Conventional Worlds: Technical Description of *Bending the Curve* Scenarios

Charles Heaps, Eric Kemp-Benedict and Paul Raskin

SEI STOCKHOLM ENVIRONMENT INSTITUTE

PoleStar Series Report no. 9, 1998

Global Scenario Group

The POLESTAR Publication Series

This publication series is produced by the Stockholm Environment Institute's PoleStar Project. Named after the star that guided voyagers through uncharted waters, the multi-year PoleStar Project addresses critical aspects of the transition to sustainability. *Scenario analysis* illuminates long-range problems and possibilities at global, regional, national and local levels. *Capacity building* strengthens professional capabilities for a new era of development. *Policy studies* fashion strategies and actions. The PoleStar System© provides a user-friendly tool for organizing pertinent data, formulating scenarios, and evaluating strategies for sustainable development. For more information, visit http://www.seib.org/polestar.html on the Internet. The *Global Scenario Group* was established to carry forward the global aspects of this work.

The PoleStar publication series includes:

1. The Sustainability Transition: Beyond Conventional Development (Raskin, Chadwick, Jackson and Leach)
2. PoleStar System Manual (Raskin, Heaps and Sieber)
3. Global Energy in the 21st Century: Patterns, Projections and Problems (Raskin and Margolis)
4. Water and Sustainability: A Global Outlook (Raskin, Hansen and Margolis)
5. Global Land and Food in the 21st Century: Trends and Issues for Sustainability (Leach)
6. Accounting for Toxic Emissions from the Global Economy: The Case of Cadmium (Jackson and MacGillivray)
7. Branch Points: Global Scenarios and Human Choice (Gallopin, Hammond, Raskin and Swart)
8. Bending the Curve: Toward Global Sustainability (Raskin, Gallopin, Gutman, Hammond and Swart)
9. Conventional Worlds: Technical Description of "Bending the Curve" Scenarios (Heaps, Kemp-Benedict and Raskin)

Global Scenario Group

The *Global Scenario Group* engages a diverse group of development professionals in a long-term commitment to examining the requirements for sustainability. The *GSG* is an independent, international and inter-disciplinary body, representing a variety of geographic and professional experiences. Its work program includes global and regional scenario development, policy analysis and public education. The diversity and continuity of the *GSG* offer a unique resource for the research and policy communities. The *GSG* pursues its objectives through research, publication and collaboration with regional sustainable development projects. This report is a companion to *Bending the Curve*: *Toward Global Sustainability* (PoleStar #8), which reviews the broad trends and policy implications of two *Conventional World* scenarios. This report provides additional detail on the data sources, methods and results for those scenarios. For more information, visit http://www.gsg.org on the Internet.

Conventional Worlds:
Technical Description of *Bending the Curve* Scenarios.

Charles Heaps, Eric Kemp-Benedict, Paul Raskin

Stockholm Environment Institute
Lilla Nygatan 1, Box 2142
S-103 14 Stockholm
Sweden
Phone: +46 8 412 14 00
Fax: +46 8 723 0348
Email: postmaster@sei.se
Web: http://www.sei.se

Front cover photo: View of Africa and Saudi Arabia from Apollo 17. NASA/NSSDC.

ISSN: 1400-7185
ISBN: 91 88714 62

TABLE OF CONTENTS

ANNEX

TABLE OF FIGURES

Table of Tables

TABLE OF BOXES

Acknowledgements

The authors are grateful to the members of the *Global Scenario Group* for their advice and guidance. Special thanks go to Gilberto Gallopin, Pablo Gutman, Al Hammond and Rob Swart. Gil Pontius and David Calef provided significant contributions to the preparation of the analysis. We are grateful to Amy DiBiasio and Faye Camardo for their editorial assistance.

1. Introduction

The *Global Scenario Group* is developing a range of global scenarios, intended to inform global, regional and national strategies for sustainable development. The scenarios are based on a two-tier hierarchy introduced in *Branch Points: Global Scenarios and Human Choice* (Gallopin et al., 1997). The two tiers are *classes*, distinguished by fundamentally different social visions, and *variants*, reflecting a range of possible outcomes within each class. Three broad classes have been depicted: *Conventional Worlds*, *Barbarization*, and *Great Transitions.* These are characterized by, respectively, essential continuity with current patterns, fundamental but undesirable social change and fundamental and favorable social transformation. *Conventional Worlds* envision the global system of the 21st Century evolving without major surprises, sharp discontinuities, or fundamental transformations in the basis for human civilization. The future is shaped by the continued evolution, expansion and globalization of the dominant values and socioeconomic relationships of industrial society. By contrast, the *Barbarization* and *Great Transition* scenario classes relax the notion of the long term continuity of dominant values and institutional arrangements.

Bending the Curve: Toward Global Sustainability (Raskin et al., 1998), which we refer to in this report as *BTC*, reviews the broad trends and policy implications of two *Conventional Worlds* scenario variants: *Reference*[1] and *Policy Reform*. The present report is a companion to *BTC*, providing detail on data sources, methods and results. An overview of the scenarios can be found in the *BTC* Scenario Highlights.

The current accounts and scenarios described in this report have been developed with the help of the *PoleStar* system, a software tool for mounting economic, resource and environmental information, and for examining alternative development scenarios. A copy of the PoleStar system can be downloaded for evaluation purposes from the SEI-Boston web site (http://www.seib.org/polestar.html).

1.1 Conventional Worlds Scenarios

BTC provides a detailed description of the basis for two archetypal *Conventional Worlds* scenarios: *Reference* and *Policy Reform*. Here, we briefly summarize the text from that document — describing the basis for the two scenarios and reviewing the main targets set in the *Policy Reform* scenario.

1.1.1 The Reference Scenario

Within *Conventional Worlds*, the *Reference* scenario is a story of a market-driven world in the 2lst Century in which demographic, economic, environmental and technological

---

[1] Our analysis of current patterns and the *Reference* scenario are based, to a large extent, on three earlier PoleStar studies that developed *Conventional Development* scenarios for the energy sector (Raskin and Margolis, 1995), for agriculture, land and food (Leach, 1995) and for water (Raskin et al., 1995; Raskin et al., 1997). In addition, our *Reference* scenario also updates the Toxic Waste scenario described in Raskin et al. (1996). Our analysis uses a later year base year (1995 instead of 1990), newly updated sources of data (described in this document), and updated methodologies for making projections of certain key variables.

trends unfold without major surprise. Continuity, globalization and convergence are key characteristics of world development — institutions gradually adjust without major ruptures, international economic integration proceeds apace and the socioeconomic patterns of poor regions converge slowly toward the model of the rich regions. Despite economic growth, extreme income disparity between rich and poor countries, and between the rich and poor within countries, remains a critical social trend. Environmental transformation and degradation is a progressively more significant factor in global affairs.

1.1.2 The Policy Reform scenario

In contrast to the *Reference* scenario, the *Policy Reform* scenario assumes the emergence of a popular consensus and strong political will for taking action to ensure a successful transition to a sustainable future.

Rather than a projection into the future, the normative *Policy Reform* scenario is constructed as a backcast *from* the future (Robinson, 1990). We begin with a vision of a desired future state defined by a set of sustainability goals, and seek to identify plausible development pathways for getting there. In the *Policy Reform* scenario, we examine the requirements for simultaneously achieving social and environmental sustainability goals.

BTC sets out target values for a common set of core global indicators. Social indicators and targets are summarized in Table 1-1, environmental indicators and targets are summarized in Table 1-2. For detailed information on how target values were developed, see *BTC*.

Table 1-1. Social indicators and targets

Indicator		1995	Target in 2025	Target in 2050
Hunger	millions of people	900	445	220
	% of 1995 value	-	50%	25%
	% of population	16%	6%	2%
Unsafe Water	millions of people	1,360	680	340
	% of 1995 value	-	50%	25%
	% of population	24%	9%	4%
Illiteracy	millions of people	1,380	690	345
	% of 1995 value	-	50%	25%
	% of population	24%	9%	4%
Life Expectancy	Years	66	> 70 in all countries	

Source: *BTC*, which discusses the basis for target values.

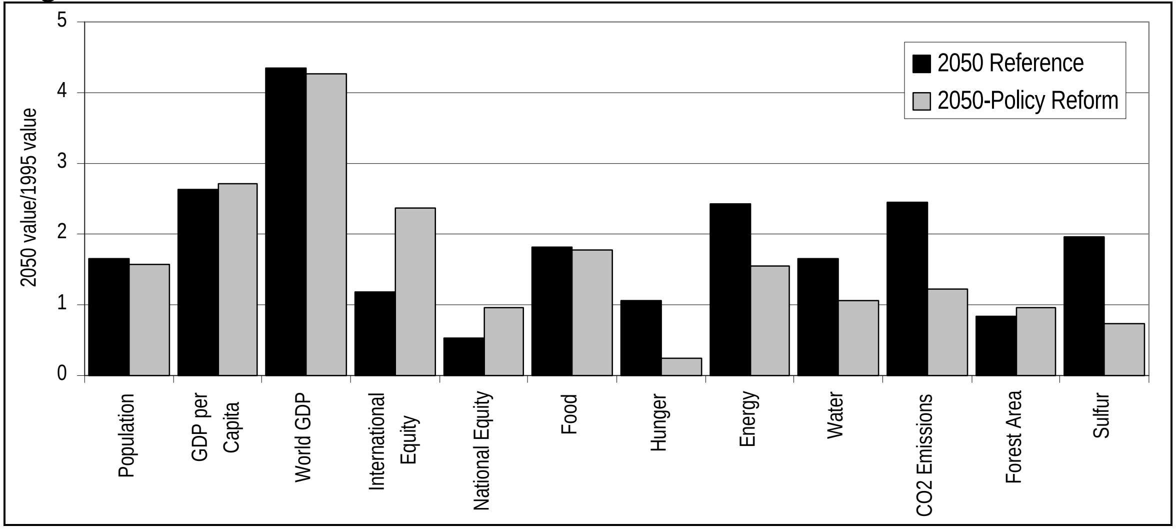
Table 1-2. Environmental indicators and targets

Region	Indicator	1995	Target in 2025	Target in 2050
Climate				
World	CO_2 concentration	360 ppmv	stabilize at < 450 ppmv by 2100	
	Warming rate		average 0.1°/decade, 1990-2100	
	CO_2 emissions		< 700 GtC cumulative, 1990-2100	
OECD	CO_2 emissions rate	various and rising	< 65% of 1990 (< 90% of 1990 by 2010)	<35% of 1990
non-OECD	CO_2 emissions rate	various and rising	increases slowing, energy efficiency rising	reach OECD per capita rates by 2075
Resource Use				
OECD	Eco-efficiency	$100 GDP/300 kg	4-fold increase ($100 GDP/75 kg)	10-fold increase ($100 GDP/30 kg)
	Materials use/capita	80 tonnes	< 60 tonnes	< 30 tonnes
non-OECD	Eco-efficiency	various but low	converge toward OECD practices	
	Materials use/capita	various but low	converge toward OECD per capita values	
Toxics				
OECD	Releases of persistent organic pollutants & heavy metals	various but high	< 50% of 1995	< 10% of 1995
non-OECD	Releases of persistent organic pollutants & heavy metals	various and rising	increases slowing	Converge to OECD per capita values
Freshwater				
World	Use-to-Resource ratio	various and rising	reaches peak values	0.2-0.4 maximum (in countries>.4 in 1995, less than 1995 values)
	Population in water stress	1.9 billion (34%)	less than 3 billion (<40%)	less than 3.5 billion, begins decreasing (<40%)
Ecosystem Pressure				
World	Deforestation	various but high	no further deforestation	net reforestation
	Land degradation	various but high	no further degradation	net restoration
	Marine over-fishing	fish stocks declining	over-fishing stopped	Healthy fish stocks

Source: *BTC*, which discusses the basis for target values.

Figure 1-1 summarizes the values in 2050 of a range of indicators from the *Reference* and *Policy Reform* scenarios relative to their 1995 values. The chart shows both the results of the *Reference* scenario, and the constraints governing the evolution of the *Policy Reform* scenario. Notice that both scenarios share very similar assumptions about population levels, average per capita incomes and total global economic output. However, the scenarios clearly differ in terms of their attainment of social and environmental goals.

Figure 1-1. Selected scenario indicators



1.2 Global Regions

As with other global assessments, we have adopted multi-country regions as the basic structure of analysis. Specifically, we have grouped countries into ten global regions, based on the comparability of socioeconomic development and geopolitical considerations. The regional groupings used in this analysis and the countries included in each region are displayed in Table 1-1.

In some cases, we further combine the ten regions into three *macro-regions*: *Transitional* (FSU and Eastern Europe), *OECD* (North America, Western Europe, and OECD Pacific) and *Developing* (Africa, Latin America, Middle East, China+ and South and Southeast Asia).

Table 1-1: Regional structure

North America
The Bahamas
Canada
Puerto Rico
United States

Western Europe
Austria
Belgium
Bosnia & Herzegovina
Croatia
Denmark
Finland
France
Germany
Greece
Iceland
Ireland
Italy
Luxembourg
Macedonia, FYR
Malta
Netherlands
Norway
Portugal
Slovenia, Rep
Spain
Sweden
Switzerland
Turkey
United Kingdom
Yugoslavia, FR (Serbia/Montenegro)

Pacific OECD
Australia
Fiji
Japan
Kiribati
Marshall Islands
Micronesia, Fed. Sts.
New Zealand
Solomon Islands
Tonga
Vanuatu
Western Samoa

Eastern Europe
Albania
Bulgaria
Czech Republic
Hungary
Poland
Romania
Slovak Republic

Africa
Algeria
Angola
Benin
Botswana
Burkina Faso
Burundi
Cameroon
Cape Verde
Central African Republic
Chad
Comoros
Congo
Cote d'Ivoire
Djibouti
Egypt, Arab Rep.
Equatorial Guinea
Eritrea
Ethiopia
Gabon
Gambia, The
Ghana
Guinea
Guinea-Bissau
Kenya
Lesotho
Liberia
Libya
Madagascar
Malawi
Mali
Mauritania
Mauritius
Morocco
Mozambique
Namibia
Niger
Nigeria
Rwanda
Sao Tome and Principe
Senegal
Seychelles
Sierra Leone
Somalia
South Africa
Sudan
Swaziland
Tanzania
Togo
Tunisia
Uganda
Zaire
Zambia
Zimbabwe

Latin America
Antigua and Barbuda
Argentina
Aruba
Barbados
Belize
Bolivia
Brazil
Chile
Colombia
Costa Rica
Cuba
Dominica
Dominican Republic
Ecuador
El Salvador
Grenada
Guatemala
Guyana
Haiti
Honduras
Jamaica
Mexico
Nicaragua
Panama
Paraguay
Peru
St. Kitts and Nevis
St. Lucia
St. Vincent and the Grenadines
Suriname
Trinidad & Tobago
Uruguay
Venezuela

Former Soviet Union (FSU)
Armenia
Azerbaijan
Belarus
Estonia
Georgia
Kazakstan
Kyrgyz Republic
Latvia
Lithuania
Moldova
Russian Federation
Tajikistan
Turkmenistan
Ukraine
Uzbekistan

Middle East
Afghanistan
Bahrain
Cyprus
Iran, Islamic Rep.
Iraq
Israel
Jordan
Kuwait
Lebanon
Oman
Qatar
Saudi Arabia
Syrian Arab Republic
United Arab Emirates
West Bank & Gaza
Yemen, Rep.

China+
China (including Hong Kong)
Korea, Dem. Rep.
Lao PDR
Macao
Mongolia
Vietnam

South and Southeast Asia
Bangladesh
Bhutan
Brunei
Cambodia
India
Indonesia
Korea, Rep.
Malaysia
Maldives
Myanmar
Nepal
Pakistan
Papua New Guinea
Philippines
Singapore
Sri Lanka
Taiwan
Thailand

1.3 The Structure of this Report

Each chapter of this report deals with a major topic or sector. We first introduce the data and assumptions used to construct the current accounts (base year) data for the topic. The base year is 1995, the most recent year for which data are generally available across a wide range of topics. Next, we introduce the data, methodologies and assumptions used to construct the *Reference* and *Policy Reform* scenarios for each topic, and review the detailed results of the scenario projections.

- **Chapter 2** summarizes the methodology used for developing demographics, economics, equity and poverty patterns in the scenarios.

- **Chapter 3** examines energy sector and climate change issues. Climate goals are translated into carbon emissions budgets, which constrain energy sector production and consumption patterns in the *Policy Reform* scenario. Consumption is analyzed for five sectors: industry, transport, households, services and agriculture.

- **Chapter 4** discusses agriculture, land and food. It considers the demands for food and other agricultural products that result from the population and income assumptions of the two scenarios. Also it considers the agricultural production systems that satisfy those demands and the impact on land resources.

- **Chapter 5** considers final water requirements and the sufficiency of water resources. It examines trends in water use and water scarcity in the scenarios, and describes how, in the *Policy Reform* scenario, measures are introduced to mitigate water scarcity.

- **Chapter 6** reviews local and regional environmental issues, focusing specifically on acidification, toxic wastes and indoor air pollution associated with the use of traditional biomass fuels.

2. Demographics, Economics, Equity and Poverty

BTC describes the major regional trends in demographics, economics, equity and poverty in the two scenarios, including information about sources of data, methods and major assumptions. In this chapter, we provide additional details. Section 2.1 reviews demographic and economic patterns in the scenarios. Section 2.2 examines the sectoral distribution of GDP (sectoral value added). Section 2.3 examines income distribution and poverty and describes the hunger-projection methodology.

Demographic and economic assumptions play a fundamental role in driving patterns of resource consumption and pollutant emission in the scenarios. They are also important in the poverty analysis, where in combination with assumptions about income distribution, they determine the incidence of poverty.

- In the *Reference* scenario, poverty levels are a consequence of the assumed trends in population, average income and income distribution, each of which is developed to reflect the overall business-as-usual perspective of the scenario.
- In the *Policy Reform* scenario, achieving the normative social targets constrains the set of assumptions. The economic growth rates and national income distributions are chosen to be consistent with these goals.

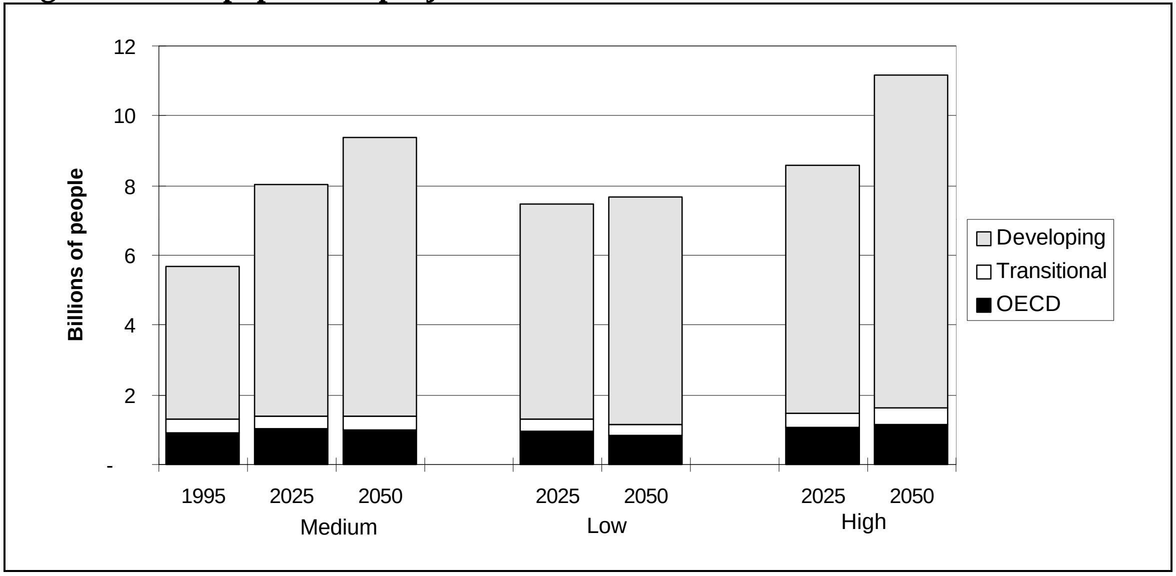
2.1 Demographics and GDP

Population

In the *Reference* scenario, populations are assumed to follow the mid-range UN (1997) “medium” projections, in which global population increases from 5.7 to 9.4 billion people between 1995 and 2050. The projections are shown in Figure 2-1. For comparison, the “low” and “high” UN population projections are also shown in the figure.

In the *Policy Reform* scenario, as described in *BTC*, the population growth assumptions for the OECD regions are those of the *Reference* scenario, while those for the non-OECD regions are slightly smaller: by 2% in 2025 and by 5% in 2050.

Figure 2-1. UN population projections to 2050



Source: UN (1997)

GDP

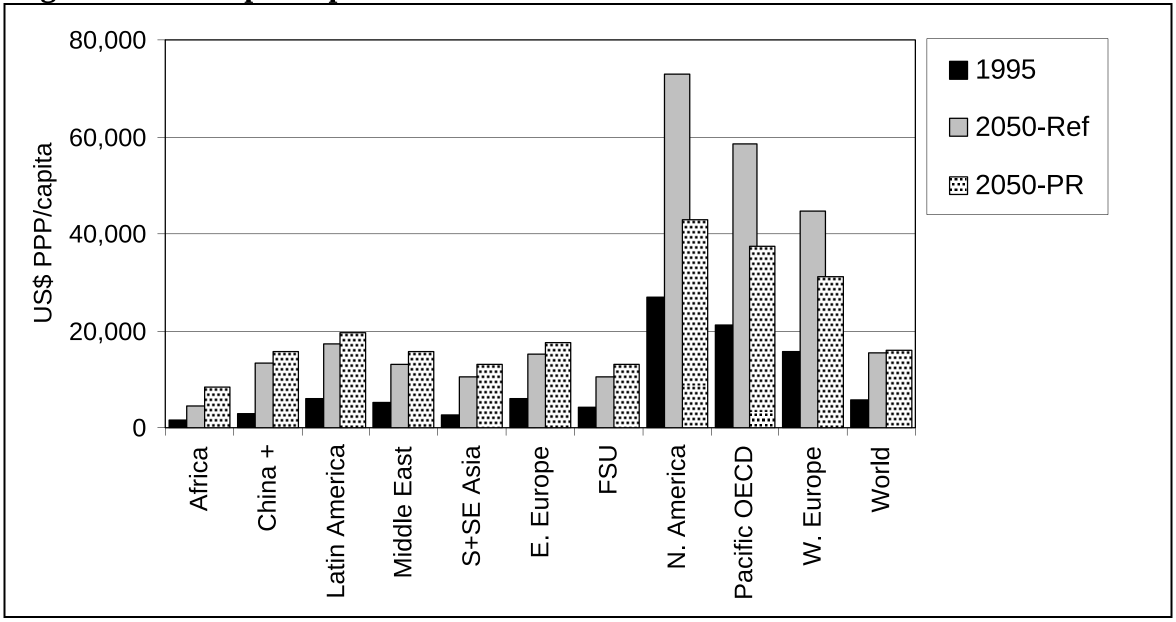
Reference scenario economic trends are based on the mid-range assumptions of the IS92 IPCC scenarios (IPCC, 1992). In the IPCC studies, economic growth rates were applied to GNP per capita at market exchange rates (MER), or GNP_{MER} per capita. In Raskin et al. (1996), the rates were adapted for the ten global regions used in the study, and applied to regional GDP_{MER} per capita. However, as discussed in *BTC*, for this analysis GDP adjusted for purchasing power parity (PPP) is used, rather than GDP at market exchange rates. The PPP conversion factors give the amount, in national currencies, that would buy the same amount of goods and services that one dollar would buy in the U.S. (WRI, 1998). To construct growth rates for GDP_{PPP} per capita that correspond to the MER growth rates of Raskin et al. (1996), we project values for the ratio GDP_{PPP}/GDP_{MER}, or *exchange rate deviation index* (ERD). Typically, the ERD is higher than 1 for developing countries, and close to 1 for most OECD countries.

We examined cross-sectional data for different years to look for quantitative patterns. The historical data, taken from WRI (1996b), suggest that the ERD is close to 1 for countries whose GDP_{PPP} per capita is higher than about one-half the U.S. value. In the scenarios it is assumed that regional ERDs vary with income in different ways depending on whether the income is greater than or less than one-half the North American value. Specifically, the ERD for non-OECD regions is set to 1 when GDP_{PPP} per capita is above one-half the North American value. Otherwise the ERD varies along a curve that includes the base-year value and the point defined by (income = one-half the U.S. value, ERD = 1). The OECD regions were treated differently from the non-OECD regions. For Pacific OECD, where the ERD was unusually low in 1995, the ERD was set close to 1 in 2025 and 2050, while the ERDs for the other two OECD regions were kept at their base year values.

In the normative *Policy Reform* scenario, regional patterns of average income growth and income distribution are set to meet the hunger reduction target (see Section 2.3).

Regional and global scenario values for GDP_{PPP} per capita are shown in Figure 2-2. Average GDP_{PPP} per capita for the world is roughly the same in both scenarios, but the regional distribution is quite different. In the *Policy Reform* scenario incomes are higher in the non-OECD regions and lower in the OECD regions than in the *Reference* scenario. (See Sheet E-3 in *BTC* for growth rates.)

Figure 2-2. GDP per capita in the scenarios



2.2 Sectoral Value Added

Total GDP is reported in national accounts as contributions of value added from different sectors of the economy. Value added is used in this study as a measure of sectoral activity. Figure 2-3 shows how the structure of economic output in the three macro-regions evolve over time in the scenarios. It changes as consumption patterns continue along historical trends toward greater emphasis on services and light manufacturing, and away from agriculture and industry.

Regional GDP_{PPP} is first decomposed into three major economic sectors: Services, Industry, and Agriculture. The current breakdowns by sector (World Bank, 1997) are adjusted over time based on the following approach.[2]

1. In the OECD regions, agricultural GDP_{PPP} per capita is assumed to remain constant at 1995 values. This assumption is broadly supported by trends in agricultural GDP_{PPP} per capita since 1970 in a number of OECD countries. Since total GDP_{PPP} is growing

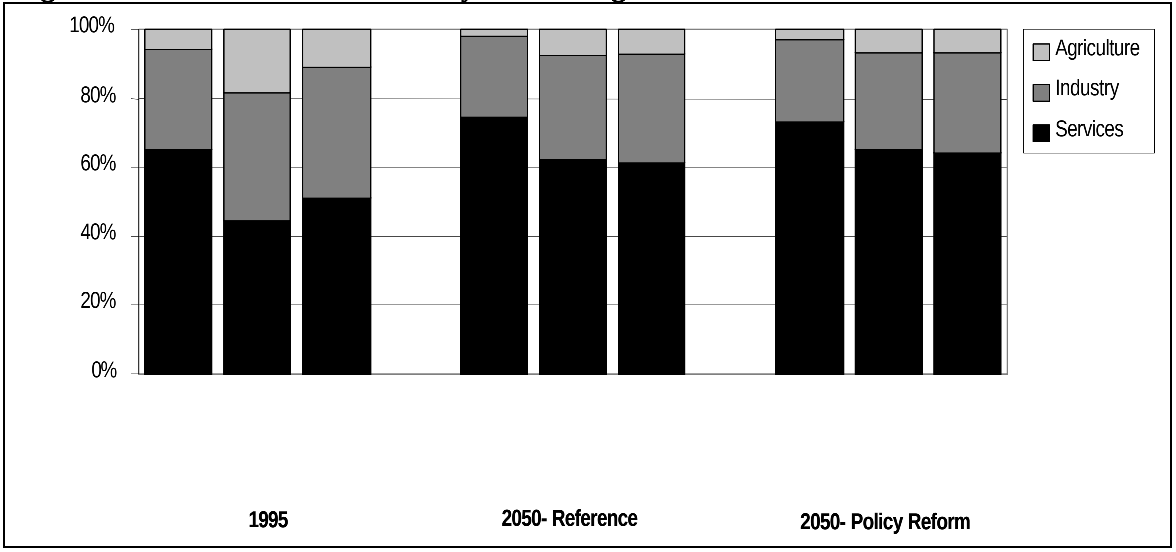
---

[2] The approach used here is based on that of the *Conventional Development* scenario (Raskin et al., 1996). The text in this subsection draws on that report.

faster than population in these regions, the effect is that the agricultural share of value added continues to decrease over time. In non-OECD regions future agricultural GDP_{PPP} per capita values approach the base year OECD average values as their GDP_{PPP} per capita approaches the base year OECD GDP_{PPP} per capita.[3]

2. For certain countries in the OECD regions, the share of GDP in industry decreased about 3-4% per decade between 1970 and 1990 (WRI, 1992b). This trend is assumed to continue at a slower rate in the scenarios, leading to an additional 5% decrease by 2050. In the non-OECD regions the a convergence algorithm (see Annex) is used to determine the share of GDP in industry.
3. The share of GDP in services is computed as the remainder.

Figure 2-3. Value added shares by macro-region



2.3 Income Distribution and Poverty

In order to see how the scenarios address both social and environmental goals, poverty is treated explicitly. The analytic focus here is on hunger as a representative indicator of many possible measures of absolute deprivation. In the *Policy Reform* scenario, the hunger reduction targets constrain the range of possible income growth rates. However, average income alone is not sufficient to characterize poverty, so the distribution of income within countries is also taken into account.

---

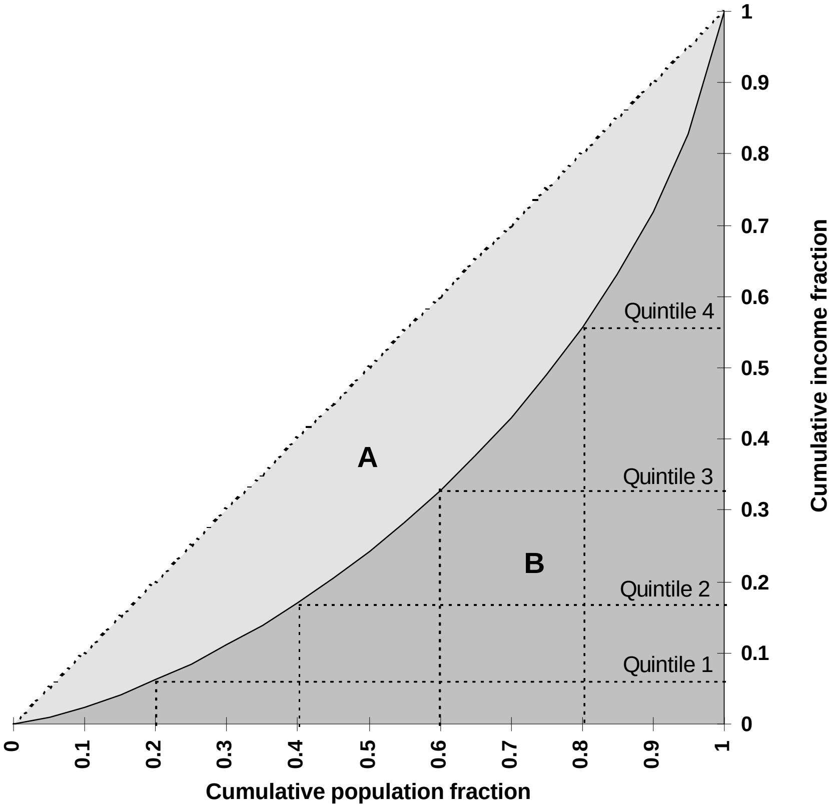
[3] This is a departure from the standard convergence algorithm used elsewhere in the analysis (see Annex). The modified convergence algorithm applied to agricultural production reflects a convergence to current patterns, rather than the technological leapfrogging embodied in the standard algorithm.

2.3.1 Methodology

Representing Income Distribution

The distribution of national income can be presented in more than one way. One convenient form is the *Lorenz curve*, a plot of the fraction of total income held by a given fraction of the population, with the lowest-income portion of the population counted first. A representative Lorenz curve is shown in Figure 2-4. Also shown in the figure are the *quintiles*, the fraction of total income held by the lowest-earning 20%, 40%, 60% and 80% of the population. They are often reported in tabulations of income distribution data, such as the ones used for this study (Deininger and Squire, 1996; USBC, 1997; Tabatabai, 1996; World Bank, 1998).[4] Another summary measure of income distribution that is often reported is the *Gini coefficient*, given by the ratio of the areas A and $(A+B)$ in Figure 2-4. The coefficient can take values from zero to one, with zero representing complete equality. Throughout this report, Gini coefficients and ratios of the average income of the lowest-earning 20% of the population to the highest-earning 20% (the "low/high" ratio) are used as measures of inequality. The low/high ratio is given in terms of the quintiles as (Quintile 1)/(1 - Quintile 4).

Figure 2-4. The Lorenz curve and quintiles



---

[4] The definition of the quintiles may vary from source to source. For example, the second quintile is sometimes given as the difference between Quintile 2 and Quintile 1, as they are defined in Figure 2-4.

The Lorenz curve contains information about how income is distributed throughout a population, but has no information about the scale of the national income or the size of the population. This information, which is needed for analytically addressing poverty, is included in the *income distribution function*, which gives the number of people who receive a certain income, per unit income. That is, if the income distribution function is represented by $f(y)$, where y is the income, then $f(y)\cdot\Delta y$ is the number of people with incomes between y and $y+\Delta y$.

The Lorenz curve and the income distribution function are related in the following way. The cumulative population fraction with income below some cutoff value y_c is given by

$$\text{Cumulative population fraction} = \frac{1}{P}\int_0^{y_c} dy\, f(y)\,, \tag{2-1}$$

while the cumulative income fraction below the same cutoff y_c is given by

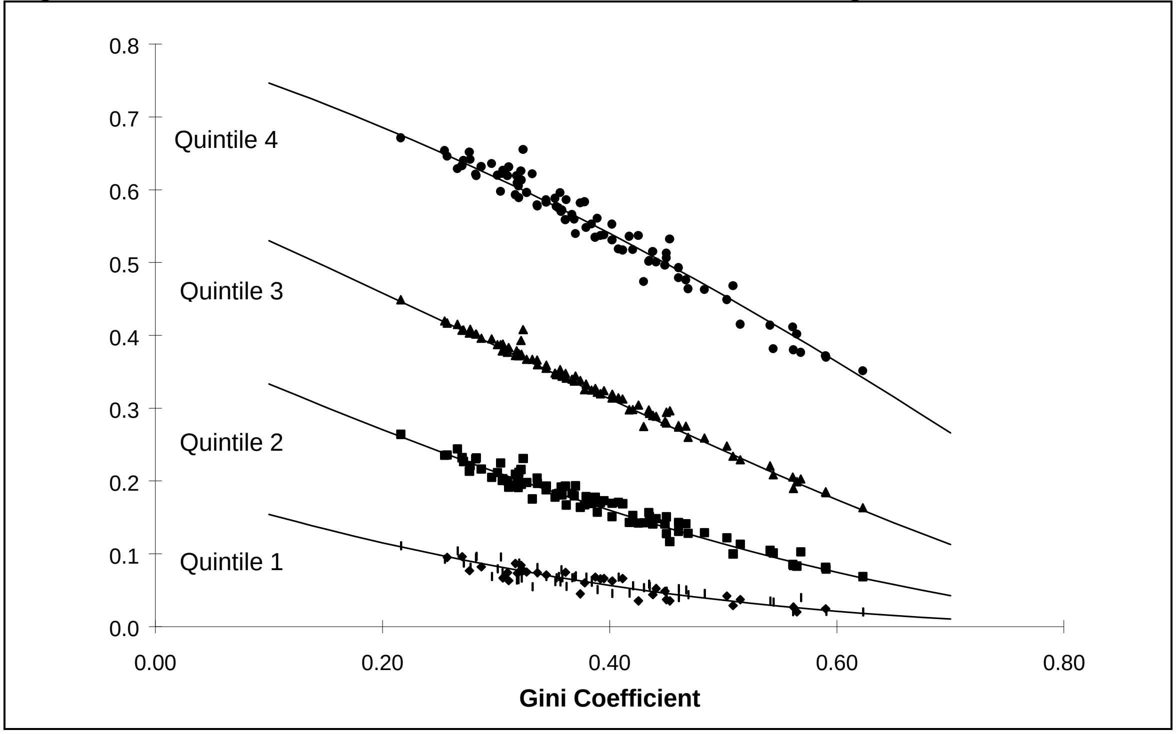
$$\text{Cumulative income fraction} = \frac{1}{P\bar{y}}\int_0^{y_c} dy\, yf(y)\,. \tag{2-2}$$

As the cutoff value y_c ranges over the incomes represented in the country, from the lowest to the highest, the cumulative population and income fractions take different values. Plotting those values against each other gives the Lorenz curve.

Approximating National Distributions: The Lognormal Distribution

In principle, many variables might be required to characterize a country's income distribution, in addition to population and average income. However, by examining pooled national data, we found that they can be satisfactorily represented by a function with one additional parameter. We took the following approach: for many of the countries for which Gini coefficients are available, quintile values have also been computed. If one parameter is sufficient to characterize income inequality, then any summary measure of inequality (such as the Gini coefficient, low/high ratio or one of the quintiles values) should depend only on that parameter. In this case, if we pool national data we should observe a strong correlation between Gini coefficients and quintiles. A plot of measured quintiles against Gini coefficients shows that they are strongly correlated (Figure 2-5).

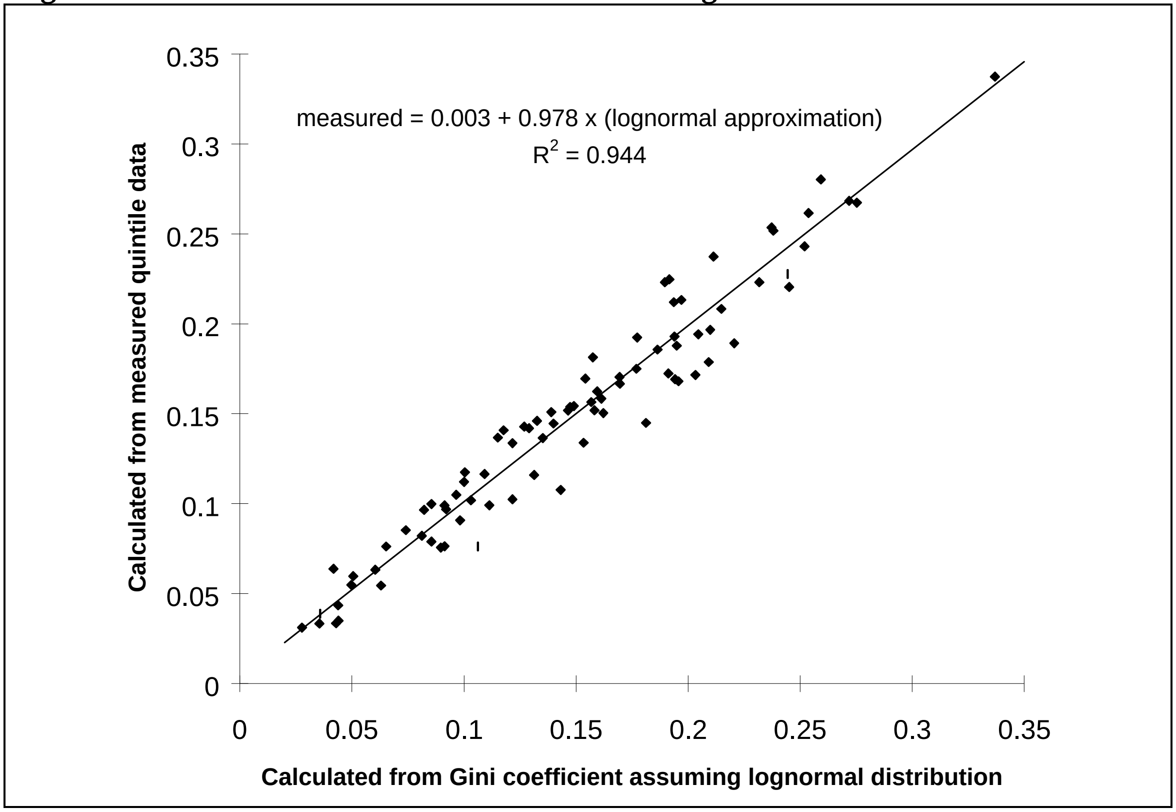
Figure 2-5. Quintiles vs. Gini Coefficients: National Values and Lognormal Distribution



The solid lines shown in Figure 2-5 were calculated using a particular income distribution function, the *lognormal*. Some of the properties of the lognormal function are given below. In particular, it depends on three parameters: population, average income and a measure of inequality. From Figure 2-5 it appears that the lognormal curve fits the measured data well, suggesting that national income distributions can be reasonably represented by lognormal distribution functions.

We further tested this conclusion by performing a regression analysis. National low/high ratios were computed using the measured quintile data shown in Figure 2-5. These were then compared to low/high ratios calculated from the Gini coefficient assuming a lognormal income distribution. The results are shown in Figure 2-6. Also shown in the figure is a linear least-squares fit to the data. If the national income distributions were exactly lognormal, then the estimated and measured low/high ratios would be identical. In that case, the data would lie on a straight line with a slope of one and an intercept of zero. Since we do not expect the relationship to hold exactly, and expect that there will be errors in the measurements, we ask instead that the slope and intercept of the regression line be consistent with values of one and zero, respectively. In fact, the estimated value for the slope is 0.978±0.026, where 0.026 is the standard error, and the intercept is 0.003±0.004. The lognormal distribution function passes the test: a slope of one is within one standard error of the estimated slope, and an intercept of zero is within one standard error of the estimated intercept.

Figure 2-6. Measured vs. estimated national low/high ratios



Based on these results, for this study national income distributions are approximated by lognormal distributions. As mentioned above, the lognormal distribution depends on three parameters: the total population *P*; the mean income $\bar{y}$; and a measure of income inequality, denoted by s. It has the functional form

$$f(y) = \frac{P}{\sqrt{2p}\, s y} \exp\left[-\frac{1}{2s^{2}} \left(\ln(y/\bar{y}) + s^{2}/2 \right)^{2} \right]. \tag{2-3}$$

The Gini coefficient and s are related by

$$\text{Gini} \;=\; \frac{1}{\sqrt{p}} \int_{0}^{s} dy\, \exp\left(-y^{2}/4\right) \;=\; 2N\left(s/\sqrt{2}\right) - 1\,, \tag{2-4}$$

where $N(x)$ is the cumulative normal distribution,

$$N(x) = \frac{1}{\sqrt{2p}} \int_{-\infty}^{x} dy\, \exp\left(-y^{2}/2\right). \tag{2-5}$$

Using Equations (2-1) and (2-2), the cumulative population and income distribution fractions below a cutoff income y_c are given by

$$\text{Cumulative population fraction} = N\left[\left(1/s\right)\ln(y_c/\bar{y}) + s/2\right] \qquad (2\text{-}6)$$

and

$$\text{Cumulative income fraction} = N\left[\left(1/s\right)\ln(y_c/\bar{y}) - s/2\right]. \qquad (2\text{-}7)$$

Connecting Income Distribution to Poverty

Using the lognormal approximation for national income distributions, we can address poverty issues in the scenario analysis. As mentioned above, in this study hunger is used as a primary indicator of poverty. We define a "hunger line," a threshold income below which an individual is unable to obtain the calories required to sustain a normal level of activity. The hunger line, the number of people hungry and the income distribution $f(y)$ are related by

$$\#\ \text{hungry} = \int_0^{\text{hunger line}} dy\ f(y)\ . \qquad (2\text{-}8)$$

Note that the hunger line represents more than the cost of food, since clothing, shelter and fuel must also be obtained even by those just able to meet their basic nutritional needs. Also, the hunger "line" is of course an approximation: some people with incomes above the line will suffer from hunger and some people below the line will be adequately fed. Finally, it should be noted that while GDP_{PPP} per capita is used in this study as a proxy for income, they are not, in fact, identical.[5]

The estimation of income inequality and future hunger levels is performed at the national level, and the results aggregated to give regional totals. Gini data are not available for 1995 for most countries, so the most recent values available from 1985 to 1995 are used (Deininger and Squire, 1996; USBC, 1997; Tabatabai, 1996; World Bank, 1998). Where data on income distribution are lacking, values are estimated from available data, as described below.[6]

Statistics on the incidence of chronic undernutrition are collected by the FAO for developing countries (FAO, 1996e; 1997a). The most recent survey was for 1990-92.

---

[5] As a consequence, hunger lines estimated using Equation (2-8) from base-year data do not represent actual income levels. However, since the difference between GDP_{PPP} per capita and income is "built into" the estimated base-year hunger lines, projections from the base year will also reflect this difference.

[6] The only exception is Ethiopia, for which no recent national survey data were available and the estimation procedure based on other data gave an unrealistic result. The Gini coefficient used here is from a 1981 survey that covered 80% of the population.

(The values are three-year averages.) The hunger figures were brought forward to the 1995 baseline taking into account changes between a previous FAO study for 1969-1971 and the one for 1990-1992 (FAO, 1997a).

For OECD and transitional countries comparable hunger estimates are not collected. For this study, hunger in the United States is given by the prevalence of "food insecurity" as defined and measured by the U.S. Department of Agriculture (USDA) (reported in Rose et al., 1995).[7] For countries with no data on hunger, but with income distribution data, hunger levels are estimated, as explained below.

For countries where both hunger and income distribution data are available, it is possible to calculate base year hunger lines. The estimated values for developing countries and for the U.S. are plotted against income in Figure 2-7. For the developing countries, hunger data from 1990-92 are taken from the FAO (1997a), and GDP_{PPP}/capita for 1991 (in constant 1985 international dollars[8]) from WRI (1996b). The 1985 currency values are converted to 1995 currencies using a deflator derived from historical data (WRI, 1996b). For the U.S., the hunger figure from Rose et al. (1995) and the 1995 income from the CIA *World Factbook* are used (CIA, 1997). For all countries the Gini coefficients are from the set compiled for this study.

The hunger lines in Figure 2-7 tend to increase with income. Possible reasons for this behavior are given in *BTC* (page 41). In the scenarios, national hunger lines are assumed to increase from their base-year values toward $3,670, the current inferred value for the United States, as mean income approaches $21,880. This is the income at which the regression line in Figure 2-7 intersects the constant line at $3,670. Above an income of $21,880, hunger lines remain constant.[9] Note that this approach builds in some convergence toward U.S. economic patterns. Also, as noted above, GDP_{PPP} per capita is not identical to income; this approach implicitly assumes that the ratio of GDP_{PPP} per capita to income converges toward the U.S. value in 1995.

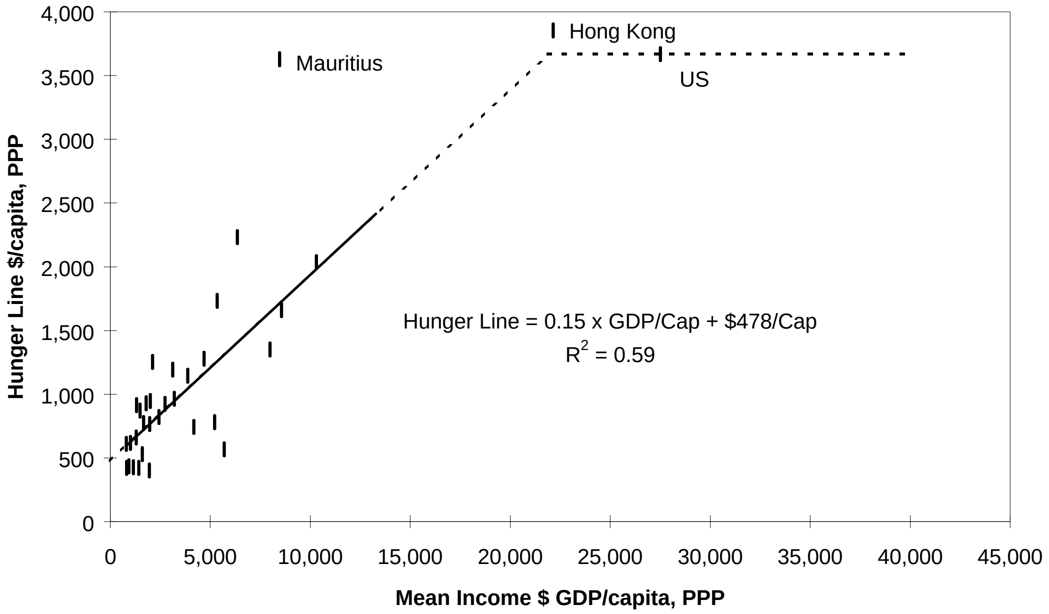
---

[7] Provisional estimates of the prevalence of undernutrition using a method consistent with the one the FAO applies to developing countries were prepared by the USDA's Economic Research Service (ERS), with the Center for Nutrition Policy and Promotion (CNPP) (Rose, 1997). The USDA researchers were critical of the applicability of the FAO method to the U.S., so the estimates were not used for this study. However, it is interesting to note that after ERS and CNPP adjusted for some factors that tended to inflate the result, the estimated incidence of hunger was close to the value used in this study.

[8] PPP-adjusted GDP figures, which differ from GDP converted to U.S. dollars using market exchange rates, are reported in "international dollars" (WRI, 1998).

[9] The base-year data for four of the countries — Brazil, Hong Kong, Mauritius and Turkey — were atypical in some way. For these countries slightly different approaches were adopted from the general one described here.

Figure 2-7. Hunger lines vs. mean income: measured and assumed in the study



Note: Mauritius, Hong Kong and the U.S. are excluded from the regression. See the text for sources and procedures.

In constructing the current accounts, the dashed line in Figure 2-7 is used to estimate either the incidence of hunger or the Gini coefficient for countries where one of these values is lacking, but the other is available. The relationship given in Equation (2-8) between the hunger line, number of people hungry and income distribution is used to create the estimated hunger levels or Gini coefficients.[10]

In the scenarios, national levels of income inequality are assumed to converge to a narrower range than is seen today. As discussed in *BTC* (page 39), in the United States inequality has been increasing for the last 30 years. In the *Reference* scenario, the Gini coefficient for the United States is assumed to increase at half the historic rate, while the other countries converge toward the U.S. pattern. In the *Policy Reform* scenario, all countries converge toward a common pattern; this pattern, and the income growth assumptions, are set so that the hunger reduction targets are met in the scenario. Combining the assumptions about Gini coefficients with the population and income growth assumptions, levels of hunger in the scenarios are computed using Equation (2-8) on page 16.

---

[10] In some cases the estimation procedure gives an unrealistically high or low Gini coefficient, or no Gini coefficient is found that solves Equation (2-8). These countries are excluded when estimating regional hunger levels.

2.3.2 Sensitivity and Comparative Studies

As discussed in *BTC,* in the *Reference* scenario the world's hungry population grows from about 900 million in 1995 to 950 million in 2050—a 6% increase. This increase in hunger follows from the model described above, as well as scenario assumptions about key variables as discussed in *BTC.* In this section, we explore the sensitivity of the *Reference* scenario results to some of the model parameters and assumptions. In addition, other topics are addressed: how the model performs when applied to historical data; alternative ways of meeting the hunger targets; and a comparison of the scenario results to those of an FAO study (Alexandratos, 1995; FAO, 1996c).

Sensitivity to Base Year Gini Coefficients

Data on income distribution are relatively scarce. In order to get the fullest coverage possible for each region, we expanded the set of Gini coefficients using three procedures. First, as explained in the previous section, we used the most recent results of surveys carried out between 1985 and 1995. Second, we used Gini coefficients estimated from both income and expenditure surveys (although wherever possible we used the results of income surveys). Third, where hunger data were available but income distribution data was not, we estimated Gini coefficients from the available data on hunger and average income, using the relationship shown in Figure 2-7 between the hunger line and average income. The scenario hunger estimates could potentially be sensitive to any of these procedures. Data limitations prevented us from testing the sensitivity to the first procedure — the use of data from multiple years. Below, we present the results of sensitivity studies of the second and third procedures.

According to Deininger and Squire (1996), expenditure survey Gini coefficients tend to be lower than ones estimated from income surveys by about 6.6 percentage points a difference which could affect the estimated hunger levels. To test the sensitivity of the *Reference* scenario result to the inclusion of Gini coefficients from different types of surveys, all expenditure survey Gini coefficients were increased by 6.6 percentage points. This produces slightly lower global average values for *national equity* (population-weighted average low/high ratios) in 1995, 0.13 rather than 0.15. Under *Reference* scenario assumptions, hunger increases 13% rather than 6% between 1995 and 2050. The basic conclusion of persistent poverty in the *Reference* scenario remains unchanged.

Table 2-1. Regional Population Represented

	Estimated Ginis Excluded	 Included
Africa	70	90
Latin America	85	100
Middle East	45	98
China+	98	98
S+SE Asia	94	95
E Europe	97	97
FSU	100	100
N America	100	100
W Europe	92	92
Pacific OECD	99	99

The populations represented in each region when countries with estimated Gini coefficients are included or excluded from the data set are shown in Table 2-1. The largest differences are in Africa and the Middle East, where the incidence of hunger is high. As a result, when countries with estimated Gini coefficients are excluded from the calculation, the incidence of hunger in the base year drops by 4%, from 898 million to 860 million.[11] It is therefore important to include these countries in the base-year hunger estimates. This procedure would be problematic if the estimated levels of inequality depended in a sensitive way on the estimated Gini coefficients. However, excluding countries with estimated Gini coefficients has little effect on the average measure of income distribution or the rate of increase of hunger in the scenarios. The global average of national equity estimates in the *Reference* scenario remains unchanged, while hunger increases by 5% rather than 6% from 1995 to 2050. In Africa, base-year national equity changes from 0.13 to 0.12, while in the Middle East it changes from 0.10 to 0.11.

Dependence of the Hunger Line on Average Income

A key element in determining hunger levels in the scenarios is the hunger line, as shown in Equation (2-8). Different assumptions about the way hunger lines change in the scenarios could have a significant effect on the estimated hunger levels. The reasonableness of the method for projecting hunger lines used for this study is tested here: by studying the sensitivity of the *Reference* scenario result to different values for the regression parameters in Figure 2-7, and by applying the methodology to historical data.

The parameters in the regression line shown in Figure 2-7 have standard errors associated with them, reflecting the degree of scatter around the regression line. The standard error for the slope is 16% of its value, or 0.02. Adding this to the slope, hunger increases 20% rather than 6% in the *Reference* scenario between 1995 and 2050. Subtracting the standard error from the slope, hunger decreases by 7% over the course of the scenario. The quantitative value for the hunger level is therefore somewhat sensitive to changes in this parameter, in that a given percent change in the slope leads to roughly the same percent change in the level of hunger in 2050. However, the qualitative picture of widespread poverty persisting into the next half-century remains the same, when the slope is varied within its standard error. The sensitivity to the intercept is much less than the sensitivity to the slope. Adding the standard error of $66 for the intercept to its value of $480 leads to an increase in hunger of 7%, rather than the 6% increase seen between 1995

---

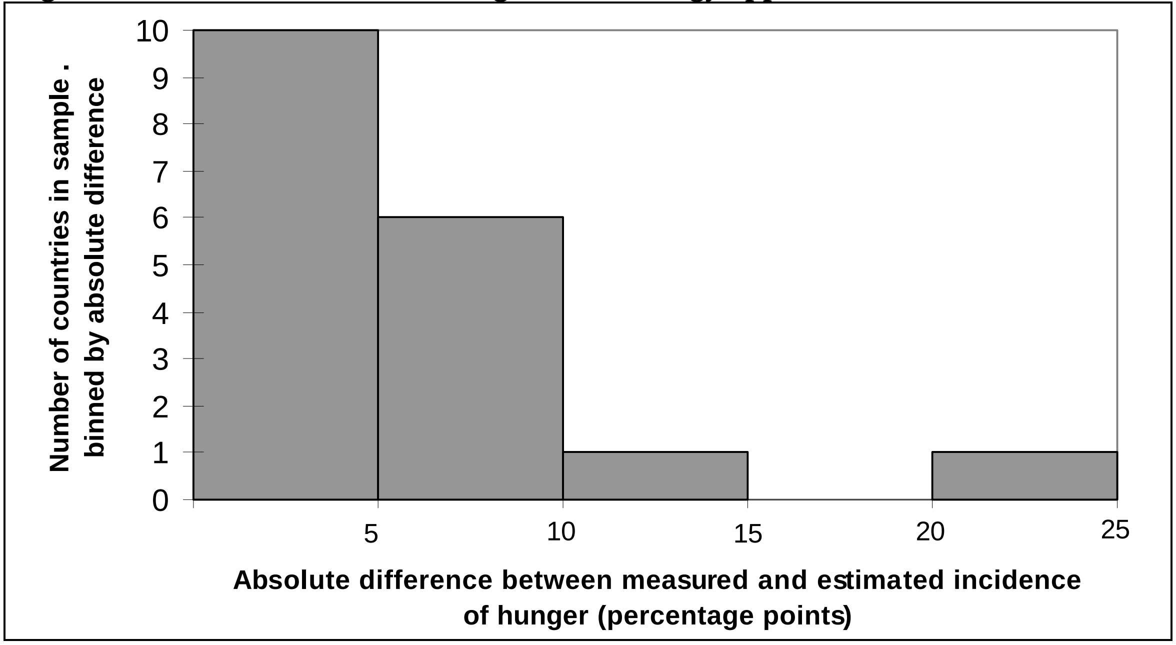
[11] In each case the hungry population is estimated by multiplying the percentage of the population that is hungry by the total regional population.

and 2050 in the *Reference* scenario. Subtracting the error from the intercept leads to an increase of 5% between 1995 and 2050.

Comparison to Historic Data

For a few countries, historical data are available for hunger, income distribution and GDP per capita adjusted for purchasing power parity: FAO estimates of the incidence of hunger are available for 1969-71 and 1990-92 (FAO, 1997a); the income distribution data set of Deininger and Squire (1996) contains values for multiple years for some countries, and for some countries Gini coefficients estimated from the same type of survey are available for years close to 1970 and 1991; finally, historical values for GDP_{PPP} per capita are available for many countries (WRI, 1996b). Using these data it is possible to apply the methodology described in the previous section to a 1970 base year, to construct estimated hunger levels for 1991. We performed this calculation for 18 countries. The difference between the estimated and measured incidence of hunger in 1991, as a percentage of the population, are shown in Figure 2-8. Generally, the methodology performed well. For 10 of the 18 countries the estimated value is within 5 percentage points of the measured value (and for 7 of the 10 it is within 2 percentage points). For all but two of the countries the estimated value is within 10 percentage points of the measured value. For two of the countries (Bangladesh and the Philippines) the approach used for this study did not do well, with the difference between the estimated and measured values exceeding 10 percentage points.[12] In the case of Bangladesh the methodology led to an underestimate of the actual hunger level, while for the Philippines it led to an overestimate.

Figure 2-8. Performance of the hunger methodology applied to historical data



---

[12] Note that large discrepancies between the estimated and measured incidence of hunger could result from several possible causes: failure of the model, errors in the data, or historical policy interventions (for example, a targeted food aid program introduced between 1970 and 1991).

Changing U.S. Gini Coefficient Trends

In the *Reference* scenario, the Gini coefficient in the United States rises at half its historical rate of increase, while Gini coefficients for the other countries move gradually toward the U.S. pattern. The assumption of global convergence is fundamental to the *Conventional Worlds* story, but certainly other assumptions could have been made about the course the U.S. Gini coefficient follows in the scenario. This would be problematic if global hunger levels in the *Reference* scenario are sensitive to small changes in the rate of increase of the U.S. Gini coefficient. However, they are not very sensitive: increasing or decreasing the U.S. rate by 10% leads to an increase or decrease of about 5% in global hunger levels in 2050. The basic conclusion of the *Reference* scenario, that hunger is unlikely to decrease significantly over the next 50 years, is unaffected by the changes.

Alternative Ways of Meeting the Hunger Target

In the *Policy Reform* scenario the hunger reduction targets constrain the income growth and income distribution assumptions. As discussed in *BTC*, a balanced approach is taken: both the relative average income levels between non-OECD and OECD regions (international equity) and national income distributions (national equity) are more equal in the *Policy Reform* scenario than in the *Reference* scenario. Here, the boundaries of the problem are explored by considering how the hunger reduction targets might be met under different demographic, economic and income distribution assumptions.

First, consider the world in 1995. What level of income redistribution within countries, all else being equal, would be required to meet the hunger targets? Leaving population and national GDP_{PPP} at 1995 levels, halving the number of hungry would require improving national equity levels from 0.15 to 0.24. This is similar to the value for Eastern Europe or the FSU in 1995 (see Sheet S-1 of the *BTC* Scenario Highlights for a summary of national equity levels in the scenarios). Reducing hunger to one-quarter of current levels would imply increasing the global average low/high ratio from 0.15 to about 0.34, a value approached by only one country (Belarus) in the base-year data set. These relatively high figures suggest that income growth is a crucial factor in reducing poverty in developing nations.

Second, consider variations away from the *Reference* scenario assumptions. In the *Policy Reform* scenario, both national equity and international equity are higher than in the *Reference* scenario. What level of effort is required if only one or the other is changed relative to the *Reference* scenario?

- **Changing only national equity:** Under *Reference* scenario assumptions for population growth and international equity, to meet hunger targets national equity must increase from 0.15 in 1995 to 0.17 in 2050. In contrast, both historical trends and *Reference* scenario assumptions suggest that national equity will decrease in the future. While not impossible, this outcome cannot be considered plausible.

- **Changing only international equity:** To meet hunger targets under *Reference* scenario assumptions for population growth and national equity would require economic growth rates in developing regions of about 6.5% per year, considerably higher than the 3.4% growth rate assumed in the *Reference* scenario. The corresponding GDP_{PPP} per capita growth rate is about 5.4% per year. This presents a picture in which the developing world as a whole experiences economic growth for fifty years similar to that of the Asian tigers over the past few decades. This is not plausible, and has not been achieved historically. Therefore, some moderation in national equity trends will need to play a role in meeting social goals.

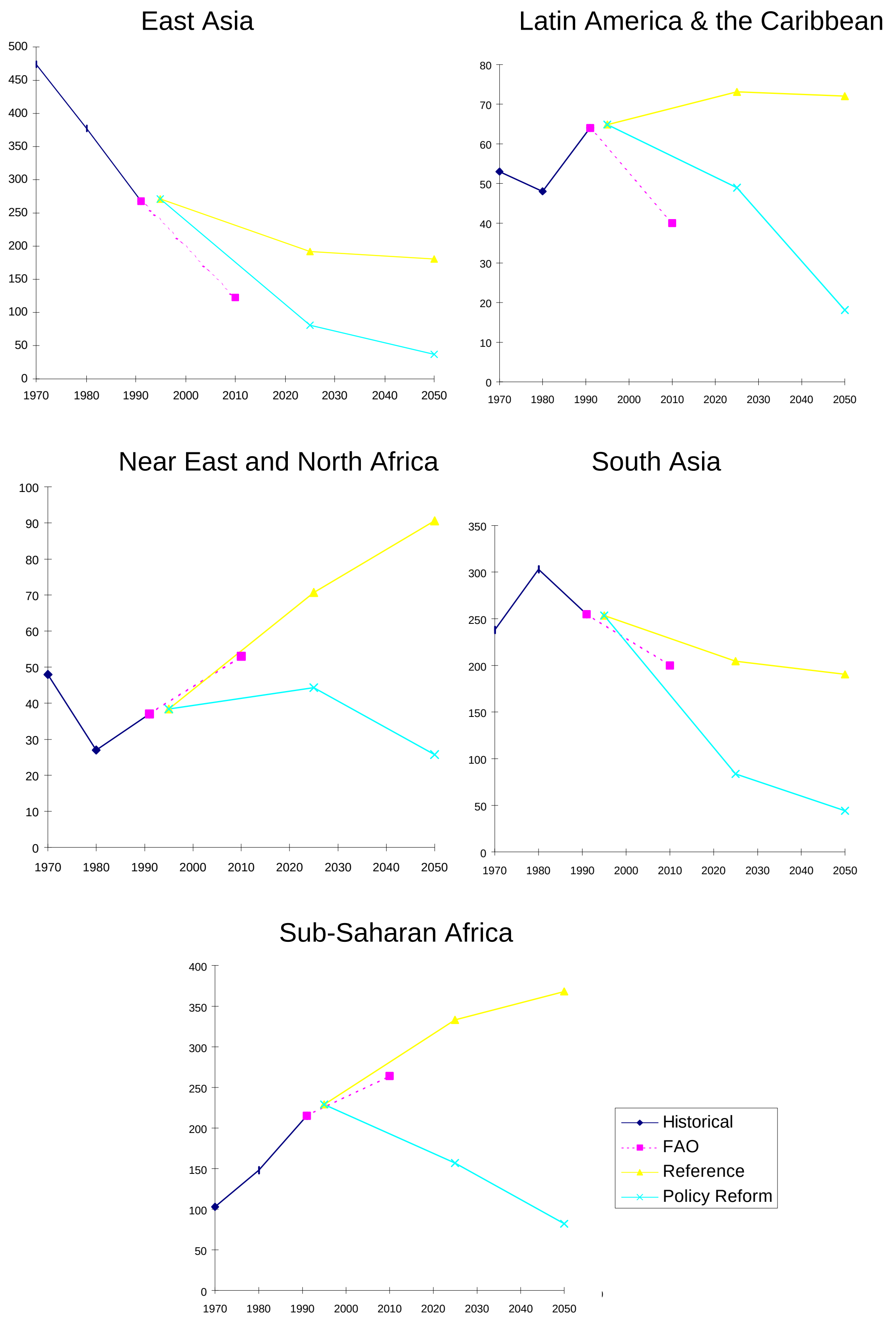
Comparison to FAO Projections

Hunger projection in the scenarios can be compared to an earlier FAO study, which projected hunger levels between 1991 and 2010 (Alexandratos, 1995; FAO, 1996c).[13] The results of the FAO study for each of five regions are displayed in Figure 2-9 alongside the hunger levels in the two *Conventional Worlds* scenarios, which have been recast to match the five regions used in the FAO study.

---

[13] Note that the FAO methodology, rather than considering income distribution, examines the distribution of caloric intake. As with the income distributions in this study, national distributions of caloric intake are represented by lognormal functions.

Figure 2-9. Hunger in the FAO regions (millions of people)



Source: Historical trends and FAO projections from FAO (1996c).

In general, the hunger levels seen in the two *Conventional Worlds* scenarios straddle those of the FAO study. The only major deviation is for Latin America and the Caribbean, where the FAO study projects sharp decreases in hunger, in contrast to both of the *Conventional Worlds* scenarios and to recent historical trends.

The FAO study relies in part on expert opinion in refining estimates of food demand, supply and other variables (Alexandratos, 1995). For this reason, it is difficult to compare the underlying assumptions of the FAO study to those in the *Conventional Worlds* scenarios. In regions where the two studies diverge, the reasons appear to be due primarily to differences in assumptions about future levels of equity, although these are left implicit in the FAO study and so cannot be directly compared. In general, the FAO study appears to assume lower levels of inequality than exist today or are likely in the future under a typical business-as-usual scenario.

3. Energy

In this chapter, we describe the data, methods and assumptions for energy and climate change in the scenario. The *Reference* scenario analysis is, to a large extent, an update of an earlier report (Raskin and Margolis, 1995), incorporating a later year base year (1995 instead of 1990), additional sources of data, and updated methodologies. Some of the text in this chapter is adapted from the earlier report.

In the *Reference* scenario, both energy and greenhouse gas emissions are driven by the demographic, economic and technical trends of the scenario. In the normative *Policy Reform* scenario energy sector trends are constrained by the climate change mitigation targets imposed on the scenario. For this reason, we start the discussion of the energy sector by reviewing the analysis of climate assumptions and the constraints imposed on greenhouse gas emissions in the *Policy Reform* scenario. Then, we review regional patterns of energy consumption, energy conversion, and primary energy supply in each of the two scenarios.

3.1 Climate Change

The climate change mitigation goals of the *Policy Reform* scenario are described in *BTC*, which also describes how a criterion in terms of temperature change can be translated first into approximate targets for atmospheric CO_2 concentrations, and then to a global cumulative emissions budget. For reference, the criterion selected is that warming should occur no faster than 0.1^{o}C/decade on average between 1990 and 2100, or a cumulative change of about 1.1° between 1990 and 2100. This translates into a target value for the equilibrium concentration of CO_2 in 2100 of about 450 ppmv, which corresponds to a cumulative carbon emissions budget between 1990 and 2100 in the 640-800 GtC range.

Energy-related emissions are computed by applying standard fuel-specific CO_2 emission factors (IPCC, 1995b) to energy use. In addition, land-use change emission factors (SEI, 1993) are applied to land-use change patterns in each scenario. In the *Reference* scenario, emissions are projected as a consequence of the energy and land-use change projections. In the *Policy Reform* scenario, targets for reducing deforestation (described in *BTC*) lead to lower land-use change emissions than in the *Reference* scenario.[14] Emissions from the energy and industrial sectors in the *Policy Reform* scenario are constrained so that total emissions fall within the target carbon emissions budget for the scenario. Energy and industrial sector emissions are allocated between regions in a manner reflecting the general spirit of improved equity in the *Policy Reform* scenario as follows:

- Each OECD region is required to reduce total annual emissions by 35% in 2025 compared to their 1990 values. This translates into reductions in each region of between 40% and 50% in 2025 compared to the *Reference* scenario.

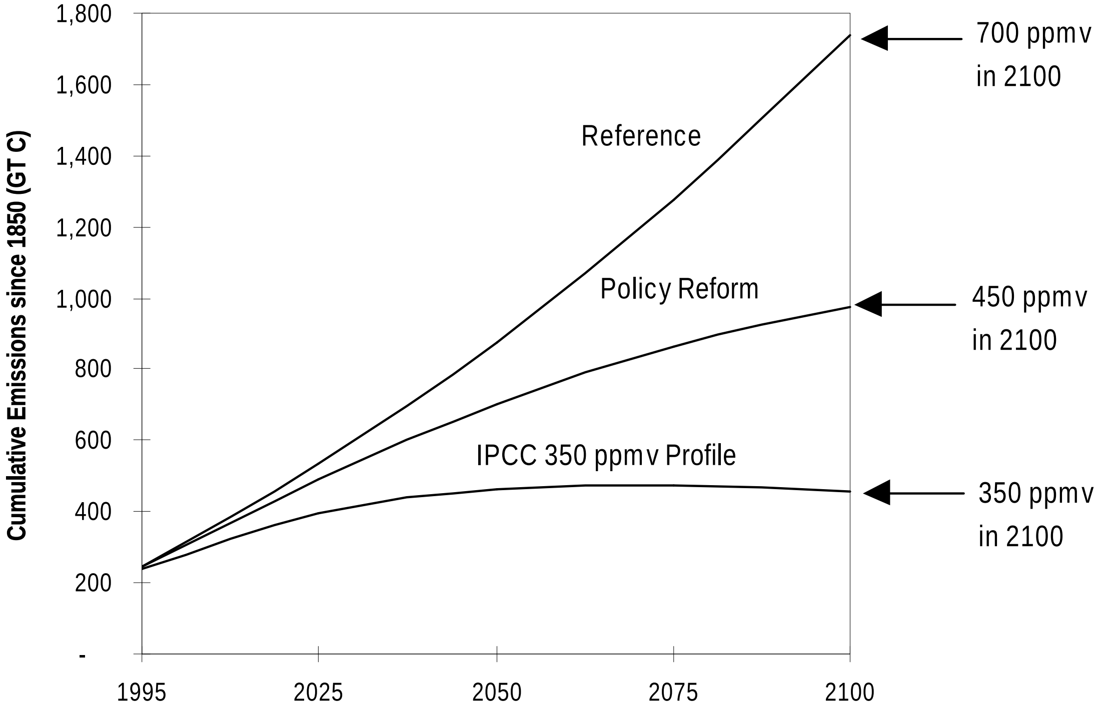
---

[14] After 2025, net reforestation acts as a net carbon sink.

