected futures as well as the types of efficiency improvements that are required to realize lower energy consumption scenarios.

Section 2 describes the methodology used to reallocate indirect energy use and CO_2 emissions from energy transformation to the end-use sectors in the historical data set. Section 3 describes the data used for projection over the period 2000–2030. Section 4 analyses historical and scenario data using the Kaya equation. Finally, Section 6 describes energy and CO_2 emissions trends over the period 1970–2030.

2. Data and methodology

Sectoral primary energy consumption and energy-related CO_2 emissions data back to 1971 and projected to 2030 were assembled in order to interpret energy consumption trends over time. Primary energy can be defined as the energy embodied in natural resources (e.g., coal, crude oil, sunlight, uranium) that has not undergone any anthropogenic conversion or transformation (IPCC, 2001) and secondary energy as the energy contained in products or carriers resulting from the transformation or conversion of primary energy. Secondary energy products mainly consist of electricity, petroleum products, and different coal products, and are the most consumed form of energy at the end-use level. The main purpose of secondary energy production is to convert energy into more useful energy products. The total energy lost during the process of converting primary energy into secondary energy is considerable, representing 31% of the total supply and resulting in 46% of the world's total CO_2 emissions in 2004 (IEA, 2006a, b).

Primary energy and CO_2 emissions factors were calculated to allow a proportional redistribution of this energy and these emissions to the end-use sectors where secondary energy products are ultimately consumed. Four sets of factors were estimated for the production of electricity, heat, petroleum products, and coal products.

A previously developed methodology to reallocate energy use in electricity and heat processes (Schipper et al., 1997; Price et al., 1998) was extended to the reallocation of energy use in the processing of petroleum and coal products. The general method employed to calculate primary factors is derived as the ratios of fuel inputs to outputs. These ratios represent the inverse efficiency of the transformation process and are greater than one. For example, a power plant with an efficiency of 33% has a primary factor of approximately three, meaning that three units of energy were required to produce an output of one unit, and two-thirds of the energy was lost in the process. CO_2 emissions factors are calculated following a similar logic, but instead of being the ratio of energy to energy, they represent the quantity of CO_2 emitted during the production of one unit of secondary energy product. The main source of historical data is the International Energy Agency (IEA, 2006a, b). Several modifications to the original time series were conducted to correct some

breaks in the series.[2] This section describes the data and the methodology used to calculate primary energy and CO_2 emissions factors at the sectoral end-use level.

2.1. Electricity and heat factors

The production of electricity and heat are the most important forms of secondary energy produced worldwide; the energy lost in their transformation represents approximately 76% of the total energy lost in secondary energy production and distribution. Electricity is the fastest-growing form of energy product consumed globally. World electricity consumption has grown at an average of 4% annually over the last 30 years, while total final energy grew at an average of 2%. Growth in electricity consumption is driven by increasing number of households owning appliances across the world and to some extent, the use of air conditioners in buildings. The reallocation of energy lost in the production of electricity at the sectoral level shows the actual demand of energy by sectors.

Primary factors were derived as the ratio of fuel inputs at power plants to electricity or heat delivered and reflects the process energy efficiency and transmission and distribution loses. Fuel inputs for electricity production were separated from inputs to heat production in combined heat and power plants (CHP) according to the shares of electricity and heat produced in these plants (IEA, 2005). Primary energy associated with secondary energy consumption was then calculated by multiplying the amount of electricity and heat consumed in the end-use sectors by these primary electricity and heat factors.

Different methodological conventions exist to account for the primary energy associated with electricity production from non-combustible-fuel energy such as renewable and nuclear energy. In this paper, the "direct equivalent" accounting method is used to be consistent with methodology used in the SRES scenarios (Nakićenović et al., 2000). This method accounts for the primary energy of the non-fossil-fuel energy at the level of secondary energy with an efficiency of a 100%. For example, the primary energy equivalence of electricity generated from solar photovoltaic or nuclear power plants is set equal to their respective gross electricity output not to the heat equivalent of the solar radiance that falls onto a photovoltaic panel or radiation energy from fissile reaction, as used with the physical energy content method, or the heat that would have been necessary by burning fossil fuels to produce the same amount of electricity as used in the so-called "substitution" accounting method. Appendix B provides a description of the primary energy accounting methodologies.

Fig. 1 shows the electricity factors calculated for 10 world regions. A region with a high-value electricity factor is a region using relatively more energy to generate electricity or using relatively more fossil fuel in the energy mix. Average factors for fossil fuel are around three and factors for renewables and nuclear energy are equal to one, according to the direct equivalent methodology. Regions like Latin America that rely on significant levels of hydroelectric power have a lower primary electricity factor. Also, countries such as those of the former Soviet Union (FSU) that produce considerable heat as a byproduct of cogeneration also have a lower factor, as the energy used for electricity generation is reduced by the quantity needed to produce the associated heat. The level of electricity lost in its transmission and distribution is reflected in the factor and tends to increase its value. Finally, the quality of data available worldwide is reflected in these factors and can explain some anomalies.

Concerning CO_2 emissions, electricity and heat represent 86% of the total CO_2 emissions resulting from the energy lost during the process of converting primary energy into secondary energy. CO_2 emissions factors were calculated to allow a proportional redistribution of these emissions to the end-use sectors where electricity and heat are ultimately consumed. CO_2 emissions factors for electricity and heat were derived as the ratio of carbon emissions resulting from fuel inputs at power plants to electricity or heat delivered. The same method as described above for the primary factors was used to separate fuel inputs for electricity production from fuel input for heat production in cogeneration (also called CHP). The total fuel inputs were then multiplied by the respective carbon emission factors for each type of fuel given by the IPCC (IPCC, 1996). CO_2 emissions factors for electricity and heat were calculated for each of the 10 regions. Carbon embodied in electricity and heat consumption was then calculated by multiplying the amount of electricity and heat used in each sectors by the electricity and heat carbon factors.

Fig. 2 shows the electricity CO_2 factors which indicate the level of CO_2 emissions that are emitted per unit of electricity produced. These factors reflect the fuel mix in the power sector and the efficiency of power generation. A region with a high share of non-fossil-fuel use in their power generation has a low coefficient. Latin America, which has a high share of hydroelectric power, has the lowest CO_2 emission factor for electricity production.

Heat primary and carbon factors were also calculated, however, due to irregularity in data availability over the years and regions, Table 2 presents factors only for 2004 and only for the regions where data were available.

[2]Modifications to the original data were performed for biomass energy consumption for the regions of former Soviet Union (FSU), South Asia, East Asia, and Africa. The IEA provides detailed information regarding biomass energy consumption only after 1994. Before 1994, no breakdown of consumption is shown and all domestic supply appears as a statistical difference. To include biomass consumption before 1994 for these regions, we extrapolated the breakdown of 1994 consumption back to 1971. For the FSU region before 1993, the IEA statistics for the buildings sector have a number of anomalous values. These values were compared with British Petroleum (BP) energy-consumption statistics, and then adjusted to produce a smoother time trend (BP, 2004).

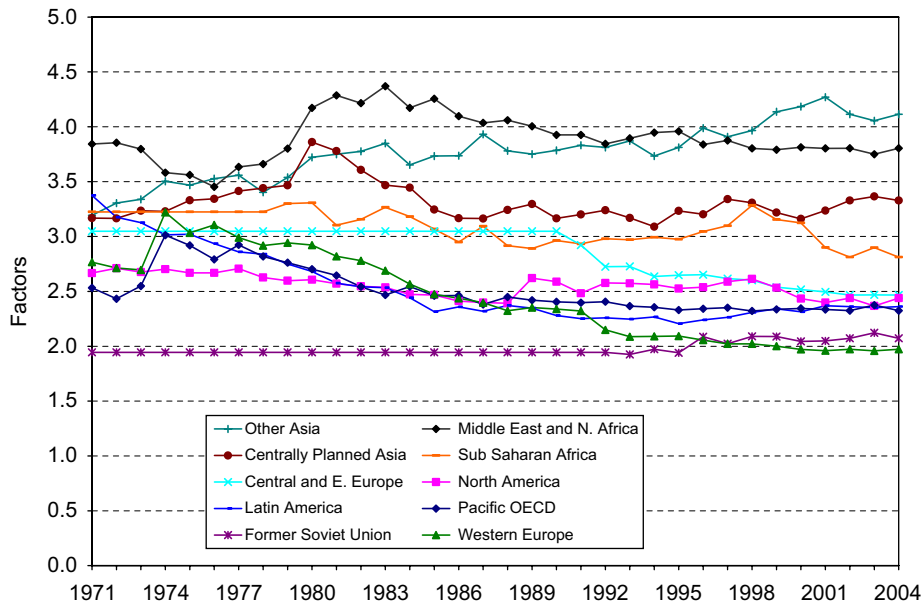

Fig. 1. Primary electricity factors. *Note*: primary electricity factor for Central Eastern Europe and FSU regions were assumed constant in time due to lack of data availability.

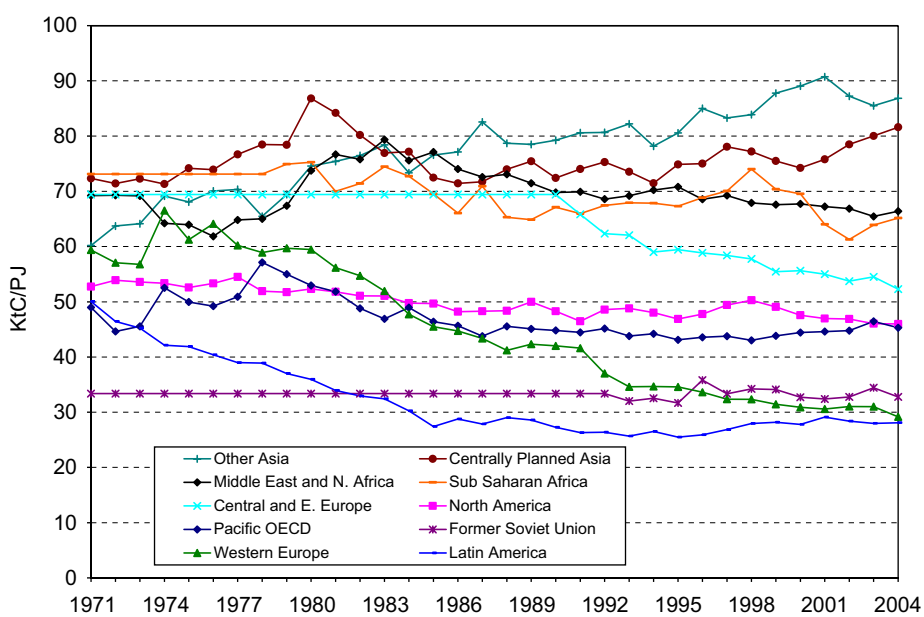

Fig. 2. Electricity carbon factors (ktC/PJ).

