TOWARDS A FOSSIL FREE ENERGY FUTURE

THE NEXT ENERGY TRANSITION

A Technical Analysis for
GREENPEACE INTERNATIONAL

Michael Lazarus
Principal Investigator

Lisa Greber, Jeff Hall

Carlton Bartels, Steve Bernow
Evan Hansen, Paul Raskin,
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STOCKHOLM ENVIRONMENT INSTITUTE
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Includes Abstracts of additional climate, economic, transport sector and policy analysis by Paul Waide, Michael Walsh & Stewart Boyle

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[With Abstracts of separate analyses on climate modelling by Paul Waide, economic analysis by Paul Waide, transport scenarios by Michael Walsh and policy issues by Stewart Boyle]

FOREWORD BY GREENPEACE

Human-enhanced global warming and related climate change threatens the very basis of survival on the planet. That is the likely consequence of our current use of fossil fuels and also the forecast of the world's top climate modellers through the work of the Intergovernmental Panel on Climate Change (IPCC). Greenpeace believes that global warming is already underway, and that we can see the first indicators of an oncoming disaster. The only solution to the problem is to phase out the use of all fossil fuels: coal, oil and gas. This was the genesis of the Greenpeace 'Fossil Free Energy Project' initiated in 1991.

Greenpeace wanted to see whether it would be possible to develop a very different type of global energy system to the one today; one which would significantly reduce the risks from climate change, as well as those from the other environmental impacts of fossil fuels and nuclear power. To that end, we commissioned a wide range of studies from energy, transport, climate and policy analysts. The major part of this analysis was the development of a 'Fossil Free Energy Scenario' (FFES) by SEI-Boston, the technical results of which are described in this report.

Carrying out energy and climate modelling work on a global basis over a timescale of 110 years is a daunting task. Based on our experiences over even the past few decades, we know that many assumptions we might make will likely be proved wrong, as both technological and political change continue to surprise us. Faced with this problem, Greenpeace opted for an approach which would allow our study to be compared with other existing global energy studies carried out by organisations such as the IPCC and the US EPA. To allow that, we had to make a number of assumptions which we do not necessarily support, and in some instances will likely prove unsustainable. Chief amongst these are the assumptions over economic growth (GDP), equity and population.

Economic growth and GDP, the indicator often used to represent this, is a poor measure of human welfare. It does not reflect the large numbers of people who do not participate in the formal economy, nor does it reflect the huge inequities hidden by average national and regional GDP figures. The levels of growth assumed under conventional thinking will also likely prove unsustainable in terms of the likely impacts of resources used and the associated environmental pollution. Nevertheless, we went along with conventional thinking in order to assess whether it was possible, even in such adverse circumstances, to achieve both major technological changes in the global energy system and reductions in carbon dioxide emissions.

Economic equity between North and South needs to be a goal in order that political and human equity can be achieved. Though the FFES assumed similar levels of global GDP as other scenarios, it considerably narrowed the current GDP gap between North and South from an average of 14:1 today to around 2:1 by the year 2100. Further narrowing of this gap was not possible without either increased growth rates in the South resulting in serious environmental damage or reduced growth rate in the North rendering the report incomparable with similar studies. This is not a true measure of equity, even though the GDP gap could be narrowed further after the year 2100. It is an acknowledgement, however crude, that to truly solve our environmental problems we need to address economic and political relationships. The FFES does show that concern about the climate should not be the preserve of the rich North. Neither can it be regarded as an excuse to impede the development aspirations of the South. The FFES and variants demonstrate that quite rapid growth which is less materials-intensive, and based on renewable energy sources, can be achieved in the South.

The results of the FFES, produced by SEI-Boston under our direction, confirm that it is possible to phase-out both fossil fuels and nuclear power and thus avoid climate disaster. That is an important conclusion, and one which is largely unrecognized among governmental policymakers. However, even the FFES results in some significant environmental impacts. The level of land use needed for 'biomass for energy' systems is significant. Additional climate damage is committed under the FFES as, under the assumptions of the study, it takes a number of decades to bring renewable energy systems up to a sizeable proportion of total energy consumption levels.

To give some indication of the likely impacts of a different approach to economic and population growth, we asked SEI-Boston to produce a number of variants to the main FFES. These looked at lower levels of GDP and/or population, and different types of growth which were based on lower levels of industrialisation or which involved some lifestyle changes. Although these could only provide some general insights to approaches and concepts of true environmental sustainability, the conclusions were important.

The variants showed that overall global energy demand could be reduced significantly, which in turn reduces the amount of renewable energy supply and fossil fuels required during the phase-out period. The land area required for biomass production for example, was reduced by up to two-thirds. The need for oil and gas is also significantly reduced. This is important, as Greenpeace are opposed to further oil and gas exploration. In the main FFES, the amount of oil and gas utilised is somewhat higher than current reserves. That does not imply that Greenpeace accepts further exploration, more a function of the high economic growth levels assumed for the scenario.

In an ideal world, a global scenario built entirely on concepts of sustainable growth, would have been produced by now. It has not. The data for this is still limited, but it is an important task that needs to be carried out in future. Despite this, we believe that the work that SEI-Boston has produced is an important contribution to the debate on these issues.

Other areas of the FFES study where further work is needed include the role of organic farming methods for 'biomass for energy' systems, and the development of sustainable afforestation. Recent analysis by Greenpeace[1] has suggested that organic farming yields can, over the longer-term, be similar to those for intensive agriculture. Whether sustainable biomass systems which have low or zero inputs from pesticides and fertilizers, can be developed on a major scale, is an important question. While the protection of primary boreal and tropical forests is an urgent priority, there is also a need for major afforestation and regeneration on degraded lands and depleted forest areas. This needs to be carried out sensitively and with the involvement of local people. So far, we only have relatively small amounts of data to suggest that the above can be a possibility on a very large scale throughout the world.

The FFES study is a beginning, not an end. It is an 'existence- proof' that a world with greatly reduced risks from climate change and nuclear power can be a reality. Achieving that reality will take policy changes and leadership at all levels of society, from the personal to the international negotiating fora.

An associated climate analysis for Greenpeace confirms that the FFES has some of the lowest impacts of any recently produced global energy scenario. What is also clear is that 'business-as-usual' energy paths have very serious potential impacts and must be avoided at all costs. Other supporting studies for the Greenpeace project suggest that the FFES could be achieved at costs similar to or less than carrying on with 'business-as- usual', an important conclusion when faced with those who oppose to current energy systems.

Achieving a fossil free energy future will require major changes in energy policy and lifestyles. The wasteful high energy consumption path that the North has enjoyed has to end. Future energy use will have to be extremely energy efficient, and increasingly based on sustainable renewable energy sources such as solar, wind and biofuels. The basis of that wasteful lifestyle is of course the economic growth and development path that we have chosen. Some counties from the South are already beginning to follow that same path. Changing that is beyond the scope of this study, but we have pointed out some areas which need urgent attention.

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1. 'Green Fields-Grey Futures: EC Agriculture Policy at the Crossroads', Greenpeace, 1992.

It is our hope that the analysis carried out for Greenpeace by SEI-Boston and the other consultants provides a glimmer of hope that a very different type of energy future can be achieved. This is a future which holds the prospect of saving our climate system from catastrophic change, and ultimately, life on Earth itself.

Greenpeace International
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TOWARD A FOSSIL FREE ENERGY FUTURE:
The Next Energy Transition - A Technical Analysis

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ACKNOWLEDGEMENTS

In mid-1991 Greenpeace International initiated the*Towards a Fossil Free Energy Future* project. This ambitous and wide ranging project is motivated by concerns over global climate change and the impression that other global studies may underestimate the potential for energy efficiency and renewable energy sources to provide cost-competitive alternatives to fossil fuels.

A major component of this project, the 'Fossil Free Energy Scenario' (FFES) analysis presented here, was prepared by the Boston Office of the Stockholm Environment Institute. Michael Lazarus led an SEI team that included Lisa Greber and Jeff Hall as primary researchers, with general support and guidance from Steve Bernow and Paul Raskin, specific contributions from Carlton Bartels and Evan Hansen on energy supply technologies and modelling, and David von Hippel on emission factors. Mark Fulmer, Kevin Gurney, David Nichols, and Daljit Singh, and the other staff of Tellus Institute, the home of SEI's Boston office, provided additional technical and editorial assistance.

Paul Waide acted as Greenpeace International's internal computer analyst and technical assessor. He helped in the process of developing the climate targets, assessed the climate benefits, acted as the principal analyst for the economic appraisal using the Edmonds Reilly model, and provided important inputs to the study design. Michael Walsh prepared the transport sector analysis, and Roger Kayes prepared a companion analysis of carbon sequestration potential. Greenpeace's Energy Policy and Research Unit coordinated the policy analysis which appears in abstract form in Section 10.

This report would not have been possible without the support, advice, and analysis of large numbers of individuals. SEI fellow Gerald Leach provided numerous useful insights and critiques. Staff of the Lawrence Berkeley Laboratory's Energy Analysis program (Nina Goldman, Rich Howarth, Florentin Krause, Jayant Sathaye, Lee Schipper, and other colleagues) provided valuable assistance with detailed data on current energy use patterns and approaches to the painstaking dissaggregated modelling, particularly for the industrial sector. Many other people contributed advice and data, including David Hall (biomass supply) and Jorgen Norgard (low energy households). Jonathen Stern gave helpful insights into natural gas reserves and markets.

The following took part in an extensive peer review process of the first draft of the FFES scenario produced by SEI:

Mark Barrett, Alfredo del Valle, Jae Edmonds, Nick Eyre, Mike Flood, Uwe Fritsche, William Fulkerson, Howard Geller, David Hall, Eberhard Jochem, Bill Keepin, Emilio Lebre La Rovere, Gerald Leach, Chris Lewis, Amory Lovins, Alan Miller, Peter Miller, David Mills, Irving Mintzer, Matthias Mors, Yasuhiro Murota, Peter Okken, Luis Pinguelli Rosa, Gabriel Sanchez-Sierra, Lee Schipper, Gianni Silvestrini, Jim Skea, Scott Sklar, Jonathon Stern, Andrew Stirling, Rob Swart, Mike Totten, William Turkenberg, Pier Vellinga, Deborah Wilson and Carl J.Winter.

Their comments provided important feedback on many elements of the study, and the final technical analysis reflects the range of helpful criticisms received. Their inclusion here does not reflect any endorsement of the final results.

A number of Greenpeace staff provided a range of important inputs for this Technical Report. Stewart Boyle managed the project throughout. Marcus Rand provided extensive administrative and technical support throughout the whole project. Simon Festing, Stephen Healy, Richard Tong and Verity Spence, volunteers at Greenpeace UK, provided valuable administrative support in the latter stages of the project. Tani Adams, Uta Bellion, Andy Biedermann, Susan George, Kevin Jardine, Michael Johann, Sara Larrain, Jerry Leggett, Tom Lent, Marcie Mersky, Steve Sawyer, Jan Sinclair, Keith Tarlo, Beverley Thorpe and John Willis, all provided valuable comments. Andrew Kerr, Kelly Rigg, Kalle Hesstvedt and Steve Elsworth

provided extensive inputs into both editorial and technical issues, often at short notice.

EXPLANATORY NOTES AND ABBREVIATIONS

UNIT PREFIXES AND NAMES

k	Kilo	10^3	Thousand
M	Mega	10^6	Million
G	Giga	10^9	Billion
T	Tera	10^{12}	Trillion
P	Peta	10^{15}	
E	Exa	10^{18}	

ENERGY UNIT CONVERSIONS (J=joule, energy unit used most extensively in this report)

1 Metric Tonne Oil Equivalent (MTOE)	= 42.62 GJ
1 Barrel Crude Oil Equivalent (BOE)	= 5.815 GJ
1 Metric Tonne Coal Equivalent (MCOE)	= 29.31 GJ
1 British Thermal Unit (Btu)	= 1.054 kJ
1 Kilowatt-hour (kWh)	= 3600 kJ

`Tonne' refers to a metric ton. (1 Metric ton or `tonne' = 1.102 short tons)

EMISSIONS UNITS

Carbon dioxide (CO_2) emissions are expressed in carbon equivalents (C)
1 gram (g) C = 3.67 g CO_2
Carbon dioxide emissions are measured here in Petagrams (Pg) carbon
1 Pg C = 1 Billion Tonnes C = 3.67 Billion Tonnes CO_2

ABBREVIATIONS

GHG	= Greenhouse Gas
IPCC	= Intergovernmental Panel on Climate Change
EPA	= U.S. Environmental Protection Agency
CC	= Combined Cycle
IGCC	= Integrated Gasification CC
AFBC	= Atmospheric Fluidized Bed Combustion
MHD	= Magnetohydrodynamics
STIG	= Steam Injected Gas Turbine
BIG-STIG	= Biomass Integrated Gasification STIG
PV	= Photovoltaic Cells

STUDY REGIONS

AFR	= Africa
CPA	= Centrally Planned Asia
EE	= Central and Eastern Europe
JANZ	= Japan, Australia, and New Zealand
LA	= Latin America
ME	= Middle East
SEA	= South and East Asia
US	= United States
USSR	= former USSR, now CIS and adjoining states
WE	= Western Europe and Canada

NOTE ON ENERGY CONVENTIONS

`Delivered', `Final', and `secondary' energy are equivalent terms for the energy products (electricity, petroleum products, biofuels etc) delivered to the final point of consumption (e.g., in the residential, transport, industrial and service sectors). Delivered energy, which is the term used throughout this report, is also referred to in other studies as `secondary' energy. `Primary' energy supply includes final energy plus the energy losses in distribution, transmission, and conversion (e.g., electricity production, oil refining) in addition to the energy delivered.

In addition to total delivered energy, we report primary energy results to enable comparison with other studies. However, this comparison is only meaningful if consistent methods are used for determining the primary energy equivalents of solar, wind, hydro, geothermal, and nuclear electricity. At least three different conventions can be used: 1) physical energy efficiencies; 2) constant fossil (and biomass) fuel equivalent efficiencies; and 3) time-varying fossil (and biomass) fuel equivalent efficiencies.

1) Physical energy efficiencies represent the actual energy output compared with energy input. For instance, for photovoltaic solar cells, their 15 percent efficiency represents the electricity output divided by the incident solar radiation striking the on panel surface, approximately 10-15 percent using contemporary single crystal technologies. This convention is useful for comparison with total available incident solar resources and between solar-based options. However, such resources are so abundant that they rarely present a major constraint. If this convention is used, a kWh of solar electricity would be reported as requiring over twice the primary energy as a kWh of coal-based electricity. If only primary energy were reported from a study, a solar-electricity-based scenario might appear to be over twice as energy intensive as a coal-electricity-based one. (Arguably from a resource and environmental point of view, we are less concerned about the 2 units of solar primary energy than the 1 unit of coal primary energy.)

2) Alternatively, the average generation efficiency of fossil fuel (and biomass) electric plants can provide more useful comparisons among the reported primary energy results of different analyses, where the fraction of renewable/nuclear/geothermal generation differ significantly. If this convention is used, switching from fossil fuels to renewables does not result in the major differences in reported energy supply that would be reported if physical energy efficiencies were used. Both the World Energy Conference and the International Energy Agency apply an effective "theoretical" efficiency of 38.5 percent to calculate primary supply from renewable, nuclear, and geothermal electricity. (IEA, 1990; WEC, 1989). However, the constant efficiency approach ignores the fact that fossil technologies improve over time.

3) By contrast, the U.S. EPA (1990) and IPCC (1991) long-term analyses to 2100 cited extensively here utilize an average fossil/biomass efficiency that changes over time with improvements in generation efficiency.[1]

The choice of primary energy reporting convention depends on the purpose of the intended comparison. Since we compare our results with U.S. EPA and IPCC studies, we too adopt a convention of time-varying, fossil/biomass generation efficiency equivalency. We use an approximate fossil equivalent efficiency of 33 percent in 1988, rising to 50 percent by 2030, and 55 percent by 2100. These estimates broadly reflect our assumptions regarding improved technologies and increased cogeneration. Intermediate year efficiencies are linearly interpolated. Primary energy results should thus be reviewed with caution, particularly when looking at specific solar, wind, hydro, geothermal, or nuclear resources across regions or time. For this purpose, we separately report delivered or final energy results, and electricity

1 The Edmonds-Reilly model used in these studies tracks efficiency for generation, transmission, and distribution.

production by resource over time. Carbon dioxide emissions are also unaffected by these reporting conventions.

Section 1: Introduction

Fossil fuel combustion is the major source of greenhouse gas (GHG) emissions, largely in the form of carbon dioxide (CO_2), accounting for 85 percent of current net anthropogenic CO_2 emissions (Subak et al., 1991).[1] Over the past 50 years, fossil fuel consumption has increased five-fold, from approximately 57 exajoules in 1937 to around 282 exajoules in 1988 (Fulkerson et al., 1990). If fossil fuel consumption continues to grow, doubling of pre-industrial CO_2 concentrations could occur as early as 2030, leading to an increase in global average temperature of 1.5 to 4.5 °C (IPCC, 1992).

This report provides technical analysis and documentation as input to Greenpeace International's project, *Towards A Fossil Free Energy Future*. It presents a main scenario and several variants for reducing greenhouse gas emissions, and the technical methods and assumptions used to develop them. These are mainly based on modelling assumptions from the United Nations, the Intergovernmental Panel on Climate Change (IPCC), US EPA and World Bank sources (IPCC; Waide, 1992b). In doing so, it alludes to several additional reports prepared by Greenpeace and its consultants. These additional reports contain: analyses of the transport sector (Walsh, 1992), climate stabilization targets (Waide, 1992a), an alternative energy-economic modelling technique (Waide, 1992b), and policy options (Greenpeace, 1992b). Abstracts of these reports summarize their analyses in the appropriate sections below.

The goal of the wider Greenpeace study is to investigate the technical, economic and policy feasibility of phasing out fossil fuel use over the next century as part of a strategy to avert unacceptably high levels or rates of global warming. The technology and policy options presented here for achieving a transition to a low carbon, renewable, fossil free-energy future can be combined with greenhouse gas reduction measures described in other Greenpeace reports and policy positions, such as the rapid phase-out of chlorofluorocarbons (CFCs) and related gases, and the reversal of deforestation trends (Kayes, 1992). Together a full strategy for climate stabilization emerges, presented by Greenpeace in its 'Policymakers Report' and (Greenpeace, 1992b) associated analyses (Walsh, 1992; Waide, 1992a, 1992b: Kayes, 1992).

Assessing the prospects for a fossil free energy future requires a detailed examination of global energy needs and supply potentials. This technical report provides an overview of energy-related GHG emission reduction potentials in the context of a *Fossil free energy scenario* (FFES) for meeting energy needs in a climate stabilized world. This considers a combination of numerous options for reducing energy-related emissions, all within the realm of energy technology and policy. We then present a range of sensitivity analyses and variants, based first of all on the assumption that alternative patterns of social, cultural, and economic development will occur, and secondly to test the robustness of our results. In order to make the assumptions demanding, the *Fossil free energy scenario* assumes technology and policy action amid a continuation of current trends towards high consumption-oriented lifestyles and existing modes of economic development. The sensitivities suggest options for achieving lower energy and resource requirements and reduced climate impacts.

The report begins with a brief review of energy and greenhouse gas studies. A range of energy and CO_2 reference cases are selected for comparison with the scenarios presented here. Section 3 describes a companion analysis (Waide, 1992b) on the climate consequences of greenhouse gas emission trajectories, and defines an emissions target for seeking a stabilized

1 Other greenhouse gases include chlorofluorocarbons (CFCs), tropospheric ozone, methane, and nitrous oxide. Carbon monoxide, nitrogen oxides, water vapor and hydrocarbons also directly and indirectly contribute to warming.

climate, using the STUGE climate model[2]. Section 4 presents an approach for creating a new set of energy and CO_2 scenarios to meet these targets. A standard set of economic growth projections are adapted. Such growth levels are high, and almost certainly environmentally unsustainable in respects other than protecting the climate. They were used in order that the GDP assumptions were consistent with other global scenarios, and to ensure that the frame of reference for the study was a demanding one. Section 5 presents the results of the *Fossil Free Energy Scenario* (FFES). Changes in how we live, the products we consume, the way we plan and organize our cities, may indeed be essential if we are to succeed in avoiding unacceptable levels of climate change. Such changes are presented as part of the scenario variants and sensitivity analyses in Section 5.2. Sections 6 and 7 discuss the demand and supply assessments underlying this scenario.. Section 8 describes an alternative modelling approach, based on the use of the macro-economic Edmonds-Reilly model. Section 9 illustrates the temperature rise and other climate impacts projected for the FFES, using the STUGE climate model. Finally, Section 10 discusses a range of policy options for moving towards a fossil free, climate stabilized world.

The main body of this report speaks primarily to the technical potential for reducing energy-related greenhouse gas emissions. Achieving the levels of energy savings increases in the use of renewable energy, and reductions in emissions presented in this report will depend most fundamentally on creating the requisite international consensus, and local and national political mandates. It will depend equally on implementing appropriate policies to overcome the multitude of institutional and market barriers that stand in the way. These issues are addressed in a policymakers summary produced by Greenpeace (Greenpeace, 1992b; see also section 10 for abstract).

Study Constraints

Greenpeace International provided several important guidelines and assumptions for this study:

1) Fossil fuel combustion is eliminated by the year 2100. This outcome should be understood as a scenario "constraint", and does not result from an economic cost-benefit or modelling analysis of the value of substituting for every energy use of fossil fuels. Indeed, the marginal cost of substituting for the last few percent of fossil fuels used for the end-uses that most favour fossil fuel could be relatively high. High energy taxes, or other strong policy measures, such as carbon dioxide emission standards, may be needed to achieve full reduction, particularly as decreasing demand leads to lower producer prices. On the other hand, motivated public concern over global warming together with technological innovation over the next century could make the effective elimination of fossil fuels a reality. Energy futures are a matter of choice, not fate.

2) Carbon removal technologies are not considered. Technologies exist for the capture of the CO_2 emitted from fossil fuel combustion (Blok et al, 1991). In addition, carbon can be removed from fossil fuels by conversion to fuels such as hydrogen. Key issues relate to storage and management of large quantities of carbon dioxide. Several options for storing captured CO_2 have been suggested, including marine organisms (via ocean fertilization), spent oil and gas wells, used coal mines, and the deep ocean. The viability of these options remains to be demonstrated and may pose further risks and uncertainties.

3) Nuclear power is eliminated by 2010. Nuclear power is not regarded by Greenpeace as a sustainable energy option. This is based on the more than 30 years experience the world has with this technology, and the significant risk factors from catastrophic accidents,

2 STUGE - Sea level and Temperature change Under the Greenhouse Effect. Developed by the Climatic Research Unit, University of East Anglia, UK, this model has been used by the Inter-Governmental Panel on Climate Change (IPCC), among others.

world has with this technology, and the significant risk factors from catastrophic accidents, nuclear weapons proliferation, plus the unresolved problems of radioactive waste management. The technology is an increasingly high cost option for generating electricity, as experience in the UK, the USA and a number of developing countries has borne out. Greenpeace projects that nearly 70 per cent of current nuclear reactors will reach the end of their planned lifetimes by 2010 (data from: Nuclear Engineering International, 1991). The assumption of a full phase out by 2010 is thus achieved through a moratorium on new reactor construction, and accelerated phase-out of existing reactors.

4) New renewable resources are subject to environmental restrictions. Concerns about the construction of new, large hydro facilities, with problems such as siltation, erosion, submergence, human settlement impacts etc, were reflected in a downgrading of the global technical/economic potential of hydropower by 35 percent. No municipal waste incineration was considered, given Greenpeace's insistence on material reuse and reduction policies, and concerns about toxic emissions from incinerators. It was also assumed that biomass for energy would only be produced in a sustainable manner, with no net carbon emissions to the atmosphere. Biomass productivities were thus assumed to be considerably lower than in other studies

Section 2: Review of Existing Studies

The past few years have witnessed a flurry of energy and greenhouse gas studies, reflecting growing global concern over climate change issues. Numerous government agencies, intergovernmental organizations, research institutes, and non-government organizations have conducted climate-related assessments. These assessments generally fall into three categories. The first, scientific analyses of the climate change process, now present a near consensus view that unabated anthropogenic emissions of the so-called greenhouse gases -- most notably, carbon dioxide (CO_2) -- will risk significant global warming and other related impacts such as changes in rainfall patterns and sea level rise. The second type of study, impact assessments of the likely consequences of global warming, show the potential for serious ecological and economic damages. Finally, a third type of analysis considers the technological, policy, and economic instruments to avoid warming and its consequences. This study falls into the third category.

In this section, we briefly review global energy and CO_2 forecasts. In particular, we compare reference case forecasts -- what analysts expect will occur under business-as-usual conditions. We then briefly list some of the more interesting global and national policy scenarios which demonstrate the potential for reducing greenhouse gas emissions, and that were consulted in the development of the Greenpeace scenarios presented in Sections 4 to 7.

Global Reference Case Forecasts

Since the mid-1970s, a series of global energy projections have been published. As concerns about CO_2 emissions and global warming increased in the early 1980s, several of these projections were also translated into carbon dioxide forecasts. Many suggested very high levels of growth in energy use and CO_2 emissions (see Keepin, 1986) and graphically illustrate the failure of supply-side orientated energy forecasting. Several of the early 1980s energy projections are illustrated in Figure 2.1 below.

By the mid 1980s, it became clear that energy patterns were undergoing some profound changes in most industrialized countries. Previously exponential growth in energy use greatly diminished, with energy use actually declining in some countries.[1] In many industrialized countries, demand for energy-intensive basic materials (e.g., steel and cement production) was reaching a plateau, while consumer demand for basic energy-intensive equipment and amenities, such as refrigerators or central heating, was levelling off. Emerging concepts of *structural change* (reflecting shifts to less energy-intensive manufacturing sectors, and, overall, shifts from manufacturing to services) and *saturation* (particularly for household appliances and basic materials) changed our understanding of energy systems and the nature of energy forecasting. The notion that economic growth must be accompanied by corresponding growth in energy consumption could no longer be accepted as inevitable.

Major global forecasts of the late 1980s and early 1990s -- the World Energy Conference (1989), US EPA (Lashof and Tirpak, 1990), Intergovernmental Panel on Climate Change (IPCC) (Swart et al., 1991b), and Manne and Richels (1990) -- projected somewhat lower growth in primary energy than had earlier studies. The range of estimates of primary energy requirements for 2025 dropped from a range of 600-1000 EJ to a range of 450-800 EJ, as shown in a comparison of Figure 2.1 and Figure 2.2. As a specific example, between its 1983 and 1989 forecasts, the World Energy Conference dropped its primary energy estimates for 2020 by about 22 percent, reflecting a greater acceptance of past successes in improving energy

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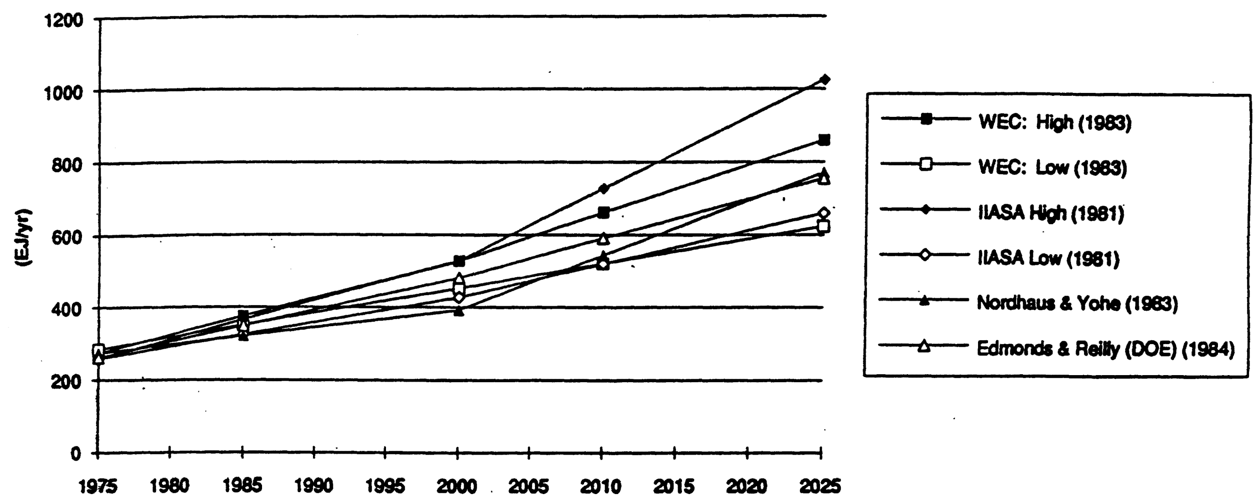
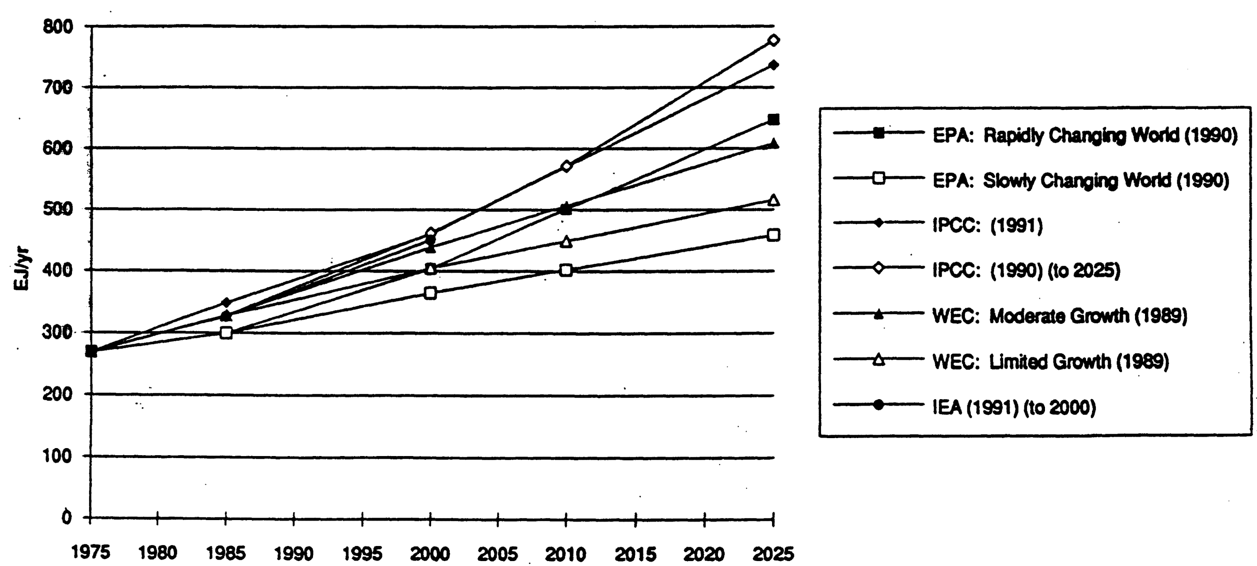
1 For example, U.K. energy demand fell 12 percent from 1973 and 1984.

Figure 2.1
Primary Energy Forecasts to 2025:
1981-1984 Vintage (EJ/yr)



Source: Toth et al, 1989.

Figure 2.2
Primary Energy Forecasts to 2025:
1989-1991 Vintage (EJ/yr)



Sources: WEC, 1989; IEA, 1991; Lashof and Tirpak, 1990; Swart et al, 1991b.

efficiency (WEC, 1989).[2] The reduction in conventional forecasts over time has been remarkably consistent over the past 20 years; ten years ago, Lovins et al. documented the same phenomenon for the U.S. (Lovins at al., 1981).

Many researchers have constructed forecasts into the early or mid 21st century. The far smaller number that have attempted to forecast to the year 2100, have done so primarily for the purpose of CO_2 projections and climate studies. Figure 2.3 presents selected primary energy forecasts to the year 2100, with associated CO_2 projections shown in Figure 2.4. Aside from total energy requirements, the projected fuel mix is the main determinant of CO_2 emissions. In most of the reference case forecasts (particularly those that use the Edmonds-Reilly model, such as EPA 1990 and IPCC 1990), energy supplies switch to heavier reliance on higher carbon fuels, coal and oil shale, as lower-cost oil and gas reserves are depleted. The introduction of some low and no carbon energy sources, such as biomass and solar, may partially offset this effect. Overall, the ratio of CO_2 emissions to primary energy requirements, stays about constant, leading to similar increases in both CO_2 emissions and energy use (see Table 5-3).

We have adopted two reference case projections for comparison with our results, the IPCC projections[3] and an average of the US EPA's Rapidly and Slowly Changing World cases.[4] This range of reference cases is shown in Figures 2.5 and 2.6 for primary energy and CO_2. There are reasons to believe that these reference cases may be high. In particular, as discussed in Section 4, underlying population and economic growth rates could be unrealistically high and unsustainable.[5] Nonetheless, they reflect two of the most widely cited and internationally reviewed long-term projections to date.