- Each transitional region is required to reduce total annual emissions by 30% in 2025 relative to the *Reference* scenario.
- Each developing region is required to reduce emissions intensities (tonnes per dollar GDP_{PPP}) in 2025 by 15% relative to the *Reference* scenario. This translates into absolute levels of emissions between 92% and 102% of those in the *Reference* scenario in all regions except Africa, where due to the much higher economic growth in the *Policy Reform* scenario, absolute emissions in 2025 are actually 40% higher than in the *Reference* scenario.
- After 2025, emissions from all regions are assumed to converge toward a common annual per capita allowance of 0.6 tC per capita. This is achieved by 2075, with equal per capita emissions thereafter. In 2100, annual global emissions are constrained to be 3 GtC per year.

Figure 3-1 summarizes cumulative global emissions pathways of the *Reference* scenario and *Policy Reform* scenarios, with the detailed results of the two scenarios to the period 2050 projected forward to the year 2100. The figure includes estimates of total industrial emissions since 1850 from combustion of fossil fuels and cement production plus estimates of net emissions from land-use change. The *Reference* scenario, which closely tracks the IPCC mid range (IS92a) scenario to the period 2050, is assumed to continue to follow the IS92a path after 2050. It is clear that the *Reference* scenario does not meet the target. Cumulative carbon emissions between 1995 and 2100 would be about 1500 GtC. This is about double the emissions from the *Policy Reform* scenario (750 GtC).

Figure 3-1: Cumulative global CO_2 emissions and atmospheric concentrations

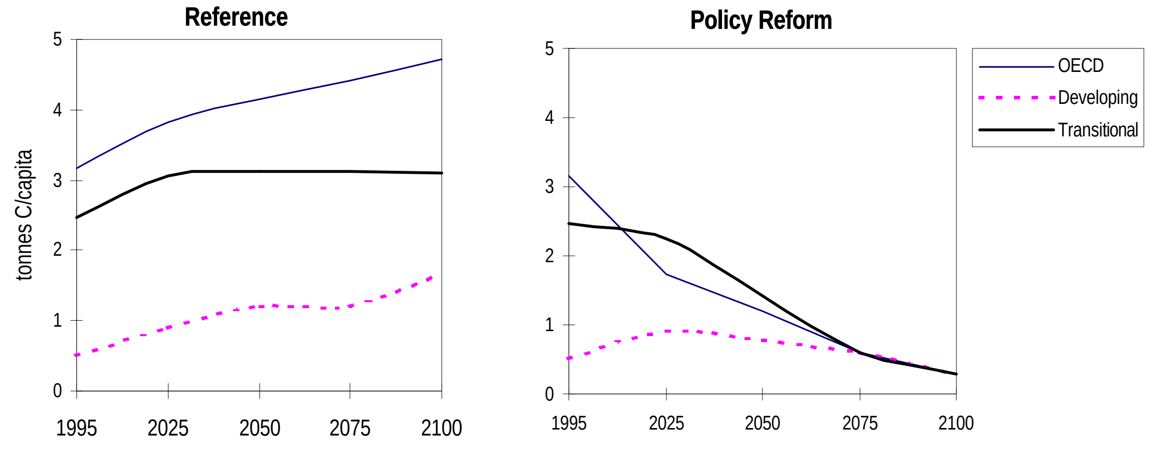


Notes:

- In addition to the *Reference* and *Policy Reform* scenario, a third profile is shown leading to stabilization at 350 ppmv, following the pathways defined in IPCC (1995a). For reference, current CO_2 concentrations stand at about 360 ppmv, while concentrations prior to the industrial revolution (pre-1850) stood at 280 ppmv. Achieving this concentration would require cumulative emissions of approximately 220 GtC between 1995 and 2100.

Figure 3-2 compares annual *per capita* CO_2 emissions for the three macro-regions of the study in the *Reference* scenario and *Policy Reform* scenario. In the *Reference* scenario, per capita emissions from all three macro-regions initially continue to grow as incomes increase. After about 2030, per capita emissions from the transitional regions level off due to the large potential for energy efficiency improvements, and for fuel switching away from coal and towards less carbon intensive fuels such as natural gas, hydropower and renewables. The *Policy Reform* scenario shows dramatically different trajectories. In the developing regions, emissions per capita start from a much lower level than in the industrialized or transitional ones. They grow steadily until 2025, without ever exceeding the industrial or transitional rates, then drop gradually to reach the 2075 convergence target of 6 tonnes per capita. Per capita emissions from all regions converge on this figure in 2075 and decline thereafter to 3 tonnes C per capita.

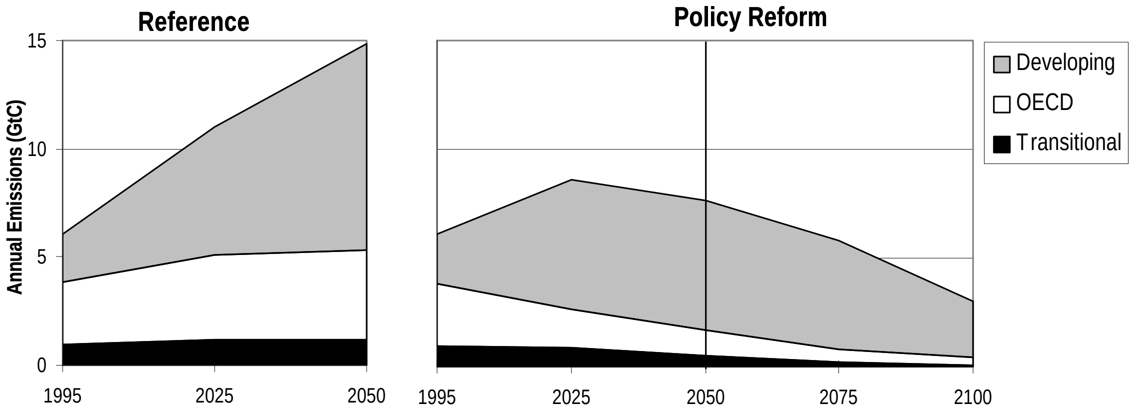
Figure 3-2. Annual Per capita CO_2 emissions



Notes: Industrial emissions (not including net land-use change emissions) divided by population in each region.

Figure 3-3 shows annual emissions by macro-region. In 1995, emissions are dominated by the OECD, which accounts for about 48% of the total. By 2050 in the *Reference* scenario, this position has altered, so that the developing regions account for 64% of total industrial emissions. By 2100 the developing regions' share rises to about 72% of global emissions. In the *Policy Reform* scenario, the developing regions share of the total increases even faster. By 2050, they account for 78% of total global emissions, and this share increases to 86% by 2100.

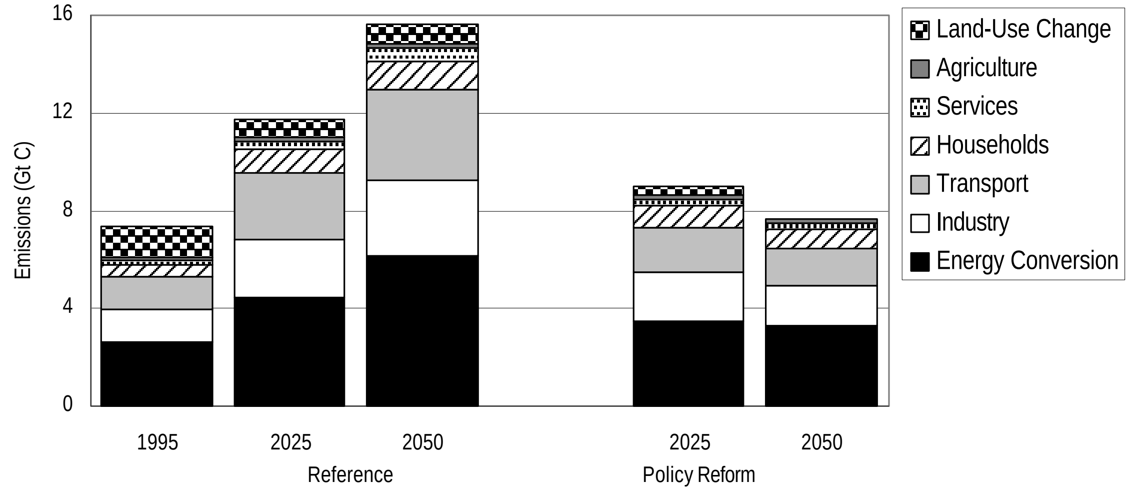
Figure 3-3. Annual CO_2 emissions by Macro-region



Notes: Industrial emissions (not including net land-use change emissions) divided by population in each region.

Figure 3-4 summarizes annual emissions by major source category for the years 1995, 2025 and 2050 (including land-use change emissions). In the *Reference* scenario industrial emissions continue to grow from about 6.1 GtC in 1995 to 14.8 GtC in 2050 and to about 21 GtC in 2100. In the *Policy Reform* scenario, total industrial emissions increase to 2025, reaching 8.6 GtC annually. Thereafter they decline, reaching 7.6 GtC in 2050 and 3 GtC in 2100.

Figure 3-4. Annual Global CO_2 emissions by source



Note: "Industry" includes all emissions from fossil fuel combustion in the industrial sector. Process emissions (primarily from cement manufacture are accounted for separately.

Annual global net CO_2 emissions from forest loss, estimated at about 1.3 GtC in 1995, decrease in the *Reference* scenario, reaching 0.78 GtC/year in 2050. Following the assumptions of the IS92a scenario, they are then expected to decline further, reaching 0.15 GtC/year in 2075 and -0.1 GtC/year in 2100 — reflecting net afforestation. In the *Policy Reform* scenario, net deforestation rates are reduced more quickly, with carbon emissions declining to 0.4 GtC/year in 2025. By 2050, net afforestation at an annual rate of 0.1GtC/year is occurring. This rate of afforestation thereafter is assumed to remain constant.

In the *Policy Reform* scenario, the cumulative emissions from fossil fuel combustion, cement production, other industrial CO_2 emissions, and net emissions from changes in forest area total about 750 GtC, which achieves the climate change mitigation target for the scenario.

3.2 Energy Consumption

Energy consumption refers to fuel and electricity requirements at the point of consumption for the various production and consumption activities of society. Consumption is analyzed in each region for each of the five major final energy-using sectors: industry, transport, households, services and agriculture. In each sector, the analysis is based on further disaggregation, subject to the availability of data. For example, the industrial sector is divided into five major energy consuming subsectors plus a sixth subsector dealing with all other energy consumption. Similarly, in the transport sector, freight and passenger transport are considered separately and each is divided by mode (road, rail, air, water).

In section 3.2.1, we summarize current total final consumption patterns and the aggregate consumption patterns in the two scenarios. In sections 3.2.2 - 3.2.6, we then examine how these patterns are built up from a detailed analysis of the five energy-consuming sectors.

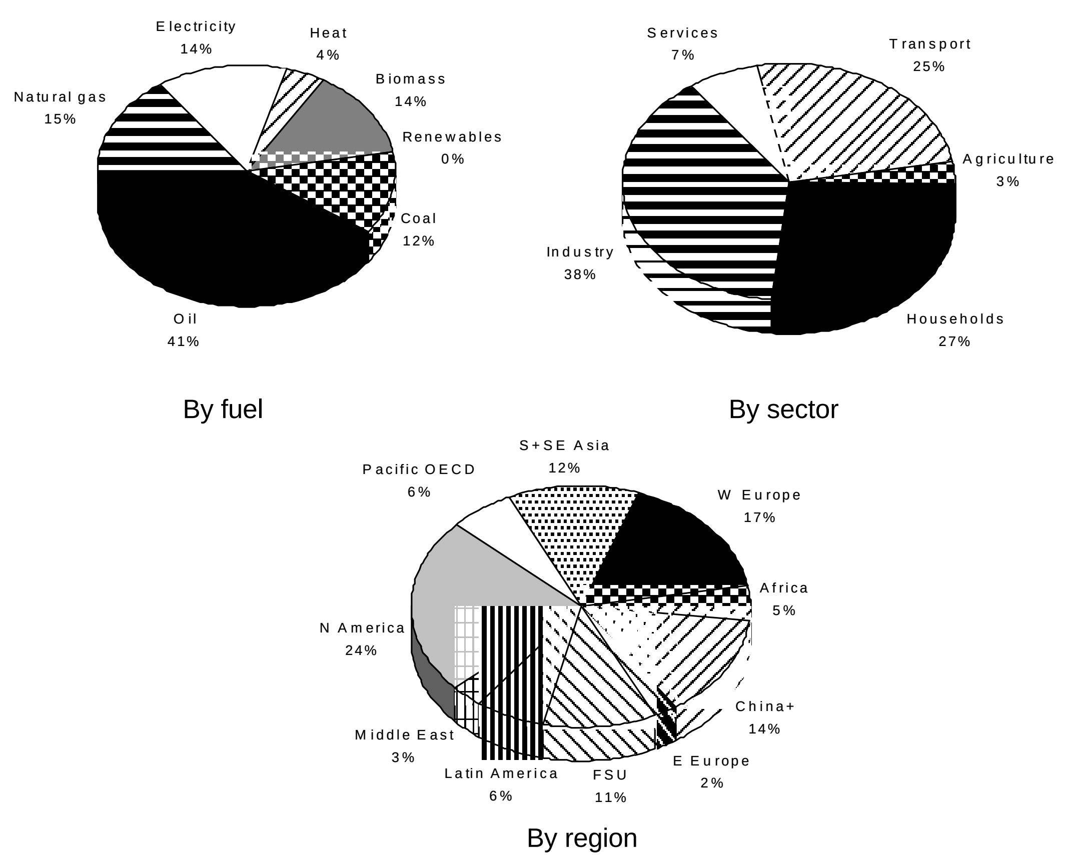
3.2.1 Total Final Consumption

Current Accounts

Global total final energy consumption in 1995 was about 271 EJ. As shown in Figure 3-5, final fuel composition is currently dominated by fossil fuels, which account for 68% of the global total. Other significant final energy forms are electricity, biomass and district heat. The direct use of non-biomass renewable energy forms (e.g., direct use of solar for water heating) currently accounts for less than one tenth of one percent of final energy consumption.

Figure 3-5 shows the breakdown of total final demand by sector. Global consumption is led by the industrial sector (38%), followed by households (27%), transport (25%), services (7%), and agriculture (3%). Turning to regional patterns, global energy consumption is dominated by the OECD regions, which account for 47% of global energy consumption. The developing regions account for 40% of global energy consumption and the transitional regions account for the remaining 13%.

Figure 3-5: Global final energy consumption shares - 1995



The breakdown by fuel is presented for each region in Table 3-2. Petroleum products account for more than 50% of final demand in 5 regions (North America, Western Europe, Pacific OECD, Middle East, and Latin America), while coal accounts for almost 50% of final demand in China+. Energy from biomass is significant in Africa, Latin America, China+ and South and Southeast Asia.

Table 3-2. Global energy consumption by fuel - 1995 (PJ)

	Coal	Oil	Natural Gas	Electricity	Heat	Biomass	Renewables	Total
Africa	665	3,182	396	1,013	-	7,847	-	13,104
China+	18,148	5,581	561	2,880	812	8,729	-	36,710
Latin America	628	9,069	2,044	2,234	-	3,542	-	17,517
Middle East	49	5,878	1,706	1,048	-	37	19	8,738
S+SE Asia	3,341	12,402	1,593	3,033	-	12,966	-	33,334
E Europe	1,500	1,503	1,474	883	793	124	-	6,277
FSU	3,278	6,100	8,064	3,210	8,280	467	-	29,399
Pacific OECD	1,846	9,426	1,262	3,741	15	327	42	16,660
W Europe	2,881	23,267	9,009	7,977	910	1,510	27	45,582
N. America	1,582	33,247	14,963	12,533	316	1,540	-	64,181
World	33,918	109,655	41,072	38,552	11,127	37,089	89	271,501
OECD	6,309	65,940	25,234	24,251	1,241	3,377	69	126,422
Developing	22,831	36,112	6,299	10,208	812	33,122	19	109,403
Transitional	4,778	7,603	9,538	4,093	9,074	590	-	35,676

The sectoral composition of final demand across regions is presented in Table 3-3. The variation of relative sectoral shares is related to a number of factors specific to each region. First, the structure of economic activity evolves with the level of industrial development and the particular economic growth strategy that has been adopted. For example, service sector output is a rising share of total national output in OECD regions; heavy industry is important in Eastern Europe, FSU, and China+; and natural resource exploitation is relatively important in the economies of many developing countries. The household sector remains dominant in Africa, where subsistence lifestyles retain their importance and modern forms of economic activity remain relatively undeveloped.

Table 3-3. Global energy consumption by sector - 1995 (PJ)

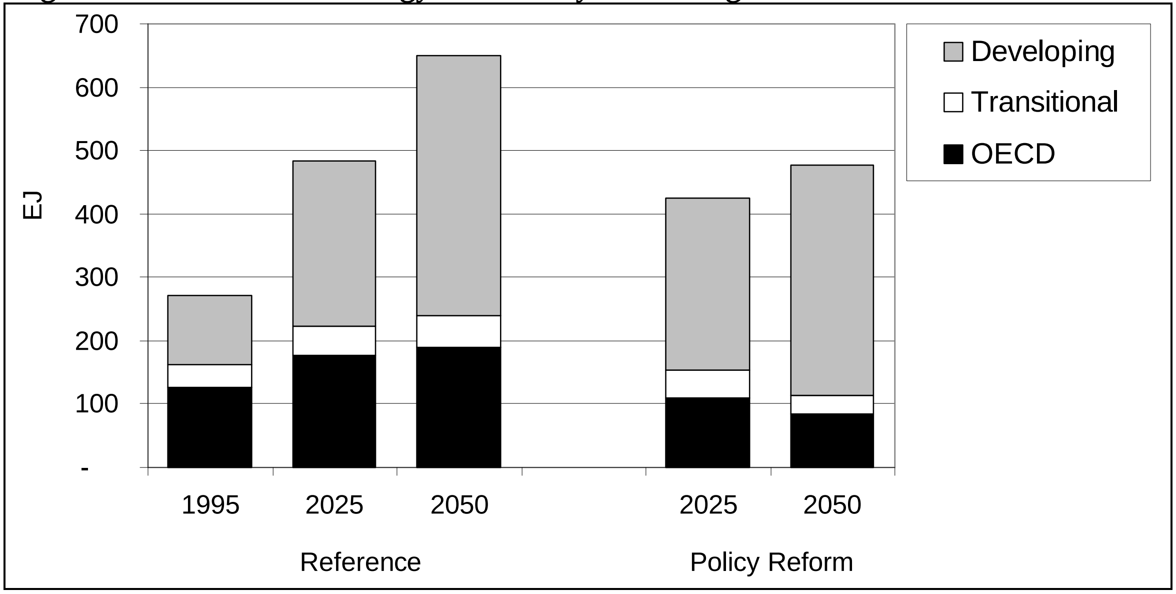
	Industry	Households	Transport	Services	Agriculture	Total
Africa	4,118	6,768	1,874	151	194	13,104
China+	19,145	12,203	2,866	1,389	1,107	36,710
Latin America	6,778	3,228	6,075	720	717	17,517
Middle East	3,447	1,595	3,165	294	237	8,738
S+SE Asia	11,351	13,976	6,665	626	716	33,334
E Europe	3,249	1,692	753	240	343	6,277
FSU	15,802	8,142	2,651	653	2,151	29,399
Pacific OECD	6,627	2,416	5,176	1,898	542	16,660
W Europe	14,904	10,637	14,578	4,316	1,147	45,582
N. America	18,383	11,616	25,109	8,257	816	64,181
World	103,805	72,272	68,911	18,543	7,971	271,501
OECD	39,914	24,670	44,862	14,471	2,505	126,422
Developing	44,840	37,768	20,645	3,179	2,971	109,403
Transititional	19,051	9,834	3,404	893	2,494	35,676

Second, the energy efficiency of end-use equipment influences the sectoral pattern. For example, electric devices, which tend to grow in importance with rising incomes, are relatively efficient at the end-use level while traditional wood stoves are quite inefficient, thereby contributing to the anomalously high share for household energy consumption in Africa. Third, infrastructure and life-style variations influence the sectoral composition. For example, in North America, where there is heavy reliance on the private automobile and a highly mobile population, the share of energy use in transportation is large.

Scenarios

Figure 3-6 summarizes total final demand in the *Reference* scenario and *Policy Reform* scenario. In the *Reference* scenario, total final demand more than doubles from 271.5 EJ in 1995 to 649 EJ in 2050. In the *Policy Reform* scenario this growth is substantially reduced, reaching 476 EJ in 2050. In the *Reference* scenario, the developing regions account for 79% of the growth in demand between 1995 and 2050, although demand also increases in both the OECD and transitional regions as well.

Figure 3-6. Global final energy demand by macro-region



In the *Policy Reform* scenario, the effects of slower economic growth and intensive policy efforts to improve energy efficiency lead to declines in energy demand in the OECD and transitional regions, where total final demand in 2050 drops to 67% and 81% of its 1995 values respectively. All of the net increase in total final demand is therefore accounted for by the developing regions where, in spite of energy efficiency improvements beyond those in the *Reference* scenario, energy demand still increases at a rate of 2.2% per year, only slightly less than the 2.4% per year growth seen in the *Reference* scenario. This does not reflect inaction, but rather the increased economic growth in the *Policy Reform* scenario compared to the *Reference* scenario.

3.2.2 Households

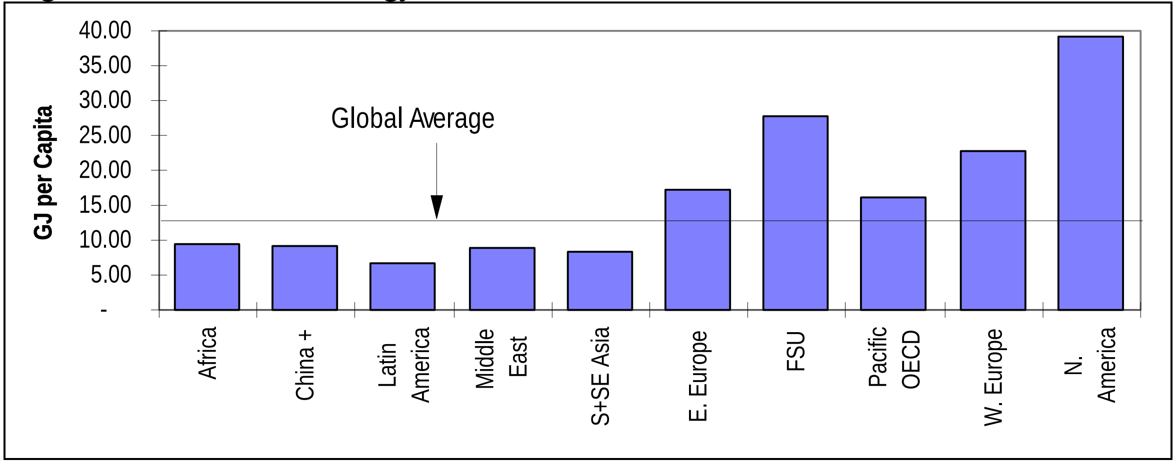
Current Accounts

Energy is used in households for a wide variety of end-uses: cooking, lighting, space heating and cooling, water heating, refrigeration, etc. The character of household consumption varies between and within regions as a function of income, culture, life-style, climate and access to energy forms, such as electricity.

Ideally, a satisfactory understanding of household energy use requires information broken down by end-use, and when examining developing countries, broken down by urban and rural households. Unfortunately, such data are available in no more than a few countries, and when analyzing global and regional patterns we have to rely upon aggregate fuel consumption data (IEA, 1997a, b). Even this data presents serious analytical problems. For example, estimates of traditional biomass consumption in developing country households (firewood, charcoal, crop and animal residues) remain poorly known.

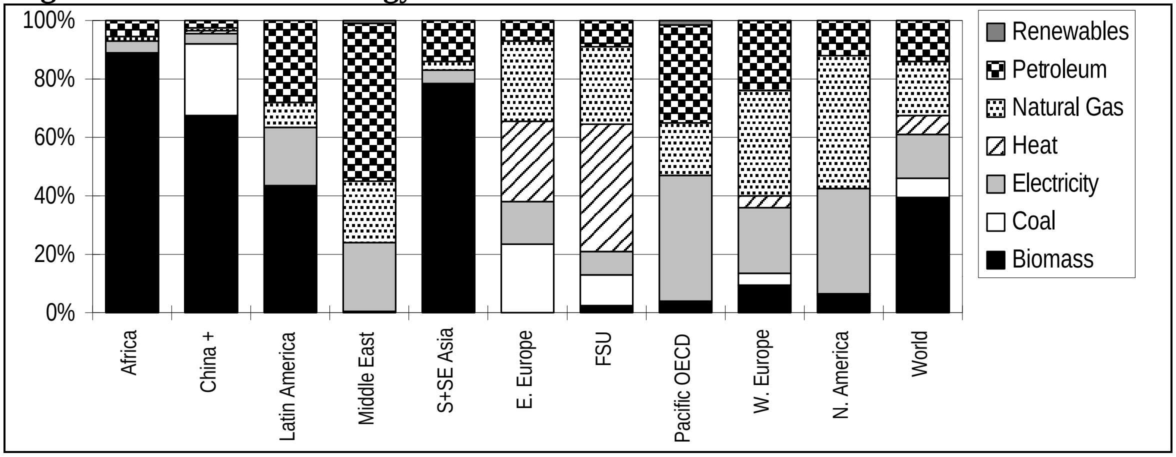
Current regional household sector energy consumption patterns are reported in Table 3-3. Figure 3-7 shows current household energy consumption per capita by region and compared to the global average, underscoring the disparity between industrialized and developing regions. Household per capita energy use in North America, for example, is four times the level in Asia. Moreover, the efficiency of converting fuel into final services (that is, cooking fuel into boiling water, boiler fuel into warm spaces) is generally higher in advanced industrial countries, implying that final energy use figures for a region such as Africa are misleadingly high since a considerable quantity of fuel is wasted in inefficient fuelwood use.

Figure 3-7. Household energy intensities - 1995



A great variation in household fuel use patterns is suggested by the fuel share breakdowns presented in Figure 3-8. Noteworthy are the large share for biomass in the household energy mix in developing regions, the importance of coal in China+ and Eastern Europe, and the increasing reliance on more convenient energy forms (electricity, natural gas and oil) as household incomes rise to OECD levels. The large share for "heat" in the fuel mix of the FSU and Eastern Europe (44% and 28% respectively) is due to the continuing widespread use of centralized district heating systems in these areas.[15]

Figure 3-8. Household energy shares - 1995



Scenarios

The household sector scenario analysis relies on three elements: a measure of activity, energy intensity and final fuel mix. The activity measure used is the population in each region. In principle, further disaggregation into household income groups would be desirable in order to illuminate energy trends as a function of changing income distribution, but there is insufficient data for this. The energy intensity is expressed as the household final energy demand per capita. Household scenarios are developed in four steps:

1. First, energy intensities (GJ/capita) are projected for the three OECD regions. Since 1973, in industrialized countries these have remained almost constant or in some cases have declined, in spite of increasing household floor space and increasing penetration of electric appliances. In the United States, for example, final energy use per capita in households declined by 11% between 1972/3 and 1988 (Schipper and Meyers, 1992). Part of the decline reflects the increased use of electricity (which is intrinsically more efficient than combusted fossil fuels), but there also appears to have been significant declines in energy intensities for heating and appliances (IEA, 1997c). Action to reduce energy use in the built environment was in part spurred by the oil crises of the 1970s. The numerous initiatives of governments, utilities, trade associations and other institutions led to new regulations mandating efficiency standards and new products such as compact fluorescent lights, more efficient refrigerators and other appliances, passive solar heating, wider adoptions of double-glazed windows and spectrally selective window glazing. These improvements can be expected to continue, and this effect is represented in the *Reference* scenario. Nevertheless, the adoption of cost-effective measures to reduce building energy use

---

[15] It is conventional to define final demand as the fuel reaching the end-user. In the case of the household sector, for example, coal used to fire an on-site boiler for space heating would be counted as final fuel use. However, coal or other fuels used to produce heat centrally is accounted for as an input to the district heating energy *conversion* process.

remains far below its economic potential. Large market barriers remain, preventing a transition to a more energy-efficient future for the household sector. Issues such as imperfect information, high transaction costs, inadequate internalization of pollution costs, and the lack of choice for consumers (who are often faced with the choice of purchasing an energy-efficient appliance or another less efficient model with a wider range of desired features) all contribute to the problem. The policies and programs considered for the *Policy Reform* scenario assume concerted action to accelerate the decline in household energy intensities, including: improved appliance and building energy performance standards, business and consumer information programs, targeted government procurement strategies, measures to promote market transformation and overcome market barriers, increased funding of research and development, and initiatives to encourage voluntary action and utility energy management programs.

Scenario energy intensity assumptions for OECD regions are informed by the recent U.S. study *Energy Innovations* (1997). The *Energy Innovations* study, based on end-use engineering and econometric analysis, examined changes in household energy intensities in light of expected trends in prices, end-use saturations and household income levels, and by making various assumptions about changes in technology. It modeled the sector using suitably constrained behavioral models that determine the least-cost technology available to meet various service demands. The study created two scenarios, called the *Present Path* and *Innovation Path,* which are broadly compatible with the viewpoints of the *Reference* and *Policy Reform* scenarios respectively. Scenario assumptions in this study are guided by more modest assumptions about rates of decline in energy intensities than the *Energy Innovations* study.

In the absence of new policy actions, the *Reference* scenario nevertheless assumes significant reductions in energy intensities, which decline at a rate of 0.7% per year in OECD regions. The improvements assume the introduction of a variety of increasingly efficient appliances and building shells, including improved heating and air conditioning systems, and more efficient lighting and cooking systems. The *Policy Reform* scenario assumes both more rapid and more widespread penetration of efficient technologies, with OECD intensities declining at a rate of 0.9% per year. In later periods, the scenario assumes the introduction of advanced technologies and building designs such as passive solar heating, efficient heat pumps and greater use of renewable energy.

2. Second, intensities for non-OECD regions are introduced. These converge towards the average values of the OECD region as average incomes increase, using a technology convergence algorithm (see Annex). Table 3-1 summarizes the evolution of energy intensities by region in each scenario. In the *Reference* scenario, developing country and Eastern European energy intensities approach a higher average intensity (15.6 GJ/capita), while in the *Policy Reform* scenario, they approach a lower average intensity (13.8 GJ/capita) as set by OECD patterns. At the same time, there is greater overall convergence in the *Policy Reform* scenario than in the *Reference* scenario, due to the assumption of improving equity and more rapid

economic growth in the developing countries in the former scenario. These two effects largely counteract one another, resulting in broadly similar trends in developing country energy intensities in the two scenarios. The exception is the FSU, where household energy intensities start at levels well above the OECD average, and thus the effects of the convergence algorithm and trends in OECD intensities reinforce one another.

Table 3-1. Trends in Household Energy Intensities (GJ/capita)

		Reference		Growth Rate	Policy Reform		Growth Rate
	1995	2025	2050	95-50	2025	2050	95-50
North America	39.2	31.7	26.6	-0.7%	29.9	23.8	-0.9%
W. Europe	22.8	18.4	15.5	-0.7%	17.3	13.8	-0.9%
Pacifc OECD	16.2	13.1	11.0	-0.7%	12.3	9.8	-0.9%
FSU	27.8	25.9	23.4	-0.3%	24.1	17.4	-0.8%
E. Europe	17.1	17.6	16.6	-0.1%	17.2	14.9	-0.3%
Africa	9.4	9.9	10.5	0.2%	10.6	11.4	0.4%
Latin America	6.8	10.7	14.0	1.3%	11.1	13.7	1.3%
Middle East	8.9	11.1	12.8	0.7%	11.5	12.8	0.7%
China+	9.2	11.6	13.3	0.7%	11.8	13.1	0.6%
S+SE Asia	8.3	10.1	11.9	0.6%	10.6	12.1	0.7%
World	3.3	4.3	6.2	1.2%	3.7	4.9	0.8%

3. In the third step, biomass fuel shares are projected for each region. Since traditional biomass fuels currently dominate household energy use in most developing countries, assumptions on modern versus traditional fuels is a key issue in the *Reference* and *Policy Reform* scenarios. Household fuel use tends to climb an "energy ladder" with rising income. As incomes increase, wood and dung are replaced by charcoal and kerosene and then by LPG and electricity. Each succeeding rung in the ladder is characterized by greater efficiency of use, but also by higher equipment prices. Consequently, differences in income and its distribution can imply very different requirements for energy.

   To shed light on this question, regression analysis was used to explore the relationship between three variables, compiled from a cross-section of national statistics: the share of biomass in the total household energy budget, average income levels and a measure of income distribution. The regression yielded low R^2 values, suggesting that additional variables are important for determining biomass consumption, which is expected since the availability of biomass varies widely across countries. Nevertheless, both the income and income distribution parameters were found to be statistically significant at the 5% level (t greater than about 2) in explaining the variation in household biomass shares, and are consistent with the energy ladder hypothesis, i.e., that biomass fuel consumption decreases as average income increases. The regression analysis guided future household biomass shares in each region and in both scenarios. Specifically, the regression was used to calculate biomass fuel shares in all regions for 2025 and 2050. In the *Policy Reform* scenario, the regression-based estimates of biomass fuel shares in 2050 for Africa, China and

Latin America were adjusted to reflect a less dramatic decline in biomass fuel use, on the assumption that in these regions, the current dominance of biomass is likely to spur modern energy-efficient uses for biomass in households and hence slow its decline relative to other fuels.

The resulting trends in the biomass shares are summarized in Table 3-2 for regions where biomass was a significant household fuel in 1995.

Table 3-2. Trends in Household Biomass Fuel Shares

		Reference		Policy Reform	
	1995	2025	2050	2025	2050
FSU	2%	1%	1%	1%	0%
Africa	89%	73%	52%	37%	15%
Latin America	43%	19%	9%	9%	5%
Middle East	1%	0%	0%	0%	0%
China+	68%	31%	16%	19%	10%
S+SE Asia	78%	47%	29%	18%	8%

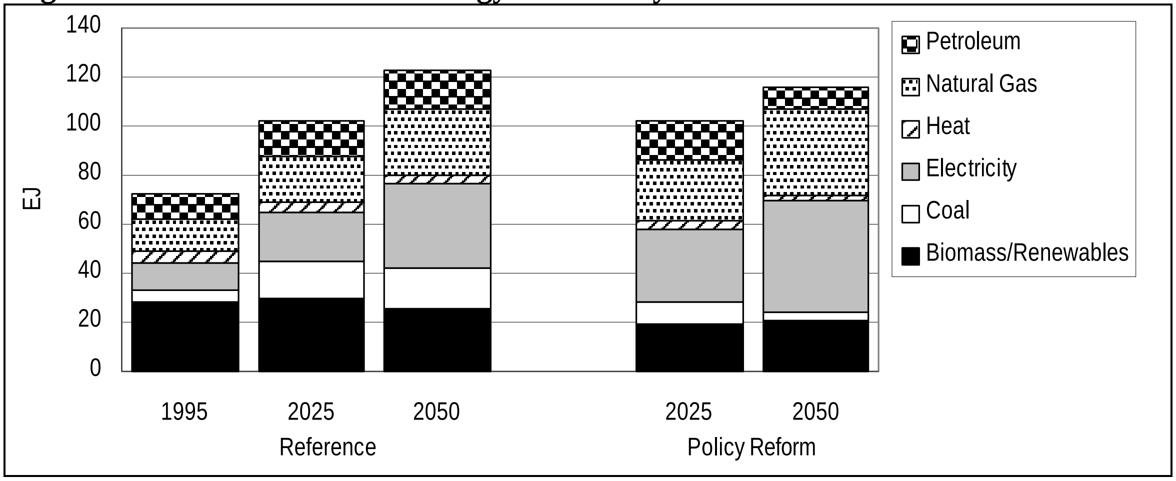
4. Finally, the shares of each non-biomass fuel are introduced. In the *Reference* scenario these are guided by household fuel consumption trends in the IPCC mid-range scenario (IPCC, 1992). These reflect the effects of changes in prices as resources are depleted and technical change occurs.[16] Taking the *Reference* scenario as a starting point, the *Policy Reform* scenario assumes an accelerated transition away from the more carbon intensive fuels (coal and oil) towards lower carbon and more convenient fuels (electricity, natural gas, and some renewables). This reflects a pattern of higher and more evenly distributed income levels in the developing countries (leading to higher consumption of the more convenient fuels), and the effects of policies to reduce greenhouse gas emissions.

Household energy demands are shown by fuel in Figure 3-9. In both scenarios, total household energy consumption increases by almost 60%, from 73 EJ in 1995 to 123 EJ in 2050 in the *Reference* scenario and to 116 EJ in 2050 in the *Policy Reform* scenario.

---

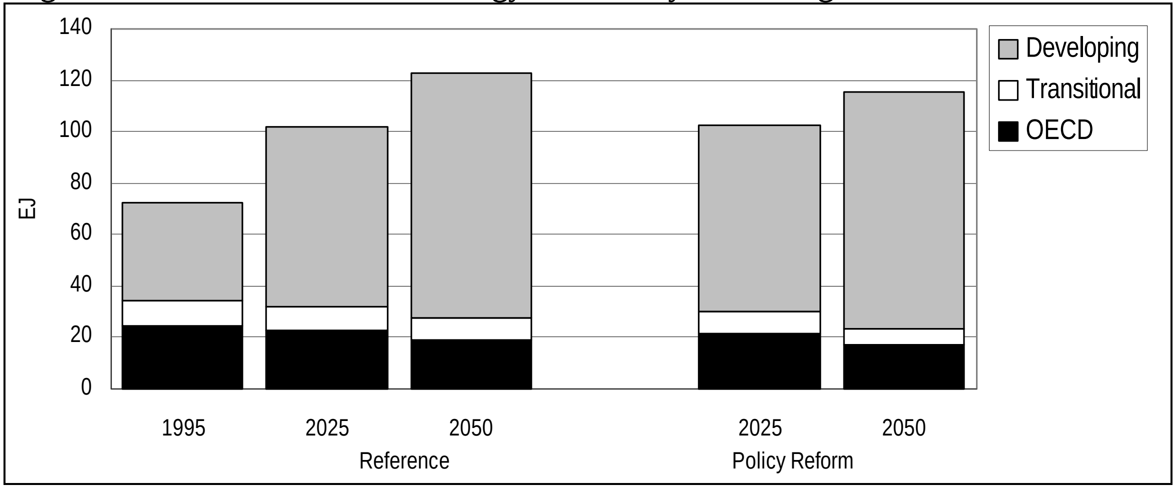
[16] In the IPCC IS92a scenario, it is assumed that the world oil price increases to $55 per bbl in 2025 and $70 per bbl in 2100, while the cost of non-fossil energy supplies are assumed to fall (e.g., the cost of solar electric energy is assumed to decline to $0.075 per kWh by 2050). Similar price trends are implied in the *Reference Scenario*.

Figure 3-9. Global household energy demand by fuel



Household energy demands are shown by macro-region in Figure 3-9 and by region in Figure 3-11. In the *Reference* scenario, the stable or decreasing household energy demands in the OECD and transitional regions are the result of low population growth, high appliance saturations, and efficiency improvements. The developing regions experience dramatic increases in household energy demand, largely due to population growth and the gradual transition to modern patterns of household energy use. Biomass energy use continues to dominate household demand in Africa and, to a lesser extent, in South and Southeast Asia, while coal continues to dominate in China+.

Figure 3-10. Global household energy demand by macro-region



Consumption of biomass fuels by households decreases over time in most regions, as increasing incomes allow people to move up the "energy ladder" to more convenient forms of household energy. However, this trend is counterbalanced by the continuing expansion of biomass use by households in Africa, in which rapid population growth and continuing poverty combine so that biomass fuels continue to dominate in the household sector until well past 2025. The overall effect is a slight decline in global household biomass use from 28 EJ in 1995 to 26 EJ in 2050. In fact, the plausibility of this scenario for Africa is questionable, since the future levels of consumption in the scenario may not be consistent with sustainable rates of extraction of biomass resources.

In the *Policy Reform* scenario, energy consumption is slightly lower than in the *Reference* scenario and is distributed differently between fuels. In particular, the scenario sees a more rapid decline in biomass consumption and a more rapid transition towards less carbon-intensive fuels and renewable energy than the *Reference* scenario. The regional distribution of consumption is also different, as illustrated in Figure 3-11. In the OECD regions, additional energy intensity improvements produce further reductions in consumption compared to the *Reference* scenario. In most non-OECD regions, energy consumption patterns are slightly lower due to two counteracting effects. First, higher levels of economic growth lead to greater convergence of energy intensities towards OECD values. However, these OECD intensities are lower in the *Policy Reform* scenario than in the *Reference* scenario. The exception is the FSU, where consumption declines are much greater — a result of the high initial energy intensities in the region.

Figure 3-11. Regional household energy demand

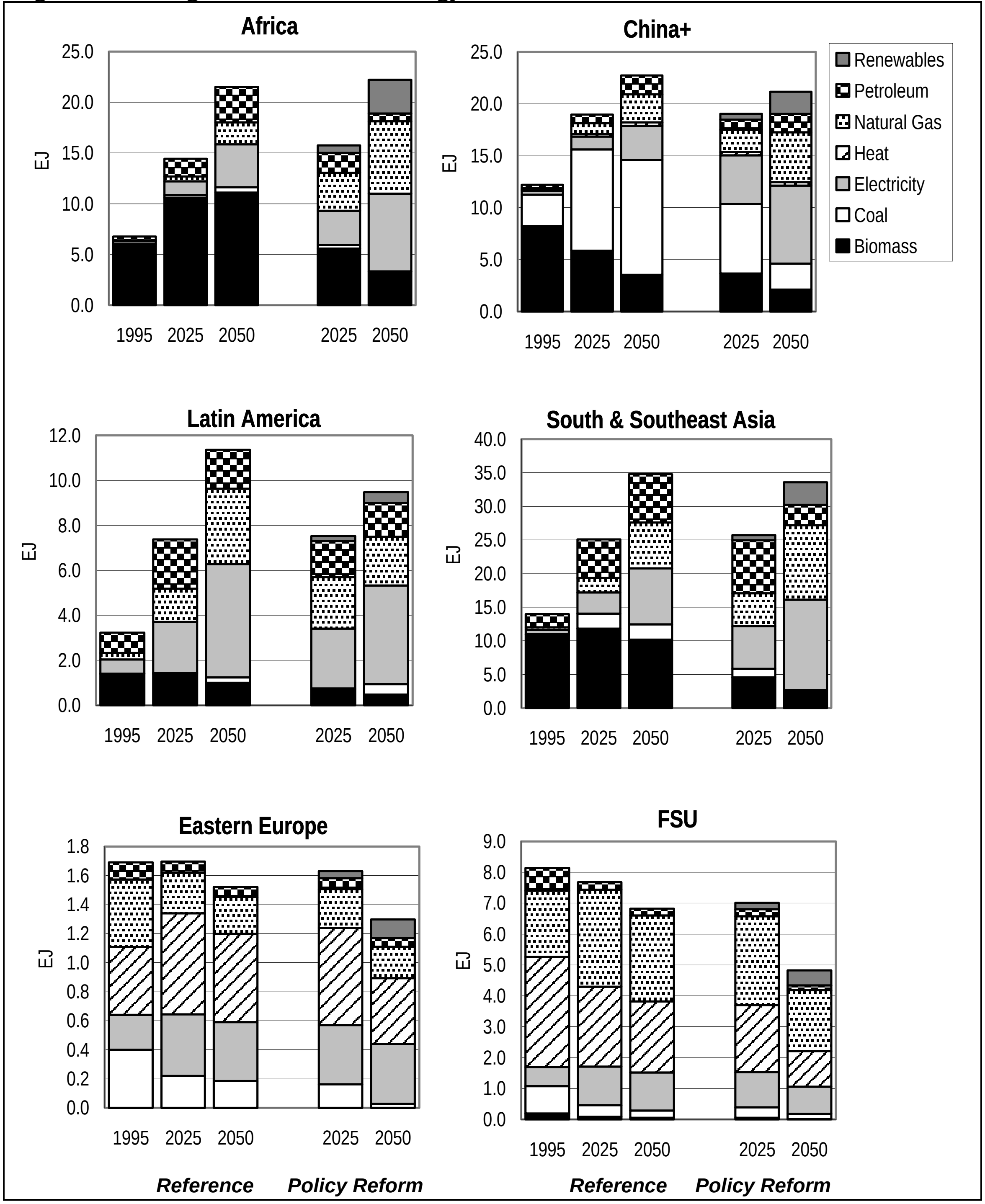
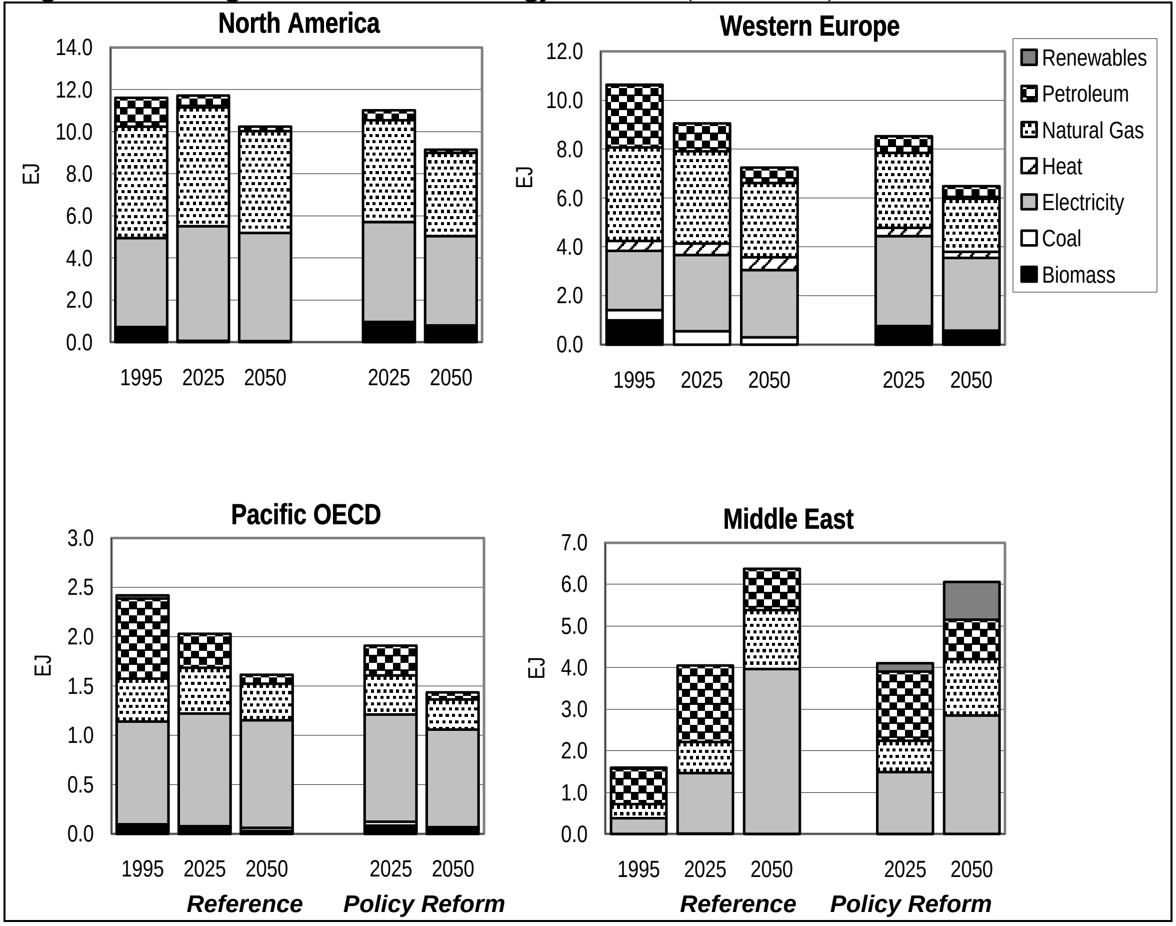


Figure 3-11: Regional household energy demand (continued)



3.2.3 Services

The service sector is broadly defined to include such economic activities as offices, retail, education, hospital and other non-industrial enterprises. Service sector energy use is largely related to building end-uses: lighting, HVAC (heating, ventilation, and air conditioning) and equipment. The assessment would benefit from subsectoral and end-use disaggregation, but the absence of reliable survey and statistical data makes this infeasible.

Current Accounts

Regional service sector energy consumption is reported in Table 3-3 (page 33). There is a striking difference between service energy use in industrialized and other regions. North America's per capita demand for energy in the service sector is more than twenty times that of the developing regions, reflecting both higher incomes, and a greater share of the service sector in overall economic activity as income increases (see Figure 3-12).

Figure 3-12. Service sector energy consumption per capita - 1995

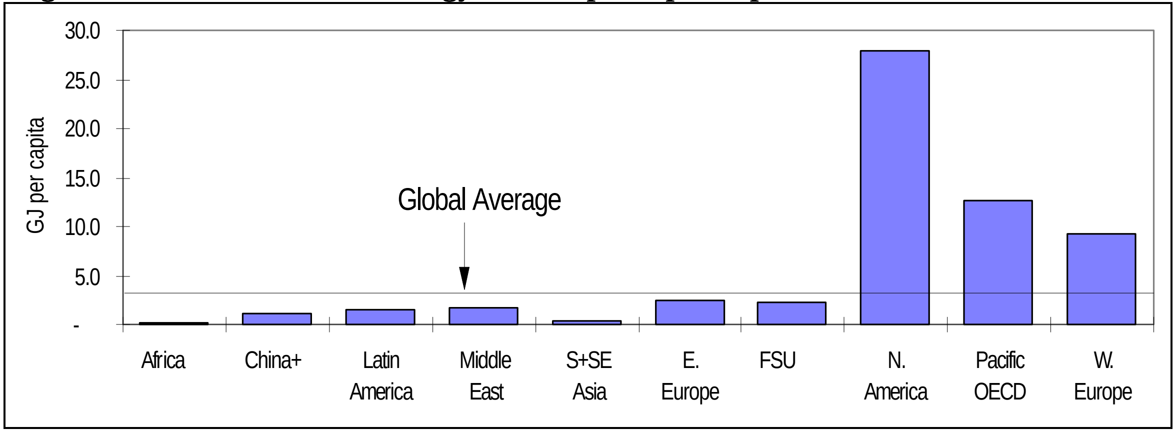
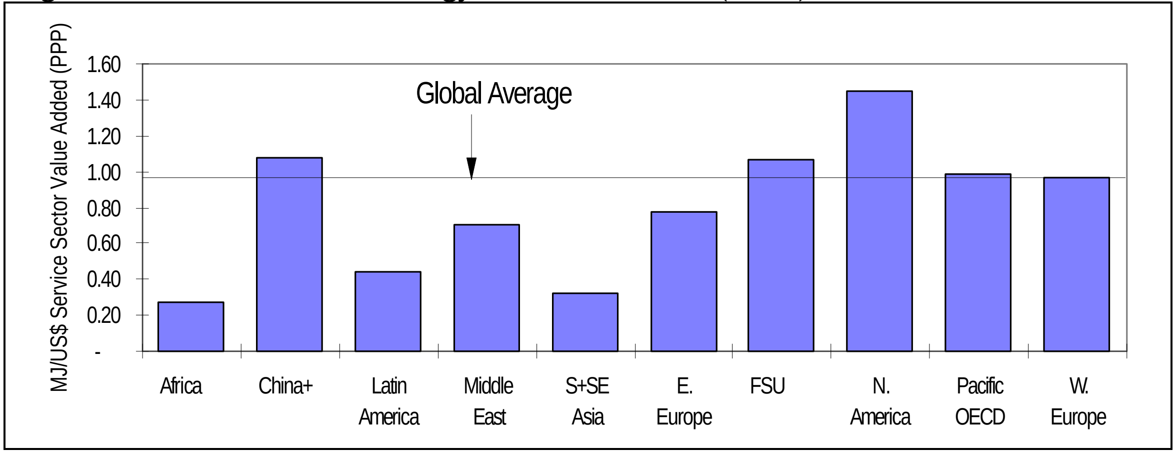


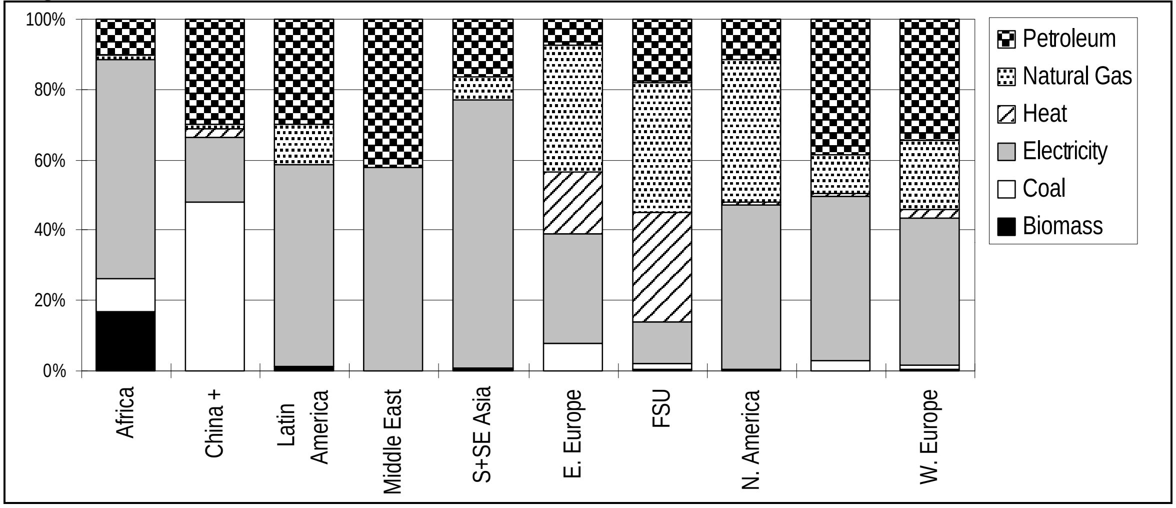
Figure 3-13 shows service sector energy consumption per dollar of service sector value added. Here there is much less variation between regions, although the OECD and transitional regions do reflect the more capital-intensive nature of services in those countries compared to the more labor-intensive service sector in developing countries. Amongst the developing economies, China's energy intensity appears anomalously high. This may reflect particular inefficiencies in energy use in China+ (which as Figure 3-14 shows, still relies heavily on coal), statistical inaccuracies, or problems in using aggregate value-added figures as the basis for energy intensities.

Figure 3-13. Service sector energy intensities - 1995 (MJ/$)



Current account fuel shares are shown in Figure 3-14. Electricity, petroleum, and natural gas are the dominant fuels accounting for more than 90% of global service sector energy consumption. Coal remains important in China+ — accounting, at least in part, for that region's high service sector energy intensity. Biomass remains important in the sector only in Africa. However, it is likely that the heavily biomass-reliant *informal sector,* the small and often unregistered enterprises in many developing regions, are not fully reflected in service sector energy statistics (O'Keefe et al., 1984). In some cases, this consumption may be included within household statistics. District heat is significant in Eastern Europe and the FSU countries and to a lesser extent in Western Europe. It remains largely undeveloped in North America and the rest of the world.

Figure 3-14. Service sector fuel shares - 1995



The current determinants of service sector energy use, and the variables which will condition future patterns, include the scale of service sector activity, the mix of activities at the subsectoral level, end-use energy efficiency, building and architectural standards, trends in office automation, and fuel availability and price. Detailed consideration of these factors is difficult because of an unusually sparse data base.

Scenarios

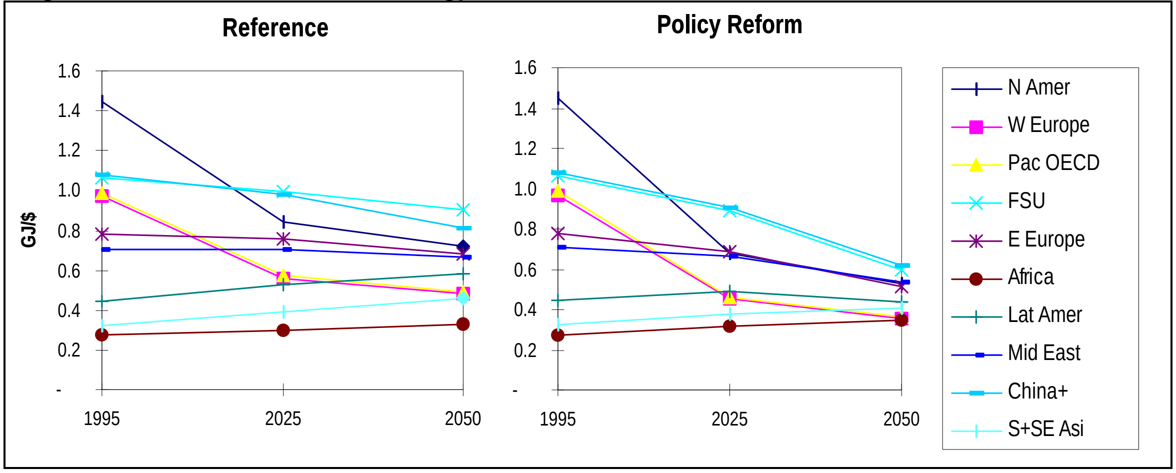
The service sector scenario analysis relies on three elements: measures of activity, energy intensity and final fuel mix. The activity measure is defined as service sector value added, the product of regional GDP and the sectoral share (Sheets E-1 and E-2 of the *BTC* Scenario Highlights). The energy intensity is expressed as the service sector final energy demand divided by value added for the sector. Service sector scenarios are developed in four steps:

1. First, energy intensity trends (GJ/$) are developed for the three OECD regions. Historically, service sector energy intensities have been declining in industrialized nations since 1973. In nine OECD countries, intensities declined by 27% over the period 1973 and 1988 (Schipper and Meyers, 1992). Declines in the energy intensity of space heating appears to be the major reason for these overall declines, as business switched from less efficient fuels and devices (e.g., fuel-oil systems) to natural gas and electricity. Additions of new buildings with lower heating requirements, retrofit improvements to existing building envelopes and improved energy management also contributed to the decline. Structural shifts between service sectors appear to have had relatively little effect (Schipper and Meyers, 1992). These improvements are expected to continue in the future even without new policy interventions, and this is reflected in the *Reference* scenario. Nevertheless, the adoption of cost-effective measures to reduce service sector energy use remains far below its economic potential. The *Policy Reform* scenario reflects concerted action to accelerate the decline in service sector energy intensities. Many of the policies and programs required to achieve this are common with those in the household sector, and are described in Section 3.2.2.

   Scenario intensities are guided by the findings of the U.S. *Energy Innovations* study (Energy Innovations, 1997). In the *Reference* scenario, OECD service sector energy intensities decline at a rate of 1.3% per year from a starting value of 1.2 GJ/$ in 1995 to 1.6 GJ/$ in 2050. In the *Policy Reform* scenario, they decline at a rate of 1.8% per year to 0.44 GJ/$ in 2050. Both scenarios require increasingly energy-efficient building shells, as well as improvements in areas such as space heating and cooling, water heating and commercial appliances. The *Policy Reform* scenario requires both more rapid and more widespread penetration of efficient technologies and, in later periods, the introduction of advanced technologies and building designs.

2. Second, intensities for non-OECD regions are introduced. In each scenario, these converge towards the average values of the OECD region as average incomes increase, using a convergence algorithm (see Annex). The overall pattern of convergence in the two scenarios is shown in Figure 3-15. In the *Policy Reform* scenario there is greater overall convergence to a lower average intensity, in accordance with the exogenous assumptions of improving equity and more rapid economic growth in the developing countries compared with the *Reference* scenario.

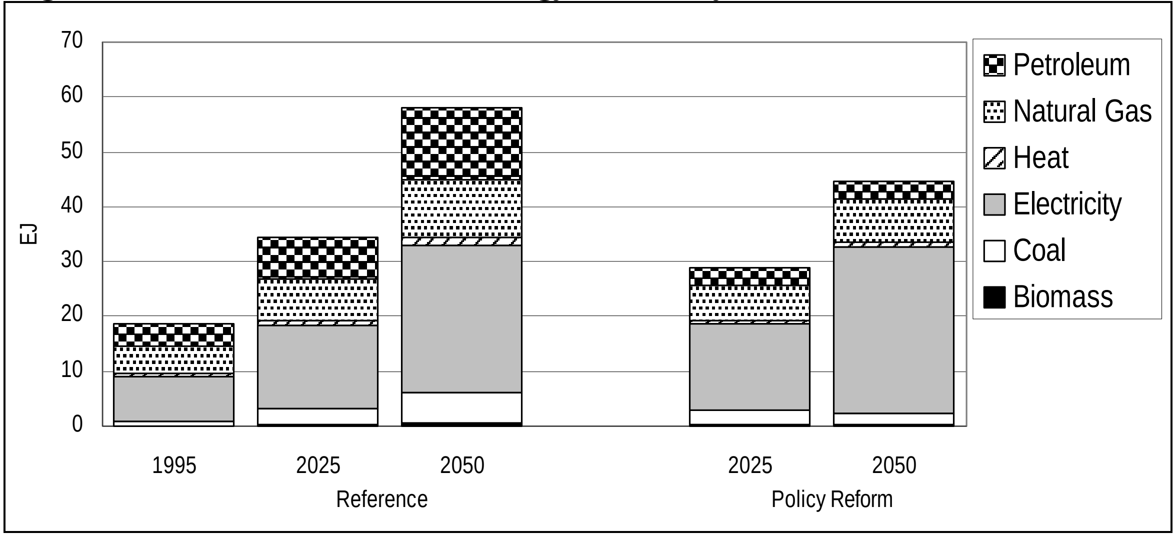
Figure 3-15. Service sector energy intensities



3. Third, fuel shares are introduced. In the *Reference* scenario, these are guided by the trends in the IPCC mid-range scenario (IPCC, 1992). Taking the *Reference* scenario trends as a starting point, the *Policy Reform* scenario assumes an accelerated transition towards lower-carbon fuels. Given the stringent CO_2 reduction targets of the *Policy Reform* scenario, by 2050 the service sector is dominated by electricity and, to a lesser extent, natural gas.

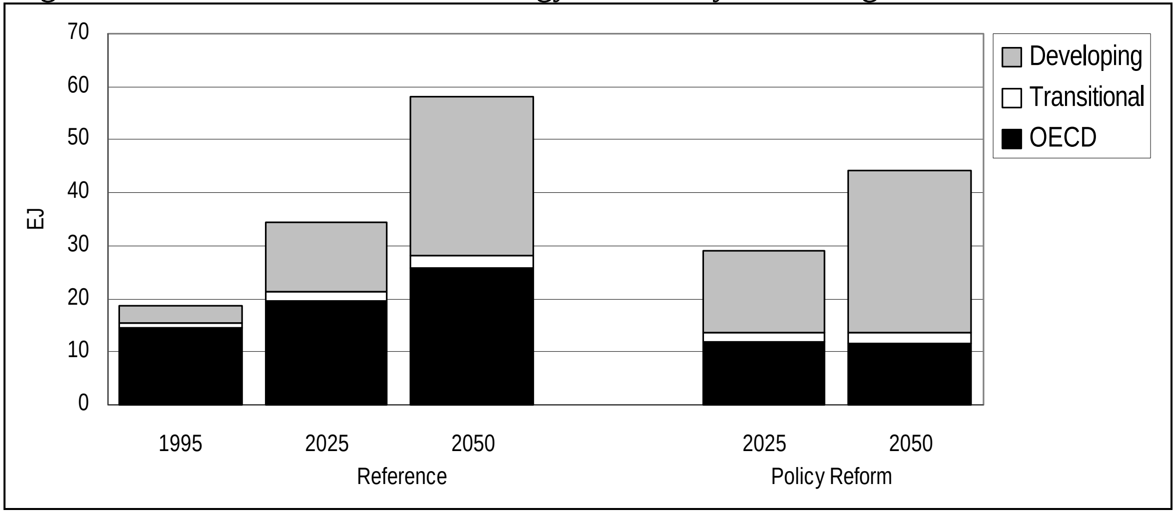
Multiplying service sector value added and the intensity figures we derive service sector energy demand. Service sector energy demand by fuel is shown in Figure 3-16. In both scenarios, the size of the global service sector (measured in PPP dollars of value added) increases by a factor of more than 5 from 1995 to 2050, increasing its share of total global GDP from 56% in 1995 to 67% in 2050.

Figure 3-16. Global service sector energy demand by fuel



Service sector energy demands are shown by macro-region in Figure 3-17. Energy requirements for the service sector grow rapidly in the *Reference* scenario, increasing globally by a factor of three over the scenario time-frame, and by factors of 8 to 14 in developing regions. The OECD region grows by a factor of 1.8 and the transitional region by a factor of 2.5 over the same time period. On a global basis, services rise from 7% of final energy demand to 9% by 2050. Increased energy efficiency results in lower growth in service sector energy demand in the *Policy Reform* scenario, which increases by a factor of 2.4 from 1995 to 2050. This growth is concentrated in the developing regions, where growth factors range from 6 to 16 over the period 1995 to 2050. OECD service sector consumption in 2050 declines to 80% of its 1995 value, while the transitional regions increase by a factor of 2.1.

Figure 3-17. Global service sector energy demand by macro-region



Service sector energy demands are shown by region in Figure 3-18. In most non-OECD regions, service sector energy consumption in 2050 is lower in the *Policy Reform* scenario than in the *Reference* scenario, as energy intensity improvements outweigh the effect of increased growth of the sector. The exceptions are Africa and South and Southeast Asia, where initially low energy intensities in the base year increase over time in the *Policy Reform* scenario, in spite of the fact that they are converging to more efficient OECD target values. This effect, when combined with rapid economic growth in those regions produces higher total energy consumption than in the *Reference* scenario.

Figure 3-18. Regional service sector energy demand

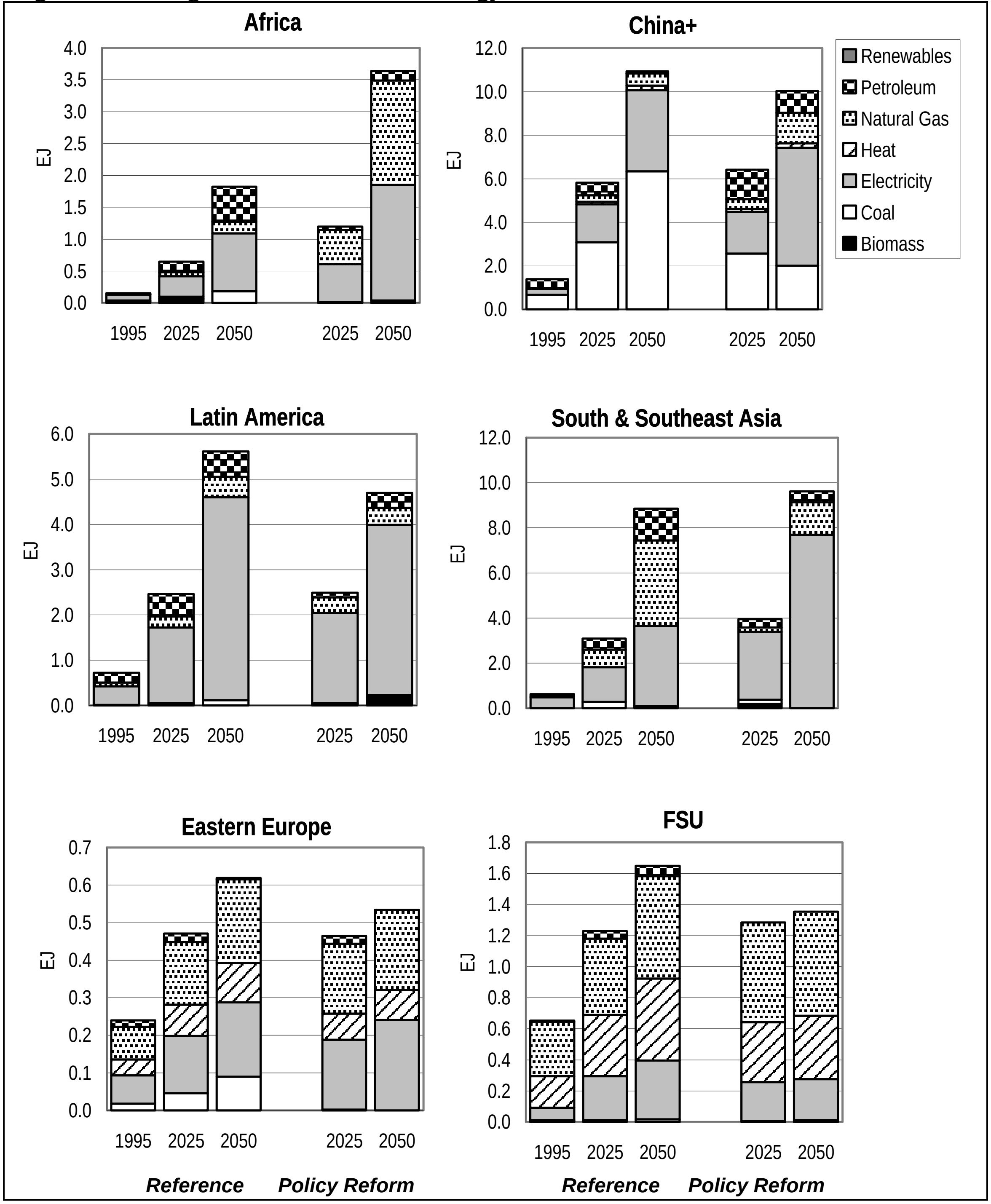
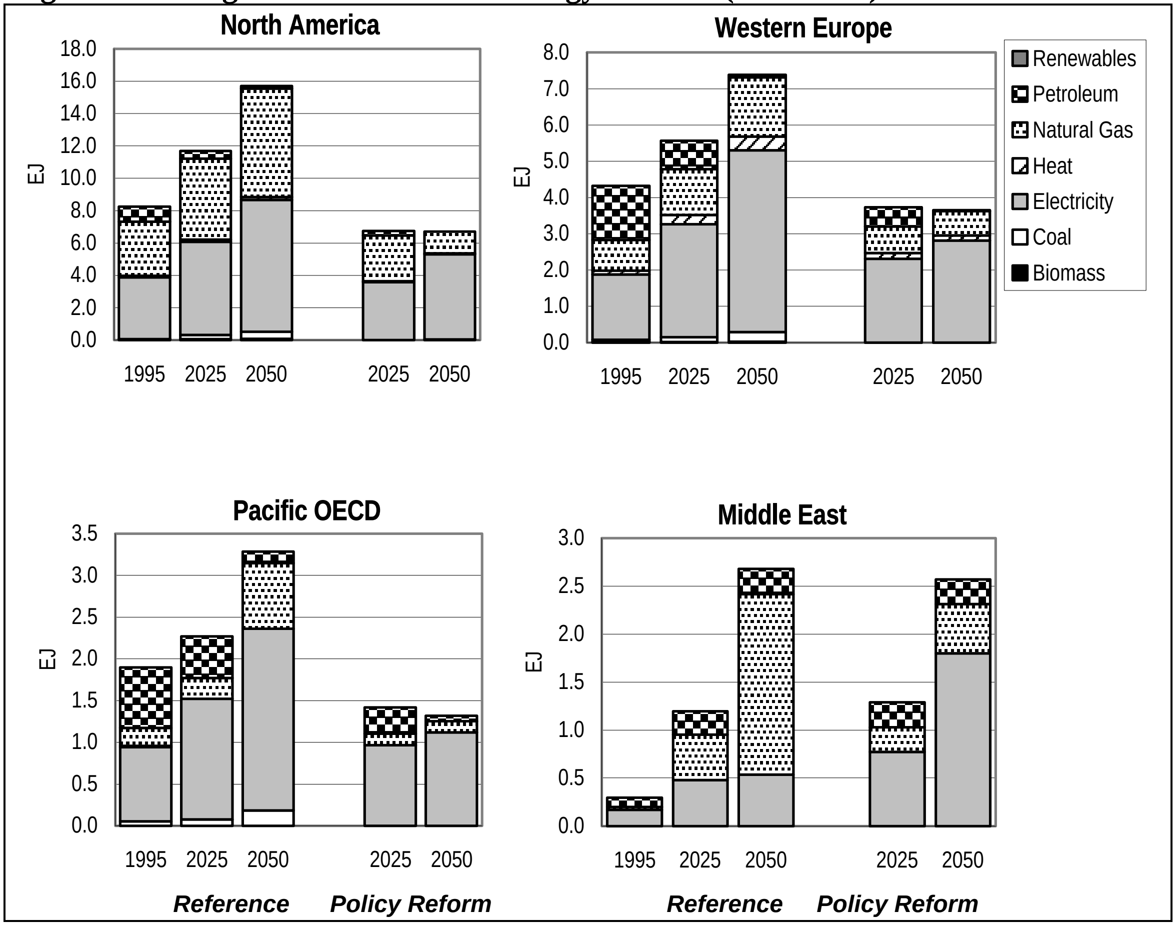


Figure 3-18. Regional service sector energy demand (continued)



3.2.4 Agriculture

The agriculture sector includes activities in farming, livestock and forestry systems. Agricultural energy consumption reflects the use of final fuels (especially, fossil fuels and electricity) consumed at the end-use, e.g., for field operations, irrigation, drying and so on. With this definition, energy used in the agricultural sector accounts for about 3% of world final energy consumption.