Table 2
Heat primary and carbon factors, 2004

	Primary factor	Carbon factor, KtC/PJ
Pacific OECD	1.40	26.52
North America	2.54	47.43
Western Europe	1.82	30.73
Central and Eastern Europe	1.85	41.14
Former Soviet Union	1.61	29.08
Centrally Planned Asia	1.55	39.93
Other Asia	1.41	39.03

2.2. Coal and petroleum products factors

About 30% energy losses remain after the reallocation of energy losses due to the production of electricity and heat. About 90% of this residual energy loss is due to the transformation of coal into more refined products and the conversion of crude oil into petroleum products. In order to redistribute this energy consumption in proportion to its final use, we calculated primary factors for coal products and petroleum products.

Primary factors for production of coal products—patent fuel, coke oven coke, coke oven gas, blast furnace gas, and

briquettes (BKB)—were derived as the ratio of fuel inputs at coke ovens, patent fuel plants, blast furnaces, and BKB plants to total coal products produced. Primary energy associated with coal products was then calculated by multiplying the amount of coal products consumed in each sectors by the coal products primary factor. Similarly, for petroleum products, primary factors for the production of petroleum products were derived as the ratio of fuel inputs at refineries and "own use" to petroleum products produced. Primary energy associated with petroleum products was then calculated by multiplying the amount of petroleum products consumed by each end-use sector by the petroleum products primary factors.

The results for coal and petroleum products are shown in Figs. 3 and 4, respectively. Coal product primary factors for the 10 regions vary between 1.5 and 2.5, meaning that it requires 1.5–2.5 times energy to produce one unit of coal products, accounting for the energy lost and used in the production of more refined coal products. Primary energy factors for oil products range between 1.05 and 1.2, meaning that it requires up to 20% more energy to transform crude oil and feedstocks in petroleum products

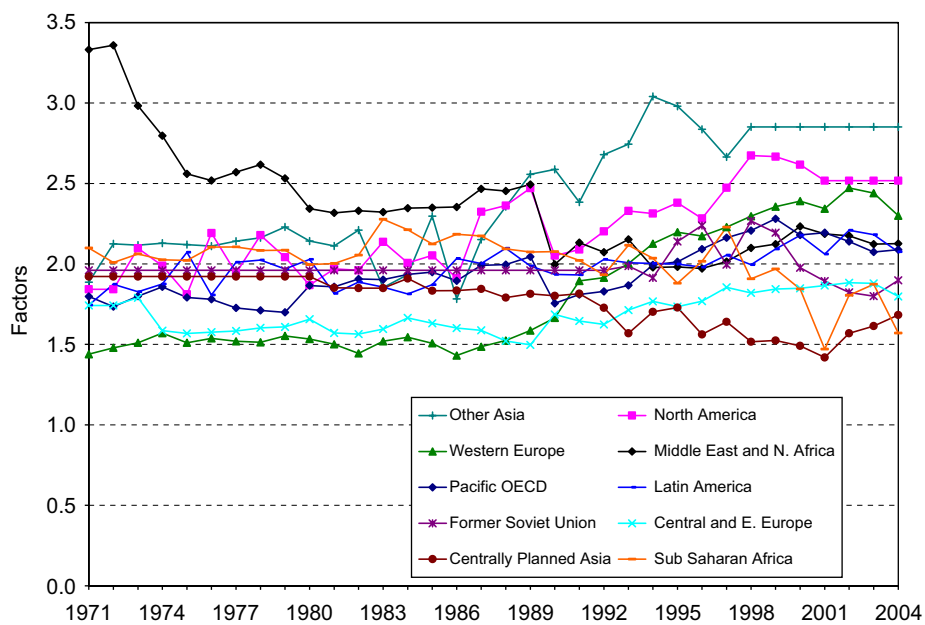

Fig. 3. Primary coal product factors.

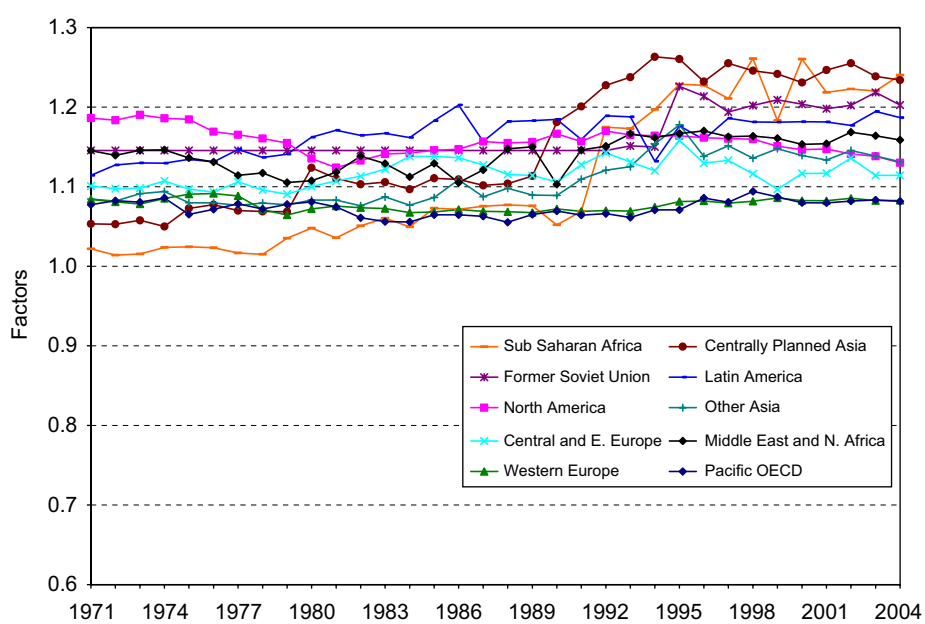

Fig. 4. Primary petroleum factors.

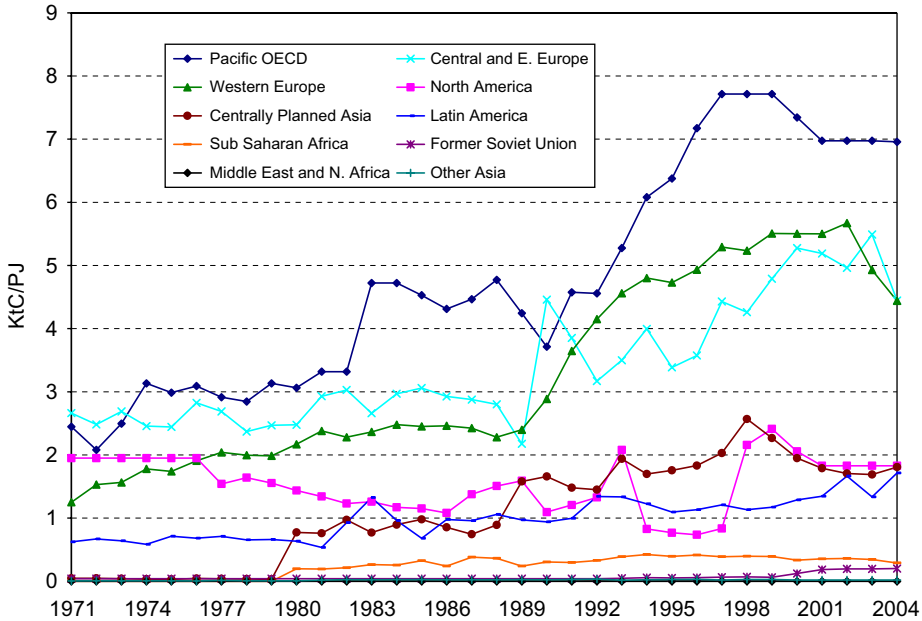

Fig. 5. Coal product CO_2 emissions factors.

than is in the products themselves. This factor is low compared with the production of electricity or coal products. However, it is applied to a much larger quantity of final products as no crude oil is consumed directly in its natural form. Additionally, the exploitation of less accessible oil and unconventional oil will augment the petroleum product coefficient as these reserves of oil require more energy to be exploited.

Carbon emissions factors associated with the production of coal products and petroleum products were also calculated. For coal products, the carbon emissions due to fuel combustion in coke ovens, patent fuel plants, blast furnaces, and BKB plants were accounted for, and then a ratio of these emissions to total coal products produced was calculated. Additional carbon embodied in the coal products process was then distributed by multiplying the amount of coal products consumed in each sectors by this ratio. For petroleum products, CO_2 emissions factors were derived as the ratio of CO_2 emissions due to fuel combustion in refineries to total petroleum product produced. This factor was used to redistribute the additional CO_2 emissions due to the production of petroleum products among end-use sectors by multiplying the amount of petroleum products consumed in each end-use sector by the CO_2 emissions factor.

The carbon emissions associated with the production of coal products and petroleum products derived through the CO_2 factors varied widely across regions (see Figs. 5 and 6) due to the quality of data available among the regions concerning these specific transformation processes. In practice, it often proves difficult to correctly account for all inputs and outputs in energy transformation industries, and to separate energy that is transformed from energy that is combusted. However, this distinction is necessary when accounting for CO_2 since the transformation of primary fuels into secondary fuels by physical or chemical processes without combustion does not result in direct CO_2 emissions.[3] Variation in CO_2 factors can be partially explained by increasing consumption of energy reported as fuel use versus input. This distinction is becoming more available in energy statistics over time.