Global Emission Reduction Policy Scenarios

Several important global policy scenarios have considered a range of options for reducing fossil fuel consumption and energy-related greenhouse gas emissions. Most notable of recent efforts are the various policy scenarios developed by U.S. EPA and IPCC, using the Edmonds-Reilly model (Lashof and Tirpak, 1990; IPCC, 1990). The most ambitious of these scenarios utilize high levels of efficiency improvements (e.g., up to 3.7 percent per year for the residential/service sectors), and heavy reliance on renewable resources (nearly 60 percent of 2100 primary energy is biomass in one U.S. EPA scenario). However, all scenarios maintain carbon emissions levels at the end of the 21st century of over 1 Pg C; they do not assume the fuller phase-out of fossil fuels. In fact, in the lowest emission scenario (EPA:RCWR), carbon emission levels are rising as we head into the 22nd century, as illustrated in Figure 2.7. The

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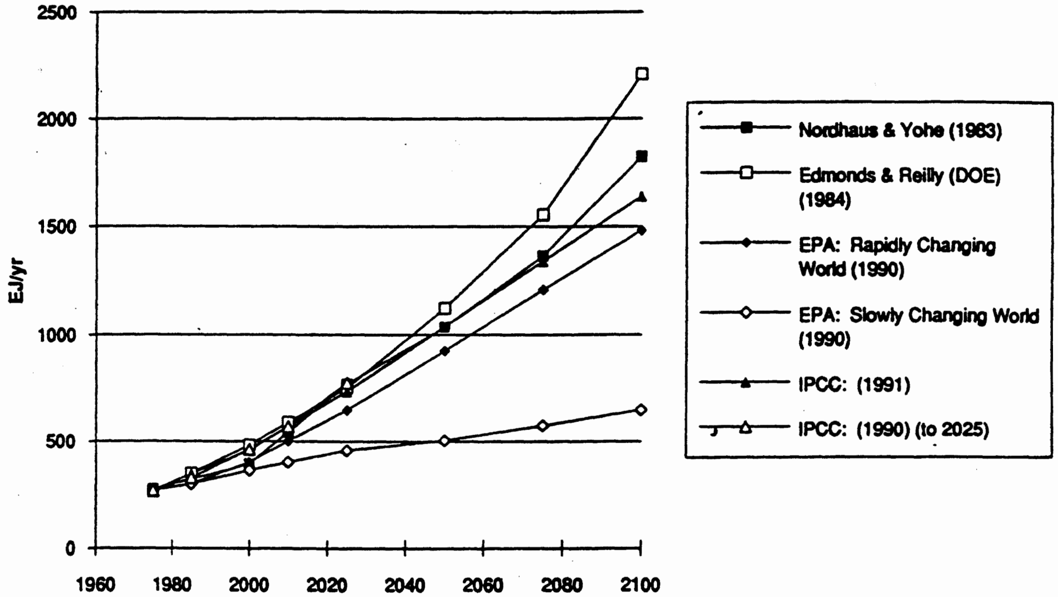
2 When adjusted for differences in population and economic assumptions, the decline between forecasts resulted in large part from a lowering of long-term income elasticity (2000-2025) from .85 to 0.54, due to assumed "continuing successful efforts in demand management beyond 2000". See WEC, 1989, p.100-2.

3 A later version of the 1991 IPCC scenarios was issued too late for incorporation into this document. The latest version now presents a range of 6 scenarios, rather than the single scenario presented here. Our IPCC reference case forecast is very similar to the central range of these revised scenarios.

4 Please note that this RCW/SCW average is by itself no longer a true scenario run by EPA, although we assume here that it is as self-consistent as each of the individual scenarios. Its results nonetheless lie within the bounds defined by the two scenarios.

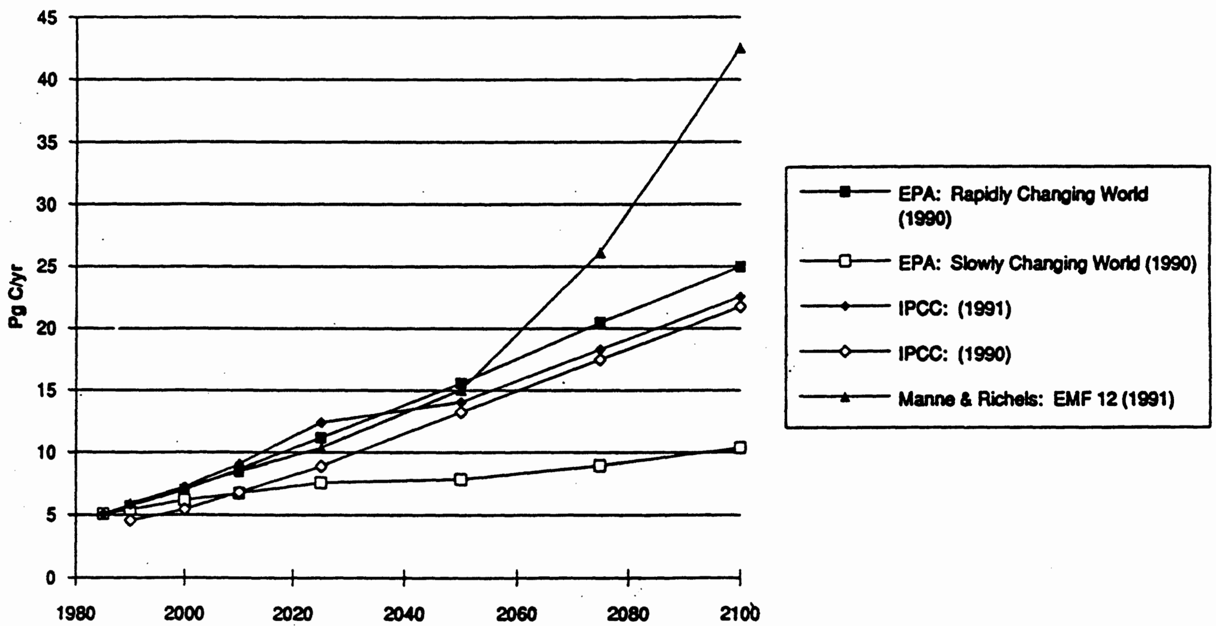
5 Furthermore, the modelling approaches and assumptions may underestimate the cost-effective potential of renewables, while overestimating the potential of high emissions resources such as coal and oil based synthetic fuels, particularly in light of their very high environmental costs. See Section 8: Economic Issues : Another Modelling Approach (Edmonds-Reilly).

Figure 2.3
Primary Energy Forecasts to 2100 (EJ/yr)



Source: Lashof and Tirpak, 1990; Toth et al, 1989.

Figure 2.4
CO2 Forecasts to 2100 (Pg C/yr)



Source: Lashof and Tirpak, 1990, Manne & Richels, 1991, Swart et al, 1991b.

Figure 2.5
Reference Case Range Adopted for Comparative Purposes: Primary Energy (EJ/yr)

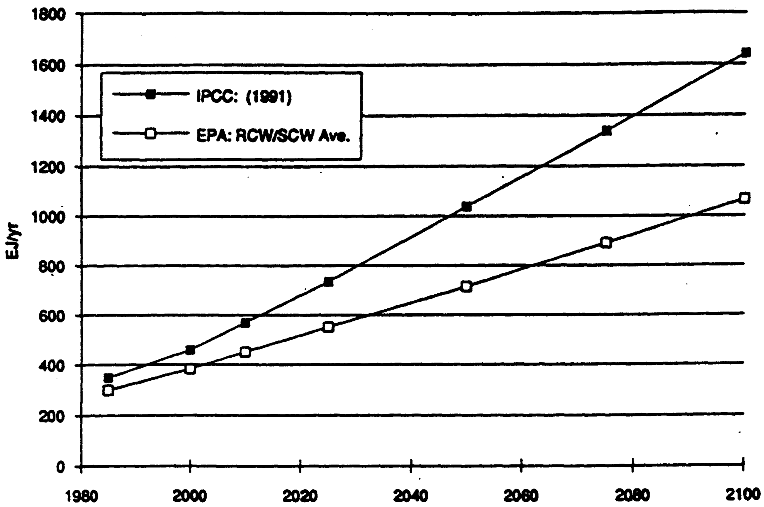


Figure 2.6
Reference Case Range Adopted for Comparison: CO2 Emissions (Pg C/yr)

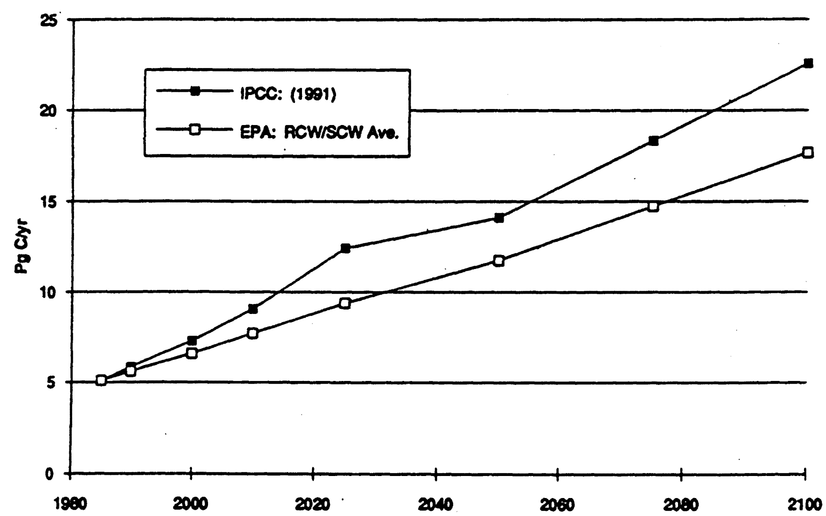
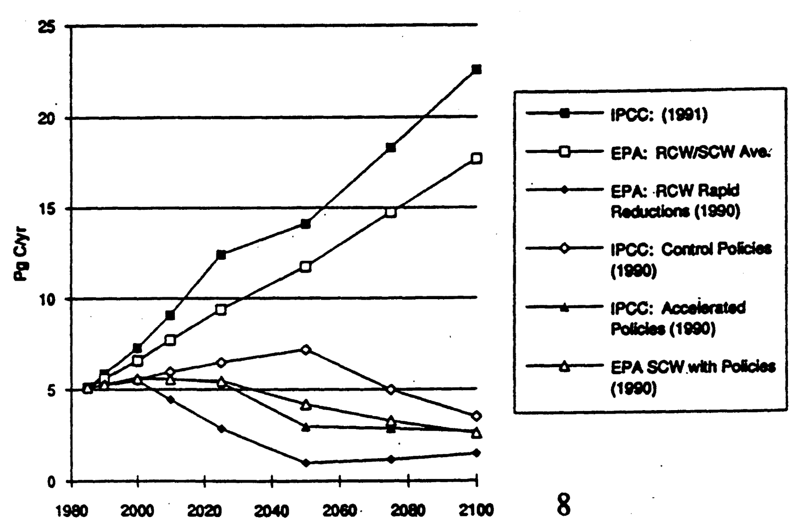


Figure 2.7
EPA and IPCC Policy Scenarios: CO2 Emissions from Fossil Fuels (Pg C/yr)



Sources: Lashof and Tirpak, 1990; Swart et al, 1991b very high biomass yields in this scenario may call into question whether excessive land use can be avoided without massive advances in genetic engineering or potentially unsustainable water and fertilizer use (see Sections 5 and 7).

Two other major energy studies, *Energy for a Sustainable World* (Goldemberg et al., 1988) and *Least Cost Energy* (Lovins et al., 1981), have looked in detail at global energy efficiency potentials, using bottom-up, end-use accounting approaches. Their overall energy and CO_2 emission results, as shown in Table 2.1, are far lower than either the EPA or IPCC scenarios, due to stronger assumed energy efficiency improvements, and, to some extent, on lower population and economic targets. The energy, GDP, CO_2 and population figures are shown in Table 2.1 below. Both of these studies present detailed evidence supporting the promise and economic benefits of specific technological options for dramatically increasing energy efficiency. In addition, *Energy for a Sustainable World* presents a thorough vision of how we might achieve this lower-energy world in practice, amid increasing equity.

National and Regional Studies

Naturally, detailed national and regional energy studies can better capture the local constraints and opportunities for reducing energy-related GHG emissions than can more aggregate global ones. The scenarios presented here were informed by numerous country and region-specific studies (see Bashmakov, 1990; Busch, 1990; Chandler et al, 1990; CEC, 1991; Danish Energy Agency, 1991; Davidson and Karekezi, 1991; Gupta et al, 1990; Johansson et al, 1989; Leach and Nowak, 1990; Levine et al, 1991; OTA, 1991; Reddy, 1991; Schipper and Cooper, 1991a; UCS et al, 1991, USSR Ac.Sc., 1990; Zhang, 1991). In particular, several of these studies assisted in the analysis of current region-specific energy use patterns and potential efficiency improvements. Several studies also provided strong evidence supporting the technical and economic potential of efficiency improvements and renewable energy technologies implemented in our scenarios; the results of a few of these studies are summarized in Section 5.

Table 2.1
Energy, CO2, GDP, and Population Projections Under Several Policy Scenarios

Scenario	Year	Primary Energy (EJ)	CO2 (Pg C)	GDP (Trillion 1985 U.S.$)	Population (Billion)
U.S. EPA: Policy Options (RCWR)	1985	300	5.1	15	4.9
	2025	520	2.9	55	8.2
	2100	799	1.5	370	10.4
IPCC90: Accelerated Policies	1985	*	5.1	15	4.9
	2030	*	4.9	49	8.8
	2100	*	2.7	213	10.4
Energy for a Sustainable World	1980	277	*	13	4.4
	2020	353	*	~20-26	7.0
Least Cost Energy	1975	241	~5.0	11	~4.0
	2000	223	~3.5	~22	~6.0
	2030	165	~1.0	~43	~8.0
	2080	112	*	~54	8.0

Notes:
GDP values are estimated: Energy in a Sustainable World assumes a 50-100% increase over 1980 levels by 2020; Least Cost Energy assumes approximately 200-500% increases over 1975 levels, 2000-2080.
* Not Reported.

Source: Lashof and Tirpak, 1990; IPCC, 1990; Goldemberg et al, 1988; Lovins et al, 1981.

Section 3: Climate Consequences of Reference Scenarios and Climate Stabilization Targets

[The following is an abstract of the analysis by Paul Waide - 'Greenhouse Modelling and Emission Targets' - based on a Greenpeace report available as a seperate Appendix to this report (Waide, 1992b)]

STUGE Greenhouse Model:

The STUGE (Sea level and Temperature change Under the Greenhouse Effect) greenhouse model (Wigley, et al., 1991) was used to assess the implications of possible future GHG emissions, and in the development of emissions control targets. STUGE is designed to simulate the future atmospheric concentrations, radiative forcing, temperature change and sea-level rise resulting from any given emissions profile over the duration of the next century. It treats the major greenhouse gases of CO_2, CH_4, N_2O, CFC-11, CFC-12 and a halocarbon substitute HCFC-22 individually, and permits the rapid assessment of future emissions scenarios.

This particular greenhouse model was chosen because it has been used extensively by the Inter-Governmental Panel on Climate Change (IPCC) Working Group 1 (Scientific Assessment, IPCC, 1990) for sensitivity testing of the type conducted in this study. The model employs a simple parameterised approach which is adjusted to concur with IPCC figures. The IPCC figures represent the mean responses from an extensive range of simulations utilizing highly complex general circulation models (GCMs). STUGE has a more simplified structure, and only reports global-mean values, although it should be stressed that the results are as likely to be as accurate as those from any of the more complex models.

The model is composed of a suite of separate algorithms. Emissions are converted to concentrations using models that agree well with the conclusions of IPCC Working Group 1. The subsequent concentration changes are converted to radiative forcing changes using the equations recommended by IPCC WG1 (Shine et al, 1990, Table 2.2). The resulting radiative forcing is applied to the upwelling-diffusion climate model of Wigley and Raper (1987, 1990) to make transient global-mean temperature projections. This model is essentially the same as the one used by the IPCC WG1.

The climate model gives output for global-mean temperature changes and the thermal expansion component of global-mean sea level change. The temperature results are input to the same ice-melt models for small glaciers and the Greenland and Antarctic ice sheets used by IPCC WG1. The ice-melt and thermal expansion terms are finally combined to give the total sea level rise projection.

Other Models

To ensure consistency and comparison with other studies, the results of STUGE simulations were compared with those generated using the Atmospheric Stabilization Framework (ASF) model of the US EPA (ICF, 1990). There is a difference between the model simulations for warming up to 1990, but beyond that date the predicted changes are very similar. The difference to 1990 may be explained by the use of inconsistent historical CO_2 concentration data.

Treating Uncertainty

With all greenhouse models there is a large measure of uncertainty, in particular concerning the strength of the feedback processes that govern temperature response to increasing GHG concentrations. The conventional means of accounting for this uncertainty is through a climate sensitivity parameter ΔT_{2x}, which is defined as the increase in global-mean temperature from pre-industrial times resulting from a doubling of equivalent atmospheric CO_2 concentrations. The IPCC specify the range of values for ΔT_{2x} as 1.5°C to 4.5°C, with 2.5°C as the most probable. However, this range does not include all sources of uncertainty, in particular some potentially important feedback processes. These additional uncertainties, associated with the thermal behaviour of the ocean and land ice sheets have a strong bearing upon the rate of warming and the extent of sea level rise. [N.B. The full study by Waide explores the impact of uncertainty for all the more important model parameters, such that the necessity for and robustness of the emissions targets developed is clearly demonstrated].

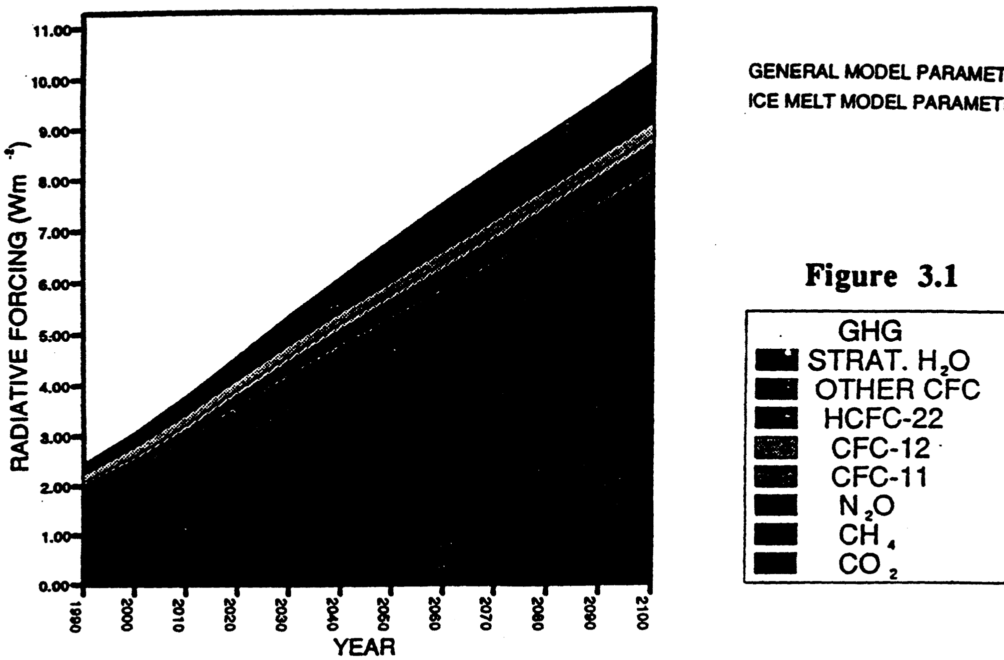
Consequences of Reference Case Scenarios

What happens if there are no modifications to energy or land-use policy from an environmental perspective over the next 100+ years and the reference scenario world becomes a reality? Emissions of carbon dioxide continue to rise unabated while global energy demand continues to be met predominantly by the inefficient use of fossil fuels as depicted under the range of reference case scenarios of Figure 2.6. The climatic consequences of these scenarios have been explored using STUGE and are illustrated in Figures 3.1, 3.2 and 3.3. By 2100 the global-mean induced radiative forcing exceeds 10 W/m^2, while in the event of a higher climate sensitivity (ΔT_{2x}=4.5°C) the global-mean temperature is forecast to exceed 6°C above pre-industrial times (4°C under a ΔT_{2x}=2.5°C sensitivity). Worse still, the impetus for global warming is not diminished. Even if emissions were held static or cut, the thermal lag of the oceans and long atmospheric residency time of GHGs would ensure that global-mean temperatures continue to rise beyond 2100.

In environmental terms, the reference case scenarios are likely to be disastrous. Sea-level rise will threaten all coastal habitats, and major ports, resulting in increased flooding, soil salinity changes, land erosion and a host of other effects. In addition, certain marine-based ecosystems may have trouble adapting to the rise in sea-level height. Climate change has the potential to disrupt existing ocean circulation patterns, and change the global supply of nutrients and heat that determines marine ecosystems. On land, rising temperature will change the climatic conditions for ecosystems at an unprecedented rate. There is a very strong correlation between climatic regions and biotic types, such that shifts in climate force ecosystem migration or extinction. In the past, climatic changes have usually occurred slowly over long time spans with little or no human intervention in migratory processes. Under the reference scenario conditions, it is very doubtful whether major land-based ecosystems can migrate successfully (given human obstacles such as farmed land, urban settlements, road networks, etc.) or fast enough to avoid mass extinction. The boreal forests would be faced with an implied Pole-wards migration rate of 2.5 kilometres per year, while even fast migration tree species have not previously adapted to rates faster than 1 kilometre per year (Krause et al, 1990).

A more direct threat to human interests is posed by changes in arable conditions. Predicted consequences of following the IPCC reference scenario envisage greater global-mean rainfall, but also greater global-mean evaporation (IPCC 1990, 1992a). On a regional basis, those areas which are currently suitable for cultivation are likely to experience changing soil moisture levels and therefore potentially reduced yields. Given enough time, cultivation of currently marginal land might become possible, but the transition period may take too long to fully accommodate an increasing world demand for agriculture.

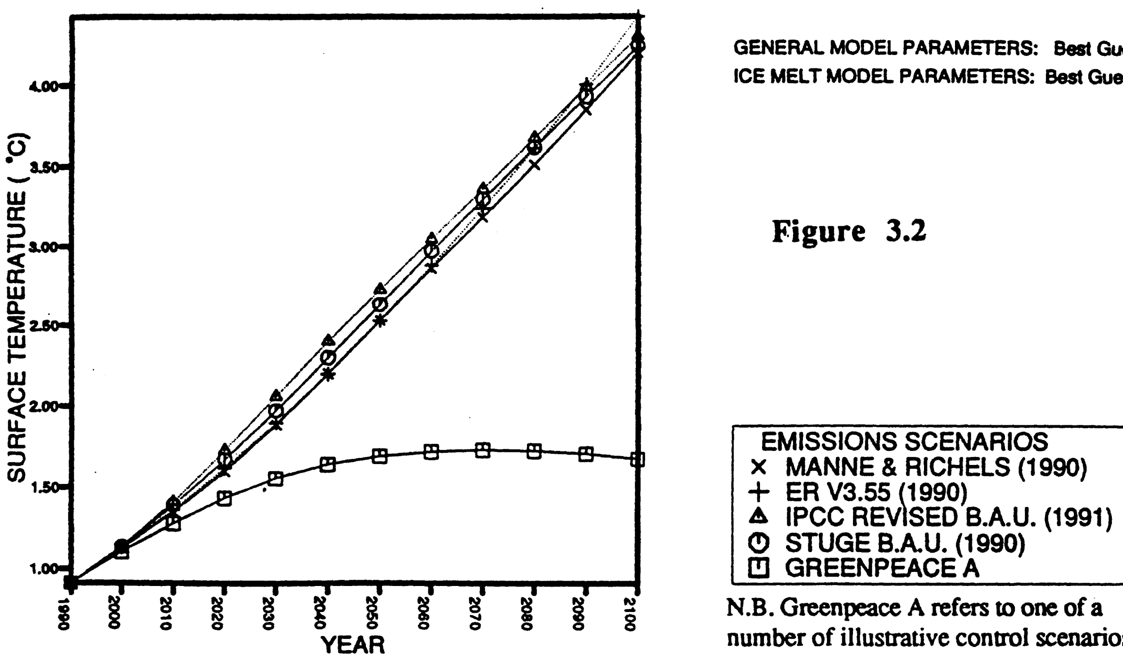
RADIATIVE FORCING COMMITMENT OF EACH ANTHROPOGENIC GHG
IPCC REVISED BUSINESS AS USUAL



GENERAL MODEL PARAMETERS: Best Guess
ICE MELT MODEL PARAMETERS: Best Guess

Figure 3.1

SURFACE TEMPERATURE AT 2.5 °C ΔT_{2x} FOR RECENT ENERGY REFERENCE CASE FORECASTS

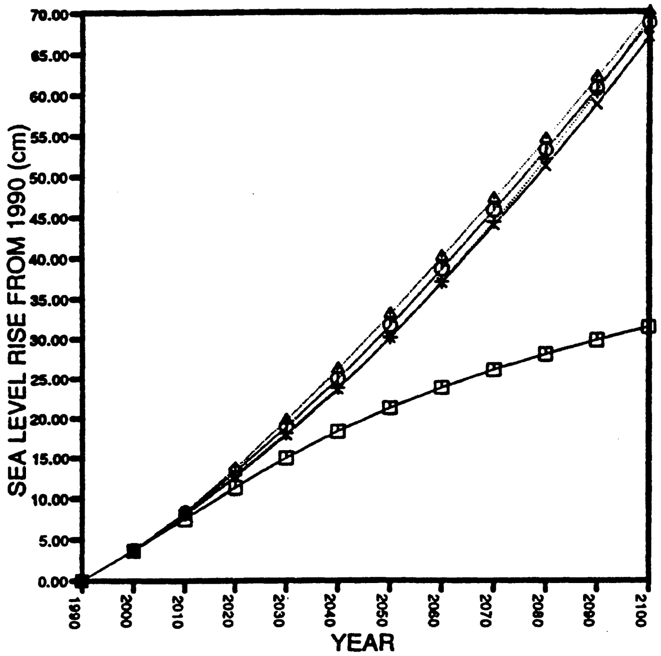


GENERAL MODEL PARAMETERS: Best Guess
ICE MELT MODEL PARAMETERS: Best Guess

Figure 3.2

N.B. Greenpeace A refers to one of a number of illustrative control scenarios.

SEA LEVEL RISE FROM 1990 AT 2.5 °C ΔT_{2x} FOR RECENT ENERGY REFERENCE CASE FORECASTS

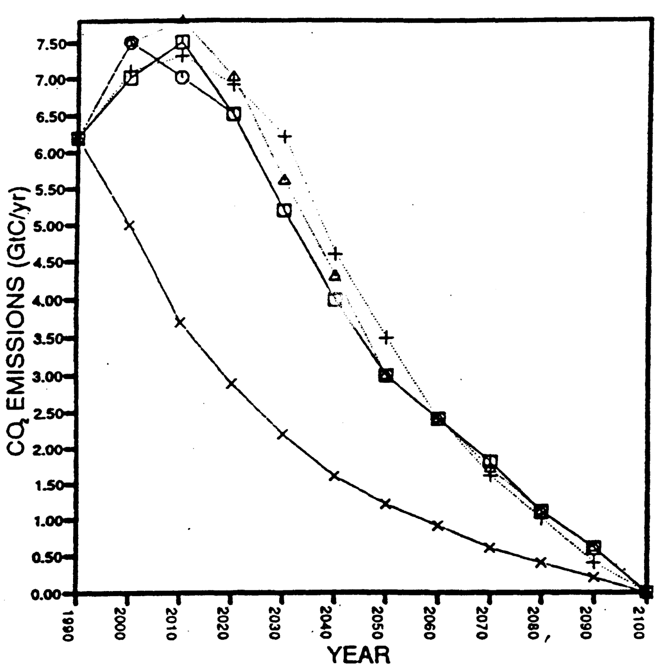


GENERAL MODEL PARAMETERS: Best Guess
ICE MELT MODEL PARAMETERS: Best Guess

Figure 3.3

EMISSIONS SCENARIOS
- × MANNE & RICHELS (1990)
- + ER V3.55 (1990)
- ▲ IPCC REVISED B.A.U. (1991)
- ○ STUGE B.A.U. (1990)
- □ GREENPEACE A

ANTHROPOGENIC CO_2 EMISSIONS FOR RANGE OF GREENPEACE CONTROLLING POLICIES SCENARIOS



GENERAL MODEL PARAMETERS: Best Guess
ICE MELT MODEL PARAMETERS: Best Guess

Figure ? 4

EMISSIONS SCENARIOS
- × CONTROL POLICIES E
- + CONTROL POLICIES D
- ▲ CONTROL POLICIES C
- ○ CONTROL POLICIES B
- □ CONTROL POLICIES A

N.B. These all refer to a range of illustrative control scenarios used to test potential climate impacts for the GES.

Emissions Targets

The broad objective of the Fossil Free Energy Scenario (FFES) and related variants is to pilot an energy strategy that strikes an appropriate balance between the satisfaction of legitimate human demands for energy services and the avoidance of climatic risk. There are a wide range of other environmental problems, both due to fossil fuels and other factors, but these are not addressed in this study. As the greenhouse modelling results in the full study make clear, our current understanding of the climate, and the factors which influence it, indicate that the environmental consequences of energy projections which are based upon the extended use of fossil fuels are likely to be extremely severe. The majority of reference case or "business as usual" energy scenarios (BAU) envisage greatly increased usage of fossil fuels and take little or no account of the global environmental impact. By proposing a ceiling upon GHG emissions aimed at stabilizing their atmospheric concentrations and thereby halting global warming, we aim to redress this imbalance. The letters referred to in Figures 3.2 to 3.4 simply refer to a range of potential control scenarios carried out seperately as guidance for the FFES exercise.

This process of target setting is influenced by considerations of the climate response, the environmental response and the feasibility or difficulty of attainment. The process as a whole is complicated by significant uncertainty with respect to environmental tolerance of global warming and sea-level rise, and uncertainty regarding the climatic change to be expected, especially on a regional scale. Nonetheless, the results from the STUGE greenhouse simulations illustrate the extreme dangers associated with the continuance of current energy usage trends and practices. The approach adopted in this study acknowledges the strengths and limitations of current scientific understanding as applied to the target setting procedure.

The dominant GHG is CO_2, accounting for 61 percent of the global warming impact of all GHG emissions in 1990, followed by methane (CH_4) at 15 percent, halocarbons (CFC's and HCFC's) with 11 percent, and nitrous oxide (N_2O) at 4 percent (Shine et al, 1990).

Considering the halocarbons first, CFC-11 and CFC-12 are already due to be phased out under the terms of the Montreal agreement because of their destructive impact upon stratospheric ozone. However, the mooted substitute gases such as HCFCs are among the most potent greenhouse gases and constitute a new and potentially substantial addition to radiative forcing[1]. They are used in a limited number of inessential or substitutable products

[1] As previously noted the BAU emissions scenarios for industrial halocarbons (CFCs, HCFCs and HCFS) have followed those of the IPCC 1990 WG1 BAU scenario. Subsequent to the completion of the climate modelling work for this study, the1992 IPCC Supplementary Assessment revised these estimates (Leggett et al, 1992), changing the composition and volume of halocarbons that could be emitted in the future under BAU assumptions.

More fundamentally however, the IPCC 1992 Supplementary Assessment and the WMO/UNEP 1991 Ozone Science Assessment have indicated a major uncertainty in the net radiative forcing induced by chlorofluorocarbons. On a globally averaged basis the radiative effect of halocarbon induced ozone losses may be of the same order but opposite sign to the direct radiative effect of CFCs (Isaksen et al, 1992). However there are a number of considerations which warrant caution before changing the basis on which the radiative forcing effect of CFCs and HFCs are calculated:

- The net effect is strongly differentiated by latitude, being net positive in the low latitudes and becoming negative in the mid-high latitudes (Isaksen et al, 1992).
- The radiative forcing on the surface-troposphere system of ozone depletion is strongly dependent on the actual altitude profile of the loss. There remain major observational and theoretical uncertainties in relation to the profile ozone loss, particularly in the vicinity of the troposphere (Isaksen et al, 1992).

Taking these and other factors into account the parameterizations used in the STUGE model to describe the radiative forcing induced by halocarbon concentrations were not changed. The net effect of the 1992 IPCC revisions would be to make the contribution of CO_2 much more significant in both the BAU and FFES scenarios. It would have a relatively small effect in the FFES, reflecting the immediate phase-out of CFCs and substitutes, with the chlorine compounds in the atmosphere being discounted as far as radiative forcing is concerned.

and are likely to be the simplest greenhouse gases to control because of their narrow production base. For these reasons Greenpeace proposes an immediate and complete phase out of radiatively significant halocarbons and substitutes. A sensitivity test was carried out on the influences of a delayed phase-out of CFCs and HCFCs. This is reported in section 9.

The sources and sinks of CH_4 and N_2O are not so well understood and accounted for. Anthropogenic methane is emitted in significant amounts from rice production, animal husbandry, biomass burning, landfills, natural gas production and distribution, and coal mining. The principal atmospheric sink for methane is its reaction with the hydroxyl (OH) radical. However the presence of OH radicals could be greatly affected by the anthropogenic emissions of other gases, such as NO_x and non-methane hydrocarbons, and the extent of these interactions are not yet well understood. While confidence in the estimates for sources and sinks of methane is growing (Lashof, 1991), there is still a high level of uncertainty. Similarly, the sources and sinks of N_2O are subject to wide margins of error such that it is very difficult to confidently quantify the impact of any given control policy upon atmospheric concentrations. In consequence, Greenpeace proposes that, where practicable, steps are enacted to reduce emissions of these gases. Though the results of these measures could be quite substantial, for the purposes of the target setting exercise we adopt more conservative CH_4 and N_2O emissions assumptions taking the average of the Rapidly Changing World with Control Policies (RCWP) and Slowly Changing World with Control Policies (SCWP) scenarios from the U.S. EPA analysis (Lashof and Tirpak, 1990). These have the effect of roughly stabilising emissions.

Getting 'acceptable' emission targets for CO_2 is not simply a case of assessing permissible or 'acceptable' environmental impacts, and subsequently backtracking to evaluate the attendant emissions limits. Considerations of physical and social feasibility, as well as scientific uncertainty are also important. Though there is uncertainty over both climate sensitivity and environmental sensitivity, several studies have attempted to suggest 'ecological targets' in order to significantly reduce risks to ecosystems, the climate and human beings. While uncertainty remains, the response ought to be one of iopting for insurance rather than inaction.

The Advisory Group for Greenhouse Gases (AGGG),Working Group 2 (Swart & Rijsberman 1990), established by the WMO, ICSU and UNEP as a forerunner to the IPCC, considered the likely environmental impacts of global warming. They recommended the following climatic targets:-

1. A maximum rate of change in global mean temperature of 0.1°C per decade.

2. A maximum temperature increase at two levels of risk:-

a. 1.0°C above the pre-industrial global-mean temperature.

b. 2.0°C above the pre-industrial global-mean temperature.