Current Accounts

Regional agricultural energy consumption is reported in Table 3-3 (page 33). Energy use in the agricultural sector is dominated by petroleum products, which account for 60% of global agricultural energy consumption (Figure 3-19). In fact, in six of the regions petroleum products account for more than 50% of agricultural energy demand. Energy use per dollar value added is reported in Figure 3-20. In general, energy intensities are much higher in the OECD and transitional countries where agriculture is far more mechanized. Other significant variations across regions may be related to underlying differences in agricultural practices such as irrigation levels and geophysical factors. However, variations may also be related to uncertainty in agriculture energy statistics and in accounting procedures. For example, it remains unclear (even with recent revisions to IEA databases) whether FSU agricultural statistics include energy consumed for food processing and transportation of agricultural products, or assign these to industry and transportation sectors, respectively, as is the practice in OECD regions. Failure to follow this practice may help to explain the unusually high intensities for agricultural energy use in the FSU. (Note, however, that FSU industrial energy intensities are also very high.)

Figure 3-19. Agriculture sector fuel shares - 1995

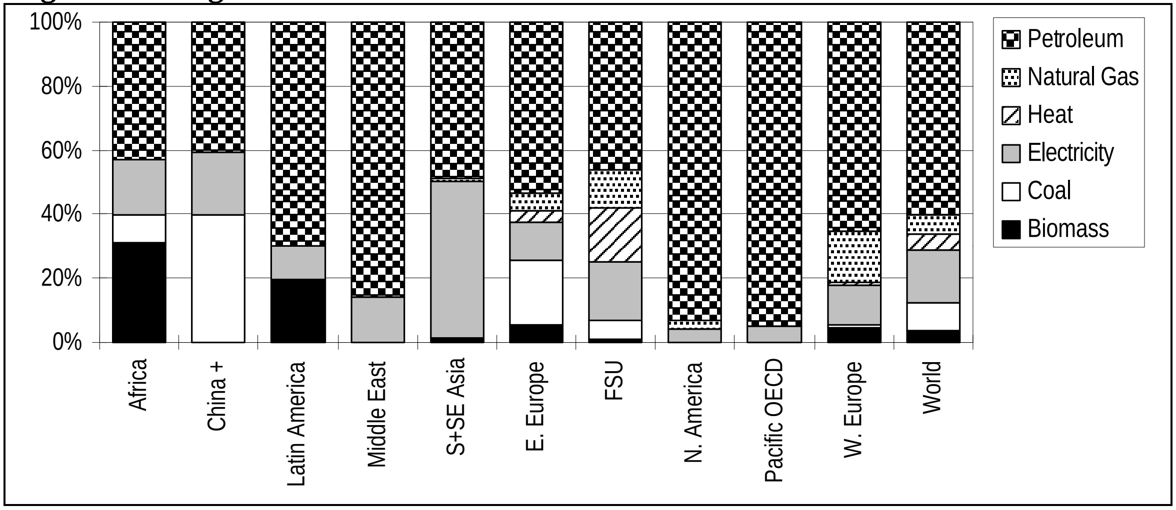
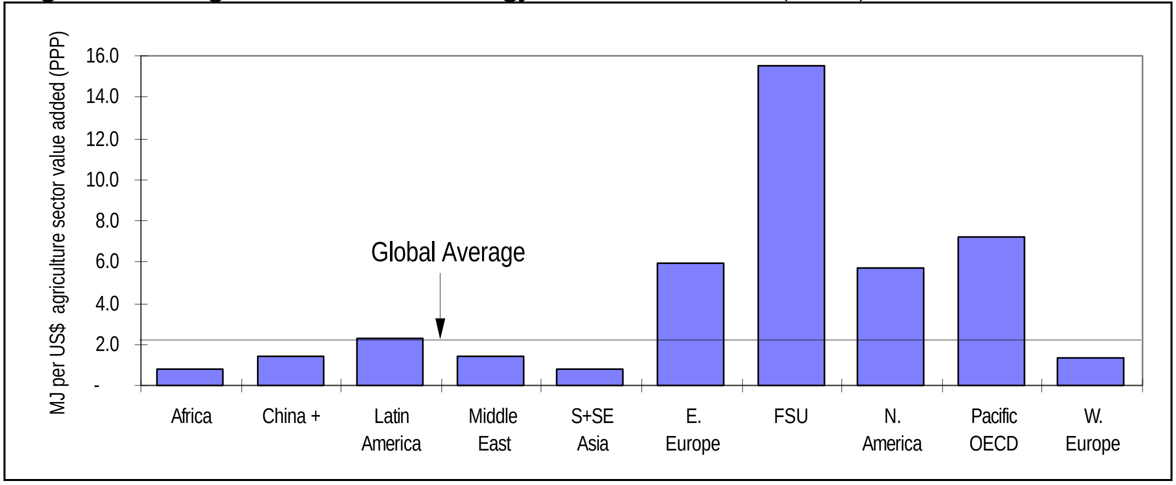


Figure 3-20. Agriculture sector energy intensities - 1995 (MJ/$)

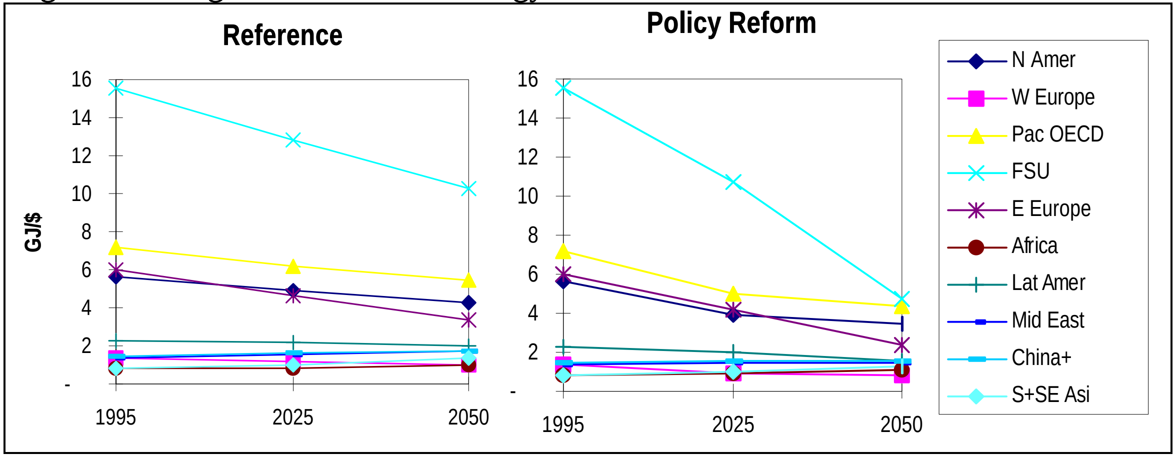


Scenarios

The Agricultural sector energy scenario is based on a three step-analysis of activity levels, energy intensities, and final fuel mix. The activity measure is defined as agricultural sector value added — the product of regional GDP and the sectoral share (see sheets E-1 and E-2 of the *BTC* Scenario Highlights. Energy intensity is expressed as the agricultural sector final energy demand divided by value added for the sector.

1. First, energy intensity trends (GJ/$) are developed for the three OECD regions. In the absence of more detailed studies of the trends in the agriculture sector, improvements in agricultural energy intensities are guided by our assumptions for the industrial sector (see section 3.2.5), with more modest rates of improvement assumed. In the *Reference* scenario, OECD agricultural sector energy intensities decline at a modest 0.5% per year from a starting value of 2.4 GJ/$ in 1995 to 1.9 GJ/$ in 2050. This is consistent with trends in OECD countries over the last few decades where the limited available data (e.g., WRI, 1992b, IEA, 1997b) suggest that agriculture energy intensities have been declining only very slowly. In the *Policy Reform* scenario, agricultural sector energy intensities decline at a more rapid 0.9% per year.
2. Second, for the non-OECD regions we apply the convergence algorithm (see Annex), assuming that agricultural practices and energy intensities approach OECD average figures as each region's GDP per capita approaches the OECD average GDP per capita in 1995. Agricultural sector energy intensities are summarized in Figure 3-21. Just as in the service and industrial sectors, the interpretation of intensity trends would be more transparent if they were expressed in physical units, e.g., energy consumption per unit of agricultural product. Then, in the transition to modern high-input agriculture, energy intensities would be driven by the interplay of two counterbalancing processes, increasing energy use per unit area and increasing product per unit area. But data inadequacies prevent conducting such an energy analysis. In relying on agriculture sector GDP, an additional variable and additional uncertainty is introduced — the relationship between physical product and the value added in the sector.

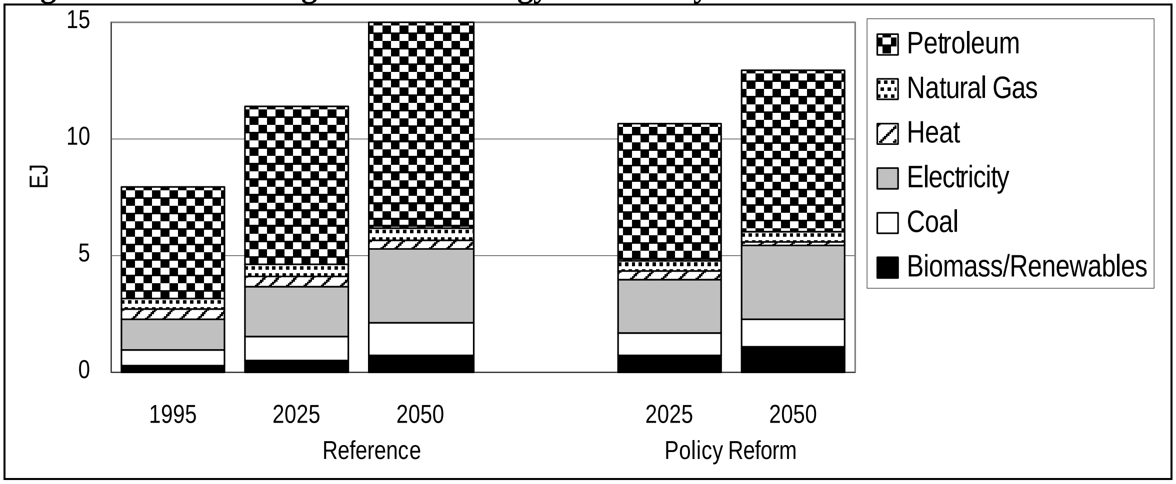
Figure 3-21. Agricultural sector energy intensities



3. Examining fuel share patterns over the time period 1970 to 1990 (IEA, 1997a, b) shows year-to-year fluctuation in the reported agriculture energy statistics, but no discernible regional trends. Thus for the *Reference* scenario, agricultural fuel shares are held constant. In the *Policy Reform* scenario, we again consider a transition to less carbon-intensive fuels, principally through greater penetration of electricity and natural gas for irrigation and other end-uses, as well as limited penetration of biomass and renewable energy for use in such applications as space heating and drying of agricultural commodities. Nevertheless, oil remains the dominant fuel in all regions in the *Policy Reform* scenario, due to the importance of motive power in the agricultural sector.

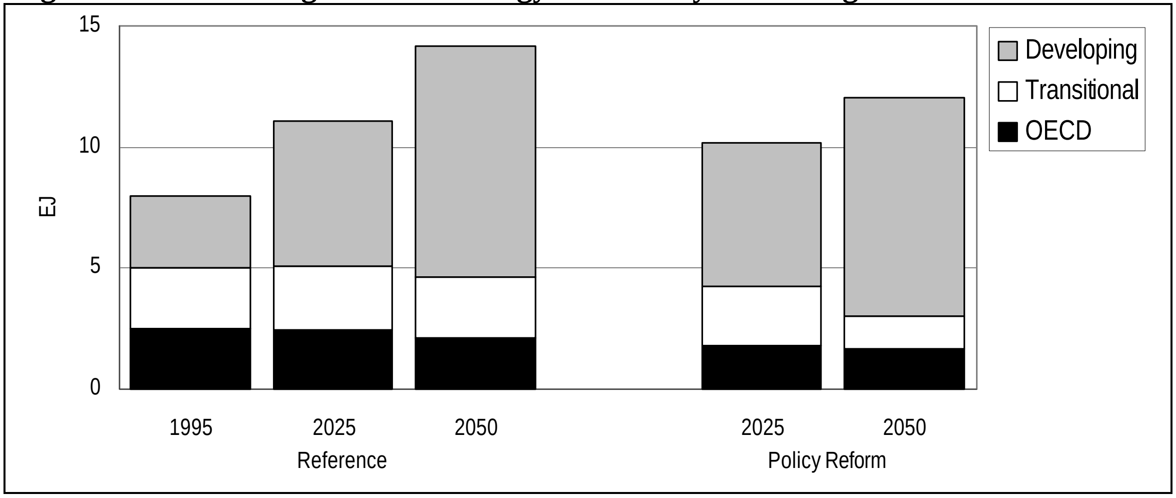
Agriculture energy demand by fuel is shown in Figure 3-24. In the *Reference* scenario, total demand increases from 8 EJ in 1995 to 14.2 EJ by 2050. This growth is slowed overall in the *Policy Reform* scenario, reaching 12.1 EJ in 2050. Demand remains dominated by petroleum fuels in both scenarios, reflecting the importance of motive power and the internal combustion engine in meeting the sector's energy demands. While a small part of the global total, the importance of coal in the sector actually increases in both scenarios, due to the large growth of agriculture in developing regions, and the importance of coal use in China (see Figure 3-24), not to a general pattern of switching to coal in other regions.

Figure 3-22. Global agricultural energy demand by fuel



Agricultural sector energy demands are shown by macro-region in Figure 3-23. Compared to the *Reference* scenario, an increased proportion of the growth in the *Policy Reform* scenario comes from the developing regions. In the OECD regions, demand declines in both scenarios from 2.5 EJ in 1995 to 2.1 EJ in 2050 in the *Reference* scenario and to 1.7 EJ in the *Policy Reform* scenario. In the transitional regions, demand remains almost constant in the *Reference* scenario at 2.5 EJ, but declines dramatically in the *Policy Reform* scenario to 1.3 EJ in 2050, reflecting the large differences in convergence between the two scenarios and the relatively high initial energy intensities in the FSU. In the developing regions, demand more than triples in both scenarios from 3.0 EJ in 1995 to 9.5 EJ in 2050 in the *Reference* scenario, and to 9.1 EJ in 2050 in the *Policy Reform* scenario.

Figure 3-23. Global agricultural energy demand by macro-region



Agricultural sector energy demands are shown by region in Figure 3-24. In most non-OECD regions, agricultural energy consumption in 2050 is lower in the *Policy Reform* scenario than in the *Reference* scenario, as energy intensity improvements outweigh the effect of increased growth in the sector. The exception is Africa where energy intensities do not change dramatically in the *Policy Reform* scenario, but rapid growth in agriculture in the region produces much higher total energy consumption than in the *Reference* scenario. Also notable is the FSU, where roughly energy consumption declines dramatically in the *Policy Reform* scenario, but remains roughly constant in the *Reference* scenario. These trends reflect the high base year energy intensities in the region, and the increased level of convergence in the *Policy Reform* scenario compared to the *Reference* scenario.

Figure 3-24. Regional agricultural energy demand

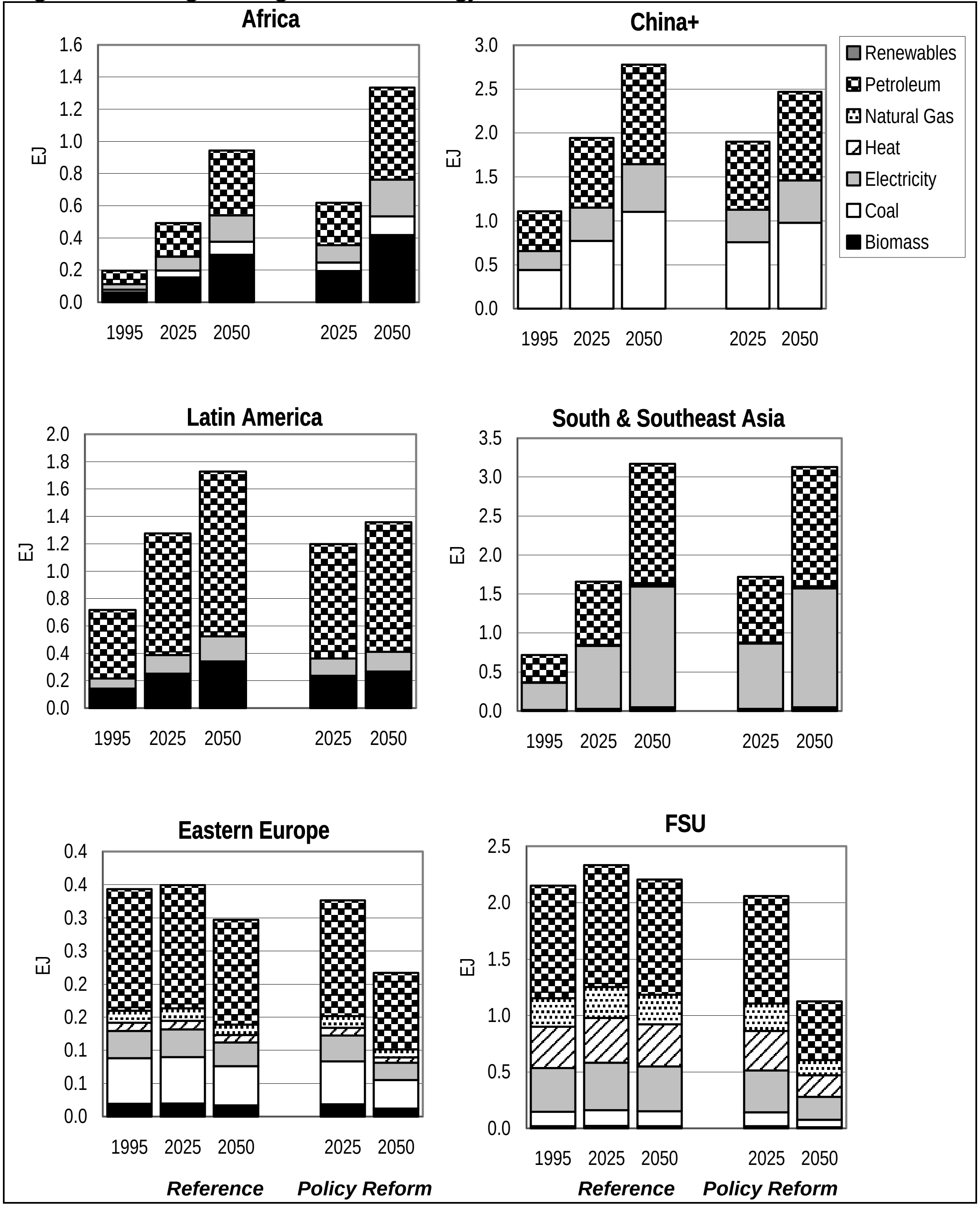
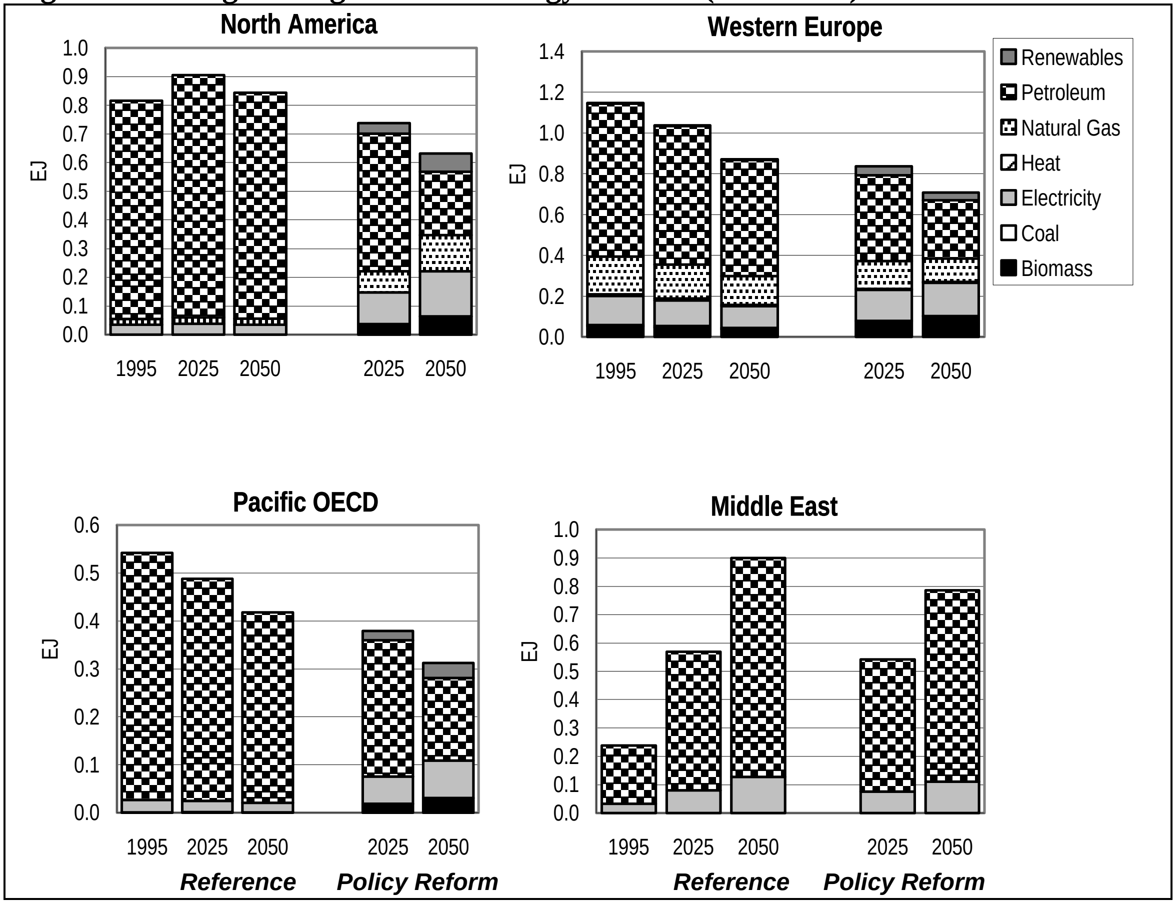


Figure 3-24. Regional agricultural energy demand (continued)

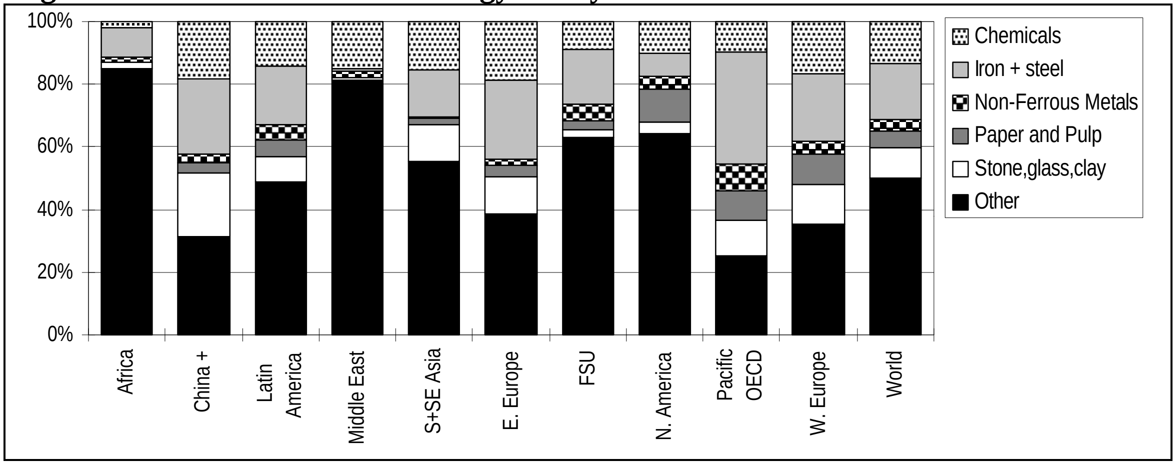


3.2.5 Industry

Current Accounts

Regional industrial energy consumption is reported in Table 3-3 (page 33). The industrial sector accounts for almost 40% of global final energy consumption[17]. The sector is dominated by five subsectors: chemicals; paper and pulp; stone, glass and clay; non-ferrous metals; and iron and steel. The global and regional breakdown of consumption by sector is provided in Figure 3-25. The five highly energy-intensive industries account for about 50% of global industrial energy use and from 15% to 71% across regions. Future industrial requirements will be strongly influenced by projected output and energy intensities in these subsectors although the relative importance of smaller sectors (included in the "other" category) is expected to increase due to saturation in the consumption of the types of raw materials produced by heavy industries.

Figure 3-25. Industrial sector energy use by sector - 1995

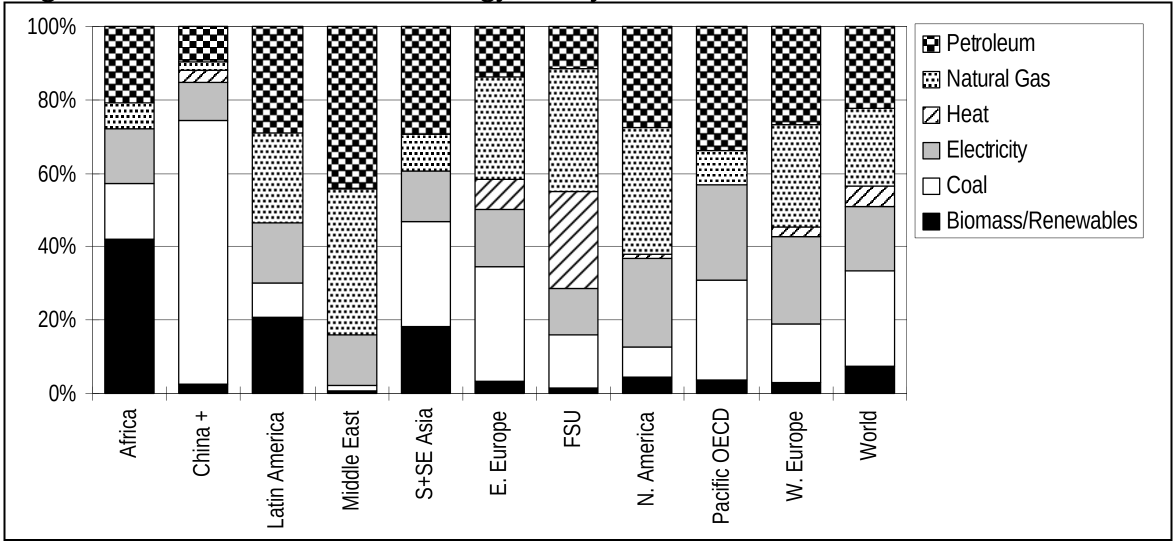


Turning to the fuel composition of industrial demand, global industrial energy demand is dominated by fossil fuels (70%) and electricity (17%), with significant variation across regions in fossil fuel choice (Figure 3-26). Industries tend to rely on domestically available and relatively inexpensive fuels. For example, in China+, coal is the dominant industrial fuel, accounting for more than 70% of industrial fuel use, while in the Middle East, oil and natural gas together account for 85% of industrial fuel use. Industrial energy use is driven largely by the requirements for process heat (although electricity for motors is also substantial).

---

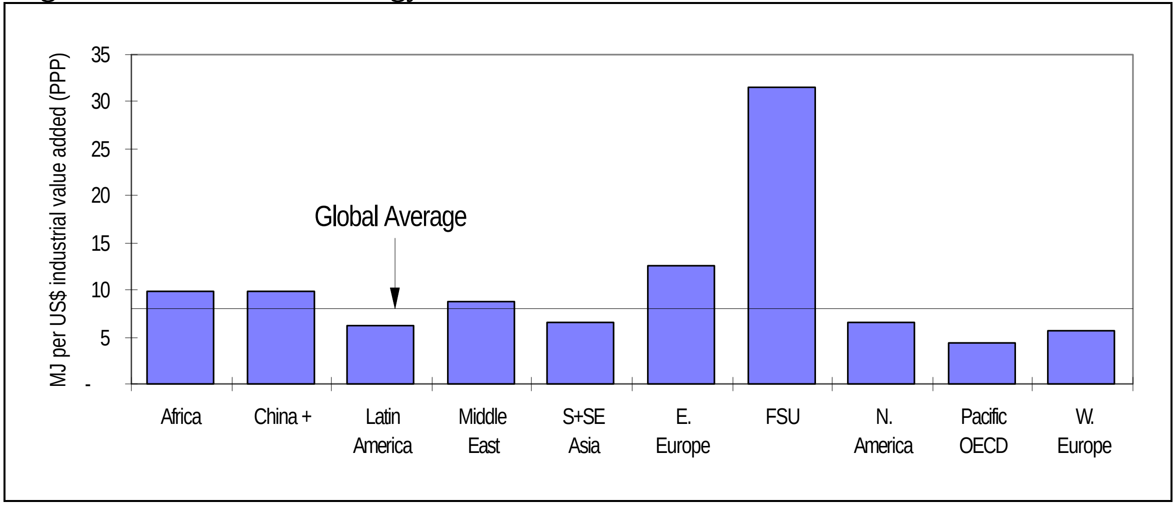
[17] Total world industrial fuel consumption (103.8 EJ in 1995) includes approximately 12.2 EJ of mainly petroleum products consumed as feedstocks in chemical processes and a further 4.2 EJ also of mainly petroleum products consumed for non-energy purposes (e.g., oil for lubricants).

Figure 3-26. Industrial sector energy use by fuel - 1995



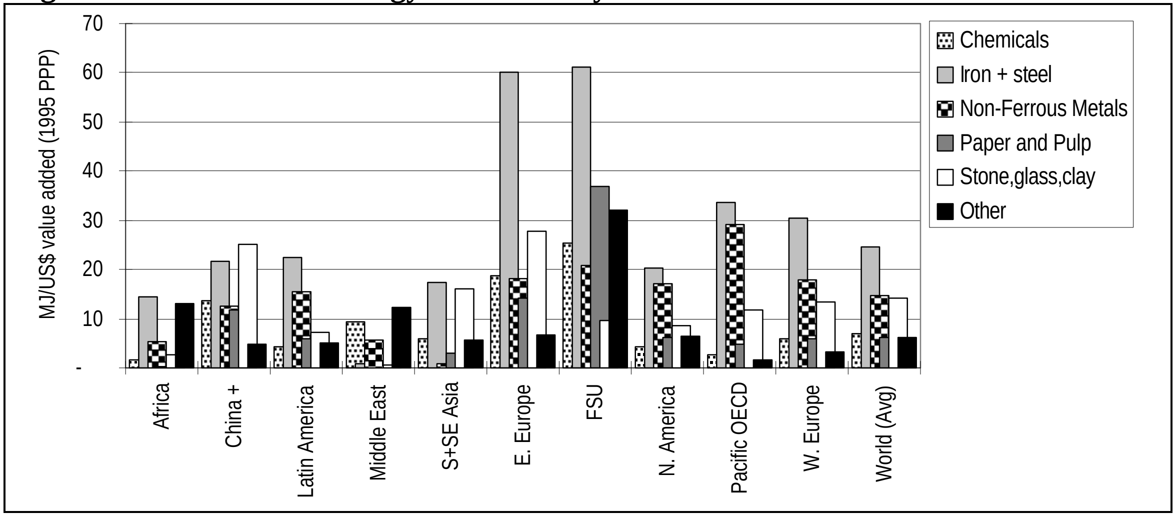
Industrial energy intensities, defined as industrial energy use divided by value added in the industrial sector are shown in Figure 3-27. These provide only a crude measure of the efficiency of converting a unit of energy input to a unit of economic output. Ideally, it would be desirable to examine industrial energy intensities in physical units of output (e.g., tonnes of steel) rather than in monetary terms since this more closely reflects the actual activities that consume energy. However, lack of data on physical outputs for the myriad products comprising an industrial sector rules this out for comprehensive representation of current energy demands. It should also be noted that additional uncertainty is introduced in cross-regional comparisons where exchange rates (even those adjusted for purchasing power parity) are needed to express national economic statistics in common units.

Figure 3-27. Industrial energy intensities - 1995



These problems notwithstanding, the high values for FSU and Eastern Europe are worth noting, though difficult to interpret. In principle, gross industrial energy intensities depend on three major factors: type of process technology, energy management and the mix of industrial activities. To shed some light on the latter, we display intensities for each major subsector in Figure 3-28, which shows that the variation in intensity for a given industrial subsector varies across regions in roughly the same manner as does industry as a whole. Consequently, it appears that process technology and management are the primary determinants of regional industrial energy intensities today. Moreover, the analysis suggests that policies to steer regions toward state-of-the-art practices could significantly decrease the energy needed per unit of industrial activity.

Figure 3-28. Industrial energy intensities by subsector - 1995



Scenarios

As with the other sectors, industrial sector scenario energy patterns are defined by future activity levels, trends in energy intensities and fuel shares. Activity levels are expressed in terms of overall value added in industry and further by the shares among the industrial subsectors.

1. Value added as a whole for industry is based on GDP and industrial share assumptions (see Sheets E-1 and E-2 of the *BTC* Scenario Highlights). Because of the different energy intensities of each subsector, we further disaggregate the analysis into five energy-intensive subsectors: iron and steel, non-ferrous metals, non-metallic minerals, paper and pulp, and chemicals. Base year shares are calculated from 3 digit ISIC subsector value added statistics (UNIDO, 1997). There are indications that in OECD countries, historical growth rates of material consumption have leveled off over recent decades (Williams et al., 1987; Bernardini and Galli, 1993). In both scenarios, we capture this saturation effect in characterizing the structure of industrial activity in our scenarios. Continuing recent patterns, we assume that value added per capita for iron and steel, and non-metallic minerals decrease by ten percent over the 1995-2050 period, and that value added per capita for non-ferrous metals, paper and pulp, and chemicals remain constant. Since industrial activity increases sector-wide more rapidly than population, these assumptions imply that expansion of industrial

sector activity in OECD regions is predominantly in the less material and energy-intensive “other” category.

2. Second, for the non-OECD regions, we apply the convergence algorithm (see Annex) to develop industrial activity assumptions for each energy-intensive subsector. Specifically, the value added per capita in a given subsector approaches the projected OECD average value added per capita as a region’s total GDP per capita approaches the 1995 OECD average GDP per capita. The value added per capita in the “other” industrial subsector is calculated as a remainder. The results are displayed in Table 3-3 and Table 3-4 for dollars value added per capita, and in Table 3-5 and Table 3-6 for total dollars value added.

Table 3-3. Industrial value added per capita in the *Reference* scenario ($/capita)

Reference	Chemical		Iron +Steel		Non-Ferr Metals		Paper + Pulp		Stone, Glass, Clay		Other	
	1995	2050	1995	2050	1995	2050	1995	2050	1995	2050	1995	2050
N. America	1,160	1,160	173	157	110	110	819	819	185	168	4,738	13,387
Pacific OECD	1,232	1,232	367	333	97	97	664	664	332	301	5,031	15,867
W Europe	712	712	177	161	56	56	428	428	233	212	2,787	8,688
E Europe	282	721	120	164	31	64	73	422	120	179	1,626	2,870
FSU	173	479	138	158	127	110	38	261	114	152	959	2,228
Africa	63	203	32	56	14	25	39	129	36	63	323	896
China+	178	643	145	170	30	61	38	380	106	168	845	2,968
Latin America	396	846	98	168	38	73	105	509	131	193	1,153	2,647
Middle East	267	630	250	217	57	70	62	350	200	205	1,131	2,527
S+SE Asia	153	515	51	112	15	45	42	297	42	118	577	2,031

Table 3-4. Industrial value added per capita in the *Policy Reform* scenario ($/capita)

Policy	Chemical		Iron +Steel		Non-Ferr Metals		Paper + Pulp		Stone, Glass, Clay		Other	
Reform	1995	2050	1995	2050	1995	2050	1995	2050	1995	2050	1995	2050
E Europe	282	834	120	174	31	73	73	512	120	193	1,626	2,895
FSU	173	607	138	166	127	102	38	355	114	168	959	2,557
Africa	63	392	32	89	14	39	39	249	36	100	323	1,565
China+	178	753	145	175	30	68	38	460	106	182	845	3,057
Latin America	396	939	98	182	38	81	105	594	131	205	1,153	2,737
Middle East	267	743	250	206	57	75	62	440	200	207	1,131	2,728
S+SE Asia	153	633	51	132	15	55	42	381	42	142	577	2,352

Note: OECD countries not shown since values are the same in both scenarios.

Table 3-5. Total Industrial value added in the *Reference* scenario ($)

Billion $_{PPP}$	Chemical		Iron + steel		Non-ferrous metals		Paper + Pulp		Stone, Glass, Clay		Other		Total	
	1995	2050-Ref	1995	2050-Ref	1995	2050-Ref	1995	2050-Ref	1995	2050-Ref	1995	2050-Ref	1995	2050-Ref
N America	344	444	51	61	32	43	243	316	56	67	1,407	5,149	2,132	6,079
Pac OECD	184	180	54	48	15	13	99	97	49	43	749	2,311	1,151	2,693
W Europe	332	331	82	77	27	24	199	201	109	101	1,300	4,063	2,049	4,796
E Europe	28	66	12	15	3	6	7	38	12	16	161	263	223	404
FSU	50	139	40	46	37	32	11	76	33	44	281	650	454	988
Africa	46	416	23	115	10	51	28	264	26	129	233	1,836	366	2,811
China+	237	1,101	193	292	39	105	50	644	141	285	1,124	5,063	1,784	7,489
Latin America	188	688	47	137	18	61	50	414	62	158	549	2,143	915	3,602
Middle East	48	314	45	108	10	36	11	176	35	102	202	1,263	351	1,999
S+SE Asia	257	1,507	86	329	25	137	69	867	71	347	967	5,944	1,475	9,131
OECD	860	955	187	186	74	80	541	615	214	211	3,456	11,523	5,331	13,569
Transitional	78	205	52	61	40	38	19	115	45	61	442	913	677	1,393
Developing	776	4,025	393	981	103	390	209	2,366	335	1,021	3,075	16,248	4,891	25,031
World	1,714	5,186	632	1,228	217	507	769	3,095	594	1,293	6,973	28,684	10,899	39,993

Table 3-6. Total Industrial value added in the *Policy Reform* scenario ($)

Billion $_{PPP}$	Chemical		Iron + steel		Non-ferrous metals		Paper + Pulp		Stone, Glass, Clay		Other		Total	
		2050-PR		2050-PR		2050-PR		2050-PR		2050-PR		2050-PR		2050-PR
N America	344	447	51	61	32	43	243	315	56	64	1,407	2,648	2,132	3,579
Pac OECD	184	179	54	48	15	14	99	96	49	43	749	1,340	1,151	1,721
W Europe	332	332	82	76	27	27	199	199	109	100	1,300	2,590	2,049	3,325
E Europe	28	73	12	15	3	7	7	44	12	17	161	252	223	408
FSU	50	168	40	46	37	28	11	98	33	46	281	706	454	1,093
Africa	46	762	23	175	10	76	28	483	26	194	233	3,042	366	4,730
China+	237	1,217	193	281	39	114	50	746	141	297	1,124	4,952	1,784	7,607
Latin Americ	188	721	47	138	18	62	50	455	62	157	549	2,105	915	3,637
Middle East	48	353	45	98	10	36	11	209	35	98	202	1,295	351	2,089
S+SE Asia	257	1,756	86	370	25	154	69	1,058	71	390	967	6,530	1,475	10,257
OECD	860	959	187	186	74	83	541	611	214	207	3,456	6,578	5,331	8,624
Transitional	78	241	52	61	40	35	19	143	45	63	442	959	677	1,501
Developing	776	4,808	393	1,063	103	441	209	2,950	335	1,136	3,075	17,924	4,891	28,321
World	1,714	6,008	632	1,309	217	560	769	3,703	594	1,405	6,973	25,461	10,899	38,447

3. Next, OECD industrial energy intensities are developed, expressed in GJ/$ value added at the industrial subsectoral level. Future energy intensities for each industrial subsector depend on changes in process efficiencies and the product mix. Historically, energy intensities have been declining steadily in the industrial sectors of OECD countries. Aggregate manufacturing intensities (measured across all industrial subsectors) decreased by an average of 40% between 1973 and 1988 across eight OECD countries. Approximately three quarters of this decline was due to improvements in the energy efficiency of industrial processes, while the remaining quarter was due to structural shifts to less energy-intensive subsectors and to the production of less energy-intensive products (Schipper and Meyers, 1992). This latter effect reflects a process of dematerialization, in which less physical material is required to deliver a given function, an example of which is the increasing miniaturization of semiconductors and related products (Ross et al., 1993) Declining intensities in industrialized nations were spurred in part by the high fuel prices seen during the oil crises of the 1970s. Increased competition between national industries also appears to have spurred intensity improvements as a means of reducing costs (IEA, 1997c).

These improvements are expected to continue in the future even without new policy interventions (although at a slower rate than in the past). In the *Reference* scenario, subsectoral energy intensity assumptions are again guided by the findings of the *Energy Innovations* study (Energy Innovations, 1997). They decrease by an average rate of 0.8% per year over the scenario period. The overall effect is that, by 2025, OECD intensities have dropped to 80% of their 1995 values, while by 2050, they have dropped to 64% of their 1995 values.

Beyond these declines, the adoption of cost-effective measures to reduce industrial energy use remains far below its economic potential. Estimating the magnitude of potential savings is difficult, because of the heterogeneity of technologies, processes and products, even within a particular subsector. Nevertheless, it is clear that significant cost-effective savings are available even in modern, efficiently-run industries (Elliot, 1994). Some generic areas in which energy can be saved include the increased adoption of efficient combined heat and power systems, retrofitting of efficient lighting and motors, improved maintenance of boilers, the “right-sizing” of compressed air and process heat delivery systems, and increased use of recycled feedstocks. In the longer term, capital turnover is capable of bringing even more dramatic reductions in energy intensities, as older, more energy-intensive processes are replaced completely. For example, in the iron and steel sector, blast furnaces fired with coke could be replaced with electric arc furnaces.

Overcoming market barriers will be key to achieving large reductions in industrial energy intensities. In part this will require changing the structure of energy prices to better reflect their full social and environmental costs. It will also require a broad package of policies such as incentives for investment in new energy efficient equipment; increased funding of research, development, demonstration and education programs; changing tax structures to eliminate subsidies for the use of virgin materials; and changing environmental regulations and electric market structures to expedite the adoption of industrial combined heat and power.

The *Policy Reform* scenario reflects this type of concerted action. With assumptions again guided by the findings of the *Energy Innovations* study (Energy Innovations, 1997), energy intensities decrease by an average annual rate of 1.7% per year, reaching 60% of their 1995 values by 2025 and 40% by 2050.

4. In the non-OECD regions, we apply the convergence algorithm (see Annex), assuming subsectoral energy intensities approach the projected OECD average energy intensity as GDP per capita approaches the current OECD average GDP per capita. This treatment captures technological leapfrogging to some extent since developing regions, rather than recapitulating OECD patterns, approach intensities which reflect the better practices assumed for OECD regions in the future. Scenario intensity assumptions are collected in Table 3-7.

Table 3-7. Industrial energy intensities (GJ/$ value added)

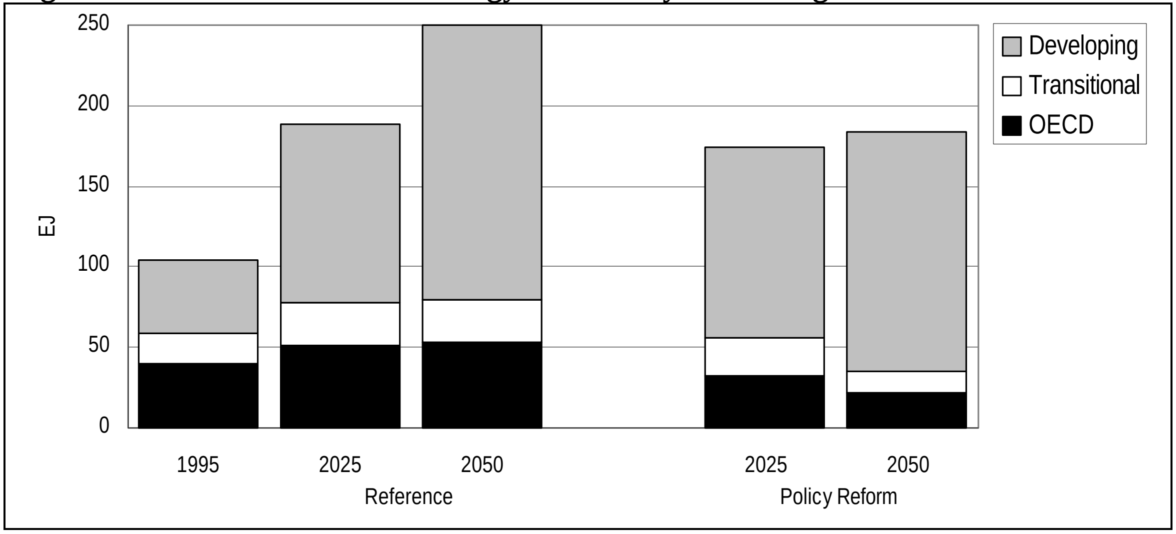
	Chemical			Iron + Steel			Non-Ferr Metals		
	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR
N America	4.2	2.7	1.6	20.2	13.0	7.9	17.0	10.9	6.6
W Europe	5.9	3.8	2.3	30.4	19.5	11.8	17.8	11.4	6.9
Pacific OECD	2.7	1.7	1.0	33.7	21.7	13.1	29.1	18.7	11.3
FSU	25.4	16.7	7.2	61.2	45.0	23.0	20.9	18.1	11.1
E Europe	18.8	8.6	3.8	60.1	33.5	17.5	18.1	15.0	9.6
Africa	1.7	1.9	1.8	14.5	15.3	13.8	5.5	6.7	6.7
Latin America	4.2	3.2	1.9	22.5	19.3	11.4	15.6	13.5	8.0
Middle East	9.5	6.1	4.3	0.8	10.3	8.5	5.7	9.7	7.6
China+	13.6	7.3	5.0	21.6	20.0	14.4	12.6	13.0	9.5
S+SE Asia	5.8	4.6	3.5	17.3	18.0	14.2	0.7	6.4	5.4

	Paper + Pulp			Stone, Glass + Clay			Other		
	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR
N America	6.3	4.0	2.4	8.5	5.5	3.3	6.4	4.1	2.5
W Europe	5.9	3.8	2.3	13.4	8.6	5.2	3.2	2.1	1.2
Pacific OECD	4.9	3.1	1.9	11.8	7.6	4.6	1.7	1.1	0.7
FSU	36.8	24.1	10.3	9.7	9.1	6.0	32.1	20.7	8.7
E Europe	14.2	7.6	3.9	27.7	14.9	7.6	6.8	4.3	2.4
Africa	0.2	0.8	1.1	2.5	3.4	3.5	13.1	11.5	9.0
Latin America	5.8	4.3	2.5	7.3	7.6	4.7	5.0	3.3	1.8
Middle East	0.1	2.2	1.8	0.6	4.4	3.6	12.3	7.4	5.1
China+	11.7	7.1	4.9	25.2	14.9	10.3	4.8	3.7	2.6
S+SE Asia	2.8	3.4	2.7	16.0	12.3	9.5	5.5	4.4	3.4

5. Finally, we complete the characterization of industrial energy use by adjusting the current mix of fuel shares. In the *Reference* scenario, the current mix is adjusted over time, again guided by the aggregate regional demand analysis in the IPCC (1992) mid-range scenario. In most regions, fuel shares are assumed to remain largely unchanged. In the *Policy Reform* scenario, we again consider a transition to less carbon-intensive fuels, principally through greater penetration of electricity and natural gas at the expense of coal and petroleum products. Increased use of renewables and modern biomass fuels is also assumed, particularly in the paper and pulp sector.

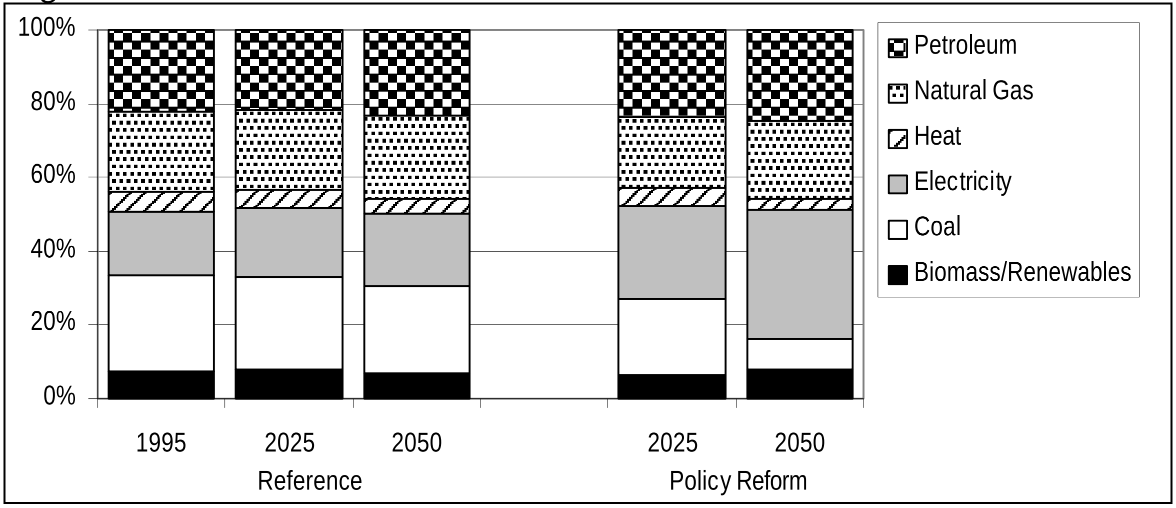
Global industrial sector energy consumption patterns are summarized by macro-region in Figure 3-30. Global industrial energy demand increases from approximately 104 EJ in 1995 to 250 EJ by 2050 in the *Reference* scenario, and to 185 EJ in 2050 in the *Policy Reform* scenario. Energy intensity improvements reduce overall growth in industrial energy demand between the *Reference* and *Policy Reform* scenarios. As in other sectors, the developing regions account for most of the growth in demand in the *Reference* scenario due to their faster rates of growth and their low average base year intensities compared to the OECD regions. In the *Policy Reform* scenario, industrial energy consumption in OECD and transitional regions decreases between 1995 and 2050 as energy intensity improvements outweigh the effect of growth in the sector.

Figure 3-29. Global industrial energy demand by macro-region



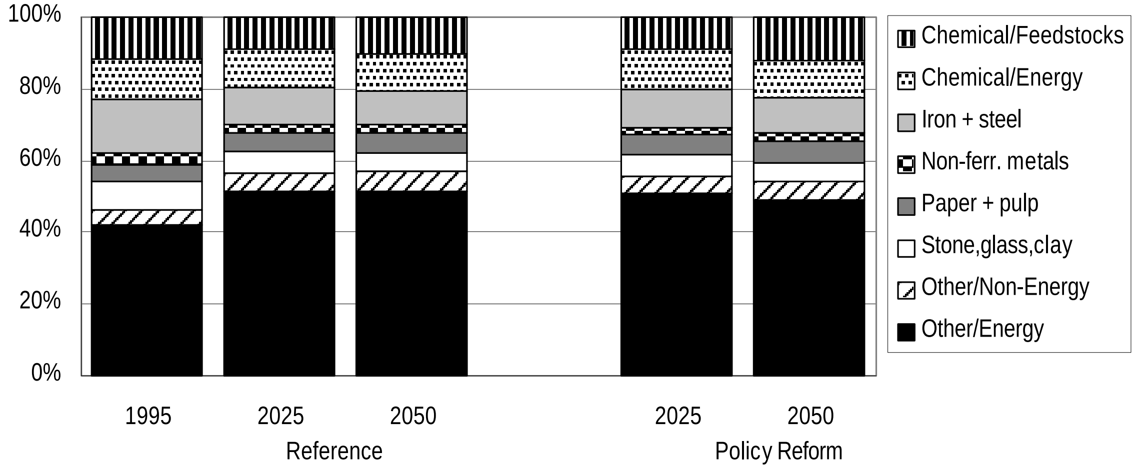
Industrial fuel shares are summarized in Figure 3-30. In the *Reference* scenario there is gradual fuel switching away from coal and biomass, and toward electricity and natural gas, reflecting ongoing trends in the OECD regions and a gradual convergence to OECD. More dramatic fuel switching is seen in the *Policy Reform* scenario with increased shares for electricity and a large drop in the share for coal, both of which reflect the need to reduce the carbon emissions associated with industrial energy consumption.

Figure 3-30. Global industrial sector fuel shares



Subsector shares are summarized in Figure 3-30. With similar energy intensity improvements assumed across all sectors, both scenarios show broadly similar subsectoral shares. In both scenarios, the growth in importance of the less energy intensive "other" sector reflects the gradual dematerialization seen in both scenarios.

Figure 3-31. Global industrial energy demand by subsector



Note: Industrial figures include fuel used for non-energy purposes. This consists of fuels used as feedstocks in the chemical industry (primarily oil and natural gas) as well as oil used for non-energy purposes (e.g., lubricants), accounted in the "other" sector. These non-energy use categories do not involve combustion of fossil fuels, but are included here because they do contribute towards total primary fossil fuel requirements.

Industrial sector energy demands are shown by region in Figure 3-32. In the *Reference* scenario, energy consumption grows in most regions between 1995 and 2050. The exceptions are Eastern and Western Europe and the Pacific OECD, where the effects of increases in industrial sector activity are outweighed by the effects of gradually decreasing energy intensities. In most regions in the *Policy Reform* scenario, energy consumption in 2050 is lower in the *Policy Reform* scenario than in the *Reference* scenario. The only exception is Africa, where rapid growth in industry in the region produces much higher total energy consumption than in the *Reference* scenario.

Figure 3-32. Regional industrial energy demand

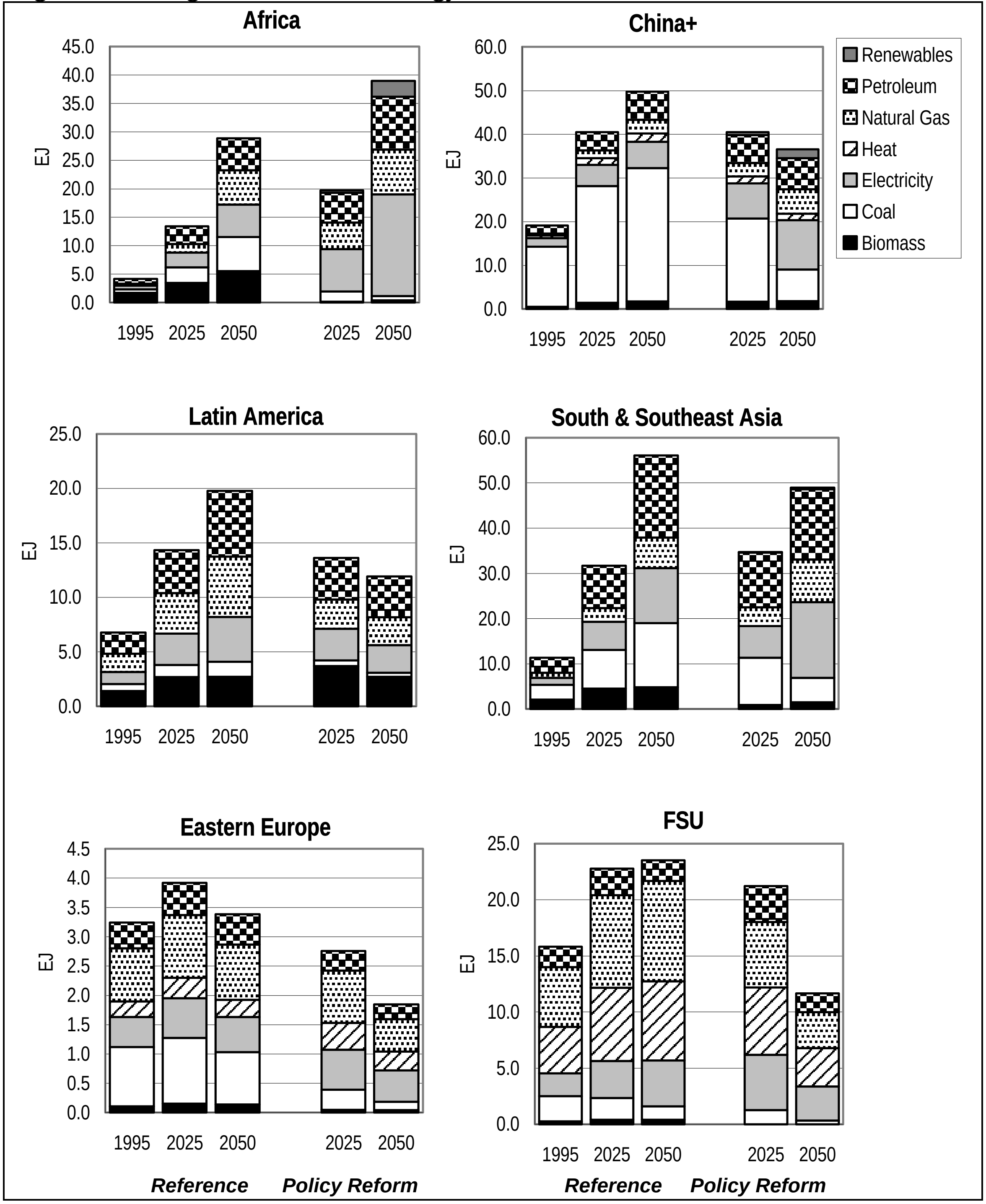
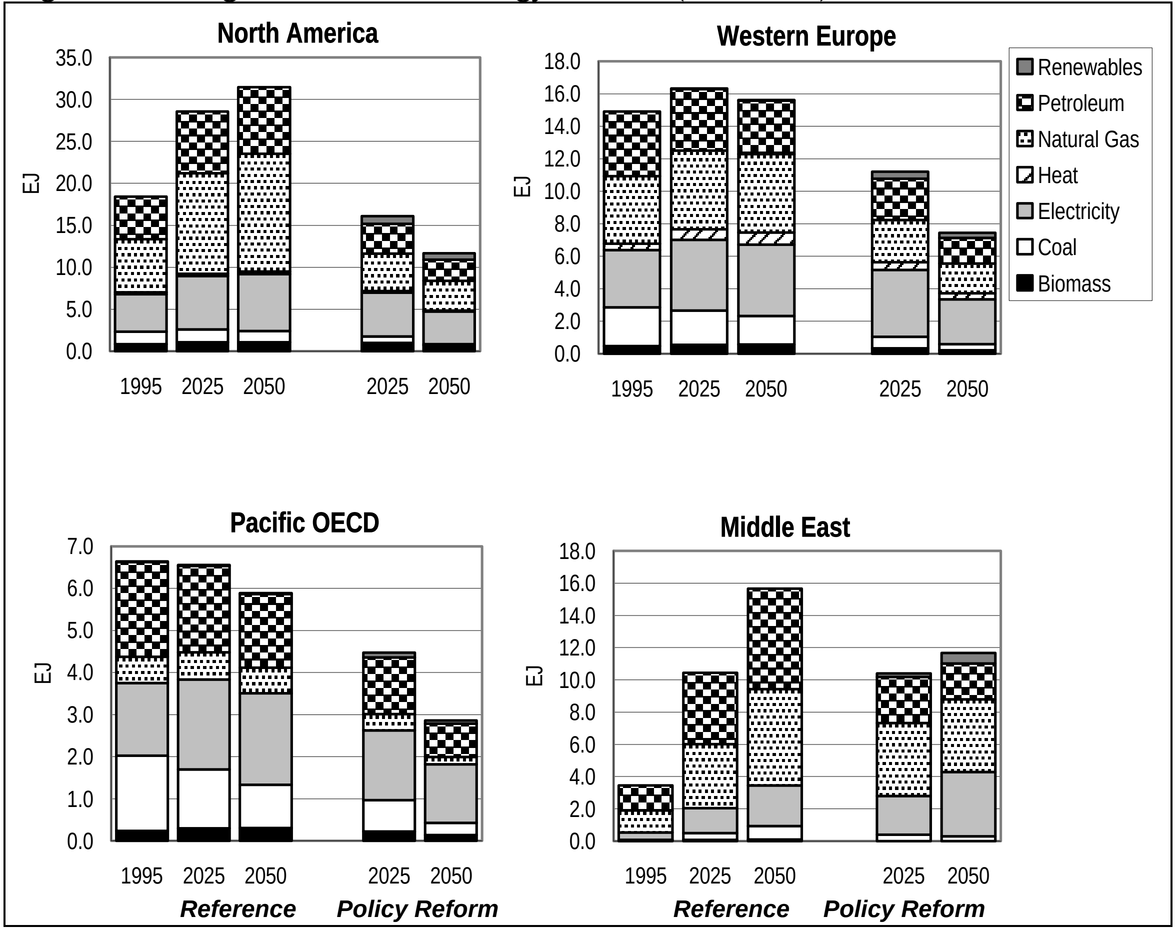


Figure 3-32. Regional industrial energy demand (continued)



3.2.6 Transportation

Current Accounts

Regional transportation energy consumption is reported in Table 3-3 (page 33). Current accounts are based on standard statistical compilations of transport activity levels and energy use. Energy use is taken from IEA (1997a, b). Activity levels are synthesized from a variety of sources including the International Road Federation (1996), Europa Publications (1997), International Union of Railways (1994), International Civil Aviation Organization (1995), Economic Commission for Europe (1995, 1996).

The analysis considers passenger and freight transport separately, since they are determined by very different factors. Within each category, transport modes are considered: road, rail, air and water (freight only) [18]. To focus on the important case of the private automobile, passenger road transport is further divided into private (i.e., cars and taxis, light trucks, motorcycles) and public (i.e., buses) sub-modes of transportation.

Passenger and freight transportation energy demand is shown for each region on a per capita basis in Figure 3-33. North America, the highest-consuming region, consumes more than 30 times more energy per capita for transportation than Africa and China+. Furthermore, per capita transport energy consumption in North America is more than two times that in the other two OECD regions. Insight into this disparity can be gleaned from examining automobile travel more closely. Here we find both average distance traveled (Figure 3-34) and average fuel intensities (Figure 3-35), which are the inverse of efficiency, to be significantly higher in North America than in other OECD regions. The disparities can be attributed to a number of factors including annual distance traveled per capita, the weight of vehicles, their load factor (the average number of vehicle occupants), and the long-term decline in the U.S. of more energy-efficient mass transit systems. These factors are in turn affected to varying degrees by variables such as average income levels, gasoline prices and transport policies. For a deeper analysis of the issues affecting transport energy use in OECD countries, see IEA (1997c).

---

[18] The IEA lists energy use in pipeline as a consumption category. In our analysis, energy use in pipelines (which is primarily used for transporting oil and natural gas products) is not included as a freight transport mode. Instead it is accounted for in our supply-side analysis of the transmission and distribution of fuels.

Figure 3-33. Transport energy demand per capita by region - 1995

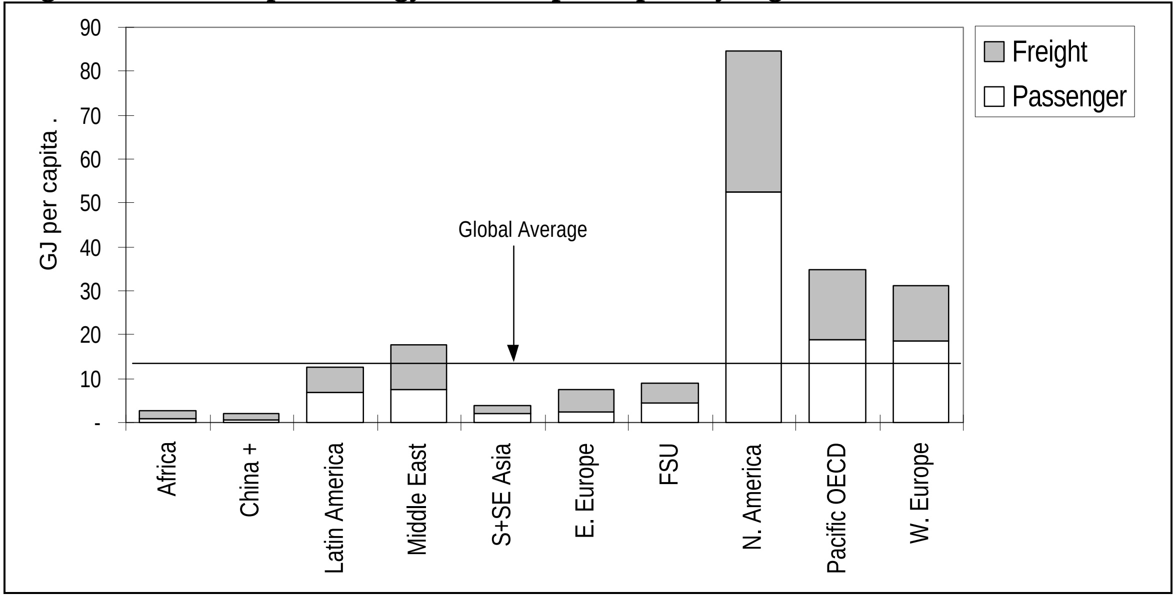


Figure -34

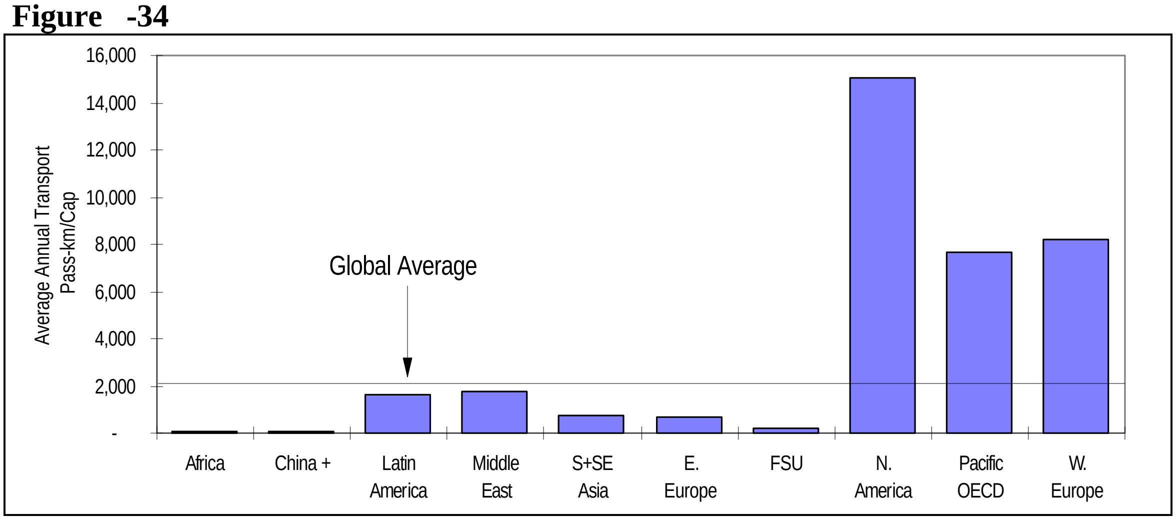
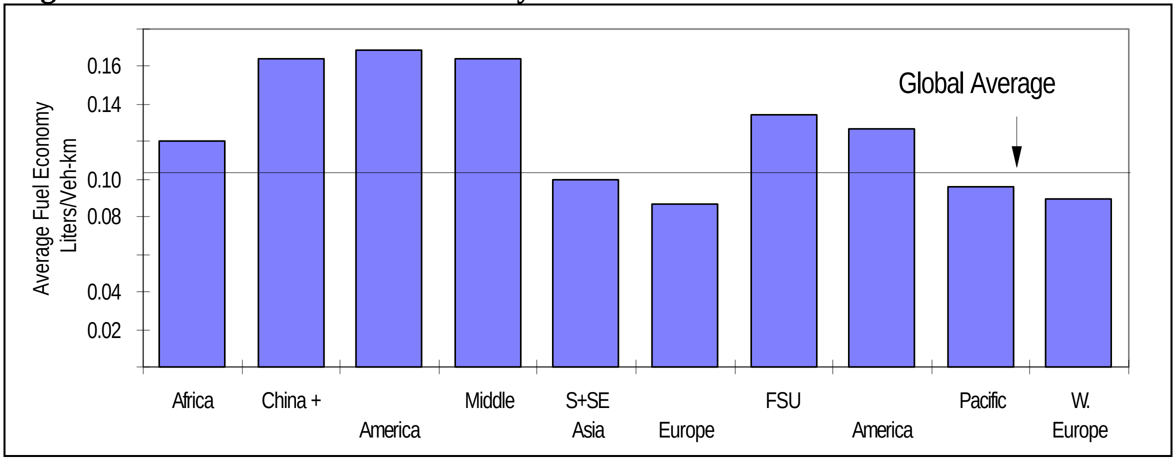


Figure 3-35. Automobile fuel economy - 1995



Patterns of transport energy use are more difficult to interpret in the developing and transitional regions, due to the lack of any but the most basic information. In particular, there are few reliable data describing vehicle fuel economy and vehicle load factors in developing countries. In most developing countries, poor road infrastructure and vehicle maintenance practices, older vehicle designs and older vehicle vintages combine to force up vehicle fuel use. However, smaller vehicle sizes, which are thought to be coupled with higher average load factors, likely bring down energy use per pass-km. We assume load factors of between 2 and 2.5 for developing countries compared to load factors of 1.5 for the USA), and 1.75 for W. Europe, Pacific OECD, Eastern Europe and FSU.[19]

The breakdown of energy use by mode is shown for passenger and freight transportation in Figure 3-36 and Figure 3-37, respectively. Road transport is clearly the dominant energy-consuming mode for both passenger and freight transportation. It accounts for more than 60% of total passenger transportation energy consumption in all regions except the FSU, Africa and China+. For freight transport, roads dominate in all regions except FSU and South and Southeast Asia.