2.3. Comparison with IEA statistics

Subsequent to the reallocation calculation, a comparison with the IEA data for primary energy was performed. An average difference of 3% was found between the total primary energy calculated using the methodology described above and the IEA Total Primary Energy Supply (TPES). An average difference of 2% was found between the total CO_2 emissions calculated by this method and the IEA data (IEA, 2006c). There are three main reasons for these differences. First, statistical differences between supply and demand in IEA energy statistics are reflected in the gap between TPES and the sectoral approach described herein. Second, imports and exports are not differentiated. The calculation of the primary energy factors and CO_2 emissions factors is applied to the final consumption without distinction between domestically produced or imported secondary products. Third, not all energy industries are taken into account. Energy used in liquefied natural gas plants, charcoal plants, and other non-specified processes is not taken into account in this reallocation scheme.

[3] CO_2 emissions can result from fugitive emissions, however, in this article only CO_2 emissions from fuel combustion are accounted for.

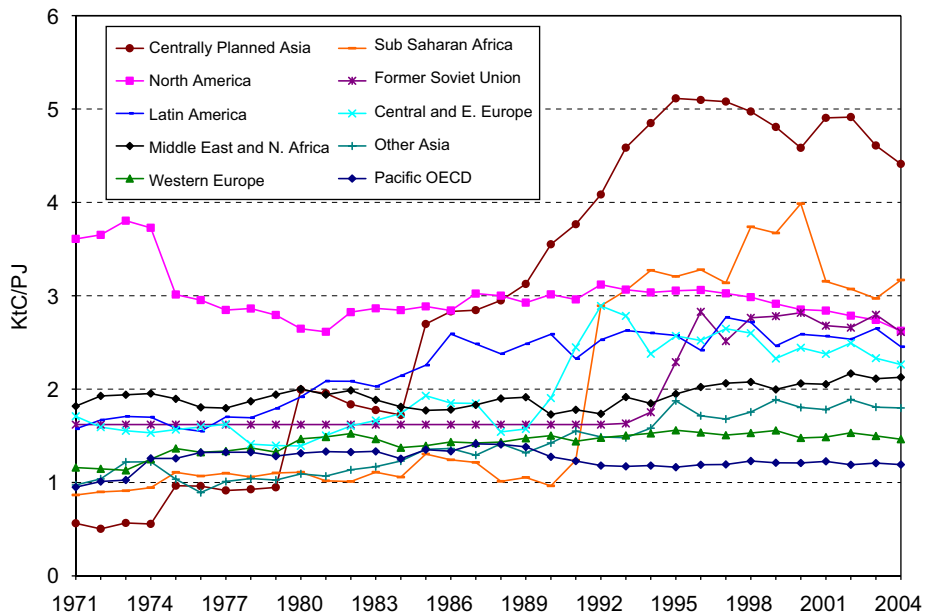

Fig. 6. Petroleum products CO_2 emissions factors.

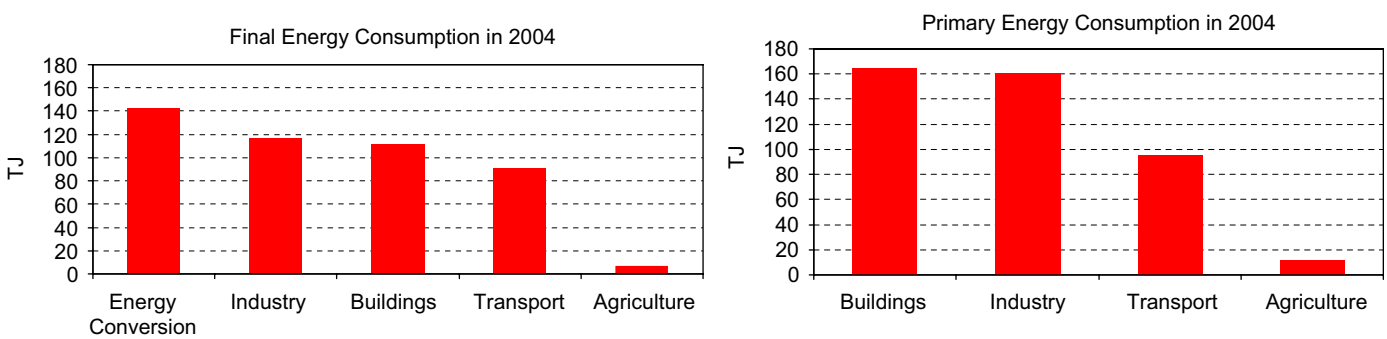

Fig. 7. 2004 final and primary energy consumption.

2.4. Reallocation of energy transformation energy use and CO_2 emissions to the end-use sectors

Fig. 7 shows world energy consumption by sectors in 2004 with the two approaches. The first graph shows energy consumption as it appears in the IEA balances and the second graph shows energy consumption after the reallocation of transformation energy consumption to the end-use sectors.

The IEA energy balances approach illustrates that the most energy is consumed in the energy conversion sector. Through the reallocation of the energy used for conversion to the end-use sectors, it is shown that bulk of this energy conversion result of the need to meet the energy demand of the residential and commercial building sector and the industrial sector. The share of electricity consumption is very high in the commercial sector, representing 50% of total final energy consumption. This is mostly due to energy consumed in developed countries that represents 75% of total energy consumed in commercial buildings. The use of electricity meets the need for lighting, water heating and air conditioning. Electricity consumption in residential sector represents a small share of 17% worldwide but is considerably higher when looking at developed countries with a share of 30%. It is most likely that electricity consumption will continue to increase in the residential and commercial building sectors.

The redistribution of CO_2 emissions using the reallocation methodology described in Section 2 is shown in Fig. 8. The first graph shows CO_2 emissions in sectors without the reallocation of CO_2 emissions from energy conversion and the second graph shows CO_2 emissions after the reallocation to the end-use sectors. In the first graph, transport appears as the largest source of CO_2 emissions after energy conversion while in the second graph industry is the largest source. The reallocation increases the share of emissions from the building sector, from 11% to 34%. The reallocation scheme results in a very different picture in the sectoral breakdown of the CO_2 emissions, emphasizing the importance of industry and buildings as the largest CO_2 emissions emitters.

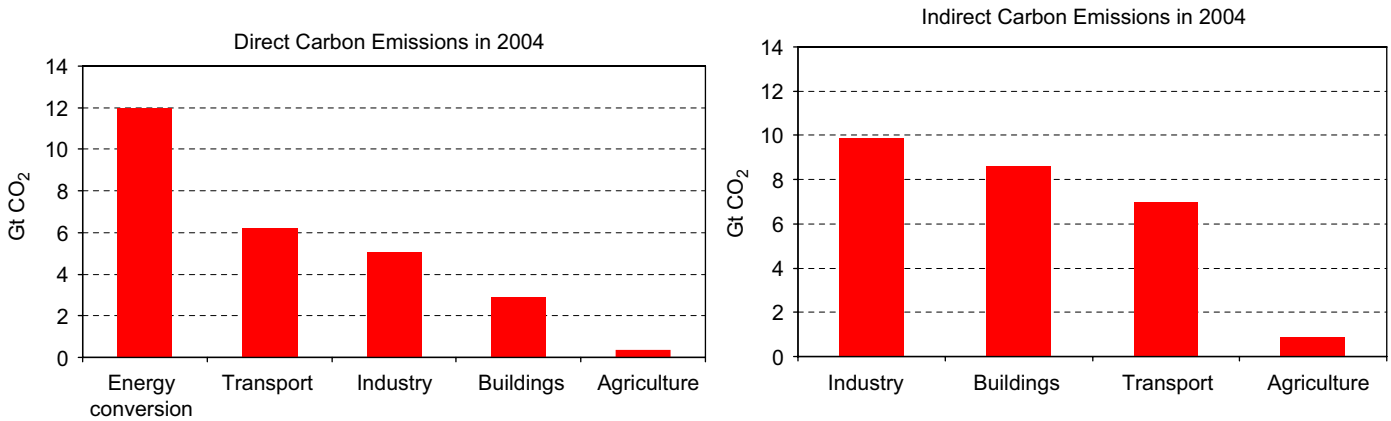

Fig. 8. 2004 direct and indirect CO_2 emissions.

3. Scenarios data to 2030

This article focuses on the SRES A1 (A1B) and B2 marker scenarios since they represent distinctly contrasting futures. The SRES reports emissions for each of these storylines by type of greenhouse gas and by fuel type to 2100 globally and for four regional groups (OECD countries as of 1990, countries undergoing economic reform, developing countries in Asia, rest of world). Specific assumptions about the quantification of scenario drivers, such as population and economic growth, technological change, resource availability, land-use changes, and local and regional environmental policies, are also provided.

Data that provide more detail than that reported in the SRES report were obtained from the SRES modeling teams. For the A1 marker scenario, the modeling team provided final energy demand and CO_2 emissions by fuel for industry, buildings, and transportation for nine world regions. For the B2 marker scenario, final energy use and CO_2 emissions for three sectors (industry, transport, buildings) were provided for 11 regions.

The two scenarios only provide total primary energy supply information and do not provide data on primary energy consumption by sector. Energy loses occurring during the conversion of primary energy into secondary products were calculated as the difference between primary and final energy consumption. Similarly, as the methodology described in Section 2, we reallocated this energy use to the end-use sectors in proportion to their consumption of secondary products, but simplified due to the limitation in data availability compare to the full balance that the IEA provides.

3.1. A1 marker scenario

Data for the A1 marker scenario were provided by the National Institute for Environmental Studies in Japan. The data provided were for final energy demand and CO_2 emissions for nine world regions (USA, Western Europe OECD and Canada, Pacific OECD, Eastern Europe and FSU, Central Planned Asia, South and East Asia, Middle East, Africa, and Latin America) by fuel for the industry, buildings, and transportation sectors.