3. A maximum rate of sea level rise between 20 and 50 mm per decade; and

4. A maximum sea level rise of between 0.2 and 0.5m above the 1990 global-mean sea level.

Krause has suggested similar targets (Krause et al, 1991), citing some essential evidence that the rates of temperature increase beyond a level of 0.1°C per decade "could far outstrip the capacity of forests to migrate". Current predicted rates of warming suggest that boreal forests would be pushed poleward by 2.5km per year. Forests unable to keep up with this rate would face a rapid dieback. Krause also sets his suggested 'ecological targets' on the

Institute, 1991; Bach and Jain, 1991) have suggested that the implied carbon budgets, in the region of 300 to 400 gigatons of carbon, be allocated to countries under various formulaes (Krause, 1990).

Estimates of environmental sensitivity quoted in the literature were combined with the greenhouse model results, using the targets discussed above for non-CO_2 GHGs and a range of possible CO_2 emission profiles, to loosely define a first order band of "acceptable" emissions profiles. Depending on the assessment of the feasibility of the initial energy/CO_2-emissions scenario, an iterative process was followed in which the benefits of deeper CO_2 emissions reductions were weighed against the problems of achieving them. Eventually this lead to a convergence of energy and CO_2-emissions scenarios at some point within the minimum acceptable bounds. The band of CO_2 emissions scenarios Greenpeace were prepared to consider are shown in Figures 3.4. The contrast of these with the range of reference scenarios is stark (see Figure 2.6). The climate consequences are shown in Figures 3.5, 3.6, and 3.7. Even at the upper emissions boundary of the Greenpeace target emissions, total equivalent GHG concentrations are halted by approximately 2050. Global-mean temperature rise is restricted to 1.7°C above the pre-industrial level with temperatures falling after 2070. The warming rate falls below 0.1°C per decade before 2040 and sea level rise is kept to 32 centimetres (all at 2.5°C climate sensitivity).

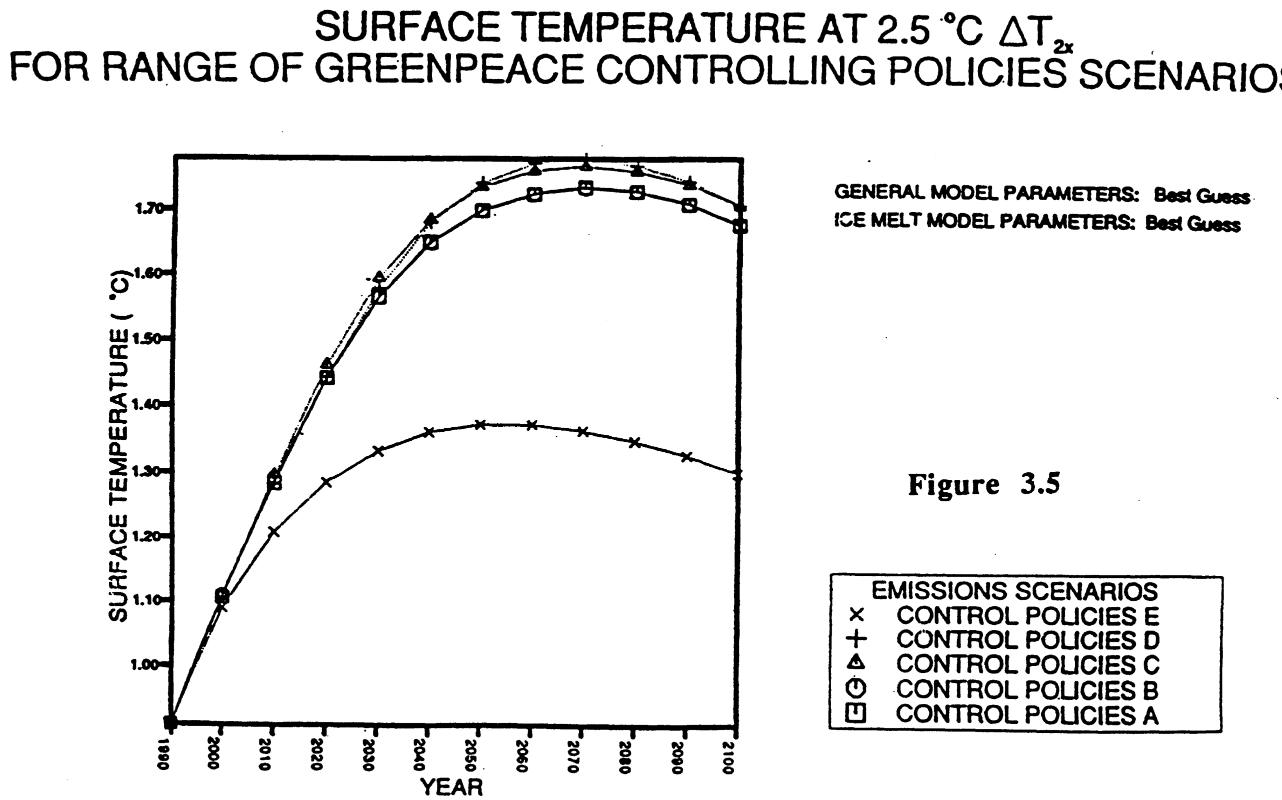
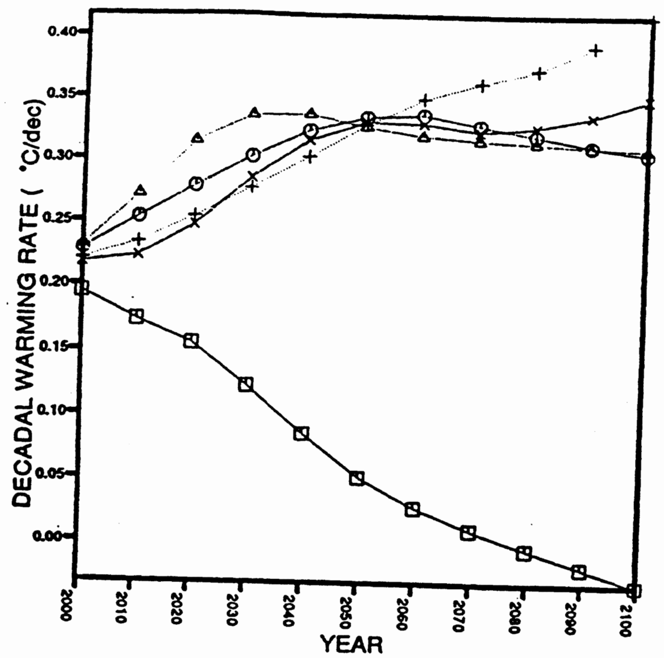


Figure 3.5

DECADAL WARMING RATE AT 2.5 °C ΔT_{2x} FOR RECENT ENERGY REFERENCE CASE FORECASTS

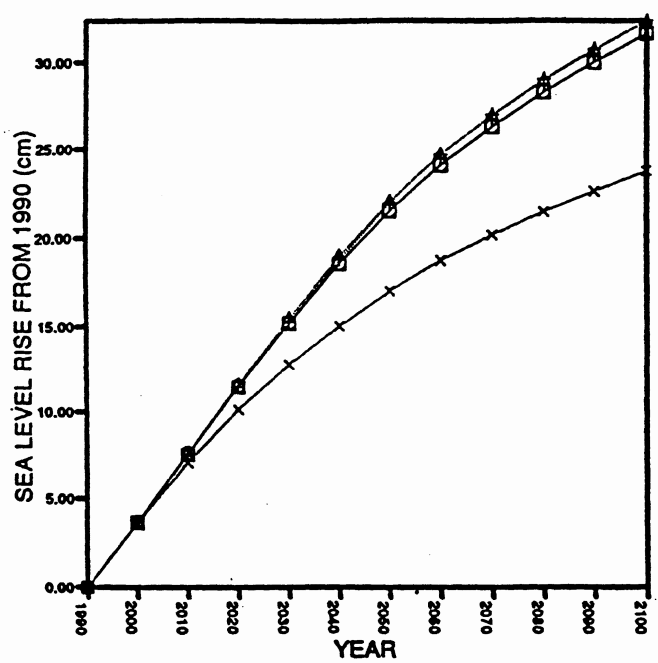


GENERAL MODEL PARAMETERS: Best Guess
ICE MELT MODEL PARAMETERS: Best Guess

Figure 3.6

EMISSIONS SCENARIOS
× MANNE & RICHELS (1990)
+ ER V3.55 (1990)
▲ IPCC REVISED B.A.U. (1991)
⊙ STUGE B.A.U. (1990)
⊡ GREENPEACE A

SEA LEVEL RISE FROM 1990 AT 2.5 °C ΔT_{2x} FOR RANGE OF GREENPEACE CONTROLLING POLICIES SCENARIOS



GENERAL MODEL PARAMETERS: Best Guess
ICE MELT MODEL PARAMETERS: Best Guess

Figure 3.7

EMISSIONS SCENARIOS
× CONTROL POLICIES E
+ CONTROL POLICIES D
▲ CONTROL POLICIES C
⊙ CONTROL POLICIES B
⊡ CONTROL POLICIES A

Section 4: Background and Scenario Approach

4.1. Overview

The perspective and methodology of this study, while similar in many aspects to some of the other analyses to date, combine a unique set of objectives :

- Meeting tough global emissions targets, based on a strongly risk-averse climate stabilization target.
- The phase-out of fossil fuels by the year 2100.
- The phase-out of nuclear power by 2010.
- A detailed, disaggregated approach; both by energy sector and by splitting the world into ten regions.
- Consideration of infrastructure, population and GDP changes as sensitivity analyses and variants to the main scenario.

4.2. Analytical Approach

Our analysis considers the world in terms of ten separate regions, reflecting, to the extent possible, varying patterns of economic activity, personal consumption, energy use, and energy resources. These regions are listed in Table 4.1. The regional groupings were based on those used in the Edmonds-Reilly energy - CO_2 model, to enable comparison with the U.S. EPA and IPCC studies, described in Section 8. This is why Canada was included in the same region as Western Europe.

The time frame for this study extends to the year 2100. This is an 'end year' common to several global studies, such as those produced by the US EPA and the IPCC. The long time frame is necessary as the climate effects of GHG emissions are expected to lag substantially behind the emissions themselves. Given the speculative nature of such long-range scenarios, we place greater emphasis on the time period between now and 2030, using greater detail in our assumptions and analysis. In fact, the next 40 years present the most challenging period, if we are to turn the corner on rising emissions of carbon dioxide and develop policies that enable us to meet climate stabilization targets. In addition, technical and economic estimates are far more tangible during this period.

4.2.1. Modelling Framework

We use several model and database systems in developing our scenarios. The Long-range Energy Alternative Planning (LEAP) system provides the organizing analytical framework for the energy and emission scenarios. We use the associated Environmental Database (EDB) as a source for specific emission coefficients. Together, LEAP/EDB comprise a computerized modelling system designed to explore alternative energy futures, along with their principal environmental impacts. Finally, we employ the Greenhouse Gas Scenario System (G2S2) as an additional source of regionally and nationally detailed energy and emissions data. LEAP, EDB, and G2S2 have been developed by the Stockholm Environment Institute - Boston, which is located at the Tellus Institute in Boston, and applied in numerous countries and regions throughout the world.[1]

Table 4.1

Regional Disaggregation for this study
(based on the Edmonds-Reilly model)

Abbreviation	Region
AFR	Africa
CPA	Centrally Planned Asia (China, Laos, Cambodia, Vietnam, N. Korea)
EE	Central and Eastern Europe
JANZ	JANZ/OECD Pacific (Japan, Australia, New Zealand, Fiji)
LA	Latin America
ME	Middle East (Asia East to Afghanistan)
SEA	South and East Asia (All other Asian countries)
US	United States
USSR*	Former USSR, now CIS and adjoining states
WE**	Western Europe and Canada

* In contrast to the Edmonds-Reilly model, we consider separately the former USSR and Eastern Europe regions.
** This region was only chosen to be compatible with the Edmonds-Reilly model of regional breakdown.

As a `bottom-up' modelling system, LEAP's principal elements are the energy and technology characteristics of end-use sectors and supply sources. LEAP has two important advantages. First, it allows very detailed specifications for key physical parameters in each end-use sector. Thus, our scenarios embody the impact of a variety of factors--including technological change, demographic variables, and structural shifts in the economy--on energy use. Second, the accounting framework in LEAP enables its results to be internally consistent; that is, assumptions made about energy use in one sector are consistent with those made in another. For example, a reduction in petroleum use in the transport sector automatically leads to a reduction in distribution losses and energy use for petroleum refining. Similarly, with its links to the Environmental Data Base, LEAP can track the pollution resulting from each stage of the fuel cycle, including the reduced emissions from extraction, processing, distribution, and combustion that would result from more efficient use of fossil fuel.

While LEAP is capable of incorporating econometric equations (e.g., production functions), it is not an econometric model that determines future energy use based on historical data. A fundamental aspect of such models is the presumption that trends observed in the past will continue into the future. Because econometric models, often considered `top down' models in contrast to the `bottom-up' approach used in LEAP, are based upon historical relationships, they have difficulty reflecting changes in the variety of technologies available, or other structural shifts that differ from historical trends. For very long term analysis, it becomes

1 LEAP is comprised of a set of flexible computer modules covering demand (sector, sub-sector, end-use/technology, and fuel), transformation (electricity supply system and other sources of energy supply), and resource (land-use and biomass resources). EDB is a computerized database of energy-related environmental impacts (coefficients for air and water pollutant emissions, land-use impacts, solid waste generation, and on-site health impacts). LEAP development was originally undertaken for the Beijer Institute for Energy and Human Ecology of the Royal Swedish Academy of Sciences, funded by the Swedish International Development Agency. EDB was originally funded by the United Nations Environmental Programme (UNEP), which administers this database along with SEI-B at Tellus. (LEAP has been applied in the U.S. (UCS et al., 1991), and over 20 countries worldwide including Brazil, China (Zhang, 1991), Hungary, Kenya (O'Keefe et al., 1984), the Philippines and Zimbabwe.

increasingly difficult to expect that historically-derived econometric relationships will continue to hold. In addition, due to their usual high level of sectoral aggregation, econometric models forego detail about changes specific to subsectors and energy end-uses such as lighting or process heat. Such changes can have major effects on overall energy use.[2]

Unlike `top-down' equilibrium models such as Edmonds-Reilly, LEAP does not simulate price and income interactions to seek a `market equilibrium' between supply and demand for each scenario.[3] As energy efficiency increases, for example, the demand for energy falls and some reduction in fuel prices might be expected. Likewise, as the cost of energy services is reduced by the use of least-cost technologies, the demand for energy can, in turn, rise somewhat. However, such interactive relationships between price and demand are notoriously difficult to accurately quantify, and the high variation among elasticities can lead to dramatically different results.

Nonetheless, the basic economic concept of supply and demand cannot be ignored. A dramatic reduction in fossil fuel demand could result in decreases in fossil fuel prices, possibly limiting the cost-effective penetration of competitive non-fossil supplies. Appropriate pricing policies, such as energy or carbon taxes, can compensate for this effect, ensuring full penetration of alternatives to fossil fuels. A related concept, often referred to as the `take-back effect' may occur in cases where more efficient technologies (e.g., compact fluorescent bulbs) decrease the cost of an amenity (e.g. lighting), leading to additional use (leaving the light on longer). Whether such a `take-back' actually takes place in reality depends on the specific end use and is subject to debate in the literature. A few of our efficiency targets embody minor adjustments for such effects.[4]

Optimization models find the economically optimal mix of technologies for a set of inputs under given constraints. This approach can be rich in technical detail and forward-looking in its technological assumptions. The complexity of the mathematical algorithms, however, often requires that key aspects of the energy system be simplified. Optimization models can be highly sensitive to relative price forecasts and the expected costs of technologies, which are, by definition, uncertain. Many policy and behavioral variables and constraints are difficult to parameterize and incorporate in these analyses.

For these reasons, we have chosen the end-use 'bottom-up' approach, embodied in LEAP, specifically to enable us to incorporate and simulate several important effects, including technological improvements and transitions, the limits imposed by saturation of several energy-intensive activities, and structural shifts among economic sectors and subsectors. We are interested in selecting the most economic resources we can to create a climate stabilized world. The end-use approach allows us to consider numerous detailed potential steps, such as

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2 In Manne and Richels' Global 2100 model, for instance, an energy supply curve is developed from technology-specific data, and price signals determine the amount of energy consumption by fuel type. Individual end-use sectors, however, are not modelled, so important shifts within and among sectors can be overlooked. Changes in end-use efficiencies are largely reflected through a single variable, the 'autonomous energy efficiency index' (AEEI in the Global 2100 model). Information about end-use technologies can be used to inform the selection of an AEEI, but the choice of efficiency options is not directly compared to supply options in the model itself. See Manne, A.S. and R.G. Richels, "CO2 Emission Limits: An Economic Cost Analysis for the USA," The Energy Journal 11(2), 51 (1990), and a critique of that paper--Williams, R.H., "Low-Cost Strategies for Coping with CO2 Emission Limits," The Energy Journal 11(3), 35 (1990).

3 Market equilibrium itself can be elusive in reality. Essentially, it assumes perfectly operating markets, and the absence of well-known market failures, such as imperfect information or the lack of consideration of the value of clean air, water, and soil (i.e. externalities).

4 For residential heating and cooling efficiency improvement potentials were partly based on an analysis for the U.S. that assumed a 5 percent take-back effect (UCS et al. 1991). For most other residential and commercial (and all industrial) end uses, any take-back effect is likely to be negligible (Henly et al. 1988; Lovins 1988).

efficiency improvements and fuel switching opportunities, as they have been identified in other studies.

Economic Criteria

We seek, where possible, to ensure that measures undertaken over the near and medium term (to 2030) yield net economic benefits or are unlikely to incur significant costs. The emphasis here is on proven or near-market technologies that have been shown to be either more cost-effective or at least cost-competitive with other options. We draw upon several recent analyses, most heavily upon a recent analysis for the U.S., that several of this report's contributors were involved with, America's Energy Choices (UCS, et al., 1991). Looking over a 40-year time horizon, the UCS study found that a 70 percent reduction in CO2 emissions could be achieved at a cumulative net savings of $2.3 trillion (1990 U.S. $). Since many of the measures found cost-effective in America's Energy Choices are also introduced here, the economic parameters are included in Appendix Table G-1 below for readers who wish to consider the underlying assumptions. However, they should not be regarded as a definitive set of price forecasts underlying this analysis. The dynamics of regional price changes in a high-efficiency, high-renewables, low fossil scenario are difficult to predict, particularly in light of various policies that might be implemented (e.g., energy or carbon taxes, efficiency rebates). The economic equilibrium model analysis included in Section 8 addresses this issue in greater detail, by applying our end-use results to the Edmonds-Reilly model. Finally, any cost estimates for the period beyond 2030 are inherently speculative; for this period, our scenarios reflect what currently appears credible and achievable.

4.3. Driving Forces: GDP and Population

While the literature diverges widely on projected energy use and CO_2 emissions, most scenarios, regardless of their source, share a common attribute: they are strongly driven by projected growth in population and income, the latter usually represented by Gross Domestic Product, or GDP. In general, GDP and population estimates have not received scrutiny and evaluation commensurate with their critical importance in most energy use and emissions projections. This disparity is most likely due to their highly political nature and the difficulty in constructing credible alternatives to standard sources (e.g., United Nations and World Bank). Consider, for example, the population and GDP growth rates assumed by the IPCC in its most recent projections (Swart et al., 1991a). World population grows to over 11 billion by the year 2100, with over five-fold growth in Africa from 560 million to almost 3 billion. South and East Asia is expected to support 3.6 billion people, up from 1.4 billion in 1988. Income (GDP) per capita in the U.S. grows to approximately $83,000 (1985 U.S. $) per capita in 2100, while that for the former USSR grows to more than $102,000 and total global GDP grows more than 14 times, as shown in Table 4.2. Meanwhile, the income of the average African 110 years from now rises to only $6000, less than half the current OECD average and over ten times lower than the richest countries in the year 2100.

The projected regional income distribution appears far from equitable[5]. Furthermore, are such high levels of economic activity in the U.S., and the world as a whole, plausible? Do we have the necessary physical resources for a world with an order of magnitude more buildings, cars, and other material and energy intensive items? Is such a future sustainable? Or must the types of human activities and the nature of production and consumption fundamentally change?

5 The IPCC projections have also been criticized for being too optimistic about short-term economic growth prospects in formerly centrally planned Europe, where low or negative growth rates seem possible throughout much of this decade.

4.3.1 GDP Projections: An Improved Equity Approach

In our analysis, we draw our population projections from the World Bank (Bulatao et al., 1990), the same source used by the IPCC, US EPA and others, and illustrated in Figure 4.1 below (Swart et al., 1991). For this analysis, we employ the IPCC (1990) (hereafter IPCC90) assumptions regarding total global GDP growth, in order to maintain the ability to compare our results with the range of reference case studies[6] (Swart et al., 1991a). Figure 4.2 illustrates that recent projections of GDP growth by IPCC and US EPA (average of EPA's RCW and SCW) yield roughly similar GDP results to ours for the year 2100; all fall within a range of $213 to $255 trillion (1985 U.S. $).

For modelling purposes we then propose an assumption for regional income equity wherein the ratio of highest to lowest average regional income drops to 2:1 by 2100, compared with the current ratio of over 14:1. We maintain the IPCC90 projected regional growth rates over the next 20 years, and then gradually adjust them over the 2010-2100 period to achieve this increased equity objective. GDP is redistributed among regions to achieve the same total world GDP as the IPCC90 forecast does in 2100: $213 trillion or $19,000 per capita (1985 U.S. $). GDP and GDP per capita for the IPCC90 and equity adjusted forecasts and shown in Tables 4.2 and 4.3, respectively. Figure 4.3 compares the resulting GDP per capita for these two cases. For the equity case, GDP per capita in all regions is higher than the 1985 OECD average of $12,200 (1985 U.S. $).

It is interesting to note that in only one region are the long-term (2010 onward) growth rates higher than those that the IPCC has estimated for the early periods. In Africa, long-term annual growth rates of 4.0-4.7 percent are required to meet the equity objectives, compared with the IPCC90 estimate of 3.3-3.7 percent for 1985-2010. All of these levels of GDP growth are within the realms of possibility and past experience.

Clearly, all 110 year economic forecasts are normative; no objective or scientific methods can be applied to such predictions. Rather than emphasize a 'business-as-usual' approach, we present a move towards greater equity, which one could argue is just as feasible[7]. This approach is similar to that taken by Mintzer for a recent global analysis, in which a narrowing of the North-South equity gap is seen as a critical component of limiting greenhouse gas emissions (Mintzer, 1992). Since, in the long run, equity is a prerequisite for true sustainability, we believe that it is more important to establish climate stabilization within such a context. Section 5.1 discusses the possible impact of moves toward greater economic equity on future CO_2 emissions. This approach effectively redistributes greenhouse gas emissions among regions, arguably in a more globally acceptable manner, but does not, by itself, substantially change the total global emissions relative to a less equitable world.

Equity is a desirable objective not only among regions, but within them. Our scenarios are based upon a notion that income distributions will improve, enabling near universal access to household amenities (lighting, refrigeration), commercial and transportation services, and consumer products both within urban and rural areas. This approach effectively redistributes greenhouse gas emissions among regions, arguably in a more globally acceptable manner, but does not, by itself, substantially change the total global emissions relative to a less equitable world.

6 The latest revisions of the IPCC 1991 analysis were not available in time for full incorporation into this analysis. These revisions address some of the concerns regarding over-optimism for former centrally-planned Europe.

7 The inequities of the business-as-usual approach could indeed undermine its own growth; e.g., with the potential need to maintain wealth with high military expenditures in an increasingly crowded, polluted world. An increased equity world could greatly reduce political and ecological pressures.

Table 4.2

Projected GDP and GDP per capita (IPCC 90)

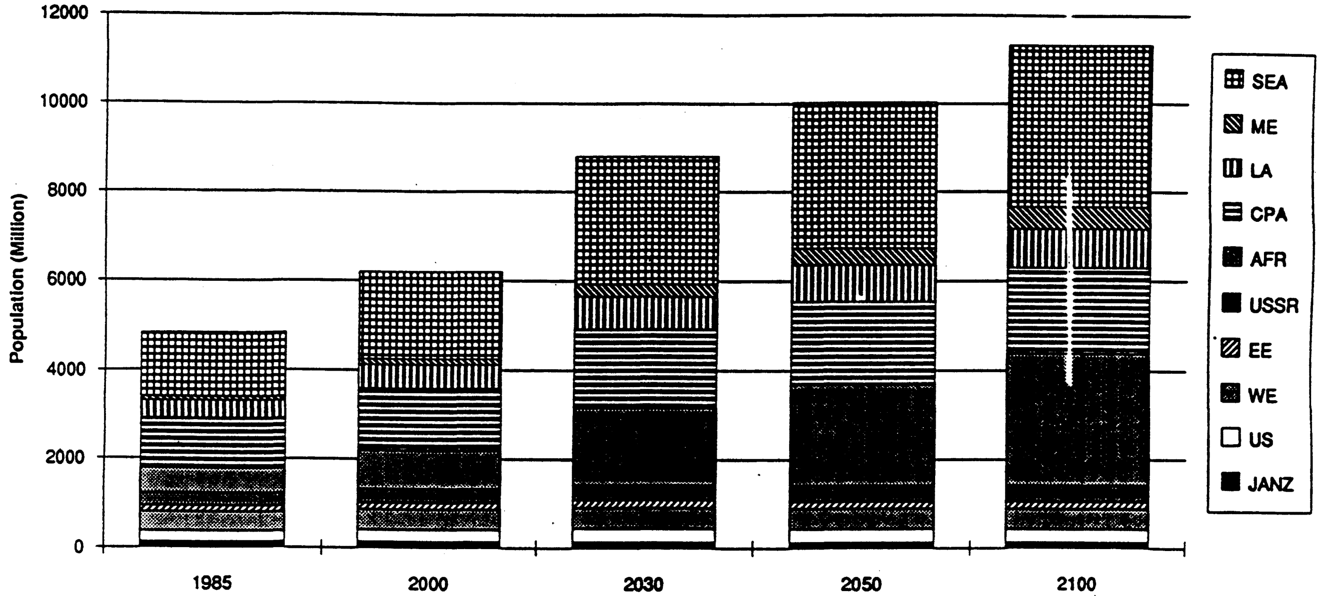
	1985	2030	2100	Average Annual Growth Rates 1985-2030	Average Annual Growth Rates 1985-2100
GDP (Billion 1985 US$)					
AFR	397	1,859	17,606	3.5%	3.4%
CPA	334	2,044	19,175	4.1%	3.6%
EE	304	1,244	5,275	3.2%	2.5%
JANZ	1,876	5,166	12,324	2.3%	1.7%
LA	806	3,491	18,999	3.3%	2.8%
ME	312	1,568	10,835	3.7%	3.1%
SEA	738	4,434	41,979	4.1%	3.6%
US	3,963	10,143	24,198	2.1%	1.6%
USSR	2,180	8,904	37,767	3.2%	2.5%
WE	4,046	10,356	24,706	2.1%	1.6%
All Industrialized	12,369	35,814	104,269	2.4%	1.9%
All Developing	2,587	13,396	108,594	3.7%	3.3%
Total	14,955	49,210	212,863	2.7%	2.3%
GDP/capita (1985 US$)					
AFR	710	1,070	5,943	0.9%	1.9%
CPA	296	1,166	10,066	3.1%	3.1%
EE	2,209	7,920	32,630	2.9%	2.4%
JANZ	13,222	33,318	84,604	2.1%	1.6%
LA	2,005	4,741	21,864	1.9%	2.1%
ME	3,781	5,644	21,506	0.9%	1.5%
SEA	510	1,544	11,437	2.5%	2.7%
US	16,561	33,624	82,185	1.6%	1.4%
USSR	7,823	25,809	102,145	2.7%	2.3%
WE	9,409	21,901	54,848	1.9%	1.5%
All Industrialized	10,076	25,016	73,329	2.0%	1.7%
All Developing	715	1,816	10,960	2.1%	2.4%
Total	3,087	5,588	18,787	1.3%	1.6%

Table 4.3

Projected GDP and GDP per capita (FFES Scenario: Improved Equity)

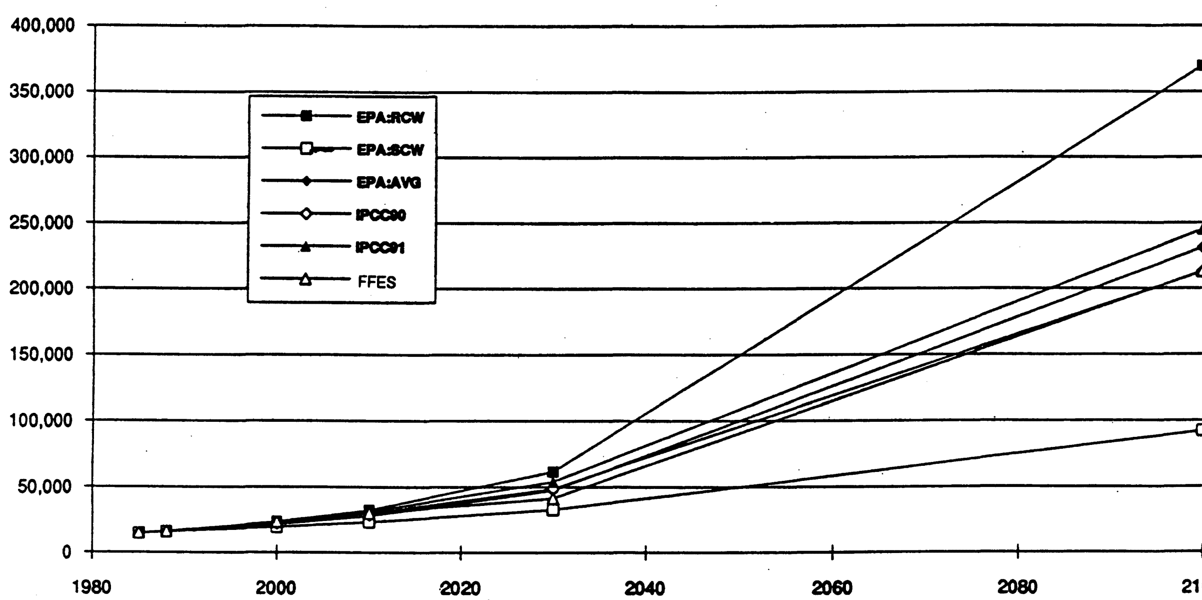
	1985	2030	2100	Average Annual Growth Rates 1985-2030	1985-2100
GDP (Billion 1985 US$)					
AFR	397	2,079	50,546	3.7%	4.3%
CPA	334	2,101	31,254	4.2%	4.0%
EE	304	1,121	3,142	2.9%	2.1%
JANZ	1,876	3,937	4,632	1.7%	0.8%
LA	806	3,326	16,607	3.2%	2.7%
ME	312	1,484	10,993	3.5%	3.1%
SEA	738	4,506	61,468	4.1%	3.9%
US	3,963	7,730	9,386	1.5%	0.8%
USSR	2,180	6,771	10,469	2.6%	1.4%
WE	4,046	8,716	14,367	1.7%	1.1%
All Industrialized	12,369	28,274	41,996	1.9%	1.1%
All Developing	2,587	13,496	170,867	3.7%	3.7%
Total	14,955	41,771	212,863	2.3%	2.3%
GDP/capita (1985 US$)					
AFR	710	1,196	17,063	1.2%	2.8%
CPA	296	1,199	16,407	3.2%	3.6%
EE	2,209	7,137	19,434	2.6%	1.9%
JANZ	13,222	25,391	31,878	1.5%	0.8%
LA	2,005	4,517	19,112	1.8%	2.0%
ME	3,781	5,339	21,921	0.8%	1.5%
SEA	510	1,570	16,747	2.5%	3.1%
US	16,561	25,624	31,878	1.0%	0.6%
USSR	7,823	20,258	28,314	2.1%	1.1%
WE	9,409	18,431	31,878	1.5%	1.1%
All Industrialized	10,076	19,899	29,537	1.5%	0.9%
All Developing	715	1,830	17,245	2.1%	2.8%
Total	3,087	4,749	18,788	1.0%	1.6%

Figure 4.1
Population Projections



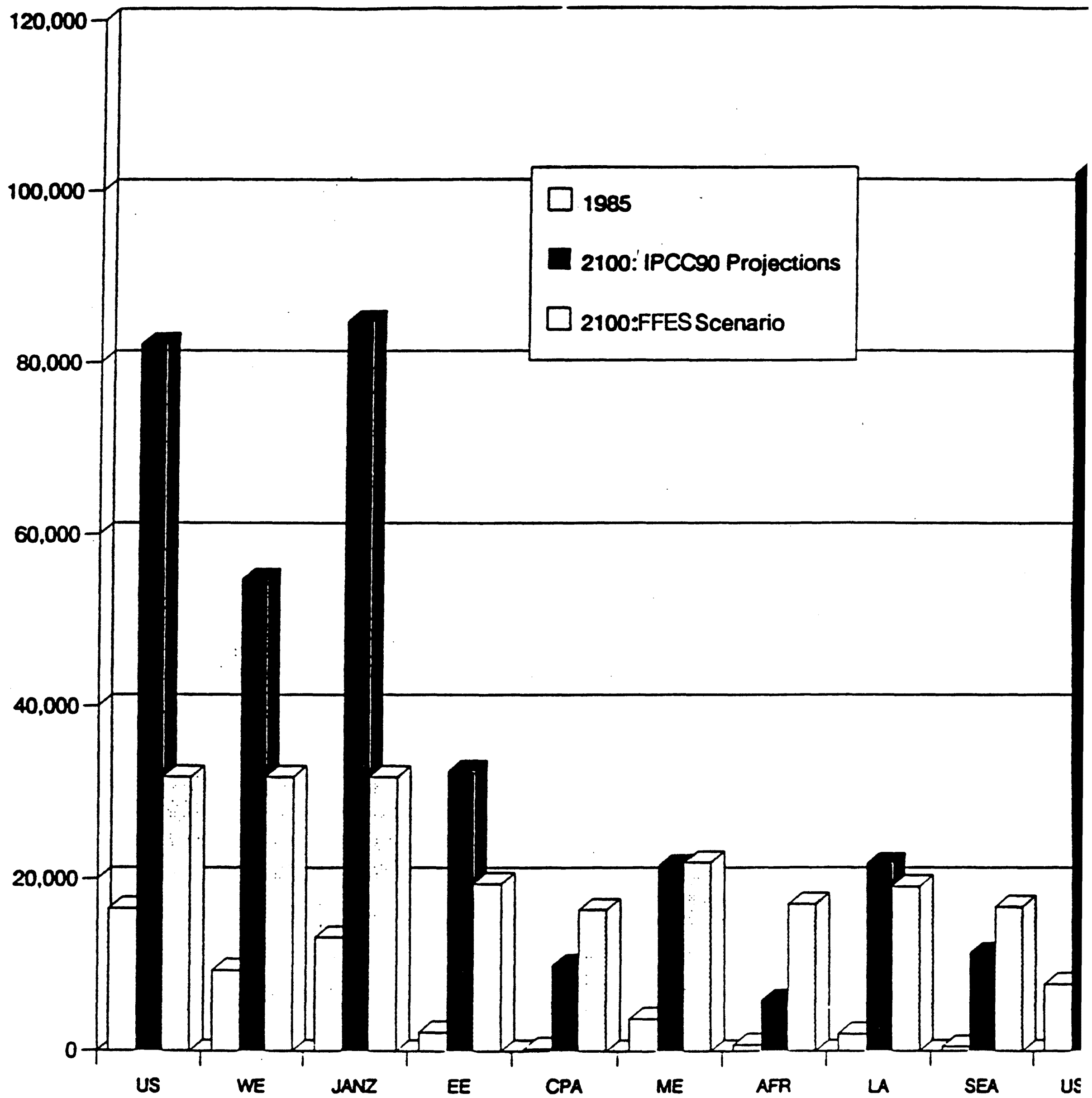
Source: Bulatao et al, 1989

Figure 4.2
World GDP Projections (Billion 1985 US$)



Sources: Lashof and Tirpak, 1990; Swart et al, 1991. 1980s GDP distribution based on Summers and Heston, 1991 and Basmakov, 1990.