---

[19] Load factor data based on country level data in International Road Federation Statistics (IRF, 1992) for USA, Western Europe and Pacific OECD.

Figure 3-36. Passenger transport energy use: modal shares - 1995

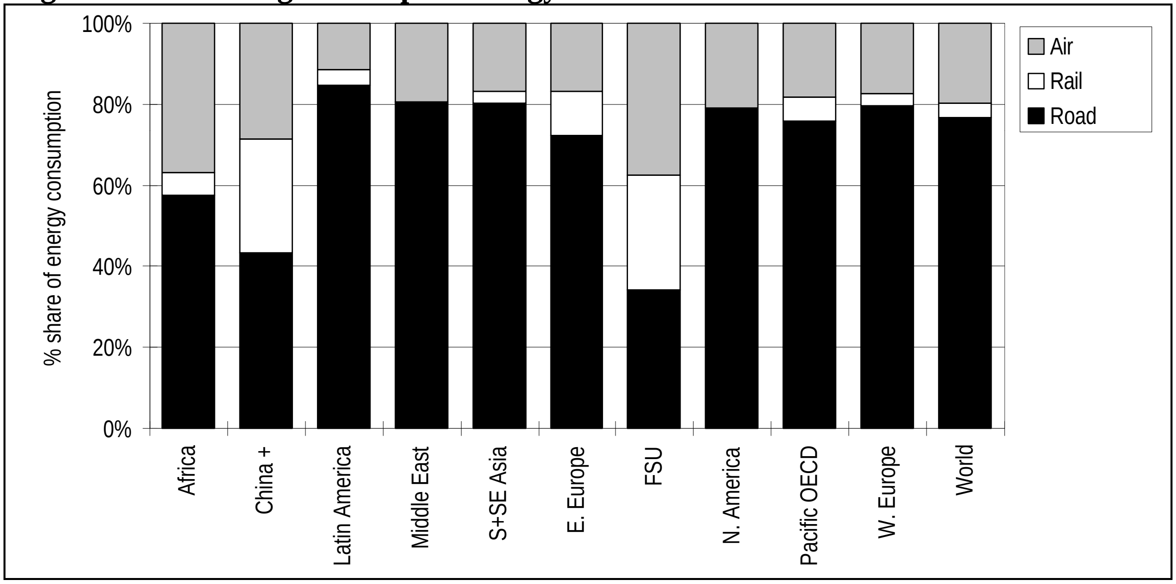
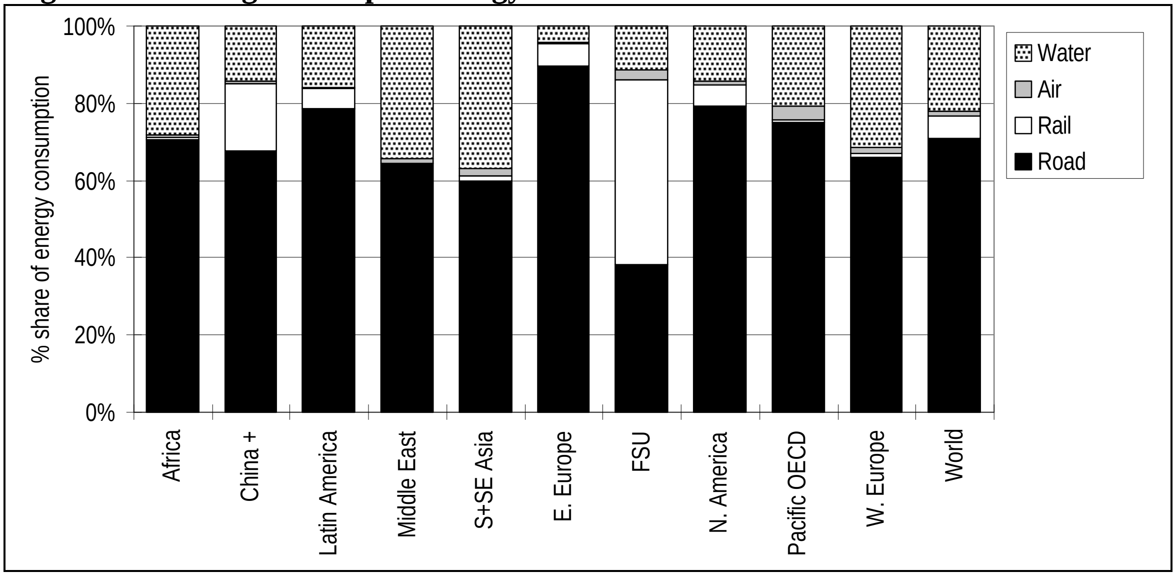


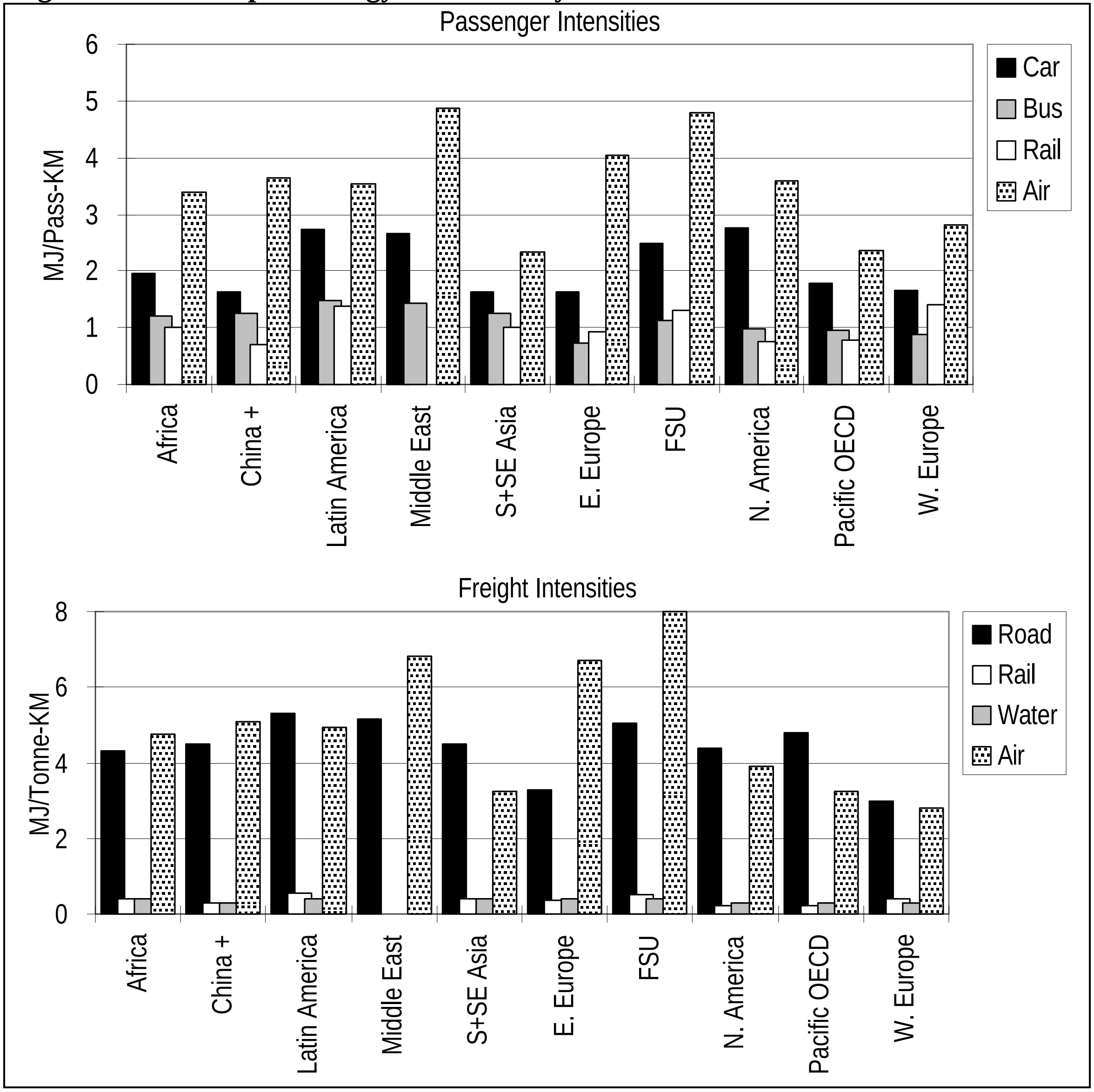
Figure 3-37. Freight transport energy use: modal shares - 1995



The figures for water transport include consumption for both inland water transportation, which is small in all regions except China+, as well as estimates of energy consumption for international transport of goods. Estimates of energy consumption in this latter category are based on sales of "bunker fuel" in each country. Because water transport has a higher efficiency on an energy/tonne-km basis than road and other modes, it accounts for a higher share of physical transport than its share of energy consumed.

Figure 3-38 displays passenger and freight energy intensities by region. For passenger transport, the charts show the energy-efficiency benefits of public mass transport modes (bus and rail) over private cars, and similarly for freight transport, they show the energy-efficiency benefits of rail and water over road transport. Perhaps more surprisingly, air transport intensities, while higher than for any other mode, are quite close to those for road transport. This is due to the high load factors and long transportation distances that apply in the air transport sector.

Figure 3-38. Transport energy intensities by mode - 1995



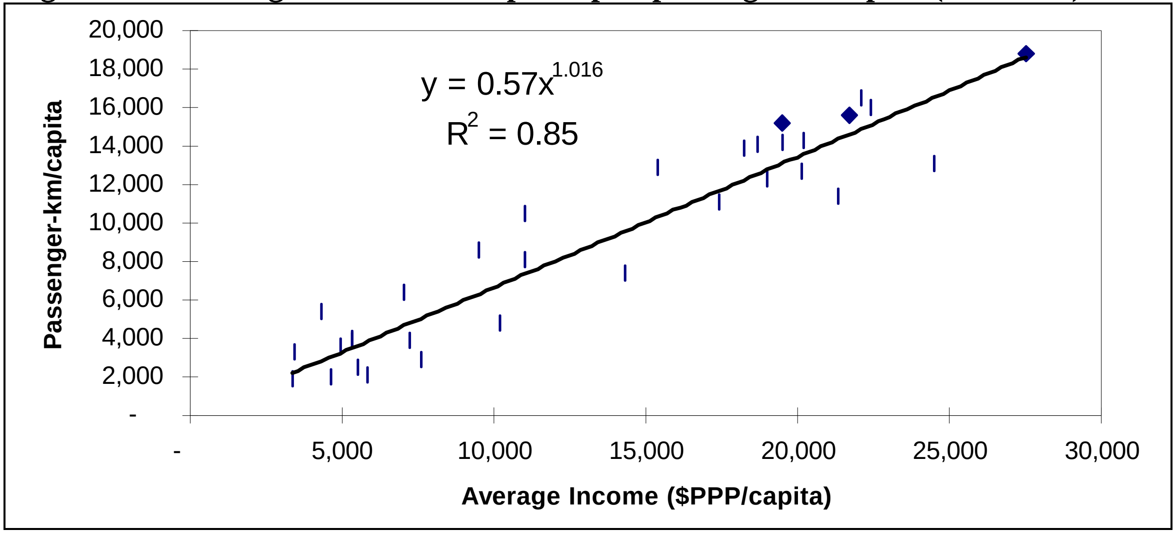
The transportation sector is almost entirely dependent on petroleum products, which account for 98% of global transportation fuel demand. The remainder is primarily due to electricity and coal for rail transport (although coal use for railways is now very limited and is important only in China+), and to alcohol fuels for road vehicles, especially in Brazil.

Passenger Transport Scenarios

Passenger transport energy patterns are defined by future activity levels, trends in energy intensities and fuel shares. For each region, we first specify the distance traveled per capita. Then we disaggregate by applying the share of travel for each mode (road, rail and air). Road transport is further split into two types of vehicles: private and public. To these modal activity levels, we then apply energy intensities (MJ per passenger-kilometer). Finally, we multiply by total population and specify fuel shares to calculate energy consumption for passenger transport.

We start by exploring passenger transport requirements across all modes (road, rail and air). To shed light on average distance traveled per capita, we begin with national figures and explore the relationship to average income. Available country level data are displayed in Figure 3-39, which plots total passenger-kilometers[20] against GDP per capita. The regression shown on the figure is used to project overall transport requirements in both the *Reference* and *Policy Reform* scenarios.

Figure 3-39. Average income versus per capita passenger transport (all modes)



While this simple cross-sectional analysis is sufficient for drafting broad sustainability scenarios, it is worth questioning whether it will tend to overstate total passenger transport requirements, especially over the longer term in OECD countries as incomes rise dramatically. With an income elasticity of 1.016, the projections foresee per capita passenger transport requirements continuing to increase with average income growth. No adjustments are made for saturation effects, since there is no evidence for impending saturation in per capita transport requirements, even in the richest economies. We do not include the effects of factors such as better land-use planning and telecommuting, which might allow the same level of consumer benefits to be provided with reduced overall

---

[20] The activity unit of passenger-kilometers is employed in distinction to vehicle-kilometers which refers to the average distance traveled per vehicle. For automobile travel, the connection between these variables is the relationship: passenger-kilometers equals vehicle-kilometers times load factor (average number of passengers per vehicle).

transport requirements. The effect of these measures on per capita passenger transport requirements is controversial and poorly understood.

Modal share patterns across countries also suggest a correlation with income. This is illustrated for country-level data in Figure 3-40, which shows the relationship between the share of total road passenger-kilometers traveled by private vehicles and GDP per capita, and Figure 3-41, which shows the relationship between air travel and GDP per capita.[21] As incomes grow, not only does total per capita travel grow, but so too do the shares of travel by private car and by air. The regressions shown in Figure 3-40 and Figure 3-41 are used to project air and private road transport requirements in both the *Reference* and *Policy Reform* scenarios.

Figure 3-40. Average income and road transport in private vehicles

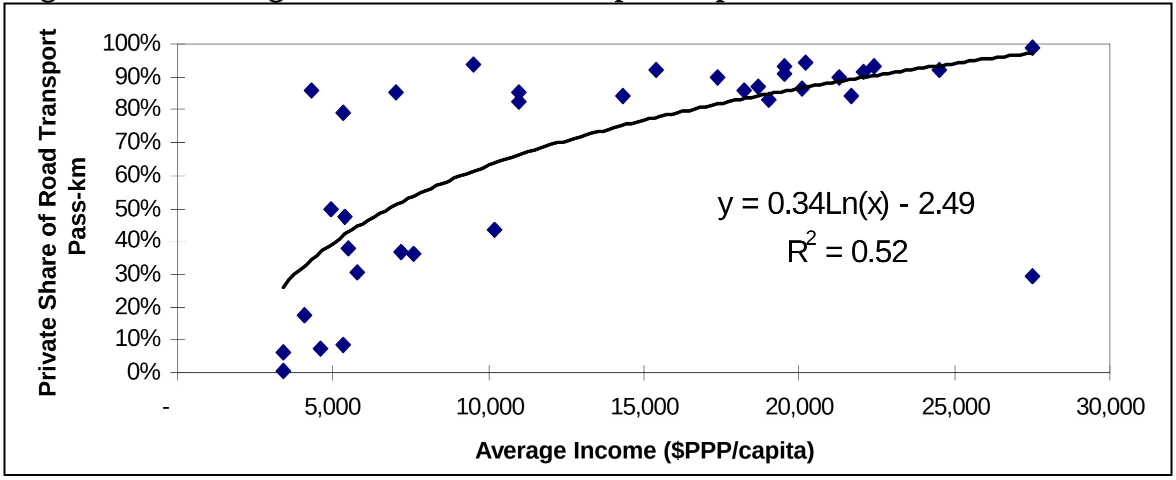
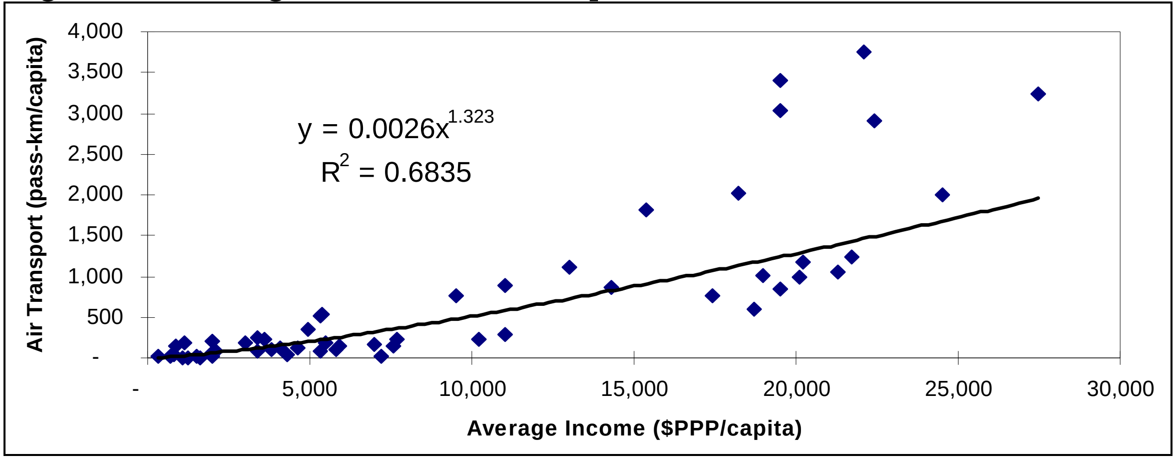


Figure 3-41. Average income and air transport



---

[21] Air travel is well documented, based on airline receipts. Travel data by private and public vehicles are more spotty. In some regions, public transportation travel is only roughly monitored. Private transportation estimates are often calculated from fuel sales data and an assumed fuel efficiency.

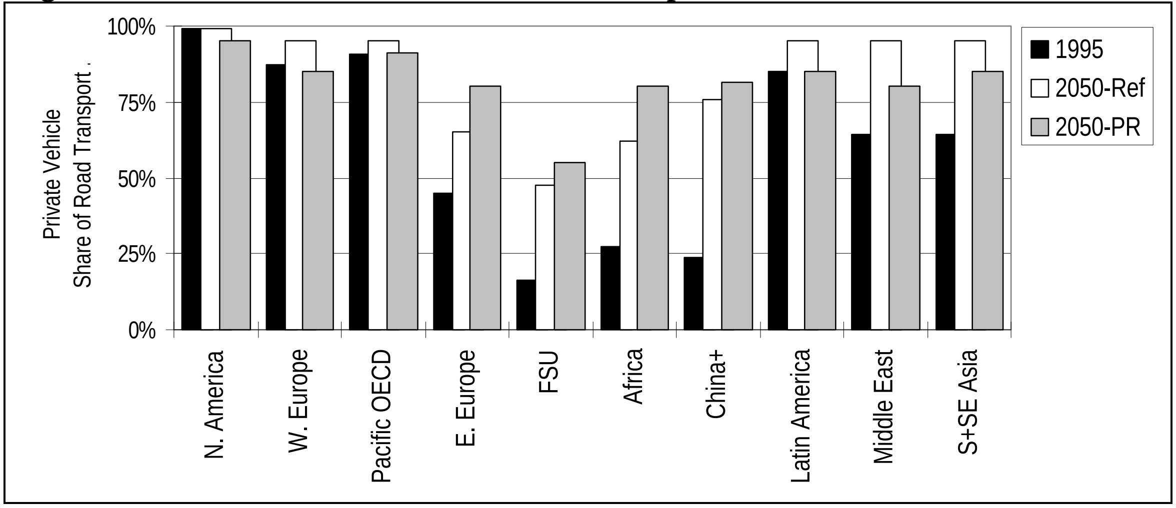
In the *Reference* scenario, rail travel per capita is assumed to remain constant, which is compatible with available historic data, and air travel per capita is assumed to vary with GDP per capita based on the regression curve shown in Figure 3-41. Road transport requirements are solved as the remainder. Finally, within road transport, the split between private vehicles and public vehicles is projected using the regression analysis shown in Figure 3-40[22]. In absolute terms, the *Reference* scenario requires a large expansion in transport infrastructure, with total pass-km increasing by a factor of 4 globally from 18,900 billion pass-km in 1995 to 72,400 billion pass-km in 2050. In the developing regions, transport requirements increase by a factor of 6.6 over the same time period. Absolute increases in road transport requirements are even more dramatic. In one region, China+, road transport requirements increase from 285 billion pass-km in 1995 to 3,270 billion pass-km in 2050, a factor of 11.5. The assumed stagnation in rail transportation leads to only small increases in rail transport from 1,800 billion pass-km in 1995 to 2,200 billion pass-km in 2050. On the other hand, passenger air transport is expected to mushroom from 2,400 billion pass-km in 1995 to 13,400 billion pass-km in 2050.

The *Policy Reform* scenario makes alternative assumptions, compatible with the notion of creating a less resource-intensive and more environmentally acceptable transport system. Specifically, the declining importance of public transport systems in the *Reference* scenario is reversed or slowed in all regions to take advantage of the energy-efficiency benefits of public transport compared to private vehicles. In the OECD regions, railways increase their share of passenger transportation with future shares based on the current maximum rail share in the OECD regions (23% in the Pacific OECD) and the current share in each region. In the developing and transitional regions, railways are assumed to maintain their existing shares, with the exception of China+ and the FSU where the current very high share for railways (52% and 45%, respectively) declines, although at a slower rate than in the *Reference* scenario. Similarly, a less precipitous decline in the public vehicle share of passenger road transport is assumed. For example, in South and Southeast Asia, the public vehicle share of road transport declines from 35% in 1995 to 15% in 2050 in the *Policy Reform* scenario, compared to a value of 5% in 2050 in the *Reference* scenario (Figure 3-42).

---

[22] Projections of private vehicle shares are assumed to reach a maximum at 95% of total road passenger-km, except in North America, where the share of private vehicles is already 99% in the base year.

Figure 3-42. Private vehicle shares of road transport



The resulting passenger transport requirements are shown in Table 3-8 and Figure 3-43. In absolute terms, *Policy Reform* scenario foresees similar global levels of passenger transport requirements (69,900 billion pass-km in 2050 compared to 72,000 billion pass-km in the *Reference* scenario in 2050). The developing regions share of this total increases from 48% in the *Reference* scenario to 60% in the *Policy Reform* scenario, and their overall transport requirements increase by a factor of 7.9 between 1995 and 2050. In spite of policies to promote rail transport, absolute increases in road transport requirements are still dramatic. In China+, road transport requirements still increase by a factor of 8.3 between 1995 and 2050, while in Africa road transport requirements increase by a factor of 11.5 over the same period. The assumed revival of rail transport in the *Policy Reform* scenario leads to dramatic increase in total rail transport requirements — by a factor of 4.7 globally. Air transport requirements increase by a factor of 5 — similar to the *Reference* scenario, although with more growth witnessed in the developing regions.

Table 3-8. Passenger transport requirements (pass-km/capita)

	Road			Rail			Air		
	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR
N America	15,184	29,992	22,286	73	73	1,472	3,062	11,465	5,682
W Europe	9,463	24,987	16,930	678	678	2,694	1,152	4,568	2,807
Pacific OECD	8,449	25,014	13,678	2,898	2,898	4,914	1,474	5,674	3,131
E Europe	1,570	4,771	3,827	494	494	2,076	102	354	599
FSU	1,129	4,546	4,049	1,229	1,229	3,098	343	1,166	1,571
Africa	344	1,005	1,521	67	67	357	91	356	812
China+	215	1,919	1,462	285	285	1,129	53	395	494
Latin America	2,282	6,837	7,305	192	192	643	227	931	1,104
Middle East	2,738	6,679	7,878	-	-	-	304	1,016	1,272
S+SE Asia	1,169	4,749	5,212	74	74	729	157	1,008	1,349

Figure 3-43. Global passenger transport requirements by macro-region

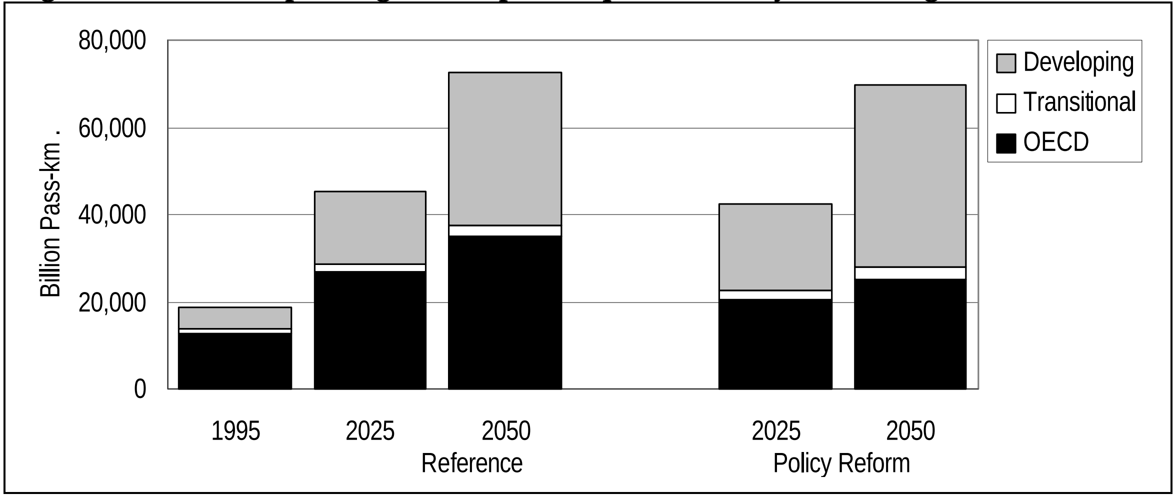
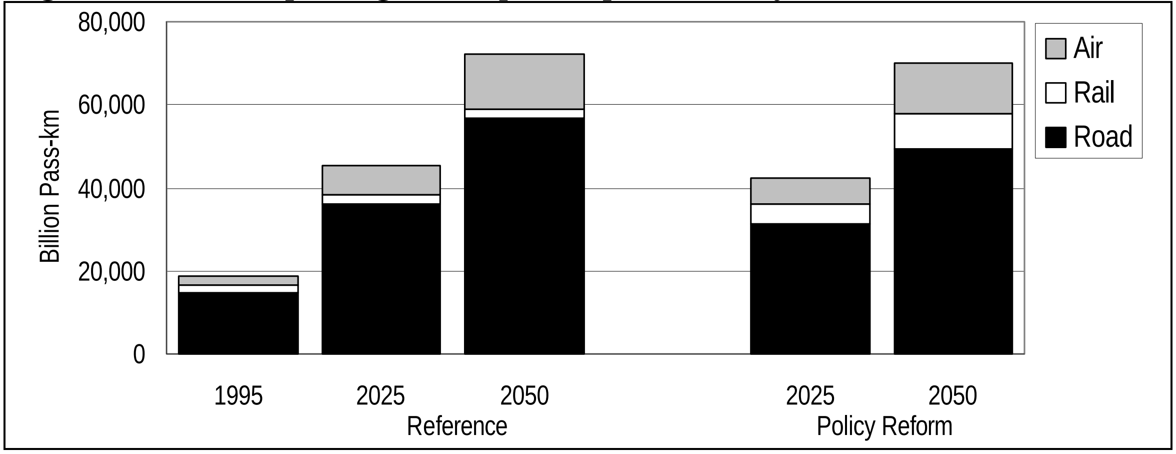


Figure 3-44. Global passenger transport requirements by mode



Transport energy intensity assumptions for OECD countries are summarized in Table 3-9, again guided by the recent *Energy Innovations* study (Energy Innovations, 1997), as well as earlier studies such as Schipper and Meyers (1992). Improvements in the *Policy Reform* scenarios assume the introduction of progressively stronger vehicle emissions standards, pricing reforms, investments in research and development and a range of market-based incentives to promote more efficient vehicles. In the longer term, the intensity projections assume the introduction of advanced vehicles and fuels, gradually replacing the petroleum-based internal combustion engine with technologies such as fuel cells and electric powered vehicles.

Table 3-9. Passenger and freight transport intensities in OECD regions

	Reference		Policy Reform	
	% Change per year	2050/1995 Intensity Ratio	% Change per year	2050/1995 Intensity Ratio
Passenger Transport				
Road	0.60%	0.72	1.80%	0.37
Rail	0.45%	0.78	1.40%	0.46
Air	1.20%	0.51	1.80%	0.37
Freight Transport				
Road	0.35%	0.82	1.00%	0.58
Rail/Water	0.45%	0.78	1.40%	0.46
Air	1.20%	0.51	1.80%	0.37

Notes: Annual % improvement and ratio of 2050 to 1995 values.

Passenger transport energy intensities for non-OECD regions are assumed to converge towards the average values of the OECD region as average incomes increase, using the convergence algorithm (see Annex). The overall pattern of convergence in the two scenarios is shown in Table 3-10. In the *Policy Reform* scenario there is greater overall convergence to a lower average intensity, in accordance with the exogenous assumptions of improving equity and more rapid economic growth in the developing countries compared with the *Reference* scenario.

Table 3-10. Passenger transport energy intensities (MJ/pass-km)

	Road			Air			Rail		
	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR
N. America	2.8	2.0	1.0	7.2	4.3	2.6	3.2	1.3	0.8
W. Europe	1.7	1.2	0.6	5.6	2.9	2.1	3.2	2.5	1.5
Pacific OECD	1.8	1.3	0.7	4.7	2.4	1.7	1.7	1.4	0.8
E. Europe	1.6	1.6	1.0	8.1	5.1	3.5	2.1	1.9	1.3
FSU	2.5	2.1	1.2	9.6	7.2	4.1	2.9	3.4	2.0
Africa	2.0	1.9	1.6	6.8	6.3	5.3	2.3	2.2	1.9
China+	1.6	1.6	1.1	7.3	5.0	3.7	1.6	1.7	1.2
Latin America	2.7	1.8	0.9	7.1	4.0	2.5	3.1	2.1	1.1
Middle East	2.7	2.1	1.4	9.7	6.4	4.8	2.3	2.0	1.5
S+SE Asia	1.6	1.6	1.2	4.6	4.1	3.4	2.3	2.1	1.6

Finally, we introduce fuel shares for each mode of transport. Given the current prototype status of alternative fueled vehicles it is hard to make predictions of future transport fuel shares. In the scenarios we assume a mix of non-conventional fuels and technologies are introduced alongside conventional petroleum-based technologies. Scenario assumptions are guided by a range of studies, including *Energy Innovations* (1997), EC (1996) and Lazarus et al. (1993), which indicate the broad potential for non-conventional fuels to replace conventional petroleum-based transport.

For road transport, the range of possible technologies include conventional internal combustion engine vehicles based on alcohol fuels and natural gas, hybrid vehicles using more than one drive train, electric vehicles, and advanced vehicles powered by fuel cells and using hydrogen. In the *Reference* scenario, we assume only very modest penetration of alcohol and electric vehicles in the OECD countries (5% biofuels, 5% electricity, 5% natural gas by 2050). Hydrogen-based vehicles do not gain a significant market share before 2050. The *Policy Reform* scenario sees more dramatic shifts in road transport fuel shares away from petroleum-based fuels towards lower carbon fuels (electricity, natural gas and biomass-based ethanol). In the OECD regions, the fuel shares of natural gas, alcohol, hydrogen and electricity reach 10%, 25%, 10% and 10% respectively by 2050, with the remaining 45% still met from petroleum fuels. In the *Reference* scenario, fuel shares in non-OECD regions converge slowly towards OECD patterns using the convergence algorithm (see Annex). In the *Policy Reform* scenario, more growth of non-conventional transport fuels is assumed in non-OECD regions, although levels of adoption of non-conventional fuels stay below the levels of adoption in OECD regions.

For rail transport the historical trend toward electrification persists in the *Reference* scenario. This leads to an increase in electrification of the rail system of approximately 0.5% per year. More rapid electrification is assumed in the *Policy Reform* scenario, in line with the general spirit of the scenario, in which policies are assumed that encourage fuel switching away from fossil fuels and towards electricity.

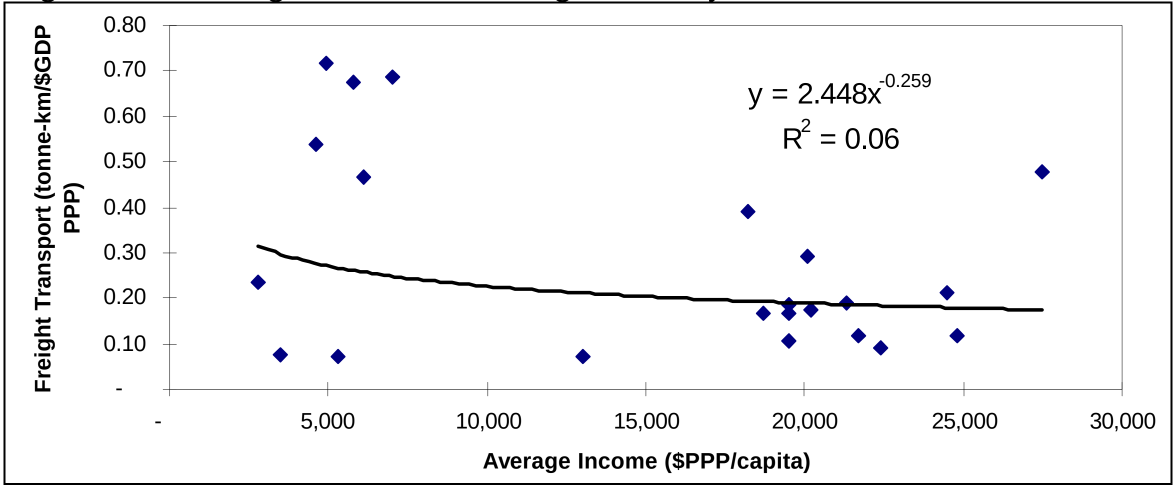
Air transport in the *Reference* scenario is assumed to remain 100% petroleum-based. In the *Policy Reform* scenario, biofuels are assumed to gain a 25% market share by 2050. Air transport is assumed to be an essentially global industry, with similar fuel shares in OECD and non-OECD regions.

Freight Transport Scenarios

Regional freight activity is the product of GDP and freight activity intensity (tonne-km per dollar). This is disaggregated by applying mode shares for road, rail, air and water. The resulting activities by mode are then multiplied by energy intensities (MJ per tonne-km). Finally, specifying fuel shares completes the energy picture for freight transport.

In both scenarios, freight activity values freight transport requirements per dollar are assumed to decrease as income levels increase. This is weakly supported by the regression shown in Figure 3-45, which plots average income against freight intensity across all modes (road, rail, air and water). With an elasticity of -0.26, freight transport requirements per dollar tend to decrease as income levels increase, probably reflecting the increasing share of economic value added which derives from those services that do not require transportation.

Figure 3-45. Average income versus freight intensity



Total global freight transport requirements continue to increase as the global economy expands in both scenarios, as shown in Table 3-11. In the *Reference* scenario, the requirements for road, rail and air transport increase by a factor of 2.2 from 11,400 billion tonne-km in 1995 to 25,300 billion tonne-km in 2050. In the *Policy Reform* scenario, they increase by a factor of 2.7, reaching 30,300 billion tonne-km in 2050. Water freight transport projections and energy requirements are included in the transport scenario analysis, but are not shown in Table 3-11 due to low confidence in water freight transport data. There is significant uncertainty in the absolute levels shown in the table, primarily for the developing and transitional regions. However, it is important to note that the scenario analyses depend only on the assumed changes in driving values and intensities, not their absolute values; so broad results are robust against uncertainties in current values.

Table 3-11. Freight transport (billions of tonne-km)

	Road			Rail			Air		
	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR
N. America	1,712	5,730	3,134	2,320	2,320	4,246	26	93	47
W. Europe	1,318	2,936	2,042	267	256	1,301	31	68	52
Pacific OECD	368	782	550	88	87	131	27	57	41
E. Europe	140	343	275	133	133	262	0	1	1
FSU	103	532	420	1,612	1,613	2,646	4	17	14
Africa	207	1,284	1,902	21	21	195	2	14	21
China+	298	2,121	1,537	1,319	1,315	4,535	3	10	11
Latin America	413	1,740	1,609	267	266	1,040	4	20	14
Middle East	225	1,242	1,339	-	-	-	4	20	21
S+SE Asia	401	2,048	2,216	113	115	623	20	98	110
World	5,185	18,757	15,023	6,139	6,125	14,978	121	397	331

Turning to modal shares, during the past 20 years the OECD regions have experienced a shift in freight activity from rail to trucks (Schipper and Meyers, 1992). These trends have been even more marked in several developing regions. The *Reference* scenario assumes a continuation of these trends, so that the share of road freight continues to increase, while that of rail freight continues to decline. Specifically, it is assumed that total rail tonne-km (not share) in each region remains constant in the future, while absolute growth in freight activity is allocated to the other modes in proportion to their current shares. The *Policy Reform* scenario reverses this assumption, assuming a range of policies to encourage rail over road freight transport. These policies assist in reducing the overall energy intensity and carbon emissions of the *Policy Reform* scenario compared to the *Reference* scenario. Specifically, rail transport is assumed to maintain its current modal share in all countries except China+ and FSU, where the rail share continues to decline, although at a much slower rate than in the *Reference* scenario. Other modal shares are allocated as in the *Reference* scenario.

Energy intensity assumptions are similar to those described for the passenger transport analysis. The overall pattern of convergence in the two scenarios is shown in Table 3-12.

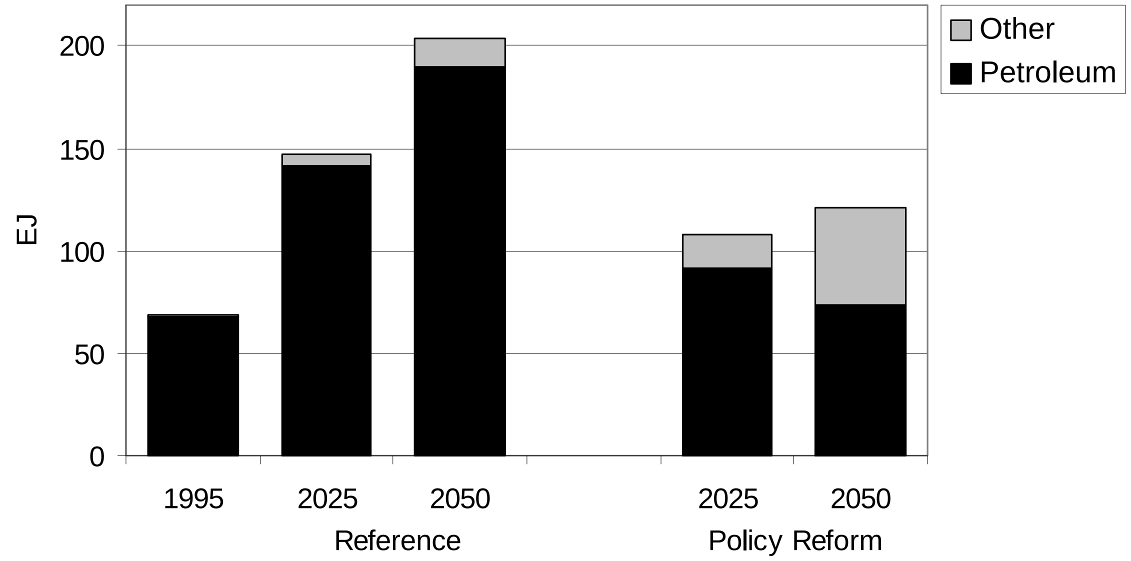
Table 3-12. Transport freight intensities (MJ/tonne-km)

	Road			Rail		
	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR
N. America	4.4	3.6	2.5	0.2	0.2	0.1
W. Europe	3.0	2.4	1.7	0.4	0.3	0.2
Pacific OECD	4.8	3.9	2.8	0.2	0.2	0.1
E. Europe	3.3	3.3	2.5	0.4	0.3	0.2
FSU	5.0	4.3	2.9	0.5	0.4	0.2
Africa	4.3	4.2	3.6	0.4	0.4	0.3
China+	4.5	3.7	2.9	0.3	0.3	0.2
Latin America	5.3	3.6	2.3	0.6	0.3	0.2
Middle East	5.2	4.1	3.2	0.4	0.3	0.2
S+SE Asia	4.5	3.9	3.2	0.4	0.3	0.3
	Air			Water		
	1995	2050-Ref	2050-PR	1995	2050-Ref	2050-PR
N. America	3.9	2.0	1.4	0.3	0.2	0.1
W. Europe	2.8	1.4	1.0	0.3	0.2	0.1
Pacific OECD	3.2	1.7	1.2	0.3	0.2	0.1
E. Europe	6.7	3.6	2.3	0.4	0.3	0.2
FSU	8.0	5.6	2.8	0.4	0.3	0.2
Africa	4.8	4.3	3.5	0.4	0.4	0.3
China+	5.1	3.1	2.3	0.3	0.3	0.2
Latin America	4.9	2.4	1.4	0.4	0.3	0.1
Middle East	6.8	4.2	3.1	0.4	0.3	0.2
S+SE Asia	3.3	2.6	2.1	0.4	0.3	0.3

Finally, we introduce fuel shares for each mode of freight transport. We assume the same penetration of alternative fuels (natural gas, biomass-based alcohol, hydrogen, electricity) as in the passenger transport analysis.

Energy demand for transportation in the scenarios is presented in Figure 3-46. In the *Reference* scenario, Global demand increases from about 69 EJ in 1995 to about 204 EJ in 2050. The fastest growth is in developing regions, which account for 51% of the total in 2050. In the *Policy Reform* scenario, total demand is reduced dramatically to 121 EJ in 2050, and the developing regions share of this increases to 68%. In the *Reference* scenario, petroleum products remain the dominant transportation fuel, accounting for 93% of total transportation energy in 2050, down from 98% in 1995. The *Policy Reform* scenario sees a marked shift towards alternative fuels with the share of petroleum products reduced to 61% by 2050.

Figure 3-46. Global transport energy demand by Fuel



Notes: “Other” fuels include current usage of electricity and coal (mainly in trains), plus current use of alcohol fuels (principally in Brazil). In the future, the “other” category includes alternative, non-petroleum based energy sources including hydrogen, natural gas, biomass-based alcohol and direct use of electricity.

Figure 3-47. Global transport energy demand by macro-region

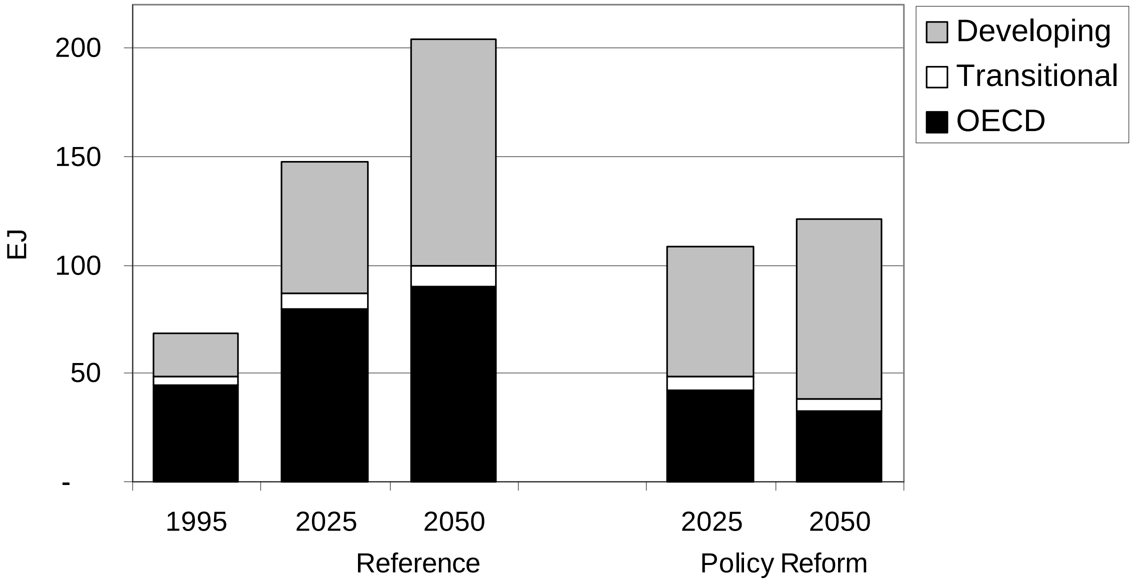
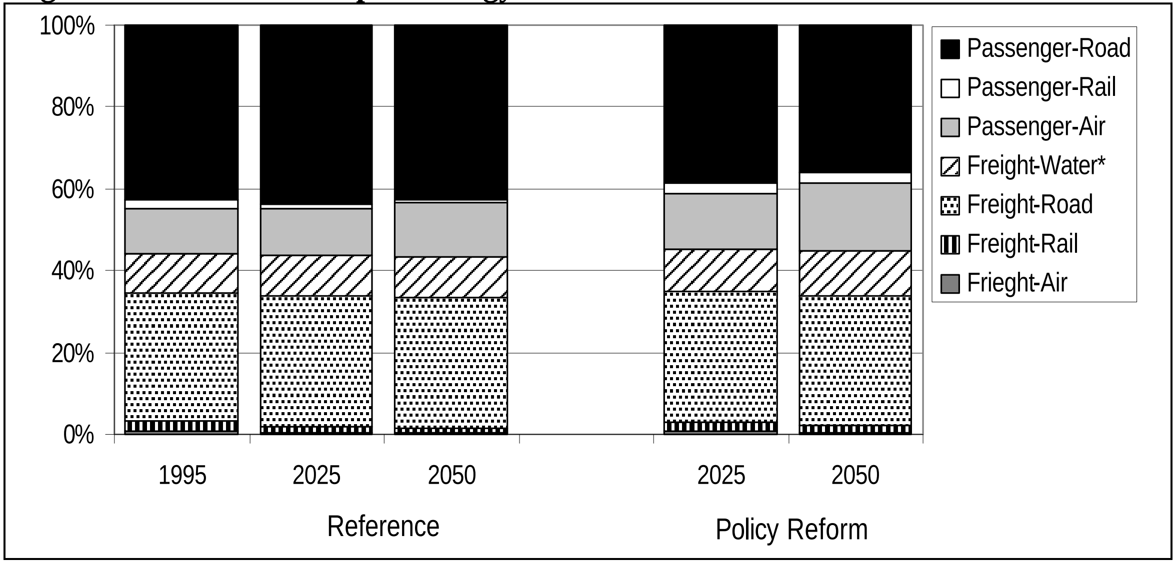


Figure 3-48. Global transport energy demand mode shares



3.3 Energy Conversion

Energy conversion refers to the transformation of primary sources of energy into products suitable for final use. Conversion accounts also include the transmission and distribution of final energy forms to end-uses. Major energy conversion sectors include electric power generation, petroleum refining, alcohol production and district heating.

Current Accounts

Table 3-13 summarizes the global energy balance for 1995.[23] Global final demand for energy is approximately 272 EJ. In addition, 113 EJ of energy are consumed in the production and distribution of final energy forms. These “conversion” losses are dominated by electric power generation (73 EJ), and by transportation and distribution losses and own-use (29 EJ).

Table 3-13. 1995 Global energy balance (EJ)

PJ	Coal	Biomass	Crude	Oil	N. Gas	Uranium	Hydro	Renew.	Elec	Heat	TOTAL
PRODUCTION	95	41	141	0	73	25	9	0	0	0	384
NET IMPORTS	0	0	0	0	0	0	0	0	0	0	0
TPES	95	41	141	0	73	25	9	0	0	0	384
ELECTR GEN	-51	-3	0	-14	-19	-25	-9	0	48	0	-73
DIST HEAT	-6	0	0	-3	-5	0	0	0	0	13	-2
OIL REFINING	0	0	-141	134	0	0	0	0	0	0	-7
ALCOHOL PROD	0	-1	0	0	0	0	0	1	0	0	-1
LOSSES & OWN USE	-4	0	0	-7	-8	0	0	0	-9	-2	-30
TFC	34	37	0	110	41	0	0	0	39	11	272
HOUSEHOLDS	5	28	0	10	13	0	0	0	11	5	72
SERVICES	1	0	0	4	5	0	0	0	8	0	19
TRANSPORTATION	0	0	0	68	0	0	0	0	0	0	69
INDUSTRY	27	8	0	23	22	0	0	0	18	6	104
AGRICULTURE	1	0	0	5	0	0	0	0	1	0	8

Note: numbers may not sum due to rounding. 0 indicates value less than 0.5 EJ.

---

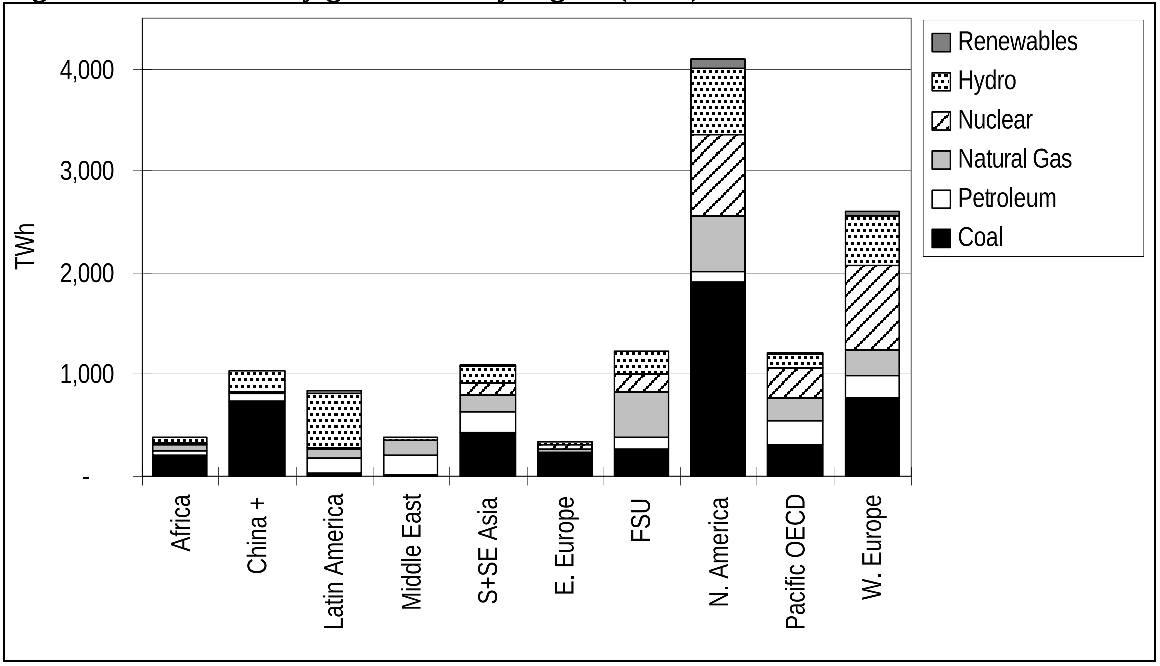
[23] Our current accounts are broadly consistent with those of the IEA (1997a, b). However, a few important differences are worth noting. First, unlike the IEA’s energy balance, our figure for global total final consumption (271.5 EJ) includes sales of bunker fuels (5.4 EJ) but excludes energy use in pipelines (1.6 EJ), which we have accounted for as usage under the transmission and distribution category. Second, the IEA’s published figures for industrial consumption of coal and oil include fuels used by auto-producers of electricity and district heat. By including this consumption as an energy demand, the IEA’s energy balance tends to overestimate the efficiencies of thermal electric generation plants and district heat plants. For example, the IEA data suggests average oil-fired plant efficiencies of 40% worldwide, with values as high as 50% for the U.S. and 70% for Pacific OECD. In our analysis, we have adjusted total industrial oil and coal consumption and used lower fossil electric generation efficiencies (using efficiency assumptions drawn from Lazarus et al., 1993 and other sources). Third, we have simplified our analysis in comparison to the IEA statistics. In particular, there is no representation of the sectors labeled Liquefaction, Gas Works or Non-specified (which are subsumed into losses and own-use). Similarly, we have not attempted to represent stock changes, transfers or statistical differences (which in the IEA data serve to reduce primary energy supply requirements by approximately. 2.9 EJ). In our analysis, these are subsumed into overall production values. In scenarios, it is reasonable to assume that these average out to zero over the long-term. Finally, we use a slightly different accounting approach for electricity generation. In a similar fashion to the IEA statistics, we express hydro power as its electric equivalent (using an efficiency of 100%) and nuclear power as its thermal equivalent (using an efficiency of 33%). However, unlike the IEA, we combine geothermal, solar and other non-biomass renewables into a single category and express their primary energy supply as an electric equivalent (using an efficiency of 100%). In contrast, IEA uses a 10% efficiency for geothermal.

Overall, our calculated primary energy supply of 384 EJ is very close to the IEA figure of 380 EJ (9.1 billion TOE), the difference being primarily due to reclassification of bunker fuels (5.4 EJ) and the elimination of statistical differences. Note though that when examining IEA statistics, world totals currently exclude biomass consumption in developing regions, due to the unreliability of that figure (33 EJ).

Regional breakdowns of electricity generation by feedstock fuel are shown in Figure 3-49. Coal, oil, hydro, nuclear and, to an increasing extent, natural gas-fired power plants dominate the picture. Recent decades have seen a virtual halt in the expansion of nuclear power in OECD countries — a technology that grew rapidly in the decades of the 1950s to 1970s. This has been due to concerns over siting, waste disposal, cost and the wider issue of nuclear proliferation. Nevertheless, it seems likely that nuclear power will form an important part of the plans of a number of developing regions to expand their generation of electricity.

It now appears that the era of centralized, public planning of electricity supply in OECD regions is giving way to a far more deregulated environment. The impact that these changes will have on the electric mix is not yet clear, although the evidence from early adoptees of this approach, such as the UK, is that plants with low capital costs, such as natural gas, will receive a significant boost. Generation from renewable energy forms such as wind, geothermal, biomass, municipal solid waste, and solar technologies remains a small fraction of total generation.

Figure 3-49. Electricity generation by region (1995)

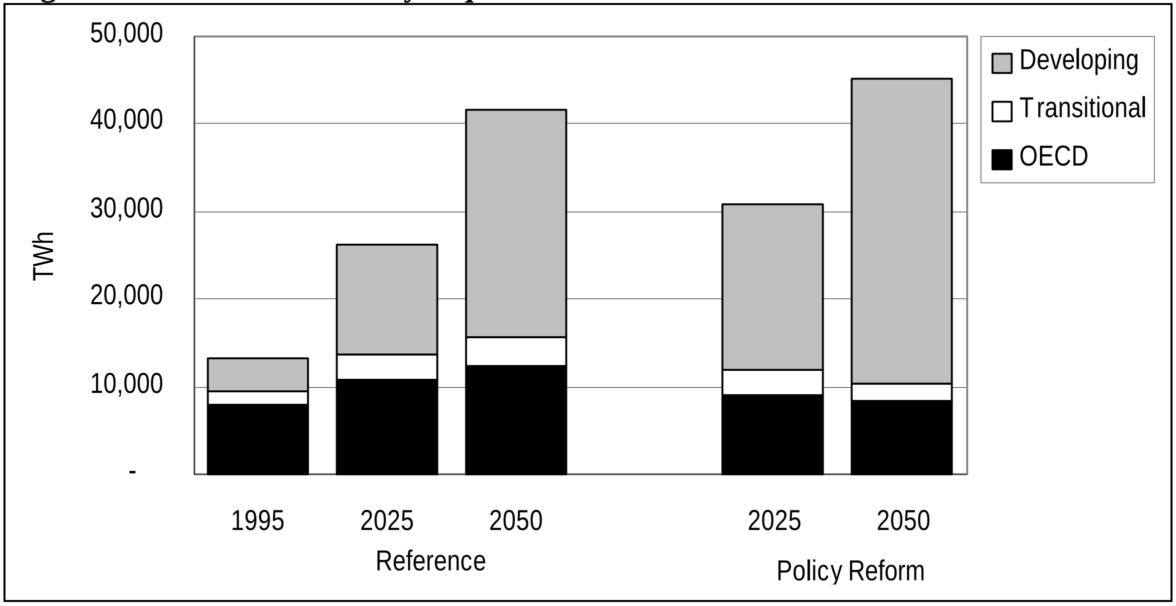


In addition to electricity generation, the current accounts data also include other conversions: the conversion of crude oil to petroleum products in oil refineries, the combustion of coal, oil and natural gas in district heating plants, the conversion of sugarcane to ethanol in alcohol plants, and losses and own-use consumption of various fuels during the conversion and transportation of fuels.

Scenarios

Global electricity requirements are shown in Figure 3-50. For each time period, these are calculated by adding total electricity demands across all final demand sectors to an estimate of electricity losses and own-use. Losses and own-use of electricity and other fuels are expected to converge towards current OECD practices in the *Reference* scenario. The *Policy Reform* scenario assumes concerted action to reduce losses in all regions, particularly in the developing and transitional regions.

Figure 3-50. Global electricity requirements



Globally, in the *Reference* scenario, annual electricity demand expands rapidly from 13.2 PWh (47.6 EJ) in 1995 to 41.7 PWh (150.2 EJ) in 2050. Global demand in the *Policy Reform* scenario is higher, reaching 45.1 TWh (162.5 EJ) in 2050. In future years in the *Policy Reform* scenario, the combined effect of changing economic activities, demand side management, and adjustments in the final fuel mix, lead to modest reductions in electricity requirements in the OECD and transitional regions compared to the *Reference* scenario. However, the demand for electricity increases rapidly in the developing regions, where rising personal incomes and industrialization are associated with increasing use of electricity in both scenarios. The growth in demand for electricity in developing country regions is particularly pronounced in the *Policy Reform* scenario. In spite of aggressive efficiency improvements, larger GDP growth relative to the *Reference* scenario and energy policies that guide final consumption away from the use of the carbon-intensive fuels, and towards electricity and natural gas, increase electricity demands.

Electricity Generation Fuel Shares in the *Reference* scenario.

As an indigenous and renewable energy resource, hydropower offers the benefits of reducing fuel import dependency and air pollution relative to fossil fuel-fired generating options. These benefits are conditional, however. The renewability of hydropower is only approximate, since reservoir siltification gradually erodes the resource potential, and the contribution of hydropower to self-reliant development is compromised insofar as the financing and construction of these capital-intensive facilities depend on external hard currency loans and foreign contractors. Beyond issues of engineering feasibility and cost-competitiveness, the construction of large-scale hydroelectric facilities can significantly disrupt local communities and ecosystems. The environmental and social impacts of hydroelectric plants include disturbance of the spawning grounds of migratory fish; flooding of natural habitats, farmlands, and communities; displacement of populations; alteration of local hydrological patterns; and risks of catastrophic flooding from dam failure. In recent years, sensitivity to the environmental and social repercussions of large-area flooding for reservoirs has increased. Political and social opposition has challenged new construction, while international donors have begun to take a tougher look at the full costs of hydropower development (Lenssen, 1992). With many of the best sites already exploited, it seems likely that opposition will increase as facilities are proposed that carry increased costs — economic, environmental and social. Meanwhile, the expansion of settled areas and farmland as populations and economies grow will encroach on potential hydroelectric sites and raise the stakes and possibility for conflict. These frictions will delimit the expansion of hydroelectric resources to well below the ultimate potential. In this regard, smaller scale hydro facilities may be an attractive alternative to large-scale projects although there is some indication that environmental impact per unit of generation does not diminish with decreasing size (Gleick, 1992).

Hydropower development in the *Reference* scenario is based on national estimates of economically exploitable hydropower capability (WEC Survey of Energy Resources, 1995). Following the approach of Lazarus et al. (1993), a reduction factor of 35% is applied to these figures to reflect growing public opposition and at least partial avoidance of the more environmentally and socially detrimental hydro projects. Achieving these levels of development will likely require greater sensitivity by development authorities to environmental and social costs in project evaluation, and more active involvement by affected communities in the siting process.

For other types of electricity generation, *Reference* scenario generation shares are based on a review of a variety of scenarios including IPCC (1992), European Commission (1997), and WEC/IIASA (1995). For North America, shares are based on two sources: for the near term, *Annual Energy Outlook* (DOE/EIA, 1996) and for the longer term, *Energy Innovations* (1997).

Electricity Generation Fuel Shares in the Policy Reform scenario.

In the *Policy Reform* scenario, future electricity generation shares for 2025 and 2050 are governed by a number of assumptions and constraining factors, and the overall requirement to substantially reduce greenhouse gas emissions relative to the *Reference* scenario:

a) First, hydropower development is constrained to be no higher than in the *Reference* scenario (for the same reasons as discussed above). This tends to increase the future share of hydro in the *Policy Reform* scenario in OECD and transitional regions, but to decrease its share in most of the developing countries where overall electricity demand substantially increases.

b) Second, nuclear power is assumed to be completely phased out by the year 2050 in all regions, for reasons discussed in *BTC* related to cost, safety, radioactive waste disposal and security issues. *Reference* scenario trends are assumed to continue at first, with new nuclear plants being added until the year 2010. Thereafter, no new nuclear plants are assumed to be added. For a more detailed review of issues related to the development of nuclear power, see Raskin and Margolis (1995).

c) Third, the market penetration of biomass and other non-hydro renewable energy forms (solar, wind, municipal solid waste, geothermal, wave and tidal) is assumed to increase dramatically. By 2050, their share of global electricity generation reaches 35%, compared to 16% in the same year in the *Reference* scenario, and up from the current fraction of about 1.4%. Assumptions are guided by a review of a number of global and regional scenarios, including *Energy Innovations* (1997), European Commission (1997), WEC/IIASA (1995), Lazarus et al. (1993) and Johansson et al. (1993). In all regions, the penetration of intermittent (non-biomass) renewables in 2050 is kept below 35%, which is well within what is considered feasible, even without considering the power storage or exchange with other systems (Grubb, 1991)

d) Finally, electric generation shares for the three major fossil fuels (coal, oil and natural gas) are developed. Future fuel shares reflect the increasing scarcity of oil over the study period; the availability of fossil resources in each region; a continuation of the current trend away from coal-fired and oil-fired electricity generation and towards natural gas-fired thermal plants; and the overall requirement to constrain CO_2 emissions in each region to within the target regional carbon budgets discussed in Section 1.1.2.

Figure 3-51 shows the resulting regional electric generation fuel shares for each scenario for 1995 and 2050. Figure 3-52 shows the breakdown of electricity generation in each of the three macro-regions. In the *Reference* scenario, generation expansion is expected for all feedstock fuels. The most rapid expansion is expected for renewable and natural gas plants, for which generation expands at an annual average growth rate of 2.8% and 6.8% respectively (the latter from a very low base in 1995). The generation from oil-fired plants almost doubles, even though the share of total electricity generated from oil declines from 6% in 1995 to 2% in 2050.

Figure 3-51. Regional electricity generation shares

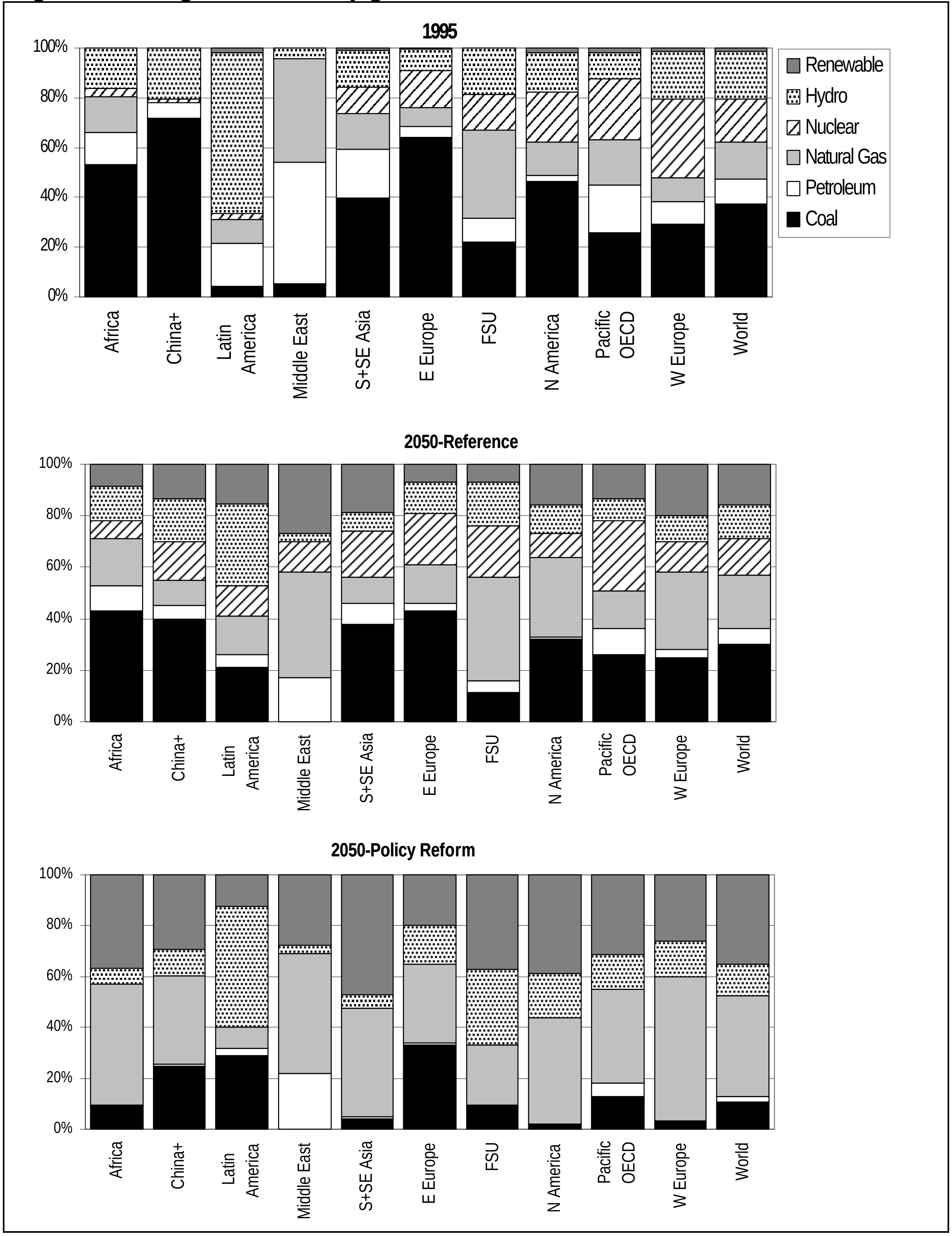
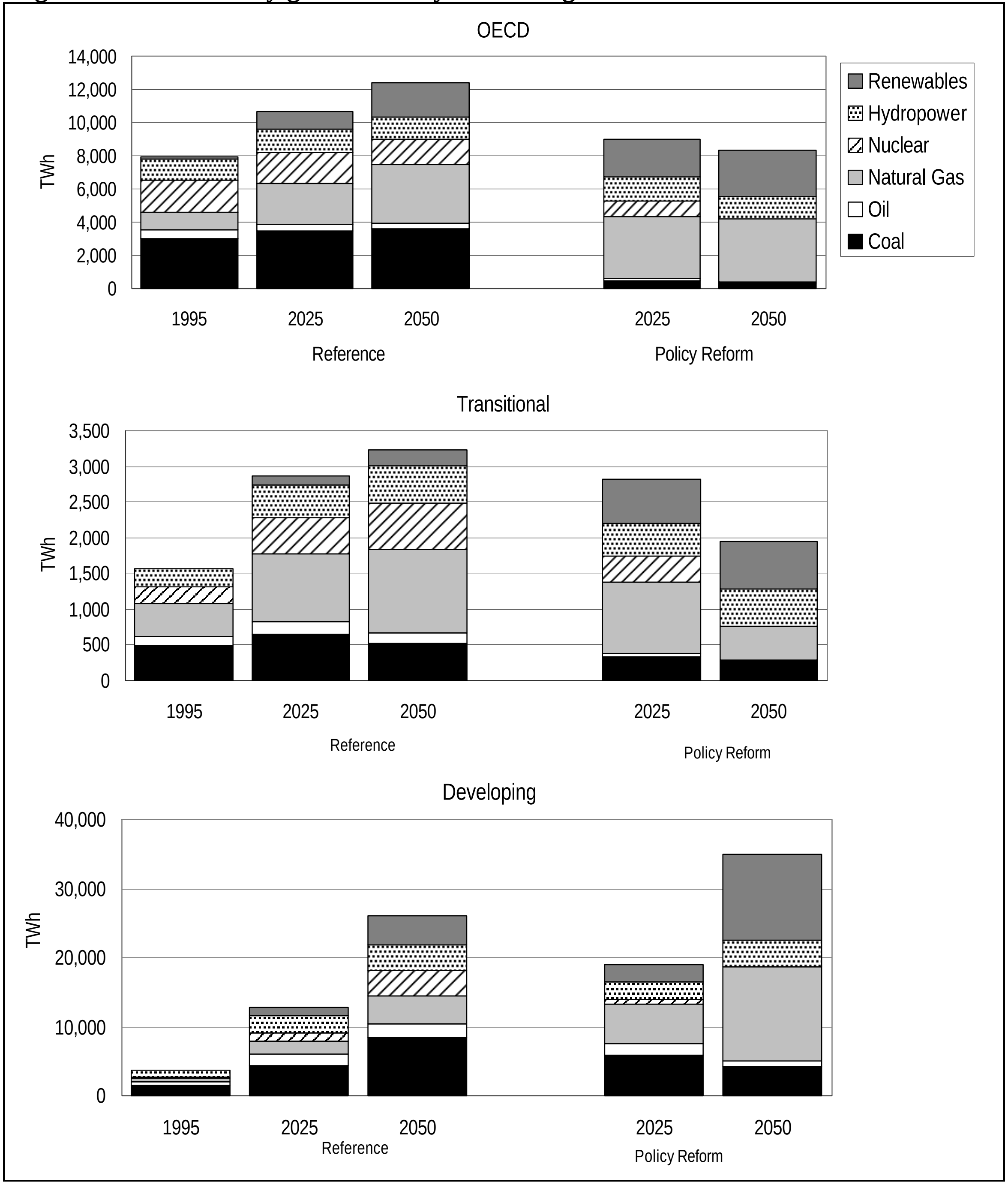


Figure 3-52. Electricity generation by macro-region



In the *Policy Reform* scenario, nuclear energy is phased out completely by 2050, while oil and coal both lose market share. By 2050, the global electric generation system comes to be dominated by advanced natural gas, biomass, hydropower, and renewable energy technologies (solar, wind, geothermal, municipal solid waste, etc.) In absolute terms, electric generation from coal declines slowly at a rate of 0.1%/year while oil-fired plants decline more rapidly at a rate of 0.5%/year. This places the burden of growth in electricity generation onto natural gas, biomass and renewables. Natural gas generation increases at an annual average growth rate of 4.1%, while for renewables a sustained growth rate of 8.5%/year is required. Although very high, it should be noted that this latter figure is based upon a very low starting point.[24]

In 2050, the total annual requirements for non-biomass renewable electricity reaches 15,872 TWh. This figure, which most likely would be met by a combination of solar, wind, geothermal and other renewable energy forms, is still far less than a recent estimate of the global potential for wind power of 53,000 TWh (Grubb and Meyer, 1993).