SRES results for A1 marker scenario provide data on total primary energy and final energy per end-use sectors. To calculate primary energy per end-use sector, the electricity consumed in each end-use sector was multiplied by a final-to-primary conversion factor that accounts for conversion, and transmission and distribution losses. This factor varied by year and by the regional groups and was determined by comparing the total final to total primary energy values reported in the SRES results for the A1 marker scenario. It is assumed that the difference between primary energy consumption and final energy consumption is the energy consumed in transformation process to produced secondary product. As only data on electricity were available, it was assumed that most of the energy consumed in the transformation sector is due to electricity production. For CO_2 emissions, the total CO_2 emissions from the electricity sectors were divided by the total electricity consumed and this factor was applied to the electricity consumed in each sector.

The nine world regions were re-aggregated into 10 world regions (Appendix A) using historical data trends. For example, in order to remove Canada from the A1 scenario's OECD-E grouping so that it could be grouped with the US to form the North America region, Historic data on Canadian and OECD Europe energy consumption by fuel type were used to determine the share of Canadian energy consumption and CO_2 emissions that would be represented in the OECD-E region. This value was then subtracted from the OECD-E region and added to the US to determine the North America region values. Similar calculations using historical data were made to split the FSU and Eastern Europe as well as to divide Africa into North Africa and Sub-Saharan Africa.

The A1 model includes the agriculture sector within the industrial sector. These two sectors were divided by using the historic ratio of agriculture to industry energy use for each region in 2000 for the 2000 scenario value and the historical ratio for 2002 for the 2005–2030 scenario values. A flat ratio over time was assumed.

3.2. B2 marker scenario

Data for the B2 marker scenario were provided by the International Institute for Applied Systems Analysis (IIASA).[4] The data provided were for primary energy use and CO_2 emissions for 11 world regions (North America, Western Europe, Pacific OECD, Eastern Europe, FSU, Central Planned Asia, South Asia, East Asia, Middle East, Africa, and Latin America)[5] by fuel for industry, transport, and residential/commercial sectors.

SRES results for B2 marker scenario provide data on total primary energy and final energy per end-use sectors. Similarly to A1 marker scenario, to calculate primary energy per end-use sector, LBNL converted the final energy to primary energy by multiplying the secondary products (electricity, heat, and synfuels) consumed by each end-use sector by a final-to-primary conversion factor that accounts for conversion, and transmission and distribution losses. This factor varied by year and for the 10 regions and was determined by comparing the total final to total primary energy values reported in the SRES results for the B2 marker scenario. For CO_2 emissions, no calculation was needed as B2 provided indirect emissions by final sectors.

As with the A1 marker scenario, the 11 world regions were re-aggregated into the 10 world regions using historical data trends. For example, in order to remove Korea from the other Pacific Asia grouping so that it could be grouped with Japan, New Zealand, and Australia to form the Pacific OECD region, historic data on Korea and other Pacific Asia energy consumption was used to determine the share of Korea energy consumption and CO_2 emissions that would be represented in the other Pacific Asia region. This value was then subtracted from the PAS region and added to Japan, New Zealand, and Australia to determine the Pacific OECD region values. Similar calculations using historical data were made to subtract Chinese Taipei from other Pacific Asia to form the Centrally Planned Asia and Other Asia regions.

The B2 scenario includes the agriculture sector within the buildings sector. These two sectors were divided by using the historic ratio of agriculture to buildings energy use or carbon emission for each region in 2000 for the 2000 scenario value and the historical ratio for 2002 for the 2005–2030 scenario values and for each fuel. A flat ratio over time was assumed.

4. Disaggregation of SRES A1 and B2 scenarios

Drivers of energy consumption and CO_2 emissions can be grouped in three main categories. The first is the size of the population. The more people who need to meet their energy needs, the more resources are consumed. The second is how and to what extent we meet our needs. According to wealth and cultural practices, these needs are met differently and varying levels of energy can be consumed to meet similar demands. The third is the pattern of development, broadly defined to include technological levels.

This section describes historical trends in CO_2 emissions and compares it with the A1 and B2 scenarios. A framework to analyze and compare historical and scenario results over time is used. This framework consists of a decomposition of CO_2 emissions growth with macro-economics drivers affecting its growth. The macro-economic drivers include the rate of population growth and the size and structure of the economy (depending on consumption patterns and stage of development). The amount of energy consumed per unit of activity, the amount of primary energy per unit of final energy, and the specific carbon emissions of the fuel mix used represent technology change and resource availability. Our discussion of the drivers is guided by the terms of the so-called Kaya identity (Kaya, 1989) as.

$$CO_2 = \mathrm{Pop} \times \frac{\mathrm{GDP}}{\mathrm{Pop}} \times \frac{\mathrm{FE}}{\mathrm{GDP}} \times \frac{\mathrm{PE}}{\mathrm{FE}} \times \frac{CO_2}{\mathrm{PE}}, \quad (1)$$

where Pop is the population, FE the final energy, PE the primary energy, and GDP the gross domestic product.

CO_2 emissions have grown by approximately 90% during the last 33 years (1971–2004). Fig. 9 shows the decomposition in growth of the different drivers. The main driving forces behind CO_2 growth include population, GDP/population, and the ratio of final energy to GDP, while the ratio of primary energy to final energy and the ratio of CO_2 emissions to primary energy have been less significant.

Population is the fundamental driver of activity. Between 1971 and 2004, world population increased 69%, with the bulk of growth in developing countries. Globally, this increase averaged 1.6% per year, led by 2%

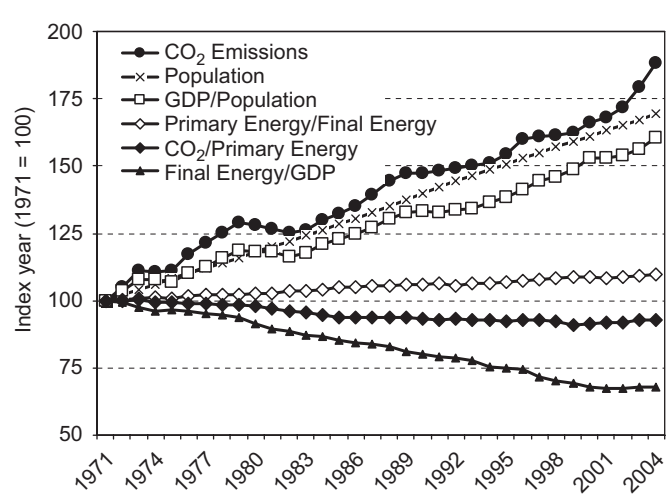

Fig. 9. Historical evolution of CO_2 emissions and macro-drivers (1971 = 100).

[4]Note that the data deviates slightly from the original SRES scenario, since it is based on the latest version of the MESSAGE model (version V).

[5]http://www.iiasa.ac.at/Research/ECS/docs/11worldregions.html for more details.

average annual growth in developing countries, 0.8% in developed countries, and 0.4% in transition economies.

GDP per capita tracks changes in how wealthy countries and regions are; typically, growth in per capita GDP is accompanied by rising demand for energy services. GDP per capita has increased 61% over the last 33 years but this increase is spread unevenly across regions. GDP per capita grew annually at an average rate of 2% in developed countries while it increased by 1% in developing countries and transition economies.

Final energy use per unit of GDP represents the final energy consumed in the economy per unit of value-added produced. It is an indicator of the intensity of the energy use compared with the evolution of GDP. This indicator has decreased by 32% over the past 33 years, reflecting a de-coupling of energy use and economic growth. Developed countries improved their energy intensity by 42% over the past three decades, mainly through investment in new technologies and a shift towards service-based economies. They achieved a relative de-coupling of economic growth from energy use (156% economic growth compared with 48% growth in final energy consumption). Conversely, the energy intensity of developing countries decreased by only 19%, due to early industrialization accompanied by increasing resource use.

The ratio of primary energy per unit of final energy reflects the inverse efficiency of energy conversion occurring in the economy. This factor increases when more secondary energy issued from fossil fuel is consumed and decreases with improved technology or switch to renewables and nuclear electricity production. Over the last 33 years, this ratio has increased slightly by 10% (at an average annual growth rate of 0.3%). The large increase in electricity demand has been partially dampened by an increasing share of nuclear and renewable energy for which the energy conversion is 100% using the direct equivalent method. Even though, electricity is still principally produced by fossil fuel, the share of its production from fossil fuel decreased from 74% in 1971 to 66% in 2004, while electricity from nuclear increased from 2% to 16% during the same period. Therefore, primary per unit of final energy were fairly constant during the last 30 years.

CO_2 emissions per unit of primary energy represent the fuel mix in an economy. This factor has declined 7% over the last 33 years, at an average annual growth rate of −0.2%, reflecting a decarbonization of energy consumption (Grübler and Nakićenović, 1996). This is explained by a switch to cleaner fuels that emit less CO_2 and to the increasing share of nuclear energy that has no CO_2 emissions associated with its use. However, since no CO_2 emissions are associated with biomass consumption in the international accounting methodology, switching from biomass energy use to fossil-based form of energy increases this ratio.

The decomposition of CO_2 emissions growth shows that historically the most important factor in limiting CO_2 emissions growth has been the final energy per GDP ratio that decreased considerably principally due to energy efficiency. If this ratio had stayed at its 1971 level, CO_2 emissions would have increased by 180% instead of 90%. Future projections are generally based on experience from the past. They can be analyzed through a similar equation and be compared with historical trends.

Fig. 10 shows the projection of the same ratio for the SRES A1 and B2 scenarios. The A1 scenario results in a doubling of CO_2 emissions between 2000 and 2030, compared with increases of approximately 90% historically and about 50% between 2000 and 2030 for the B2 scenario.