Figure 4.3
Regional Comparisons of GDP/capita Projections
(1985 US$)



Despite the many shortcomings of GDP as a measure of relative wealth and as a measure of well-being, we use it in this analysis for the purposes of comparison with other studies. A fuller discussion of GDP issues, and problems associated with the use of Purchasing Power Parity adjustments, a popular alternative, is included in Appendix D. A number of sensitivity tests using variations of GDP were carried out. The impact of lower GDP on energy demand and CO_2 emissions is discussed in section 5.2.

4.3.2 Structural Change

The concept of structural change in economies is fundamental to each of our scenarios. With the rapid GDP growth rates for the South embodied in our scenarios, we anticipate the general transition among sectors that has accompanied the industrialization process in the North: from agricultural and other primary production to a period of greater industrial activity, and finally to the ascendancy of the service sector.

For each of the study's ten regions, we have estimated the contribution to total GDP of agricultural, industrial and service sector activities. As shown for 1985 in Figure 4.4, the contribution of agricultural production declines significantly with GDP per capita from 26 percent and 22 percent in SEA and AFR, respectively, to an average of 3 percent in OECD regions. Service sector activity, in contrast, increases with per capita GDP, up to 68 percent of total GDP in the U.S.

The specific path for future economic development in the industrializing countries of the South is impossible to predict; we use the model of the currently industrialized countries as one possible option[8]. We therefore construct a scenario in which there is an initial shift towards the industrial sector during a period of infrastructure building, then a later transition to a more service-oriented economy. The share of agriculture in GDP gradually diminishes to 3 percent, the current OECD average, by the year 2100.

In the North, we project some additional shifting of economic activity from industry to services, but assume that much of this transition to service activity has already taken place. Further economic growth in OECD countries may be heavily influenced by communications, the so-called fourth sector, and vocational and leisure activities. A balance between industry and service sector activity may remain, while the character of manufacturing and services may change dramatically. We separately consider structural change *within* the industrial sector, as described for the industrial model below. Although we expect shifts from business and administrative to consumer services, including health and education, we do not consider the energy implications of sub-sector shifts within the service sector, due to the greater uncertainty of their impacts.[9]

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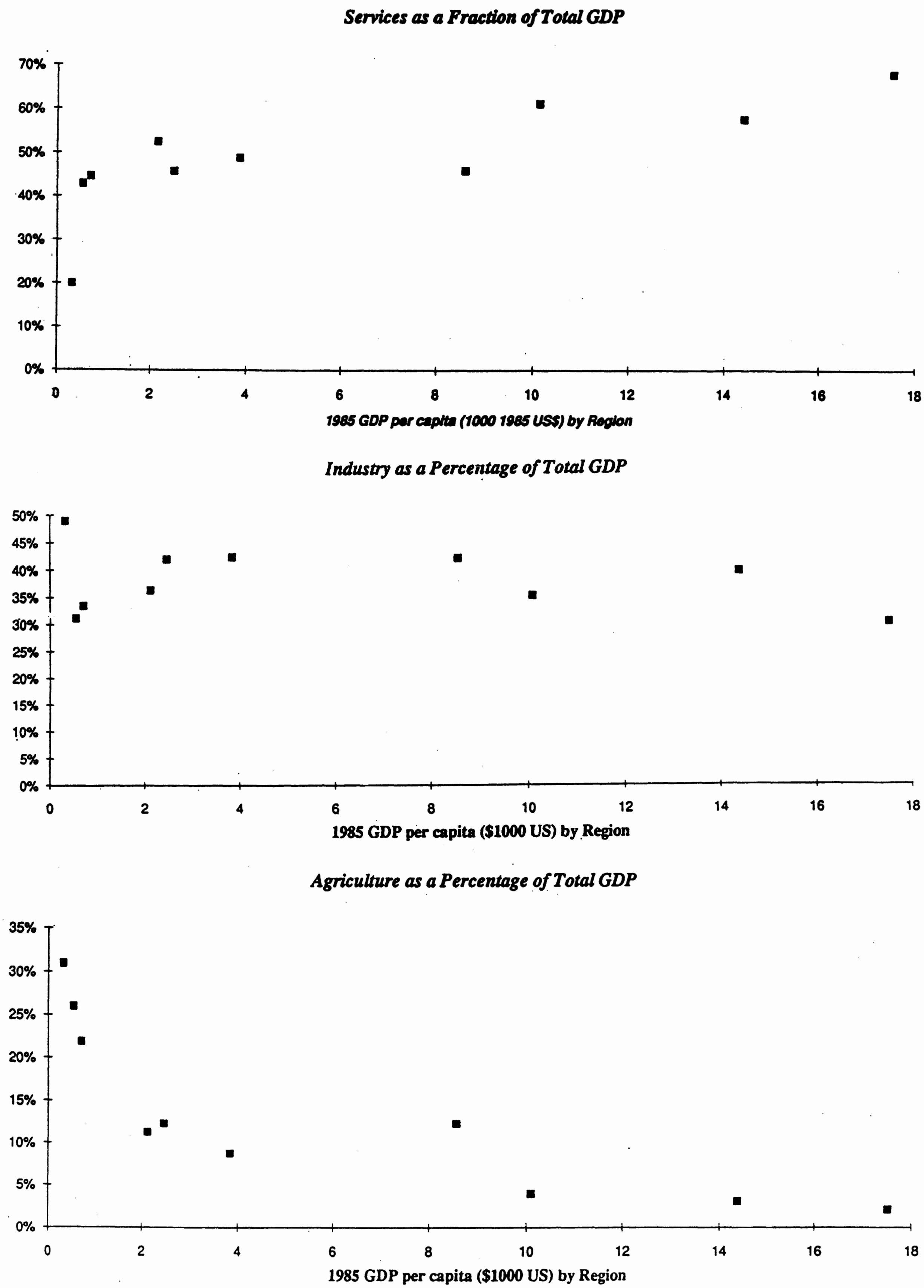
8. This model of development has serious flaws. In the absence of available alternative development models however, the conventional model was used.

9 There are various estimates of the energy use characteristics of different building types and their ancillary activities (e.g. the goods, customer, and employee transport associated with retail, office, educational, and other services). However, the relative energy intensities of the service sub-sectors (energy/GDP) vary among regions (Schipper and Meyers, 1992). In general, the differences among sub-sectors in this sector (e.g. between the energy required to provide a unit of education vs. business services) are both more uncertain and less pronounced than in the industrial sector (e.g. between the energy required to produce a unit of steel vs. aluminum).

Figure 4.4

Changing Shares of GDP with Increasing Income per Capita



Lacking a strong basis for defining residual regional differences in economic structure toward the year 2100, we assume a convergence by 2100 to a service-oriented economic structure in each region, with the industrial sector accounting for 25 percent of future GDP. These macro economic assumptions, while simple, help to capture sector-level structural change that would be expected as economies undergo transitions through industrialization in a world approaching inter-regional equity.

4.3.3 Population

The scenarios presented here rely on the World Bank population projections illustrated in Figure 4.1 (Bulatao et al., 1990), as have the IPCC, EMF (Energy Modelling Forum), and many other global studies. However, we recognize that supporting the projected 2100 population of over 11 billion at rising average standards of well-being would severely tax human and environmental resources. Again, we employ these figures for the purpose of allowing the results of this study to be compared with those of other studies which have relied on similar numbers.

Interestingly, more equitable economic growth could well result in lower future population levels. Low incomes in developing countries are key contributors to rapid population growth. For poor families, children are essential income earners, and create a safety net for aging parents. From a strictly economic viewpoint, as incomes rise, the perceived need for such a safety net diminishes, and as women's work changes from traditional to modern modes, linked to greater equality between men and women, a demographic transition leads to smaller families and lower population growth. In fact, the World Bank forecast a population decline for the OECD regions from 2030 to 2100, representing the continued economic affluence and changing cultural norms, such as increasingly older parenting, and single or childless couples and individuals. The interplay between population and socio-economic development assumptions is significant. However, here we join with the other global energy studies in treating population assumptions as exogenously assumed inputs, that is, treating them as given.[10]

4.4. Emissions Accounting

This section describes the data and methods underlying our estimates of emissions related to energy consumption and production processes.

4.4.1 Greenhouse Gases Considered

The primary greenhouse gas considered in the LEAP-based energy-emissions analysis presented here is carbon dioxide (CO_2). In addition, carbon monoxide (CO), other volatile hydrocarbon (HC or VOCs), and nitrogen oxide (NO_x) emission factors were included for indicative purposes. Other greenhouse gases -- methane (CH_4), nitrous oxide (N_2O) and chlorofluorocarbons (CFCs) were dealt with as described in Section 3.

10 The effects of alternative population assumptions on future energy use are considered in sensitivity analysis (see Section 5.2).

Carbon dioxide (CO_2), the major greenhouse gas both in terms of quantity emitted and overall effect on global warming, is released whenever a fuel that contains carbon is combusted, or oxidized. It is released in quantities generally proportional to the carbon content of the fuel. Combustion of a kilogram of fuel (such as gasoline) can yield over three kilograms of CO_2[11].

For this study, carbon dioxide emissions were described as either *non-biogenic* or *biogenic*. Non-biogenic emissions are those derived from combustion of fossil fuels and other sources of carbon dioxide (e.g. geothermal wells) for which the carbon emitted is either of geological origin or, as is the case with coal, oil, gas, and peat, was formed from biological material but on geological time scales, that is, so long ago that the fuels are essentially non-renewable. Non-biogenic emissions constitute a net addition of CO_2 to the atmospheric pool of the gas, at least on a human time scale.

Biogenic emissions, in contrast, result from biomass combustion. They do not constitute net additions of CO_2 to the atmosphere, *under conditions of sustainable biomass harvesting*. Under these conditions, the CO_2 released upon combustion of biomass-derived fuels can be recaptured during photosynthesis in the next biomass growth cycle.[12]

Non-sustainable harvesting of biomass, leading to soil and land degradation, and, in extreme cases, to deforestation and desertification will cause net additions of CO_2, if land is not restored to its original condition. The net carbon additions from deforestation are handled separately, in the development of inputs to the climate model STUGE, as summarized in Section 3. We assume that all new biomass energy developments envisioned here would be conducted in a sustainable manner. The FFES assumed biomass productivity levels are considerably lower (2.5 fold lower) than a US EPA scenario for example (US EPA, 1990b). Large scale monoculture plantations, which have caused major problems in some countries, would be largely avoided in favour of less-intensive mixed plantations, and herbaceous and short rotation woody biomass crops.

Carbon monoxide (CO) is emitted as a result of incomplete combustion of fuels. While CO is only a weak greenhouse gas by itself, it can react chemically with other gases in the troposphere (the lower part of the atmosphere) to form ozone (O_3) which is a greenhouse gas. In addition CO eventually reacts with oxygen to form CO_2. Considering both its direct and indirect effects, CO has an effect on climate, on a per unit mass basis, approximately three times that of CO_2[13]. Emissions of carbon monoxide are primarily a function of combustion conditions; inefficient combustion generally increases CO emissions. CO is produced in quantities ranging from one to four orders of magnitude less than CO_2, depending on the fuel - consuming device.

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11 This is possible because petroleum is 80-85 percent carbon and most (32/44) of the mass of CO2 comes from oxygen, which is principally derived from the air in which the fuel is combusted, and not from the fuel itself.

12 For example, if a hectare of corn were grown to produce 3,000 litres of ethanol, and the ethanol was then used as fuel, there would be a temporary addition of CO2 to the atmosphere, but the next year, planting the same hectare of corn would reclaim a similar quantity of carbon dioxide from the atmospheric pool. The key here is that biogenic emissions of CO2 can result in no net addition of CO2 to the atmosphere, and no net loss of carbon from the terrestrial biomass.

13 Note that there are several different measures of the relative effects of different GHG gases on climate. Here, we refer to the relative "Global Warming Potential" (or GWP) of the gasses, using the "100 Year Time Horizon Integration" GWP factors assembled by the Intergovernmental Panel on Climate Change (IPCC) in the 1990 report of IPCC Working Group I entitled Scientific Assessment of Climate Change, chaired by J.T. Houghton of the UK. The GWP factors are described in Chapter 2 of that report. The reader is encouraged to refer to the IPCC volume for additional detailed information about the science of climate change.

Methane ($CH4$) is emitted to the atmosphere as a by-product of fuel combustion, through leakage from natural gas, oil and coal extraction, transmission, and distribution facilities, and from agricultural and natural (non-anthropogenic) sources. Only the first two types of emissions are considered in this study. Methane is a direct greenhouse gas, but it also interacts with both tropospheric ozone and stratospheric water vapor, thus enhancing its overall contribution to global warming. The contribution of CH_4 to global warming is approximately 21 times that of CO_2 on a per-unit-mass basis. Methane is only a trace constituent of combustion products, generally on the order of 10^{-3} or less times the concentration of CO_2. Like CO, CH_4 emission factors are a function of combustion conditions and the types of devices used, with inefficient combustion resulting in higher methane emissions. The second source of anthropogenic methane emissions, fuel extraction and distribution, releases significantly greater quantities of CH_4 than are emitted from combustion sources. Methane emission factors shown in Tables 4.4 and 4.5 below are for illustrative purposes only, and were not used in the analysis described in Section 3.

Hydrocarbons other than methane are also emitted during incomplete combustion of fuels, as well as during fuel production, storage, and handling. This class of compounds has an indirect effect on global warming, and is about 11 times more powerful as a greenhouse gas, per unit mass, as CO_2. The same conditions that favour CO and CH_4 emissions tend to favour emissions of this class of compounds in quantities 10^{-2} to 10^{-5} times emissions of CO_2. Methane emissions range from about 2 to 90 percent of total hydrocarbon emissions, depending on the fuel and the combustion device.

Nitrogen oxides (NOx) are also trace constituents of exhaust gases. NO_x affects climate through an indirect effect on ozone (O_3) concentrations; its overall effect on climate per unit mass is about 40 times that of CO_2. The nitrogen in nitrogen oxide combustion products is derived from nitrogen from various compounds in the fuel and from molecular nitrogen (N2) in the air[13]. Like CO, CH_4, and other hydrocarbons, emissions of NO_x are dependent on combustion conditions, but in this case the rule of thumb is that higher combustion temperatures (which generally promote more complete combustion) tend to increase NO_x formation, as more N_2 from the air is oxidized.

The GHGs not accounted for in the energy scenarios presented in this report are *nitrous oxide* or N_2O and *halocarbons* (including Chlorofluorocarbons, or CFCs). As with deforestation, assumptions for halocarbons and nitrous oxide have been developed separately, as described in Section 3.

Nitrous oxide is a fairly powerful greenhouse gas on a weight basis, and was thought until recently to be produced in significant quantities during fuel combustion. Recent information, however, has indicated that the majority of the assays of N_2O emissions carried out before 1990 included a sampling technique[14] that tended to amplify actual nitrous oxide concentrations by up to two orders of magnitude. As a result, virtually all of the N_2O emissions factors generated before 1990 have been effectively discredited, and only a few factors generated using more robust test procedures have started to become available. As a consequence of this lack of emission factors, and because of the probable lower importance of N_2O emissions from combustion, loadings of nitrous oxide were not estimated for the scenarios described in this report.

Halocarbons encompass a broad group of compounds with moderate to very strong climate-altering potential, but their emissions primarily stem from direct production and use of

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13 Molecular nitrogen (N2) accounts for nearly 80 percent of the gas in the earth's atmosphere.

14 This technique seems to have been the major one used by the U.S. Environmental Protection Agency (US EPA) in sampling for N2O. Most of the nitrous oxide emission factors available are from this source.

chemicals such as CFC-11, used as a refrigerant, and carbon tetrachloride (CCl_4), which is used as an industrial solvent and chemical feedstock. Some of these compounds are producedin minute and relatively insignificant quantities during fuel or waste combustion.

There are uncertainties associated with the emission factors used to estimate greenhouse gas emissions. Estimates of CO_2 emission factors are primarily dependent on fuel carbon content, and thus usually have relatively little variability, particularly for petroleum products and natural gas. Carbon dioxide emission factors can probably be considered accurate to within 5 percent, even across regions. For the other greenhouse gases, emission factors are typically based on the results of a relatively small number of tests of fuel use in particular types of equipment, so in order to ascribe emission factors to specific sectors or subsectors of the energy economy it is necessary to judiciously make a number of sweeping assumptions. As a result it is difficult to even ascribe an uncertainty to these emission factor estimates. Increased emissions testing in both the developing and industrialized world, with centralized international reporting of results, could help greatly in reducing these uncertainties (see below).

4.4.2. Emission Factor Sources

EDB

The Environmental Database (EDB) associated with the LEAP system provides a comprehensive database of environmental impacts associated with energy use. It contains a large existing database of coefficients describing air, water, solid waste, and occupational health and safety effects. The core data of EDB are derived from over 70 literature sources of international origin. For greenhouse gases, two important sources of data, particularly for industrialized country emission factors, have been the emission factors databases from the U.S. Environmental Protection Agency's `National Emissions Data System (NEDS)' and its `Atmospheric Stabilization Framework' (ASF) Study[15]. Data were also drawn from, among other sources, the World Health Organization and the U.S. Department of Energy. Additional information describing EDB can be found in Appendix B.

Using EDB, we created a set of emission factors for use with the regional LEAP data sets created in this study, as described below. These emission factors were then linked within LEAP to the appropriate energy demand and supply activities, to yield the environmental loadings associated with each of our scenarios.

G2S2

The Greenhouse Gas Scenario System (G2S2) is a database and policy assessment tool that allows analysts to project greenhouse gas emissions using alternative technical assumptions and policy options. It includes greenhouse gas accounts for 142 countries for the major sources of greenhouse gas emissions, including energy consumption, cement production, CFC use, land use changes, livestock production, rice cultivation, landfills, and fertilizer consumption. Appendix C provides additional information on G2S2's design, structure, and functions.

For our scenarios here, we used the G2S2 system to provide: 1) control total checks on energy use by fuel and sector for each region; and 2) weighted-average emission factors, by demand sector and fuel (coal, oil, gas, renewables), where the G2S2 analysis has considered details on emissions and energy use specific to each region. In particular, weighted-average

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15 Note that these two databases have a good deal of information that is of common origin; many emission factors in both are originally derived from US EPA document Compilation of Air Pollutant Emission Factors, Fourth Edition, AP-42, published in two volumes in 1985 with several more recent Supplements.

regional G2S2 emission factors were used in the transport sector.[16]

4.4.3. Emission Factors

Using EDB, G2S2, and other reference sources, a set of greenhouse gas emission factors were assembled for use with the regional LEAP energy data sets. Emission source categories were created for each demand sector and each energy transformation process, for each of the fuels--coal, oil, natural gas, and renewable fuels--considered in the study. Within fuel types, some sets of emission factors differentiate between types of fuel products in order to allow for differences between regions. For example, household sector use of oil products may be principally in distillate oil-fired heating equipment in North America, but in liquified petroleum gas (LPG) stoves in South and East Asia. Thus, for household sector oil consumption, coefficients for both distillate oil/diesel devices and LPG devices were researched.

With the exception of the carbon dioxide emission factors, we have selected emission factors that lie near the middle of the range of available data, and that are consistent with other factors from the same source. For example, a methane emission factor that exceeded the emission factor for total hydrocarbons would not be consistent. For industrial and service sector sources, emission factors for boilers were generally chosen as representative of the bulk of fuel combustion in those sectors. For the household sector, data were chosen for stoves and heaters, both of `modern' (those in industrialized countries) and `traditional' (those typical of developing regions) types. For the transport sector, weighted average figures by region calculated for G2S2 were adopted as CO, CH_4, and total hydrocarbon coefficients, and NO_x estimates roughly consistent with the other emission factors were estimated from vehicle emissions data. Emission factors for electricity generation technologies were also compiled for each type of fuel and for several types of new and existing technologies. Tables 4.4 and 4.5, below, present these emission factors.

To establish a consistent set of coefficients for carbon dioxide emissions, the following procedure was used. First, a set of carbon contents by fuel was compiled from the literature[17] and, in some cases, by calculations based on fuel molecular weights. Next, these carbon fractions were multiplied by the ratio of CO_2 to carbon molecular weights (44/12) and by an assumed average fraction of fuel that goes through burners unoxidized. This `unburnt' fraction of fuel carbon, which is assumed to be primarily emitted as soot and ash, was assumed to be 1.0 percent for each type of fuel[18]. Finally, for types of fuel use (e.g. automobiles, wood stoves) where CO emissions represent a significant (c. 0.5 percent or greater) fraction of total carbon emissions, the fraction of carbon emitted as carbon monoxide was subtracted from the CO_2 emission coefficient. This avoids the problem of double-counting carbon emitted as CO. Table 4.6 shows the fuel carbon and energy content assumptions used in this study, as well as the carbon dioxide emissions (assuming complete combustion) per unit fuel energy.

16 We used G2S2 for the transport sector, because they provide a systematic weighting of emission factors from the road, air, rail and other transport subsectors. Emission factors for the transport sector, and the road subsector in particular, can vary widely by region. For future non-CO2 emissions for the transport sector, see also the companion transport analysis by Michael Walsh (Appendix F).

17 Major sources for carbon contents included Grubb, M., 1989; "On Coefficients for Determining Greenhouse Gas Emissions from Fossil Fuel Production and Consumption", P. 537 in Energy Technologies for Reducing Emissions of Greenhouse Gases. Proceedings of an Experts' Seminar, Volume 1, OECD, Paris, 1989; and ORNL, 1989, Estimates of CO2 Emissions from Fossil Fuel Burning and Cement Manufacture, G. Marland et al of Oak Ridge National Laboratory, May 1989, ORNL/CDIAC-25.

18 Note that while this assumption is consistent with literature estimates (e.g. Grubb, ibid; OECD, 1991, Background Document for the February, 1991 Workshop on Emissions Methodology, Chapter 2: "Emissions from Energy Production and Consumption"), very little recent empirical work appears to have been done to quantify the fraction of carbon left unoxidized in soot and ash after fuel combustion.

TABLE 4.4: COMPILATION OF GHG EMISSION FACTORS USED IN THIS STUDY: DEMAND SOURCES

UNITS: KG/FUEL UNIT INPUT (UNLESS NOTED)

EMISSIONS SOURCE	CO_2 Non-Biogenic	CO_2 Biogenic	CO	CH_4	HC	NO_x	FUEL UNIT
INDUSTRIAL SECTOR SOURCES							
OIL-FIRED (RESIDUAL OIL)	3.06E+00	N/A	6.31E-04	3.69E-06	3.54E-05	6.94E-03	Kilograms
OIL-FIRED (DISTILLATE OIL)	3.14E+00	N/A	6.89E-04	8.92E-06	2.76E-05	2.76E-03	Kilograms
OIL-FIRED (80%/20% RESID/DIESEL)	3.08E+00	N/A	6.31E-04	4.74E-06	3.33E-05	6.06E-03	Kilograms
OIL-FIRED (20%/80% RESID/DIESEL)	3.13E+00	N/A	6.89E-04	7.87E-06	2.98E-05	3.72E-03	Kilograms
NATURAL GAS-FIRED	1.85E+00	N/A	6.42E-04	1.26E-05	2.25E-05	8.82E-03	Cubic Meters
COAL-FIRED (BITUMINOUS)	2.71E+00	N/A	2.50E-03	2.92E-05	3.50E-05	9.59E-03	Kilograms
COAL-FIRED (LIGNITE)	1.13E+00	N/A	2.50E-03	2.92E-05	3.50E-05	3.00E-03	Kilograms
BIOMASS-FIRED	N/A	1.55E+00	2.40E-02	2.40E-04	6.99E-04	1.40E-03	Kilograms
RESIDENTIAL SECTOR SOURCES							
NATURAL GAS STOVES	1.85E+00	N/A	9.75E-06	2.73E-05	1.95E-04	3.90E-04	Cubic Meters
NATURAL GAS HEATERS	1.85E+00	N/A	3.20E-07	2.73E-05	1.28E-04	1.30E-03	Cubic Meters
DISTILLATE OIL STOVES, HEATERS	3.14E+00	N/A	7.50E-04	7.00E-06	1.40E-04	2.72E-03	Kilograms
KEROSENE LAMPS, STOVES, HEATERS	3.09E+00	N/A	4.48E-03	2.00E-05	4.00E-04	2.30E-03	Kilograms
COAL STOVES AND HEATERS	2.64E+00	N/A	4.50E-02	3.08E-05	1.00E-02	5.00E-03	Kilograms
LPG STOVES AND HEATERS	2.98E+00	N/A	4.40E-04	5.33E-05	1.58E-04	1.95E-03	Kilograms
BIOMASS STOVES/HEAT: 'MODERN'	N/A	1.38E+00	1.35E-01	3.20E-02	4.59E-02	1.36E-03	Kilograms
BIOMASS STOVES/HEAT: 'TRADITIONAL'	N/A	1.46E+00	8.00E-02	3.83E-03	7.50E-03	7.00E-04	Kilograms
SERVICE SECTOR SOURCES							
NATURAL GAS-FIRED DEVICES	1.85E+00	N/A	3.21E-04	4.29E-05	8.50E-05	1.60E-03	Cubic Meters
OIL-FIRED DEVICES USING DIST. OIL	3.14E+00	N/A	6.89E-04	3.12E-05	4.69E-05	2.76E-03	Kilograms
COAL-FIRED DEVICES	2.71E+00	N/A	2.50E-03	3.05E-04	6.49E-04	4.74E-03	Kilograms
BIOMASS-FIRED DEVICES	N/A	1.59E+00	3.18E-02	2.39E-04	6.99E-04	3.40E-03	Kilograms
TRANSPORT SECTOR SOURCES							
COAL-FUELED VEHICLES	2.71E+00	N/A	2.58E-03	7.08E-05	7.08E-05	9.60E-03	Kilograms
NATURAL GAS- (OR CNG) VEHICLES	1.85E+00	N/A	1.56E-04	4.68E-03	4.68E-03	5.46E-03	Cubic Meters
PETROLEUM-FUELED: U.S. FLEET	2.79E+00	N/A	2.71E-01	9.87E-04	9.87E-03	2.51E-02	Kilograms
PETROLEUM-FUELED: EUROPE FLEET	2.78E+00	N/A	2.71E-01	1.10E-03	1.10E-02	3.40E-02	Kilograms
PETROLEUM-FUELED: JANZ FLEET	2.76E+00	N/A	2.85E-01	1.16E-03	1.16E-02	3.72E-02	Kilograms
PETROLEUM-FUELED: USSR FLEET	2.90E+00	N/A	1.90E-01	8.63E-04	1.08E-02	4.12E-02	Kilograms
PETROLEUM-FUELED: CP ASIA FLEET	2.92E+00	N/A	1.80E-01	8.91E-04	1.11E-02	4.52E-02	Kilograms
PETROLEUM-FUELED: S&E ASIA FLEET	2.97E+00	N/A	1.36E-01	7.42E-04	1.23E-02	4.49E-02	Kilograms
PETROLEUM-FUELED: MID. EAST FLEET	2.89E+00	N/A	2.03E-01	8.93E-04	1.12E-02	4.15E-02	Kilograms
PETROLEUM-FUELED: AFRICAN FLEET	2.76E+00	N/A	2.38E-01	1.02E-03	1.02E-02	3.57E-02	Kilograms
PETROLEUM-BASED: LAT. AMER. FLEET	2.74E+00	N/A	2.75E-01	1.09E-03	1.09E-02	3.70E-02	Kilograms
HYDROGEN-FUELED VEHICLES	N/A	N/A	N/A	N/A	N/A	D/L	Cubic Meters
METHANOL-FUELED VEHICLES	N/A	1.16E+00	1.88E-01	3.33E-04	3.33E-04	2.88E-03	Kilograms
ETHANOL-FUELED VEHICLES	N/A	1.89E+00	D/L	D/L	D/L	D/L	Kilograms

Notes:
N/A = Not Applicable: Emissions zero by definition or likely very near zero.
D/L = Data Lacking: Emissions are probably non-zero, but no emission factors are available.

TABLE 4.5: COMPILATION OF GHG EMISSION FACTORS USED IN THIS STUDY: TRANSFORMATION SOURCES

(KG/FUEL UNIT INPUT, UNLESS NOTED)

EMISSIONS SOURCE	CO_2 Non-Biogenic	CO_2 Biogenic	CO	CH_4	HC	NO_x	FUEL UNIT
ELECTRICITY GENERATION							
COAL-FIRED BOILERS	2.71E+00	N/A	4.00E-04	1.85E-05	3.50E-05	1.05E-02	Kilograms
COAL-FIRED BOILERS, w/ SCRUB	2.71E+00	N/A	3.70E-04	1.85E-05	1.13E-04	5.23E-03	Kilograms
OIL-FIRED BOILERS (RESIDUAL OIL)	3.06E+00	N/A	6.10E-04	3.05E-05	2.11E-04	8.46E-01	Kilograms
NATURAL GAS-FIRED BOILERS	1.85E+00	N/A	6.63E-04	3.90E-06	2.25E-05	8.82E-03	Cubic Meters
BIOMASS-FIRED BOILERS	N/A	1.59E+00	2.35E-04	2.35E-04	6.99E-04	1.40E-03	Kilograms
OIL-FIRED (DIST) COMBUST. TURBINES	3.14E+00	N/A	2.12E-03	2.88E-05	6.58E-04	9.35E-03	Kilograms
NATURAL-GAS COMBUST. TURBINES	1.85E+00	N/A	1.13E-03	2.07E-04	2.02E-04	6.63E-03	Cubic Meters
COMBINED CYCLE: COAL-FUELED	2.71E+00	N/A	D/L	1.85E-05	2.20E-05	7.45E-03	Kilograms
IGCC: COAL-FUELED	2.71E+00	N/A	2.58E-05	1.89E-05	3.79E-05	7.57E-04	Kilograms
COMBINED CYCLE: NATURAL GAS	1.85E+00	N/A	3.69E-04	3.19E-05	1.41E-04	1.32E-03	Cubic Meters
BIOMASS GAS (BIG STIG)	N/A	1.59E+00	2.52E-05	1.89E-05	3.79E-05	7.58E-04	Kilograms
FUEL CELLS: HYDROGEN-FUELED	N/A	N/A	N/A	N/A	N/A	D/L	Cubic Meters
FUEL CELLS: METHANOL-FUELED	N/A	1.45E+00	D/L	D/L	D/L	D/L	Kilograms
FUEL CELLS: NATURAL GAS-FUELED	1.85E+00	N/A	D/L	3.45E-05	3.81E-05	9.17E-06	Cubic Meters
FUEL CELLS: GASIFIED BIOMASS	N/A	1.59E+00	D/L	D/L	D/L	9.17E-06	Cubic Meters
FUEL CELLS: GASIFIED COAL	2.71E+00	N/A	D/L	D/L	D/L	9.17E-06	Cubic Meters
PETROLEUM REFINING							
EXISTING REFINERY, EFFIC. = 94%	1.82E-01	N/A	1.72E-04	1.20E-04	9.20E-04	7.20E-04	Kilograms
IMPROVED REFINERY, EFFIC. = 96.8%	9.70E-02	N/A	9.19E-05	6.40E-05	4.91E-04	3.84E-04	Kilograms
OWN USE OF FUEL IN TRANSFORMATION (Emissions/Unit Lost)							
OIL PRODUCTION INDUSTRY	3.03E+00	N/A	6.86E-04	3.69E-06	3.84E-05	7.55E-03	Kilograms
COAL PRODUCTION INDUSTRY	2.71E+00	N/A	2.50E-03	3.00E-05	3.50E-05	9.59E-03	Kilograms
NATURAL GAS PROD. INDUSTRY	1.85E+00	N/A	4.41E-03	5.49E-04	7.20E-04	2.97E-02	Cubic Meters
ALCOHOL FUELS (Emissions/Unit Prod.)							
METHANOL (BIOMASS), EXISTING TECH.	N/A	D/L	D/L	D/L	D/L	3.63E-04	Kilograms
ETHANOL (CORN), EXISTING TECH.	1.74E-02	1.05E+00	D/L	D/L	1.14E-02	4.60E-03	Kilograms
FUEL EXTRACTION (Emissions/Unit Prod.)							
COAL MINING OPERATIONS: U.S.	D/L	N/A	D/L	9.49E-03	D/L	N/A	Kilograms
COAL MINING OPERATIONS: EUROPE	D/L	N/A	D/L	1.43E-02	D/L	N/A	Kilograms
COAL MINING OPERATIONS: JANZ	D/L	N/A	D/L	8.67E-03	D/L	N/A	Kilograms
COAL MINING OPERATIONS: USSR	D/L	N/A	D/L	1.82E-02	D/L	N/A	Kilograms
COAL MINING OPERATIONS: CP ASIA	D/L	N/A	D/L	2.42E-02	D/L	N/A	Kilograms
COAL MINING OPERATIONS: S&E ASIA	D/L	N/A	D/L	1.48E-02	D/L	N/A	Kilograms
COAL MINING OPERATIONS: MID. EAST	D/L	N/A	D/L	9.58E-03	D/L	N/A	Kilograms
COAL MINING OPERATIONS: AFRICA	D/L	N/A	D/L	1.44E-02	D/L	N/A	Kilograms
COAL MINING OPERATIONS: LAT. AMER.	D/L	N/A	D/L	1.18E-02	D/L	N/A	Kilograms
OIL PRODUCTION: UNITED STATES	D/L	N/A	D/L	2.39E-03	D/L	N/A	Kilograms
OIL PRODUCTION: EUROPE	D/L	N/A	D/L	6.53E-04	D/L	N/A	Kilograms
OIL PRODUCTION: JANZ	D/L	N/A	D/L	2.42E-03	D/L	N/A	Kilograms
OIL PRODUCTION: USSR	D/L	N/A	D/L	2.91E-03	D/L	N/A	Kilograms
OIL PRODUCTION: CP ASIA	D/L	N/A	D/L	3.06E-03	D/L	N/A	Kilograms
OIL PRODUCTION: S&E ASIA	D/L	N/A	D/L	3.06E-03	D/L	N/A	Kilograms
OIL PRODUCTION: MIDDLE EAST	D/L	N/A	D/L	1.39E-03	D/L	N/A	Kilograms
OIL PRODUCTION: AFRICA	D/L	N/A	D/L	3.86E-03	D/L	N/A	Kilograms
OIL PRODUCTION: LATIN AMERICA	D/L	N/A	D/L	3.58E-03	D/L	N/A	Kilograms
NATURAL GAS PROD.: GLOBAL AVG.	D/L	N/A	D/L	2.18E-03	D/L	N/A	Cubic Meters
TRANSMISSION & DISTRIB. LOSSES (Emissions/Unit Lost)							
NATURAL GAS TRANS. & DISTRIB.	N/A	N/A	N/A	5.72E-01	6.28E-01	N/A	Cubic Meters
PETRO. PRODS. DISTRIB. AND TRANS.	N/A	N/A	N/A	5.00E-02	1.00E+00	N/A	Kilograms

• SCR = Selective Catalytic Reduction, a type of emissions control device.