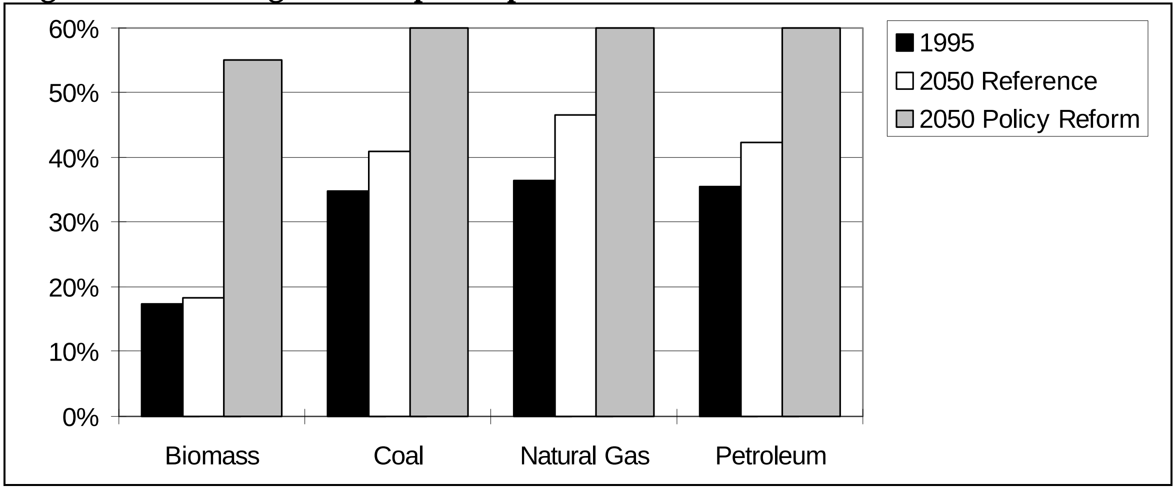
Trends in power plant efficiencies are summarized in Figure 3-53. In the *Reference* scenario, the average efficiency of plants in all regions reaches values typical of current prototype plants.[25] In the OECD regions, these efficiencies are reached by 2025 as existing plants are retired and new plants phased in. In other regions, which are lagging in these technologies, it is assumed that these efficiencies are reached by 2050. The *Policy Reform* scenario assumes a concerted drive to develop and deploy more advanced electric generation technologies, with average electric efficiencies reaching between 55 and 60% in all regions by 2050. Existing technologies, such as combined cycle thermal plants and integrated coal and biomass gasification are capable of meeting the goals set for the period to 2025 in the *Policy Reform* scenario, while in the longer term, fuel cell technologies can provide even greater improvements by overcoming the inherent thermodynamic limitations of thermal power generation. A similar effect would arise from the greatly expanded use of conventional technologies implemented as combined heat and power systems. Such systems are already capable of combined electric and heat efficiencies in excess of 60%. However, this assumes that district heating is capable of being developed much more widely than its current status, a possibility not explicitly modeled in this study.

---

[24] It may also be worth noting that in California, during the first ‘boom’ period for wind power between 1982 and 1986, annual generation from wind power was increased from 6 GWh to 1200 GWh — an annual average growth rate of 276% (Golob and Brus, 1993).

[25] In the *Reference* scenario, we use target efficiencies of 42% for coal, 45% for oil, 48% for natural gas, and 33% for biomass. In the *Policy Reform* scenario we use target efficiencies of 60% for coal, oil and natural gas and 55% for biomass, based on a range of sources including Johansson et al. (1993), and Lazarus et al. (1993).

Figure 3-53. Average electric power plant efficiencies



For district heating, the *Reference* scenario assumes the continued dominance of fossil fuels, with little change in overall fuel mixes and efficiencies. The *Policy Reform* scenario assumes efficiency improvements and gradual fuel switching away from coal and oil towards natural gas and biomass, in accordance with the overall decarbonization trends of the scenario.

3.4 Energy Supply

Primary supplies include the production of natural resources in a given region (fossil fuels, uranium, hydropower, biomass, geothermal, wind and solar), the trade in energy commodities and net changes in stocks. Primary supply in a given region is equal to primary production plus net imports (defined as imports minus exports) plus stock changes. As such, it is a measure of the total primary energy forms needed for activities in each region (and imports of final energy forms such as electricity). The energy systems of each region are linked through trade in fuel commodities and the interconnection of distribution systems.

Primary production is derived from both non-renewable natural resources (e.g., oil and gas extraction, coal mining, uranium mining) and renewable or potentially renewable resources (e.g., direct solar, wind, hydropower, biomass). Summing over regions, net imports in principle add to zero (since each unit of export from one region corresponds to an import in another).[26]

Current Accounts

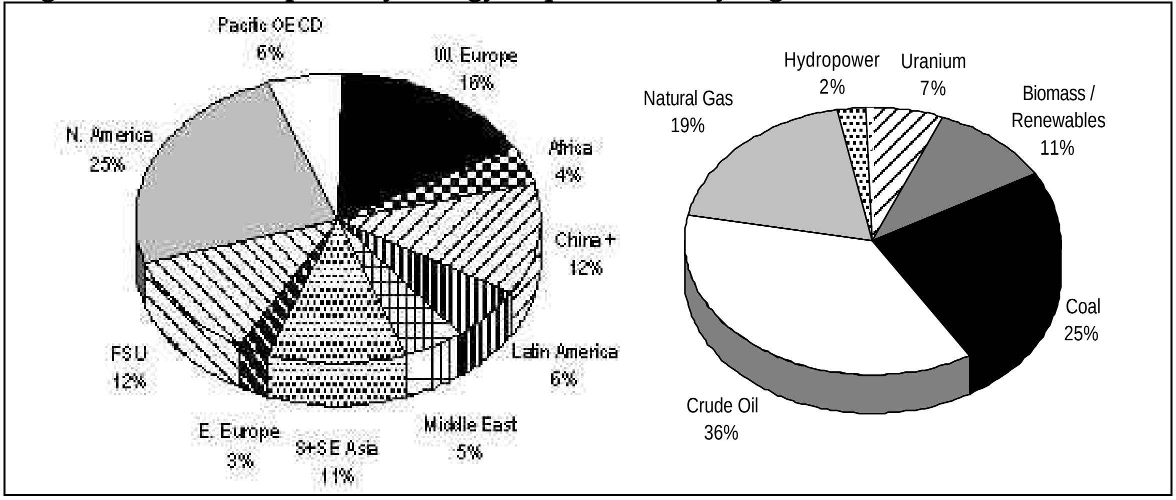
Current global primary energy use is about 384 EJ per year. The breakdown by type of energy source and region is summarized in Figure 3-54. The energy mix is dominated by fossil fuels which account for 80% of global primary energy supplies. Fossil fuels include crude oil (36%), coal (25%) and natural gas (19%), which along with uranium (7%) and hydropower (2%) comprise the major *modern* energy sources.[27] The other major primary energy source is biomass, which contributes 11% of global energy requirements. Biomass sources are dominated by the so-called *traditional* energy sources used in developing countries, such as wood for cooking, wood for charcoal kilns, dung and agricultural waste. Biomass statistics are quite uncertain, since the trade in these sources lies largely outside formal markets, where more reliable transaction statistics are available.

---

[26] In practice, they do not precisely match due to statistical and reporting errors.

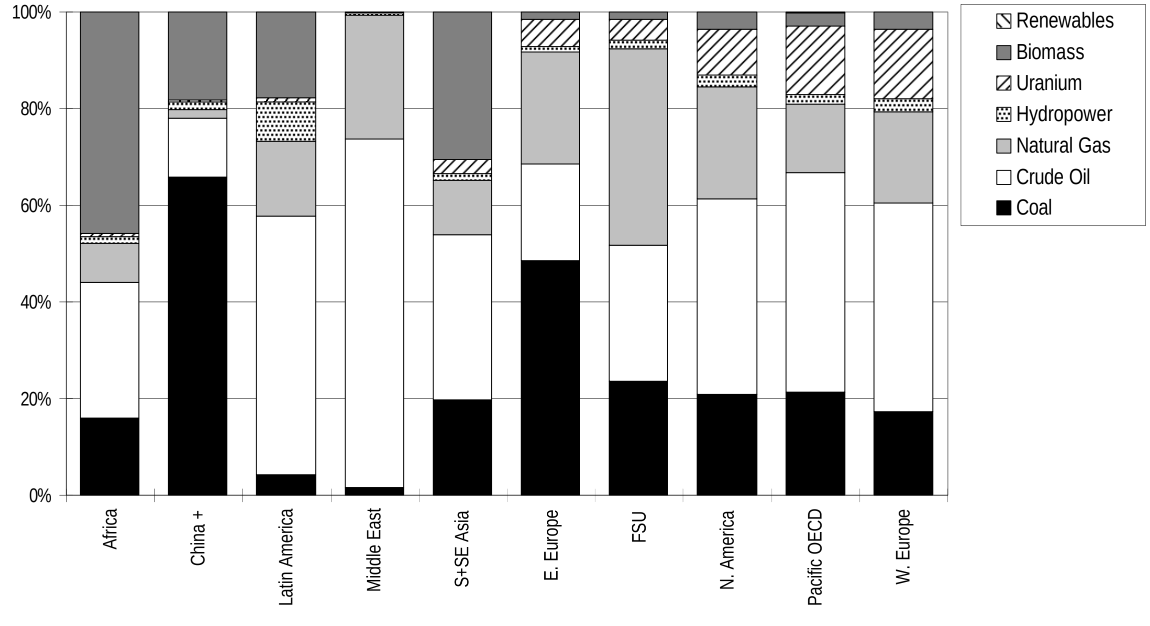
[27] Care should be taken in interpreting primary energy supply figures since different statistical sources often use different conventions for reporting the primary energy content of nuclear and renewable sources of energy. The conventions for efficiency adopted in this study are: uranium at 33%, geothermal at 10%, and hydro, wind, solar and other renewables at 100%. Other reports use the so-called “substitution” method, which express hydro resources in terms of an equivalent fossil fuel feedstock requirement.

Figure 3-54. Global primary energy requirements by region and fuel - 1995



There are substantial differences across regions in the mix of primary energy sources, as shown in Figure 3-55. For example, coal provides the largest share of primary energy in Eastern Europe and China+, while crude oil is dominant in Latin America and the Middle East. It is also worth underscoring the significant role played by biomass in Africa, Latin America, South and Southeast Asia and China+, accounting for between 18% and 46% of total primary energy.

Figure 3-55. Primary energy supply shares by region - 1995

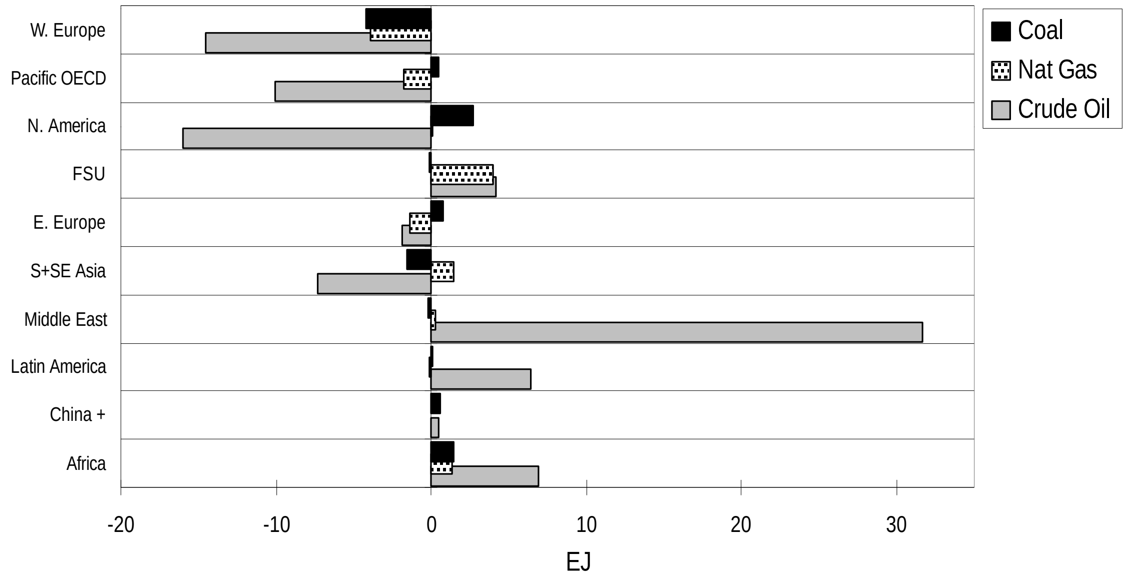


Notes: excludes electricity imports and exports

Since energy supplies are derived from either indigenous resources or from imports from other regions, the natural resource endowment is a critical factor defining a region's energy circumstance. Energy-dependent countries must devote foreign exchange earnings to cover essential energy imports for development and are vulnerable to the price fluctuations and interruptions in international energy markets. By contrast, those areas with substantial energy resources, such as the Middle East, command considerable geopolitical influence, but as exporters are also vulnerable to price fluctuations in the global market for oil.

Figure 3-56 shows net exports by region for the three major types of fossil fuels: oil, coal and natural gas. To gauge the degree of energy independence, we review the share of regional primary energy requirements currently derived from imports. The statistics are gathered in Table 3-14 for total fossil supplies and for each fuel expressed as the ratio of net exports (or imports) to primary energy supply of each fuel. A value greater than zero implies that the region is self-sufficient. One notes the high dependence of the OECD region on oil imports.

Figure 3-56. Net primary energy exports by region



Note: imports shown as negative values.

Table 3-14. Net exports as percent of primary energy supply

	Coal	Crude Oil	Nat Gas	All Fossil Fuels
Africa	52%	144%	101%	57%
China +	2%	9%	-2%	2%
Latin America	13%	50%	-2%	27%
Middle East	-80%	244%	6%	176%
S+SE Asia	-19%	-51%	30%	-18%
E. Europe	15%	-93%	-59%	-25%
FSU	-1%	33%	21%	18%
N. America	14%	-42%	1%	-14%
Pacific OECD	9%	-97%	-56%	-50%
W. Europe	-39%	-53%	-33%	-36%

Trade patterns correspond directly to the availability of exploitable reserves. Mineral statistics are generally organized into the categories of *resources*, which are estimates of all physical deposits, and *reserves*, that proportion of resources which is considered economically exploitable. The latter is in turn composed of proven reserves, which can be commercially exploited under today's technological and economic conditions, and estimated additional reserves recoverable, which are estimated to be recoverable (with reasonable certainty) given current geological and engineering information. Fossil fuel and nuclear reserves, including both proven and additional, are gathered in Table 3-15.

Table 3-15. Proven and additional reserves (EJ)

	Coal	Crude Oil	Natural Gas	Uranium @ < $130/kg
Africa	1,854	491	512	384
China+	7,958	1,606	142	2
Latin America	609	2,371	705	59
Middle East	8	3,899	2,793	-
South+South East Asia	4,543	140	442	19
E Europe	2,765	12	61	7
FSU	7,230	336	3,173	-
North America	7,475	264	726	268
Pacific OECD	15,748	17	57	311
W Europe	3,147	143	289	53
World	51,336	9,279	8,900	1,102
Developing	14,971	8,507	4,593	463
Transitional	9,995	348	3,234	7
OECD	26,370	424	1,072	632

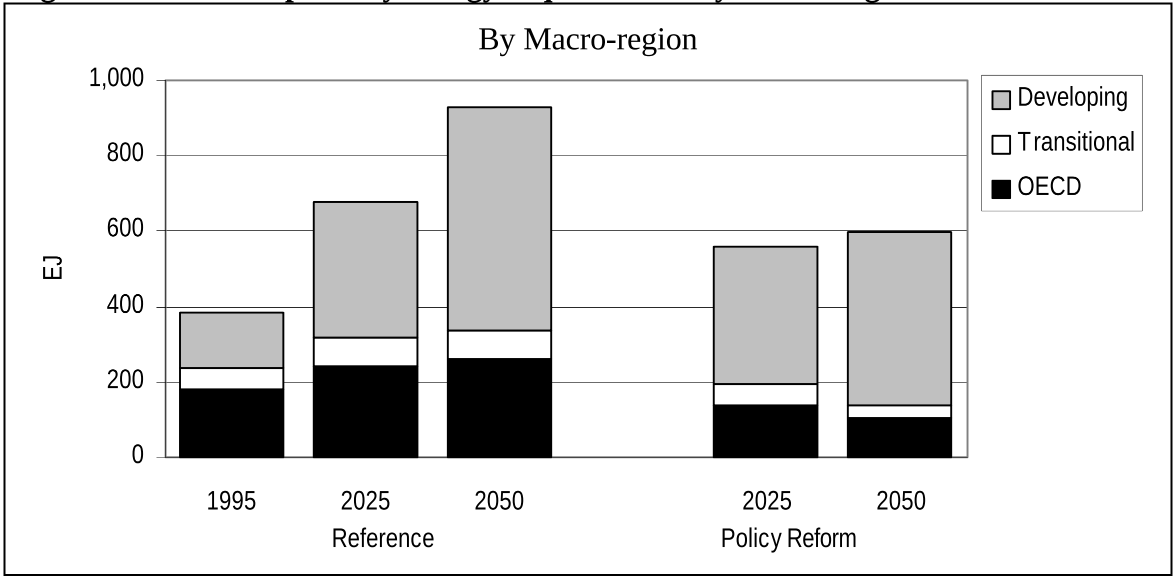
Source: Survey of Energy Resources (WEC, 1995 and WEC, 1992). Data for uranium are converted from mass to energy units assuming 1 tonne of uranium = 336 TJ, a figure appropriate for conventional open-cycle reactors. If fast-breeder reactors are assumed, the resource estimate increases by a factor of about 60.

A crude measure of the sufficiency of global energy reserves is obtained by dividing world reserves by the current annual consumption — about 141 EJ for crude oil, 73 EJ for natural gas, 91 EJ for coal and 25 EJ for uranium. If current patterns were to continue, the reserves reported in Table 3-15 would satisfy many decades of requirements for oil, natural gas and uranium, and several centuries of coal use. However, growing energy demands, environmental pressures and geopolitical concerns would constrain the abundance of these resources substantially, as we shall discuss in the next section.

Scenarios

Global primary energy requirements by macro-region are shown in Figure 3-57. They are also summarized by region and by source in sheets En1-1 and En-2 of the *BTC* Scenario Highlights, respectively. In the *Reference* scenario they grow at an annual average rate of 1.6% per year from 384 EJ in 1995 to over 900 EJ in 2050. A particularly rapid expansion is seen in the developing regions, where primary energy use quadruples from 150 EJ in 1995 to 591 EJ in 2050 — reaching more than half of the global total. By 2050, China+ overtakes the U.S. to become the single largest user of primary energy. Fossil fuels continue to dominate, accounting for 82% of global primary energy supply in 2050 compared to 80% in 1990. Nevertheless, over the same period these is significant absolute expansion in all fuels, particularly biomass and renewable energy forms.

Figure 3-57. Global primary energy requirements by macro-region



The annual average rate of growth in global primary energy requirements is halved to 0.8% per year in the *Policy Reform* scenario, with global primary energy requirements reaching 599 EJ in 2050. Fossil fuels continue to dominate, although their share falls to 72% of global primary energy supply in 2050. Primary energy requirements fall in the OECD and transitional regions to 58% and 62% respectively of their 1995 values, while demand in the developing regions triples, reaching 460 EJ — 77% of the total. By 2050, the primary energy use of the South and Southeast Asia region alone is more than the total of all OECD and transitional region countries. The changing mix of primary energy requirements is also noteworthy. Total requirements for coal decrease by about one third — reflecting the need to find less carbon-intensive fuels to help meet greenhouse gas mitigation targets. Because of its dominance in the transport sector, reducing oil consumption proves more difficult, so that in spite of initiatives to reduce its use in other sectors, overall oil consumption actually increases slightly, growing at an annual average growth rate of 0.1% per year. Natural gas and renewable energy forms grow rapidly; however, because of the lower total primary requirements, absolute natural gas requirements in 2050 are only 6% higher in the *Policy Reform* scenario than in the *Reference* scenario (215 EJ compared to 203 EJ respectively).

3.5 Energy Resources

BTC reviews the long-term adequacy of fossil fuel resources in the two scenarios. This section expands upon that discussion.

While additions to proven reserves of crude oil continue to keep pace with increases in demand, the long-term outlook for conventional crude oil resources is less comforting. Estimates of ultimately recoverable reserves — the total of previously extracted, proven and undiscovered reserves recoverable — have not increased greatly since the 1960s (Masters et al., 1990). Rather, estimated additional reserves have been gradually reclassified as *proven* reserves.

Remaining proven *and* estimated undiscovered oil reserves are approximately 1600 billion barrels (WEC, 1995; Masters et al., 1994), of which 1000 billion barrels is proven. As the demand for oil grows in both scenarios, these reserves would be depleted around 2035 (Figure 3-58). However, according to standard theories of oil exploitation, production decreases may occur much sooner, perhaps as early as 2010 when *half* of the global resource will have been extracted. These theories were first exploited in 1956 by M. King Hubbert to correctly predict that oil production from the lower 48 American states would peak around 1969 (Hubbert, 1956). According to the theory, adding the output of fields in a large region usually produces a bell-shaped curve that predicts crude oil production over time. While this simple production-based model does not take economic or political factors affecting consumption into account, its empirical approach does embody long-run technical improvements in extraction technologies (Mackenzie, 1996). Table 3-16 shows a range of estimates of ultimate crude oil resources and, using a simple linear interpolation of scenario crude oil consumption patterns, calculates the approximate date at which half the ultimate resource base will have been consumed in the two scenarios.

Table 3-16. Date at which cumulative oil consumption equals half ultimate resource

	Cumulative Production to date - 1995	Utlimate Resource	Aproximate date at which cumulative consumption = half of resource	
	GBO	GBO	*Reference*	*Policy Reform*
Reference Reserves	770	2,363	2009	2011
Low Reserves	770	1,770	1999	1999
High Reserves	770	2,890	2019	2021

Sources: Cumulative production based on Masters et al. (1994). Reference reserves from WEC (1995) and Masters et al. (1994), Low reserves from Campell and Laherre (1998), High reserves from WEC/IIASA (1995).

The results are remarkably insensitive to the differences in consumption between the two scenarios. Even with the most optimistic combination of the highest reserve estimate and the lower consumption levels seen in the *Policy Reform* scenario, the half-way point (beyond which rates of production could begin to fall) is reached by about 2021. It is worth noting that in the *Reference* scenario, annual crude oil requirements continue to grow enormously over the whole study period — more than doubling by 2050. Even in the *Policy Reform* scenario, annual requirements continue to grow at a rate of almost 1% per year until 2025 before declining thereafter. Even so, the rate of consumption in 2050 remains almost 10% higher than in 1995 — an outcome that does not appear plausible if the Hubbert theory proves correct, unless massive levels of unconventional oil are brought into production (see note 2 in Figure 3-58).

In practice, the gap between oil supply and demand is likely to be closed in a number of ways: supply might be increased by new discoveries of conventional sources, though this is not likely, or by unconventional options such as tar sands and oil shale (see notes to Figure 3-58). However, exploitation of these unconventional resources is likely to pose severe environmental problems and to be much more costly than conventional crude. On the demand side, the pressure on oil resources could be curtailed through fuel switching and efficiency improvements — options taken up in the *Policy Reform* scenario. Similarly, renewable and biomass-based substitutes for oil (e.g., hydrogen and ethanol) may gain acceptance more quickly than is assumed in either the *Reference* or *Policy Reform* scenario. The evolution of the transport sector will be especially important in this regard. Overall though, in the *Reference* scenario, the heightened risk of economic vulnerability and international conflict challenges the continuity and growth assumptions of the scenario.

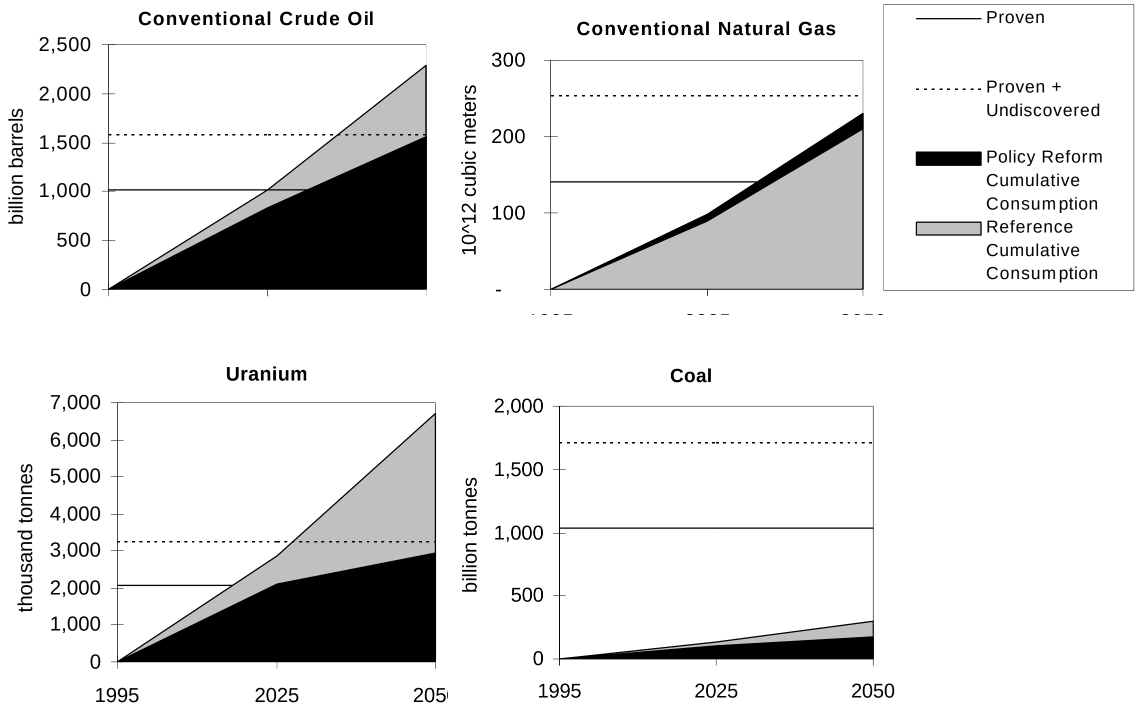
To a lesser extent, natural gas requirements in the scenario also push against conventional resource constraints, with the *Policy Reform* scenario actually requiring higher consumption than the *Reference* scenario. Global proven and undiscovered natural gas reserves are estimated at about 10-15 EJ (WEC, 1995; Masters et al. 1994) — roughly 300-400 trillion cubic meters. In both scenarios, proven global reserves are depleted around 2035, while remaining undiscovered resources are between 60% and 80% exhausted by 2050 in the *Reference* and *Policy Reform* scenarios, respectively. Coal reserves remain abundant despite the increasing demands in the *Reference* scenario. Environmental concerns further restrict the use of coal in the *Policy Reform* scenario.

Beyond global supply and demand relationships, the geopolitics of oil seems set to become a resurgent theme in the *Reference* scenario as industrialized regions increasingly depend on imports from the Middle East and Latin America (Swart, 1996). As shown in Figure 3-59, remaining oil reserves are heavily concentrated in the Middle East (42%), Latin America (26%) and China+ (17%).[28] The rest of the world, including OECD regions, accounts for only 15% of proven and additional oil reserves. Natural gas reserves are heavily concentrated in the FSU (36%), the Middle East (31%), Latin America (8%) and North America (8%).

---

[28] Again, these figures reflect *both* proven and undiscovered reserves. Considering proven reserves alone, the Middle East share rises to 64%.

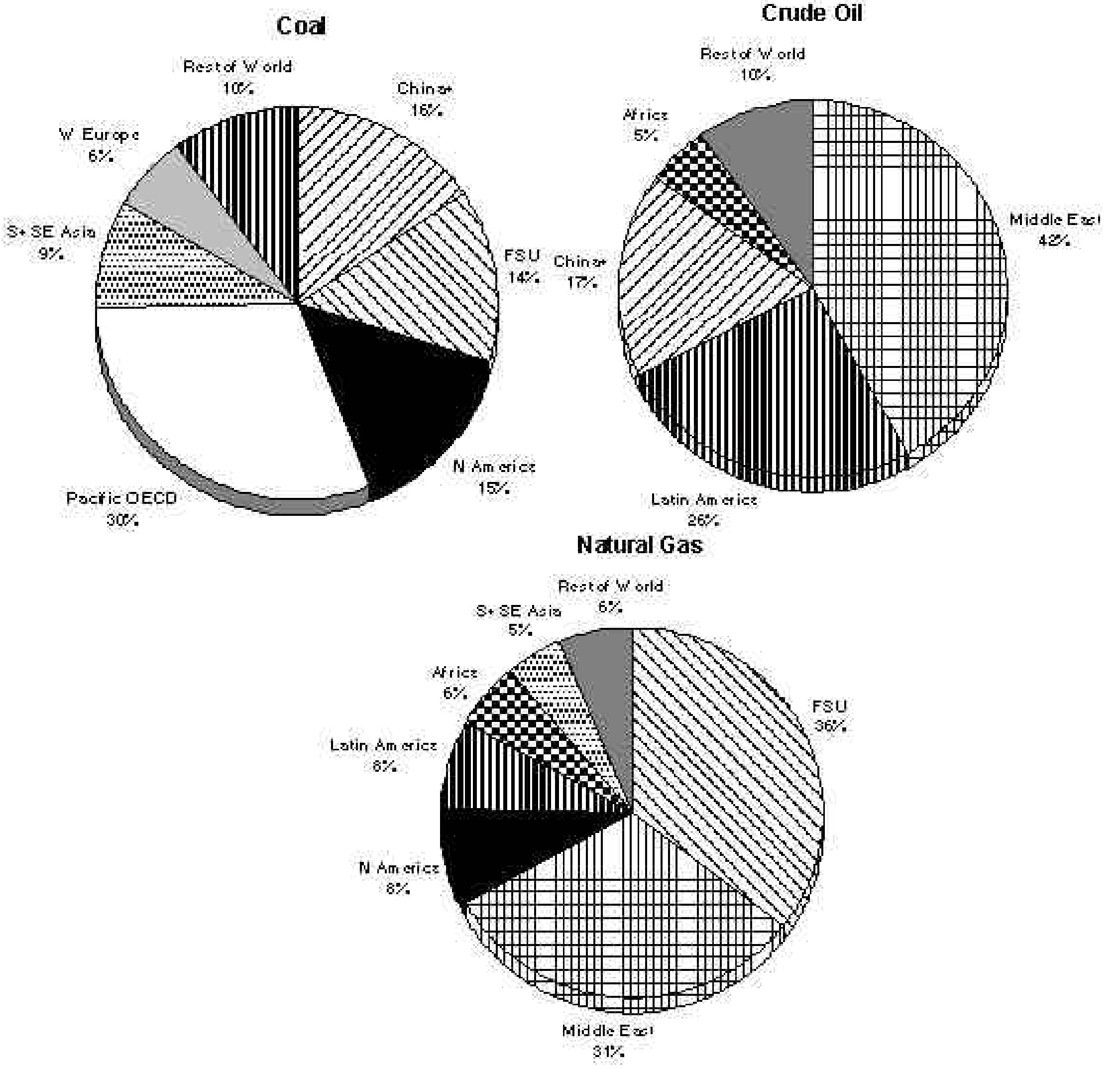
nium reserves compared to requirements



Notes:

1. Our estimate of crude oil reserves are based on WEC (1995) and Masters et al. (1994). We estimate proven reserves at 1,010 GBO with an additional 580 GBO of undiscovered reserves. A recent critique of industry figures (Campbell and Laherre, 1998) suggests that total unrecovered reserves may be much lower, due primarily to inflated estimates of current reserves based on P90 (90% probability) assessments, which by definition are 90% likely to be exceeded. That study asserts that much of the apparent recent increase in global oil reserves is actually due to reclassification of existing oil reserves, as early P90 estimates are upwardly revised. They estimate that remaining global proven reserves at the end of 1996 are as low as 850 GBO, and that undiscovered reserves account for only an additional 150 GBO. Other studies have used higher estimates of total unrecovered reserves (e.g., WEC/IIASA, 1995 uses an estimate of about 2,120 GBO), but these are based on P05% estimates, which by definition are only 5% likely to be met or exceeded. Advances in crude oil recovery technologies will probably help extend crude oil reserves, although Campbell and Laherre (1998) assert that oil companies routinely count on technological progress when computing reserve estimates
2. Estimates of conventional fossil reserves do not include non-conventional sources of oil and natural gas. Reserves of these fuels are poorly known but are likely to be enormous. They include, for example, an estimated 1,200 GBOE of heavy oil in the Orinoco oil belt in Venezuela, and 300 GBO of tar sands and oil shale mainly in Canada and the FSU. Exploitation of these resources, which will require large-scale strip-mining, is likely to pose severe environmental problems and to be much more costly than the exploitation of conventional crude oil. Natural gas hydrates (icy substances composed of methane and water found in sediments below the oceans and in cold regions such as Alaska, Canada and Siberia) are also a potentially huge source of fossil energy. One estimate (WEC/IIASA, 1995) places reserves of hydrates at 13,500 GBO. Again however, exploitation of these resources would be costly and pose environmental problems.
3. Uranium estimates assume conventional fission reactors. A full shift by 2025 to breeder reactors, which generate fissionable materials as a by-product and use uranium 60 times more efficiently than open-cycle reactors, would address the resource constraint in the scenario. However, in addition to the proliferation risks discussed elsewhere, breeder reactors pose the risks of higher cost and increased complexity relative to conventional nuclear designs. The only functioning breeder reactor, the Superphenix in France, has had severe operating difficulties (Sanger, 1994). The expansion of breeder reactors to meet the nuclear power requirements of the *Reference* scenario cannot be considered likely.

Figure 3-59. Unrecovered reserves of fossil fuels - 1995



Notes: Includes regional shares of proven plus undiscovered reserves. Shares based on physical units (tonnes of coal, barrels of oil, m^3 of natural gas) rather than energy content.

As a consequence of increasing oil demands and the regional variation in resource endowments, areas relatively poor in resources become increasingly dependent on imported oil. In the *Reference* scenario, by the year 2025, North America, Western and Eastern Europe, the Pacific OECD, South and Southeast Asia, and the FSU have become almost completely dependent on imports. The Middle East, China+ and Latin America are net exporters, while Africa meets more than half of its own requirements. These patterns have profound ramifications for international politics, global economic stability (the oil shocks of the 1970s suggest the potential vulnerabilities to oil price manipulations), and international security (the 1990 Gulf War is a recent case where oil politics contributed to international conflict). The *Policy Reform* scenario helps extend the timeframe over which the OECD and transitional regions can adapt their energy policies but, nevertheless, by 2050 all of the OECD and transitional regions are essentially completely dependent on imported oil. Developing countries, because of the increased levels of consumption in the *Policy Reform* scenario, become even more dependent on oil. Thus, both of these *Conventional Worlds* scenarios progressively intensify the role of the politics of oil in world affairs, with the attendant risks of economic vulnerability and heightened international tensions.

International trade is more constrained for natural gas because transport is more costly and technically complex than for oil. Most current trade occurs between contiguous regions using natural gas pipelines. For example, natural gas is piped in substantial quantities from the FSU to Europe, and from Canada to the United States. In addition, a significant amount of liquefied natural gas (LNG) is shipped from South and Southeast Asia to Japan, and from Northern Africa to Western Europe. However, the end-use costs of LNG are 30-80% higher than for natural gas, due to increased processing and shipping costs (BP, 1993).

As with oil, increasing natural gas demands and regional variations in resource endowments cause regions with relatively small resources to become increasingly dependent on imported natural gas. By the year 2025, in the *Reference* scenario, North America, Europe and the Pacific OECD all become more than 50% dependent on imported natural gas. The main exporters are Middle East, Latin America, FSU and, to a lesser extent, Africa. Between 2025 and 2050 all other regions become increasingly dependent on exports from these four regions. Similar patterns are seen in the *Policy Reform* scenario, except that the general level of dependency on imports in the OECD and transitional regions is reduced and that Africa becomes a net importer before 2025. These patterns of supply dependence have similar implications as those discussed above for oil.

Hydropower

Annual hydroelectric power production increases from about 2,530 TWh in 1995 to 5,560 TWh in 2050, in both scenarios. This level of output is well below both the technically exploitable potential, which is estimated to be 13,500 TWh/year (WEC, 1995), as well as the economically exploitable potential, which is estimated to be up to 8,830 TWh/year (WEC, 1995). In both scenarios, hydropower development has been explicitly limited to reflect at least partial avoidance of more environmentally and socially detrimental hydro projects (see Section 3.3). This stipulation severely limits hydropower development in the OECD, where hydropower generation increases by only 2% over the period 1995 to 2025. In the transitional regions, hydropower generation is able to expand by a factor of 2, while in the developing countries it almost quadruples.

Traditional Biomass Fuels

The debate about the “woodfuel crisis” has progressed since the early days in the early 1980s when woodfuel consumption was thought to be leading to large-scale deforestation in Africa and other regions. Since then, most experts have come to agree that traditional woodfuel consumption is not the major cause of deforestation in most parts of the world. Land clearing for agriculture and logging are now seen as the most common culprits of deforestation (see, for example, O’Keefe et al., 1984; Leach and Mearns, 1988; Munslow et al., 1988; Heaps et al., 1993). Nevertheless, issues of resource sufficiency, rural economic development and environmental stress remain important when considering traditional fuel scenarios.

While a lack of good data on consumption, collection, and resources makes the issue hard to quantify, there are known to be many areas of woodfuel shortage today. Indicators of shortage are increasing wood collection distances by rural householders (generally women and children), the substitution of animal dung and agricultural waste for woodfuel, and actions by rural people to either use wood more efficiently or plant trees.

In the *Reference* scenario, there is a gradual transition away from traditional biomass fuels as incomes improve and people move up the "energy ladder" to cleaner and more convenient fuels. However, this effect is counteracted by the high rate of population growth so that actual levels of household biomass consumption decline only slightly, from 28.5 EJ in 1995 to 25.8 EJ in 2050. In the *Policy Reform* scenario, strong actions to reduce poverty also tend to dramatically reduce traditional household biomass consumption, so that the total falls to 10.1 EJ in 2050. These declines in traditional biomass consumption are more than offset by the large increases in biomass consumption and production for "modern" uses such as electricity generation and production of transportation fuels. These "modern" forms of biomass are assumed to be grown sustainably and, while they do contribute to pressures on agricultural lands, they are assumed not to compete with existing stocks of wood used to meet traditional biomass energy requirements.

3.6 A Comparison with Selected Global Energy Scenarios

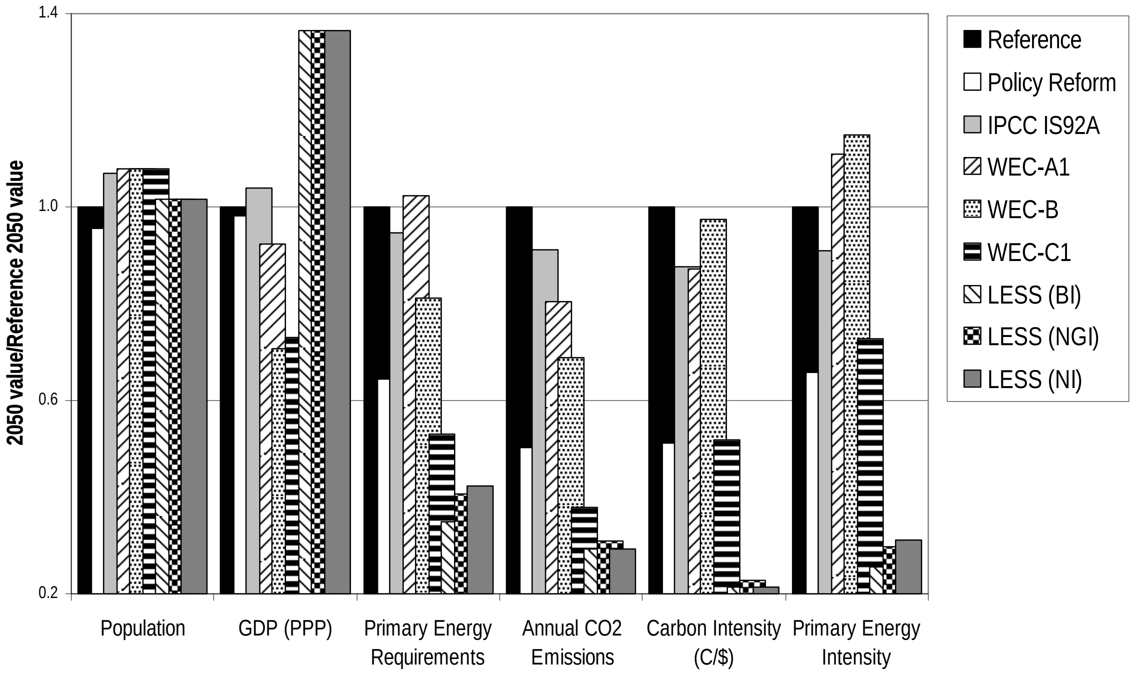
The two *Conventional Worlds* scenarios may be compared to the A1, B and C1 scenarios created for the report *WEC Global Energy Perspectives to 2050 and Beyond* (WEC/IIASA, 1995), the IPCC IS92a scenario (IPCC, 1992) and variants of the *Low CO_2-Emitting Energy Supply System (LESS)* (Williams, 1995). Where appropriate, we have interpolated the published results of those scenarios or converted them to a common basis to make them comparable to those from the two *Conventional World* scenarios presented in this report. The basic features of these scenarios are listed in Table 3-17.

Table 3-17. Characteristics of selected energy scenarios

Author	Scenario	Characteristics
IPCC	IS92a	The IPCC's reference greenhouse gas emissions scenario. Assumes carbon intensive supplies, moderate efficiency gains, moderate deforestation, and modest emissions control technologies. Additional variants (IS92b-f) reflect uncertainty in a range of assumptions for population and economic growth rates, energy supplies, restrictions on CFCs and other gases, etc. (not reviewed here).
Williams	LESS (BI)	Biomass-intensive variant of a scenario examining supply-side options for climate change mitigation.
	LESS (NI)	Nuclear-intensive variant.
	LESS (NGI)	Natural gas-intensive variant. Assumes high recoverable reserves and modest decarbonization of natural gas. Additional coal-intensive and high demand variants not examined here.
WEC/IIASA	A1 - "High Growth"	High economic growth, high fossil resource availability, moderate energy intensity improvements, and no CO_2 emissions constraints. Variant A2 assumes lower oil and gas availability and extensive switching to coal (not reviewed here).
	B - "Middle Course"	Medium economic growth, medium fossil resource availability, low energy intensity improvements, and no CO_2 emissions constraints.
	C1 - "Ecologically Driven"	Medium economic growth, low fossil resource availability, high energy intensity improvements, and CO_2 emissions constraints. Variant C2 is a nuclear-intensive variant (not reviewed here).

Figure 3-60 shows selected scenario indicators in 2050 for each of the scenarios relative to the equivalent value in the *Reference* scenario. All six of the scenarios show similar levels of population growth. However, the scenarios diverge on their assumptions concerning world economic growth. In particular, the LESS scenarios assume a world economy that is approximately 40% larger in 2050 than the IPCC or *Conventional Worlds,* while the WEC scenarios assume a world economy that is between 8% and 27% smaller than the *Conventional Worlds* scenarios.

Figure 3-60. Indicators for selected scenarios in 2050

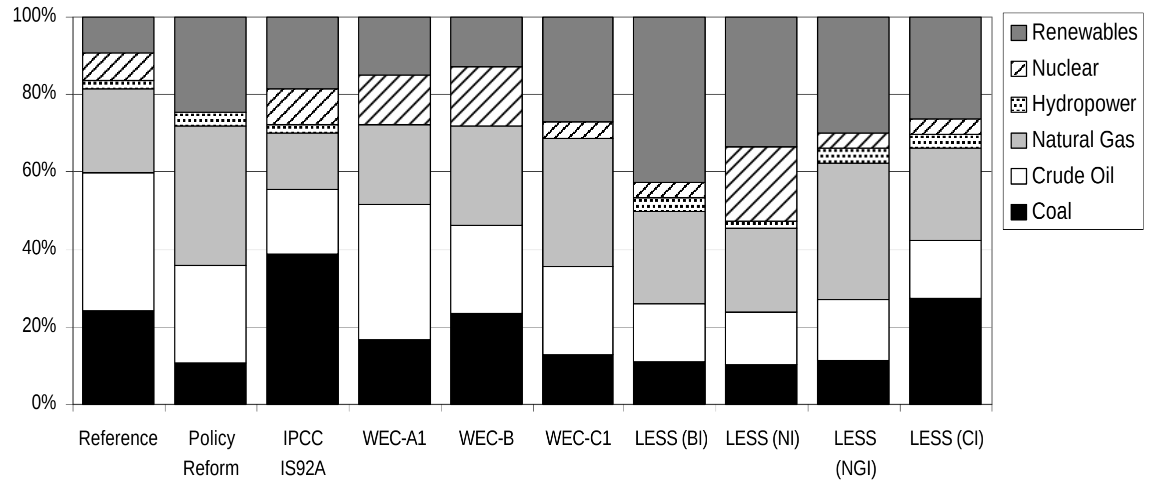


Note: GDP and primary energy requirements adjusted to conventions used in this study.

Primary energy use varies widely. The IPCC IS92a and WEC-A1 scenarios show similar levels of primary energy use to the *Reference* scenario, reflecting their overall ‘business-as-usual’ perspective. Given their different perspectives, it is not surprising that the various scenarios embody different emissions trajectories. In particular, the three LESS scenarios and the WEC-C1 scenario all depict emissions trajectories that are consistent with stabilization of CO_2 concentrations at below the 450 ppmv assumed in the *Policy Reform* scenario.

The consequences of these policies can be seen in the primary energy requirements in 2050 for each the scenarios, shown in Figure 3-61. The three ‘business-as-usual’ scenarios (*Reference*, IPCC IS92a and WEC A-1) show a continuing dominance of fossil fuels and relatively modest penetration of renewables. The remaining three scenarios show varying degrees of fuel-switching, away from coal and oil and towards natural gas and renewable energy forms, and varying perspectives on the future role of nuclear energy. Note the broad similarities across the *Policy Reform* scenario and the WEC-C1 (“ecologically driven”) scenario.

Figure 3-61. Primary energy requirements in 2050 for selected scenarios



Notes:

- Primary energy is expressed using IEA conventions for primary energy content (as used in the rest of this study). Hydropower and non-biomass renewables are expressed as their electrical energy equivalent.
- The WEC scenarios do not explicitly separate hydropower, biomass and renewables. For these scenarios, hydropower is subsumed into the renewables category.

4. Agriculture, Land and Food

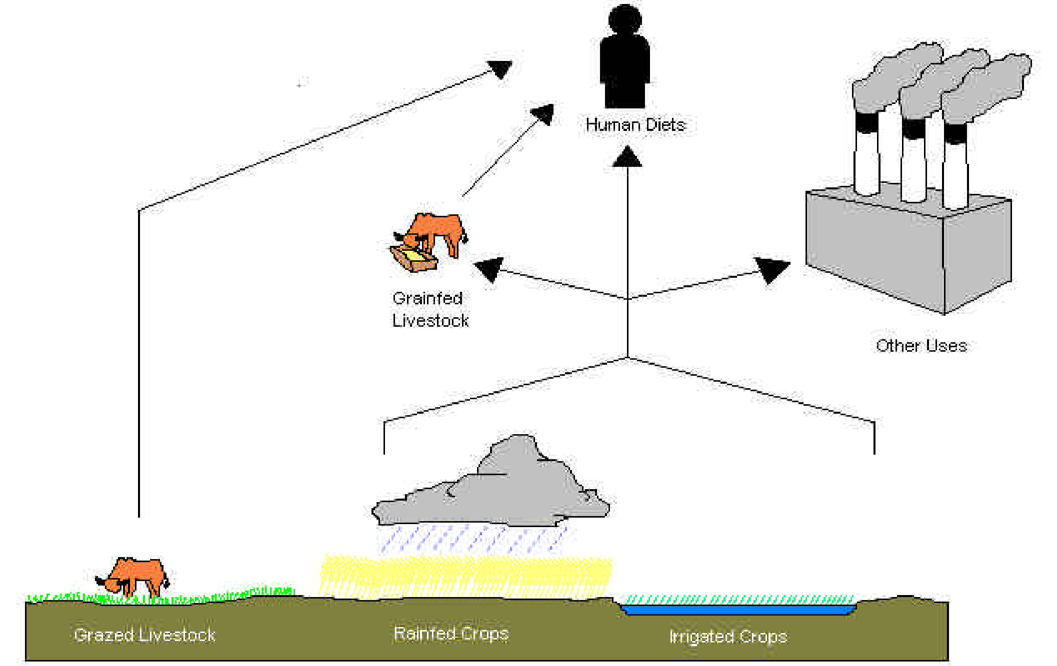
4.1 Land and Food

Agriculture and land are treated together because of the important role that agriculture plays in determining how land is used, through requirements for cropland and grazing land. These agricultural demands compete with land requirements for human settlements, parks and protected reserves, issues which are explored in Section 4.6. Agriculture also places pressure on freshwater supplies, for irrigation, watering of livestock and aquaculture. Of these, irrigation is by far the most important, and will be treated with other water requirements in Section 5. Finally, demand for seafood places pressures on fisheries, which are already stressed today (FAO, 1997c). This topic will be addressed in various subsections.

The *Reference* scenario analysis is an update and elaboration of an earlier study of agricultural production and land use (Leach, 1995). The analysis uses a later base year (1995 versus 1990), newly updated sources of data, and updated methodologies for making projections of certain key variables. Some of the text in this chapter is adapted from the report of the earlier study.

In one sense the agriculture scenarios can be seen as translating human dietary and industrial requirements for agricultural products into a land-use “footprint” (fisheries aside). The linkages are illustrated in Figure 4-1. In the analysis, agricultural products are separated into crops and animal products. Both crops and animal products are consumed for food and feed; in addition, some crops are used as fuel or as industrial feedstocks. As illustrated in the figure, crops can be grown on either rainfed or irrigated land. Livestock can be raised on feedlots, on grazing land, or through some combination of these two sources. In addition, livestock can be fed crop residues or wastes. The food production capacity in a given region depends on the amount of land and water available, the yields that can be achieved, and the mix of crops, livestock and production practices that are adopted.

Figure 4-1. **Principal connections between land use and food consumption**



Note: Some livestock products (e.g., milk) are consumed by livestock as feed, a link not shown here.

In the land-use analysis, requirements for livestock and crop production are balanced against other demands. As populations and average incomes increase, the built environment (land for human settlements) expands into cropland, grasslands, forest and other areas. In many countries land is set aside for preservation, recreation and scientific study, and expansion into these protected areas is limited in the scenarios. Increasing demands for crops, livestock and settlements lead to a loss of forest land. In this study, the difference between the total land area in each region and the sum of cropland, grazing land, the built environment, forest, woodland and protected areas is a category called "Other Land." It can include wasteland, parks (other than those included in protected areas or built environment), and any other land not included in the other categories.

The principal source for data on food and land for this analysis is the FAOSTAT database (FAO, 1996b).[29] The nominal base year for the analysis is 1995. However, not all statistics were available for 1995, so the current accounts are based on the 1994 values. Also, the land-use categories in the FAOSTAT database differ from the ones used in this study; they have been supplemented with information from other sources, as explained in Section 4.6.

Requirements for agricultural products as food are presented first, in Section 4.2. Livestock production and demand for feed is treated in Section 4.3. Crop requirements

---

[29] Some adjustments have been made to the FAO statistics to construct the dataset used in the analysis. For example, the barley used in beer is added to total grain consumption, applying an assumed ratio of tonnes of barley per tonne of beer to the FAOSTAT figure for beer production. Several adjustments are necessary for the FSU, where there are gaps in the available data.

other than for food and feed are treated in Section 4.4. Crop production and trade is discussed in Section 4.5. The land-use scenario is presented in Section 4.6.

4.2 Demand for Food

Current Accounts

The composition of human diets varies widely from region to region, based on the availability of different foods and local preferences. At the coarsest level, the analysis starts with the calories per capita of food available for human consumption in each region.[30] The total is then separated into consumption from different commodity groupings. Note that total calories per capita is larger than the amount of food actually consumed (FAO, 1996b). The remainder is lost to spoilage and plate waste (W. H. Bender, 1994; 1997).

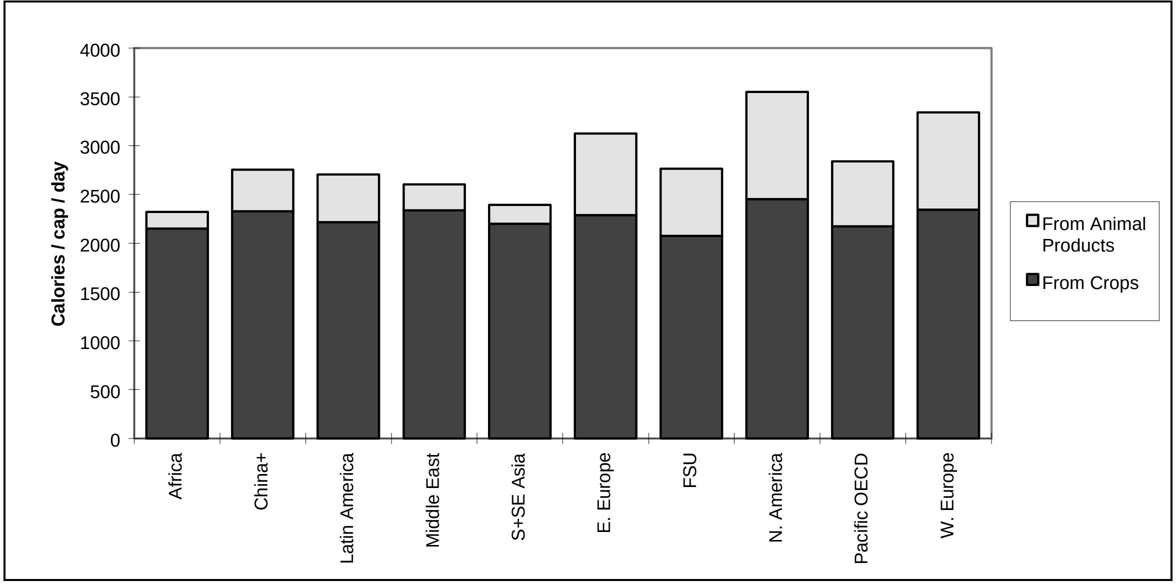
Of the total calories consumed, some come from crop products and some from animal products (including fish). Total caloric consumption, with the contribution from these two broad sources, is shown in Figure 4-2. Consumption in the OECD and transitional regions is higher than in the developing regions, and more of the calories come from animal products. The lowest level is in Africa, about 2320 Calories per capita. The highest is in North America, where average consumption is 60% higher than the physiological food requirements estimated by Bender (1997) for high-income countries, indicating high levels of waste (W. H. Bender, 1994; 1997) or overeating. Note that the average does not represent the food availability for each individual; unequal distribution of food can lead to chronic hunger in part of a population, even if the average consumption is sufficient.[31] The approach to estimating chronic hunger in the scenarios is discussed in Section 2.

---

[30] In food consumption analysis, the unit "Calorie" (= 1,000 standard calories) is often used, a convention we employ here in reporting quantitative results.

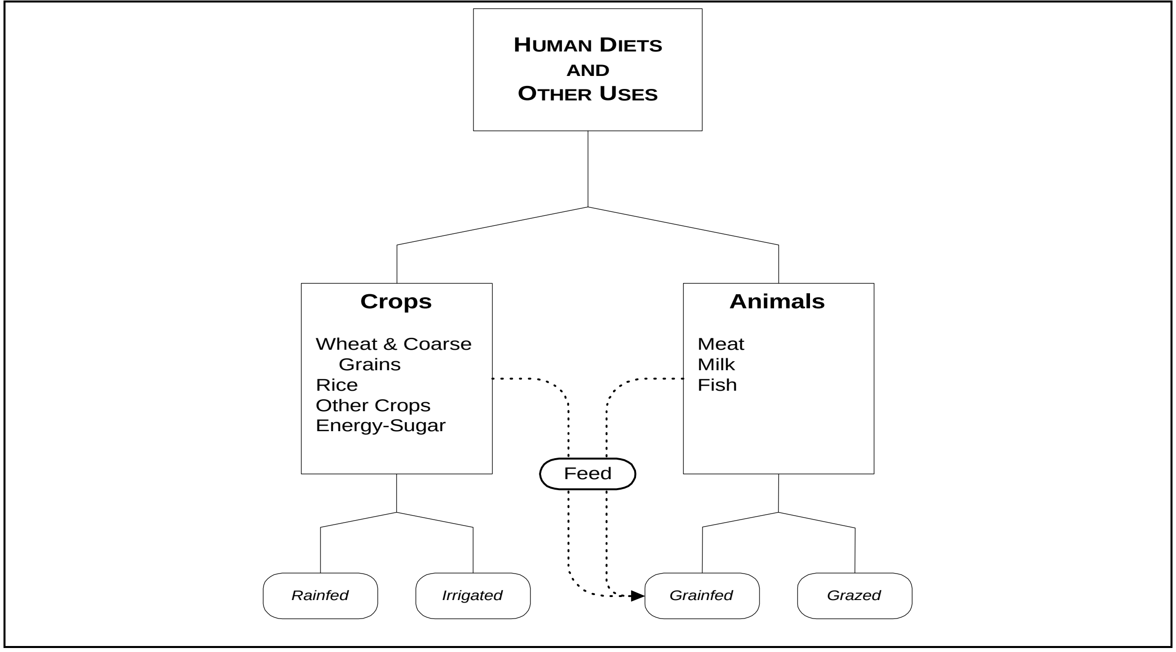
[31] Assuming a minimum plausible spread for the distribution of calories within a country, the FAO (1996e) estimated that 2700-2860 Calories per capita are required for food adequacy in developing countries.

Figure 4-2. **Caloric consumption per capita per day**



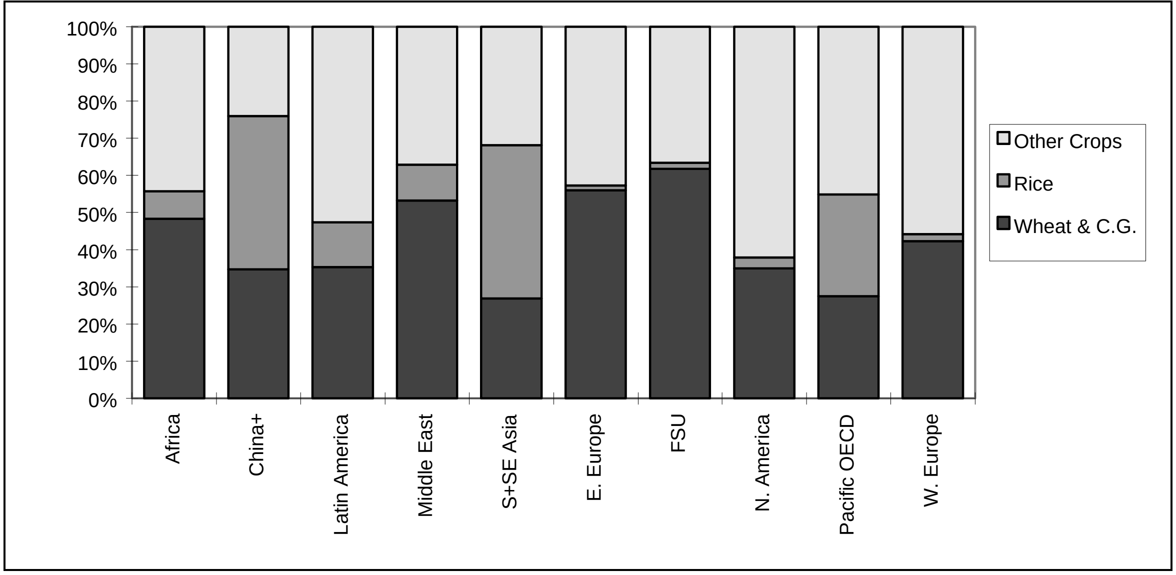
Diets are broken down further into contributions from individual crop commodities and animal products. This detailed disaggregation structure is shown in Figure 4-3. Crops used primarily as food and feed are grouped into the categories "Wheat and Coarse Grains," "Rice" and "Other Crops." This last category incorporates all non-cereal crops, such as vegetables, fruits, tubers and sugar crops. Sugarcane used for energy is put in a separate category, "Energy-Sugar." Today, only Latin America has substantial sugarcane production for energy. The animal products are separated into "Meat," "Milk," and "Fish," which includes all seafood.

Figure 4-3. **Crop and animal commodities**



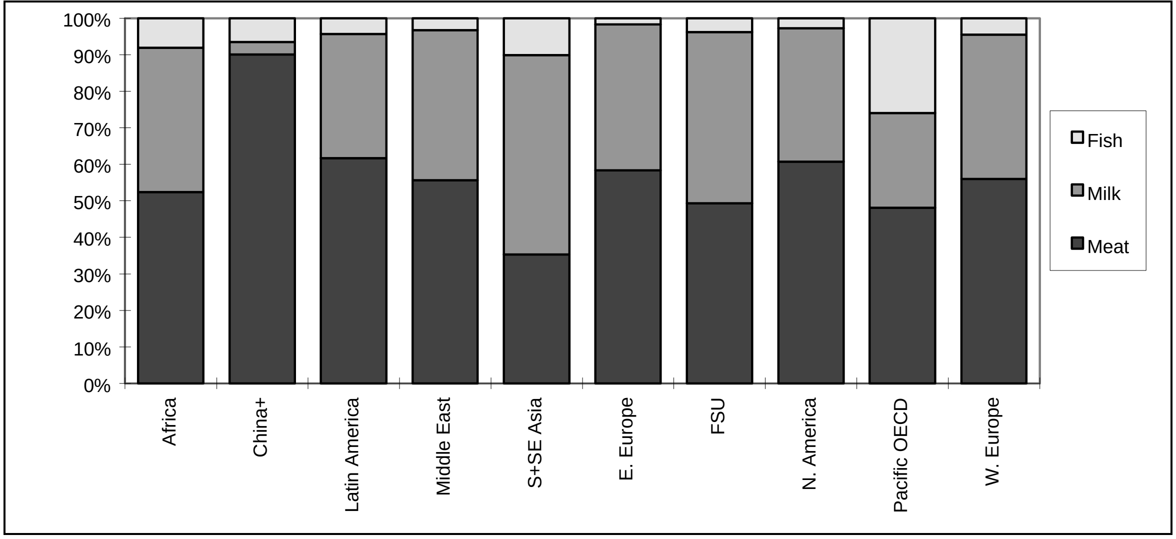
The shares of individual crop commodities in total crop product calories in diets varies considerably between regions, as shown in Figure 4-4. Cereals (wheat, coarse grains and rice) provide more than half the calories from crops in seven of the ten regions, the exceptions being Latin America (where fruit and starchy roots form a large part of diets), and the affluent regions of North America and Western Europe. The smaller fraction of cereals in the OECD is consistent with a general trend of a decreasing contribution of starchy foods to diets as incomes grow (W. H. Bender, 1994; 1997). Rice makes a relatively small contribution to the diets in most regions, with the exception of the Asian regions — China+, Pacific OECD and South and Southeast Asia — where the climate is favorable for rice production, and rice has long been a staple crop. However, because of the large populations in these regions, rice production worldwide (by weight) slightly exceeded that of wheat in 1994, and was only slightly less than that of maize. The three together amounted to 84% of all cereal production.

Figure 4-4. **Crop commodity shares in diets**



The shares of different animal products in total animal product calories in diets are shown in Figure 4-5. The relative contributions of milk and meat products to diets vary over a broad range from region to region. Meat dominates the caloric intake of animal products in China+ and Pacific OECD, while milk contributes the least. Fish is relatively unimportant as a source of calories for regions overall, with the exception of Pacific OECD. However, they can be important sources of protein and fats (Leach, 1995).

Figure 4-5. **Animal commodity shares in diets**



Putting all of these factors together—calories per capita, the fraction of calories from animal or crop products (crop or animal share), and the share of total animal or crop-derived calories from individual commodities (commodity shares)—and multiplying by the regional population, gives requirements for different foods within each region, in caloric terms. For the analysis, a further conversion is needed. In trade balances, production and net exports of agricultural products are conventionally expressed in mass terms, rather than energy terms, and this convention is followed here. The necessary conversion factor, the *energy content* of the agricultural commodities, can be calculated using FAOSTAT data, as the calories of food produced per unit mass of commodity leaving the farm. Combining all of these elements, the human food requirements, in tonnes, for a particular commodity are given by

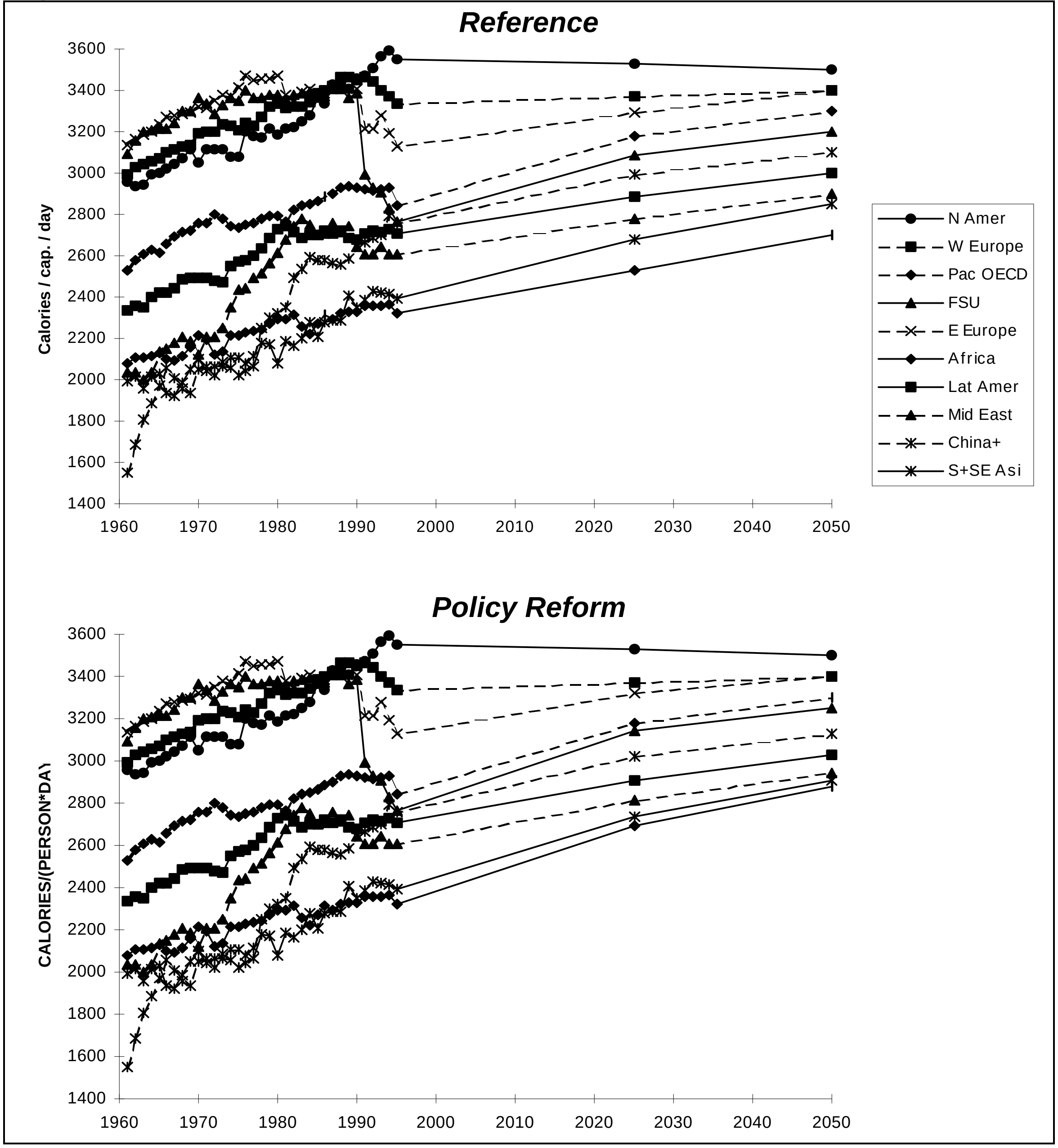
$$\text{Requirements} = \text{Population} \times \text{Caloric Intake} \times \text{Crop or Animal Share} \times \frac{\text{Commodity Share}}{\text{Commodity Energy Content}} . \tag{4-1}$$

Scenarios

In the scenarios, requirements for food are determined once each of the factors in Equation (4-1) is given a value. The populations in the *Reference* scenario are the UN medium projections, while those in the *Policy Reform* scenario are slightly smaller, as explained in Section 2. The caloric intake and shares give the composition of average regional diets; the scenario assumptions for these factors are described below. The energy contents are left at their base year values, which carries an implicit assumption that the composition within the different groupings stays roughly the same throughout the scenario.

The *Reference* scenario projections are based on those of Leach (1995). They take historical trends into account, as well as anticipated departures in the future from the historical trends. In North America and Western Europe, where caloric intake per capita is currently high (Bender, 1997), it is expected that intake levels off, or declines, due to saturation effects and health concerns, e.g., with respect to high-fat diets. In the other regions, as they become more urbanized and their average incomes grow, diets tend towards the pattern typical of Europe today. Historical trends and scenario projections are shown in Figure 4-6.

Figure 4-6. **Daily per capita caloric consumption; historical patterns and scenarios**



In the *Policy Reform* scenario, the relatively higher incomes in developing and transitional regions lead to higher average caloric intake.[32] In most regions the differences from the *Reference* scenario are small. The largest difference in caloric intake in 2050 between the scenarios is in Africa; consistent with this, the difference in hunger levels in 2050 between the two scenarios is also largest in Africa.

Generally, the variations in the contribution of animal products to total calories across regions is expected to converge in the scenarios to a narrower range than is seen today, varying in the *Reference* case in 2050 from about 13% in Africa to about 30% in the OECD and transitional regions, and in the *Policy Reform* case from about 17% to 30%. In contrast, today the figures range from about 7% to 31%. The recent trend in North America of decreasing animal calories continues in both scenarios, but at a slower rate, while in most other regions the contribution of animal products in diets grows, primarily at the expense of grains, as incomes and average caloric intake increase.

The historical patterns and scenario values are shown in Figure 4-7, and total consumption of animal products is shown in Table 4-1. The combination of population growth, increasing caloric intake and an increasing share of animal products in diets leads to large increases in requirements in some regions. In the *Reference* scenario, in Africa and the Middle East, requirements increase by over five times between 1995 and 2050, while in China+ they more than double. In the OECD and transitional regions changes are much less extreme, the largest being a 31% increase in FSU. In all regions except Africa, requirements in the *Policy Reform* scenario are close to those in the *Reference* scenario, as relatively higher consumption per capita in the non-OECD regions is offset by the smaller populations assumed.

---

[32] In both scenarios, caloric intake per capita in non-OECD regions is assumed to follow an "s"-shaped (logistic) curve with increasing income, asymptotically approaching 3400 Calories/capita. The other two parameters in the curve are fixed for each region by the base year intake and the intake in 2050 assumed in the *Reference* scenario. (In Eastern Europe, where caloric consumption is assumed to reach exactly 3400 Calories/capita in 2050, the value in 2025 is a linear interpolation.)