The difference in the outcomes of the scenarios stems predominantly from different assumptions regarding the evolution of GDP. The A1 scenario is a scenario with high GDP growth (4.1% over 2002–2030) while the B2 scenario has intermediate GDP growth (2.9% over 2002–2030). Historically, GDP growth was closer to the B2 scenario with a 3.1% annual average rate over the period 1971–2004. However, the growth in GDP will results in higher income distribution as future population growth is expected to grow much slower than in the past. Both scenarios have similar assumptions concerning population. Population is forecast to grow by 34% in the A1 scenario and 37% in B2 scenario, lower than the 65% growth

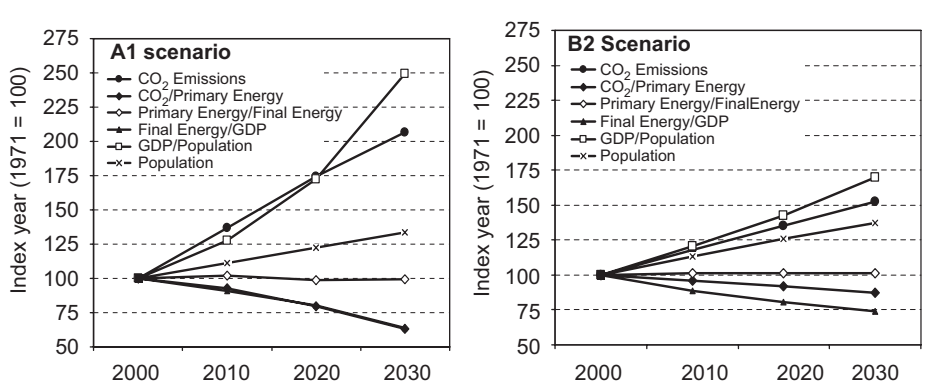

Fig. 10. Evolution of CO_2 emissions projections from the A1 and B2 scenarios (1971 = 100).

experienced during the past 30 years. The A1 scenario projects an increase of 150% in GDP/capita while the B2 scenario project an increase of 70% compared with historical growth, which was 50% over the last 30 years.

As shown in Fig. 9, historically, the major reason for CO_2 emissions to follow population growth more closely than GDP growth was largely due to the decline in final energy demand per unit of GDP (32%). The A1 scenario forecasts GDP energy intensity to continue to decrease in a similar manner over the next 30 years (36%) while the B2 scenario forecasts this indicator to decrease only by 26%.

The high GDP growth in the A1 scenario is accompanied by a rapid decrease in the CO_2 per primary energy indicator (37%), reflecting a switch toward an increasing share of less carbon-intensive fuels such as renewables and nuclear. The B2 scenario projects this indicator to decrease at a much slower rate of 12%. However, this still reflects a projection of relatively more intense decarbonization of the economy than has historically occurred (6%). A1 forecasts primary energy from nuclear to increase by an annual average rate of 6.7% and B2 by 3.4%, and primary energy from renewables to increase by 4.2% in A1 and 4.6% in B2. The primary energy per final energy consumption indicator is forecast to remain constant in both scenarios. The projected increasing share of electricity and other forms of secondary energy will be accompanied by continuing improvement in technology energy conversion and an increasing share of nuclear and renewables that reduce primary energy demand.

5. Sectoral and regional trend analysis

Disaggregation of sectoral energy use and CO_2 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 section examines global and regional historical and projected trends in energy use and carbon emissions in the industrial, buildings, and transport sectors.

Using the methodologies described in Section 2, historical primary energy and CO_2 emissions (1971–2000) were calculated for the 10 world regions by final sectors. Using the scenario data provided by the SRES modelers, the projected primary energy use (2000–2030) for the A1 and B2 scenarios for the industrial, buildings, and transport sectors for the 10 world regions were compiled.[6]

A1 projections for primary energy consumption are expected to grow at an annual rate of 2.8%, in contrast to the B2 scenario, which predicts a much smaller growth at an annual growth rate of 1.7%, approximately the same as the historical rate (1.8%). Both scenarios project their fastest growth in different sectors. The A1 scenario forecasts the highest energy consumption growth of 3.1% in the industrial sector, compared with 1.8% in the B2 scenario and 1.5% historically. A possible reason for this result might stem from the industrialization of developing countries in a scenario of high economic growth. Similar to historical trends, the fastest growth in the B2 scenario is in the transport sector, although with a projection of 2.1% it is slightly lower than the historical trend of 2.5%. The A1 scenario projection for the transport sector of 3.0% is higher than both the historical trend and the B2 scenario. For the buildings sector, the A1 scenario forecasts a growth of 2.5% and the B2 scenario forecasts a growth of 1.5%, while the historical growth was 1.8%. In term of shares, the share of primary energy consumption in the building sector in B2 scenario is forecast to continue to grow at the same level than primary energy consumption in the industry sector, while A1 project that the share of primary energy consumption in the industrial sector will exceed consumption in the building sector. Conversely, historical trends show a decreasing share of the industry sector, from 40% to 36% for primary energy consumption, due to higher energy efficiency in this sector, a shift toward less energy-intensive industries, and higher growth in the other sectors. Fig. 11 illustrates the sectoral trends in primary energy consumption for both the historical data from 1971 to 2000 and the SRES A1 and B2 scenario data, while Fig. 12 illustrates the sectoral trends in CO_2 emissions.

In term of CO_2 emissions, the rate of growth follows closely the same growth pattern for primary energy, meaning that the CO_2 emission from fuel use in each sector remains on average approximately equal. No increase in carbon-intensive fuel use or the opposite can be observed.

5.1. Industrial sector

The industrial sector used 160 exajoules (EJ) of global primary energy in 2004. The industrial sector is extremely diverse and includes a wide range of activities. This sector is particularly energy intensive, as it requires energy to extract natural resources, convert them into raw materials, and manufacture finished products. The industrial sector can be broadly defined as consisting of energy-intensive industries (e.g., iron and steel, chemicals, petroleum refining, cement, aluminum, pulp, and paper) and light industries (e.g., food processing, textiles, wood products, printing and publishing, and metal processing). The aggregate energy use depends on technology and resource availability, but also on the structure of the industrial sector. The share of energy-intensive industry in the total output is a key determinant of the level of energy use.

Fig. 13 shows historical and forecast industrial energy consumption for the 10 world regions for the A1 and B2 scenarios, while Fig. 14 shows the energy-related CO_2 emissions. Primary energy consumption in the industrial

[6]The time series reported here use historical data from 1971 to 2000 and scenario data from 2000 to 2030. Since the actual 2000 value and the 2000 values in the scenarios differed, the actual value was used for 2000 and the values between 2000 and the scenario value for 2010 were extrapolated. Thus, the values for 2000–2009 do not exactly match the reported scenario values. The 2010–2030 values exactly match the scenario values.

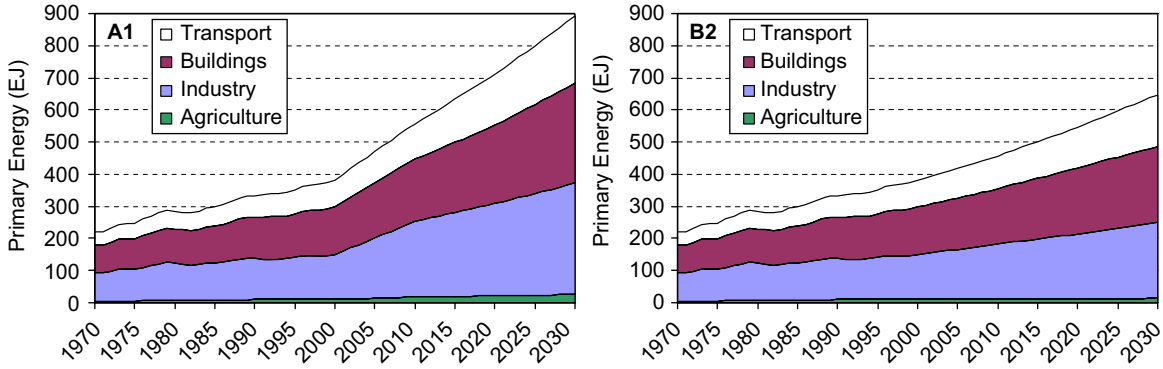

Fig. 11. Global primary energy by end-use sector, historical to 2000 and projected by the SRES A1 and B2 scenario to 2030.

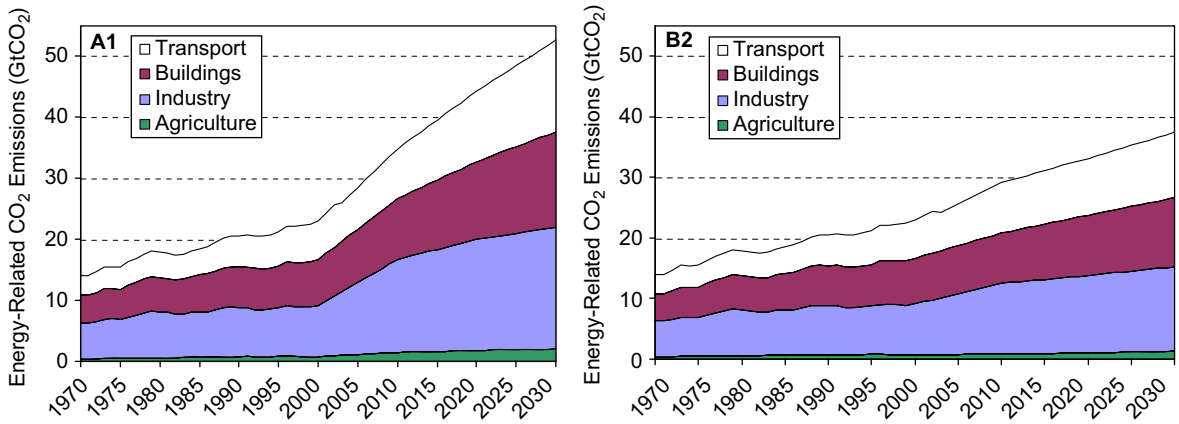

Fig. 12. Global energy-related CO_2 emissions by end-use sector, historical to 2000 and projected by the SRES A1 and B2 scenarios to 2030.