As touched on briefly above, the international pool of GHG emission factors could stand to be widened, deepened, and standardized considerably. In many cases emission factors used for entire classes of fuel-consuming devices are derived from the results of a few empirical tests on a few specific types of devices. Often, the data quality of these test results is not as high as would be desirable. It would be helpful to have a coordinated international effort to substantially accelerate emissions testing, both in industrialized and developing countries,and to compile test results in a standardized format available to all countries and researchers. Another form of standardization would be for countries and researchers conducting greenhouse gas accounting and scenarios formulation to agree on protocols and emission factors for compiling greenhouse gas loadings estimates. Processes now in progress under the auspices of the Intergovernmental Panel for Climate Change (IPCC) and the OECD[19] are geared, in part, to accomplishing this goal.

The available technologies for reducing greenhouse gas emissions vary with the greenhouse gas species considered. For carbon dioxide, the principle methods of reducing non-biogenic emissions are to use fossil fuels more efficiently, switch to fuels that produce less non-biogenic CO_2 per unit energy, switch to renewable fuels, or, preferably, a combination of these

TABLE 4.6

CARBON DEMAND ENERGY CONTENT ASSUMPTIONS, AND CO_2 EMISSIONS PER UNIT ENERGY[b]

FUEL	CARBON CONTENT	ENERGY CONTENT[c]	kg CO_2/GJ
NATURAL GAS	0.51 kg/m3	0.03545 GJ/m3	52.8
GASOLINE	84.6% by wt	43.96 GJ/tonne	70.6
KEROSINE/JETFUEL	85% by wt	43.2 GJ/tonne	72.1
DIESEL/GAS OIL	86.5% by wt	42.5 GJ/tonne	74.6
RESIDUAL/FUELOIL	84.4% by wt	41.5 GJ/tonne	74.6
LPG/BOTTLED GAS	82% by wt	45.54 GJ/tonne	66.0
CRUDE OIL	83.5% by wt	41.87 GJ/tonne	73.1
COAL BITUMINOUS	74.6% by wt	29.31 GJ/tonne	93.3
COAL LIGNITE	31% by wt	11.3 GJ/tonne	100.6
FIREWOOD	43.8% by wt	16 GJ/tonne	100.4
ETHANOL[a]	52.2% by wt	0.0219 GJ/l	110.8
METHANOL[a]	40% by wt	0.0168 GJ/l	109.7
HYDROGEN	none	0.0108 GJ/m^3	0.0

a Ethanol and Methanol carbon contents converted to CO_2/GJ using densities of 0.789 and 0.796 kg/l, respectively.

b This table shows only gross CO_2 emissions from fuel consumption, and does not include CO2 impacts from fuel production (e.g., hydrogen from coal).

c Based on net or lower heating values.

techniques. All of these policies are considered in the scenarios described in the following sections of this report. While there are technologies under development for capturing CO_2 (Blok et al, 1991) from the exhaust gases of combustion equipment or for pre-processing fuels to remove carbon, these technologies are not considered here, as discussed in Section 1.

19 The OECD, in February 1991, hosted a "Workshop on Emissions Methodology". Preparations for this workshop included a Background Document that proposed emission factors and estimation protocols for GHG emissions from the major anthropogenic sources, including energy-sector emissions.

As with carbon dioxide, emissions of carbon monoxide, methane, and hydrocarbons per unit energy services provided can be reduced through efficiency improvements and fuel-switching. In addition, emissions of these gases from existing equipment can be reduced by optimizing combustion conditions and by proper maintenance of fuel consuming devices. For example, older automobiles on average typically produce much higher emissions of CO and HC per mile as they age, partially due to neglected maintenance. In addition, new equipment can be designed so as to both burn the fuel more cleanly and to trap pollutants, via various types of control equipment, before they reach the atmosphere. As an example of the effectiveness of these measures, emissions of CO and HC from new U.S. cars are roughly 10-fold lower than for 20-year old cars in the U.S. fleet.

Nitrogen oxides are produced virtually any time a fuel is combusted in air, but technologies exist that can reduce NOx emissions from new and existing equipment. Some of these technologies act to reduce the amount of NO_x formed during combustion ('low-NO_X burners') by modifying combustion conditions, and others (e.g. Selective Catalytic Reduction for power plants) trap NO_X or convert it to other nitrogen compounds.

Emissions of greenhouse gases from fuel extraction, transmission, and distribution facilities can be reduced by improving and maintaining equipment, such as finding and fixing leaks in natural gas transmission pipelines, or by technologies that capture greenhouse gases before they reach the atmosphere such as 'gob wells', which are drilled into coal-bearing rock formations to remove trapped methane from coal seams before it is released during mining. As with other greenhouse gas emissions, however, the most reliable reduction path is to simply consume less fuel.

The reader should note that at present the effects of current and future emission reduction technologies for non-CO_2 pollutants have not been fully included in this study, therefore our future estimates, as shown in Table 5.4, are likely to be high. Our emphasis here is on CO_2 emissions.

Section 5: Scenario Results

5.1 Fossil Free Energy Scenario

The findings of the *Fossil Free Energy Scenario* (FFES) indicate that a combination of efficiency improvements, renewable energy technologies, and fuel switching, could achieve significant long-term reductions in CO_2 emissions. As shown in Figure 5.1, annual CO_2 emissions peak around the year 2000, and decline to 48 percent and 29 percent of current global levels by 2030 and 2075 respectively, before reaching the target of zero net CO_2 emissions by 2100. The initial rise in CO_2 emissions reflects the momentum of current energy use patterns, the embedded stock of energy-inefficient equipment, and the time required to effect large shifts in fuel and technology choices throughout the world. The scenario roughly achieves the 20 percent reductions among industrial nations by 2005 called for by the 1988 Toronto Conference. Nearly all industrialized countries have already pledged to either stabilize or lower emission levels by that time. In the scenario reported here, CO_2 emissions from 1988 to 2000 decline by 3-12 percent in industrialized regions, while increases in developing regions from 21 percent in Latin America to 55 percent in South and East Asia, lead to a 6 percent overall increase in CO_2 emissions.

Between 2000 and 2010, the effects of technology improvements begin to outweigh the underlying forces of economic and population growth, and global CO_2 levels begin to decline. Reductions in all industrialized regions offset continued increases in all developing regions. Beyond 2010, emission levels decline in all regions, as the current stock of energy consumption and production equipment turns over, and high efficiency end-use and electricity generation technologies are widely implemented. Reduced dependence on coal and modest levels of renewable fuels and electricity further contribute to CO_2 savings; the contribution of fuels to total delivered energy is shown in Figure 5.2.

By 2030, a new generation of lower-cost renewable supply technologies provide a cleaner, low-CO_2 mix of fuels and electricity. Over the longer-term, the transition to a solar and biomass-based energy system, as illustrated in terms of primary energy supply in Figure 5.3, leads to the complete reduction of energy-related carbon dioxide emissions by 2100[1].

Estimated cumulative global CO_2 emissions from 1988 to 2100 amount to 314 (Pg C), as shown in Table 5.1. The climatic implications of these emissions are discussed in Section 9. Emissions from the five industrialized regions account for 53 percent (165 Pg C) of these cumulative emissions, over 70 percent (118 Pg C) of which occur by 2030. Thus, despite high levels of economic growth in the South, the North remains the major contributor to CO_2 emissions overall, and particularly in the near and medium term. Accelerating the adoption of emission reduction measures in industrialized countries would appear the most important area for additional improvements, even under the improved equity assumptions of this scenario. Concern over the rate of emissions during the next few decades and resulting warming adds to the importance of additional near and medium-term reductions.

The emission trajectory shown in Figure 5.1 may appear ambitious in its reductions, yet it is marked by numerous and substantial `conservatisms', suggesting that CO_2 emissions and energy and resource requirements could actually be far lower. These conservative

1 All remaining fuel oxidation, the process whereby CO2 is formed, either converts hydrogen (H2) to water (H2O), or biomass carbon (C) to carbon dioxide (CO2). In both cases the water and carbon dioxide are cycled back in the process of fuel production: solar/wind electrolysis for hydrogen production and biomass regrowth.

Figure 5.1
Carbon Dioxide Emissions by Region (Pg C)

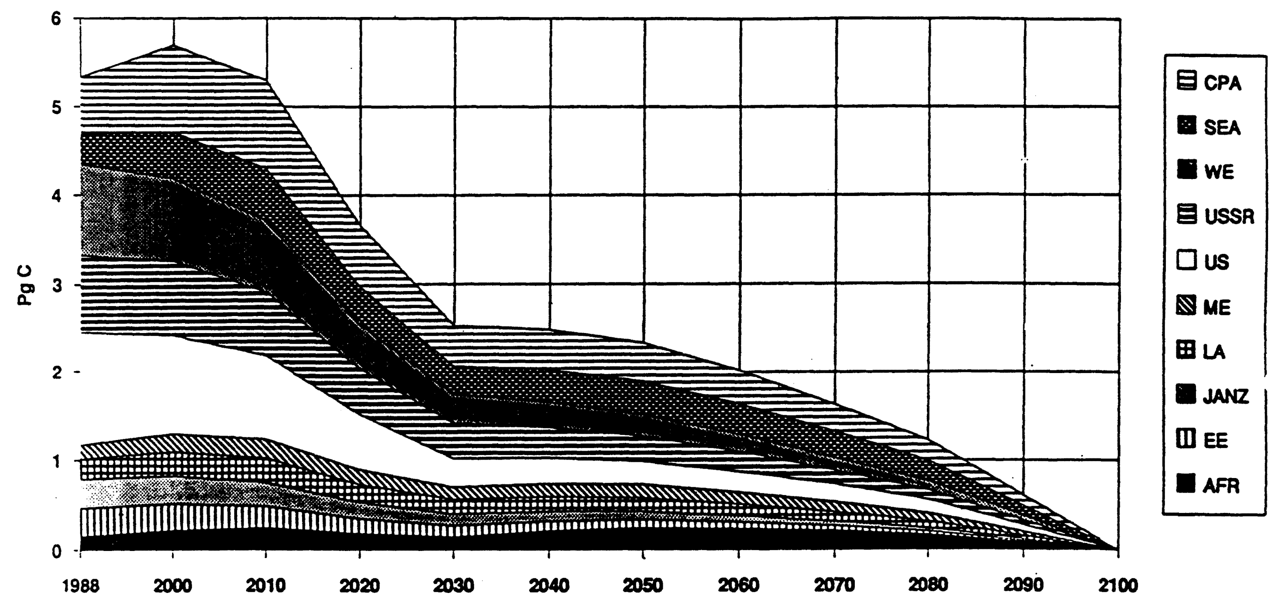

Figure 5.2
Delivered Energy Consumption by Fuel: 1988-2100

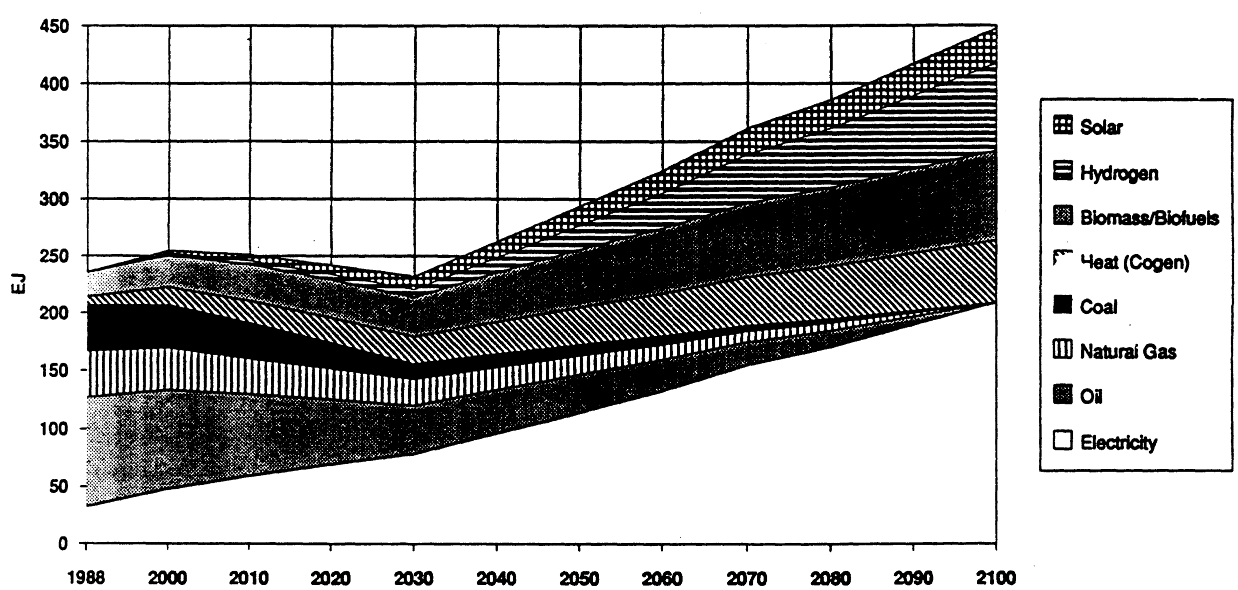

Table 5.1
Carbon Dioxide Emissions by Region: 1988-2100
(Pg Carbon)

	1988	2000	2010	2020	2030	2040	2050	2075	2100	Estimated Cumulative 1988-2100
AFR	0.16	0.23	0.26	0.19	0.16	0.22	0.26	0.22	0.00	22
CPA	0.65	0.98	1.00	0.69	0.46	0.46	0.43	0.28	0.00	55
EE	0.31	0.29	0.24	0.16	0.12	0.10	0.09	0.04	0.00	14
JANZ	0.32	0.30	0.25	0.18	0.13	0.11	0.09	0.04	0.00	14
LA	0.22	0.27	0.28	0.20	0.17	0.17	0.15	0.10	0.00	18
ME	0.16	0.20	0.21	0.17	0.14	0.15	0.15	0.11	0.00	15
SEA	0.34	0.53	0.59	0.44	0.32	0.37	0.38	0.29	0.00	39
US	1.28	1.13	0.97	0.65	0.33	0.30	0.28	0.21	0.00	53
USSR	0.88	0.85	0.73	0.52	0.40	0,34	0.28	0.14	0.00	43
WE	1.01	0.90	0.74	0.50	0.33	0.28	0.24	0.12	0.00	42
TOTAL	5.34	5.68	5.26	3.69	2.55	2.50	2.35	1.56	0.00	314
North	3.81	3.47	2.92	2.01	1.31	1.14	0.97	0.55	0.00	165
South	1.53	2.21	2.33	1.69	1.24	1.36	1.38	1.01	0.00	148

Percent Reduction of Carbon Dioxide Emissions in Comparison with Base Year Emissions

	1988	2000	2010	2020	2030	2040	2050	2075	2100
AFR		-45%	-62%	-21%	2%	-40%	-64%	-41%	100%
CPA		-51%	-53%	-6%	29%	30%	33%	57%	100%
EE		6%	24%	47%	61%	67%	72%	86%	100%
JANZ		7%	24%	45%	61%	66%	73%	87%	100%
LA		-21%	-23%	10%	24%	26%	32%	56%	100%
ME		-26%	-34%	-5%	14%	7%	5%	31%	100%
SEA		-55%	-74%	-28%	6%	-8%	-13%	14%	100%
US		12%	24%	49%	74%	76%	79%	84%	100%
USSR		3%	17%	41%	55%	61%	68%	84%	100%
WE		11%	27%	51%	68%	72%	76%	88%	100%
		-6%	2%	31%	52%	53%	56%	71%	100%
North		9%	23%	47%	66%	70%	74%	86%	100%
South		-44%	-52%	-10%	19%	11%	10%	34%	100%

Table 5.2

Primary Energy Supply, 1988-2100
(EJ)

Source	1988	2000	2010	2030	2100
Oil	116 *(34%)*	112 *(28%)*	93 *(23%)*	59 *(15%)*	0 *(0%)*
Coal	93 *(27%)*	93 *(23%)*	85 *(21%)*	28 *(7%)*	0 *(0%)*
Natural Gas	65 *(19%)*	96 *(24%)*	105 *(26%)*	57 *(15%)*	0 *(0%)*
Hydro/Geothermal*	23 *(7%)*	26 *(7%)*	28 *(7%)*	30 *(8%)*	28 *(3%)*
Biomass**	22 *(7%)*	38 *(10%)*	52 *(13%)*	91 *(24%)*	181 *(18%)*
Solar/Wind*	0 *(0%)*	20 *(5%)*	36 *(9%)*	118 *(31%)*	778 *(79%)*
Nuclear*	19 *(6%)*	12 *(3%)*	0 *(0%)*	0 *(0%)*	0 *(0%)*
Total	338	396	400	384	987

*Solar, wind, hydro, geothermal and nuclear energy converted from electricity to primary energy using then-current average fossil/biomass plant efficiencies (see Explanatory Notes following Section 10).

**Note that 1988 biomass figures reflect UN estimates (UN, 1990) and may be low by a factor of 2 (see Hall, 1991).

assumptions are summarized in the text box on page 45. Major elements of the *Fossil Free Energy Scenario* are described below .

Improved end-use energy efficiency in residential, industrial, transport and service sectors, *accounts for the major source of emissions reductions between now and 2030*. For the period beyond 2030, we assume smaller improvements in end-use efficiencies. As illustrated in Figure 5.2, total delivered energy rises from 236 EJ in 1988 to 255 EJ in 2000, and then decreases to 232 EJ by 2030, before increasing again to 448 EJ in 2100. The dip in energy use from 2010 to 2030, followed by a subsequent rise for the remainder of the scenario, largely results from strong efficiency improvements prior to 2030 that outweigh the dual forces of growing economies and population for a brief period of time. Beyond 2030, we assume much slower rates of efficiency improvement. As a result, continued economic and population growth in the South leads to growing energy requirements.[2]

The levels of end-use efficiency improvements included in this scenario are based upon current assessments of economic and technical potential: levels based on market or near-market technologies that can be implemented within 40 years. Beyond 2030, our more conservative estimates (0.5 percent annual efficiency improvement for most end uses) could well be overly pessimistic. If so, the doubling in delivered energy from 2030 to 2100 could be avoided.

Improved efficiency on the supply side, including the more efficient use of fossil fuels for electricity production (e.g., combined cycle and fuel cell systems), refinery improvements, and reduced transmission and distribution losses, provide important contributions to reducing emissions over the next 40 years. This also includes the overall efficiency gains offered by on-site and centralized combined heat and power generation (cogeneration). After 2030, approximately 20 percent of global electricity demand is supplied from centralized and on-site cogeneration.

Fuel switching from coal and oil to natural gas, also plays an important role in reducing emissions in the near and medium term (to 2030). Estimates were made for each region regarding the ability to switch to lower carbon fuels, based on the availability of fossil fuel supplies, particularly natural gas, and end-use considerations. The resulting primary energy shares are shown in Table 5.2. For regions heavily dependent on coal, with limited supplies of natural gas and other fuels, coal continues to account for an important but declining share of primary supply. For example, in Centrally Planned Asia, coal use drops from 72 percent of primary energy in 1988, to 51 percent in 2010, and to 22 percent in 2030. Globally, coal and oil use declines from 27 and 34 percent of total primary energy supply in 1988, to 21 and 26 percent by 2010, and 7 percent and 15 percent, respectively, by 2030. Meanwhile, the share of natural gas rises from 19 to 26 percent from 1988 to 2010, before dropping to 15 percent in 2030. The adequacy of natural gas reserves is discussed further in Section 7.3.

A major transition to solar and biomass sources of energy, as illustrated in Figure 5.3, *accounts for most emission reductions after 2030*. Over the next 40 years, several renewable sources play an important role, including biofuels for transport, wind energy for electricity, and various cost-effective applications of solar technologies. After 2010, more rapid penetration of low-carbon systems begins as the current stock of technologies turns over,

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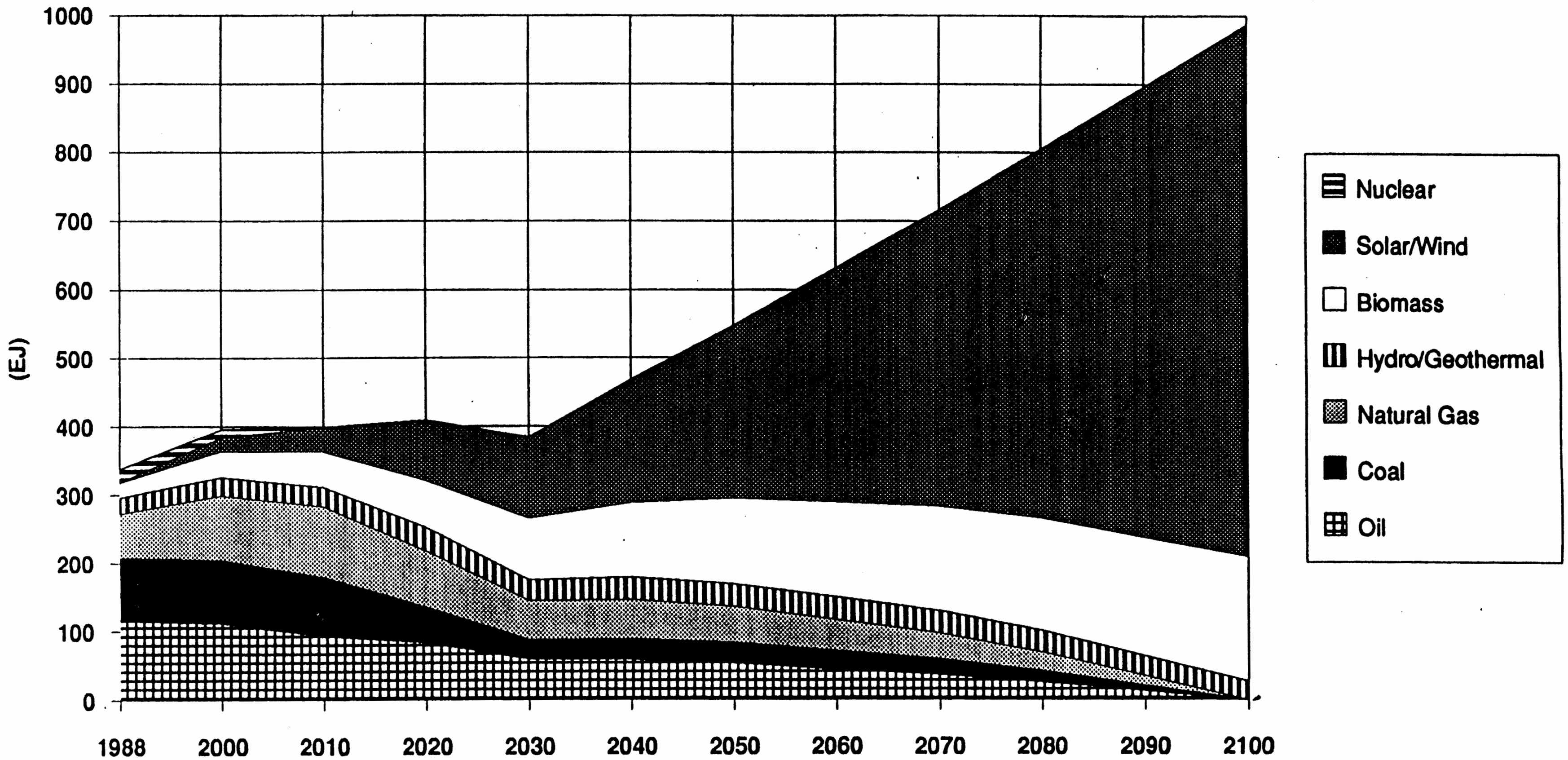
2 The dip in global energy consumption and primary supply from 2000 to 2030 and subsequent rise is largely an aggregate result not observed in the 10 individual study regions. In all northern regions, energy use continues to drop from 2000 through 2100. In all southern regions with the exception of CPA, energy use rises continuously throughout the 1988-2100 period. Continued growth in global energy demand and primary energy supply beyond the year 2100 is a reflection of the assumptions made in the study on economic growth, the type of economic growth, and population levels.

Figure 5.3

Primary Energy Supply Mix: 1988-2100



Solar, wind, hydro, geothermal and nuclear energy converted from electricity to primary energy using then-current average fossil/biomass plant efficiencies (see explanatory notes).

Major 'Conservatisms' of the Fossil Free Energy Scenario(FFES)

Continued high population growth, despite increasing equity. There are many indications that improved economic well-being can lead to declining population growth, for reasons enumerated in Section 4.3.3. Nonetheless, we have maintained the World Bank population estimates that do not reflect these considerations for the purposes of comparing this study to others. If, instead, we were to assume lower population consistent with improved equity, energy use and CO_2 emissions would decline in rough proportion to population (see section 5.2 for population variant results).

Limited efficiency improvements beyond 2030. We assume a maximum of 0.5 percent per year for energy intensity reductions after 2030. With this assumption, delivered energy requirements grow from 232 EJ in 2030 to 448 EJ in 2100. However, if the higher rates of energy intensity reductions assumed for the 1988-2030 period were to continue indefinitely, delivered energy would drop throughout the 2030-2100 period. Continued technological developments (or lifestyle and infrastructure changes) could enable continued reductions in the energy required to provide end-use services well beyond the low 2030-2100 levels estimated here. For example, advanced fluorescent lamp technologies (e.g. "two-photon" phosphors and electrodeless lamps) could potentially decrease energy requirements for lighting to less than half the level in the FFES scenario (McGowan, 1989).

Land use requirements for solar and biomass assume no major breakthroughs in solar collection efficiency or biomass yields. The biomass yields adopted in the study are below those already occurring in some countries, and significantly below those assumed in other studies (eg. US EPA , 1990b). The reported land use requirements could be significantly reduced with advancements in solar technologies and biomass methods (see table 7.3).

Commercial sector energy use is likely overestimated. Data limitations led to the use of GDP rather than floor space as the driving variable for energy use. While floor space is a better correlate of energy use, adequate regional floor space data were not available. Since GDP will tend to grow faster than floor space, the use of GDP will tend to overestimate energy use.

No improved efficiency credit is taken for switching from direct use of fossil fuels to electricity in the commercial and industrial sectors. Switching from fossil fuels to electricity can entail significant reductions in energy intensity. However, due to the difficulty in assessing the appropriate credit for electrification (due to high levels of data aggregation and uncertainty regarding interaction with our efficiency improvement assumptions), we assumed that 1 joule of electricity would be required to substitute for 1 joule of fuel. One study has estimated that electricity can substitute 20 percent of current coal and oil use in U.S. industry at a rate of 1 joule of electricity for every 3 joules of fuel. (Ross, 1991). Another study indicates even higher fuel savings from electrification for an average of 11 industrial electric technologies. Since these savings were not incorporated in our analysis, our industrial and other sector electricity consumption - and thus, our near-term CO_2 emissions and long-term solar and biomass requirements - are likely overstated.

Other conservative assumptions include **high levels of energy-intensive (e.g., steel and cement) production** given the potential for substitution of high quality, low energy intensity, advanced materials (e.g. ceramics and composites), the **omission of ocean and wave energy, and hot dry rock geothermal energy,** and the **exclusion of waste incineration,** the **down-grading of the potential of hydro,** and the **exclusion of new geothermal resources.**

emerging technologies mature, and appropriate infrastructures are established. By the mid 21st century, solar and wind energy systems begin to account for the largest share of primary supply. The scenario encompasses a diversity of renewable supply sources including high-efficiency biomass gasification, agricultural residue-based cogeneration systems, hydrogen and biofuels as fossil fuel substitutes for vehicular and other uses, and direct solar thermal applications. Due to continuing growth in population and income, energy demand continues to grow through the end-year of this study, suggesting the importance of continuing efficiency improvements, and the need to develop policies that achieve alternative economic and development goals and lower population levels.

Land use considerations impose limits to the maximum penetration of biomass energy sources. Biomass energy -- delivered in the form of biofuels and electricity -- could require as much as 120-380 million hectares worldwide to provide 91 EJ (or 24 percent) of 2030 primary supply. This requirement compares with 8.7 billion hectares of current combined crop, pasture, forest and wood land area and 13 billion hectares of global land area. In comparison, solar and wind collection, which accounts for 118 EJ (fossil equivalent) or 31 percent of 2030 primary supply, would likely require less than 15 million hectares from land surface areas (arid areas, rooftops, etc.) that may pose fewer conflicts. By 2100, the biomass energy supply and land use requirements roughly double their 2030 levels to 181 EJ, implying land use of 290-720 million hectares, and could be of greater concern than the estimated 50-110 million hectares required for solar and wind. The high estimates assume no breakthroughs in biomass yields or solar capture efficiency (e.g., 15 percent efficient photovoltaics), and thus are conservatively high. In addition, as pointed out in the adjoining text box, 2100 electricity requirements are likely to be overstated, and as noted in Section 7, storage requirements may be as well, suggesting significantly lower solar and wind electric requirements (see tables 7.2, 7.3 and 7.9 for further details). It is also important to note, however, that a coal and oil shale based future would also present high land use requirements, and more destructive environmental impacts. (Pasqualetti, 1984; Gipe 1991)

Because of the potentially high water and fertilizer requirements, and possible impacts on biodiversity of very high-yielding biomass species, we assumed lower than potentially achievable biomass yields for this study. Where possible, low or zero artificial input biomass farming should be a goal. Land availability for biomass energy will depend on the ability of improved agricultural productivity, and the recycling and reduction of wood and paper products (thereby reducing land use for commercial wood), to reduce competition for suitable land[3].

The CO_2 emission reductions are achieved in a world in which differences between regions are greatly reduced. What effect do these reduced economic differentials have on our results? First of all, as described in Section 4, we redistributed future GDP growth among regions, but did not alter the total GDP relative to IPCC forecasts. The scenario developed by US EPA (RCWR) (see table 5.3) has demonstrated that it is possible to significantly reduce carbon dioxide emissions even where large economic disparities remain between North and South. As is discussed elsewhere however (see Section 5.1.1), there are serious environmental implications in relation to land-use associated with the development of large biomass-for-energy plantations in this scenario.

The FFES effectively redistributes emissions among regions, arguably in a more globally acceptable manner, but does not, by itself, change the total global emissions relative to a less equitable world. This result may appear counter-intuitive, but it is a conclusion shared

3. A 1991 workshop on ecological guidelines for large-scale biomass energy development concluded that: "land appropriate for plantations from an ecological perspective is abundant. Degraded land is abundant, especially in the tropics"(pp3-5, National Audubon Society, 1991).