Figure 4-7. Contribution of animal products to diets

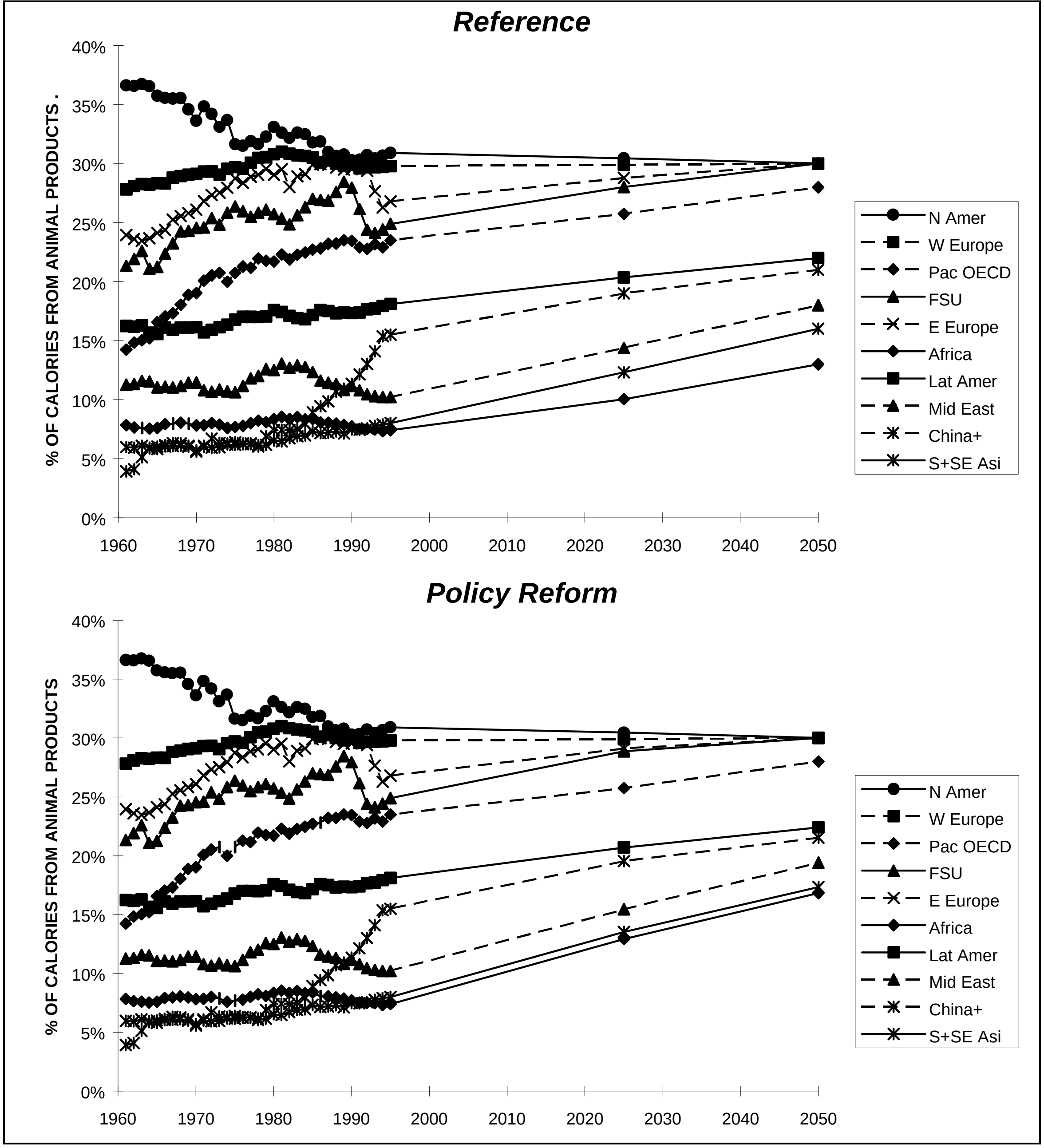


Table 4-1. Food requirements for animal products in the scenarios

Million tonnes		Reference		Policy Reform	
	1994	2025	2050	2025	2050
Africa	43	123	234	162	302
China+	101	180	220	190	222
Latin America	81	137	183	141	175
Middle East	16	47	84	49	85
S+SE Asia	118	260	412	295	419
E. Europe	27	29	29	29	28
FSU	67	82	88	84	85
N. America	124	149	154	149	154
Pacific OECD	35	44	46	44	46
W. Europe	160	169	162	169	162
World	772	1221	1613	1314	1679

In most developing regions, grains decline as a fraction of total diet. This is in keeping with historical patterns, in which higher-valued foods are substituted for grains as incomes increase (Conway, 1997; Leach, 1995). In Africa, grain consumption per capita increases as a substitute for other starchy foods, such as roots and tubers, which are included in the non-cereal "Other Crops" category. In South and Southeast Asia, grain consumption per capita declines slightly in preference for higher-valued crops, such as vegetables and fruit, as incomes rise. In the Asian regions, where rice consumption is high, wheat and coarse grains gradually substitute for rice in diets, in keeping with recent trends (Leach, 1995). Growing pressures on fish stocks lead to increasing use of aquaculture in both scenarios. However, the resulting increases in the price of fish are expected to constrain the growth of fish consumption in the scenarios.

Total food requirements for crop products are shown in Table 4-2. In the developing and transitional regions, total requirements are generally smaller in the *Policy Reform* scenario than in the *Reference* scenario, due to a relatively smaller share of crop products in diets and smaller populations. In most regions in both scenarios, the increases in requirements for crop products are not as dramatic as for animal products, a result of the declining share of crop products in diets. The largest increase is a factor of 3 in Africa over the course of the scenario.

Table 4-2. Food requirements for crop products in the scenarios

Million tonnes	Reference			Policy Reform	
	1994	2025	2050	2025	2050
Africa	393	817	1167	844	1141
China+	663	899	958	876	900
Latin America	385	592	711	577	685
Middle East	118	251	340	247	325
S+SE Asia	932	1580	2019	1549	1942
E. Europe	70	72	70	71	66
FSU	202	234	233	231	228
N. America	233	291	300	291	300
Pacific OECD	89	105	101	105	101
W. Europe	357	379	366	379	366
World	3441	5221	6265	5172	6055

4.3 Livestock

The nutritional requirements of livestock place significant pressures on land resources. They can do so directly, when the animals are grazed, or indirectly, when they are fed grain or other crops grown on cropland. The increasing consumption of animal products that occurs in the scenarios (Table 4-1) leads to large increases in feed demand.

4.3.1 Animal Products as Feed, Other Uses and Losses

Animal products are used for purposes other than just food. For example, cows' milk is used as feed for calves, and casein, a product of milk, is used in making paint and other products. The FAOSTAT database records consumption of animal products as feed and for "other uses," including industrial uses. These, combined with food requirements, give the total demand for animal products. In addition, there are inevitably some losses in collecting and transporting the final product: these are also recorded in the FAOSTAT statistics.

In the analysis, consumption of animal products for other uses is combined with losses. Together, in the base year they amount to less than 10% of total requirements in every region. In the scenarios, consumption for other uses and losses as a fraction of total production are kept at their base-year value.

Animal products used as feed are treated in a similar fashion to other uses and losses. Feed products are treated as a by-product of livestock production systems, rather than a target for production, which is reflected in the analysis by keeping the fraction of total production of animal products used for feed at the base year value in each region throughout the scenario. The resulting feed requirements are shown in Table 4-3.

Table 4-3. Requirements for animal products as feed

Million tonnes	Reference			Policy Reform	
	1994	2025	2050	2025	2050
Africa	2.2	5.3	9.2	6.1	10.5
China+	6.1	12.1	15.6	12.8	15.8
Latin America	8.0	13.5	16.9	13.7	16.2
Middle East	2.3	7.4	11.9	7.5	11.9
S+SE Asia	14.8	28.5	41.8	30.7	41.7
E. Europe	3.9	4.1	4.3	4.1	4.2
FSU	26.6	30.3	33.6	31.4	33.0
N. America	4.9	6.6	6.8	6.6	6.9
Pacific OECD	6.3	7.9	7.3	7.9	7.4
W. Europe	32.4	33.1	33.1	33.6	33.7
World	107.6	148.8	180.6	154.6	181.3

4.3.2 Trade

The sum of food, feed and other uses in each region is the domestic demand for agricultural products. Demand can be met through production within the region or through trade.

Current Accounts

According to FAOSTAT figures, in 1994 some 30 million tonnes of fish and 20 million tonnes of other kinds of meat were shipped across national borders. Regional flows, computed by aggregating from the national to the regional level, are smaller than national flows, since some national exchanges are internal to regions.

Net exports are reported here both in absolute terms and in terms of a *self-sufficiency ratio* (SSR). The SSR is defined as the amount of food (in tonnes) available from domestic sources, divided by requirements. In the FAOSTAT statistics, domestic production and changes in stocks are recorded for each country. In the current accounts, both of these are considered as domestic sources when computing the SSR, while in the scenarios, stock changes are set to zero. The SSR is given by:

$$\mathrm{SSR} = \frac{\text{Production} + \text{Stock Drawdowns}}{\text{Requirements}} = 1 + \frac{\text{Net Exports}}{\text{Requirements}}. \qquad (4\text{-}2)$$

Trade in animal products is shown in Table 4-4. Note that global net exports are not zero; this is a reflection of statistical errors in the reported data. The SSRs for most regions are quite close to one. The smallest ratio is that of the Middle East, with a value of 0.79. The small variation in the SSRs indicates that there is little trade compared to domestic production.

Table 4-4. Exports of animal products

	Net Exports (million tonnes)	SSR
Africa	(6)	0.88
China+	(4)	0.96
Latin America	5	1.05
Middle East	(4)	0.79
S+SE Asia	(7)	0.95
E. Europe	2	1.05
FSU	9	1.09
N. America	(1)	1.00
Pacific OECD	5	1.11
W. Europe	8	1.04
Total	7	1.01

Scenarios

In the scenarios, patterns of trade in animal products are based on those for the base year. The SSRs (Table 4-5) change little between 1995 and 2050. With the exception of China+, SSRs increase for regions that were net exporters in the base year and decrease for base-year importers. China+ moves gradually from a position of near self-sufficiency in the base year to complete self-sufficiency in 2050. The largest change is in the Middle East, where the SSR decreases in the *Reference* scenario from 0.79 in 1995 to 0.64 in 2050. This helps to reduce the pressures placed by livestock on land resources. SSRs in the *Policy Reform* scenario are very close to those of the *Reference* scenario, with slight adjustments to ensure that global net exports are zero.

Table 4-5. SSRs for animal products in the scenarios

		Reference		Policy Reform	
	1994	2025	2050	2025	2050
Africa	0.88	0.83	0.84	0.84	0.85
China+	0.96	0.98	1.00	0.98	1.00
Latin America	1.05	1.09	1.08	1.10	1.09
Middle East	0.79	0.66	0.64	0.66	0.64
S+SE Asia	0.95	0.95	0.96	0.95	0.96
E. Europe	1.05	1.07	1.11	1.09	1.13
FSU	1.09	1.09	1.13	1.10	1.15
N. America	1.00	1.09	1.13	1.10	1.15
Pacific OECD	1.11	1.11	1.19	1.13	1.21
W. Europe	1.04	1.06	1.12	1.07	1.13

4.3.3 Production

In the FAOSTAT database, the amount of each crop and animal product that is consumed as feed in the base year is recorded (in ktonnes), as is total meat and milk production (in both Calories and ktonnes). For this analysis, it is necessary to make some additional assumptions, to allocate feed resources to the production of different animal products. In this study three feed sources are considered explicitly: non-fodder crops, animal products and grazing land.[33] Other possible sources, which are not treated explicitly, are fodder crops, crop residues and wastes. Crop residues and wastes are important feed sources in developing regions. All three sources are expected to increase in importance in the *Policy Reform* scenario as part of combined crop-livestock systems. They are included implicitly in the analysis as a contribution to the productivity of grazing land.

Livestock production in the scenario is governed by the practice employed (grazing versus feedlot) and the productivity of each practice (the *land-to-production ratio* or *feed-to-production* ratio). Key considerations guiding scenario assumptions on productivity include:

- **Animal characteristics:** Energy requirements and the production of meat, milk and other products vary both between and within species. Animal characteristics have been improved in the past in all regions through breeding. The result of this historical effort is a variety of animals specially adapted for specific tasks, such as milk or meat production, or draft. In the scenarios, breeding programs are assumed to continue. In the future, improvements may also be gained through genetic engineering, a more controlled but perhaps more risky approach to producing animals with desirable characteristics (Conway, 1997; Krimsky and Wrubel, 1996).
- **Feed characteristics:** The quality and quantity of available feeds and forages vary from region to region. In the *Reference* scenario, in some regions continuing rangeland degradation is expected to lead to the replacement of grasses with less palatable plants. This trend will be reversed in the *Policy Reform* scenario. In both scenarios, production on grazing land may be improved by introducing new forage species.
- **Disease:** One-third of Africa is affected by trypanosomiasis (sleeping sickness), which limits cattle densities to as little as 30% of their potential in humid areas, and to 63% of their potential in sub-humid areas (FAO, 1998). Where it is not fatal, it reduces animals' weight, fertility, milk production and work performance. The disease has also seriously impeded growth in crop production, as it limits the number and productivity of draft animals in affected areas. In both scenarios the impact of trypanosomiasis and other diseases is expected to decline as a result of focused programs. Also, in the case of trypanosomiasis, the decrease will occur as a side-effect of clearing land (Crosson and Anderson, 1992).
- **Competition for feed resources:** Livestock are raised for many purposes other than the production of food; for example, they may be raised for draft, manure, prestige or financial security (Galaty and Johnson, 1990; Conway, 1997; Hudson, 1992; Durning

---

[33] "Grazing Land" is land suitable for grazing livestock (see, e.g., FGTC, 1991). Here the term is applied to the FAOSTAT land-use category "Permanent Meadows and Pastures." The composition of this category can vary from region to region, since often it is difficult to establish whether land suitable for grazing animals is actually used for that purpose (FAOSTAT Inquiries, 1998). As a result, this category is best thought of as a mixture of land use (land where livestock is grazed) and land cover (land suitable for grazing livestock). Note that this explains some variation in the reported totals. For example, in the United States, the USDA gives an area of 51 Mha for pastureland and 212 Mha for rangeland in 1992 (USDA, 1994), while the FAOSTAT total for the same year is 239 Mha. In contrast, Maheshwari (1995) reports that in India 4% of total land area is pastures (which agrees with the FAOSTAT figure), while 40% of the total area is available under rangelands.

and Brough, 1991). Animals raised for these purposes compete for feed with animals raised for food, increasing the ratio of input to food production. On grazing land, domesticated animals may also compete with wildlife for forage. In developing regions competition is expected to decline in both scenarios, as mechanization replaces draft power, chemical fertilizers replace manure, the social importance of livestock is reduced in the process of globalization and increasing wealth in all regions makes animals less important as "savings accounts." With the expansion of commercial ranching, wildlife densities are expected to decrease on rangelands.

- **Husbandry practices:** Many factors affect the overall productivity of a herd, such as the size of the breeding herd relative to the number of productive animals and the rate at which animals are culled and slaughtered . In the scenarios, practices may vary from region to region depending on local conditions, but to the extent possible, they are expected to approach those of the OECD and transitional regions, where the emphasis is on commercial food production.
- **Infrastructure:**. The availability of markets, veterinary services, wells, dip tanks and other resources affects overall productivity. In areas where these are scarce, a hardy but low-yielding animal is preferable to a higher-yielding but susceptible one (Homewood and Rogers, 1991). In the scenarios, the supporting infrastructure is expected to expand in developing regions.

Current Accounts

Feedlots

Total feed requirements for crop products are shown in Table 4-6. The highest demand for feed is in North America, where meat consumption is high. Western Europe and China+ have comparable levels of feed consumption, despite the much larger population in China+, due to different dietary preferences and degree of feedlot use.

Table 4-6. Feed from crops in 1994

Million tonnes	Cereals	Other Crops
Africa	15	8
Latin America	57	35
Middle East	18	1
China+	69	86
S+SE Asia	23	12
E Europe	40	17
FSU	94	26
N America	189	6
W Europe	108	40
Pacific OECD	22	1

The amount of meat and milk production on feedlots in the current accounts is estimated using a two-step procedure. First, the mass of feed consumed is converted to a caloric equivalent using the energy contents of crops estimated from FAOSTAT food statistics. Second, the estimated calories of feed are divided by a caloric feed-to-production ratio to obtain an estimate of the amount of production attributable to feedlots. For simplicity, the feed-to-production ratios in this study are taken to be the same for each region, with separate values for meat and milk.[34]

---

[34] The values used in the analysis are: 2 calories of feed per calorie of food produced from milk products, and 7 calories of feed per calorie of food produced from meat products. These values are based on the ratio of the mass of feed to mass of product used in

Using the assumed values for the feed-to-production ratios, and the FAOSTAT data on feed consumption and animal production, the *feedlot fraction* (the fraction of production attributed to feed from crops) can be estimated. For simplicity, in the analysis we assume that the feedlot fractions are the same for milk and meat production. The resulting estimates are shown in Table 4-7.

Feed requirements for fish are not considered explicitly in the analysis. Most of the feed demand for grain today is from cattle, pigs, sheep and poultry, with only about 5% being fed to fish.[35]

Table 4-7. Estimated base-year feedlot fractions

Africa	0.28
China+	0.18
Latin America	0.40
Middle East	0.75
S+SE Asia	0.18
E. Europe	0.71
FSU	0.73
N. America	0.70
Pacific OECD	0.31
W. Europe	0.35

Grazing Land

All livestock production that does not take place in feedlots is attributed to grazing land, with the total allocated to meat and milk production in proportion to the calories of meat and milk produced. The resulting estimates of the calories of meat and milk produced per hectare of grazing land are shown in Table 4-8. The ratios vary over a wide range, consistent with the general comments above about the variation in productivity and practices, and the uncertainty in the utilization of land.

Table 4-8. Meat and milk production on grazing land

	Million Calories per hectare
Africa	0.03
China+	0.31
Latin America	0.09
Middle East	0.02
S+SE Asia	2.56
E. Europe	0.75
FSU	0.07
N. America	0.15
Pacific OECD	0.06
W. Europe	1.65
World	0.17

---

the study by Tyers and Anderson (1992). Note that they are smaller than the feed-to-production estimates given in, e.g., Balch and Reid (1976), because the energy contents used to convert the feed from mass units to energy units are calculated from FAOSTAT data on food for human consumption, while (ruminant) animals can make use of more of the plant matter than humans can. After correcting for this factor, the feed-to-production ratios used in this study were found to be comparable to reported estimates.

[35] Based on figures from Brown et al. (1998), aquaculture production was 23.1 million tonnes in 1996, of which 85% was from non-carnivorous species. These require about 2 tonnes of grain per tonne of fish produced, which implies feed requirements of about 40 million tonnes, compared to 865 million tonnes of crops used for feed in 1994.

As discussed in the introduction to this section, the estimates in Table 4-8 of production from grazing land implicitly include crop residues, wastes and fodder crops (to the extent that the feed-to-production ratios are accurate). For this reason, the very high value of 2.6 million Calories of meat produced per hectare of grazing land in South and Southeast Asia may reflect a substantial amount of livestock production from sources other than feedlots or grazing land (Crotty, 1980), or it may be a result of different ways of defining "Permanent Meadows and Pastures" (see Footnote 33).

Scenarios

Feedlots

In the developing regions in both scenarios, demand for animal products increases more rapidly than population, with greater increases in the *Policy Reform* scenario than in the *Reference* scenario. As requirements for meat increase, it is expected that economic shifts and growing pressures on grazing land will lead to increased use of feedlots (*BTC*; Leach, 1995). In both scenarios the caloric feed-to-production ratios are kept at their base-year values, as are the energy content of the feed and its composition. Requirements for feed are then determined by the required livestock production (given by the regional demand, less net imports) and the amount of production that takes place on feedlots. In both the *Reference* and *Policy Reform* scenarios feedlot fractions increase steadily from 1995 to 2050. Base year estimates and scenario assumptions for feedlot fractions are presented in Table 4-9. The feedlot fractions increase faster in the *Policy Reform* scenario than in the *Reference* scenario, substantially faster in Africa, where the increase in meat consumption relative to the *Reference* scenario is greater than in the other regions. In part, this is due to the higher value placed on forests and productive cropland in the *Policy Reform* scenario relative to the *Reference* scenario, which constrains the expansion of grazing land.

Table 4-9. Feedlot fractions in the scenarios

		Reference		Policy Reform	
	1994	2025	2050	2025	2050
Africa	0.28	0.32	0.33	0.45	0.58
China+	0.18	0.19	0.20	0.19	0.24
Latin America	0.40	0.41	0.41	0.42	0.50
Middle East	0.75	0.85	0.89	0.87	0.92
S+SE Asia	0.18	0.21	0.23	0.30	0.35
E. Europe	0.71	0.75	0.76	0.75	0.78
FSU	0.73	0.80	0.81	0.80	0.81
N. America	0.70	0.76	0.79	0.78	0.82
Pacific OECD	0.31	0.45	0.52	0.50	0.55
W. Europe	0.35	0.42	0.46	0.43	0.47

Combined with the rapid increase in meat demand, the increase in feedlot fractions leads to very high rates of growth in feed requirements. Over the course of the *Policy Reform* scenario, feed requirements for wheat and coarse grains as a fraction of total requirements increase from 14% to 49% in Africa, from 14% to 53% in South and Southeast Asia and from 39% to 61% in the Middle East.

Requirements for crops as feed are shown in Table 4-10. Between 1995 and 2050, global feed demand for crops increases by over two times in the *Reference* scenario and by almost three times in the *Policy Reform* scenario. The increases are much higher in some developing regions: by a factor of over 4 in Africa, and over 5 in the Middle East.

Table 4-10. Requirements for crop products as feed

Million tonnes	Reference			Policy Reform	
	1994	2025	2050	2025	2050
Africa	23	85	178	169	424
China+	155	256	322	268	381
Latin America	92	174	241	193	292
Middle East	19	62	115	68	122
S+SE Asia	35	123	240	210	385
E. Europe	57	70	77	72	76
FSU	119	196	232	206	229
N. America	194	255	286	262	303
Pacific OECD	23	47	66	54	71
W. Europe	148	192	216	198	218
World	865	1460	1974	1699	2502

Grazing Land

In the scenarios, assumptions are made of the change in productivity of grazing lands, expressed as the calories of animal products produced per hectare. In the *Reference* scenario, the transitional and OECD regions maintain the same caloric production per unit area as in the base year. In the developing regions production per unit area increases steadily throughout the scenario.

The scenario results suggest that in Africa and South and Southeast Asia, the area of grazing land must increase to accommodate the increased demand for animal products in the scenarios. In Africa, grazing land area increases by 36% over the course of the scenario, while in South and Southeast Asia it increases by 54% (albeit from a relatively small base). This is in contrast to historical trends in the FAOSTAT data, which show slightly decreasing, but almost constant grazing land areas in these two regions since 1961. However, the qualitative trend of increasing grazing land in these regions is in agreement with the results of a study by RIVM and UNEP (1997). The increase takes place despite large increases in feed consumption and robust assumptions about improvements in land-to-production ratios.

Changes in a wide range of factors can lead to increased productivity. Some contributing factors were discussed in the introduction to this section. Furthermore, due to the ambiguity in the definition of “Permanent Meadows and Pastures” in the FAOSTAT database it is possible that some of the reported land area is underutilized; expanding into this land would increase production per hectare. A further factor affecting production of grazing land in this analysis is the implicit contribution of crop residues to increases in the productivity of grazing land. In both scenarios, crop production increases, and with it, crop residue production. However, in general, the amount of crop residues available for feed can be expected to increase at a slower rate than crop production, and may even decrease. In part, this is because an important strategy for increasing yields in plant breeding programs is to breed crops with a greater "economic" portion of the crop (e.g., the grain) relative to the rest of the total biomass; since the rest of the above-ground biomass is the residue, this is expected to lead to a declining ratio of residue production to crop production. Furthermore, if developing regions follow the pattern of OECD regions of separating livestock and crop production, then it may not be economical to transport the residues to the animals. Finally, in developing countries today, use of crop residues as feed is diverting nutrients from the soil (Bumb and Baanante, 1996); if more residues are retained in the future to improve the soil, it will reduce the supply available for animals. However, with total crop production almost tripling in Africa, and doubling in South and Southeast Asia in the scenarios, it can be expected that in some areas more crop residues will be available as feed. Moreover, in the *Policy Reform* scenario, especially, increased recycling of crop residues and wastes is expected as part of combined crop-livestock systems, in which a portion of the nutrients removed from the field with the residue returns in the form of manure (Conway, 1997; J. Bender, 1994).

In the *Reference* scenario no distinction is made between the different effects listed above; they are all combined into one improvement factor. The improvement factors are shown in Table 4-11.

Even with the assumed increases in productivity from grazing land and a shift to feedlots, grazing land area expands in several regions, especially Africa and South and Southeast Asia. The changes are shown in Table 4-12. The small relative changes in the Middle East are nevertheless significant, since over one-third of the land area is designated as "Permanent Meadows and Pastures" in FAOSTAT. In comparison, only 7% of the land area was under crops in 1994.

Table 4-11. Improvement factors in the *Reference* scenario

	2025	2050
Africa	2.3	4.0
China+	1.7	1.9
Latin America	1.8	2.3
Middle East	1.6	2.1
S+SE Asia	1.8	2.7
E. Europe	1.0	1.0
FSU	1.0	1.0
N. America	1.0	1.0
Pacific OECD	1.0	1.0
W. Europe	1.0	1.0

Table 4-12. Grazing land area in the scenarios

Million hectares		Reference		Policy Reform	
	1994	2025	2050	2025	2050
Africa	884	1082	1202	1136	1102
China+	518	531	552	517	510
Latin America	590	618	646	599	577
Middle East	225	228	229	217	212
S+SE Asia	36	48	56	51	48
E. Europe	14	14	14	14	12
FSU	354	364	379	371	358
N. America	267	265	251	264	250
Pacific OECD	429	448	462	448	464
W. Europe	78	76	71	74	72

In the *Policy Reform* scenario, it is assumed that actions are taken to meet terrestrial ecosystem preservation goals by reducing grazing land requirements. In most developing regions, increasing diets and animal fractions lead to more meat consumption than in the *Reference* scenario, despite slightly smaller populations. Using *Reference* scenario practices, this would lead to an expansion in grazing land requirements. Changes in practices and improvements in herds, including changes brought about through biotechnology, lead to improvements over the *Reference* scenario. For the developing regions there is an assumed 2.5% improvement over *Reference* practices in 2025 and a 5% improvement in 2050. In addition, there is a greater use of feedlots. The ratio of the area of grazing land to the area of cropland for feed required to support the same production of animal products is taken to be 1.8 for all regions.[36] With this combination of practice changes, improvements, and shifts to feedlots, the increase in grazing land area in the *Policy Reform* scenario is less than in the *Reference* case in developing regions, as shown in Table 4-12.

4.3.4 Fisheries and Aquaculture

Production of seafood from fisheries and aquaculture is summarized on Sheet P-9 in the Scenario Highlights of *BTC*. In the base year, demand for seafood is about 100 million tonnes, while the current yield from fisheries is between 85 million and 90 million tonnes (FAO, 1997c). The remaining demand is met from aquaculture. However, the fishery yield today is not optimal. Production can be increased in some areas, while in others stocks are being over-fished. In many areas there is potential for increasing yields by reducing discarded by-catch.

In the *Reference* scenario the demand for fish and other seafood increases between 1995 and 2050 from about 100 million tonnes per year to 170 million tonnes. The production from fisheries is assumed to stay at base-year levels, while aquaculture production increases from about 10-15 million tonnes to 80-85 million tonnes.

---

[36] The factor of 1.8 was arrived at by examining characteristic production parameters for grazed livestock in the U.S. and comparing the estimated productivity to the productivity from cropland in North America, using the feed-to-production ratios adopted for this analysis.

In the *Policy Reform* scenario the demand for seafood in 2050 is slightly less than that in the *Reference* scenario, about 160 million tonnes. The main reason for the difference is the slightly smaller populations assumed in the *Policy Reform* scenario. Production from fisheries is assumed to increase over the course of the scenario to a level of about 100 million tonnes, through improved planning and reduction of discards, as explained in *BTC*. As a result of the higher production from fisheries and lower demand, production from aquaculture in 2050 (60 million tonnes) is about 25% lower than in the *Reference* scenario.

4.4 Other Uses for Crops and Losses

Current Accounts

Agricultural products may meet with a variety of fates in addition to being consumed as food or feed, although these are by far the most important. Crop and animal products are also used as industrial feedstocks of various kinds. Also, unless seeds must be purchased, as for some disease-resistant hybrids (Conway, 1997; Krishnamoorthy, 1983), some of the harvest from crops must be retained as seed for the next season’s planting. Added to all of the requirements are the inevitable losses between the farm and market. In the base year, industrial uses of crops are less than 10% of total requirements in every region, while losses range from about 5% to 15%, using FAOSTAT figures. Seed requirements are less than 10% of crop production.

Scenarios

In future years in both scenarios, with the important exception of sugarcane for alcohol in Latin America, industrial consumption for crops is kept in the same proportion to the total food and feed requirements as in the base year. Similarly, the fraction of the harvest retained as seed is kept at its base year value in each region. Losses as a fraction of total production are kept at the base year value.

Requirements for sugarcane for fuel are derived from the demand for fuel alcohol calculated as part of the energy scenarios (see Section 3). In the base year, Latin America is the only region with a significant use of sugarcane as an energy crop, and this is assumed to be true in the scenarios as well. Other energy crops that may become important in the future are perennial grasses and tree crops. These are not included in the scenarios but, because of their potential impact on land use, a rough estimate of the amount of land that might be required for energy crops is given below.

Tree Crops for Energy

One potentially important type of energy crop is fast-growing tree crops. In the base year, such crops make a negligible contribution to either land cover or energy. It is anticipated that targeted policies will be required if they are to become an important energy source, so they will not make a significant impact in the *Reference* scenario. For this calculation, in the *Policy Reform* scenario it is assumed that all biomass requirements above those in the base year are supplied by tree crops. This assumption allows us to make an order-of-magnitude estimate of the amount of land required.[37] Taking losses into account, Hall et al. (1993) estimate that hybrid poplar can provide 224 GJ of energy per hectare, using current technology. Applying this to the difference in biomass energy requirements in 2050 and those in the base year, gives an estimated 200 Mha of land required. This is 11% of cropland area in 2050, 5% of forest area and 6% of grazing land area; energy crops could potentially compete for land with any of these other uses. However, in developing regions, biomass plantations are likely to be sited on deforested or otherwise degraded land (Hall et al., 1993). These lands contribute to “other” land in this analysis, so the establishment of biomass plantations does not necessarily conflict with the expansion of cropland that occurs in the scenarios, or with the sustainability goal for deforestation. The estimated area required for biomass is 8% of “other” land area in 2050.

4.5 Crops

In the preceding sections regional crop requirements for food, feed and other uses were developed. The requirements are met either through production within regions or through trade. The potential to expand production in each region is determined by the area of land suitable for crop production and the potential for increasing the productivity of cropland. In this study, expansion of cropland and potential increases in yields are set based on historical trends, following Leach (1995). Regional scenario assumptions are constrained by the assumption of continuity in trade patterns: i.e., SSRs are consistent with historical trends.

Crop production over the past 30-40 years was characterized by the advances of the Green Revolution (Conway, 1997). World production of cereals more than doubled between 1961 and 1994, while cropland increased by only 8% over the same period.[38] The considerable expansion in production, combined with only modest increases in cropland area, were made possible by increasing the yield for each harvest and the number of harvests each year on a given piece of land, through the introduction of improved crop varieties, widespread use of fertilizer and pesticides, expanded irrigation and mechanization. The rapidly increasing yields over this period were driven in large part through the efforts of international agricultural research centers, such as those of CGIAR (Conway, 1997). They developed and disseminated new varieties of plants and encouraged the use of fertilizers and pesticides to increase production.

These efforts undoubtedly enabled the world to avoid severe food shortages in developing countries: around 1970, 35% of the population in developing regions was hungry. By 1991 the percentage had dropped to 20%, despite an almost 60% increase in population in developing regions (FAO, 1996e). The absolute number of hungry in developing regions also fell slightly over the same period, by 8%, from 918 million to 841 million (FAO, 1996e). However, despite these successes, extreme hunger still persists, as discussed in

---

[37] The “biomass” category in the energy scenarios (Section 5) covers a diverse set of fuels, including wood and wood residues, charcoal, dung, agricultural residues and municipal solid waste. The provisional estimate made here can give an idea of the potential land-use requirements, but is not intended to replace a detailed analysis.

[38] Cropland is the sum of the FAO categories “arable land” and “land under permanent crops.”

Section 2. Also, the general improvement masks considerable differences between regions. In the effort to increase global production, agricultural research initially focused on improving yields on the best land (Conway, 1997). As a result, gains were concentrated in the "Green Revolution Lands" of South and East Asia, West Asia, North Africa and Latin America. People in less well-endowed countries and poorer people in better-endowed countries working poor and marginal lands, experienced much smaller productivity increases. The greatest decrease in hunger occurred in East and Southeast Asia, where many of the benefits of the Green Revolution technologies were concentrated, while in Sub-Saharan Africa the hungry population more than doubled between 1970 and 1991, from 103 million to 215 million (FAO, 1996e). Furthermore, recently growth in production has shown signs of slowing for some crops and some regions (Conway, 1997; Brown et al., 1997; Pinstrup-Anderson et al., 1997). Faced with a 60% increase in world population over the next half-century, this raises the crucial question of whether crop production will be sufficient to feed the world.

Today, the focus is shifting. While research in the 1960s and 1970s was aimed towards breeding improved varieties of the world's main grain crops, rice, wheat and maize, more recently research programs have expanded to include other crops, such as potatoes, sorghum and millet. There are calls for improving production on marginal land and finding solutions that have local, rather than global, applicability (Conway, 1997; Hudson, 1992).

4.5.1 Cultivated Land

Current Accounts

Globally, cropland accounts for 11% of total land area (Table 4-13). About 18% of cropland is irrigated, with the proportion differing considerably from region to region. In China+, for example, about half of the total area is irrigated, much of it riceland, while in Africa only 7% of the land is irrigated.

Table 4-13. Cropland area

	Area in Mha		Cropland as %
	Rainfed	Irrigated	of total land area
Africa	173	12	6
China+	54	53	9
Latin America	126	18	7
Middle East	29	15	7
S+SE Asia	205	84	34
E. Europe	35	5	44
FSU	209	19	10
N. America	211	22	13
Pacific OECD	50	5	7
W. Europe	108	16	27
World	1200	250	11

Potentially Cultivable Land

Increases in cropland area in the scenarios are constrained by the suitability for crop production of land currently being used for other purposes. For rainfed crops, several factors limit potential productivity (Alexandratos, 1995). The supply of rainfall must satisfy the water requirements of the crops, which are affected by environmental factors. The ability to grow crops is also affected by the fertility, slope and other properties of the soil. Note that these factors are not constant: the fertility of the soil can be enhanced or degraded by agricultural practices, pollution, or other causes.

Estimates of potential productivity of rainfed land for 91 developing countries were prepared by the FAO and the International Institute for Applied Systems Analysis in Vienna (Alexandratos, 1995; Fischer, 1993). The extent of potentially cultivable land and its distribution in different land-use categories was calculated based on these estimates. The results are shown in Table 4-14. In the *Reference* scenario, the land under built environment or in protected areas is considered unavailable for cultivation, so cropland can expand only into the potentially available land currently under forests and grasslands. (In the *Policy Reform* scenario, in the OECD regions some land currently protected or under the built environment is converted to cropland, as described in Section 4.6.) In Africa and Latin America, potentially available arable land accounts for about 80% of the total cultivable land, indicating considerable scope for rainfed cropland expansion in these regions. In the Middle East and South and Southeast Asia, only about 30% of the potentially cultivable land was undeveloped in 1989.[39]

Table 4-14. **Potentially cultivable land in developing regions**

Area circa 1989 (millions of hectares)	Total Rainfed	Under Forest and Grazing Land	Under Built Environment and Protected Land
Africa	973	793	101
China+	190	83	16
Latin America	944	777	110
Middle East	20	10	1
South and Southeast Asia	316	102	56

Source: Based on Fischer (1993).

In areas where rainfall is insufficient to support crops, or where limited rainfall constrains the length of the growing season, cropland can be irrigated to make it productive. However, estimates of irrigation potential are beset with difficulties: in particular, they are influenced by economic and political considerations, especially when the water must be transported across country boundaries (Alexandratos, 1995).

---

[39] A peculiarity of the data in Table 4-14 is that the reported total area of potentially cultivable rainfed land in the Middle East is smaller than the extent of rainfed land actually cultivated in 1989, an area of some 26 million hectares. However, as noted in Alexandratos (1995), land classified as “not suitable” based on potential yield may still be used for rainfed agriculture in some circumstances. They note that in North Africa and the Near East a large amount of potentially productive land is located in mountainous areas, much of which is judged unsuitable because of the steep slope of the land. Nevertheless, such land may be terraced to make it productive, overcoming one of the criteria used in the assessment (Alexandratos, 1995). In this study it is assumed that the economic and social conditions that make otherwise marginal land attractive for cultivation in the Middle East continue in the future, so the total increase in cultivated area in the scenarios exceeds the 10 million hectares reported in the table.

Bearing the uncertainties in mind, various sources suggest that the potential for expansion of irrigated agriculture is generally much less than that of rainfed agriculture (Alexandratos, 1995; FAO, 1995; Leach, 1995; Seckler, 1996). In the scenarios, the expansion of irrigated land is based on Leach (1995). The increase in irrigated area is modest, consistent with the general consensus.

Scenarios

Changes in cropland area in the scenarios are based on historical trends. As seen in Figure 4-8 and Figure 4-9, rainfed cropland area either remained steady or declined in most of the regions between 1961 and 1994. In only three regions — Africa, Latin America and Pacific OECD — did rainfed area grow over the period. However, the growth in all three regions is showing signs of slowing. In the *Reference* scenario, rainfed cropland decreases in China+ and increases in Africa, Latin America and Pacific OECD, in keeping with the historical trends. However, with the exception of Africa, the rates of change are slower than in the past. For Africa, which has a large area of potential cultivable land, the rapidly growing food demand that occurs in both scenarios is met in large part by expanding rainfed cropland.

Figure 4-8. Index of rainfed area in developing regions, 1961-1994

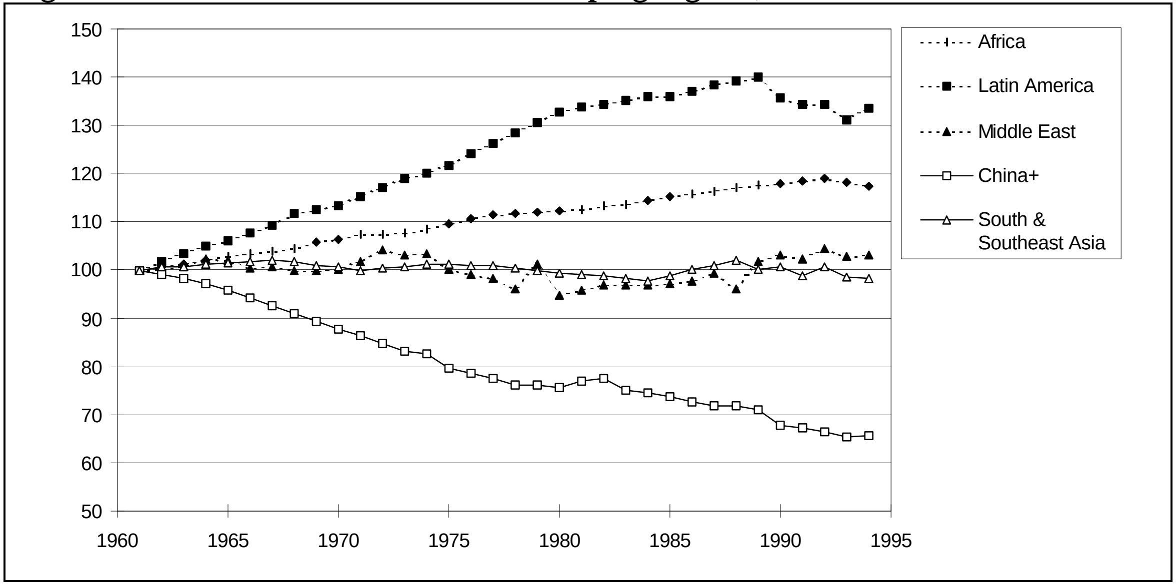
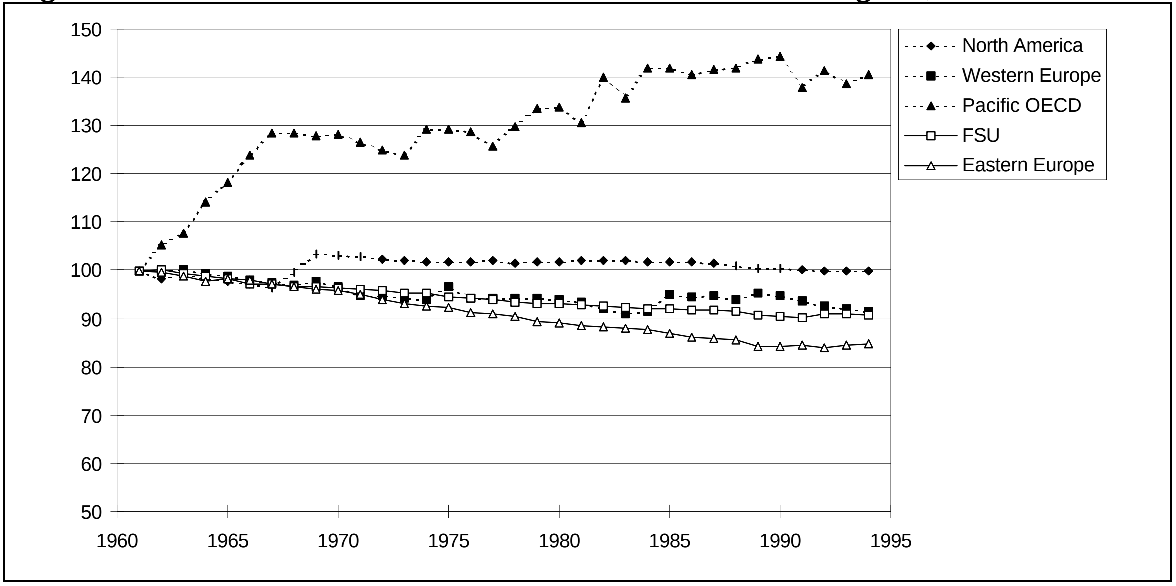


Figure 4-9. Index of rainfed area in OECD and transitional regions, 1961-1994



In contrast to the historical trends in rainfed cropland area, irrigated area increased in all 10 regions between 1961 and 1994, as shown in Figure 4-10 and Figure 4-11. The recent decrease in irrigated area in the FSU is assumed to reverse in the scenarios. In the *Reference* scenario, irrigated land area in every region is assumed to either increase or remain steady.

Figure 4-10. Index of irrigated area in developing regions, 1961-1994

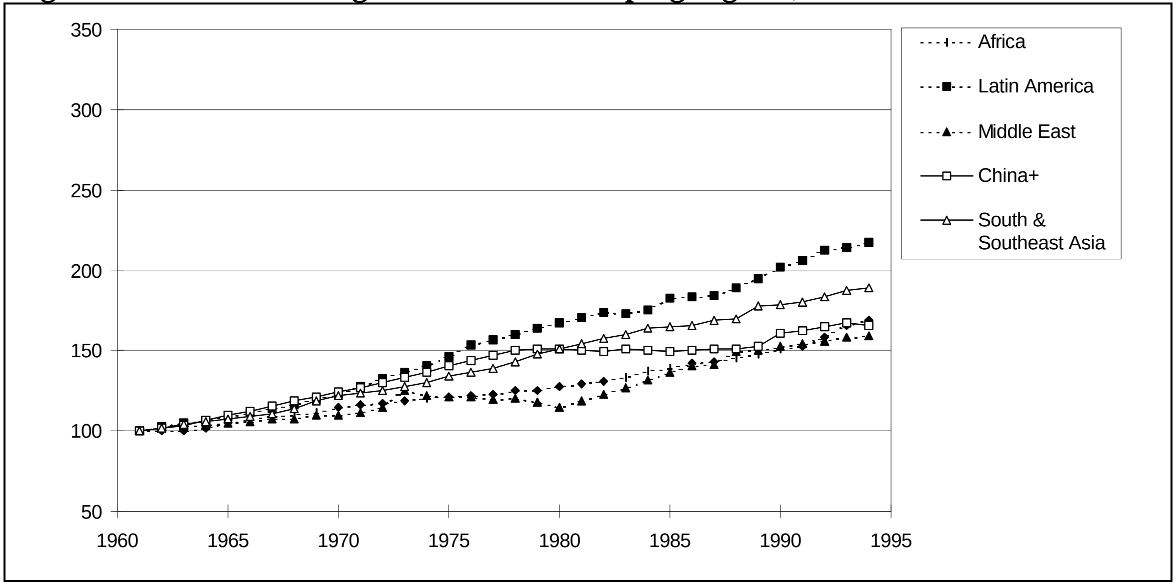
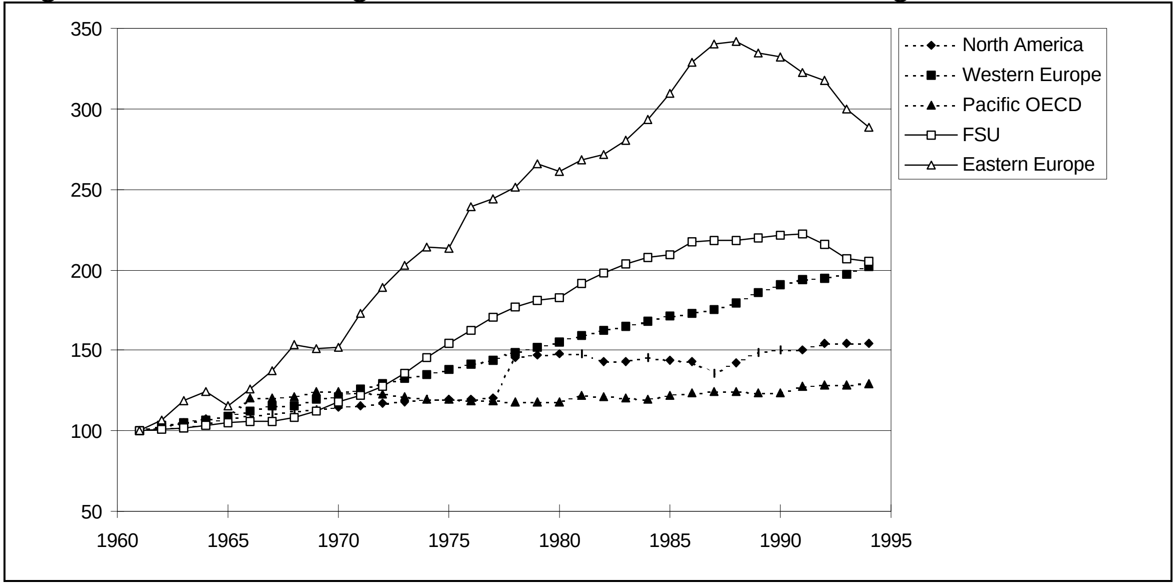


Figure 4-11. Index of irrigated area in OECD and transitional regions, 1961-1994



The cropland assumptions in the scenarios are shown in Table 4-15. In the Middle East, in the *Policy Reform* scenario water-conserving policies increase the cost of water, so irrigation water is increasingly diverted to higher-valued uses, leading to a decrease in the irrigated area. At the same time, the efficiency of application of irrigation water improves (see Section 5). In other regions, irrigated areas are the same in both scenarios. Higher demand for food and feed in the *Policy Reform* scenario leads to almost 10% more cropland area than in the *Reference* scenario in 2050.

Table 4-15. Cropland area in the scenarios

Area in Mha			Reference			
	1994		2025		2050	
	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
Africa	173	12	242	14	263	14
China+	54	53	54	56	47	58
Latin America	126	18	142	20	153	22
Middle East	29	15	29	17	29	17
S+SE Asia	205	84	199	95	210	99
E. Europe	35	5	32	5	32	5
FSU	209	19	198	21	204	23
N. America	211	22	202	23	213	24
Pacific OECD	50	5	57	6	59	6
W. Europe	108	16	105	17	108	19
World	1200	250	1260	274	1318	288
			Policy Reform			
			2025		2050	
			Rainfed	Irrigated	Rainfed	Irrigated
Africa			261	14	273	14
China+			58	56	51	58
Latin America			151	20	174	22
Middle East			39	14	44	13
S+SE Asia			188	95	159	99
E. Europe			35	5	36	5
FSU			214	21	229	23
N. America			229	23	307	24
Pacific OECD			57	6	54	6
W. Europe			115	17	135	19
World			1347	271	1461	283

In the *Reference* scenario most of the increase in land area occurs in Africa, Latin America and Pacific OECD. In Africa the increase of 49% over the course of the scenario occurs due to pressure on agricultural production systems for food and grain as populations increase, and as diets improve and include more meat. In the *Policy Reform* scenario, the largest increase is also in Africa, where cropland expands by 55% between 1995 and 2050. Land areas also increase significantly in Latin America, North America and Western Europe, in part from increases in exports to meet the demand from the increasingly affluent developing regions. (Exports also increase substantially in Eastern Europe and FSU, but the increased production is met primarily through yield increases.) Cropland area also expands in the Middle East, despite substantial imports, by almost 30%, much more than the 5% increase in the *Reference* scenario. In part, the relatively greater area is made possible because of the greatly reduced rate of land degradation assumed in the *Policy Reform* scenario (see Section 4.6.2). Sustainable production on the fragile rainfed land in this region will be challenging, especially if slower land degradation is to be achieved.

4.5.2 Crop Yields and Cropping Intensity

Current Accounts

The FAOSTAT database provides data on the production and area harvested for each crop. The ratio of these is the yield per harvest. Also provided in the database is total cropland area. The ratio of total harvested area to total cropland area is an aggregate measure of *cropping intensity*, the number of crops planted each year on the same piece of land. The cropping intensity can be less than one, if land is left fallow or planted to forage crops in some years, and can be greater than one if conditions are suitable for having two or three crop cycles in one year.

Separate yields (by crop) and aggregate cropping intensities on rainfed and irrigated land were available for four regions: Africa, Latin America, the Middle East and South and Southeast Asia (Fischer, 1993). These regions are primarily tropical, while the others are primarily temperate. Estimates of separate yields and cropping intensities on rainfed and irrigated land were made for the temperate regions, but due to the uncertainty in these estimates, for these regions only average yields and cropping intensities will be reported.[40] Base year estimates for cereal crops are shown in Table 4-16, and for non-cereal crops in Table 4-17. Also shown are the annual yields, the product of the yield per harvest and the cropping intensity.[41]

Table 4-16. Yields and crop intensities for cereals

	Harvest Yield (t/ha)		Crop Intensity		Annual Yield (t/ha/yr)	
	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
Africa	1.0	3.8	0.8	1.2	0.8	4.6
Latin America	2.0	4.5	0.8	1.1	1.5	4.7
Middle East	0.9	2.4	0.5	1.1	0.4	2.7
S+SE Asia	1.7	3.2	0.9	1.2	1.5	3.7
China+	4.4		1.4		6.3	
E. Europe	3.0		0.8		2.4	
FSU	1.5		0.6		0.8	
N. America	4.9		0.6		2.7	
Pacific OECD	2.1		0.4		0.8	
W. Europe	4.1		0.7		2.9	

Note: For the four developing regions listed separately, separate data on rainfed and irrigated production were available from Fischer (1993). For the other six regions estimates were constructed for yields and cropping intensities on rainfed and irrigated land to project water and fertilizer requirements, but are not reported here.

---

[40] The data from Fischer (1993) for the tropical regions are from around 1990; to assign values for the 1995 baseline, the ratios of the irrigated and rainfed yields were kept the same as in the original data, but the absolute values were adjusted to recover the average yields in the FAOSTAT database. For temperate regions the crop yields were derived from FAOSTAT data, and then split into separate values for irrigated and rainfed land using the average irrigated : rainfed ratios for the tropical regions.

[41] Note that it is likely that the actual yields in China+ are lower than the reported ones by as much as 15-20%, because the area of cropland is regularly underreported (Paarlberg, 1997). Taking this into account, the actual yields achieved may be closer to 5 tonnes/ha·yr for cereals and 10 tonnes/ha·yr for non-cereal crops. These values are still large compared to other regions because of extensive multiple cropping.

Table 4-17. Yields and crop intensities for non-cereal crops

	Harvest Yield (t/ha)		Crop Intensity		Annual Yield (t/ha/yr)	
	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
Africa	3.5	19.6	0.8	1.2	2.9	22.9
Latin America	6.6	34.6	0.8	1.0	5.2	35.9
Middle East	2.9	10.1	0.4	0.9	1.1	9.1
S+SE Asia	3.2	17.7	1.0	1.2	3.1	20.9
China+	8.6		1.4		12.3	
E. Europe	8.9		0.8		7.1	
FSU	5.5		0.5		3.0	
N. America	5.4		0.6		3.0	
Pacific OECD	11.3		0.4		4.3	
W. Europe	10.4		0.7		7.4	

Scenarios

The yield and cropping intensity projections for both scenarios are based on those of Leach (1995). In that study, no attempt was made to separate the various biophysical and social effects. Instead, the yield projections were based on historical trends and available data on maximum yields and potential improvements that had already been identified. As shown in Figure 4-12 and Figure 4-13, the productivity of cropland increased in all regions between 1961 and 1995, and yields continue to increase in the scenarios. Note, however, the wide disparities in historical yield increases; e.g., between China+ and Africa, or Western Europe and the FSU.

Figure 4-12. Historical annual cereal yields in developing regions

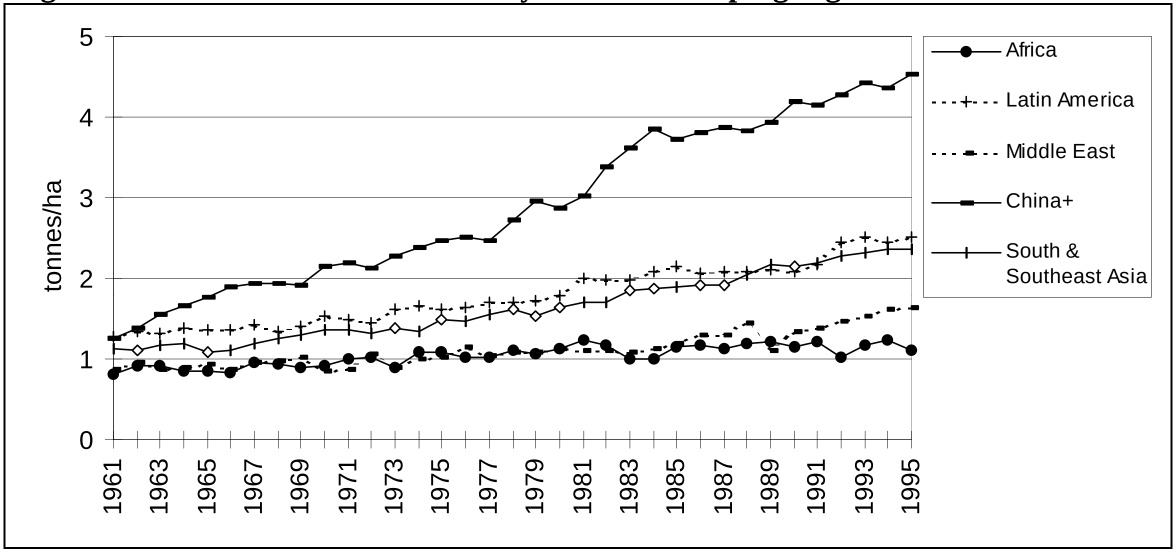
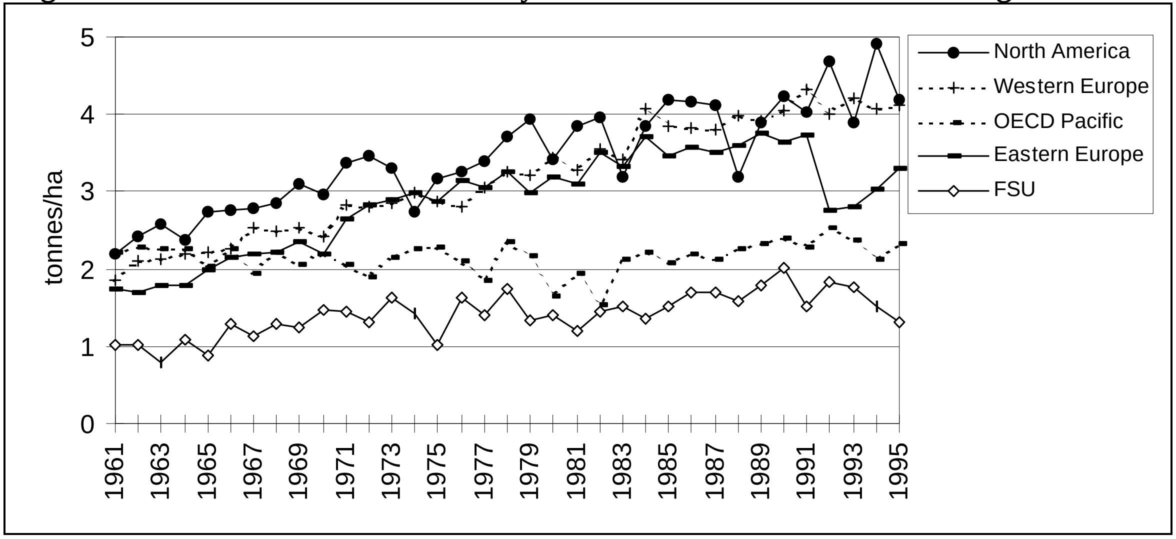


Figure 4-13. Historical annual cereal yields in transitional and OECD regions



As discussed above, the base year yield and cropping intensity values are calculated from 1994 data in the FAOSTAT database and other sources. Because yields can fluctuate significantly from year to year due to weather and economic conditions, the different base-year values in some cases led to trends from 1994 to 2025 that were different from those assumed in Leach (1995). Nevertheless, the same arguments that led to the particular values for the yields and intensities are assumed to hold in the *Reference* scenario.[42] The yields and cropping intensities in the *Policy Reform* scenario are assumed to be the same as in the *Reference* scenario. The social, economic and policy environments in the two scenarios are quite different; however, some of the differences would lead to higher yields and some to lower yields when comparing one scenario to the other. Different influences are discussed below.

The annual yields assumed in the two scenarios are shown in Table 4-18 and Table 4-19.[43] These include the combined effect of changes in harvest yields and cropping intensities. The differences between the two scenarios are due to different mixes of crops, in the case of cereals, and, for the temperate regions, different mixes of production on irrigated and rainfed land.

---

[42] Briefly, the assumptions were that for most crop groups and most regions, yields and cropping intensities increase steadily throughout the scenario, but at slower rates than in the past. The yields in 2050 were kept below the maximum national yields achieved as of 1989. In Africa, the Middle East and the transitional regions of the FSU and Eastern Europe, in contrast to the general trend, yield increases are assumed to be faster than in the past. Also, yields for certain crops, which in this study are placed in the "Other Crops" category, were assumed to increase faster than historical yields because of recent scientific advances or existing opportunities to increase productivity.

[43] In all regions except China+, the yields assumed for 2050 are well below the constraint-free yields estimated by Luyten (1995) in a global study. The "crop" used for the estimates has characteristics typical of a modern high-yielding cereal crop. If the constraint-free yield for China can be taken as a guide, then considering the likely inflation of the base year yields for China (Paarlberg, 1997) and the recent progress toward developing a high-yielding rice plant suitable for irrigated rice production (IRRI, 1998) (the most important in China), the yields for China+ in 2050 appear challenging, but achievable.

Table 4-18. Annual cereal yields in the scenarios

tonnes / ha / yr			Reference				Policy Reform			
	1994		2025		2050		2025		2050	
	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
Africa	0.8	4.6	1.6	7.1	2.2	8.4	1.6	7.1	2.2	8.4
Latin America	1.5	4.7	2.1	6.2	2.4	7.4	2.1	6.2	2.4	7.4
Middle East	0.4	2.7	0.7	4.5	1.2	5.7	0.7	4.5	1.2	5.8
S+SE Asia	1.5	3.7	2.7	6.2	2.9	7.6	2.9	6.2	3.3	7.6
China+	6.3		9.0		10.1		8.5		9.5	
E. Europe	2.4		4.1		4.4		4.1		4.4	
FSU	0.8		2.1		2.3		2.0		2.2	
N. America	2.7		3.3		3.6		3.2		3.4	
Pacific OECD	0.8		1.2		1.3		1.2		1.3	
W. Europe	2.9		4.5		4.6		4.4		4.4	

Table 4-19. Annual yields for non-cereal crops in the scenarios

tonnes / ha / yr			Reference				Policy Reform			
	1994		2025		2050		2025		2050	
	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated	Rainfed	Irrigated
Africa	2.9	22.9	3.8	35.7	5.9	51.4	3.6	34.3	5.7	49.5
Latin America	5.2	35.9	7.4	50.7	8.9	58.7	6.8	49.2	9.9	57.2
Middle East	1.1	9.1	2.5	16.8	3.4	21.3	2.4	16.1	3.2	20.5
S+SE Asia	3.1	20.9	4.3	30.4	5.9	37.4	4.1	29.2	5.7	35.9
China+	12.3		15.0		18.7		17.4		21.0	
E. Europe	7.1		8.8		11.0		9.4		11.1	
FSU	3.0		4.8		5.9		5.3		6.3	
N. America	3.0		4.4		4.7		4.2		4.5	
Pacific OECD	4.3		4.1		4.7		4.5		4.9	
W. Europe	7.4		8.6		9.3		8.2		8.8	

One factor that could lead to increased yields in the *Policy Reform* scenario relative to the *Reference* scenario is wider use of small-scale soil and water-conserving technology. Increasing the efficiency of use of available rainwater can effectively extend the growing season, so that more than one crop can be harvested. This can be accomplished in several ways: surface runoff can be captured behind earthen bunds; conservation tillage can be introduced; and in areas with a monsoon season, water storage and mulching can make water available for crops during the dry season (Hudson, 1992; Conway, 1997; Krishnamoorthy, 1983). These efforts and others can reduce the rate of cropland degradation, in addition to raising yields.

The effects of degradation are present in the historical yield trends. Since the *Reference* scenario projections are based in part on the historical trends, to some degree the effects of future land degradation are incorporated in the scenario (Leach, 1995). In the *Policy Reform* scenario, land degradation is assumed to slow and then reverse, as damaged land is recovered through careful management. Land degradation has had a profound effect on the world's agricultural land. In a study commissioned by UNEP, it was estimated that almost 2 billion hectares of cropland, grazing land and forest has been degraded to some degree as a result of human action since the second world war (Oldeman, 1991). Of this, about 30% was due to agricultural practices. In some cases the damage led to reduced yields, through nutrient loss, salinization or other reasons. In other cases, however, the effects were severe enough that working the land became infeasible. The scenario assumptions for land degradation of this severity are discussed in Section 4.6.2. The effects of land degradation on yields have been found to be significant in the few cases where they have been estimated (Scherr and Yadav, 1996). In Africa, for example, as a consequence of erosion, yields may have been between 2% and 40% lower than they would have otherwise. The effect in the *Policy Reform* scenario of reduced land degradation could have a significant impact on yields.

One factor that can lead to lower yields in the *Policy Reform* scenario relative to the *Reference* scenario is the replacement of high-input farming practices with low-input approaches. For example, as discussed in *BTC*, application of manufactured fertilizer is assumed to decrease in the *Policy Reform* scenario relative to *Reference* scenario practices. The reduction is accompanied by increases in natural inputs, such as green fertilizer, manure and crop resides. As discussed in the next section, in the analysis it is assumed that manufactured inputs can be cut in half without a significant decrease in yields or cropping intensities. However, note that this would most likely not be true if inputs were removed completely, as soil nutrients might then be a limiting factor on production, leading to a reduction in yield (Penning de Vries et al., 1996). Also, the necessity of introducing nitrogen-fixing crops into a crop rotation sequence can reduce the production of food crops.

4.5.3 Fertilizer

Plant growth can be restricted if any of several crucial chemical elements are in short supply. Furthermore, unless nutrients are replenished, agriculture will gradually deplete the soil, as nutrients are carried away from the field with the harvest, or washed away with the soil exposed by land clearing.

Mineral shortages can be corrected, and nutrient levels maintained, by applying fertilizers. Fertilizers play an important role in producing and sustaining the yield increases assumed in the scenarios. However, they also pose both social and environmental problems. They are associated with pollution and health problems and, in the case of manufactured fertilizers, their manufacture consumes nonrenewable resources. However, there are alternatives to manufactured fertilizers. Knowledge-intensive and management-intensive farming methods can reduce external inputs while greatly enhancing crop yields (Leach, 1995). Some approaches are discussed in *BTC*.

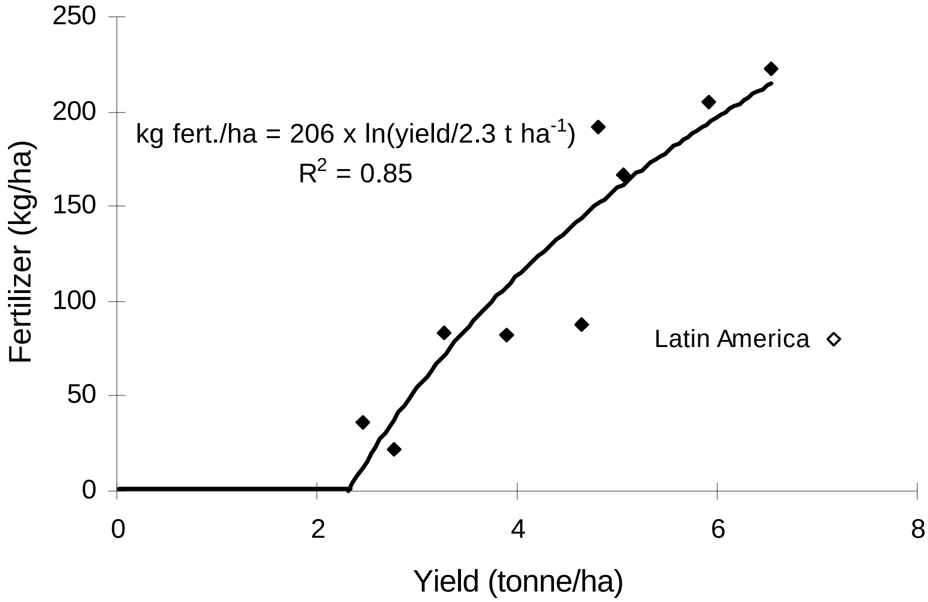
In this study we construct a *Reference* scenario for manufactured fertilizer use, and then explore the potential for reducing manufactured inputs in agriculture in the *Policy Reform* scenario relative to the *Reference* scenario. In the analysis, only manufactured fertilizers are considered. The amount of manufactured fertilizer applied per hectare (the intensity) is calculated in terms of yields, so that the trends in fertilizer use are consistent with the yield assumptions described in Section 4.5.2.

In the *Policy Reform* scenario, it is assumed that alternatives to manufactured fertilizer are introduced in varying combinations in different regions. Combined with improvements in the efficiency of fertilizer application relative to the *Reference* scenario, it is assumed that use of manufactured fertilizers can be cut in half without affecting yields or cropping intensities.

Current Accounts

The FAOSTAT database gives total national consumption of different kinds of fertilizer. Regional consumption of manufactured fertilizer is plotted against average yield for all crops in Figure 4-14. The curve in the figure was used to allocate fertilizer use to different crops in the base year. Using this approach, fertilizer application is greater on irrigated land than on rainfed land, consistent with the greater benefits that can be achieved from fertilization on irrigated land.

Figure 4-14. Manufactured fertilizer application versus average yield



Note: Latin America is excluded from the regression.

Scenarios

In the *Reference* scenario, fertilizer use is estimated as a function of yields, based on the same curve used for the current accounts (Figure 4-14). In the *Policy Reform* scenario, an initial estimate for fertilizer application is computed based on yields, as in the *Reference* scenario, but is then reduced by 25% in 2025 and 50% in 2050. The yield assumptions for both scenarios are given in Section 4.5.2.

In the *Reference* scenario, fertilizer consumption in the developing regions increases from 71 million tonnes in 1995 to 132 million tonnes in 2025 and 174 million tonnes in 2050. In the transitional and OECD regions it increases from 52 million tonnes in the base year to 74 million tonnes and then 78 million tonnes in 2025 and 2050.

4.5.4 Trade

The sum of food, feed and other uses in each region is the domestic demand for crop products. Demand can be met through production within the region or through trade.

Current Accounts

According to FAOSTAT figures, in 1994 some 240 million tonnes of cereals and 80 million tonnes of fruit were shipped across national borders. Most of the exchanges are commercial transactions: cereal food aid shipments were about 9.5 million tonnes in 1994/95 (FAO, 1997d), or about 4% of total cereal exports. As for trade in livestock products, discussed in Section 4.3.2, net exports are reported both in absolute terms and as self-sufficiency ratios.

Table 4-20. Cereal exports and self-sufficiency ratios in 1994

	Net Exports (million tonnes)	SSR
Africa	(30)	0.79
China+	(3)	0.99
Latin America	(21)	0.84
Middle East	(21)	0.63
S+SE Asia	(20)	0.95
E. Europe	(1)	0.99
FSU	(51)	0.74
N. America	98	1.35
Pacific OECD	(13)	0.74
W. Europe	25	1.12
Total	(37)	0.98

For cereals as a whole (Table 4-20), in 1994 eight of the ten regions were net importers, with North America and Western Europe the only net exporters, although Eastern Europe and China+ were very close to being self-sufficient. However, for rice, China+ and South and Southeast Asia were net exporters, as well as North America and the FSU. The arid Middle East had the lowest SSR, 0.63. Note that global net exports are not zero; this is a reflection of statistical errors in the reported data. In the developing regions as a whole, cereal production fell short of needs by about 95 million tonnes.

The pattern of trade for the "Other Crops" category (Table 4-21) is the reverse of that for cereals, with the developing regions being net exporters, while each of the OECD regions is a net importer. The range of self-sufficiency ratios is not as large as that for cereals, although the value for the Middle East, 0.65, is close to that for cereals. The exports from the developing regions are entirely from Latin America and South and Southeast Asia. A variety of crops are exported from Asia, while fruit dominates exports from Latin America.

Table 4-21. Exports and self-sufficiency ratios of "other crops" in 1994

	Net Exports (million tonnes)	SSR
Africa	(22)	0.94
China+	(12)	0.98
Latin America	117	1.29
Middle East	(35)	0.65
S+SE Asia	20	1.03
E. Europe	(1)	0.99
FSU	(46)	0.78
N. America	(0)	1.00
Pacific OECD	(8)	0.90
W. Europe	(34)	0.92
Total	(20)	0.99

Total world crop production was close to 5 billion tonnes, or just under one tonne per person. Production per capita in the OECD and transitional regions (1.4 tonnes) was almost twice as great as in the developing regions (0.76 tonnes).

Scenarios

In the *Reference* scenario, assumptions are made for the demand and production of crop products. In the analysis, trade — the difference between the two — emerges principally as a residual factor. As discussed in Sections 4.5.1 and 4.5.2, crop production in the scenarios is set by specifying the future productivity of cropland, as well as future growth in cropland area. The areas under rainfed cropland, yields for non-cereal crops and self-sufficiency ratios are initially set to values based on those of Leach (1995), and then adjusted so that, globally, net exports are zero. Generally, the rainfed areas and yields were only allowed to vary by a few percent; the self-sufficiency ratios were the most important adjustment parameter in balancing net trade.

In the *Policy Reform* scenario, it is assumed that regions will rely to a greater extent on trade than in the *Reference* scenario. Regional production levels are constrained by the sustainability targets given in Section 1. The target of halting, and then reversing, deforestation, and the requirement to minimize the growth in water stress, strongly restrict the expansion of cropland and irrigation in some regions.