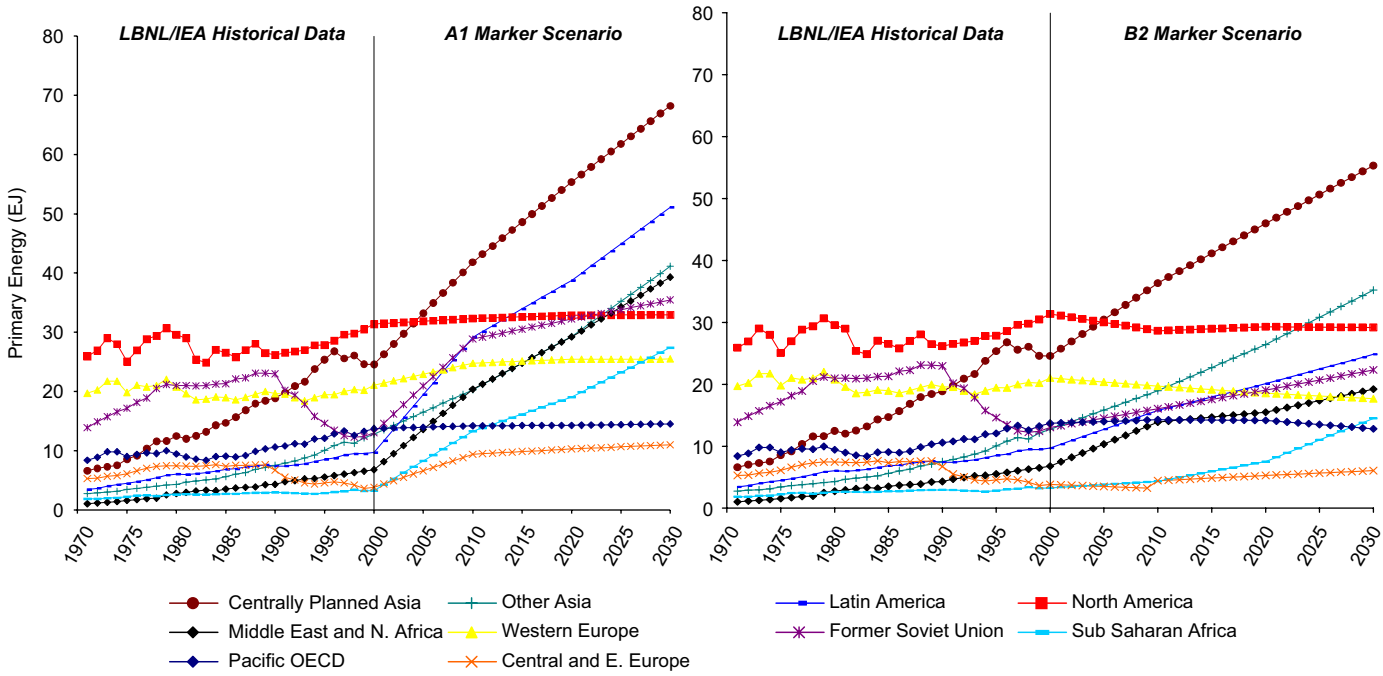

Fig. 13. Historical and projected industrial sector primary energy, 1971–2030 (EJ).

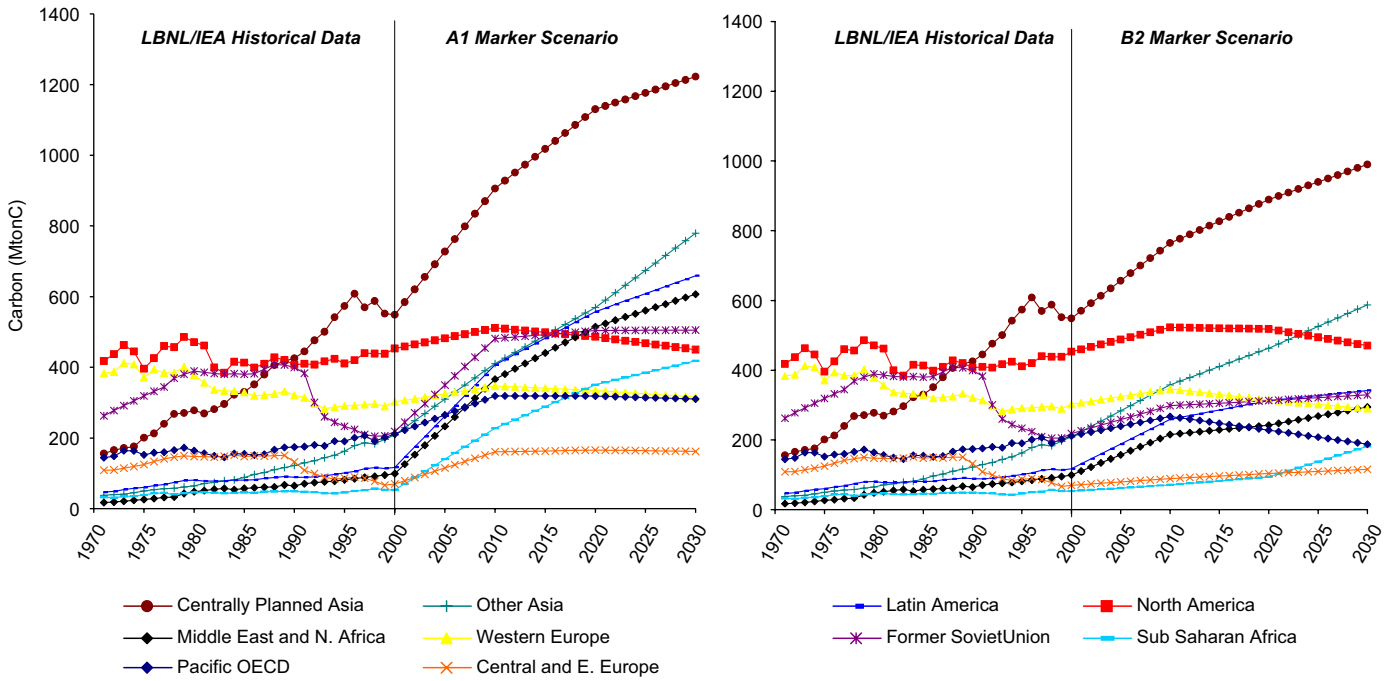

Fig. 14. Historical and projected industrial sector CO_2 emissions, 1971–2030 (MtC).

sector grew from 89 EJ in 1971 to 140 EJ in 2000. Primary energy consumption in developing countries, which accounted for 47% of total industrial primary energy use in 2000, grew at an average annual rate of 4.6% per year over this time period.[7] Developed countries experienced much slower average growth of 0.7% per year, while primary energy consumption for industry in the countries that make up the FSU and Eastern and Central Europe declined at an average rate of −0.4% per year. The North America region is the largest industrial energy-consuming region, closely followed by Centrally Planned Asia region. More recent statistics showed that Centrally Planned Asia region has surpassed Noth America region since 2003 with impressive growth rates of 7.5% in 2001, 10.9% in 2002, 16.4% in 2003 and 20.2% in 2004 (IEA, 2006a). This growth is closely related to the growth of material production from energy-intensive industries in China. In 2005, China produced 45% of the world's cement production, 35% of the world's iron and steel, and 23% of the world's aluminum (USGS, 2007).

Both the A1 and B2 scenarios forecast most growth to occur in the developing countries due to the energy required to fuel their growing needs in infrastructure and housing construction. In general, the A1 scenario envisions more intensive growth in the developing countries than the B2 scenario. The Centrally Planned Asia region is the region that is expected to have the highest growth by far, reaching an energy consumption level of 68 EJ in the A1 scenario and 55 EJ in the B2 scenario by 2030.

In both scenarios, primary energy consumption and CO_2 emissions in the industrial sector are projected to continue increasing for all regions until 2010 when developed countries will peak and start declining.[8] In both scenarios, emissions from developing countries and economies in transition are forecast to continue their growth after 2010, albeit at a much slower pace. In absolute terms, developing countries are expected to be by far the largest contributor to the growth in annual emissions due to increased industrial activity. The A1 scenario forecasts that most developing countries today will exceed the CO_2 emissions from developed regions in the industrial sector by 2020. In the B2 scenario, only the two Asian regions will surpass the emissions of the North America region.

5.2. Buildings sector

The buildings sector is composed of both residential and commercial buildings. The residential sector is characterized by a striking contrast in fuel use between developed and developing countries. More than half the world's population lives in rural areas, of which more than 90% are in developing countries. The vast majority of this population is dependent upon traditional wood fuel to serve the basic need of cooking and water heating. Hence the share of biomass in the global residential final

[7]Developing countries include the region of Centrally Planned Asia, Other Asia, Latin America, Sub-Saharan Africa, and Middle East/N. Africa. Developed Countries include Pacific OECD, North America, and Western Europe. Transition economies include Central/E. Europe and FSU. See Appendix A for a listing of which countries are in each region.

[8]For the A1 scenario, one of the reasons is the scaling between 2000 actual data and 2010 projected data. The non-adjusted data for A1 actually show starting decreasing CO_2 emissions from the period 2000–2010 for developed countries.

consumption represents more than 40% in 2004. In developed countries, natural gas and electricity are the most used fuel in residential buildings. While energy demand growth in residential sector was 1.4% over the period 1971–2000, growth in the commercial sector was 2.4%. Three quarters of the energy use in the commercial sector is currently consumed in developed countries. The commercial sector is characterized by a high level of electricity consumption, representing almost half of the total energy use (48%) in 2004. The major drivers of buildings energy demand are population growth, economic development, diffusion level of energy use equipment, size of households, square meters of buildings areas, and behavioral factors.