Table 5.3
Summary Comparison of Results

	1988	2000	2010	2030	2100
Fossil Free Energy Scenario					
CO2 (Pg C)	**5.3**	**5.7**	**5.6**	**2.6**	**0.0**
Global GDP (Billion 1985 US$)	$16,351	$23,451	$30,116	$41,771	$212,863
Delivered Energy (EJ)	236	255	251	232	448
Primary Energy (EJ)***	338	396	400	384	987
From Renewables (%)	*13%*	*21%*	*29%*	*62%*	*100%*
From Solar/Wind (%)	*0%*	*5%*	*9%*	*31%*	*79%*
*From Biomass (%)*****	*7%*	*10%*	*13%*	*24%*	*18%*
Primary Energy/CO2 (kJ/g)	64	69	71	148	-
Energy/GDP (kJ/$)	21	17	13	9	5
CO2/GDP (Tg/$)	0.32	0.24	0.19	0.06	0.00
IPCC91: Reference Case*					
CO2 (Pg C)	**5.9**	**7.3**	**9.4**	**12.8**	**22.5**
Global GDP (Billion 1985 US$)	$18,340	$24,858	$32,781	$56,466	$255,103
Delivered Energy (EJ)			Not Yet Available		
Primary Energy (EJ)	349	460	571	797	1641
From Renewables (%)					
From Solar/Wind (%)			Not Yet Available		
*From Biomass (%)*****					
Primary Energy/CO2 (kJ/g)	60	63	61	62	73
Energy/GDP (kJ/$)	19	18	17	14	6
CO2/GDP (Tg/$)	0.32	0.29	0.29	0.23	0.09
EPA: Reference Case (RCW/SCW avg.)**					
CO2 (Pg C)	**5.1**	**6.6**	**7.7**	**9.9**	**17.7**
Global GDP (Billion 1985 US$)	$15,520	$22,532	$29,242	$49,427	$238,395
Delivered Energy (EJ)	239	288	333	420	639
Primary Energy (EJ)	302	384	451	585	1067
From Renewables (%)	*7%*	*8%*	*10%*	*13%*	*19%*
From Solar/Wind (%)	*0%*	*0%*	*1%*	*2%*	*7%*
*From Biomass (%)*****	*0%*	*0%*	*1%*	*3%*	*5%*
Primary Energy/CO2 (kJ/g)	59	58	58	59	60
Energy/GDP (kJ/$)	19	17	15	12	4
CO2/GDP (Tg/$)	0.33	0.29	0.26	0.20	0.07
EPA: "Rapid Reductions" (RCWR)**					
CO2 (Pg C)	**5.1**	**5.5**	**4.5**	**2.5**	**1.5**
Global GDP (Billion 1985 US$)	$15,520	$24,758	$34,130	$64,448	$380,813
Delivered Energy (EJ)	232	249	284	346	471
Primary Energy (EJ)	302	334	408	545	799
From Renewables (%)	*7%*	*10%*	*38%*	*68%*	*77%*
From Solar/Wind (%)	*0%*	*1%*	*2%*	*4%*	*9%*
*From Biomass (%)*****	*0%*	*0%*	*26%*	*54%*	*58%*
Primary Energy/CO2 (kJ/g)	59	61	92	216	533
Energy/GDP (kJ/$)	19	14	12	8	2
CO2/GDP (Tg/$)	0.33	0.22	0.13	0.04	0.00

Source: Lashof and Tirpak (1990), IPCC (1991)

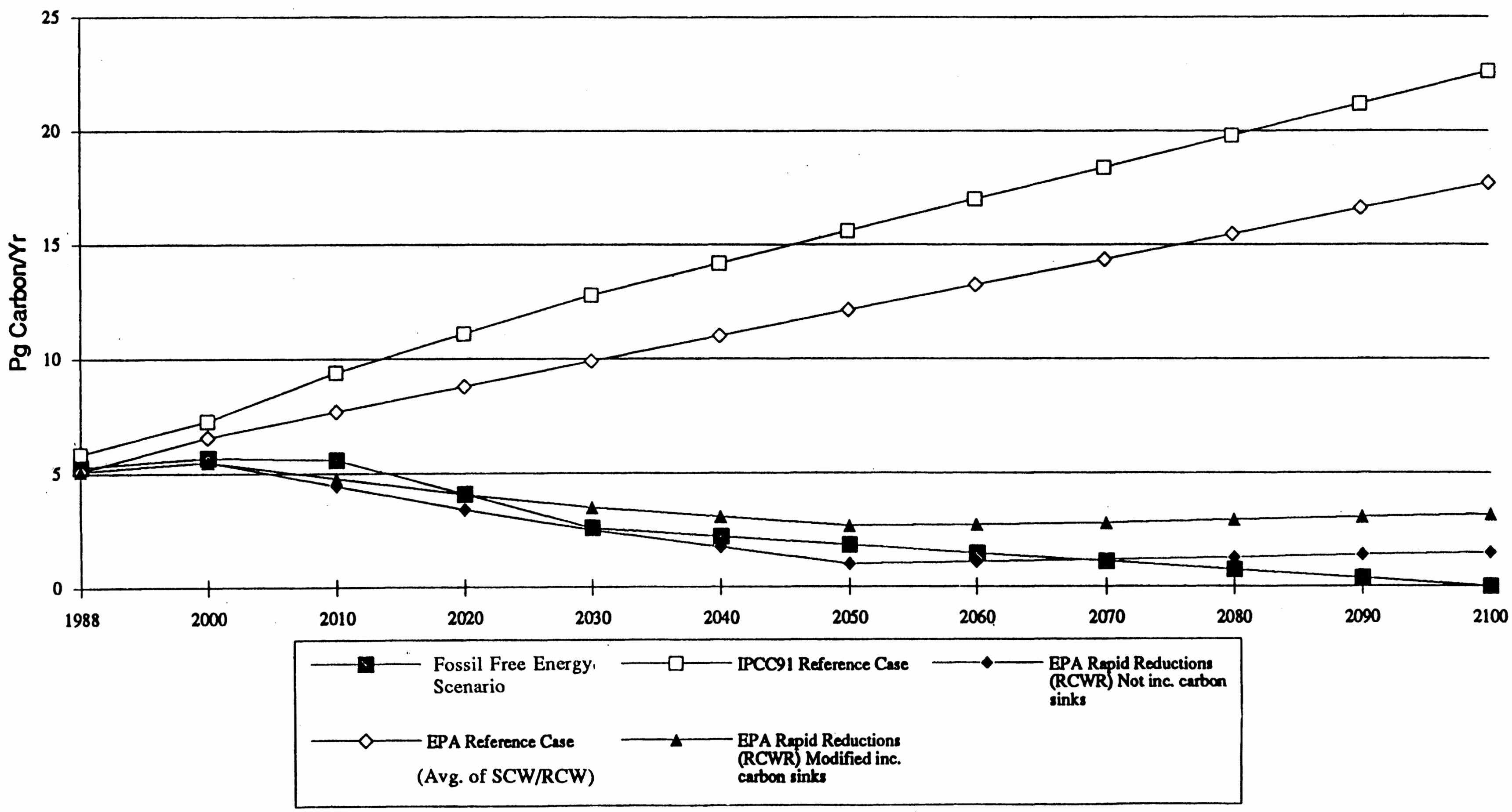
* For the IPCC scenario, the values shown are for 1990, not 1988.

** For the U.S. EPA and IPCC, the 1988, 2010, and 2030 values were interpolated based on 1985, 2000, 2025, and 2050 results.

*** Primary energy totals include traditional biomass fuels.

**** Note that 1988 biomass estimates reflect UN estimates (UN, 1990) and could be low by a factor of 2 (See Hall, 1991).

Figure 5.4 : Summary Comparison of Results



also by Mintzer (Mintzer, 1992) in a global scenario that, like the FFES, increases economic equity between North and South, and achieves significant CO_2 reductions. In this scenario, average rates of GDP growth in the North up to 2075 are between 2 to 3 percent per year, while those in the South are between 5 to 6 percent per year. Mintzer notes that his scenario is based on "economic growth in the developing world (which) is not principally directed towards export markets but instead is aimed at meeting basic human needs and building capital infrastructures in the rural areas of each country. This pattern of development is assumed to be facilitated by a program of technology transfer and development assistance from the industrialised world..".

A truly equitable world would yield a far different set of economic infrastructures, energy supply systems, and individual energy use patterns compared to today. For a given level of global population in an equity-based world it is likely that:

1) more efficient industrial infrastructures would evolve, and that structural shifts to less energy-intensive manufacturing and service sector activities would be more pronounced during the 21st century among the currently developing countries.

2) efficient, renewable-based supply systems would develop more rapidly, given greater financial means for technology transfer and local development. In addition, one could expect the reduction of large agricultural surpluses, linked to increases in agricultural productivity to free up more land for biomass energy production.

3) rising incomes would lead to greater personal consumption levels. In the household sector, we reflect this in a rapid transition away from traditional fuels in developing countries and a full penetration of household amenities (running hot water, refrigeration, lighting, washing machines, etc.).

Without a rapid transition to energy-efficient technologies, rapid economic growth in developing countries based on fossil fuels and energy-inefficient technologies would make climate stabilization impossible. Conversely, without rapid economic development and strong policy measures in developing countries, the ability to adopt innovative technologies and implement efficiency improvements could be undermined, also increasing the likelihood for unacceptable levels of global warming. Several of the US EPAs scenarios (Rapidly Changing World; Rapidly Changing World with Policies) turn over capital goods more quickly due to higher and faster economic growth, and hence more efficient and lower-polluting equipment comes into the global economy earlier. However the higher level of economic activity means that emissions of all greenhouse gases are higher than in the Slowly Changing World scenarios.

5.1.1 Comparison of Results

Table 5.3 and Fig 5.4 compare the results of the *Fossil Free Energy Scenario with the two IPCC and EPA reference case scenarios, and the EPA's lowest CO_2 emission scenario, Rapidly Changing World with Rapid Reductions* (RCWR). Comparison with the two reference cases indicates significant reductions in delivered energy and CO_2 emissions throughout the time horizon considered. In the FFES, primary energy requirements are only 8 percent lower than the EPA (RCW/SCW) reference case in 2100, while delivered energy requirements are 30 percent lower. This difference is largely a reflection of differences in the supply mix, including higher electrification and solar/wind use in the FFES scenario[4]. However, CO_2 emissions are far greater in the RCW and SCW scenarios due to their heavy reliance on coal and oil shale in the longer term.

Although the RCWR scenario reduces CO_2 emissions more rapidly than the FFES scenario through 2030, there are three important distinctions to be made. First, the RCWR scenario relies far more heavily on biomass resources and, unlike the FFES, includes biomass carbon sinks in its calculations of total scenario emissions. The RCWR scenario depends on very high biomass yields to achieve the 294 EJ and 463 EJ supplied in 2030 and 2100. The RCWR scenario embodies assumptions of biomass yield improvements of 150 to 500 percent over current biomass plantations. The ecological implications of such high yield plantations are uncertain, but may be adverse; fertilizer and water use requirements could be very high. If the lower base biomass yield assumptions in the FFES were used, the land use requirement for the RCWR scenario would consume approximately 20 percent of global current crop, pasture, forest and woodland area by 2100. Second, the RCWR scenario assumes a growing contribution from nuclear energy throughout the study period (12 percent of primary supply in 2100 - equivalent to more than 1000 1GW nuclear reactors). Finally, as noted in Section 2, in the RCWR CO_2 emissions begin to rise after 2050, and coal and oil use are increasing as the scenario heads into the 22nd century.

5.1.2 Costs

Considerable evidence suggests that implementation of the measures in the FFES could be achieved at modest cost, or even at a net economic benefit relative to continuation with a business-as-usual world. Projections of renewable energy supply costs indicate that solar, wind, and biomass technologies could be close enough to those of fossil fuels to enable a transition to occur without major economic penalties (see Figure 7.1 and Table 7.5). Throughout Section 6, we point to specific efficiency improvements that have been shown cost-effective in a number of other studies. Major economic benefits in avoided electric capacity requirements could result from investments in efficient end-use technologies. The potential capital savings from the production and installation of compact fluorescent bulbs, as discussed below (See Section 6 box: 'Technological Leapfrogging'), provides one rather dramatic example. Furthermore, a full benefit analysis would include the avoided costs and capital requirements (e.g., dikes to stem coastal flooding) that would otherwise be needed to mitigate the impacts of global warming, if the world were to continue its current dependence on fossil fuels.

A recent global study for the U.S. Working Group on Global Energy Efficiency illustrates the potential capital savings that could accrue from greater penetration of efficiency improvements (Levine et al., 1991). The study compared an Efficiency scenario with Reference scenario over the 1985-2025 period, the latter based upon EPA's Rapidly Changing World scenario. The Efficiency case achieves 29 percent and 28 percent reductions in energy use and fossil fuel CO2, respectively. At the same time, the Efficiency scenario reduces cumulative 1985-2025 capital requirements from $7800 billion to $4100 billion (1990 U.S.$). In capital-constrained developing and Eastern Europe countries, efficiency investments could cut capital requirements in half (projected decrease from $4700 to $2300 billion), thereby freeing up important resources for further development.

Perhaps closest to reflecting the types of options -- renewable energy and energy efficiency -- and their levels of penetration shown here, is the *America's Energy Choices* study. (UCS et al., 1991) As noted in Section 4.2, this study found that a 70 percent reduction

4 The FFES scenario assumes a greater level of electrification by 2100 (47% of delivered energy in the FFES scenario vs. 20-30% in SCW and RCW, and 37% RCWR), explaining a large part of the difference between delivered and primary energy. The FFES scenario also includes significant losses associated with storage requirements for solar and wind. An equivalent fossil or biomass scenario would not require such storage losses, and its primary energy would thus appear lower. However, the limitations on the primary fossil and biomass resources are far greater than those of solar energy, again pointing to the problems associated with comparing primary energy figures.

in CO_2 emissions could be achieved in the USA with net cumulative savings of $2.3 trillion from 1990 to 2030 (3 percent real discount rate, other economic parameters in Appendix Table G-1).

A study of five of the largest Western European countries (France, FRG, Italy, Netherlands, and U.K.) found that CO_2 emissions could be reduced by 18-41 percent below 1985 levels by 2020 at a net energy cost savings of 13 to 27 percent relative to a European Community business-as-usual projection. (Krause et al., 1992) The annual savings by 2020 would be sufficient to provide each European resident with approximately $600 to $900 in savings (1989 U.S.$). A deeper CO_2 reduction, `Minimum Risk', scenario indicates that emissions could be reduced 58 percent below 1985 levels by 2020, with energy cost savings of 2 to 12 percent.

Most recently, a 'Renewables-Intensive Global Energy Scenario' analysis found that renewable energy could provide 60 per cent of global electricity and 25 percent of direct fuel use by 2025, and 40 percent of direct fuel use by 2050. This scenario reduced carbon dioxide emissions by 25 percent by 2050 from 1988 levels. On the basis of detailed technological and economic analysis for a wide range of renewable energy resources and technologies, the authors concluded that the scenario "could be achieved at no additional cost" (Johansson et al, 1993).

Taken together, these studies suggest the likelihood that the FFES could be achieved at low cost or even with net economic benefits. Section 8 summarises the results of an alternative modelling approach which provides some additional economic analysis (Waide, 1992b) and suggests that the FFES could be achieved at a cost equal to or less than 'business-as-usual'. A brief discussion on discount rates is in the abstract in Section 8.

5.1.3 Climate Impacts of FFES

The climate impacts of the FFES were estimated independently by Waide (1992a) and are summarized in the abstract in Section 9. Linked to assumptions on CFC phase-out and stabilisation of CH_4 and N_2O emissions, global temperature increase is limited to less than 1.5 °C above pre-industrial levels (at a 2.5 °C Climate Sensitivity), rates of temperature change are reduced to less than 0.1 °C per decade within 30 years, and sea level rise is limited to 20 centimetres.

5.2 Variants of the Fossil Free Energy Scenario

5.2.1 Alternative Patterns of Socio-Economic Development

The previous section described a scenario (FFES) that is based on a continuation of the basic consumption patterns of today's industrialized countries. Indeed, *the Fossil Free Energy Scenario (FFES)* presumes a massive expansion of this style of development to all regions, with a doubling of world population and an increase in the scale of the world economy to over 14 times its current level by 2100. The point of the scenario is to show the tremendous scope for reducing greenhouse gas emissions through better technologies, even with standard assumptions on population growth and the conventional model of industrial development.

However, how valid is the assumption of an indefinite expansion of contemporary industrialized lifestyles? The advantages of the industrial culture in material well-being, personal mobility, and social fluidity have also come at the cost of a reduced sense of community and work fulfilment, and have led to the immediate problems of environmental risk and inter-generational inequity.

These problems suggest that it is important to critically reflect on the conventional notion of modernization and industrial development, and seek modes of development that foster harmonization between human endeavour and nature in the context of ea more equitable world. These issues formed some of the most contentious discussions in the meetings prior to and during the 1992 Earth Summit in Rio, among governments and NGOs. Ways must be found for existing generations to live in a manner that does not disadvantage future generations by excessively consuming natural capital stocks or placing excessive pressure on global and regional ecosystems. Ways must also be found for the current inequities between and within countries to be significantly reduced.

The FFES includes some implied lifestyle changes. For example, the transport sector analysis by Walsh assumes some constraints on the role of cars, particularly within urban areas, implying the development of car-free city centres and a heavy emphasis on public transport. The residential sector analysis envisages very large improvements in the energy efficiency of buildings and related services and appliances. Though this can be substantially attained through technology switching, it is clear from the analysis of successful efficiency projects that good management of these newer technologies is crucial. Thus greater public involvement in the energy aspects of living is implied. Overall, however, the FFES does not rely upon substantial lifestyle shifts.

Underlying much of the current debate in industrialized countries is the question of the character of the `good life'. If over the next decades there is an evolution from an emphasis on consumerism, work, and individualism toward, leisure time and community, it could have significant impacts on settlement patterns, material flows, and technology. The transition to a culture where individuals measure their well-being more in terms of community, work fulfilment, and the quality of their environment, and less in terms of consumerism and possessions, would be a transition to a less material and energy-intensive way of living.

Such a shift would affect lifestyles and infrastructures, the wide range of activities and structures that make up our daily lives -- where and how much we work, how we transport ourselves, what kinds of houses we live in and how we design our cities. From the point of view of minimizing climate risk, such a social transition would be a welcome complement to the technological orientation of the FFES.

Furthermore, while the technological opportunities could well be sufficient to greatly reduce greenhouse gas emissions, as suggested by the FFES, their achievement will depend upon the timely development of effective policies and programs for technology dissemination and implementation. Can these delivery mechanisms be devised and deployed in time? This is the risk of putting all of the eggs in the technology basket.

In the developing countries, the question is not simply what 'lifestyle' changes might occur in a post-industrial economy, but whether or not the development model of the currently industrialized countries is the best path to follow. Although we have assumed that developing countries follow an OECD model of development, this is only one possibility. It may fail to allow poor people throughout the world to meet their aspirations and lead to serious problems of land-use conflict, resource and capital conflict, and maintenance of exploitative practices. Despite the rapid economic growth in many developing countries, the gap between rich and poor remains large. For example, during the 1980s, average GDP growth rates in Brazil were about 8 percent, while no significant narrowing of this gap took place.

Instead of following a pattern of development that brings developing countries into the global market and maintains high levels of materials consumption, countries could aspire to greater self-reliance and local sustainability. The data and experience of such approaches is however very limited and tends to be at a very local level, making it difficult to extrapolate the global, regional or even national implications. However, it is likely that a lower energy consumption would result, as the OECD model of development is an energy-intensive one.

There are a variety of ways in which the above considerations could alter scenario assumptions. The following sections are only suggestive of the types of changes that could be considered for each sector. In the long term, the sectoral changes could be part of a profound restructuring of urban areas (including changes in zoning regulations that permit more integration of work, living, and commercial areas, and alteration of transport services), agricultural practices, and personal time budgets. These suggestive changes are reflected through several broad variants. The impact of lower population, GDP, slower rates of energy efficiency improvement and higher solar and biomass efficiencies, are also assessed.

Residential and Services

In the residential and service sectors, more innovative building designs could aim closer to the no-energy or low-energy goal. Stronger penetration than assumed in the FFES of passive heating and cooling features, as well as on-site solar devices (PV panels and hot water) could further reduce other energy requirements. In addition to these technologies, alternatives to large, dispersed single-family housing, with its associated high per capita space and energy requirements, like co-housing, could gain more rapid and wide acceptance. Co-housing communities combine private homes and shared community spaces and facilities to gain the advantages of both.

Transportation

Personal transportation in urban areas could evolve to draw people out of their cars for both commuting and other short-trip requirements (shopping, entertainment). In the near term, the greater use of mass transit systems could become the norm. Then, more car-free zones and more modular work-home communities could increase the attraction of pedestrian and bicycle transport. No doubt some private motorized transport would continue in an alternative lifestyle scenario. But one can assume that smaller cars, e.g., electric cars, are used for short trips in urban and suburban areas. People might be willing to sacrifice some performance and interior space for the sake of less congestion, less pollution, and greater vehicle efficiency. Larger vehicles for short term use could still be available when needed.

The need for commuter transport services can be reduced by several factors: improved electronic media for conferencing; smaller, local companies handling local demands; and reduced work weeks. The shorter average work load is compatible with the overall reduction in product output in this scenario. Finally, goods transport could decrease as a higher percentage of food and agricultural products and other heavy products (building materials, etc.) are produced locally.

Industry

As in the Fossil Free Energy Scenario, we would expect that the industrial sector would move away from primary materials to more finished goods in an alternative scenario. But the amount and type of goods will vary. An emphasis on increased durability and modular design of manufactured products would reduce production requirements. Agricultural chemical production could decline as organic methods gain wider acceptance. Production of many industrial chemicals could be reduced as `clean production' technologies capture and reuse more chemicals on-site or substitute mechanical processes for chemical cleaning. In the primary materials sector, higher rates of materials reuse and recycling are possible. Finally, reduced military expenditures could reduce heavy manufacturing requirements.

The overall effect of the types of adjustments suggested here is to reduce average work loads; increase the time for leisure, hobbies, and craft production; and decrease the scale of economic output throughout the economy. The translation of an alternative lifestyle vision into quantitative end-use assumptions for driving energy requirements require a level of understanding of the interplay of consumption, behaviour, and production patterns that is beyond the scope of this analysis. However, we can explore the sensitivity of the scenario results to at least two sets of alternative macro-economic assumptions reflecting the downsizing of production and consumption that might accompany the value reorientation discussed above.

Variant 1 - 20 Percent Reduction in Overall Growth: We assume that the scale of the economy is reduced by 20 percent (with no changes in population growth), with proportionate reductions in energy demand in all sectors and all regions. This variant still implies a more than elevenfold growth in global economic activity from 1985 to 2100 (from 15 to 170 trillion 1985 US $).

Variant 2 - Shift from Materials to Services: The following is assumed:

1) reduced production in the five energy-materials industrial sub-sectors to reflect increased durability, demilitarization, organic agriculture (lowered needs for chemicals), and decreased material consumerism. In this sensitivity, we reduce target steel, chemicals, aluminum, and cement production levels by 40 percent from the levels in the *Fossil Free Energy Scenario*, with paper and pulp production levels down 20 percent. While the FFES materials targets already reflect some reduction from current OECD levels due to materials substitution and the achievement of infrastructure building, as discussed in Section 6.4.1, they do not consider the effect of changing consumption patterns as suggested here.

2) a shift of 20 percent of industrial sub-sector GDP to services (with its lower energy intensity - GJ/$ output) to maintain the same global GDP as the *Fossil Free Energy Scenario.*

3) a 20 percent decrease in household energy use to reflect co-housing and other more communal living arrangements (decreased floor space per capita; joint appliance usage etc.).

4) a 20 percent decrease in transport energy use to reflect concepts noted above.

The effect of these variants on final energy consumption, primary energy, and CO_2 emissions is shown in Table 5.5 and Fig 5.5 overleaf. Though primary energy demand falls 14 to 20 per cent relative to the main FFES, the overall reductions in cumulative CO_2 from the variants - 10 percent (*20 Percent Reduction*) and 6 percent (*Materials to Services*) respectively - appear small overall because much of the decline in energy consumption occurs over the long-run as the energy supply mix becomes increasingly less carbon-intensive. For instance, reducing driving distances has much less effect in terms of CO_2 once the vehicle stock is fuelled largely by alcohol or renewable-based electricity.

Three points are worth emphasizing regarding the importance of lifestyle and infrastructure changes. First, if the penetration of efficiency improvements and renewables is slower than was envisioned in the FFES, the CO_2 emissions would be correspondingly higher, as would the impact of the CO_2 reductions of the sensitivities. Thus, even if the FFES emphasizes a technology-oriented approach to reducing emissions, lifestyle and infrastructure changes provide an important insurance policy in the event that obstacles appear in the way of technology dissemination and implementation. Second, one of the major benefits of reduced long-term energy supply will be to lessen capital, land use and other requirements. Figure 5.2 shows energy supply requirements continuing to increase into the 22nd century in the FFES. Barring some dramatic new low-cost, low-impact, virtually unlimited energy resource, renewable resource constraints, most notably land requirements, will become increasingly important. Finally, lifestyle changes with more immediate impacts such as voluntary simplicity -- driving less, consuming less, etc. -- should be able to achieve greater short-term reductions than shown here. The possibilities, from low-tech to high-tech, are indeed boundless and this cursory set of sensitivities merely hints at some of the potential strategies and their suggestive implications.

Table 5.5

Sensitivity Results

Fossil Free Energy Scenario

	1988	2000	2010	2030	2100	Cumulative 1988-2100
CO_2 Emissions (Pg C)	5.3	5.7	5.3	2.6	0.0	314
Final Energy Consumption (EJ)	236	255	251	232	448	
Primary Energy Requirements (EJ)	338	396	400	384	987	
Average GDP/Capita (1985 U.S. $)	$3,087	$3,780	$4,234	$4,743	$18,788	
World Population (Billion)	5.0	6.2	7.1	8.8	11.3	

Alternative Patterns of Socio-Economic Development

Variant 1 -20 Percent Lower Growth

	1988	2000	2010	2030	2100	Cumulative 1988-2100
CO_2 Emissions (Pg C)	5.3	5.5	4.9	2.2	0.0	284
Final Energy Consumption (EJ)	236	247	236	207	357	
Primary Energy Requirements (EJ)	338	383	376	342	784	
Average GDP/Capita (1985 U.S. $)	$3,087	$3,672	$4,113	$4,269	$15,030	
World Population (Billion)	5.0	6.2	7.1	8.8	11.3	

Variant 2 - Shift from Materials to Services

	1988	2000	2010	2030	2100	Cumulative 1988-2100
CO_2 Emissions (Pg C)	5.3	5.5	5.0	2.4	0.0	295
Final Energy Consumption (EJ)	236	247	239	219	377	
Primary Energy Requirements (EJ)	338	384	381	363	853	
Average GDP/Capita (1985 U.S. $)	$3,087	$3,780	$4,234	$4,743	$18,788	
World Population (Billion)	5.0	6.2	7.1	8.8	11.3	

GDP and Population Variants

Variant 3-35 Percent Lower GDP by 2100

	1988	2000	2010	2030	2100	Cumulative 1988-2100
CO_2 Emissions (Pg C)	5.3	5.4	4.9	2.3	0.0	284
Final Energy Consumption (EJ)	236	246	235	209	360	
Primary Energy Requirements (EJ)	338	381	373	344	788	
Average GDP/Capita (1985 U.S. $)	$3,087	$3,323	$3,418	$3,566	$12,212	
World Population (Billion)	5.0	6.2	7.1	8.8	11.3	

Variant 4-Intermediate Low Population, Same Total Regional GDP

	1988	2000	2010	2030	2100	Cumulative 1988-2100
CO_2 Emissions (Pg C)	5.3	5.7	5.2	2.5	0.0	307
Final Energy Consumption (EJ)	236	254	247	224	423	
Primary Energy Requirements (EJ)	338	395	393	371	933	
Average GDP/Capita (1985 U.S. $)	$3,087	$3,849	$4,501	$5,479	$26,607	
World Population (Billion)	5.0	6.1	6.7	7.6	8.0	

Table 5.5 (cont.)

Sensitivity Results

GDP and Population Variants

Variant 5-Low Pop' Same Reg'l GDP

	1988	2000	2010	2030	2100	Cumulative 1988-2100
CO_2 Emissions (Pg C)	5.3	5.7	5.2	2.5	0.0	306
Final Energy Consumption (EJ)	236	255	247	224	416	
Primary Energy Requirements (EJ)	338	397	393	371	918	
Average GDP/Capita (1985 U.S. $)	$3,087	$3,849	$4,501	$5,481	$33,183	
World Population (Billion)	5.0	6.1	6.7	7.6	6.4	

Variant 6-Intermediate Low Population, Same Regional GDP/Capita

	1988	2000	2010	2030	2100	Cumulative 1988-2100
CO_2 Emissions (Pg C)	5.3	5.6	5.1	2.4	0.0	292
Final Energy Consumption (EJ)	236	254	244	214	349	
Primary Energy Requirements (EJ)	338	394	388	354	765	
Average GDP/Capita (1985 U.S. $)	$3,087	$3,815	$4,316	$4,935	$19,100	
World Population (Billion)	5.0	6.1	6.7	7.6	8.0	

Variant 7-Low Population, Same Regional GDP/Capita

	1988	2000	2010	2030	2100	Cumulative 1988-2100
CO_2 Emissions (Pg C)	5.3	5.6	5.1	2.4	0.0	285
Final Energy Consumption (EJ)	236	254	243	214	296	
Primary Energy Requirements (EJ)	338	394	387	354	645	
Average GDP/Capita (1985 U.S. $)	$3,087	$3,815	$4,316	$4,935	$18,896	
World Population (Billion)	5.0	6.1	6.7	7.6	6.4	

Slower Penetration of Efficiency Improvements

	1988	2000	2010	2030	2100	Cumulative 1988-2100
CO_2 Emissions (Pg C)	5.3	6.1	6.2	3.8	0.0	399
Final Energy Consumption (EJ)	236	277	299	325	633	
Primary Energy Requirements (EJ)	338	425	464	516	1,356	
Average GDP/Capita (1985 U.S. $)	$3,087	$3,780	$4,234	$4,743	$18,788	
World Population (Billion)	5.0	6.2	7.1	8.8	11.3	

5.2.2 Population and GDP Variants

The results of five additional variants of the population and GDP projections used in the *FFES* are shown in Table 5.5, and are described below.

Variant 3 - *35 Percent Lower GDP by 2100*: In this variant, energy use and CO_2 emissions decline, as total the global economy grows more slowly that in the *FFES*. Projected global GDP is 25 percent lower by 2030 and 35 percent lower by 2100, but is still nine times higher than 1985 levels ($15 trillion US$) by 2100 (138 trillion US$). No other parameters, including population, are varied. The *FFES* 2:1 richest to poorest region ratio for 2100 is maintained here, as is the relationship between the industrial, service, and agriculture sectors as described in Section 4. The lower economic growth assumptions lead to a drop in primary energy requirements of 10 percent by 2030 and 20 percent by 2100. Cumulative global CO_2 emissions decrease by 10 percent, from 314 to 284 Pg C.[5]

Variant 4 - *Intermediate Low Population, Same Total Regional GDP*: This variant modifies population while assuming the same regional and global total GDP: a world with fewer but wealthier people. We use the World Bank's 1990 intermediate low population forecast which projects a world population of 8.0 billion in 2100, 29 percent lower that the mid forecast used in the *FFES* (Bulatao et al., 1990, Lovins et al., 1981). Since we assume no resulting change in the scale of the world economy, average per capita income increases 42 percent, and the reduction in energy use (2100 consumption is down 5.6 percent), and CO_2 emissions (cumulative emissions are down 2.2 percent) are relatively small.

Variant 5 - *Low Population, Same Total Regional GDP*: This variant parallels the previous one, with an even lower population forecast, projecting a world population of 6.4 billion in 2100, 43 percent lower that the mid forecast used in the *FFES*. (Bulatao et al., 1990) As in the previous sensitivity, as there is no change in the scale of the world economy, the reductions in energy use (2100 consumption is down 7.1 percent) and CO_2 emissions (cumulative emissions are down 2.5 percent) remain small. Since the world population is the same as the previous sensitivity through 2030, and post-2030 cumulative CO_2 emissions are relatively small, the difference in total cumulative emissions is negligible.

Variant 6 - *Intermediate Low Population, Same Regional GDP per Capita*: Rather than assuming the same total GDP by region, unaffected by population changes, as in the preceeding variants, here we assume that average per capita GDP remains the same as in the *FFES* as shown in Table 4.3. As a result, total GDP declines in direct proportion with population. The two variant approaches -- same total GDP and same GDP per capita -- bracket a more likely outcome: i.e. that lower population growth would accompany increasing per capita income, but that total GDP would be lower than that of a more populous world. In this variant, cumulative CO_2 emissions decline 7.0 percent from the *FFES* to 292 Pg carbon over the 1988-2100 period. The 2100 energy supply requirements decrease by 22 percent, and land use requirements for solar, wind, and biomass would decrease by approximately this level as well.

(Note that while regional per capita GDP values were maintained, the relative population distribution among regions changes, leading to slightly different global total and per capita average GDP compared with the *FFES*, as seen in Table 5.5.)