The resulting scenario values for the self-sufficiency ratios for cereals are shown in Table 4-22. All of the developing regions are cereal importers in the base year, and they continue to be net importers in both scenarios (Figure 4-15). For the developing regions as a whole, imports are greater in the *Policy Reform* scenario than in the *Reference* scenario, both as a response to greater demand for agricultural products and as a strategy for reducing pressure on land and water resources. In the *Reference* scenario the regional pattern and total imports for developing regions in 2025 are comparable to the projections to 2020 by the International Food Policy Research Institute (IFPRI) (Pinstrup-Andersen, et al., 1997). Turning to the OECD and transitional regions, in the base year North America and Western Europe are the only net cereal exporters (Figure 4-16). In the scenarios, Pacific OECD continues to be a net importer, while the transitional regions of Eastern Europe and the FSU become significant exporters, as they recover from a recent drop in production and as yields in the FSU, which today are well below those of Western Europe and North America, increase. The *Reference* scenario values in 2025 are again broadly comparable to those of IFPRI. In particular, the transitional regions become net exporters in the IFPRI scenario.

Table 4-22. SSRs for cereal crops in the scenarios

	Reference			Policy Reform	
	1994	2025	2050	2025	2050
Africa	0.79	0.80	0.70	0.69	0.52
China+	0.99	0.91	0.93	0.95	0.96
Latin America	0.84	0.84	0.92	0.89	0.89
Middle East	0.63	0.44	0.39	0.40	0.35
S+SE Asia	0.95	0.93	0.92	0.82	0.78
E. Europe	0.99	1.39	1.46	1.38	1.57
FSU	0.74	1.15	1.21	1.19	1.30
N. America	1.35	1.41	1.57	1.57	2.05
Pacific OECD	0.74	0.62	0.61	0.56	0.55
W. Europe	1.12	1.31	1.40	1.41	1.61

Figure 4-15. Net cereal imports of developing regions

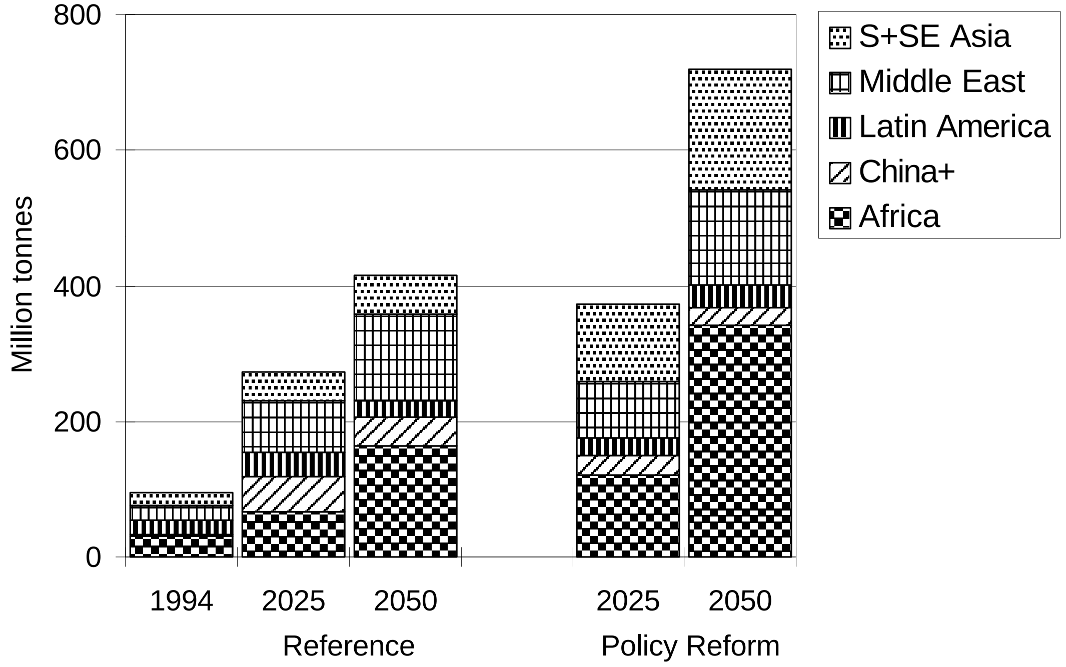
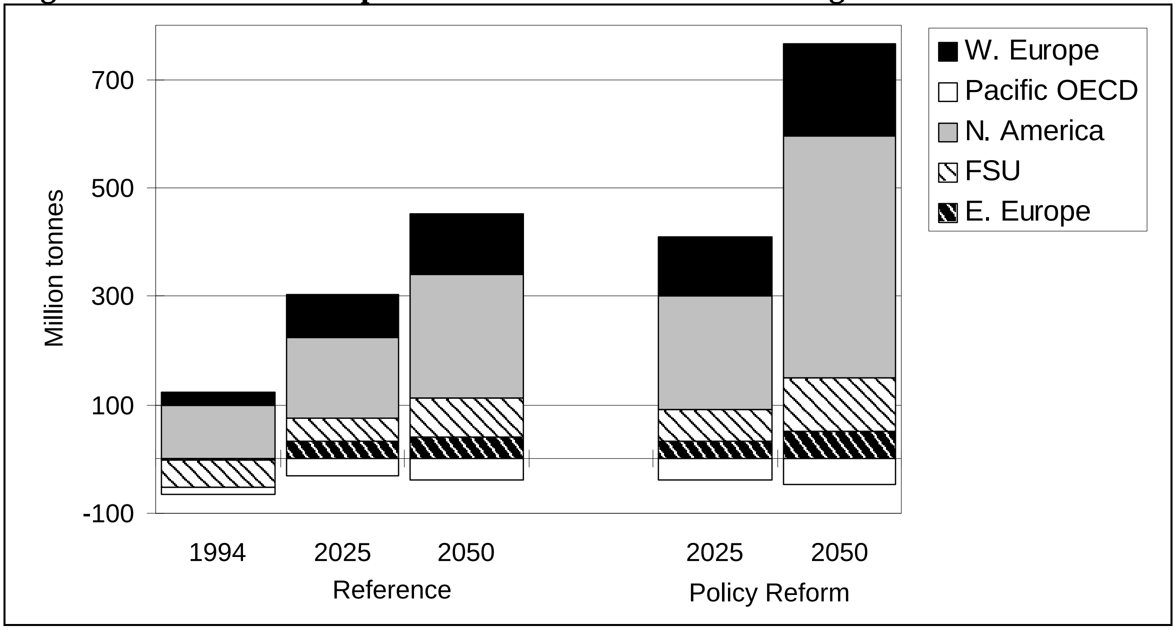


Figure 4-16. Net cereal exports of OECD and transitional regions



The self-sufficiency ratios for non-cereal crops are shown in Table 4-23. In the *Reference* scenario, the OECD and transitional regions maintain self-sufficiency ratios close to one; for the FSU this represents an increase in self-sufficiency relative to the base year. Latin America remains the dominant exporter, although exports decline as a fraction of consumption over the course of the scenario. South and Southeast Asia, also, maintains its position as an exporter. In the *Policy Reform* scenario the pattern is substantially the same. However, Latin America exports more than in the *Reference* scenario, while South and Southeast Asia becomes a significant importer by the end of the scenario, as policies aimed at reducing and then reversing forest loss (see Section 4.6.4) constrain the expansion of rainfed cropland.

Table 4-23. Self-sufficiency ratios for "other crops" in the scenarios

	Reference			Policy Reform	
	1994	2025	2050	2025	2050
Africa	0.94	0.83	0.93	0.84	0.90
China+	0.98	0.99	1.04	0.99	1.08
Latin America	1.29	1.27	1.15	1.28	1.20
Middle East	0.65	0.67	0.65	0.64	0.63
S+SE Asia	1.03	1.01	1.02	1.01	0.90
E. Europe	0.99	0.96	1.05	1.10	1.25
FSU	0.78	1.02	1.02	1.02	1.33
N. America	1.00	1.04	0.97	1.04	1.07
Pacific OECD	0.90	0.99	1.01	0.99	1.02
W. Europe	0.92	0.99	0.97	0.99	1.07

Box 4-1. Grain production in China

Recently, the future of cereal imports in China has received close attention, spurred by the claim of Brown (1995) that China will have difficulty feeding its population from its own resources, as a result of increasing food consumption, land degradation, conversion of land for urban expansion and industry, increasing contribution of meat in diets and declining potential for increasing yields. Brown's story has some similarities to the one presented here, with similar consequences: to meet the growing demand China must increase imports. However, the two analyses differ in the degree to which imports will increase. The results obtained here do not paint as dire a picture as that presented by Brown, principally because this study is more optimistic about the potential for China to continue raising cereal yields (discussed in Section 4.5.2). As a result, although in the *Reference* scenario cropland in China+ is lost to expanding human settlements and degradation at a rate of about one million hectares per year between 1995 and 2025, net cereal imports in 2025 are 50 million tonnes per year, compared to Brown's anticipated range of 207-369 million tonnes per year by 2030. In the *Policy Reform* scenario, China+ has smaller net imports in 2025 than in the *Reference* scenario, about 27 million tonnes. These values are similar to those presented in a recent article by Rozelle and Rosegrant (1997), which summarized the conclusions of the papers collected in a special issue of *Food Policy* devoted to a discussion of China's agricultural potential. Rozelle and Rosegrant constructed several scenarios for agricultural production in China in 2020, differing in the economic growth rate assumptions and the degree of land degradation. For two of the scenarios, the income growth in China is similar to the income growth assumed here for the China+ region, about 4.5% per year. The imports in both the *Reference* and *Policy Reform* scenarios fall between the projected imports for these two scenarios: one in which resource degradation is assumed to continue at historical rates, in which case their imports are 25 million tonnes; and one in which degradation proceeds at twice historical rates, in which case imports are 70 million tonnes.

4.6 Land Resources and Land Use

The requirements for cropland and grazing land place considerable pressure on existing land resources. These are exacerbated by land degradation, since severely degraded land must be replaced by land elsewhere to maintain production. These agricultural demands compete with other demands, which are incorporated in the scenarios, as discussed below. Forests are valued for their products, as carbon sinks and for other reasons. Also, land is required for human settlements, recreation and nature. For this study land is separated into six land-use types: built environment, cropland, grazing land, forest, protected land and a residual "other" land category. In this section each land-use type is discussed, with the procedure for estimating the base-year values, and the rates of conversion of each land-use type to and from the others.

For the analysis, net conversion between different land-use types is determined in a stepwise, hierarchical manner, and this section is arranged in the same way. First, land required for the built environment is determined, as well as the conversion to the built environment from other types of land—forest, cropland, grazing land and "other" land. Next, cropland is considered: the total area is determined by agricultural production; the area of cropland converted to the built environment and the amount of cultivated land lost to degradation is subtracted from the total; and any additional cropland area required is converted from the remaining suitable land uses. Grazing land is considered next, then forest and finally "other" land. (With the exception of North America in the *Policy Reform* scenario, protected land is kept at its base year value throughout the scenario.)

The overall pattern of land-use changes in the scenarios are described in *BTC*. Most of the changes seen for the world are dominated by changes in the developing regions, where the built environment, cropland and grazing land expand at the expense of forests and "other" land.

4.6.1 Built Environment

Current Accounts

People settle land for many purposes other than agriculture. In both urban and rural settings, land is cleared and altered for businesses, residences, roads, parking lots, parks, landfills, burial grounds and other uses. The area of this *built environment* is not well known (Crosson and Anderson, 1992). For this study a combination of different sources and estimates was used to arrive at regional estimates for built-up land. The area of the built environment per capita is shown by region in Table 4-24, along with the sources on which the estimates are based. The highest value by far is that for North America, where at 0.13 ha/capita, people on average require twice as much space as in Africa, with the second highest land requirements. (Note that the North American figure agrees with the estimate of urban density in the U.S. given in Crosson and Anderson, 1992).

Table 4-24. **Current accounts built environment per capita**

	ha/capita	Source
Africa	0.07	1
Latin America	0.05	1
Middle East	0.06	1
China+	0.03	1
S+SE Asia	0.03	1
E Europe	0.04	2
FSU	0.04	4
N America	0.13	3
W Europe	0.06	2
Pacific OECD	0.06	4

Sources: (1) based on Fischer (1993); (2) based on WRI (1996a); (3) estimate given by the area of "built-up land" (USDA, 1994) less the area of state parks (USBC, 1992; 1995); (4) own estimates based on other regional values.

Scenarios

In the *Reference* scenario, the growth in built environment was guided by the assumption that the amount of built-up land each person requires is determined primarily by the amount of land available and secondarily by cultural preferences and income. Support for this view can be found in Table 4-24: regions with relatively low incomes and high population density, such as China+ and South and Southeast Asia, have low built environment per capita; regions with higher income and high population density, such as Europe, have built environment per capita higher than in the Asian regions, but smaller than in North America; finally, in Africa and Latin America, where land is plentiful but incomes are relatively small, built environment per capita is comparable to that of Western Europe.

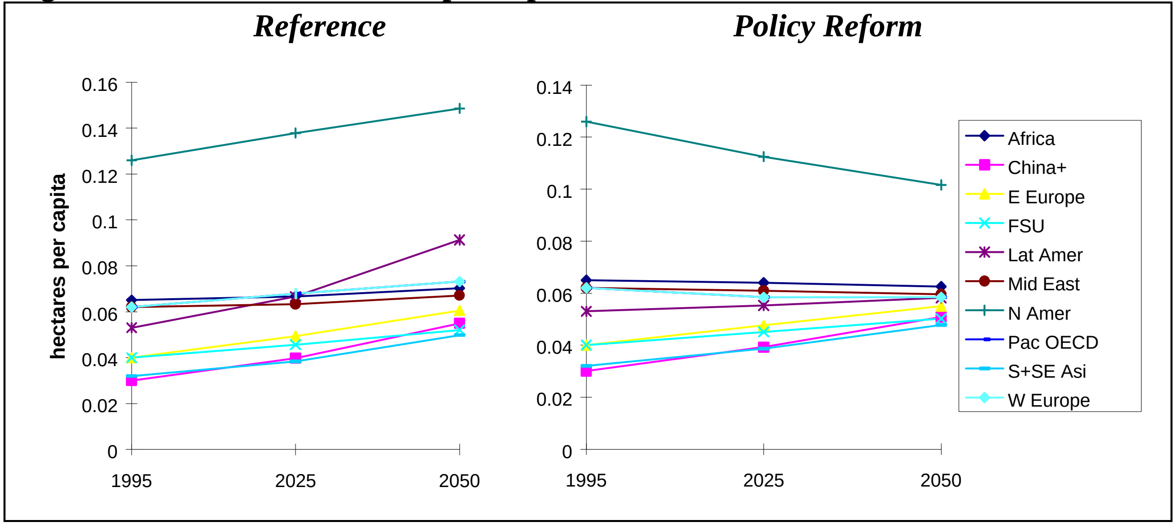
In the OECD regions built environment in the *Reference* scenario increases at a fixed rate based on historical trends in the United States, consistent with the similar economic growth in those regions. In the U.S., between 1982 and 1992 developed land per capita increased at a rate of about 0.6% per year on average. It is assumed that built environment per capita increases in all OECD regions at half this rate, 0.3% per year, throughout the scenario. For the other regions the convergence algorithm was applied (see Annex), but with different convergence targets for different regions, consistent with the comments above: Africa and Latin America converge towards the OECD average, while China+, South and Southeast Asia, the Middle East, Eastern Europe and FSU all converge towards the more compact value for Western Europe and OECD Pacific.[44] The resulting values are shown in Figure 4-17.

In the *Policy Reform* scenario, as discussed in *BTC*, policies to protect forest and cropland from encroaching human settlements are expected to restrain the growth in the built environment in all regions compared to the *Reference* scenario, although this tendency is counteracted to some extent by relatively higher income growth in developing regions. Specifically, it is assumed that all regions approach the Western European average, while in Western Europe itself human settlements become slightly more compact throughout the scenario. The developing regions approach the Western European pattern as their incomes approach the base year OECD values, using the convergence algorithm. The scenario values are shown in Figure 4-17.

---

[44] In the Middle East land is plentiful, but water is not. The convergence towards the Western European value rather than towards the OECD average is based on an assumption that the costs of expanding water delivery systems will limit the growth of the built environment. The convergence pattern for the FSU region, where land is also plentiful, is based on the assumption that FSU will tend more towards European patterns than towards North American ones. In the case of FSU, alternative assumptions would have little effect on land pressure.

Figure 4-17. Built environment per capita in the scenarios



For developing regions, in the *Reference* scenario it is assumed that built environment expands into cropland, pasture land, forest and "other" land in the same proportion in both scenario years, 2025 and 2050. The distribution in each region was based on data from Fischer (1993). For the OECD and transitional regions it is assumed that built environment expands into pasture land, cropland and forest in equal proportions (30% to each), and the remainder (10%) into other land. This assumption is based on observed land-use changes in the U.S. between 1982 and 1992 (USDA, 1994).

For the developing regions, in the *Policy Reform* scenario, consistent with the sustainability targets given in Section 1, conversion of forests to the built environment slows. Conversion of other land-use types is assumed to continue in the same proportions as in the *Reference* scenario. In the OECD and transitional regions the area under built environment declines between 2025 and 2050, the result of tighter settlement patterns and, in some regions, declining populations.

4.6.2 Land-Use Changes from Cropland Expansion

Current Accounts

The current distribution of cropland is described in Section 4.5.1. The percentage of total cropland area varies considerably from region to region, ranging from 6% in Africa to 44% in Eastern Europe.

Scenarios

Requirements for cropland in the scenarios and its distribution are discussed in Section 4.5.1. Future demands are driven by dietary and other requirements for crops, moderated by assumed increases in cropland productivity.

In the *Reference* scenario, cropland in the developing regions expands into pasture land and forests in proportion to the amount of potentially cultivable land currently under those uses.[45] For the OECD and transitional regions it is assumed that cropland expands into forest and grazing land in equal proportions. Historical rates for these processes are shown in Box 4-2.

Even as requirements for cropland increase in the scenario, some existing cropland becomes degraded to the point where it is no longer productive. Historical rates of cropland degradation are discussed in Box 4-2. In the analysis this is represented as a conversion from cropland to "other" land. Degradation processes add to the total area of forest and grazing land that must be brought under cultivation in the scenario. Globally, cropland is assumed to be lost to severe degradation in the *Reference* scenario at a rate of 3 million hectares per year.[46] The regional distribution is discussed below.

On average, crop area increases by about 3 million hectares per year throughout the *Reference* scenario (Section 4.5.1). Added to the 3 million hectares lost each year to severe degradation, this gives roughly 6 million hectares of land that must be converted from existing forest or grazing land, close to the total of 5.7 million hectares per year shown in Box 4-2.

---

[45] Ideally, the estimated rates would take into account the suitability of the land for different crops, its availability for exploitation, or the productivity of the additional land compared with land already under cultivation. However, data were not available to this level of detail.

[46] This value is higher than the historical rate of 2.15 million hectares per year, shown in Table 4-26, but lower than some estimates of current rates of degradation. Kendall and Pimentel (1994) report that cropland is lost to urbanization and degradation at a rate of over 10 million hectares per year. In the *Reference* scenario, cropland is converted to the built environment at about 1.5 million hectares per year on average: added to degradation rates, the total loss of 4.5 million hectares per year is about half their estimate.

Box 4-2. Historical Cropland Trends

Clearing for Cropland

Historical rates of land use change were estimated by Houghton and Hackler (1995) for eight regions, six of which are very similar in composition to six of the ten regions used in this study. Coverage in time, and coverage of ecosystems, was limited by the available data: for South and Southeast Asia they present conversions from six forest types and grassland to cropland, while for tropical Africa they present only total clearing rates for two types of forest. The rates of conversion of all forest types and grassland to cropland for each of their regions are shown in Table 4-25.

Table 4-25. Clearing for cropland (million hectares per year)

Mha / year	Forest + Woodland		Grass + Scrub		Year of Estimate
	Clearing	Shifting Cult.	Clearing	Shifting Cult.	
N. America	0.00	-	0.00	-	1980
Pacific Dev.	0.08	-	0.12	-	1980
Europe	-0.60	-	-0.20	-	1980
FSU	0.02	-	0.02	-	1985
Tropical Africa	Forest clearing: 6 Mha/year				1990
N. Africa+Middle East	0.15	-	1.32	-	1980
China	0.07	-	0.59	-	1980
S+Central America	1.13	16.25	0.52	-	1990
S+SE Asia	2.46	10.68	0.00	0.00	1990

Source: Houghton and Hackler, (1995).

Based on these estimates, about 3.3 million hectares of forest and 2.4 million hectares of grassland are cleared annually for crops. A further 27 million hectares of forest land is cleared each year for shifting cultivation. This temporary clearing is generally part of a long-term cycle, in which previously cleared land is allowed to grow back under native vegetation (Greenland and Okigbo, 1983). However, within the past decade, at least, the rate of clearing appears to be exceeding the rate of regrowth (FRA, 1996).

Cropland Degradation

The major effect of cropland degradation is to reduce yields, but some degradation is severe enough that the land must be pulled from production. Rates for such processes are difficult to estimate, and strongly debated. A recent study, the Global Assessment of Soil Degradation (GLASOD) was conceived in response to this debate (Oldeman et al., 1991), although these rates have also been disputed (Alexandratos, 1995). The goal of the project was to provide an estimate of the extent of global soil degradation, using a systematic set of criteria for all parts of the world. The study covers land degradation that has occurred roughly in the period following the end of the second world war. Four degrees of degradation were distinguished: “light,” “moderate,” “strong” and “extreme.” The last two represent land so degraded it must be pulled from production, and are differentiated from one another by the effort required to return them to use. Moderately degraded land is considerably reduced in quality, but can still support some level of production. Historical values of land degradation from agricultural practices are shown in the text below, in Table 4-26. The rates shown in the table were estimated by dividing the total area by 45 years, roughly the period covered by the GLASOD study. The rate of severe degradation is much higher in the developing regions than in the transitional or OECD regions, with the highest rate occurring in Africa. The pattern for moderate degradation is more varied between the macro-regions. The highest rate occurs in North America, mostly as a result of topsoil loss from wind and water action, while the second highest occurs in Africa.

Historical rates of cropland degradation are shown in Table 4-26. In the future, some of the land that is “moderately” degraded today is likely to become severely degraded, and in this way serves as an indicator of possible future trends. However, note that in all but one of the transitional and OECD regions rates of moderate degradation are considerably higher than rates of severe degradation, indicating that some effort has been expended to keep cropland from becoming unproductive. After examining the historical rates of moderate and severe degradation, and bearing in mind this pattern in the OECD and transitional regions, the rates of cropland loss due to severe degradation shown in Table 4-26 were adopted for the *Reference* scenario. In all regions except the Middle East the rate of cropland degradation in the scenario is between the rates of "moderately" and "severely" degraded cropland in the past. (In the Middle East there is very little potentially cultivable land left, and it is assumed that even in the *Reference* scenario some effort will be made to slow the rate of degradation.)

Table 4-26. Land degradation from agriculture: historical and *Reference* scenario rates

	Average rate (Mha / year)			
	Light	Moderate	Severe	1995-2050
Africa	0.59	1.16	1.03	1.08
China+	1.01	0.99	0.38	0.68
Latin Amer	0.73	1.09	0.25	0.66
Middle Eas	0.04	0.21	0.30	0.15
S+SE Asia	0.22	0.40	0.10	0.25
E. Europe	0.12	0.17	0.02	0.05
FSU	0.56	0.25	0.02	0.07
N. America	0.16	1.27	0.00	0.02
Pacific OE	0.09	0.03	0.05	0.04
W. Europe	0.49	0.22	0.01	0.01
World	4.00	5.78	2.15	3.00

Notes: "Severely" degraded land is the sum of "strongly" and "extremely" degraded land in Oldeman et al. (1991). The estimates in the table were developed using the electronic map constructed by GRID/UNEP from the GLASOD map (GRID/UNEP, 1991). Regional areas were estimated by summing up degraded areas in polygons whose centroid lay within the regional boundaries; at the regional level the differences between the areas estimated using this approach and the actual areas are small.

In the *Policy Reform* scenario, in keeping with the sustainability goals described in Section 1, land degradation is assumed to proceed at less than the historical rate. For lightly and moderately degraded land this contributes to the maintenance of yields relative to the *Reference* scenario, as discussed in Section 4.5.2. It is also reflected in a lower rate of cropland loss to severe degradation. Between 1995 and 2025 cropland is lost at half the *Reference* rate (1.5 Mha/year). Between 2025 and 2050 the trend reverses as severely degraded land is returned to production, so that there is no net loss of cropland over the period 1995 to 2050.

In addition to reduced land degradation, in the *Policy Reform* scenario conversion of forests to cropland slows. As a result, most of the new cropland in the scenario is converted from grazing land. Also, in North America in the *Policy Reform* scenario some farmland currently withheld from production (and included with "other" land here) is returned to cultivation in response to increasing global demand for agricultural products. This land-use conversion is considered below, in the discussion of "other" land.

4.6.3 Pasture and Rangeland

Current Accounts

The available data on pasture and rangeland were described in Section 4.4, as well as the current distribution of grazing land among the ten scenario regions. As discussed in that section, there is little quantitative information on the dynamics of grazing land use. However, some qualitative trends have been described. For example, in the High Plains of the United States around the turn of this century, and today in the Sahel, grasslands used for grazing have been converted to cropland by sedentary farmers (Moran, 1982; Durning and Brough, 1991), while in Latin America, grazing lands have expanded at the expense of forests.[47]

Scenarios

The changes in grazing land area in the scenarios, driven by meat and milk production requirements, are discussed in Section 4.4. In previous subsections, conversion of grazing land to the built environment and cropland was described. To make up the total requirement for grazing land in the scenario, it expands at the expense of forest and “other” land. There are few data on the composition of “other” land, in each region, and little information about the relative rates of conversion for these two land use types. For simplicity, in the *Reference* scenario it is assumed that in every region half of the land converted to grazing land is from forest and half from “other” land. In the *Policy Reform* scenario, most of the conversion is from “other” land, with the portion from forest gradually dropping to zero in the course of the scenario.

4.6.4 Forests

Current Accounts

From 1980 to 1995, the average rate of forest loss worldwide was about 12 million hectares each year (FAO, 1997b). In the developing world there was a net loss of some 200 million hectares over this period, while net reforestation and afforestation in the industrialized countries added about 20 million hectares. This reduction of forest area means the loss of many valued services (FAO, 1997b): forests are believed to contain two-thirds of the world’s species; they are home to forest-dwelling people; they provide a potentially renewable supply of a variety of products for human needs; they are a source of income for the poor; and they are a potentially important component in mitigating global climate change. In both scenarios, deforestation continues as a result of expanding human settlements and agricultural land.

The term “forest” is applied to a wide range of land covers. For this study, the FAOSTAT category “forest and woodland” is used.[48] Within this category are included natural

---

[47] Although it is not treated explicitly in the scenarios, land has also been degraded in the past due to grazing practices. As with cropland, the main effect is reduced productivity, but a certain amount of the degradation is severe enough to make the land unusable for livestock production. Also as with cropland, rates and the degree of severity are subject to debate.

[48] For six of the regions — the OECD and transitional regions and China+ — protected forest area was removed from the total. For these regions data on total protected area and protected forest area were taken from WCMC (1998a; 1998b). For the remaining

forests and plantations, and such diverse habitats as closed forests and sparse woodlands. In a recent assessment of forest cover change in tropical countries, it was found that between 1980 and 1990, 92 million hectares of closed forest were lost in the survey area, while only 4 million hectares were added (FRA, 1996). Of the total lost, about 60% was converted to land types with some woody cover, but with significantly reduced biomass, such as open or fragmented forest; much of this change would result in no net loss of "forest land" as the term is used here. Also, the forest land category does not take into account the quality of the forests — their health, genetic diversity and age profile (WRI, 1998). Finally, the total area does not capture the extent of fragmentation of forests, which affects their resilience, as fragmented forests cannot provide secure habitats for native plants and animals (WRI, 1998).

As a result of the diverse set of land covers included within the forest land category, the deforestation rates reported here are consistent with a range of scenarios for biomass and biodiversity loss. However, some indications can be gained from detailed studies of past land-use changes. From the study mentioned above of forest cover changes in tropical regions, between 1980 and 1990 the most stable land-cover classes were forest plantations and non-forested land. Thus, afforestation and reforestation were not dominant trends. For both plantations and non-forested land about 99% of the land area that was in the category in 1980 was still in that category in 1990. The least stable category was fallow land associated with shifting cultivation ("long fallow"), with 86% remaining in the same category, while 8% was converted to short fallow or non-forested land. Note that even in the case of shifting cultivation, where in traditional systems forest cover is allowed to regenerate, the dominant change is to land with lower biomass content. The percentages of closed and open forest in 1980 that remained in 1990 were similar to each other, about 93%, but because of the much larger area of closed forest, the absolute changes were larger. Overall, conversion of forest land was dominated by the loss of closed forest, and nearly all of the changes were to land with smaller biomass content.

Scenarios

In both scenarios, deforestation rates are determined as a result of all of the land-use conversions described above: to the built environment, cropland and rangeland. The resulting land areas are shown in Table 4-3. In the *Reference* scenario there is a steady loss of forest land, with the total area decreasing at close to historical rates. On average, about 12.5 Mha of forest land is lost each year between 1995 and 2050. Most of the decrease is in the developing regions, where forest area decreases at about 11.5 Mha per year over the course of the scenario. In the *Policy Reform* scenario, as a result of policies aimed at protecting forests, there are fewer conversions of forest to other land-use types, and less deforestation between 1995 and 2025 than in the *Reference* scenario. The sustainability target of halting, and then reversing, deforestation given in Section 1 constrains the expansion of cultivated land in developing regions, and drives the agricultural trade assumptions in the *Policy Reform* scenario (discussed in Section 4.5.4).

---

regions, data on protected area were taken from Fischer (1993), to maintain consistency with the estimates of the distribution of potential cultivable land in these regions reported in Section 4.5.

Between 2025 and 2050 there is net regrowth of forests in all developing regions, while forest areas in transitional and OECD regions remain steady. However, the regrowth is not sufficient for forest areas to return to base year levels.

Table 4-27. Forest area in the scenarios

Millions of hectares		Reference		Policy Reform	
	1994	2025	2050	2025	2050
Africa	721	523	403	602	622
China+	174	142	109	163	172
Latin America	922	862	805	896	899
Middle East	18	9	2	13	16
S+SE Asia	341	290	225	310	315
E. Europe	24	24	22	23	23
FSU	795	794	778	786	786
N. America	725	722	715	718	718
Pacific OECD	163	146	137	155	155
W. Europe	141	139	137	138	138

4.6.5 Protected Land

Current Accounts

In many countries land has been set aside for environmental protection, scientific research, education, maintenance of traditional cultures and other reasons. The extent of this *protected land* is generally well recorded. For the base year accounts, two different sources were used for two groups of regions. For Africa, Latin America, the Middle East and South and Southeast Asia and China+, data from Fischer (1993) were used.[49] For the other regions, data on total protected areas and protected forest land from the World Conservation Monitoring Centre were used (WCMC, 1998a; 1998b). The amount of land protected in each region is shown in Table 4-28 as a percentage of total land area. Globally, about 6% of all land is listed as protected for some purpose or another. In the OECD regions, Eastern Europe and South and Southeast Asia close to 10% is protected, while in other regions the amount is smaller. Only about 0.1% of land area in China+ is reported as being protected.

Table 4-28. Protected land

% of total land area	
Africa	5.5
Latin America	7.6
Middle East	3.2
China+	0.1
S+SE Asia	9.1
E Europe	8.1
FSU	3.2
N America	10.2
W Europe	9.8
Pacific OECD	12.4
World	6.3

---

[49] The data from Fischer (1993) were used to maintain consistency with the estimates of the distribution of potential cultivable land in these regions reported in Section 4.5.

Scenarios

In the *Reference* scenario it is assumed that there is no net change in protected areas, which are kept at the base year value in every region. In the *Policy Reform* scenario some protected land is removed and some added, as a result of changing land-use policies. In the U.S. circa 1995, about 14 million hectares of land were held in the Conservation Reserve Program (USDA, 1994; FSA, 1998). This represents land that has been pulled from agricultural production because it is highly erodible. It has been estimated that one-third can be safely returned to production (Conway, 1997). In the *Policy Reform* scenario it is assumed that this area of about 5 million hectares is returned to production, represented in the land accounts as a shift from protected land to cropland. In the *Policy Reform* scenario, as discussed in *BTC*, it is also assumed that protected forest land increases, as one of several policy measures to reduce the rate of deforestation.[50]

4.6.6 Other Land

Current Accounts

"Other" land contains any land that is not included in any of the previous categories. It might include wetlands, deserts and barren land, semi-desert areas with vegetation too sparse to support livestock or ice. It might also include rangeland that is suitable for grazing but not used for the purpose.

The "other" land category used for this study differs from that in the FAOSTAT database, because some protected land and the built environment have been subtracted from the FAO totals. The land areas computed this way are shown in Table 4-29. The amount of total land area classified as "other" varies widely between different regions. In the Middle East nearly half of the total land area is in this category, while in Eastern Europe only 1% is.

Table 4-29. "Other" land

% of total land area	
Africa	32.5
Latin America	9.1
Middle East	47.5
China+	27.4
S+SE Asia	6.0
E Europe	0.8
FSU	33.5
N America	21.2
W Europe	9.6
Pacific OECD	8.5
World	23.4

---

[50] However, this is not recorded in the land-use balances, as it would give an apparent reduction in forest area where none exists.

Scenarios

In the scenarios, there are no requirements for “other” land. Instead, the area of “other” land is determined by its conversion to other types of land use, as described above, in a manner similar to the evaluation of changes in forest area. In the scenarios, land in this category is converted to the built environment and grazing land, and land is added to it through cropland degradation. The land areas in both scenarios are show in Table 4-30.

Table 4-30. Area of “other” land in the scenarios

Millions of hectares		Reference		Policy Reform	
	1994	2025	2050	2025	2050
Africa	964	844	776	698	667
China+	317	308	297	300	283
Latin America	183	176	164	160	146
Middle East	287	280	274	280	271
S+SE Asia	51	44	35	33	16
E. Europe	1	2	3	1	0
FSU	736	734	726	719	715
N. America	389	388	390	381	319
Pacific OECD	71	60	53	53	39
W. Europe	44	44	45	42	25

In both scenarios “other” land tends to decrease in all regions. The decrease is much greater in the *Policy Reform* scenario than in the *Reference* scenario, as a result of lower cropland degradation rates and a slower rate of expansion of grazing land into forest.

5. Water

In this section the current accounts and scenarios for water use are described. Because of the strong local nature of water supply problems, the analysis is performed at a national level, with the results presented for the ten global regions.[51]

Section 5.1 discusses freshwater resources. Section 5.2 discusses withdrawals and water stress. Section 5.2.1 covers the current accounts, and Section 5.2.2 describes the scenarios.

5.1 Resources

Data on national renewable freshwater resources use for this study are drawn primarily from compilations conducted for the UN Comprehensive Freshwater Assessment (Najlis, 1996; Shiklomanov, 1997), and supplemented by data from Raskin et al. (1995). For the national-level analysis, river inflows from adjacent countries are included in the totals, which may lead to double counting of freshwater supplies in some cases (Raskin et al., 1995). Nonrenewable sources — such as "fossil" aquifers that are either not being recharged or are being recharged very slowly — are not included in total resources, since their use cannot be sustainable over the long term.

Total annual water resources are shown for each of the ten regions in Table 5-1. For the regional totals, national cross-border flows have been excluded. Resources per person vary from 1,500 cubic meters per year in the Middle East to 22,200 cubic meters per year in Latin America — a fifteen-fold difference. Variation within regions is hidden by the regional totals, but is captured to some degree in the estimates of national water stress levels, as described below.

Table 5-1. Annual renewable water resources

	Total * (1000 km^3)	Per Person (1000 m^3/capita)
Africa	4.0	5.5
Latin America	10.6	22.2
Middle East	0.3	1.5
China+	3.5	2.7
S+SE Asia	9.3	5.5
E Europe	0.2	2.1
FSU	4.9	16.7
N America	5.3	17.9
W Europe	2.0	4.4
Pacific OECD	1.2	8.4
World	41.3	7.3

* Totals exclude cross-border river flows

In the scenarios it is assumed that renewable resources remain at base-year levels. This assumption would be violated if the global climate changes significantly, as current models suggest (Raskin et al., 1997). Also, in many places, water pollution is reducing the usable freshwater resources (Postel, 1992). It is also possible to add to the useful resources, by capturing water that is currently lost as runoff using small-scale technology (Conway, 1997; Hudson, 1992; Postel, 1992). In addition to these changes in useable renewable resources, many countries today

---

[51] Ideally it would be performed at a river basin level, but data relating to current and potential demands, grouped by river basin, are not widely available. The use of a national-level analysis is a compromise consistent with the availability of the data.

effectively increase their resources by recycling wastewater and desalinating brackish water and sea water. In some cases, these sources contribute significantly to total water supplies (FAO, 1996a; Postel, 1992). In the analysis, these supplies are included explicitly, as discussed below.

Desalinated Water and Wastewater

In the base year, several countries in the Middle East and North Africa supplied some of their water needs from desalinization and wastewater treatment plants. In the context of the high water stress found in the scenarios, these countries may be forced to rely more heavily on this expensive option, with negative but uncertain implications on economic growth. The scenario assumptions for supplies from these sources are shown in Table 5-2. In the *Reference* scenario, supplies roughly double in the Middle East between 1995 and 2050, while in North Africa they more than double. In the *Policy Reform* scenario, as part of the effort to meet the sustainability goals outlined in Section 1, supplies from desalinization and wastewater treatment plants increase more rapidly than in the *Reference* scenario. The increase is greatest in the Middle East, where production from these sources increases by 9 times over the course of the scenario. However, as a fraction of withdrawals, the supply from desalinization and wastewater treatment plants in the Middle East in 2050 is only 6% of the withdrawals in that year. This is close to the value for Jordan in the base year, but well below that of Bahrain, the United Arab Emirates, Qatar and Kuwait, where between 16% and 60% of water withdrawals were supplied by treated water.

Table 5-2. Desalinized Water and Recycled Wastewater in the Scenarios

Million cubic meters		Reference		Policy Reform	
	1995	2025	2050	2025	2050
Middle East	1,403	2,121	2,649	7,176	12,671
North Africa	493	752	1,096	6,681	12,510

Sources: 1995 values based on FAO (1996a) and Gleick (1993)

5.2 Withdrawals and Water Stress

In the analysis, the estimation of water stress is determined at the national level, since regional aggregation can mask local problems. However, water withdrawals are developed using a disaggregated approach at the sectoral level. For this study, the sectoral analysis was performed at the regional level, so in the scenarios withdrawals are determined at the regional level. The analytical approach is outlined below.

Withdrawals Analysis

Water withdrawals are disaggregated at the sectoral and subsectoral level. Ideally, withdrawals would be disaggregated to the level of end-uses; for example, toilets in households, or particular processes and technologies in industries. However, data limitations do not permit this level of detail in this study. Instead, withdrawals are assigned to the agriculture, domestic, industry and energy sectors, further broken down by manufacturing subsector and energy conversion process (thermal electric generation and oil refining). However, even at this level data are rarely available, so in constructing the current accounts, for several regions sectoral water withdrawals are estimated, based on available data.

In the analysis, sectoral withdrawals are expressed as the product of an activity level — such as population in the household sector or subsectoral value added in the industrial sector — and an intensity. In the scenarios, the activity levels are determined by assumptions made outside of the water analysis: population and income growth, changing sectoral composition of GDP, and irrigated harvested area. The emphasis in the water-use analysis is therefore on the changing intensities. The relationship between sectoral withdrawals, activity levels and intensities can be expressed as:

$$\text{Withdrawal} = \text{Activity Level} \times \text{Intensity}. \tag{5-1}$$

Water Stress Analysis

As described above, water withdrawals in both scenarios are computed at the regional level. However, because water supply issues are very local in nature, the analysis of the degree of water stress is performed at the national level.

Several measures of "water stress" have been introduced (Raskin et al., 1997). Depending on the measure, they are intended to provide rough indicators focusing on different aspects of water stress: the pressures placed on water resources, the reliability of water supplies, or the ability for society to cope with limited renewable freshwater supplies. The measure used in this analysis is the *use-to-resource ratio*, the ratio of total freshwater withdrawals to renewable freshwater resources. The ratio is a measure of the pressure placed on water resources. In some countries, part of the withdrawal demand is supplied by desalinization and wastewater treatment plants. These withdrawals are excluded when computing the use-to-resource ratio, since they do not put pressure on renewable water resources. Expressed as a formula, the water-stress indicator used in this study is given by:

$$\text{Use-to-Resource Ratio} = \frac{\text{Withdrawals} - (\text{desalinization \& wastewater})}{\text{Renewable resources}}. \tag{5-2}$$

A population in a given area is considered to be in water stress if the use-to-resource ratio for that area exceeds certain critical values. In Raskin et al. (1997), the following criteria were used: a use-to-resource ratio of less than 0.1 indicates no stress, between 0.1 and 0.2 low stress, between 0.2 and 0.4 stress, and greater than 0.4, high stress. At use-to-resource ratios higher than 0.2, water stress can begin to be a limiting factor on economic development (Raskin et al., 1997). Using an approach adapted from that of Raskin et al. (1997), the population within a country in areas of water stress, expressed as a proportion of the total population in the country, is assumed to increase smoothly as the national use-to-resource ratio rises from 0.1 to 0.4. When the national use-to-resource ratio is 0.1, none of the population in the country is in water stressed areas, and when the use-to-resource ratio is 0.4, all of the national population is experiencing water stress.

5.2.1 Current Accounts

In global compilations of water use, withdrawals are usually reported for three sectors: domestic, industrial and agricultural. The sources for this study provide withdrawals in these categories (Najlis, 1996; Shiklomanov, 1996; Raskin, et al., 1995). Withdrawals for these sectors are shown by region in Table 5-3.

Table 5-3. Withdrawals by sector and region in 1995

km^3	Domestic	Industrial	Agricultural	Total
Africa	16	12	139	167
Latin America	15	20	222	257
Middle East	9	2	188	200
China+	87	31	436	553
S+SE Asia	107	48	986	1,142
E Europe	6	34	22	63
FSU	47	170	164	381
N America	72	255	212	540
W Europe	42	125	107	275
Pacific OECD	21	40	61	121
World	423	738	2,538	3,699

The domestic sector includes water use in households and in the service sector. The industrial sector includes energy sector uses (thermoelectric generation and petroleum refining), in addition to standard industrial activities (manufacturing, mining, quarrying, and construction). Water is used in agriculture for irrigation, watering livestock and aquaculture. However, nearly all of the water withdrawn for agriculture is used for irrigation (Raskin et al., 1995; Luyten, 1995), and in this study, all of the reported agricultural withdrawals are assumed to be for irrigating crops. As mentioned in Section 5.2.1, in this study withdrawals are assigned to domestic uses, manufacturing subsectors, energy conversion processes and agriculture. The allocation is based on the available data, as described below.

Domestic

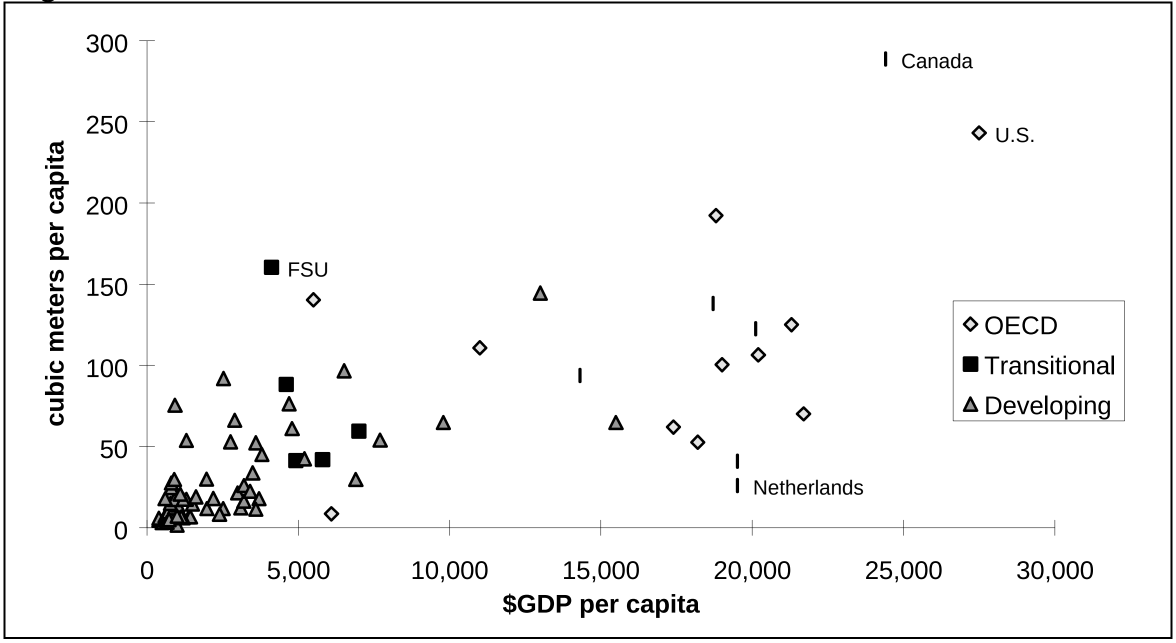
Water is used in households for human consumption, toilets, dish washing, bathing, cleaning and outdoor use (e.g., lawn watering, car washing and decorative uses). The service sector includes such water-intensive establishments as restaurants, cleaners, hotels and hospitals. Data limitations require that we aggregate over these diverse activities.

Table 5-4. Domestic withdrawal intensities

m^3/capita	1995
Africa	22
Latin America	32
Middle East	53
China+	65
S+SE Asia	64
E Europe	66
FSU	160
N America	244
W Europe	91
Pacific OECD	138

Water requirements in each sector are calculated as the product of two factors: an activity level and a water intensity. For domestic withdrawals, the activity level is population and the water intensity is water use per person. Domestic water intensities in a given region reflect many factors, for example, income levels, water infrastructure, technology and water availability. As illustrated in Figure 5-1, current domestic water intensities vary widely between countries and regions, and generally increase with income. Regional annual per capita withdrawals are shown in Table 5-4. Values range from as little as 22 cubic meters per person each year in Africa to over 240 cubic meters in North America.

Figure 5-1. Household withdrawals vs. income



Manufacturing

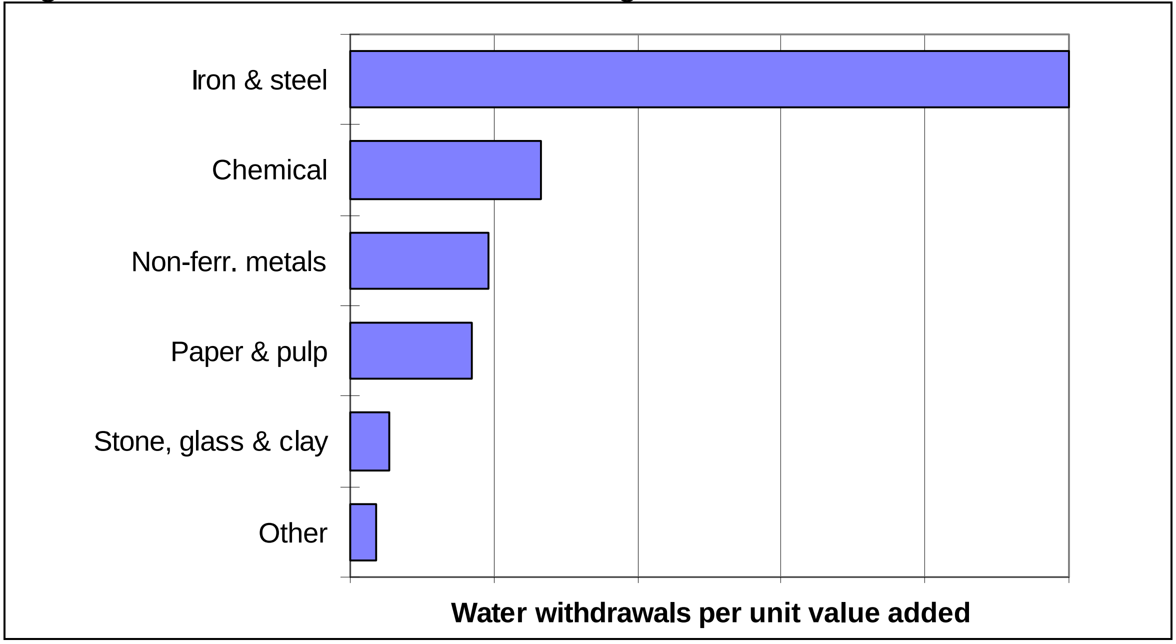
Water withdrawals for manufacturing are disaggregated by the six subsectors introduced in the energy analysis in Section 3.2.4: iron and steel; non-ferrous metals; non-metallic minerals; paper and pulp; chemicals; and a miscellaneous "other" category. The five subsectors that are treated explicitly are relatively more water-intensive than the ones grouped into the "other" category (Raskin et al., 1995). The activity level for this sector is subsectoral value added. The water intensity is defined as withdrawals per unit value added.

Table 5-5. Manufacturing water intensities

m^3/\$1000 VA	1995
Africa	9
Latin America	10
Middle East	3
China+	5
S+SE Asia	5
E Europe	28
FSU	89
N America	16
W Europe	19
Pacific OECD	34

Withdrawals for manufacturing contribute to total industrial withdrawals, the conventional category in international compilations of water use. Withdrawals for energy conversion, described in the next subsection, also contribute to the total. For the non-OECD regions, the general approach taken in constructing the current accounts data set is to start with estimated intensities for manufacturing and energy conversion based on available data, and then to adjust them to reproduce the reported industrial withdrawals. Withdrawal data by manufacturing subsector are scarce, so in every region, manufacturing intensities are based on data for the United States in the mid-1980s (Raskin et al., 1995). The relative intensities in each subsector, shown in Figure 5-2, are the same for every region. The absolute intensities are set so that when they are multiplied by the base-year subsectoral value added, they reproduce the total regional manufacturing withdrawals, which are adjusted in combination with withdrawals for energy conversion.

Figure 5-2. Relative values for manufacturing intensities



The aggregate intensities are shown in Table 5-5. The values vary over a wide range. Generally, the intensities are lowest in the developing regions, and highest in the transitional regions. The highest value for any region is that for the FSU, at 89 cubic meters of water per $1,000 of value added. As shown in the next subsection, the estimated intensity for thermoelectric generation is also high in the FSU.

Energy Conversion

As for the other sectors, water withdrawals for energy conversion processes—petroleum refining and thermal electric generation—are expressed as the product of an activity level and an intensity. For this sector, energy production is used as an activity measure. Petroleum and electricity production are discussed in Section 3.3.

Water is used in thermoelectric generation principally for cooling purposes. A variety of cooling technologies is available. These include once-through systems, which have high withdrawal rates, but low consumption rates (Gleick, 1993); cooling towers, which have low withdrawal rates but relatively high consumption rates (Gleick, 1993); and closed systems, which have both low withdrawal and low consumption rates (Willenbrock and Thomas, 1980). Closed systems are usually introduced when little or no water supply is available, and are not widely used.

Data on water withdrawals for energy conversion are relatively scarce. The OECD collects data on water use for thermoelectric generation from its members (OECD, 1996). In addition, data on water use for oil refining are available for the United States. The estimated thermoelectric intensities for the OECD countries, computed using the withdrawal statistics from the OECD and energy production data from IEA (1997) are shown in Table 5-6. The values vary over a wide range, due to differences in the mix of generation and cooling technology, as discussed above, and in the fraction of total water requirements that are supplied from freshwater sources. For example, Japan meets much of its requirements for thermoelectric cooling using salt-water (Raskin et al., 1995).

Table 5-6. Thermoelectric cooling intensities in OECD countries

m^3/GJ	1995
Canada	37
United States	16
Austria	13
Finland	2
France	15
Germany	13
Italy	10
Netherlands	16
Portugal	28
Spain	11
Sweden	0.1
Turkey	24
United Kingdom	4
Japan	0.3

Using the available data for the OECD regions and estimated intensities for the non-OECD regions as developed for the *Conventional Development* scenario (Raskin et al., 1995), regional base-year intensity estimates are developed (see Table 5-7). For the OECD regions, the thermoelectric intensities are computed directly, extrapolating from the figures in Table 5-6. Refining intensities for the OECD regions are set based on the value for the United States. For the non-OECD regions, the intensities of Raskin et al. (1995) are applied initially, and then adjusted in combination with the manufacturing intensities to reproduce the reported base-year industrial withdrawals. The thermoelectric and refining intensities are adjusted by the same factor, while ensuring that the adjusted thermoelectric intensities were kept within the range of values seen in the OECD regions (Table 5-6).

Table 5-7. Thermoelectric water intensities

m^3/GJ	1995
Africa	5.8
Latin America	3.2
Middle East	0.3
China+	5.5
S+SE Asia	10.0
E Europe	22.3
FSU	28.4
N America	14.7
W Europe	9.0
Pacific OECD	0.2

Agriculture

Nearly 70% of current global fresh water withdrawals are for agricultural applications, as seen in Table 5-3. In the developing regions, agriculture claims the dominant share of freshwater withdrawals. In the OECD and transitional regions, agricultural withdrawals are also important, roughly equaling the total requirements from industry.

For this analysis, all agricultural withdrawals are assigned to irrigation. In the agriculture sector, the activity level is the harvested irrigated area, and the intensity is water withdrawal per harvested area. The distribution of irrigated land is discussed in Section 4.5. Roughly 17% of the world's cultivated land is currently under irrigation, with yields typically much higher than for rain-fed agriculture. For example, in the United States, average irrigated farming yields are about four times those of rain-fed farms (Bajwa et al., 1987). Irrigation water intensities depend on a number of factors, including the local climate and soils, crop mix, practices, efficiency of water use and economic conditions. As a result of these interacting factors, aggregate irrigation intensities, shown in Table 5-8, show considerable variation between regions.

Table 5-8. Irrigation water intensities

$1000\ m^3/ha$	1995
Africa	9
Latin America	12
Middle East	12
China+	5
S+SE Asia	10
E Europe	4
FSU	11
N America	12
W Europe	7
Pacific OECD	22

Water Stress

The total regional water withdrawals given above in Table 5-3 are constructed based on withdrawal data at the national level. National levels of water stress are determined by the national use-to-resource ratio, or the withdrawals as a fraction of total renewable resources, as discussed in Section 5.2.2. The results, aggregated to the regional level, are shown in Table 5-9.[52] The local nature of water-supply problems is evident from the patterns seen in the table, in that there is no sharp distinction between the OECD and developing regions. This is in contrast to many of the other issues explored in the *Conventional Worlds* scenarios. The incidence of water stress in the transitional regions is low because of relatively abundant water resources. At a global level, about one-third of the world's population experiences some degree of water stress.

Table 5-9. Population in water stress

1995	Millions of People	% of Regional Population
N. America	88	30
Pacific OECD	29	19
W. Europe	182	39
E. Europe	17	17
FSU	-	-
Africa	155	22
China +	338	25
Latin America	74	16
Middle East	164	92
S+SE Asia	816	49
Developing	1,549	35
Transitional	17	4
OECD	298	33
World	1,863	33

5.2.2 Scenarios

In this section the water scenarios are presented. The *Reference* scenario analysis is, to a large extent, an update and elaboration of two earlier studies (Raskin et al., 1995; Raskin et al., 1997). The analysis uses a later year base year (1995 instead of 1990), newly updated sources of data, and updated methodologies for making projections of certain key variables. Some of the text in this chapter is adapted from the reports of those studies.

As discussed in Section 5.2.1, withdrawals are determined at the sectoral level. Sectoral intensities are then multiplied by sectoral activity levels to determine withdrawals. The assumptions for each sector are introduced below, after first discussing the sustainability goals.

The sustainability of the *Reference* scenario is determined by comparing the national use-to-resource ratios in the scenario to the sustainability goals introduced in Section 1. The *Policy Reform* scenario is constructed to satisfy the goals. Two indicators are used to define the goals: the use-to-resource ratio and the population in water stress. The scenario goals are summarized here.

To meet the goals, the use-to-resource ratio must peak by 2025, and then decrease. In 2050, for countries that were not experiencing high water stress in the base year (i.e., a use-to-resource ratio greater than 0.4), the use-to-resource ratio in 2050 should be less

---

[52] For countries in the Middle East and North Africa, the contribution from desalinization and wastewater is first subtracted from the withdrawals, as shown in Equation (5-2). The contribution from these sources for each country is discussed in the next section.

than some value in the range 0.2-0.4, with the particular value depending on the level of effort required to meet the goal in the particular country. For countries in high stress in the base year, the use-to-resource ratio must be below the base-year level. Considering the high population and income growth in developing regions in the *Policy Reform* scenario, these targets present considerable challenges for countries with limited water resources.

In the specification of the sustainability goals, there is some flexibility in that there is no general target for the use-to-resource ratio in 2050. The particular target varies from country to country depending on the level of effort required. The required level of effort is determined for the *Policy Reform* scenario based on the withdrawals that would arise in each year assuming *Reference* scenario intensities, but *Policy Reform* scenario activity levels. These withdrawal levels are estimated by scaling *Reference* scenario withdrawals by a GDP-dependent factor.[53]

In terms of the population in water stress, the target is to restrain the size of this population to less than 40% of the total world population. This is an increase over 1995 levels, when 34% of the world was experiencing water stress. After 2050, the population experiencing water stress is targeted to decrease.

In constructing the *Policy Reform* scenario, the following approach is taken:

1. **Maximum Withdrawals:** Maximum withdrawals from renewable freshwater sources are set at the country level, consistent with the sustainability goals. Added to these are contributions from desalinated water and recycled wastewater. The total from these two sources gives the maximum water available for withdrawal, within the constraints placed by the scenario goals.
2. **Standard Intensities:** Regional withdrawals in the scenarios, which are determined from a sectoral analysis, are kept below the maximum levels. This is achieved by having sectoral intensities move away from *Reference* level intensities toward "standard" values (which they do not necessarily reach) over the course of the *Policy Reform* scenario. The standard intensities are discussed for each sector below. Within a particular region, the degree to which the region approaches the standards is set to be the same for each sector.

Domestic

Reference

Domestic water intensities in the *Reference* scenario are based on trends in the OECD regions. Historically, in the United States, the intensity of domestic water withdrawals increased between 1960 and 1980, after which it leveled off. The earlier rise in water use was due in part to the growth in single-family suburban housing, where large lots required

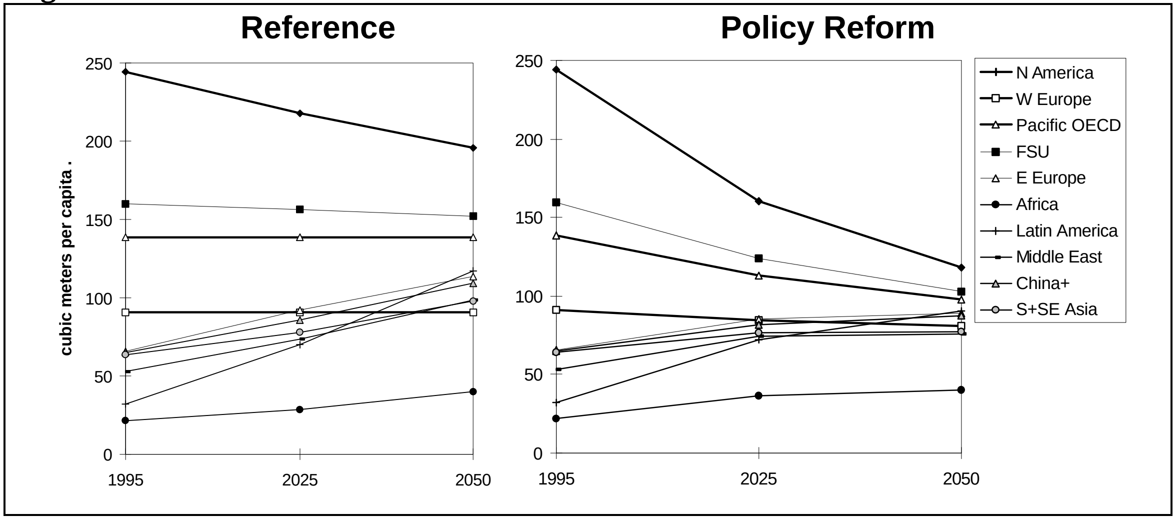
---

[53] The scaled withdrawals are intended as rough guides, in the absence of a detailed sectoral analysis at the country level. Change in GDP is used as a proxy for changes in industrial value added and energy use. The other drivers — population and harvested irrigated area — are very similar in the two scenarios.

more water, especially for outdoor use (Raskin et al., 1995). In the future, domestic water withdrawals per capita are expected to decline in the United States, based on recent policies and available technologies.

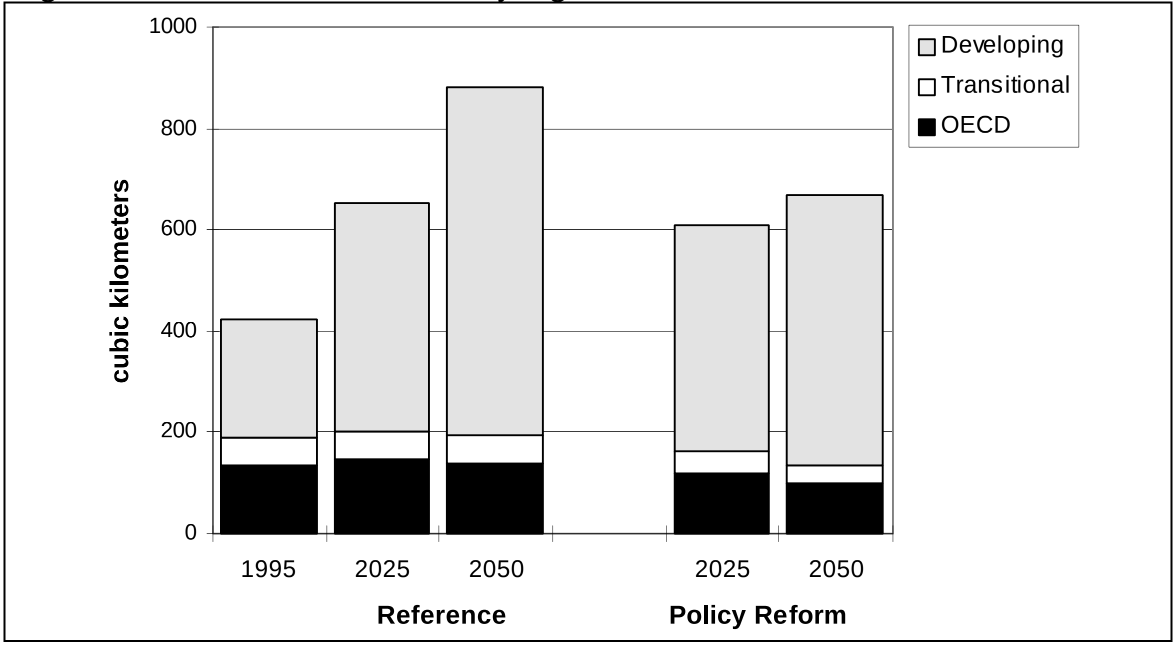
In North America, domestic water intensities are assumed to decrease by 20% over the course of the *Reference* scenario, from nearly 250 to a little under 200 cubic meters per capita per year. In Western Europe and Pacific OECD, current domestic intensities are much less than those in North America, about 90 and 140 cubic meters per capita per year, respectively. In the scenario, domestic water intensities in these regions are assumed to remain constant. In the developing regions, intensities converge toward average OECD patterns following the convergence algorithm (see Annex). The resulting intensities are shown in Figure 5-3.

Figure 5-3. Domestic water intensities in the scenarios



Domestic water withdrawals are computed by multiplying these intensities by the population assumptions in the scenario. The results are shown in Figure 5-4. Water use in the OECD and transitional regions changes little, due to low population growth and relatively steady water intensities; however, the developing regions show large increases. Withdrawals for the developing regions as a whole nearly double over the course of the scenario. This increase dominates the global trend, in which domestic withdrawals reach 653 km^3 in 2025 and 882 km^3 in 2050, compared to 423 km^3 currently.

Figure 5-4. Domestic withdrawals by region in the scenarios



Policy Reform

As discussed in the introduction to this section, in the *Policy Reform* scenario, standard intensities are set in each sector. Over the course of the scenario, regional intensities move toward the standard value relative to the *Reference* value. For the domestic sector, several factors were considered when setting the standard: current patterns, basic needs, the potential for efficiency improvements, and the global convergence that is part of the *Conventional Worlds* story.

Current domestic withdrawals per capita are given in Table 5-4. There is a more than 10-fold difference between the value for Africa, 22 cubic meters per capita per year, and North America, with 244 cubic meters per year. The lowest intensity in the OECD is in Western Europe, at about 90 cubic meters per capita. The average values in every region are well above the minimal requirements for metabolic, hygienic and domestic requirements as estimated by the World Health Organization, a value of about 7 cubic meters per person annually (World Bank, 1998). However, the value for Africa is only slightly higher than the estimated minimum requirement reported in Seckler et al. (1998) of 20 cubic meters per person for basic domestic needs each year. As discussed in *BTC*, in OECD regions, domestic intensities can be reduced through expanded use of water-efficient appliances and tighter plumbing codes. In addition, water use for landscaping and lawns can be reduced through better practices, and in arid regions native plants can be used for landscaping, rather than more water-intensive ones (Postel, 1992; Gleick et al., 1995). In non-OECD regions, increased use of water-consuming appliances is expected to increase in the process of convergence, leading to increasing withdrawals.

For the scenario, for every region except Africa, the standard value is set to about 80% of the current value in Western Europe, or 75 cubic meters per capita per year. In Africa a smaller value is used.[54] The domestic water intensities in the scenario are shown in Figure 5-3.

Domestic withdrawals are computed by multiplying the intensities by the populations assumed in the scenarios (discussed in Section 2). The results are shown in Figure 5-4. There are decreases in the OECD and transitional regions, compared to the almost constant level of withdrawals in the *Reference* scenario. The developing regions still show significant increases, but the withdrawals for the developing regions as a whole are about 20% less than those in the *Reference* scenario in 2050.

Manufacturing

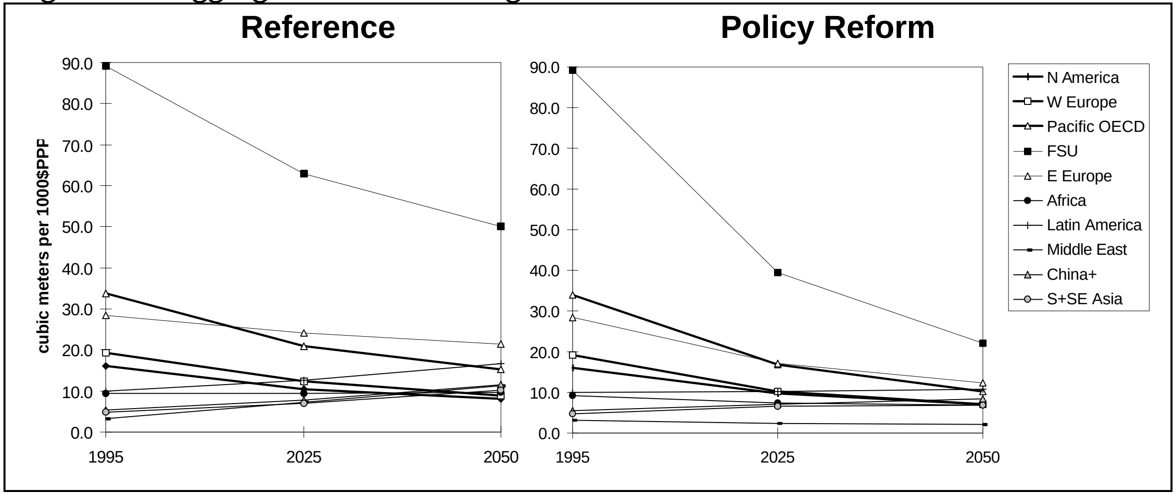
Reference

Subsectoral water intensities in the scenario are based on historical and anticipated trends in the United States, where disaggregated time-series data are available. The water withdrawal intensity in manufacturing decreased by about 50% between 1960 and 1990. The drop was due both to the decreasing share of total manufacturing output from water-intensive subsectors and the penetration of more efficient water-use practices (Raskin et al., 1995). The two effects that caused a decrease in the U.S. in the past play a role in the scenario as well. In the OECD regions, the rising share of the less water-intensive manufacturing subsectors in itself lowers aggregate manufacturing water intensity (Table 5-6). This is traced to the stable per capita output of traditional heavy industries such as iron and steel, non-ferrous metals, paper and pulp and chemicals, as discussed in Section 3.2.5. Consequently, the mix of manufacturing output shifts toward less water-intensive subsectors, thereby lowering the aggregate manufacturing water intensity. Increasing efficiency and the changing mix of industrial activities are reflected in the aggregate manufacturing intensities shown in Figure 5-5. Manufacturing intensities in the non-OECD regions are assumed to converge toward the average for the OECD regions as incomes rise (see Annex). The changing subsectoral intensities, combined with the subsectoral composition of industrial value added, leads to the aggregate manufacturing intensities shown in Figure 5-5.

---

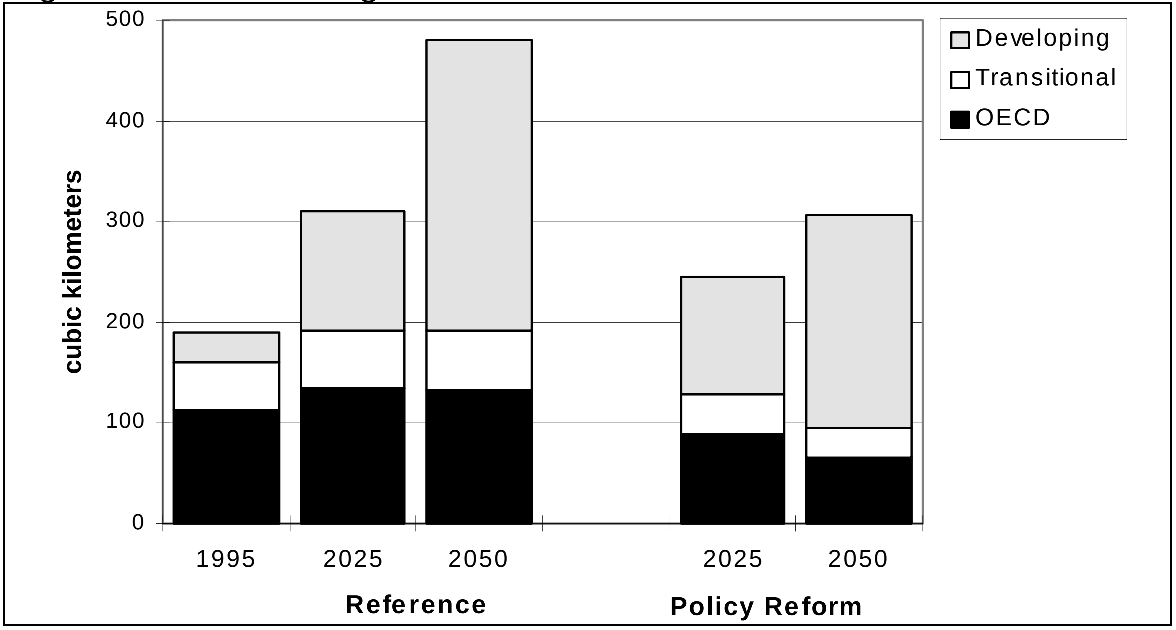
[54] In Africa, the standard domestic intensity of 75 cubic meters per capita is higher than the *Reference* scenario intensities, while the standard agricultural intensity (discussed below) is lower than the intensities in the *Reference* scenario. For increasing degrees of convergence toward the standard intensities across sectors, agricultural withdrawals decrease, but domestic withdrawals increase, resulting in no solution to the sustainability constraint. Unlike the domestic standard intensity, the agricultural and industrial standards are set based on technical potential, so the domestic standard was adjusted to meet the sustainability goal. For Africa, a standard intensity of 40 cubic meters per capita is assumed.