Results from the A1 and B2 scenarios do not provide a disaggregation between energy use in the residential sector versus commercial sector. In the buildings sector overall, the breakdown by region shows very different results between the two scenarios (see Fig. 15). The A1 scenario forecasts a growing demand for all regions, while the B2 scenario foresees the growth to be mainly in North America. The high growth in North America in the building sector is in part due to a rapid increase of the demand for electricity driven by increasing air conditioning, which has a high primary factor (Fig. 16).

The A1 scenario forecasts CO_2 emissions from the buildings sector to decline in the North America and Western Europe regions, while emissions in Pacific OECD region are forecast to grow at average rate of 0.5%. The B2 scenario projects CO_2 emissions from developed countries to level off around 2020 for the North America and Pacific OECD regions. The projection for transition economies varies between scenarios and reflects the differences of energy consumption during the period that followed the collapse of the Soviet Union. In absolute terms, the A1 scenario projects that the two Asian regions will have exceeded the amount of CO_2 emitted in the North America region by 2030, currently the highest emitting region. The B2 scenario envisions that most of the growth for this sector is to be expected from developed countries. Developing countries remain at a lower level of emissions than industrialized countries in terms of level of absolute emissions in 2030.

5.3. Transport sector

The transportation sector accounts for 22% of global primary energy use and 27% of global CO_2 emissions in 2004. Petroleum products consumption represents 94% of the energy use in this sector, while natural gas represents 3%, and electricity and biofuels represent 1% each (IEA, 2006a). Road vehicles account for about 83% of all transportation energy use, while aviation represents 12%, rail 3%, and navigation 2%. Transport energy demand in developed countries represents the bulk of the world transport energy use with a share of 65%. However, energy use in transport has grown considerably faster in developing countries during the 1971–2000 period, at an annual rate of 5% compared with 2.1% for developed countries.

Primary energy consumption in the transport sector represented 22% of total primary energy consumption in the world in 2000, an annual increase of 2.5% since 1971. This sector is expected to grow in all regions but

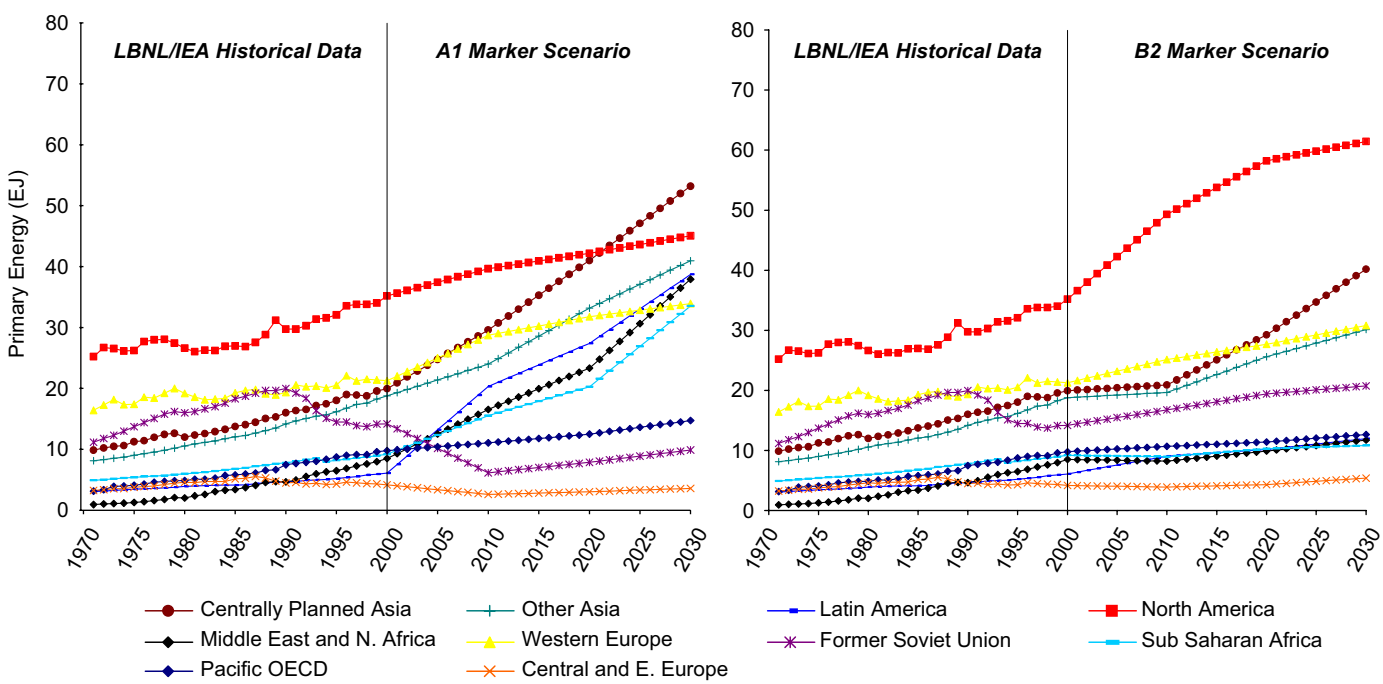

Fig. 15. Historical and projected buildings sector primary energy, 1971–2030 (EJ).

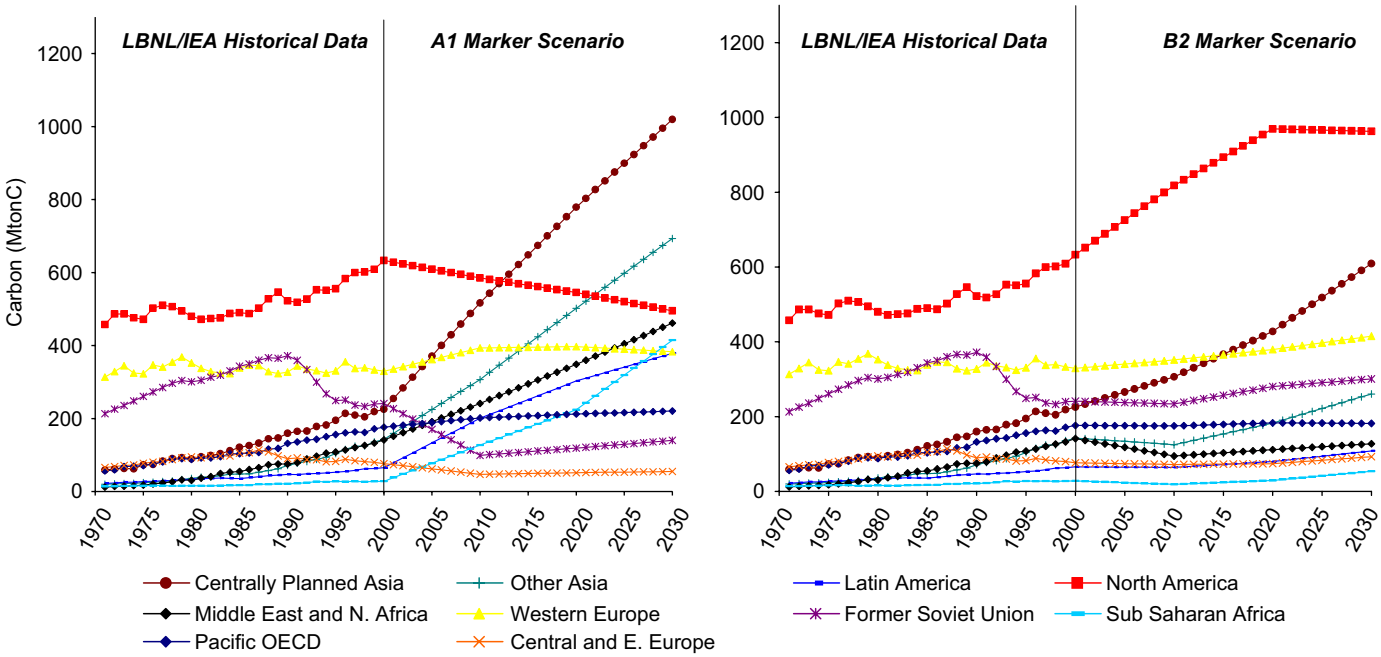

Fig. 16. Historical and projected buildings sector CO_2 emissions, 1971–2030 (MtC).

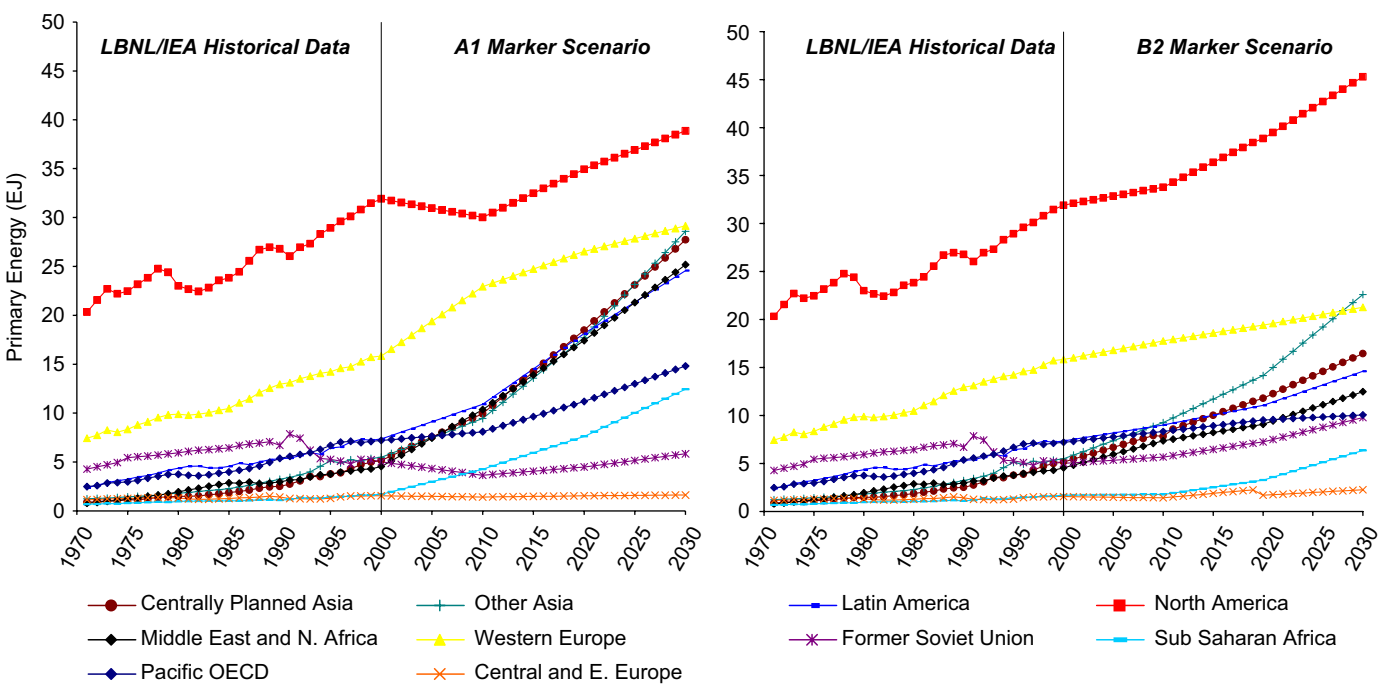

Fig. 17. Historical and projected transport sector primary energy, 1971–2030 (EJ).