Variant 7 - *Low Population, Same Regional GDP per Capita*: This variant is identical to the previous one through 2030. The 2100 projected population, and as a result of the constant GDP per capita assumption, total GDP are about 43 percent lower than the *FFES*, compared with a 29 percent decrease in the previous variant. Cumulative CO_2 emissions are 9.2 percent lower than the *FFES*. This decrease is surprisingly small, because the effects of slower

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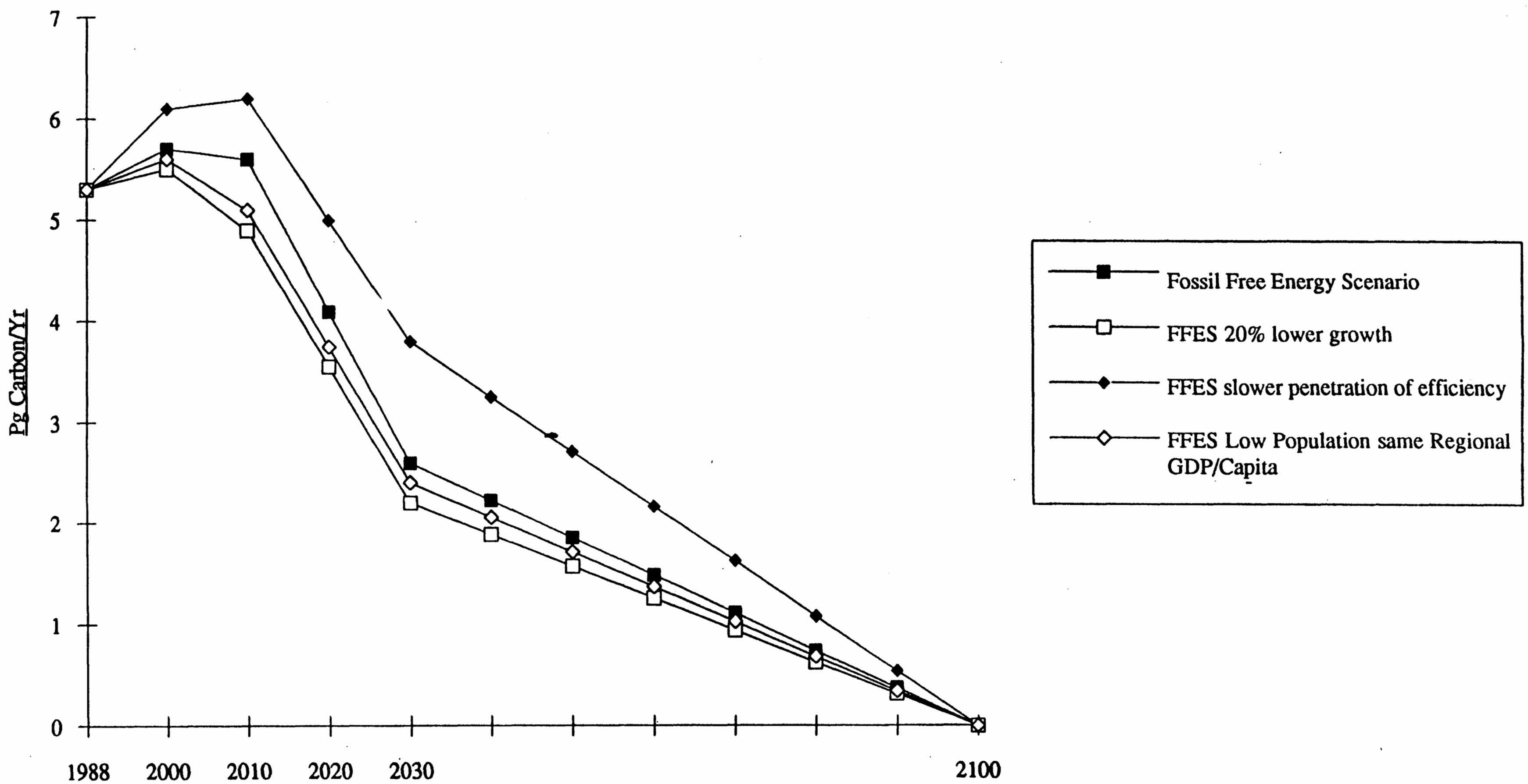
5 The mean global GDP per capita in 2100 under all the lower GDP growth variants is still substantially greater than at present.

Figure 5.5: Sensitivity Analysis of FFES



population growth take place largely over the longer term, when energy supply systems are largely based on renewables.

5.2.3 Slower Penetration of Improved Energy Efficiency

Variant 8 - Lower Rates of Energy Efficiency: This variant underscores the importance of achieving the technical and economic potential for improved efficiency. In this scenario, energy efficiency improvements are scaled back by one-third through 2030. From 2030 to 2100, a 0.5 percent per year efficiency improvement rate was assumed, as in the main *FFES*. The result of this sensitivity is a substantial increase in CO_2 emissions over the next 40 years relative to the *FFES*: projected emissions increase from 5.3 to 6.1 Pg C in 2010 and from 2.6 to 3.8 Pg C by 2030. Cumulative emissions rise to nearly 400 Pg C, a 27 percent increase.

5.2.4 Higher Solar and Biomass Efficiencies

As noted earlier, land use requirements in the main FFES are quite extensive, particularly for biomass energy over the period 2030 to 2100. By lowering primary and final energy requirements by up to 35 percent, the lower GDP and population variants would reduce estimated land use requirements in proportion.

In addition, Table 7.3 illustrates the implications of increasing biomass and solar productivities. Assuming that the current efficiencies of solar/wind could be doubled by 2030, that biomass productivities could be doubled (relative to the main FFES assumptions), and that 25 percent of biomass residues could be recovered, the combined solar/wind and biomass land use requirements drop from 400 million hectares to 170 million hectares in 2030, and from 830 million hectares to 380 million hectares in 2100. The combination of these higher renewable resource and technology efficiencies and lower population and GDP variants could reduce the land-use requirements to as low as 250 million hectares in 2100, between 2 percent of total global land area (3 percent of current global cropland, permanent pasture, and forest and woodland).

Section 6: Detailed Results of FFES: Demand Assessment

6.1. Overview and Results

Results

This section begins with a brief discussion of overall delivered energy requirements of the *Fossil Free Energy Scenario*, followed by an overview of the approach used in assessing methods to reduce them or change the fuels used. Supporting analyses for three of the four sectors -- residential, industrial, and services/other -- are then presented in detail in subsequent sections 6.2, 6.3, and 6.4. Full analysis of the transport sector is presented in a separate Greenpeace appendix by Michael Walsh - 'Transport Sector Analysis'. The transport results shown in section 6.5 are discussed in the abstract included as Appendix F.

The results of the *Fossil Free Energy Scenario* indicate that global delivered energy needs in 2030 could be met at 1988 levels (about 230 EJ). Over the full study period, substantial end-use efficiency improvements and structural change assumptions enable developing regions to exceed 1985 OECD per capita GDP levels by 2100, with less than a doubling of delivered energy requirements (90 percent increase 1988 to 2100). By 2100, all regions are assumed to reach saturation levels in building appliance amenities (refrigeration, heating, lighting, etc.) and energy-intensive materials requirements (steel, cement, aluminum, etc.) based on notions of current industrialization patterns. Although delivered energy appears be rising as the 22nd century begins, a saturation of energy service needs combined with a slowdown or cessation of population growth (World Bank forecasts) suggest that delivered energy requirements could begin to level off sometime after 2100. Given the solar/wind/biomass/hydro energy supply system, such a plateau in global energy requirements would in turn indicate the potential for realization of a truly sustainable energy system.

From 1988 to 2100, total global delivered energy rises at an average rate of 0.6 percent per year. As discussed in Section 5, the pattern of increase is marked by a dip around 2030 and subsequent rise (see Figure 5.2), resulting from the more conservative assumptions regarding efficiency improvements after 2030 (a maximum of 0.5 percent per year), and continuing increases in population and GDP.

Global average delivered energy per capita remains between 1 and 1.5 kW throughout the scenario, despite massive increases in living standards, GDP, and energy services in line with Goldemberg et al (1988)[1]. Within regions, however, the average delivered energy per capita changes considerably. In 1988, the range was over 20 fold, from 0.4 kW in South East Asia (SEA) to 8 kW in the U.S. By 2100, the range drops significantly from 1 kW in SEA to 3 kW in the U.S., as a function of our study assumptions (high efficiency) and GDP targets (e.g. 2:1 difference in the highest to lowest per capita GDP among regions).

Table 6.1a shows delivered energy by region. Delivered energy declines in all industrialized regions throughout the scenario, with the exception of a slight increase in JANZ (7 percent) from 1988 to 2000. Delivered energy in the South, on the other hand, grows continuously from 71 EJ (30 percent of total) in 1988 to 112 EJ (44 percent) in 2010. By 2030, the South accounts for approximately half of total delivered energy, and by 2100 for nearly 80 percent.

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1 1 kW = 31.5GJ/year

Table 6.1a
Delivered Energy by Region
EJ

	1988	2000	2010	2030	2100
AFR	9 *(4%)*	12 *(5%)*	13 *(5%)*	17 *(7%)*	93 *(21%)*
CPA	24 *(10%)*	35 *(14%)*	40 *(16%)*	32 *(14%)*	71 *(16%)*
EE	11 *(5%)*	11 *(4%)*	9 *(4%)*	8 *(4%)*	7 *(1%)*
JANZ	13 *(6%)*	14 *(5%)*	14 *(5%)*	12 *(5%)*	9 *(2%)*
LA	15 *(6%)*	18 *(7%)*	20 *(8%)*	22 *(10%)*	44 *(10%)*
ME	7 *(3%)*	9 *(4%)*	11 *(4%)*	11 *(5%)*	34 *(8%)*
SEA	17 *(7%)*	24 *(9%)*	28 *(11%)*	32 *(14%)*	114 *(25%)*
US	58 *(25%)*	52 *(21%)*	44 *(17%)*	32 *(14%)*	24 *(5%)*
USSR	39 *(17%)*	39 *(15%)*	36 *(14%)*	33 *(14%)*	25 *(6%)*
WE	43 *(18%)*	41 *(16%)*	38 *(15%)*	32 *(14%)*	27 *(6%)*
TOTAL	236	255	251	232	448

Table 6.1b
Delivered Energy by Fuel
EJ

	1988	2000	2010	2030	2100
Electricity	32 *(14%)*	48 *(19%)*	59 *(24%)*	79 *(34%)*	209 *(47%)*
Oil	95 *(40%)*	86 *(34%)*	70 *(28%)*	41 *(18%)*	0 *(0%)*
Natural Gas	39 *(17%)*	36 *(14%)*	30 *(12%)*	22 *(10%)*	0 *(0%)*
Coal	41 *(17%)*	38 *(15%)*	32 *(13%)*	14 *(6%)*	0 *(0%)*
Heat (Cogen)	7 *(3%)*	15 *(6%)*	19 *(8%)*	23 *(10%)*	55 *(13%)*
Biomass/Biofuels	21 *(9%)*	28 *(11%)*	32 *(13%)*	35 *(15%)*	78 *(17%)*
Hydrogen	0 *(0%)*	2 *(1%)*	3 *(1%)*	7 *(3%)*	75 *(17%)*
Solar	0 *(0%)*	3 *(1%)*	5 *(2%)*	11 *(5%)*	30 *(7%)*

Table 6.1c
Delivered Energy by Sector
EJ

	1988	2000	2010	2030	2100
Residential	54 *(23%)*	51 *(20%)*	48 *(19%)*	47 *(20%)*	53 *(12%)*
Services	30 *(13%)*	32 *(12%)*	33 *(13%)*	40 *(17%)*	99 *(22%)*
Transportation	62 *(26%)*	66 *(26%)*	65 *(26%)*	62 *(27%)*	99 *(22%)*
Industry	90 *(38%)*	106 *(42%)*	106 *(42%)*	84 *(36%)*	196 *(44%)*

* Note that 1988 biomass estimates reflect UN estimates (UN, 1990) and could be low by a factor of 2 (See Hall 1991).

As shown in Table 6.1b, the *Fossil Free Energy Scenario* embodies a significant growth in the role of electricity, rising from a 14 percent share in 1988 to 34 percent by 2030 and 47 percent in 2100. At the same time, electricity is increasingly generated from renewable, low-CO_2 sources, as discussed in Section 7. As noted in section 5, we may have overestimated total electricity demand by not sufficiently accounting for all of the efficiency benefits of electrification, particularly in the industrial sector (and even more specifically in the `all other' sub-sector).

In 1988, direct use (cogeneration excluded) of petroleum products accounted for 40 percent of delivered energy. This share declines to 18 percent by 2030, and is eliminated by 2100. This reduction results largely from switching to electricity and biofuels. Natural gas and coal consumption also decrease steadily from 17 percent each in 1988, 10 percent and 6 percent, respectively by 2030. Hydrogen, generated from renewable electric resources (solar and wind), plays an important role only after 2030, when sufficient infrastructure is in place to enable its share to rise from 3 to 17 percent of delivered energy. Through 2030, a transition from traditional biomass use in developing regions is roughly balanced by increasing biomass use in industry applications, such as the extensive use of biomass wastes in the paper and pulp industry, and biofuels for transport and other applications. By 2100, biofuels and solid biomass are equal to hydrogen consumption, at 75 EJ. With significant near-term cogeneration potentials, cogenerated heat (including district heat) grows to 15 EJ in 2000 and 23 EJ in 2010, representing 10 percent of delivered energy requirements. The fuel shares for cogeneration are accounted for on the supply side in Section 7[2]. Finally, direct solar heat applications (e.g., industrial process heat, domestic solar water heating) increase to 5 percent of delivered energy in 2030 and 7 percent in 2100. The changing role of fuels in each region is depicted in Figures 6.1 (a-c).

In 1988, industry was the largest energy consuming sector at 38 percent of total delivered energy, as shown in Table 6.1c. Transportation accounted for 26 percent, while residential and services accounted for 23 and 13 percent respectively. The major change in sectoral distribution over the course of this scenario is the increase in service sector and decrease in residential sector delivered energy. Saturation of appliance, heating, cooling, and cooking needs effectively limits overall growth in residential energy consumption. In addition, the potential for residential efficiency improvements is very high; in fact, there is no overall growth in total delivered energy from 1988 to 2100. With structural economic shifts from industry accompanying economic growth in developing regions, service sector activity grows faster than any of the other three sectors, averaging 1.1 percent per year from 1988 to 2100. However, the industrial sector remains the dominant energy sector throughout the study period, largely due to the achievement of basic materials targets (steel, cement, etc.) as discussed in Section 6.4 below.

Additional tables of delivered energy results can be found in Appendix E.

A Bottom-Up Approach

To the extent possible, we used a disaggregated approach in characterizing current and projecting future energy use patterns. To do so, we collected a substantial number of reports on energy use by country and by region. Based on the detail and accuracy of available data, we used the LEAP system to construct separate end-use `models' for each region and sector.

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2 Cogeneration (including district heat) is represented as follows in our analysis: Demand-side analysis includes the requirements for captured/district heat and electricity from cogeneration. Electricity requirements are analyzed independent of source (cogeneration/self-generation or grid) and thus total electricity requirements are reported in this section. Supply results are presented in Section 7, including the levels of cogeneration and fuel shares. In the supply model, cogenerated electricity offsets the requirement for additional generation.

Figure 6.1a
1988 Delivered Energy Consumption (EJ)

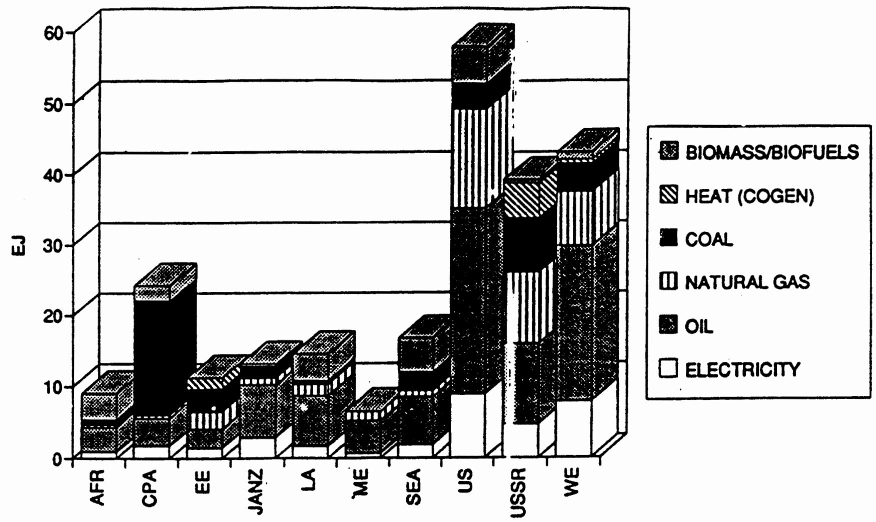


Figure 6.1b
2030 Delivered Energy Consumption (EJ)

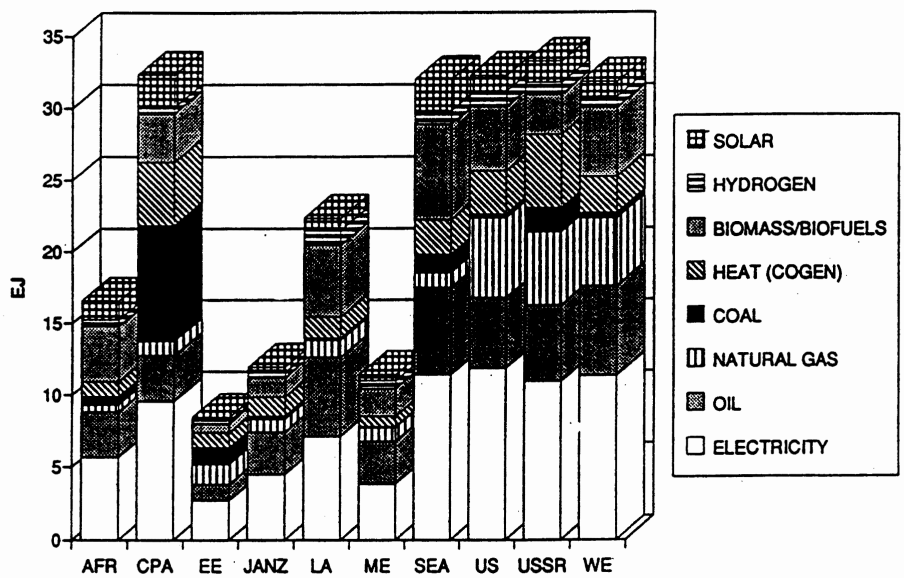
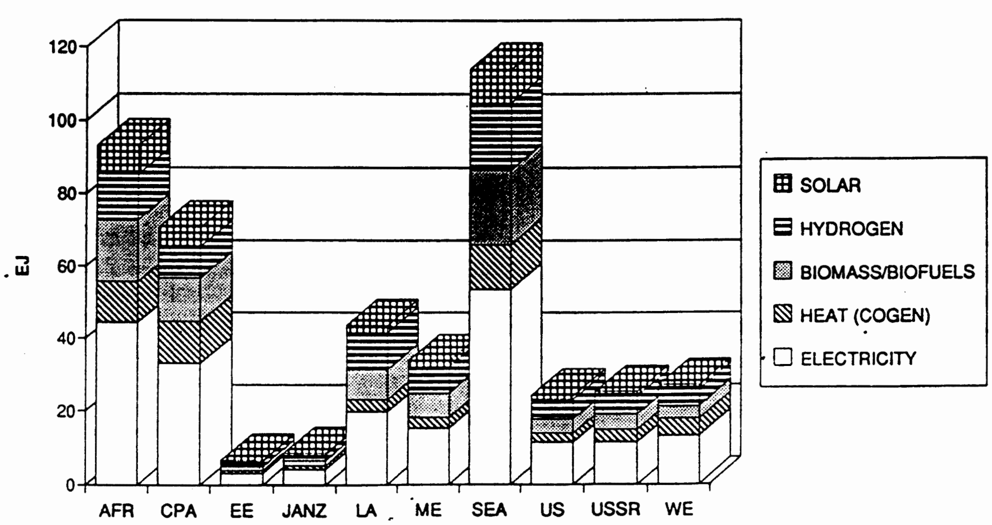


Figure 6.1c
2100 Delivered Energy Consumption (EJ)



A considerable amount of data are required for these end-use models. Energy use surveys and statistical compendia can provide much of this data for individual countries, but incomplete and inaccurate data, particularly for many non-industrialised regions, pose analytical difficulties.

Therefore, to ensure consistency, we normalized our regional energy use (and supply) totals to International Energy Agency and United Nations data (IEA, 1990, U.N., 1988). We recognize that these international compendia may suffer from problems of data accuracy and reporting consistency. Biomass data are particularly questionable[3]. Nonetheless these sources offer the most comprehensive and consistent source available, for the most recent year with relatively complete data, 1988.

Once these models were constructed, the potentials of the following six categories of emission reduction options by sector and region were assessed[4].

- improving end-use efficiency.
- switching from higher to lower carbon content fossil fuels, e.g., coal and oil to natural gas, as a transition option.
- switching from fuel use to electricity (the increasingly renewable, low carbon generation mix is described in Section 7).
- switching from fossil fuels to renewable *fuels*, as they become available (e.g., biofuels or hydrogen).
- direct use of renewable *energy* (e.g., solar hot water).
- combined heat and power (cogeneration) in the residential, service and industrial sectors.

Improving End-Use Efficiency

No other option offers such significant cost-effective near and medium-term opportunities for reducing greenhouse gas emissions. In spite of some of the impressive gains witnessed during the 1970s and 1980s, the potential for cost-effective conservation has barely been tapped. Proven technologies for vehicles, buildings, appliances, and industrial processes can reduce energy consumption by 15 to over 90 percent while providing equal or improved services, as compared with existing technologies.

The immediate challenge in improving efficiency lies in overcoming current market barriers and consumer behaviour. While we assume that technical, economic energy efficiency potential can be achieved to a large extent, numerous constraints will mean that it may take decades for full penetration of improvements available today. For these constraints to be overcome, appropriate policies -- market incentives, dissemination programs, must be designed and implemented.

While the details of efficiency targets are presented on a sector-by-sector basis below,

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3 We have used UN/FAO data for biomass use (UN, 1990), but these data contain significant underestimates. Hall suggests that these data may be low by a factor of 2. (Hall, 1991)

4 The reference cases alluded to earlier (IPCC and US EPA) also assume some level of implementation of these measures under more "business-as-usual" conditions.

efficiency targets for each region, sector, and end-use were derived as follows:

1) A recent, detailed analysis of potential efficiency improvements for the United States provided many of our baseline efficiency targets (UCS et al., 1991). Key economic parameters for this analysis are shown in Appendix G (Table G-1). To reflect the administrative costs associated with implementation of conservation programs, 10 percent was added to costs of residential, service and industrial measures[5]. In addition, penetration rates were developed based upon experience with recent policies and programs, and are used in our analysis as appropriate.

2) From a review of numerous regional and national studies related to energy use patterns and efficiency potentials, additional estimates were made. The current efficiency of energy using equipment and processes varies widely among regions, and among countries in each region. For instance, the relatively efficient industrial sector in Japan leaves considerably less room for improvement than the industrial base found in many developing countries. We have distinguished the different `starting-point' efficiencies of each region.

3) With much of their industrial infrastructure yet to be built and consumer durables yet to reach saturation, developing countries technically have a great opportunity to install state-of-the-art, energy efficient technologies. For the purposes of this discussion we ignore the barriers presented by the preference of large funding agencies to invest in expanding fossil fuel energy supplies. For such technological *leapfrogging* (see box overleaf) to occur, substantial improvements in technology transfer and terms of financial assistance will be required. These improvements can enable developing countries to upgrade industrial process, building, appliance, and vehicle efficiency to their economic potential. We assume that the process is successful in achieving wide technology dissemination and implementation in this scenario. This assumption translates into international equivalency in items such as average refrigerator and vehicle efficiency around the middle of the 21st century[6], and similar levels of improvement in region-specific end-uses such as heating and cooling requirements.

4) In many cases energy intensity targets (GJ/$GDP or GJ/device, etc.) were developed for the year 2030 based on available technology and other study estimates. For the North, 75 percent of these reductions were assumed to be attained by 2010 for most end-uses and sectors. In the South, it was assumed that improvements would be more gradual, due to greater obstacles to improving efficiency (e.g. lack of investment capital, decreased availability of improved technologies, and higher consumer discount rates). In addition the North faces greater political pressure to improve energy efficiency as a means to reduce emissions over the near term.

Switching from Higher to Lower Carbon Content Fossil Fuels

For appropriate end-uses, switching from higher to lower carbon content fuels, such as from coal to natural gas, can offer an important transition strategy. Moreover, natural gas usage envisaged in the scenario is part of an overall commitment to achieving tough climate

5 UCS et al., 1991. Based on S. Nadel, Lessons Learned: A Review of Utility Experience with Conservation and Good Management Programs for Commercial and Industrial Customers, ACEEE, Washington, 1990.

6 If approximately the same equipment is sold and used globally, their energy use may still vary somewhat by region. For instance, ambient temperature and humidity would affect refrigerator energy use, as would average household size and dietary and other differences. We do not consider these difficult-to-quantify and, likely, second-order effects.

targets (Section 3). A switch to natural gas is not an end goal in itself, but part of a comprehensive strategy which moves the global energy system away from all fossil fuels. This scenario embodies a continuous shift from coal and oil to renewables where these are available and to natural gas where they are not, with the expectation that natural gas leakage can be effectively controlled.

In some cases, fuel substitution can be carried out with little new investment, such as with dual-fuel boilers, now fairly common in industrial applications. For instance in the U.S., short-term fuel substitution could displace almost 20 percent of fuel oil use with natural gas (DOE as quoted in IEA, 1991, p.123, Greenhouse Gas Emissions). In general, the potential for short-term fuel switching is limited by the requirements of retrofitting or replacing energy using equipment; over a 10-30 year time period, however, equipment stock turnover in all sectors can be expected to enable far greater levels of fuel switching.

Switching from Fuels to Electricity

Depending on how it is generated and consumed, electricity can be either more or less efficient than fuel for end-use applications, when the full fuel cycle is considered. A commonly cited example of inefficient electricity use is the resistance-heated building.

Technological 'Leapfrogging'

The term *technological leapfrogging* has been used to describe a process whereby developing countries can jump past the inefficient technologies still in wide usage, and instead, take advantage of modern, highly energy-efficient technologies and practices in building their infrastructures.

In terms of manufacturing capability for energy-efficient equipment, many developing countries are already expert, but the products are generally destined for consumption in the North. As Lovins and Gadgil (1991) point out, "all the efficient refrigerator compressors made in Brazil, and 95% of the compact fluorescent lamps made in Mexico, are exported to the U.S.". As they document, the local manufacture and dissemination of highly efficient bulbs, refrigerators, vehicles, and other equipment offers great economic potential.

Consider, for example, a modern factory to produce quadrupled-efficiency compact -fluorescent lamps. The output of such a \$7.5 million lamp factory saves as much electricity as a billion-dollar, 700-megawatt power plant makes. But the lamp factory needs 140 times less capital investment than the power plant, and avoids its fuel cost and pollution. Compared with coal-fired generation, each compact fluorescent lamp, over its 10,000-hour life, keeps roughly a ton of CO_2 out of the air, plus acid gas. Since incandescent lamps normally contribute to peak loads late on summer days, it is more valid to compare efficient lamps with the *peak* generating capacity they displace: in India, the \$7.5 million lamp factory would displace 3,700 megawatts of on-peak capacity costing at least \$2.2-5.6 billion (using gas turbines or intermediate-load-factor coal plants) -- 300-750 times as much.

Delivered electricity from fossil fuel combustion can impose losses of 60 to 70 percent in steam cycles, compared with losses of 20 to 30 percent if the same fuel is used to heat the building directly.

In contrast, some applications of electricity offer significant efficiency improvements that can help to offset electric generation losses. Examples include high COP (coefficient of performance) heat pumps for water and space heating, electric arc furnaces for steel-making, and many process applications. With advanced highly efficient electricity generation technologies (e.g., fuel cells), switching from fuels to electricity for appropriate end-uses can provide significant overall savings. In addition, electricity offers an important carrier for low-carbon renewable energy sources, such as geothermal, wind, and hydro. When moving to a renewable-based energy economy, electricity must be weighed together with other convenient energy carriers such as biogas, alcohol, and hydrogen, all produced through conversion processes that also impose energy losses and usually additional non-CO_2 emissions.

Switching from Fossil Fuels to Renewable Fuels

In order to fully replace fossil fuels, acceptable low-carbon solid, liquid, and gas fuels will be required, preferably derived from renewable sources. The other option is an all-electric-energy world, an option that, while conceivable, we do not consider here. Biomass offers the most abundant, renewable combined feedstock and energy source, and the possibility of producing a wide range of biofuels, including methanol, ethanol, methane-rich biogas, producer gas (CO/H_2), and diesel substitutes. The other major renewable fuel that we consider is hydrogen, which can be produced using either biomass or solar energy[7].

Direct Use of Renewable Energy

By direct use of renewable energy, we refer to applications such as active solar collectors for domestic hot water or industrial steam that do not require conversion to an intermediate carrier, such as electricity, hydrogen, or biofuels. Major options include direct consumption of biomass, capture of solar or geothermal heat, or mechanical energy from wind or hydro. To determine the cost-effective potential of direct renewable energy use, we have adapted the results of several other analyses, most notably those of Dessus et al. (1991) and UCS et al. (1991).

Combined Heat and Power (Cogeneration)

When electricity is produced from the combustion of fuels, from 60 to 70 percent of the total energy content of the fuel is typically lost as waste heat, discharged to the local environment. Combined heat and power, or cogeneration, systems take advantage of the heat generated for industrial process applications or for space and water heating in buildings. In these systems only 20 to 40 percent of the total energy content of the fuel is lost. Different types of systems are possible based on whether its primary purpose is electricity or heat production or a combination thereof. The technical characteristics of cogeneration systems assumed here are described in Section 7.

Cogeneration systems can be used in the service, residential, and industrial sectors. For commercial and residential buildings, both centralized and on-site cogeneration options are possible, while large, centralized station cogeneration units can feed district heating networks, many of which currently exist in Europe, the U.S., USSR, and China. Smaller, on-site cogeneration units can be implemented in numerous industrial, as well as many commercial and residential situations. Modular, high-efficiency fuel cells offer the potential to greatly increase the cogeneration market in the medium term. For instance, in Japan, a 40-fold expansion of cogeneration and district heat using fuel cells has been suggested, as constrained by geography and NOx emissions (Yamamura, 1991).

7 Hydrogen and other synthetic fuels produced from fossil fuel feedstocks are not considered here.

There are important interactions between building shell improvements and the economics of district heating. For instance, Geller (1980) found that a 50 percent reduction in annual district heat demand through conservation efforts resulted in a nearly two-thirds increase in the distribution cost per unit of delivered heat. Sufficient heat and hot water loads are needed to justify district heating systems; we thus restricted district heat penetration to colder climate areas, and areas where multi-family dwellings and denser cities predominate (i.e. former USSR, China, Northern and Eastern Europe, and part of North America).

Specific assumptions regarding the penetration of on-site and central cogeneration with district heat are detailed for each of the sectors below.

6.2. Residential Sector

6.2.1 Methods

We have constructed a generalized model for the residential sector, as illustrated below in Figure 6.2a. For industrialized regions, we estimate the average current levels of energy used to provide four basic types of amenities: space heating, hot water, cooking, and other end-uses. Among these other appliances, we distinguish the energy used by refrigerators and lighting. The remaining other appliances -- televisions, radios, VCRs, washing machines, clothes dryers, freezers, etc. -- are combined due to the lack of adequate data by region for deeper analysis.

A fifth category for developing regions corresponds to current (non-electric) fuel use for cooking, water heating, and other end uses. This category is dominated by small stoves using commercial fuels and traditional stoves using biomass fuels. With the adoption of modern stove and water heaters, this category disappears over time.

To develop estimates of current energy use, fuel shares, and energy incentives by end use on a regional basis, we used numerous country studies and statistical compendia. Aggregation to regional averages require assumptions regarding representative countries or groups of countries (e.g., the EEC for Western Europe)[8]. In all cases, fuel totals were adjusted to match IEA statistics (IEA, 1990).

The end-use breakdowns provide a more reasonable basis for projections than aggregate residential figures. They enable us to reach targets over time that are not strictly coupled to base year figures and their related imprecision.

The residential model projects energy use for each region based on the following relationship:

$$E_{u,t,f} = HH_t * EI_{u,t,f} * S_{u,t} * FS_{u,t,f}$$

where,

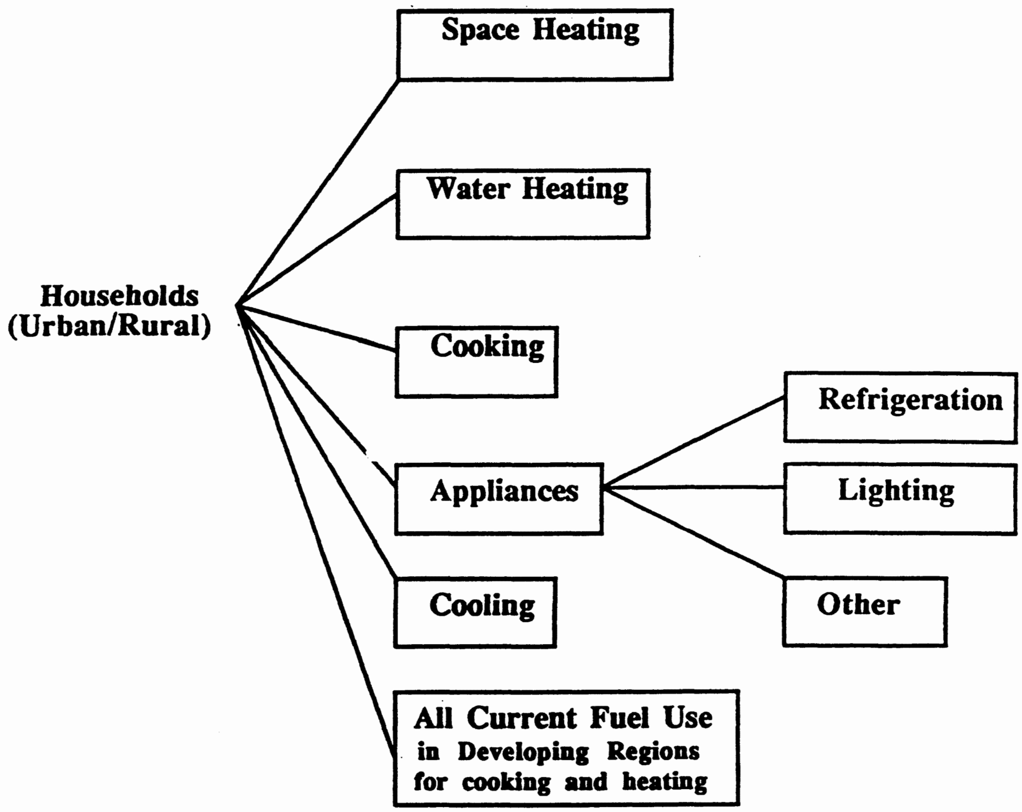
E is the energy use in time t, for end-use u, and energy source f

HH is the number of households (urban and rural separately for Latin America, Centrally Planned Asia, Africa, and South and East Asia)

8 These estimates were based on a review of numerous data sources. For other industrialized regions we relied upon numerous studies, in particular, upon EEC, (1990); Schipper, et al., (1985); Schipper and Meyers, (1992); and UCS et al., (1991). For developing regions, several sources were used (e.g. Sathaye and Goodman, 1991; Sathaye et al., 1988; Tata Energy Research Institute, 1988; Geller, 1991; Sathaye and Tyler, 1991; Zhang, 1991; Zhou et al., 1989)

Figure 6.2a

Schematic Diagram of Residential Model



EI	is the energy intensity, alternatively referred to as specific consumption, unit usage, or unit consumption -- a function of equipment efficiency, usage patterns, and levels of end-use amenity (indoor temperature, refrigerator size, etc.)
S	is the saturation or the percent of households with end use u, and
FS	is the share of energy source f providing an end-use u.