Figure 5-5. Aggregate manufacturing water intensities



Manufacturing water withdrawals in the scenario are given by the product of the subsectoral intensities and subsectoral value added. Results are shown for the three macro-regions in Figure 5-6. Globally, annual water withdrawals in the sector increase by 2050 to over 2.5 times the 1995 value. Regional variations are due to the interplay of region-specific assumptions about industrial scale, structure and water intensity. The dramatic growth in developing regions is particularly striking: mainly as a result of economic growth, withdrawals for the developing regions as a whole in 2050 are greater than the world total in 1995.

Figure 5-6. Manufacturing withdrawals in the scenarios



Policy Reform

The standard value for manufacturing intensities is based on industrial water use in Israel. As a result of low water pricing policies, and efficiency standards, industrial water use in

Israel today is very efficient compared to other countries (Lonergan and Brooks, 1994). The intensity standard used for all regions (Table 5-10) is set to 80% of the estimated subsectoral value for Israel, assuming the same relative subsectoral intensities in Israel as for the United States in 1990.[55,56] Methods for achieving efficiency improvements are given in *BTC*. The manufacturing intensities in the scenario are shown in Figure 5-5.

Table 5-10. Standard manufacturing intensities

m^3/$1000	
Iron & Steel	51
Chemical	14
Non-ferr. metals	10
Paper & pulp	9
Stone, glass & clay	3
Other	2

Total manufacturing withdrawals are given by the product of subsectoral value added and the intensities. Scenarios for value added in manufacturing subsectors are described in the context of the energy analysis in Section 3.2.5. The resulting water withdrawals are shown in Figure 5-6. For the OECD regions, slower economic growth in the *Policy Reform* scenario compared to the *Reference* scenario, combined with sharp reductions in manufacturing intensities, lead to withdrawals in 2050 roughly half those of the *Reference* scenario. In the developing regions the gains are not as great, due to higher economic growth. However, despite the higher growth, as a result of the lower intensities, manufacturing withdrawals in 2050 in the *Policy Reform* scenario are 27% lower than those in the *Reference* scenario.

Energy Conversion

Reference

Trends in petroleum refining intensities are assumed to be the same as in the manufacturing sector. Intensities in the OECD regions decrease by 10% in 2025 and 20% in 2050, due to assumed efficiency improvements, while in the non-OECD regions, intensities converge toward the OECD average following the convergence algorithm (see Annex).

For thermoelectric generation, the scenarios are based on historical data for the United States. Between 1960 and 1990, average freshwater intensity in the U.S. decreased by 60%, as cooling systems became less water-intensive and power plant efficiencies

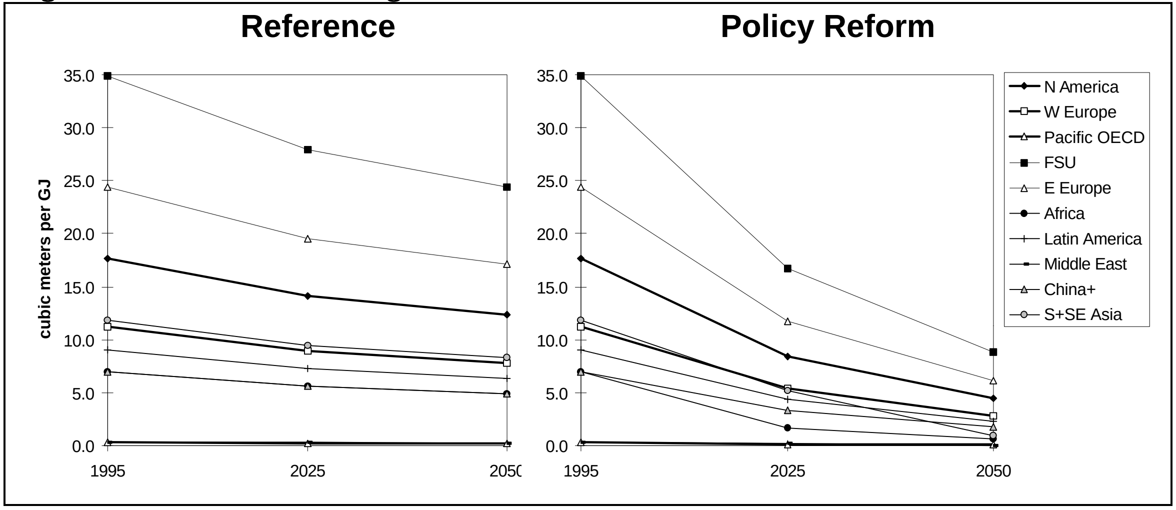
---

[55] Since electric generating plants in Israel use salt water for cooling (Lonergan and Brooks, 1994), and oil refining generally makes a small contribution to industrial withdrawals, all of the reported industrial water withdrawals may be assigned to manufacturing.

[56] For some regions, including the Middle East, the base-year values were below the standard. This may indicate inconsistencies in the base-year data, or the limitation of using value added, rather than physical production, as a measure of activity. In view of the considerable water-supply constraints in the Middle East, the manufacturing intensities for the region were kept at their base-year values in the scenario.

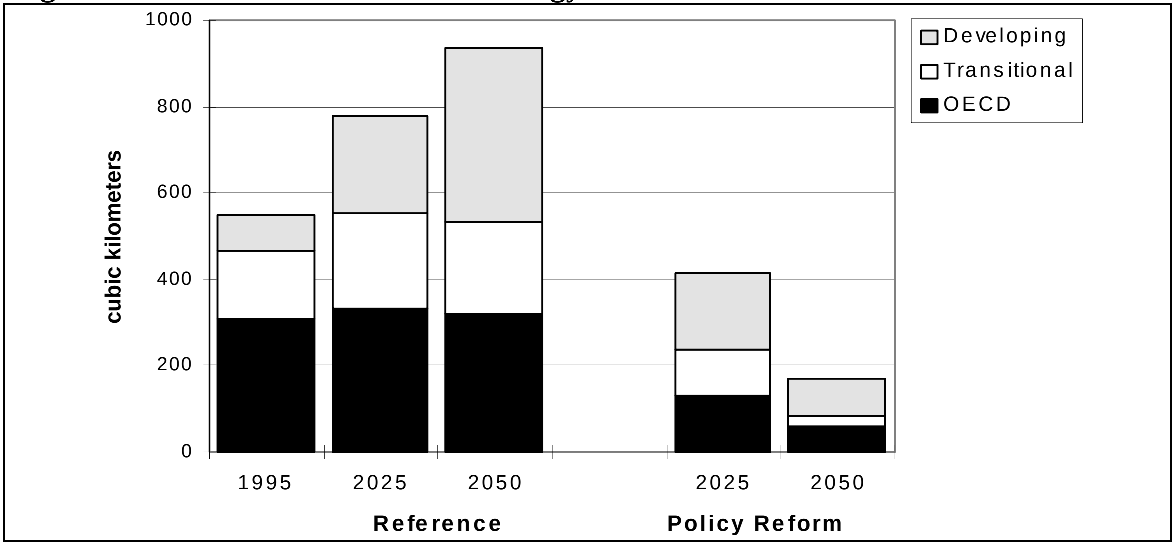
improved (Raskin et al., 1995). This trend toward lower water intensities is assumed to continue in the future, though at a slower rate. In the *Reference* scenario, it is assumed that in all regions thermoelectric generation water withdrawal intensities decrease by 20% between 1995 and 2025 and by 30% between 1995 and 2050. The resulting intensities are shown in Figure 5-7.

Figure 5-7. Thermoelectric generation intensities in the scenarios



Multiplying the intensities with the scenario assumptions for thermal electric generation and petroleum production (Section 3.3) gives the withdrawals shown in Figure 5-8. Withdrawals for the OECD and transitional regions stay fairly steady, while those of the developing regions increase sharply, a result of increases in energy consumption.

Figure 5-8. Water withdrawals for energy conversion in the scenarios



Policy Reform

A wide range of technologies is available for cooling thermoelectric plants. The water withdrawal requirements range from over 30 cubic meters per GJ to zero, indicating considerable scope for reducing withdrawals. However, the technologies that result in essentially zero withdrawals are either expensive and not thoroughly tested on a large scale (closed systems) or are relatively expensive and require special siting (once-through cooling with sea water). Consequently, it is not expected that regions will reach these levels. However, in the spirit of the "standard" intensities, it is expected that regions will move toward using technologies that require no withdrawals. So, for the *Policy Reform* scenario, a value of zero withdrawals is used as the standard in every region. Information on potential efficiency improvements for refining withdrawals are scarce. Given the lack of information and the small contribution of refining withdrawals to total water requirements, an intensity of zero was also chosen as a standard value for this use.

The water intensities for thermoelectric plants in the *Policy Reform* scenario are shown in Figure 5-7. Note that the rate of decrease in North America is similar to the historical rate of decrease in the United States between 1960 and 1990.

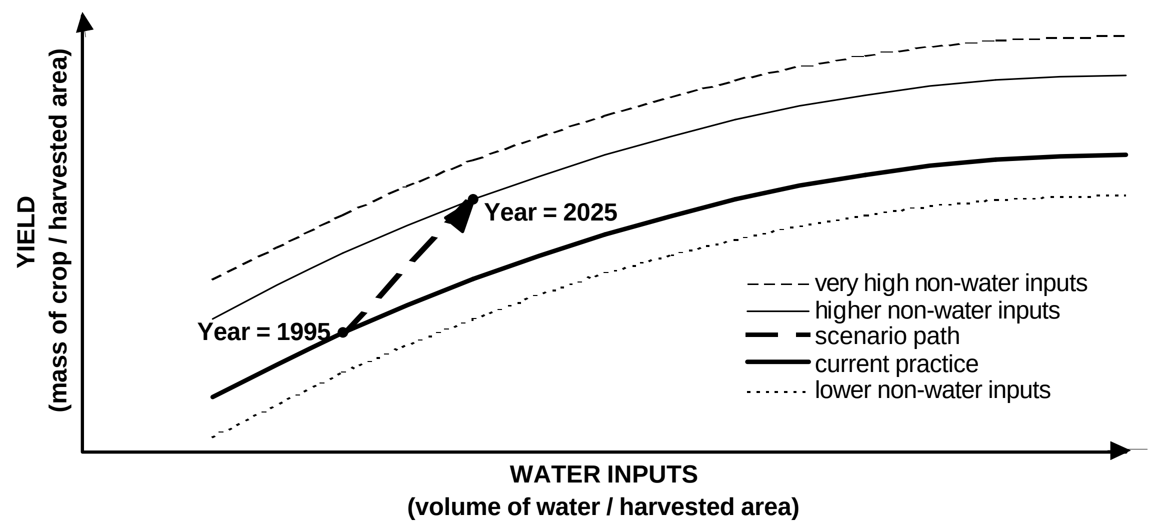
Combining the thermoelectric and petroleum refining intensities with the values for electricity and oil production results in the withdrawals shown in Figure 5-8. The withdrawals in each of the macro-regions is much lower in the *Policy Reform* scenario than in the *Reference* scenario. This results both from the lower intensities shown in Figure 5-7 and from the greater use of renewable fuels in electricity production.

Agriculture

Reference

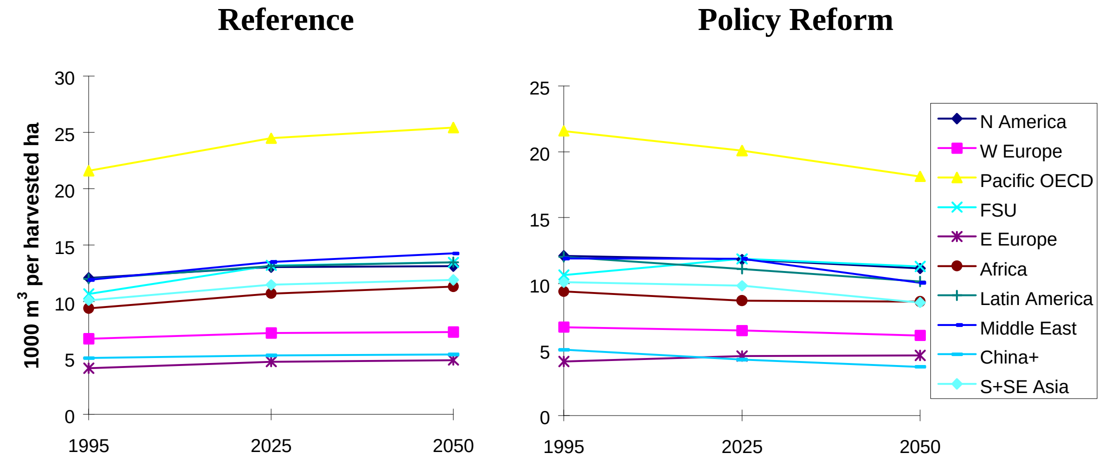
Irrigation water intensities depend on a number of interacting factors. These include crop mix, land quality, weather conditions, irrigation methods, management practices, non-water inputs, relative prices of water and crops, and yield response to irrigation. Figure 5-9 illustrates the relationship between yield response and water intensity for irrigated agriculture. Different curves are shown for different levels of non-water inputs. The crop yields in the *Reference* scenario are assumed to increase for two reasons: 1) increases in water intensity; and 2) improvements in non-water agricultural inputs, such as management practices, chemical applications, and improved crop varieties. Following Raskin et al. (1997), for this study the increase in yield associated with an increase in water intensity is estimated based on empirical yield-response curves (Hexem and Heady 1978). The resulting intensities are shown in Figure 5-10. They increase gradually in every region, consistent with the increasing yields.

Figure 5-9. Yield response to water and non-water inputs



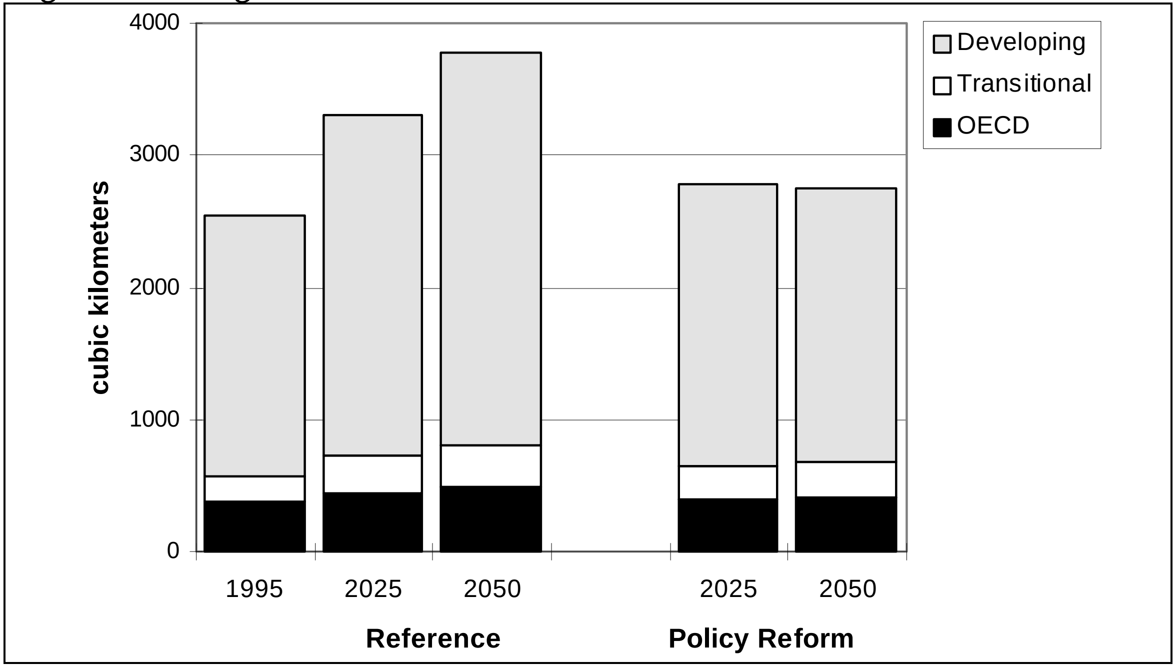
Note: Figure from Raskin et al. (1997).

Figure 5-10. Irrigation water intensities in the scenarios



Irrigation withdrawals in the scenario are determined by multiplying the intensities by the irrigated harvested area (Section 4.5.1). The result is shown in Figure 5-11. The relative increase in withdrawals is highest in the transitional regions, which experience a 70% increase in total withdrawals. However, the absolute increase is much greater in the developing regions, where the increase in water requirements is greater than the total withdrawals of the OECD and transitional regions in the base year.

Figure 5-11. Irrigation water withdrawals in the scenarios



Policy Reform

In part, the irrigation intensities for the *Policy Reform* scenario are developed in the same way as for the *Reference* scenario, with crop water requirements assumed to increase consistent with the increases in yields. However, moderating the increase in water requirements are improvements in irrigation efficiency over base-year practices. For the agriculture sector, rather than a standard intensity value, regions move toward a standard irrigation efficiency *improvement* relative to the base year. Separate potential improvements were developed for each region, based on a study by Seckler et al. (1998). In that study, potential efficiency improvements were estimated by country, covering all of the regions used in this study except the FSU. Current irrigation efficiencies were estimated by comparing reported water withdrawals to the water requirements of a reference crop, taking into account the water supplied by rainfall, and allowing for water storage between planting seasons. The current efficiencies were then compared to a potential efficiency of 70%. For this study the potential efficiency for the Middle East was assumed to be 85%, anticipating that water shortages will make more expensive but water-conserving alternatives more cost-effective than in the other regions. For comparison, the basin-wide efficiency of the Nile basin has been estimated at 91% (Keller and Keller, 1996), while at the farm level, the efficiency of drip irrigation systems can reach 95% (Lonergan and Brooks, 1994). The potential improvement in the FSU was set close to the value for Western Europe.

Regions approach the standard efficiency improvements over the course of the *Policy Reform* scenario. The resulting improvements over base-year practices are shown in Table 5-11, along with the standard efficiency improvement in each region. Improvements in the developing regions range from 12% to 19% in 2025 and from 24% to 30% in 2050. The corresponding intensities are shown in Figure 5-10.

Multiplying the intensities by the irrigated harvested area (Section 4.5.1) gives the irrigation water withdrawals shown in Figure 5-11. Irrigation withdrawals are almost constant as a result of the assumed irrigation efficiency improvements and, in the Middle East, a decline in the harvested irrigated area over the course of the scenario.

Table 5-11. Irrigation efficiency improvement over base-year practices

% Improvement	2025	2050	Standard
N America	9	15	24
W Europe	11	17	26
Pacific OECD	18	29	45
FSU	10	16	25
E Europe	3	5	8
Africa	19	24	27
Latin America	15	25	39
Middle East	12	29	30
China+	19	30	48
S+SE Asia	14	28	32

Water stress.

The incidence of water stress in the scenarios is determined at the national level. National water withdrawals within regions are set in proportion to their base-year withdrawals, such that the total regional withdrawals equal the total determined by the sectoral analysis. The use-to-resource ratios are then computed as in Equation (5-2). The contribution from desalinization and wastewater treatment plants (Table 5-2) is first subtracted from the total withdrawals, and the result compared to the renewable resources. The incidence of water stress is then estimated from the use-to-resource ratios as explained in Section 5.2.2. The changing levels of water stress in the two scenarios are described in *BTC*, and the results for the 10 regions are presented in Sheet P-3. The results are summarized here.

In the *Policy Reform* scenario, as a result of the measures taken in each of the sectors, although the total population experiencing some stress increases steadily throughout the scenario, the growth is much less than in the *Reference* scenario: an 82% increase rather than the 158% increase under *Reference* scenario assumptions. As a percentage of the population, the incidence of water stress stays almost constant between 2025 and 2050, below the 40% required by the sustainability goals. Also, the total population in severe stress stays almost constant over the same period, in contrast to the increase of about 30% in the *Reference* scenario.

6. Local and Regional Pollution

Conventional Worlds scenarios are implicated in numerous regional and local environmental impacts. Problems such as oil spills, indoor air pollution, urban air pollution, regional acidification and exposure to toxic and hazardous wastes will be affected in different ways by the *Reference* and *Policy Reform* scenarios.

While some impacts may be controlled in an evolutionary way, in other cases, the development patterns of the *Reference* scenario present a huge challenge for the future. The environmental sustainability goals of the *Policy Reform* scenario (e.g. climate change mitigation and toxic waste reduction) generally reduce various other local and regional environmental impacts. These *co-control* benefits amplify the social and economic benefits of the *Policy Reform* scenario as compared to the *Reference* scenario. Moreover, in some policy-making contexts — particularly in the developing regions — the regional and local pollution control benefits of the *Policy Reform* scenario are likely to be of more importance than the climate change mitigation benefits of the scenario. We focus here on three examples of impacts at the local and regional level: indoor air pollution from the use of traditional biomass fuels, acidification from the deposition of regional sulfur and nitrogen oxide pollutants, and levels of production of toxic wastes.

6.1 Traditional Biomass Fuels and Indoor Air Pollution

Traditional biomass fuels — wood, charcoal, animal dung and agricultural waste are widely used in developing countries, particularly for domestic cooking. Rural households generally rely on fuelwood and, as this resource becomes more scarce, on dung and wastes. In some countries, many urban households use charcoal, a compact and transportable fuel with cost advantages over direct use of fuelwood in certain areas where markets are far from forest and other wood resources.

In addition to pressure on wood resources, the production and use of biomass fuels raise other environmental issues, most notably the human health impacts of indoor air pollution. Smith (1987) identifies four major groups of indoor air pollutants contained in the smoke from biomass fuel combustion: carbon monoxide, particulates, polycyclic organic matter, and formaldehyde. These pollutants are associated with a range of health impacts including: respiratory infections in young children; adverse pregnancy outcomes (including low birth weights of babies) for women exposed during pregnancy; chronic lung diseases and associated heart diseases; and cancer.

There is increasing evidence of a correlation between high exposure to pollution and ill health. Smith (1993) describes a number of studies that have found strong relationships between exposure to indoor air pollution and adverse health impacts. However, quantitative assessment of the issue is complicated by the lack of reliable health data, the overlapping effect of other pollutants such as tobacco smoke and outdoor air pollution, and the lack of proper monitoring of exposure levels. In addition, some studies have failed to find such connections. A study of health effects in low-income urban women in Lusaka, Zambia (Ellegard and Egneus, 1992) failed to find evidence that the health of biomass-fuel users was significantly poorer than those using cleaner fuels (electricity or kerosene). This negative result does not disprove the link between biomass use, indoor pollution and health, but does point to the necessity for local studies (which can correct for possible compounding factors such as smoking and socioeconomic status) and monitoring of exposure. In the particular example of Lusaka, the measured exposure levels were found to be much lower than those in other parts of the world, probably due to site-specific factors such as stove location, ventilation, mode of food preparation and type of housing.

Historically, industrializing countries have undergone an energy transition from traditional fuels to modern fuels and electricity as incomes rise. This dynamic is also seen in the *Reference* scenario and in more dramatic form in the *Policy Reform* scenario. While we do not explicitly link the scenarios to their associated indoor air pollution human health impacts, it is worth noting what effect each scenario has on levels of traditional biomass use in the developing regions, and thus on expected human health impacts.

In the *Reference* scenario, as incomes increase, the use of biomass fuels gradually declines as households switch to electricity and modern fossil fuels. For example, in Africa the share of biomass fuels in average household energy budgets declines from 89% in 1995 to 52% in 2050. Similar declines are seen in all of the developing regions. This occurs as populations become more urbanized and average incomes increase. Per capita biomass fuel use declines in all developing regions over the period 1995-2050 by amounts ranging from a 35% decline in Africa to a 66% decline in China+. Indoor air pollution can be expected to decline as the overall level of traditional biomass fuel use decreases. Far more dramatic declines are seen in the *Policy Reform* scenario. For example, in Africa, the share of biomass fuels in average household energy budgets declines from 89% in 1995 to only 15% in 2050, reflecting the increased economic development in the region in the *Policy Reform* scenario. Similar patterns occur in the other developing regions. Per capita traditional biomass fuel use also declines dramatically in the *Policy Reform* scenario in the developing regions over the period 1995 to 2050: by over 80% in all developing regions. This rapid decline is likely to be associated with dramatic decreases in the human health impacts associated with indoor air pollution

6.2 Acidification

Small amounts of sulfur are naturally present in the environment through volcanic eruptions, from sea bacteria and other sources (RIVM/UNEP, 1997). When deposited onto soils and lakes, the naturally occurring quantities of sulfur are normally small enough to be beneficial to plants, without causing acidification to soil and water.[57] Ultimately, most sulfur passes into the oceans.

---

[57] A notable exception is the case of volcanic activity, which can cause high levels of sulfur deposition.

Human economic activity, leading to high emissions of sulfur and nitrogen oxides can lead to levels of deposition of pollutants so large that they cannot be fully attenuated by the natural geochemical cycle. Acidification can cause a range of environmental impacts including effects on human health, corrosion of materials, reductions in crop yields, loss of fish stocks, and possible forest damage. Until recently, these impacts were largely confined to Europe and North America. It now appears that regional air pollution is a serious and growing problem in many parts of the World, particularly in certain developing countries (SEI-York, 1998).

In terms of ecological impacts, the problem of acidification arises when high levels of acid deposition occur in regions where soils, forests and aquatic ecosystems are particularly sensitive to acidification.

Acidification is related to deposition of both sulfur and nitrogen oxides. While emissions of nitrogen oxides, which arise primarily from the combustion of fuels in the energy conversion and transport sectors, are not covered by this analysis, they are thought to be an important contributor to the acidifying load in a number of regions (see for example, Brodin and Kuylenstierna, 1992).

6.2.1 Current Accounts

Estimates of current emissions of sulfur are shown below in Table 6-1. The estimates include emissions from the combustion and conversion of fossil fuels, which in 1995 amounted to approximately 68 million tonnes of sulfur (equivalent to 132 million tonnes of SO_2). The combustion of coal for electricity generation and other purposes accounts for approximately 70% of this figure, the remainder arising primarily from the combustion and refining of oil products. The estimates also include non-energy related emissions from industrial processes, which arise primarily from the smelting of non-ferrous metals (zinc, copper, and lead) plus smaller amounts from the pulp and paper sector.

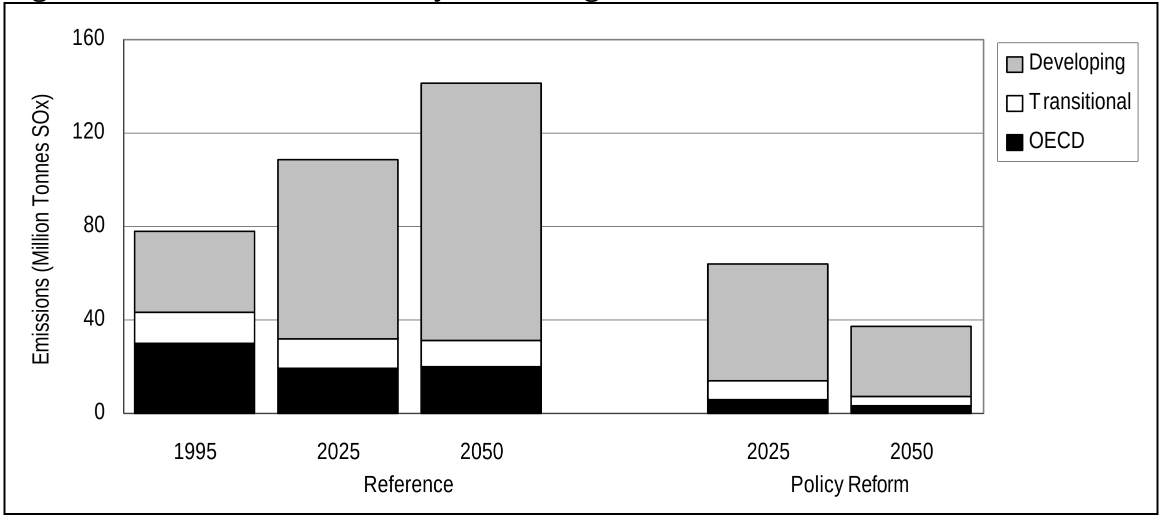
Current sulfur emissions are based on a review of various sulfur emissions inventories for 1990 by Posch et al. (1996) and Kuylenstierna (1998). The 1995 estimates account for changes in fuel consumption in each region and changes in economic output in the non-ferrous metals subsector in each region between 1990 and 1995.

Table 6-1. Global Emissions of Sulfur Oxides by Sector in 1995

Emissions (million tonnes S)	Energy Sector	Industry combustion	Industry process	Other combustion	Total
Africa	0.9	0.2	1.4	0.3	2.8
China+	4.4	4.9	2.1	2.1	13.5
Lat Amer	0.8	0.6	1.4	0.6	3.4
Mid East	0.7	0.3	1.0	0.4	2.4
S+SE Asi	2.3	1.1	2.6	1.3	7.3
E Europe	1.2	0.3	0.5	0.2	2.2
FSU	3.5	0.7	5.6	0.7	10.5
N Amer	5.7	0.6	4.8	1.2	12.3
Pac OECD	1.6	0.6	2.3	0.5	4.9
W Europe	2.7	0.8	4.0	1.2	8.8
Developing	9.0	7.0	8.5	4.8	29.4
Transitional	4.7	1.1	6.1	0.9	12.7
OECD	10.0	2.0	11.1	2.9	25.9
World	23.7	10.1	25.6	8.6	68.0

6.2.2 Scenarios

Figure 6-12. Sulfur Emissions by macro-region



In the *Reference* scenario, emissions increase over time from 68 million tonnes of sulfur in 1995 to 133 million tonnes sulfur in 2050. Over this period, emissions from the OECD regions decrease slightly reflecting small amounts of growth in the use of coal (a 13% increase in primary coal requirements over the period 1995-2050), and at the same time, the widespread adoption of more efficient coal-fired power plants (average efficiencies increase from about 39% to about 42%) using sulfur emission controls that cut the rate of emissions from approximately 0.32 kg/GJ to approximately 0.09 kg/GJ of coal consumed. The decrease in emissions in the OECD regions also reflects the slow rate of growth in the non-ferrous metals sector, where total value added increases by less than 9% over the period 1995-2050.[58]

In the developing and transitional regions, *Reference* scenario sulfur emissions more than triple. This reflects the dramatic increases in coal consumption expected in the scenario (primary coal consumption increases by a factor of 3.88 over the period 1995 to 2050) and the assumption of a lower rate of adoption of more efficient power plants using sulfur controls. The scenario also reflects the high levels of growth expected in the industrial sectors of the developing regions. Total value added in the non-ferrous metals sector in the developing regions increases by a factor of 3.8 over the period 1995-2050. Coupled with the assumption of constant emission factors, this leads to dramatic increases in industrial sector process emissions of sulfur.

The *Policy Reform* scenario achieves dramatic reductions in sulfur emissions with total emissions reduced from 68 million tonnes sulfur in 1995 to 50 million tonnes sulfur in 2050. In part, the scenario reflects the co-control benefits of the greenhouse gas mitigation policies that guide the scenario. Those policies require a dramatic shift away from the combustion of coal towards other less carbon-intensive, and at the same time less sulfurous fuels (biomass, renewables and natural gas). At the same time, the scenario reflects substantial decreases in emission factors in the non-ferrous metals sector, with all regions reaching the current best regional average by 2050.

Sulfur emissions in OECD regions fall dramatically from 26 million tonnes in 1995 to 6 million tonnes in 2050. Fuel-switching policies, when combined with a greater emphasis on demand-side and electricity generation efficiency, dramatically reduce the primary requirements for coal in the OECD regions from 35 EJ in 1995 to only 3 EJ in 2050 (compared to a slight increase to 40 EJ in 2050 in the *Reference* scenario).

Emissions of sulfur from the developing regions increase from 29 million tonnes in 1995 to 41 million tonnes in 2050 in spite of fuel-switching policies and substantial efforts to reduce emission factors (for example reflected in the rapid introduction of sulfur control technologies in the electricity generation sector). In these regions, absolute increases are due, not to a lack action, but rather to the dramatic increase in economic activity and the continued reliance of a number of the developing regions on coal. This is reflected in the primary consumption of coal in the developing regions, which continues to grow from 44 EJ in 1995 to 54 EJ in 2050.

Linkage between Acidification and Climate Change

It is worth noting two important linkages between acidification and climate change. Firstly, changes in weather patterns stimulated by climate change may change the intensity and distribution of acid deposition; and secondly, emissions of sulfur dioxide, which lead to the accumulation of particles in the upper atmosphere, are thought to partly mask the global warming trends caused by other greenhouse gases. One recent analysis

---

[58] In the *Reference* scenario, we assume that emission factors for industrial process emissions and all non-electric sector fuel consumption remain constant over time in each region.

using energy assumptions similar to our *Reference* scenario, estimated a cumulative masking effect of approximately 0.25ºC by 2050 compared to a similar scenario in which concentrations of pollutants are assumed to remain constant (RIVM/UNEP, 1997).

6.3 Toxic Waste

A wide variety of toxic and hazardous substances is used in the manufacture of industrial products. Nearly 100,000 industrial chemicals are now in commercial use worldwide, and this figure is increasing by 500 to 1000 each year. Some of these chemicals may not present significant threats to human health or to the environment, while others are known to represent specific toxicological and ecotoxicological impacts. However, there is insufficient scientific information even for a partial health assessment for about 90% of them (NAS, 1984). Toxic wastes pose particular threats in the environment on account of their toxicity, persistence, and tendency to "bioaccumulate" in living organisms, and through the food chain (Jackson and Taylor, 1992; Dethlefson et al., 1993).

The material and chemical flows underlying the modern industrial economy are immensely complicated and are not well-tracked and understood. Nevertheless, it is important to develop estimates of existing levels of emission of toxic and hazardous substances into the environment, to project trends and to explore alternative scenarios for keeping emissions within acceptable risk levels.

With this aim in mind, the World Bank has devised an "Industrial Pollution Projection System" based on U.S. data, which provides lower bound toxics "emission factors" for many industries expressed as emissions per unit of value added in each industrial subsector (Hettige et al., 1994). These factors have been updated and adapted for use with the value added data used in this analysis (expressed in purchasing power parity units).

The *Reference* scenario analysis of toxic wastes is an update and expansion of an earlier report (Raskin et al., 1996). Some of the text in this chapter is adapted from that report.

6.3.1 Current Accounts

Applying the emission factors to industrial sector value added current accounts yields total emissions of approximately 22 million tonnes in 1995. Figure 6-14 shows how this is broken down by region and industrial subsector. The chemicals industry has the largest sectoral share (37%) with metals industries also significant. The regional picture is dominated by the OECD regions, which account for 46% of all toxic releases.

Figure 6-13. Current Accounts Toxic Waste Emissions

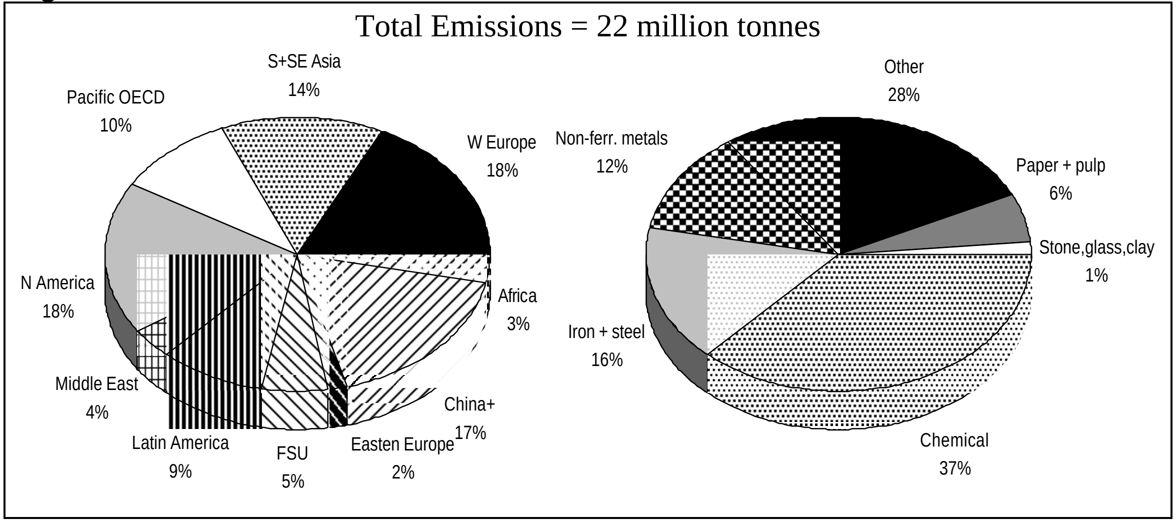
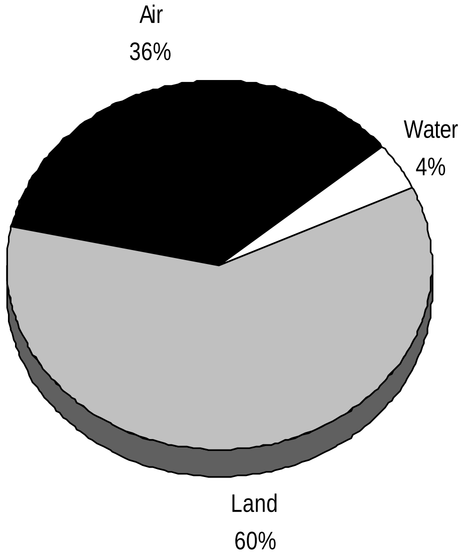


Figure 6-14. Lower Bound Toxic Emissions by Emission Medium (1995)



The fate of toxic emissions by environmental media is presented in Figure 6-14: 60% of emissions are to land, about 36% to the atmosphere, with aquatic environments receiving only 4% of the total burden. Note that these proportions refer only to the initial partition of emissions into specific environmental media. The "ultimate" fate of emissions is determined by environmental transport and transfer mechanisms. In particular, atmospheric emissions will be subject to subsequent deposition both on land and into waters. Moreover, chemicals deposited on land may leach into water supplies. However, it is infeasible to compute the ultimate burden on specific environmental media which depends not only on transport and deposition, but also on metabolization rates, sedimentation patterns, plant uptake, and so on.

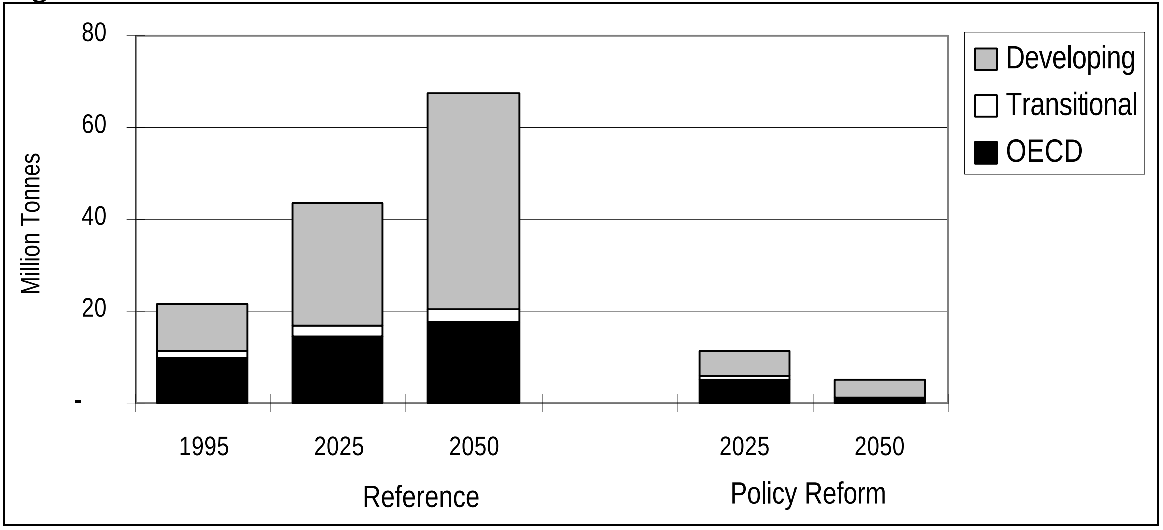
These estimates should be regarded as illustrative only, and a number of limitations concerning the quality of the data, and the applicability of the accounting methodology, need to be highlighted. In the first place, the data have been drawn from a single country (the U.S.) and the degree of validity of extrapolation on a global basis is not clear, particularly since the factors are based on monetary measures of industrial activity rather than a more accurate physical measure (e.g., tonnes of output by industrial subsector). Although the pattern of technological development in other OECD regions may not be vastly dissimilar to the U.S. example, the extension of these emission factors to less developed economies may introduce significant inaccuracies. In general, the effect will be to underestimate actual emissions in less developed regions, because technological efficiencies and environmental controls are likely to be inferior (Jackson and MacGillivray, 1995).

6.3.2 Scenarios

The *Reference* and *Policy Reform* scenarios examine how toxic waste emissions might evolve over time. In the *Reference* scenario, emission factors per unit of value added are assumed to remain constant, while in the *Policy Reform* scenario, emissions are projected in two phases. Firstly, total emissions in OECD regions are assumed to decrease to 50% of 1995 levels by 2025 and further to 10% of 1995 levels by 2050. Secondly, the emission factors implied by this level of decrease are applied also to non-OECD regions, and the results used to calculate overall levels of emissions. This is an ambitious target, but one in line with the general eco-efficiency assumptions of the scenario as described in *BTC*.

The results for each scenario are shown in Figure 6-15. In the *Reference* scenario, emissions increase dramatically especially in the developing regions, to a level that is likely to be unacceptable. The sectoral composition of this burden is similar to the current allocation. The chemicals sector is still important, as are the metals sectors. However, a greater proportion of the burden now comes from "other" sectors — an effect consistent with the reduction in material intensity of conventional materials, such as iron and steel, which is assumed in the scenario. In the *Policy Reform* scenario, dramatic reductions are achieved as a result of the stringent emissions targets set in the scenario.

Figure 6-15. Lower Bound Toxic Emissions Scenarios



References

Alexandratos, N. (ed.) 1995. *World Agriculture: Towards 2010.* Chichester, U.K.: John Wiley and Sons.

Bajwa, R., W. Crosswhite and J. Hostetler. 1987. *Agricultural Irrigation and Water Supply*. Washington, D.C.: U.S. Department of Agriculture Economics Research Service. Agricultural Information Bulletin 532.

Balch, C. C. and J. T. Reid. 1976. "The Efficiency of the Conversion of Feed Energy and Protein into Animal Products," in *Food Production and Consumption: The Efficiency of Human Food Chains and Nutrient Cycles*. Amsterdam: North-Holland Publishing Company.

Bender, Jim. 1994. *Future Harvest: Pesticide-Free Farming*. Lincoln: University of Nebraska Press.

Bender, William H. 1994. "An End Use Analysis of Global Food Requirements." *Food Policy* 19(4), pp. 381-395.

Bender, William H. 1997. "How Much Food Will We Need in the 21st Century?" *Environment* 39(2), pp. 7-11, 27-28.

Bernardini, O. and R. Galli. 1993. "Dematerialization: Long-term Trends in the Intensity of Use of Materials and Energy," *Futures* May, pp. 431-448.

British Petroleum (BP). 1993. *BP Statistical Review of World Energy* (June). London: British Petroleum Company.

Brodin, Y-W, and J. C. I. Kuylenstierna. 1992. "Acidification and Critical Loads in Nordic Countries: A Background," *Ambio* 21, pp.332-338.

Brown, L. R. 1995. *Who Will Feed China?: Wake-Up Call for a Small Planet*. New York: W. W. Norton & Company.

Brown, L. R., C. Flavin, H. French, J. Abramowitz, C. Bright, G. Gardner, A. McGinn, M. Renner, D. Roodman and L. Starke. 1997. *State of the World: A Worldwatch Institute Report on Progress Toward a Sustainable Society*. New York: W.W. Norton and Company.

Brown, L. R., M. Renner and C. Flavin. 1998. *Vital Signs 1998: The Environmental Trends that are Shaping Our Future*. New York: W. W. Norton & Company.

Bumb, B. L. and C. A. Baanante. 1996. *The Role of Fertilizer in Sustaining Food Security and Protecting the Environment to 2020*. Washington, D.C.: IFPRI. Food, Agriculture and the Environment Discussion Paper 17.

Campbell, C. J. and J. H. Laherre. 1998. "Preventing the Next Oil Crunch," *Scientific American*, March, pp. 77-84.

Central Intelligence Agency (CIA). 1997. *The World Factbook 1996*. McLean, Virginia: Central Intelligence Agency. Available from http://www.odci.gov/cia/; INTERNET.

Conway, G. 1997. *The Doubly Green Revolution: Food for All in the 21st Century*. London: Penguin Books.

Crosson, P. and J. R. Anderson. 1992. *Resources and Global Food Prospects: Supply and Demand for Cereals to 2030*. Washington, D.C.: The World Bank. World Bank Technical Paper Number 184.

Crotty, R. 1980. *Cattle, Economics and Development*. Slough, Eng.: Commonwealth Agricultural Bureaux.

Deininger, K. and L. Squire. 1996. “A New Data Set Measuring Income Inequality,” *The World Bank Economic Review* 10(3), pp. 565-591.

Department of Energy, Energy Information Administration (U.S.) (DOE/EIA). 1996. *Annual Energy Outlook 1997*. Washington, D.C.: Energy Information Administration.

Dethlefson, V., T. Jackson, and P. Taylor. 1993. “The Precautionary Principle,” in *Clean Production Strategies: Developing Preventive Environmental Maintenance in the Industrial Economy,* T. Jackson (ed.). Boca Raton, Florida: Lewis Publishers.

Durning, A. B. and H. B. Brough. 1991. *Taking Stock : Animal Farming and the Environment*. Washington, D.C.: Worldwatch Institute. Worldwatch Paper 103.

Economic Commission for Europe. 1995. *Annual Bulletin of Transport Statistics for Europe and North America*. New York: United Nations.

———. 1996. *Annual Bulletin of Transport Statistics for Europe and North America*. New York: United Nations.

Ellegard, A. and H. Egneus. 1992. *Health Effects of Charcoal and Woodfuel Use in Low-Income Households in Lusaka, Zambia*. Stockholm: Stockholm Environment Institute. Report.

Elliot, R. N. 1994. *Electricity Consumption and the Potential for Electric Energy Savings in the Manufacturing Sector*. Washington, D.C.: American Council for an Energy-Efficient Economy.

Energy Innovations. 1997. *Energy Innovations: A Prosperous Path to a Clean Environment.* Washington, D.C.: Alliance to Save Energy, American Council for an Energy-Efficient Economy, Natural Resources Defense Council, Tellus Institute, and Union of Concerned Scientists.

Europa Publications. 1997. *The Europa World Yearbook 1997*. London: Europa Publications.

European Commission (EC). 1996. *European Energy to 2020: A Scenario Approach*. Luxembourg: European Commission. Energy in Europe (special issue), Spring 1996.

FAO (Food and Agriculture Organization of the United Nations). 1995. *Irrigation in Africa*. Rome: FAO.

———. 1996a. *AQUASTAT Database*. Rome: FAO. Available from http://www.fao.org; INTERNET.

———. 1996b. *FAOSTAT·PC*. Rome: FAO.

———. 1996c. “Food, Agriculture and Food Security: Developments Since the World Food Conference and Prospects,” Technical Background Document 1, Volume 1, to the World Food Summit. Rome: FAO. Available from: http://www.fao.org/WFS/final/e/volume1/t1-e.htm; INTERNET.

———. 1996d. *Report of the World Food Summit*. Rome: Food and Agricultural Organization. Available from http:///www.fao.org/wfs/homepage; INTERNET.

———. 1996e. *Sixth World Food Survey*. Rome: Food and Agricultural Organization.

———. 1997a. *Mapping Undernutrition* (poster). Rome: Food and Agricultural Organization.

———. 1997b. *State of the World’s Forests 1997*. Rome: Food and Agriculture Organization.

———. 1997c. *The State of World Fisheries and Aquaculture 1996*. Rome: Food and Agricultural Organization.

———. 1997d. *The State of Food and Agriculture 1997*. Rome: Food and Agriculture Organization.

———. 1998. “Helping People to Live With Trypanosomiasis—One of the Greatest Constraints to African Agricultural Development,” *News & Highlights*, 28 May 1998. Rome: FAO. Available from: http://www.fao.org/News/1998/980506-e.htm; INTERNET.

FAOSTAT Inquiries. 1998. Personal communication.

Fischer, Günther. 1993. Personal communication.

The Forage and Grazing Terminology Committee (FGTC). 1991. *Terminology for Grazing Lands and Grazing Animals*. Available from http://www.forages.css.orst.edu/; INTERNET.

Forest Resources Assessment 1990 Project (FRA). 1996. *Forest Resources Assessment 1990: Survey of Tropical Forest Cover and Study of Change Processes*. Rome: FAO.

Farm Service Agency (U.S.) (FSA). 1998. “Total CRP Enrollment Reduced 7 Percent Under New Requirements,” News Release No. 1469.98. Washington, D.C.: Farm Service Agency.

Galaty, J. G. and D. L. Johnson. 1990. “Introduction: Pastoral Systems in Global Perspective,” *in* J. L. Galaty and D. L. Johnson, Eds. *The World of Pastoralism: Herding Systems in Comparative Perspective*. New York: The Guilford Press.

Gallopin, G. A. Hammond, P. Raskin and R. Swart 1997. *Branch Points: Global Scenarios and Human Choice*. Stockholm, Sweden: Stockholm Environment Institute. PoleStar Series Report No. 7.

Gleick, P. 1992. “Environmental Consequences of Hydroelectric Developments: The Role of Facility Size and Type,” *Energy* (17), pp. 737-747.

Gleick, P. H. (ed.). 1993. *Water in Crisis: A Guide to the World’s Fresh Water Resources*. New York: Oxford University Press.

Gleick, P. H., P. Loh, S. V. Gomez and J. Morrison. 1995. *California Water 2020: A Sustainable Vision*. Oakland, California: Pacific Institute for Studies in Development, Environment, and Security.

Golob, R. and E. Brus. 1993. The almanac of renewable energy :New York : H. Holt.

Greenland, D. J. and B. N. Okigbo. 1983. “Crop Production Under Shifting Cultivation and Maintenance of Soil Fertility,” in *Symposium on Potential Productivity of Field Crops Under Different Environments*. Los Baños, Phillipines: International Rice Research Institute.

Global Resource Information Database/United Nations Environment Program (GRID/UNEP). 1991. *Global Assessment of Human Induced Soil Degradation (GLASOD): Global Digital Database*. Nairobi: GRID.

Grubb, M. J. 1991. “The Integration of Renewable Electricity Sources,” *Energy Policy*, September, p. 684.

Grubb, M. J. and N. I. Meyer. 1993. “Wind Energy: Resources, Systems and Regional Strategies,” in *Renewable Energy: Sources for Fuels and Electricity*, T. B. Johansson, H. Kelly, A. K. Reddy and R. H. Williams (eds.). Washington, D.C.: Island Press.

Hall, D. O., F. Rosillo-Calle R. H. Williams and J. Woods. 1993. “Biomass for Energy: Supply Prospects,” *in* T. B. Johannson, H. Kelly, A. K. N. Reddy and R. H. Williams, eds., *Renewable Energy: Sources for Fuels and Electricity*. Washington, D.C.: Island Press.

Heaps, C., M. Lazarus, P. Raskin, and D. von Hippel. 1993. “Considerations in Energy Planning Models for Wood Energy Planning,” in *Wood Energy Development: Planning, Policies* *and Strategies.* Vol II, Proceedings of the Expert Consultation on Data Assessment and Analysis for Wood Energy Planning. Bangkok: FAO.

Hettige, H., P. Martin, M. Singh and D. Wheeler. 1994. *The Industrial Pollution Projection System*. Washington, D.C.: The World Bank.

Hexem, R. W. and E. O. Heady. 1978. *Water Production Functions for Irrigated Agriculture*. Ames, Iowa: The Iowa State University Press.

Homewood, K. M. and W. A. Rogers. 1991. *Maasailand Ecology: Pastoralist Development and Wildlife Conservation in Ngorongoro, Tanzania*. Cambridge: Cambridge University Press.

Houghton, R. A. and J. L. Hackler. 1995. *Continental Scale Estimates of the Biotic Carbon Flux from Land Cover Change: 1850 to 1980*. Carbon Dioxide Information Analysis Center. NDP-050. Available from http://cdiac.esd.ornl.gov; INTERNET.

Hubbert, M. K. 1956. "Nuclear energy and the fossil fuels"; *American Petroleum Institute Drilling & Production Practice Proceedings, Spring Meeting,* San Antonio, Texas, 7-25.

Hudson, N. 1992. *Land Husbandry*. Ithaca, N.Y.: Cornell University Press.

Intergovernmental Panel on Climate Change (IPCC). 1992. *1992 IPCC Supplement*. Geneva: World Meteorological Organization.

———. 1995a. *Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios.* J. T. Houghton, L. G. Meira Filho, J. Bruce, Hoesung Lee, B. A. Callander, E. Haites, N. Harris and K. Maskell (eds.). Cambridge: Cambridge University Press.

———. 1995b. *IPCC Greenhouse Gas Inventory Reference Manual: IPCC Guidelines for National Greenhouse Gas Inventories*. Vol. 3. Bracknell, UK: IPCC.

International Civil Aviation Organization. 1995. *Civil Aviation Statistics of the World*. Montreal: ICAO.

International Union of Railways. 1994. *International Railway Statistics 1994*. Paris: Secretariat Général de l'Union Internationale des Chemins de fer.

International Energy Agency (IEA). 1997a. *Energy Balances of Non-OECD Countries, 1960-1995* (electronic distribution). Paris: OECD.

———. 1997b. *Energy Statistics of OECD Countries, 1960-1995* (electronic distribution). Paris: OECD.

———. 1997c. *Indicators of Energy Use and Efficiency: Understanding the Link Between Energy and Human Activity*. Paris: OECD/IEA.

International Rice Research Institute (IRRI). 1998. *Sustaining Food Security Beyond the Year 2000: A Global Partnership for Rice Research*. *Strategic Overview*. Available from http://www.cgiar.org/irri/; INTERNET.

International Road Federation (IRF). 1992. *World Road Statistics 1987-1991*. Geneva, Switzerland: International Road Federation.

———. 1996. *World Road Statistics*. Geneva, Switzerland: International Road Federation.

Jackson, T. and A. MacGillivray. 1995. *Accounting for Toxic Emissions from the Global Economy: the Case of Cadmium*. Stockholm: Stockholm Environment Institute. PoleStar Series Report No. 6.

Jackson, T. and P. Taylor. 1992. "The Precautionary Principle and the Prevention of Marine Pollution," *Journal of Chemistry and Ecology* 7, pp. 123-134.

Johansson, T. B., H. Kelly, A. K. Reddy and R. H. Williams. 1993. "A Renewables-Intensive Global Energy Scenario," in *Renewable Energy: Sources for Fuels and Electricity*, T. B. Johansson, H. Kelly, A. K. Reddy and R. H. Williams (eds.) Washington, D.C.: Island Press.

Keller, Andrew A. and Jack Keller. 1996. "Effective Irrigation Efficiency: A New Parameter for Quantifying Freshwater Conservation." *Conserv '96*.

Kendall, H. and D. Pimentel. 1994. "Constraints on the Expansion of the Global Food Supply," *Ambio* 23, No. 3, pp. 198-205.

Krimsky, S. and R. Wrubel. 1996. *Agricultural Biotechnology and the Environment: Science, Policy and Social Issues*. Urbana, Illinois: University of Illinois Press.

Krishnamoorthy, Ch. 1983. "Low Input Cropping Systems," in *Symposium on Potential Productivity of Field Crops Under Different Environments*. Los Baños, Phillipines: International Rice Research Institute.

Kuylenstierna, J. 1998. Personal communication.

Lazarus, M., L. Greber, J. Hall, C. Bartels, S. Bernow, E. Hansen, P. Raskin and D. Von Hippel. 1993. *Towards a Fossil Free Energy Future: The Next Energy Transition*. Amsterdam: Greenpeace International.

Leach, G. 1995. *Global Land & Food in the 21st Century: Trends & Issues for Sustainability*. Stockholm: Stockholm Environment Institute. PoleStar Series Report No. 5.

Leach, G. and P. Mearns. 1988. *Beyond the Woodfuel Crisis: People, Land and Trees in Africa*. London: Earthscan.

Lenssen, N. 1992. *Empowering Development: The New Energy Equation*. Washington, D.C.: Worldwatch Institute. Worldwatch Paper 111.

Lonergan, S. and D. Brooks. 1994. *Watershed: The Role of Fresh Water in the Israeli-Palestinian Conflict*. Ottawa: International Development Research Centre.

Luyten, J. C. 1995. *Sustainable World Food Production and Environment*. DLO Research Institute for Agrobiology and Soil Fertility. AB-DLO Report 37.

Mackenzie J. J. 1996. *Oil as a Finite Resource: When is Global Production Likely to Peak?* World Resources Institute. On-line resource paper. Available from http://www.wri.org/wri/climate/finitoil; INTERNET.

Maheshwari, M. L. 1995. "Rangeland Nutritional Resource for Livestock in India," in *Range Management in Arid Zones: Proceedings of the Second International Conference on Range Management in the Arabian Gulf*, ed. S. A. S. Omar, M. A. Razzaque and F. Alsdirawi. London: Kegan Paul, International.

Masters, C., D. Root and E. Attanasi. 1990. "World Oil and Gas Resources — Future Production Realities," *Annual Review of Energy* 15, p. 23.

Masters, C. D., E. D. Attanasi and D. H. Root. 1994. *World Petroleum Assessment and Analysis.* Proceedings of the 14th World Petroleum Congress, held in Stavanger. Norway.

Moran, E. F. 1982. *Human Adaptability: An Introduction to Ecological Anthropology*. Boulder: Westview Press.

Munslow, B., Y. Katerere, A. Ferf and P. O'Keefe. 1988. *The Fuelwood Trap: A Study of the SADCC Region*. London: Earthscan.

Najlis, P. (Officer-in-Charge, Energy and Natural Resources Branch. Division for Sustainable Development, DPCSD). 1996. Personal communication.

NAS (National Academy of Sciences). 1984. *Toxicity Testing: Strategies to Determine Needs and Priorities*. Washington, D.C.: National Academy of Sciences.

OECD (Organisation for Economic Co-operation and Development). 1997. *OECD Environmental Data: Compendium 1997*. Paris: OECD.

O'Keefe, P., P. Raskin and S. Bernow. 1984. *Energy and Development in Kenya: Opportunities and Constraints*. Stockholm: Beijer Institute. Energy, Environment and Development in Africa, vol. 1.

Oldeman, L., R. Hakkeling and W. Sombroek. 1991. *World Map of the Status of Human-Induced Soil Degradation: An Explanatory Note*. Second revised edition. Nairobi: United Nations Environment Program.

Paarlberg, R. L. 1997. "Feeding China: A Confident View," *Food Policy* 22(3), pp. 269-279.

Penning de Vries, F. W. T., H. van Keulen and J. C. Luyten. 1996. "The Role of Soil Science in Estimating Global Food Security in 2040," in *The Role of Soil Science in Interdisciplinary Research*. Madison, Wisconsin: American Society of Agronomy and Soil Science Society of America. SSSA Special Publication 45.

Pinstrup-Anderson, Per, Rajul Pandya-Lorch and Mark W. Rosegrant. 1997. *The World Food Situation: Recent Developments, Emerging Issues, and Long-Term Prospects*. Washington, D.C.: International Food Policy Research Institute. 2020 Vision Food Policy Report.

Posch, M., J.-P. Hettelingh, J. Alcamo and M. Krol. 1996. "Integrated Scenarios of Acidification and Climate Change in Asia and Europe," *Global Environmental Change* 6(4), pp. 375-394.

Postel, S. 1992. *Last Oasis: Facing Water Scarcity*. New York: W.W. Norton & Company.

Raskin, P. M. Chadwick, T. Jackson and G. Leach. 1996. *The Sustainability Transition: Beyond Conventional Development.* Stockholm: Stockholm Environment Institute. PoleStar Series Report No. 1.

Raskin, P., G. Gallopin, P. Gutman, A. Hammond, and R. Swart. 1998. *Bending the Curve: Toward Global Sustainability*. Boston: Stockholm Environment Institute-Boston. PoleStar Series Report No. 8.

Raskin, P., P. Gleick, P. Kirshen, G. Pontius and K. Strzepek. 1997. *Water Futures: Assessment of Long-range Patterns and Problems.* Background Document for the SEI/United Nations Comprehensive Assessment of the Freshwater Resources of the World. Stockholm: Stockholm Environment Institute.

Raskin, P., E. Hansen and R. Margolis. 1995. *Water and Sustainability: A Global Outlook*. Stockholm: Stockholm Environment Institute. PoleStar Series Report No. 4.

Raskin, P. and R. Margolis. 1995. *Global Energy in the 21st Century: Patterns, Projections and Problems*. Stockholm: Stockholm Environment Institute. PoleStar Series Report No. 3.

RIVM/UNEP (Netherlands Institute of Public Health and the Environment/United Nations Environment Program). 1997. *The Future of the Global Environment: A Model-based Analysis Supporting UNEP's First Global Environment Outlook.* Bakkes, J. and J. van Woerden (eds.). Bilthoven, The Netherlands: RIVM.

Robinson, J. 1990. "Futures under glass: a recipe for people who hate to predict," *Futures* October 1990.

Rose, D. 1997. *Assessing Food Insecurity in the United States: Background Information for Domestic Follow-up Activities to the World Food Summit*. Washington, D.C.: U.S. Department of Agriculture Economic Research Service. ERS Staff Paper No. 9706.

Rose, D., P.P. Basiotis and B.W. Klein. 1995. "Improving Federal Efforts to Assess Hunger and Food Insecurity," *Food Review* 18, Jan-Apr.

Ross, M., P. Thimmapuram, R. Fisher, and W. Maciorowski. 1993. *Long-Term Industrial Energy Forecasting (LIEF) Model (18 Sector Version)*. Argonne, Illinois: Argonne National Laboratory.

Rozelle, S. and M. W. Rosegrant. 1997. "China's Past, Present, and Future Food Economy: Can China Continue to Meet the Challenges?" *Food Policy* 22(3), pp.191-200.

Sanger, D. 1994. "Effort to Solve Energy Woes Clashes with Nuclear Safety," *The New York Times*, August 20: 1, 4.

Scherr, S. and S. Yadav. 1996. *Land Degradation in the Developing World: Implications for Food, Agriculture, and the Environment to 2050.* Washington, D.C.: IFPRI.

Schipper, L. and S. Meyers. 1992. *Energy Efficiency and Human Activity: Past Trends, Future Prospects*. Cambridge: Cambridge University Press.

Seckler, D. 1996. *The New Era of Water Resources Management: From "Dry" to "Wet" Water Savings*. Colombo, Sri Lanka: International Irrigation Management Institute (IIMI).

Seckler, D., U. Amarasinghe, D., Radhika de Silva and R. Barker. 1998. *World Water Demand and Supply, 1990 to 2025: Scenarios and Issues.* IIMI Research Report 19.

Shiklomanov. 1997. *Assessment of Water Resources and Water Availability of the World*. Geneva: World Meteorological Organization.

Smith, K. R. 1987. *Biofuels, Air Pollution, and Health - A Global Review*. New York: Plenum Press.

Smith, K. R. 1993. "Fuel Combustion, Air Pollution Exposure, and Health: The Situation in Developing Countries," *Annual Review of Energy and the Environment* 18, pp.529-66.

Stockholm Environment Institute (SEI). 1993. *G2S2: Greenhouse Gas Scenario System.* Database and User Guide. Boston: Stockholm Environment Institute-Boston.

Stockholm Environment Institute-York (SEI-York). 1998. Personal communication.

Swart, R. 1996. "Security Risks of Global Environmental Changes: Viewpoint," *Global Environmental Change* 3(3), pp. 187-192.

Tabatabai, H. 1996. *Statistics on Poverty and Income Distribution: An ILO Compendium of Data*. Geneva: International Labour Office.

Tyers, Rod and Kym Anderson. 1992. *Disarray in World Food Markets: A Quantitative Assessment*. Cambridge: Cambridge University Press.

United Nations (UN). 1997. *Annual Populations 1950-2050* (1996 rev., electronic distribution). New York: United Nations.

United Nations Industrial Development Organization (UNIDO). 1997. *UNIDO Industrial Statistics Database 1997 (diskette)*. Vienna, Austria: United Nations Industrial Development Organization.

United States Department of Agriculture (USDA). 1994. *1992 National Resources Inventory: 1992 NRI Changes in Land Cover/Use Between 1982 and 1992*. Available from: http://www.nhq.nrcs.usda.gov/land/tables/t2211.html; INTERNET.

United States Department of Commerce, Bureau of the Census (USBC). 1992. *Statistical Abstract of the United States*. Washington, D.C.: U.S. Government Publishing Office.

———. 1995. *Statistical Abstract of the United States*. Washington, D.C.: U.S. Government Publishing Office.

———. 1997. *Historical Income and Poverty Tables (Table H-4)*. Washington, D.C.: United States Bureau of the Census. Available from http://www.census.gov/hhes/income/histinc/index/html; INTERNET.

World Conservation Monitoring Centre (WCMC). 1998a. *Global Forest Information Service World Tables*. Cambridge: WCMC. Available from: http://www.wcmc.org.uk; INTERNET.

———. 1998b. *Global Protected Areas Summary Statistics*. Cambridge: WCMC. Available from: http://www.wcmc.org.uk; INTERNET.

World Energy Council (WEC). 1992. *1992 Survey of Energy Resources*, 16th Edition. London, UK: World Energy Council.

———. 1995. *1995 Survey of Energy Resources*, 17th Edition. London, UK: World Energy Council.

World Energy Council and International Institute for Applied Systems Analysis (WEC/IIASA). 1995. *Global Energy Perspectives to 2050 and Beyond.* London: World Energy Council.

Willenbrock, J. H. and H. R. Thomas (eds.). 1980. *Planning, Engineering and Construction of Electric Power Generation Facilities*. New York: John Wiley & Sons.

Williams, R., E. Larson and M. Ross. 1987. “Materials, Affluence and Energy Use,” *Annual Review of Energy* 12, pp. 99-144.

Williams, R. H. 1995. *Variants of a Low* CO_2*-Emitting Energy Supply System (LESS) for the World*. Richland, Washington: Pacific Northwest Laboratories.

World Bank. 1997. *World Development Indicators* (electronic distribution). Washington, D.C.: World Bank.

———. 1998. *World Development Indicators 1998*. Washington, D.C.: World Bank.

World Resources Institute (WRI). 1992a. *World Resources, 1992-93: A Guide to the Global Environment*. New York: Oxford University Press.

———. 1992b. *World Resources 1992-93, Data Base Diskette*. Washington, D.C.: World Resources Institute.

———. 1996a. *World Resources, 1996-97*. New York: Oxford University Press.

———. 1996b. *World Resources 1996-97 Database Diskette*. Washington, D.C.: World Resources Institute.

———. 1998. *World Resources 1998-99.* New York: Oxford University Press.

Annex: The Convergence Algorithm

A central feature of the *Conventional Worlds* scenarios is the gradual convergence of regional consumption patterns. To aid in the development of the scenarios, in several instances we used a *convergence algorithm,* which reflects the basic features of convergence.

The algorithm is based on the idea that, in the course of economic development, the structure of economies, certain activity levels (such as travel patterns) and intensities in non-OECD regions converge toward those of the highly industrialized societies with increasing GDP/capita. However, the non-OECD regions are not expected to recapitulate the history of the OECD regions; rather, they are expected to move more quickly along the development path, through technological "leapfrogging," as they take advantage of improved technologies and materials use that were not available earlier.

In mathematical terms, the algorithm used in the scenarios to reflect this behavior can be expressed as:

$$V_{r,2025} = V_{r,1995} + (V_{\mathrm{OECD},2025} - V_{r,1995}) \times \left(\frac{i_{r,2025} - i_{r,1995}}{i_{\mathrm{OECD},1995} - i_{r,1995}} \right)$$

and

$$V_{r,2050} = V_{r,2025} + (V_{\mathrm{OECD},2050} - V_{r,2025}) \times \left(\frac{i_{r,2050} - i_{r,2025}}{i_{\mathrm{OECD},1995} - i_{r,2025}} \right).$$

where $V_{r,y}$ is the value of the value added share, activity level or intensity in region *r* in year *y*; $V_{\mathrm{OECD},y}$ is the average OECD value in year *y*; $i_{r,y}$ is the income (GDP/capita) in region *r* in year *y*; and $i_{\mathrm{OECD},y}$ is the corresponding average OECD value.

The formulas produce a basic pattern of convergence, in that the regional value in the scenario year (2025 or 2050) approaches that of the OECD in the scenario year as the regional income increases; the linear dependence on income is chosen for simplicity. Moreover, the formulas reproduce the basic pattern of technological leapfrogging, because the regional value converges to the OECD value as the regional GDP/capita approaches that of the OECD in the *base year*, rather than the scenario year, arriving at the OECD level at a lower income than in the OECD. Table A-3 shows the convergence factors calculated in the scenarios

Table A-1: Scenario Convergence Factors

	Reference Scenario		*Policy Reform* Scenario	
Non-OECD Region	2025	2050	2025	2050
Africa	0.06	0.10	0.15	0.25
China+	0.26	0.46	0.33	0.61
Latin America	0.34	0.69	0.41	0.94
Middle East	0.23	0.39	0.30	0.55
S & SE Asia	0.18	0.33	0.25	0.46
E Europe	0.34	0.47	0.41	0.68
FSU	0.20	0.23	0.28	0.38

Notes:

1. In any given column, the convergence factor is the following ratio $\left(\frac{i_{r,\,futureyear} - i_{r,1995}}{i_{\mathrm{OECD},1995} - i_{r,1995}}\right)$
2. In the *Policy Reform* scenario, the convergence factors for the FSU shown in the above table were relaxed in some parts of the energy analysis. Specifically, the low levels of convergence in the FSU were increased to produce additional energy efficiency improvements beyond what might be expected from the income effect of the convergence algorithm.

THE STOCKHOLM ENVIRONMENT INSTITUTE

The Stockholm Environment Institute (SEI) is an independent, international research organization committed to the implementation of practices supportive of global sustainable development. SEI conducts a comprehensive research, consulting and training programme that focuses on the links between ecological, social and economic systems at global, regional, national and local levels. In its commitment to bridge the gap between science and policy-making, SEI employs innovative methods to communicate its work to governments, the private sector and society-as-a-whole. To meet these challenges, SEI has created an international network of centers and has established partnerships with sustainable development organizations throughout the world.

Stockholm Environment Institute
Executive Director: Nicholas C. Sonntag
Address: Lilla Nygatan 1, Box 2142
S-103 14 Stockholm
Sweden

Phone: +46 8 412 14 00
Fax: +46 8 723 0348
Email: postmaster@sei.se

SEI-York
Director: Johan Kuylenstierna
Address: Biology Dept. University of York
P.O. Box 373, York YO10 5YW
UK

Phone: +44 1904 432 897
Fax: +44 1904 432 898
Email: ac29@york.ac.uk

SEI-Boston
Director: Paul Raskin
Address: 11 Arlington Street
Boston, MA 02116-3411
USA

Phone: +1 617 266 8090
Fax: +1 617 266 8303
Email: info@seib.org

SEI-Tallinn
Director: Olavi Tammamae
Address: Lai 34, Box 160
EE-0090 Tallinn
Estonia

Phone: +372 6 314 200
Fax: +372 2 313 240
Email: postmaster@seit.ee

Stockholm Environment Institute - Boston
Tellus Institute
11 Arlington Street
Boston, MA 02116-3411, USA
Phone: (617) 266 8090
Fax: (617) 266-8303
Email: info@seib.org
Web: http://www.seib.org