most intensively in developing countries (see Fig. 17). The A1 and B2 scenarios project an annual growth rate of 3% and 2.1%, respectively, for the period 2000–2030 (Fig. 18).

Transportation is the fastest-growing source of CO_2 emissions globally. Both scenarios forecast transportation-related emissions from industrialized countries to continue to grow at a slower pace over time. Conversely, developing countries in both scenarios are expected to grow rapidly, albeit much more rapidly in the A1 scenario. In absolute terms, the additional CO_2 emissions per year in 2030 versus 2000 are higher in developing countries. However, their contribution is lower in the B2 scenario, where the growth in emissions from developing countries only represents 60% of total global growth, compared with 80% in the A1 scenario.

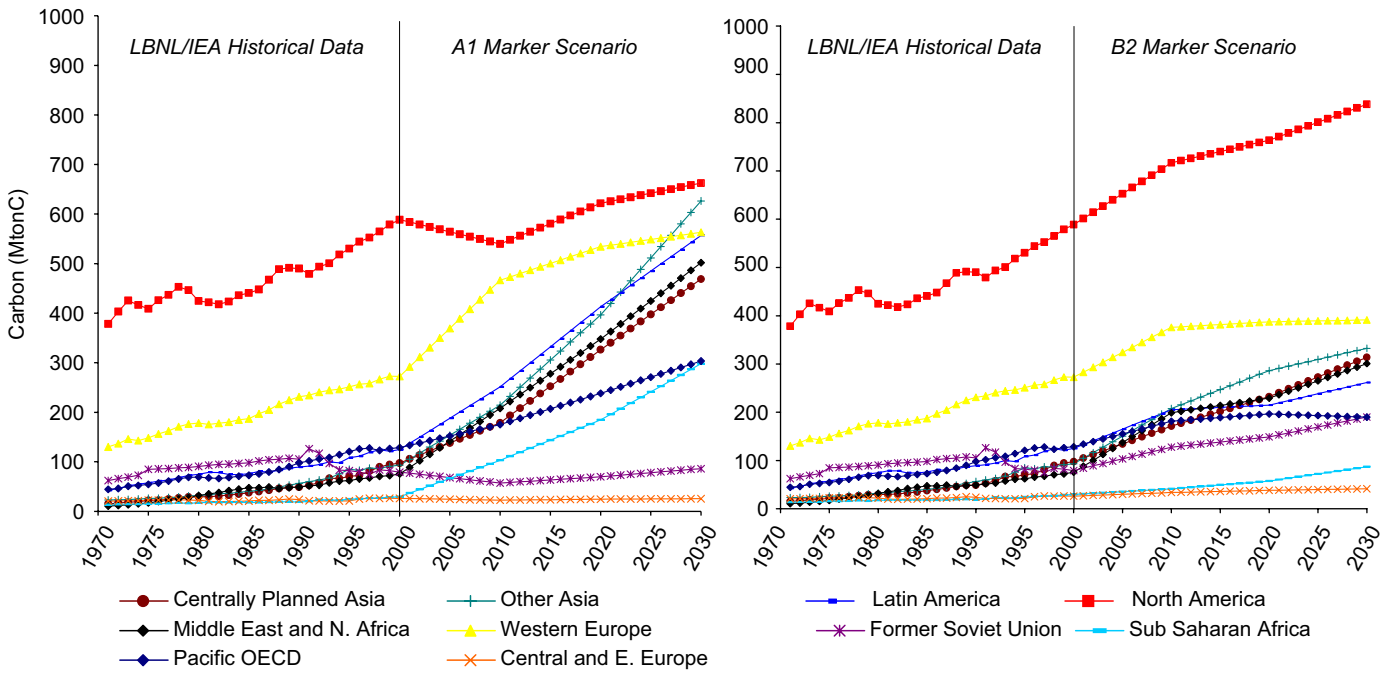

Fig. 18. Historical and projected transport sector CO_2 emissions, 1971–2030 (MtC).

6. Discussion

Energy demand forecasts are useful for analysts who want to study the future of energy demand and possible alternative paths. The scenarios presented herein are baseline scenarios, and analysis on potential energy savings can be drawn with the adjustment of energy-intensity variables.

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. Activity and economic drivers such as urbanization rates, appliance saturation, car ownerships as well as trends in energy and carbon intensity at the sectoral level are needed.

Moreover, a recent LBNL report from which part of this article is issued (Price et al., 2006), look at one region and one sector more closely and analyze the results of A1 and B2 scenarios. It concluded that electricity consumption increases in the Centrally Planned Asia region appears low for an economy that has increasing population with higher spending level.

End-use sector-level results for buildings, industry, or transportation or information regarding adoption of particular technologies were not provided in the SRES. More detailed information on the SRES scenarios at the end-use level, including historical time series data, is needed to understand the forecast implications in terms of end-use efficiency to 2030.

7. Conclusions

Driving forces of global energy use take place at the sectoral level. Disaggregation of sectoral energy use and greenhouse gas emissions trends for particular regions of the world is crucial to understand the challenge that energy demand is facing. Understanding key driving forces in the energy end-use sectors provides insights for development of projections of future greenhouse gas emissions.

End-use sectoral information is valuable for policy-makers who want to understand the implications of certain projected futures as well as the types of efficiency improvements that are required to realize lower energy consumption scenarios. In applying this approach to global scenarios, a balance must be found between the level of detail needed to clearly represent major technological features, clarity of presentation to users of scenario results, and data availability across countries and regions. In principle, greater detail is desirable, but currently available statistics and survey information tends to be sketchy and intermittent for most countries, and users should not be overwhelmed with technical minutiae.

Using this methodology, LBNL is pursuing this effort for some major developing countries in the world. Working in collaboration with institutions around the world, LBNL is collecting data and building the LEAP model in order to provide a richer characterization of the SRES results. This methodology can be applied to any macro-level model results and, as such, is envisioned as a powerful tool for providing end-use detail associated with myriad scenario projections.

Acknowledgments

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Appendix A. Ten world regions

Regions/countries	
Pacific OECD	Australia, Japan, Korea, and New Zealand
North America	Canada and the United States
Western Europe	Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Gibraltar, Greece, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, and United Kingdom
Central and Eastern Europe	Albania, Bosnia-Herzegovina, Bulgaria, Croatia, Czech Republic, Former Yugoslav Republic of Macedonia (FYROM), Hungary, Poland, Romania, Serbia/Montenegro, Slovak Republic, and Slovenia
Former Soviet Union	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, and Uzbekistan
Latin America	Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenanda, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, St Kitts and Nevis, St Lucia, St Vincent and Grenadine, Suriname, Trinidad and Tobago, Uruguay, and Venezuela
Middle East and North Africa	Algeria, Bahrain, Egypt, Islamic Republic of Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria, Tunisia, United Arab Emirates, and Yemen
Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Congo, Cape Verde, Central African Republic, Chad, Democratic Republic of Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Swaziland, United Republic of Tanzania, Togo, Uganda, Zambia, and Zimbabwe
Centrally Planned Asia	China, Chinese Taipei, Hong Kong, DPR of Korea, and Vietnam
Other Asia	Afghanistan, Bangladesh, Bhutan, Brunei, Fiji, French Polynesia, India, Indonesia, Kiribati, Malaysia, Maldives, Myanmar, Nepal, New Caledonia, Pakistan, Papua New Guinea, Philippines, Samoa, Singapore, Solomon Islands, Sri Lanka, Thailand, and Vanuatu

Appendix B. Primary energy accounting methodologies

Direct equivalent method (SRES method): The primary energy of the non-fossil fuel energy is accounted for at the level of secondary energy, that is, the first usable energy form or "currency" available to the energy. For instance, the primary energy equivalence of electricity generated from solar photovoltaic or nuclear power plants is set equal to their respective gross electricity output, not to the heat equivalent of radiation energy from fissile reaction, the solar radiance that falls onto a photovoltaic panel, or the heat that would have been necessary by burning fossil fuels to produce the same amount of electricity as generated in a photovoltaic cell or a nuclear reactor (as used in the so-called "substitution" accounting method) (Nakicenovic et al., 2000).

Physical energy content method (IEA method): This method uses the physical energy content of the primary energy source as its primary energy equivalent. In the case of nuclear and geothermal electricity, heat is the primary energy form considered and the conventional efficiencies are 33% and 10%, respectively. In the case of other non-fossil fuel energy (hydro, solar, and wave/tide), the primary form of energy considered is the electricity produced and hence efficiency of 100% applies, similar to the previous method.

Substitution energy method: This method attributes 33% efficiency for all non-fossil fuel i.e. as if this energy had been generated by a fossil fuel power plant.

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