Residential energy use is projected as a function of the number of households, urban and rural, in each region. Since we assume the number of persons per household to continue to decrease throughout the world, numbers of households grow faster than population.[9] Population and household estimates are shown with other demographic assumptions in Table 6.2a. Estimates of persons per household through 2030 are based on several previous studies (Sathaye et al., 1991; Sathaye et al., 1988; UCS et al., 1991; Mintzer, 1988). Beyond 2030, we assume continued declines in developing, Eastern Europe, and former USSR regions. The somewhat higher 2100 levels in developing regions reflects the somewhat lower GDP/capita and the assumption that currently stronger family traditions will not fully disappear.

We distinguish urban and rural households in developing regions, due to their substantially different energy use patterns. In doing so, we attempt to capture the effects of rural-urban migration. Cities and towns offer access to modern fuels (electricity, gas, petroleum products) that are often unavailable or limited in rural areas. They also offer greater possibilities for gaining the cash income necessary to purchase appliances and modern energy forms. At the same time, limited economic growth has lead to the emergence of poor peri-urban areas. While much effort has been directed towards promoting economic development in rural areas, rapid migration to urban and peri-urban areas continues in most countries. We have not assumed any major changes in current trends; our urbanization projections shown in Table 6.2a are based on the World Bank (1990). However, the equity premises of our scenario broadly imply that the urban slums of today will gradually diminish.

Although our residential model does not use income explicitly to explain household energy use, the effects of increasing income are reflected in increasing appliance ownership and household amenities, and a transition from traditional biomass to modern, convenient fuels. We discuss the issues underlying our projections of changing levels of amenity and energy intensity for each end use below.

6.2.2 Results and Analysis

Projected residential sector energy consumption and fuel mix are illustrated in Figure 6.2b and 6.2c below. The results reflect a convergence by the year 2100 on a standard set of highly efficient electric appliances, increased levels of hot water usage in most regions, and region-specific targets for cooking, space heating and cooling, based on notions of climate and cultural differences. They encompass major improvements in building shell efficiency, reduced heating and cooling energy requirements, increased district heating in temperate climates, solar water heating, electric heat pumps, and towards the end of the study period the dominance of solar and biomass fuels.

Between 1988 and 2030, global residential energy use declines, as shown in Table 6.2b, amid a rapid increase in access to household amenities, such as refrigeration and hot

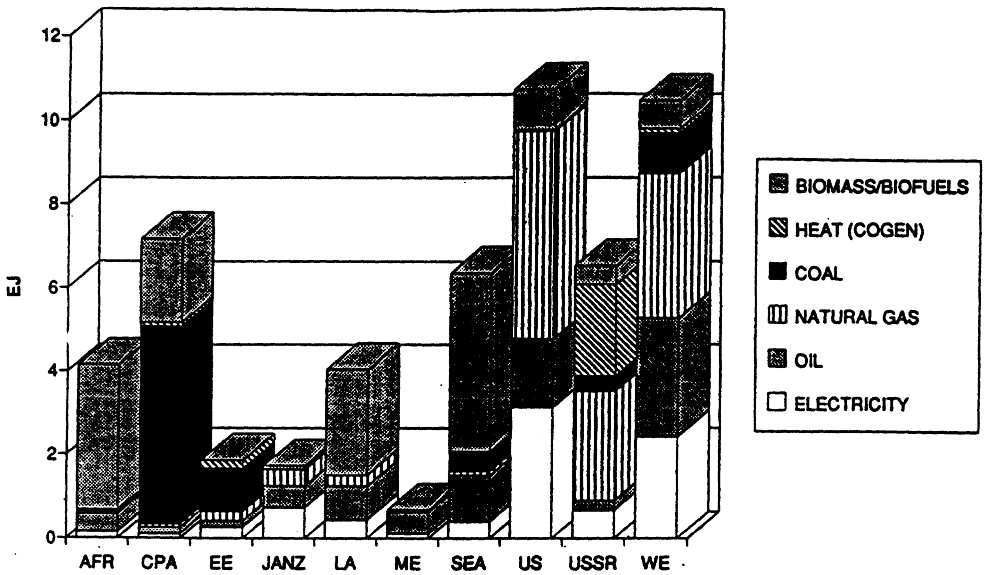
9 On the one hand, this method might tend to overestimate energy use, as smaller households tend to use somewhat less energy. On the other hand, we have not considered the likely growth in the physical size of houses and apartments, particularly in Asia and many developing regions that would increase the area to be air conditioned or heated. For this study, we have assumed that these effects tend to cancel each other, but a more detailed study would be useful.

Table 6.2a
Demographic Assumptions

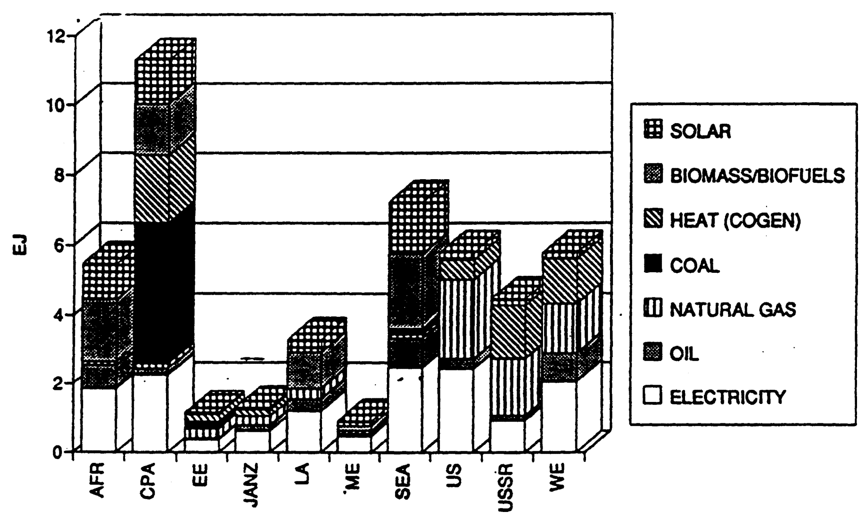
	1988	2000	2010	2030	2100
Population (Million) (1)					
AFR	609	870	1,139	1,737	2,962
CPA	1,196	1,393	1,533	1,753	1,905
EE	139	146	151	157	162
JANZ	143	154	158	155	145
LA	421	529	603	736	869
ME	86	132	175	278	501
SEA	1,482	1,949	2,282	2,871	3,670
US	246	269	284	302	294
USSR	284	306	321	345	370
WE	428	456	467	473	451
Persons/Household (2)					
AFR	5.2	5.0	4.9	4.6	4.0
CPA	4.2	4.1	4.0	3.9	3.5
EE	3.9	3.9	3.8	3.8	3.5
JANZ	3.6	3.6	3.5	3.5	3.5
LA	4.5	4.2	4.0	3.6	3.5
ME	6.0	5.6	5.3	4.7	4.0
SEA	5.1	5.1	5.1	5.1	4.0
US	2.7	2.5	2.4	2.2	2.2
USSR	3.9	3.9	3.8	3.8	3.5
WE	2.7	2.7	2.6	2.6	2.6
Households (Million)					
AFR	117	174	234	378	741
CPA	285	340	383	449	544
EE	36	38	40	41	46
JANZ	40	43	45	44	42
LA	94	126	151	205	248
ME	14	23	33	59	125
SEA	291	382	447	563	918
US	91	108	119	139	136
USSR	73	79	84	91	106
WE	159	169	179	182	173
Urbanization (% of Pop.) (1)					
AFR	33%	41%	47%	60%	80%
CPA	32%	47%	56%	69%	80%
LA	70%	76%	80%	86%	90%
SEA	28%	35%	43%	56%	70%
Urban Electrification (%of HH) (3)					
AFR	60%	66%	70%	80%	100%
CPA	95%	96%	98%	100%	100%
LA	97%	98%	99%	100%	100%
ME (All HH)	65%	72%	78%	90%	100%
SEA	75%	82%	88%	100%	100%
Rural Electrification (% of HH)					
AFR	7%	18%	27%	45%	100%
CPA	75%	78%	80%	85%	100%
LA	45%	59%	71%	95%	100%
SEA	6%	30%	50%	90%	100%

Sources: Bulatao et al. (1990) (1); Mintzer (1988) (2);Sathaye et al. (1988) (2), (3),
Sathaye and Goldman. (1991) (2), UCS et al. (1991) (2).

Figure 6.2b
1988 Residential Sector Delivered Energy Consumption (EJ)



2030 Residential Sector Delivered Energy Consumption (EJ)



2100 Residential Sector Delivered Energy Consumption (EJ)

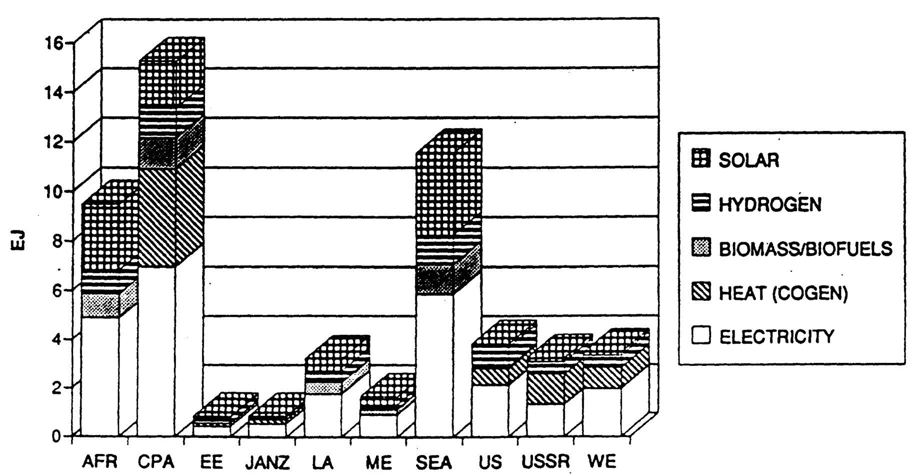
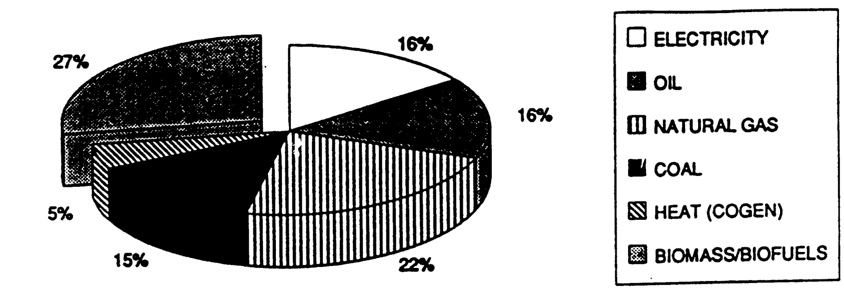
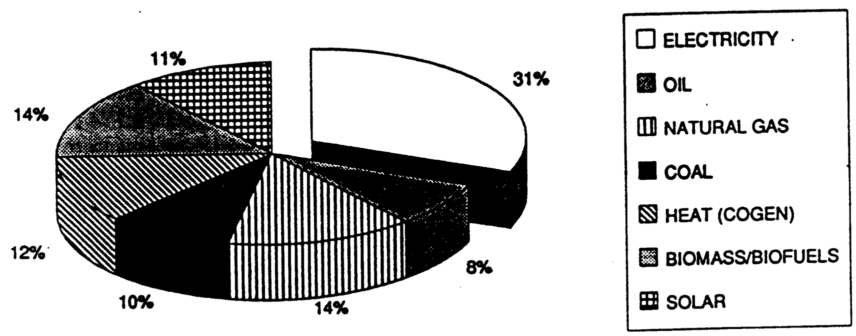


Figure 6.2c

1988 Residential Sector Fuel Shares



2030 Residential Sector Fuel Shares



2100 Residential Sector Fuel Shares

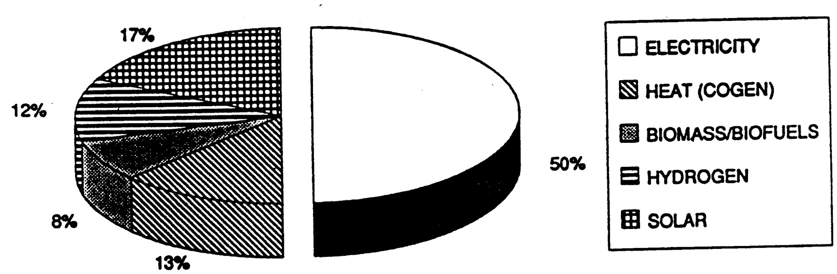


Table 6.2b
Residential Sector Energy Consumption
by Region
EJ

	1988	2000	2010	2030	2100
AFR	4.15 *(8%)*	4.55 *(9%)*	4.74 *(10%)*	5.48 *(12%)*	9.49 *(18%)*
CPA	7.17 *(13%)*	7.95 *(16%)*	8.97 *(19%)*	11.31 *(24%)*	15.25 *(29%)*
EE	1.86 *(3%)*	1.60 *(3%)*	1.36 *(3%)*	1.17 *(3%)*	0.85 *(2%)*
JANZ	1.73 *(3%)*	1.63 *(3%)*	1.52 *(3%)*	1.31 *(3%)*	0.86 *(2%)*
LA	4.04 *(8%)*	3.78 *(7%)*	3.45 *(7%)*	3.30 *(7%)*	3.21 *(6%)*
ME	0.67 *(1%)*	0.80 *(2%)*	0.84 *(2%)*	0.92 *(2%)*	1.65 *(3%)*
SEA	6.35 *(12%)*	6.72 *(13%)*	6.69 *(14%)*	7.23 *(15%)*	11.54 *(22%)*
US	10.74 *(20%)*	9.42 *(18%)*	7.54 *(16%)*	5.81 *(12%)*	3.84 *(7%)*
USSR	6.53 *(12%)*	5.84 *(11%)*	5.14 *(11%)*	4.48 *(10%)*	3.25 *(6%)*
WE	10.47 *(19%)*	8.92 *(17%)*	7.41 *(16%)*	5.79 *(12%)*	3.46 *(6%)*
TOTAL	53.72	51.21	47.67	46.80	53.39

water, a 60 percent increase in global population, and a significant decline in persons per household. Such a surprising result reflects the massive technical potential of improving household energy efficiency[10]. Combined with fuel switching from coal to natural gas, and to electricity and renewable fuels, CO_2 emissions decline substantially even further.

So-called `intelligent buildings' or `smart houses' show potential for reducing energy use at reasonable cost without requiring significant occupant effort. Electronic equipment and sensors can help to ensure that heating, cooling, and illumination are directed to occupied spaces, and managing the energy systems of the building while occupants are away. Recent market surveys indicate a penetration rate of over 6 percent per year in the Europe for intelligent building systems (residential and services) (IEA, 1991b).

Household Energy Transition in Developing Countries

The major differences between our household analysis of developing and industrialized regions lies in the treatment of energy transition issues in developing countries, as discussed in the text box below. Developing regions currently use a significant amount of traditional biomass fuels (firewood, charcoal, animal and crop wastes) for cooking, water heating, and small-scale enterprises, such as beer brewing, food curing, and pottery. For this scenario, we have postulated a full transition from traditional biomass fuels to more convenient fossil and renewable fuels. Figure 6.2d illustrates the decreasing role of traditional biomass in meeting household energy demands, that we project to accompany rising incomes. The major assumptions underlying the decline of traditional biomass fuels are as follows:

1) In urban areas, complete fuel switching to modern fuels (including biofuels) occurs by 2030, replacing traditional biomass sources with fuels and electricity used for cooking, water heating, and other purposes. This is consistent with the equity aspect of our scenario: increasing income per capita and distribution are necessary to provide the cash for modern fuels and investment for devices to use them.

2) In rural areas, fuel switching from biomass to modern fuels occurs more slowly, due to greater accessibility of biomass resources and slower integration into the cash economy[11]. We project that complete transition will occur over the next 60-70 years, except in the Middle East and Latin America, where the rural transition is already well underway, and a more rapid transition by 2030 is more likely.

3) Several fuels and energy carriers can play an important role in displacing traditional biomass use including electricity, LPG, and kerosene. In many rural areas, newer biomass technologies such as digesters and gasifiers have an important role. At the same time, social forestry and agro-forestry programs could help to improve sustainable wood yields. While the increased use of fossil fuels and fossil-based electricity will contribute to greenhouse gas emissions, the overall effect of displacing traditional biomass fuels for cooking and hot water would be relatively small compared

10 Achieving technical potential will not only require effective policies for ensuring implementation; it will also require changes in household habits consistent with achieving these goals. Unlike in industry and large commercial buildings, energy management in the home is not done by trained professionals seeking to save costs. Instead, lights may be left on, unoccupied rooms heated or cooled, and so on. Various studies have shown that energy management and consumer behaviour can account for about half of the variation in household energy demand (See Schipper et al., 1989). While our analysis focuses on technical potentials, other analysis of efficiency improvements that embody these behavioral variables also suggest similar levels of efficiency improvement (See Schipper and Meyers, 1992).

11 One could argue also that in many regions urban dwellers have easier access to biomass fuels. Denser rural populations in marginally productive areas may have access to limited woodfuel supplies while urban areas can be supplied by charcoal made or wood collected in distant less populated areas.

with the emissions from other sectors and from other end-uses in the residential sector

Household Energy Transition in Non-Industrialised Countries

The transition from traditional biomass fuels, to modern fuels has been fairly rapid in Latin America and many Asian cities (Sathaye and Tyler, 1991). This transition has been slow in other areas. Income levels and the physical availability of wood and charcoal in cities and other biomass fuels in rural areas remain major determinants of energy transitions. Among high income households in many developing countries, biomass consumption can still be significant. With smaller households, fuller entry of women into the work force, and changing eating habits, convenient fuels -- electricity, LPG, and natural gas -- become essential.

Whether rapid transitions will occur elsewhere in developing regions, particularly in rural areas, and what form this transition will take has been a subject of great debate in the literature (Leach and Gowen, 1987; Leach and Mearns, 1988). Such changes in energy use patterns will ultimately depend on the speed and shape of economic transformations that could occur. Korea provides a model of an extremely rapid transition: as recently as 1962, firewood accounted for 55 percent of total energy demand and, by implication, a large majority of household energy use (Asian Development Bank, 1991). By 1988, firewood accounted for less than 2 percent of Korea's energy demand, while oil and electricity use accounted for 64 percent, up from 10 percent in 1962.

A different story however has taken place in the Southern African (Southern African Development Coordination Conference, SADCC) region, where biomass fuels account for 80 percent of the regional energy mix (Raskin and Lazarus, 1991): "imprecise biomass demand data, the lack of time-series data, and the highly localized nature of surveys make it difficult to track trends in biomass use. However, it is clear that a significant substitution of modern for biomass fuels -- the so-called energy transition -- has not occurred in Southern Africa in the 1980s. As per capita modern fuel consumption declined, there even are indications of "backward fuel switching" in recent years from modern fuels to woodfuels in urban areas and from woodfuel to agricultural residues in rural areas." (Southern African Development Coordination Conference, 1989).

With 95 percent of SADCC households relying primarily on biomass fuels for meeting their energy needs, the sustainability of biomass resources is arguably the most important and immediate energy issue affecting human well-being in the region. The socio-economic and environmental implications of biomass collection and use are complex. Under conditions of increasing scarcity in many parts of SADCC, deficiency of biomass resources could be an important obstacle to both rural and urban development.

Nonetheless, the relationship between increasing incomes and decreased reliance on biomass fuels is evident from a cross-sectional analysis of SADCC countries. Figure 6.2e illustrates a negative relationship between biomass use and per capita GDP among SADCC countries. This relationship suggests that economic development would lead to an energy transition towards modern fuels. In contrast, decreased woodfuel availability alone does not appear to be capable of forcing such a transition. In Tanzania, Malawi, and Mozambique, the biomass share tops 90 percent, despite many regions of scarcity (SADCC, 1989).

(e.g., appliances). Renewable fuels and electricity offer the ideal solution, and play a stronger role in the longer term, aside from certain near-term applications, such as solar hot water, biogas, and certain other applications.

Figure 6.2d
Traditional Biomass Use as a Percent of Total Residential Delivered Energy Demand

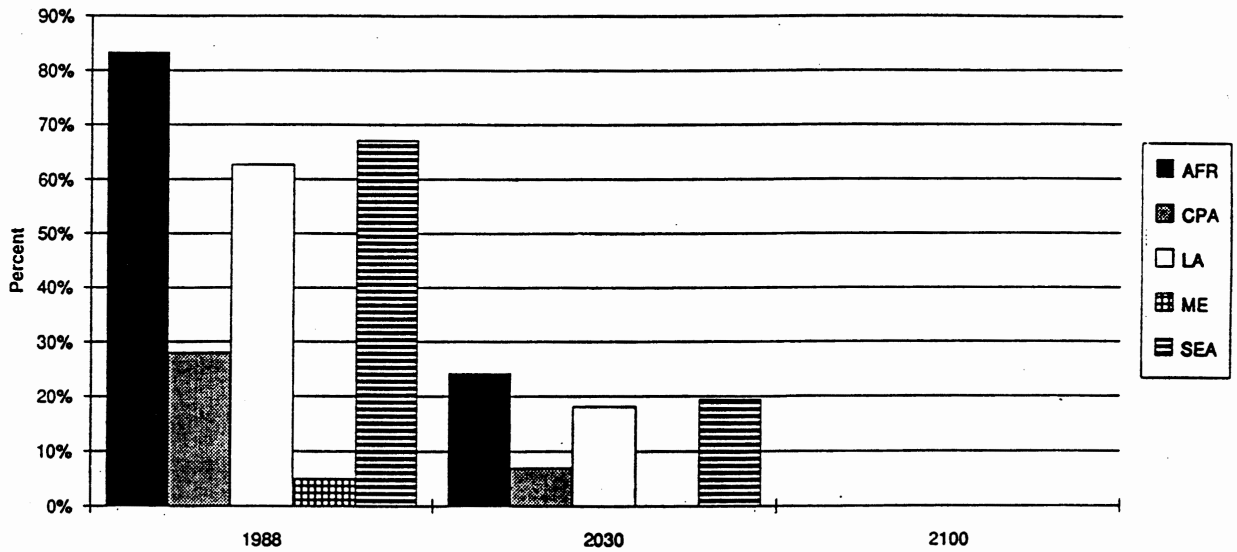
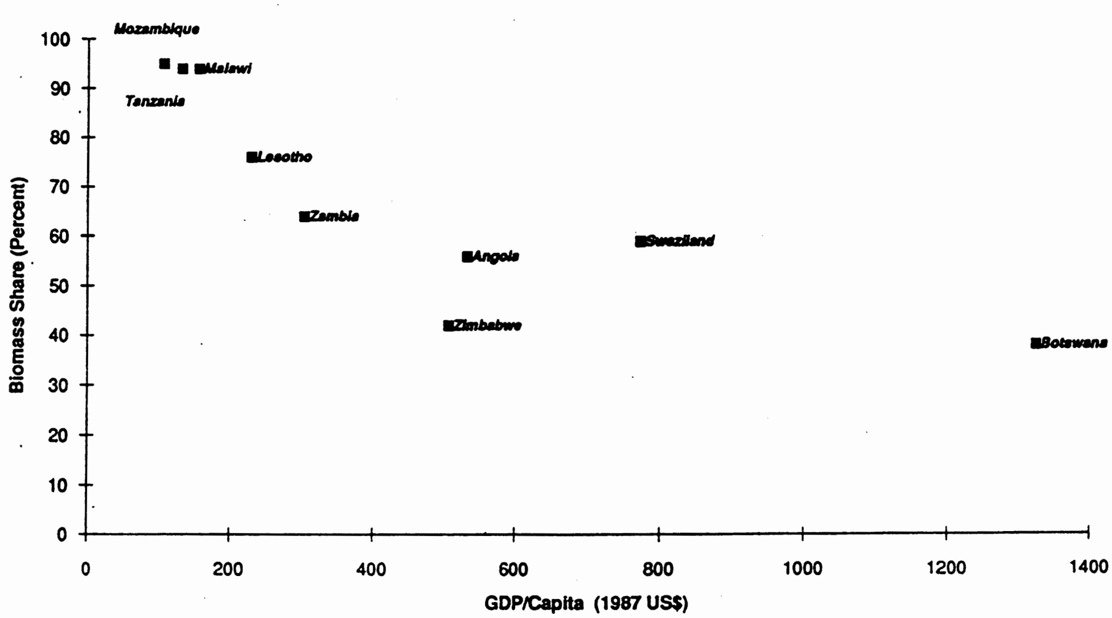


Figure 6.2e
Biomass Share of Total Delivered Energy Use vs. Economic Development (Southern Africa)



Source: SADCC, 1989; Raskin and Lazarus, 1991

More in-depth analysis and assumptions for each of the major residential end-uses -- electric appliances and lighting, space heating, space cooling, hot water, and cooking -- are described in further detail below.

Electric Appliances and Lighting

Over the past 30 years, the acquisition of household appliances resulted in rapid growth in electricity consumption in OECD countries. Currently, major energy-using appliances are close to saturation. Most households have lighting, refrigerators and freezers, clothes washers and dryers, televisions, and numerous others electric appliances and devices. In 1988, these end-uses combined, accounted for approximately 6,000 kWh per household, or 65 percent of total residential electricity consumption in the U.S. (UCS, et al., 1991). At the same time, in four major EC countries these end uses averaged 1,700 kWh per household (43 percent of total residential), and in Japan they comprised 2,600 kWh per household, 75 percent of total residential (Schipper and Meyers, 1992). Assuming that new energy-intensive technologies do not appear[12], OECD electricity use in this category could decline dramatically as a function of much improved equipment. In contrast, many developing regions are currently witnessing rapid growth in appliance ownership (Sathaye and Tyler, 1991, Geller, 1991b).

The current and projected saturation levels for refrigerators and lighting are presented in Table 6.2c. Saturations for 1988 presented here are based on an extensive review of the literature. We assumed that the saturation of electricity uses for lighting and other purposes in developing regions is limited by the rate of electrification of rural areas, as shown in Table 6.2a. Otherwise, we assume that all electrified households have access to lighting and that full penetration of refrigerator/freezers occurs by 2030 in urban and 2100 in rural areas.

In our analysis, we considered improvements in three categories: refrigeration, lighting, and other appliances and uses. These are discussed in order below:

Refrigeration: In the U.S. refrigerators and freezers accounted for over 13 percent of residential electricity use in 1988. In Denmark, they accounted for 28 percent. The unit electricity consumption of refrigerators varies considerably depending on size, features, and whether a freezer compartment is included. Table 6.2d shows the average electricity consumption of refrigerators in various countries, along with some improved models and designs that could greatly reduce energy use from current levels. In many countries, smaller refrigerator size accounts for lower unit consumption. However, increasing income levels could rapidly lead to larger refrigerators. In Japan, for example, refrigerator consumption increased from 400 to 600 kWh from 1973 to 1988 due to growth in size and features (Schipper and Meyers, 1992).

In selecting a global `target' technology, we considered that a relatively large refrigerator by global standards would likely be desired, as incomes rise and less time is available for same-day food shopping. With an efficient compressor and good insulation, a combined refrigerator-freezer could use as little as 228 kWh per year, with the same interior space as current large U.S. models (UCS, et al., 1991). The components of this technology are detailed in Table 6.2f, along with the characteristics of other improved appliance technologies. In the U.S., a 228 kWh/year refrigerator-freezer design was found to be cost-effective based on projected U.S. fuel costs (see Appendix Table G-1). As shown in Table 6.2f, the average cost of saved energy for this technology in the U.S. is \$.035/kWh (1990 U.S.\$), and the marginal cost of saved energy, for the last measure installed, is \$.064/kWh. These costs are

12 Schipper (1991b) notes that high-resolution television is currently up to 10 times more energy intensive than the average current model, but that intensity could decrease dramatically as the technology matures.

Table 6.2c
Saturation and Energy Intensity Values for Electric End-Uses by Region 1988, 2030, and 2100 Values

	Africa			CPA			LA			ME			SEA		
	1988	2030	2100	1988	2030	2100	1988	2030	2100	1988	2030	2100	1988	2030	2100
URBAN HOUSEHOLDS															
Refrigeration															
Saturation	*29%*	*80%*	*100%*	*17%*	*100%*	*100%*	*80%*	*100%*	*100%*	*65%*	*90%*	*100%*	*30%*	*100%*	*100%*
Energy Intensity (kWh/HH)	721	346	228	284	241	228	709	343	228	715	344	228	700	341	228
Lighting															
Saturation	*60%*	*80%*	*100%*	*95%*	*100%*	*100%*	*97%*	*100%*	*100%*	*65%*	*90%*	*100%*	*75%*	*100%*	*100%*
Energy Intensity (kWh/HH)	417	282	240	49	194	240	285	251	240	351	267	240	250	242	240
Air Conditioning															
Saturation	*4%*	*15%*	*30%*	*0%*	*5%*	*20%*	*8%*	*20%*	*50%*	*5%*	*25%*	*50%*	*0%*	*6%*	*20%*
Energy Intensity (kWh/HH)	1,700	667	667	667	667	667	899	667	667	700	667	667	667	667	667
Other Appliances															
Saturation	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Energy Intensity (kWh/HH)	326	563	774	148	383	774	231	435	774	1,143	1,040	774	146	382	774
RURAL HOUSEHOLDS															
Refrigeration															
Saturation	*8%*	*43%*	*100%*	*0%*	*38%*	*100%*	*26%*	*90%*	*100%*	Rural and Urban are Combined Above			*1%*	*38%*	*100%*
Energy Intensity (kWh/HH)	721	346	228	284	241	228	714	344	228				350	257	228
Lighting															
Saturation	*7%*	*45%*	*100%*	*75%*	*85%*	*100%*	*45%*	*95%*	*100%*				*6%*	*90%*	*100%*
Energy Intensity (kWh/HH)	158	220	240	25	188	240	306	256	240				72	200	240
Other Appliances															
Saturation*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*				*100%*	*100%*	*100%*
Energy Intensity (kWh/HH)	46	319	774	8	301	774	126	369	774				69	334	774

Table 6.2c (cont.)
Saturation and Energy Intensity Values for Electric End-Uses by Region
1988, 2030, and 2100 Values

	JANZ			US			WE			EE			USSR		
	1988	2030	2100	1988	2030	2100	1988	2030	2100	1988	2030	2100	1988	2030	2100
Refrigeration															
Saturation**	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Energy Intensity (kWh/HH)	610	319	228	1,201	460	228	800	365	228	800	365	228	398	269	228
Lighting															
Saturation	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Energy Intensity (kWh/HH)	576	321	240	1,295	493	240	320	259	240	320	259	240	523	304	240
Air Conditioning															
Saturation***	*63%*	*75%*	*75%*	*100%*	*100%*	*100%*	*0%*	*10%*	*25%*	*0%*	*10%*	*25%*	*0%*	*10%*	*25%*
Energy Intensity (kWh/HH)	300	300	300	2,277	760	535	300	300	300	300	300	300	300	300	300
Other Appliances															
Saturation*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*
Energy Intensity (kWh/HH)	1,611	774	774	3,661	774	774	1,081	774	774	1,087	774	774	1,889	774	774

* The saturation values in the other appliance category are arbitrarily set to 100% in developing regions despite the fact that many households do not have electricity.

** Refrigerator saturation for industrialised regions are normalised to 100%, although actual saturations for the regions may differ. The other appliance category captures the differential energy consumption between 100% refrigerator saturation in the base year, 1988 (and between 0% and actual air conditioning saturation in Europe). By 2030, 1 refrigerator per household is assumed to be achieved in most areas with the average refrigerator stock approaching the energy intensity of the target technology, based on assumed penetration rates.

***Air conditioning saturation in the United States is set at loo% despite the fact that the actual saturation is lower. The energy intensity value is scaled back to reflect this lower saturation.

near or below the marginal costs of producing electricity in many regions of the world[13]. Although beyond the scope of this project, the impact of non-CFC alternatives within refrigeration is an important issue. Though alternative refrigerants, foam blowing agents, and insulating materials such as propane/butane, ammonia CO2 and mineral wool were thought to be less energy efficient than CFC based systems, recent evidence suggests that the impact may be neligible (DDK Scharfenstein, 1992; ICI 1992). Overall energy efficiency within this end-use sector reflects the need to optimise a range of components.

Table 6.2d

Household Refrigeration Electricity Use

Country	Annual Electricity Use (kWh/yr)	Type	Size(litres)	Source
Current Averages (Illustrative Examples)				
US	1200	Refrig/Freezer	510	(UCS et al, 1991)
EC-Ave.	369	Refrigerator	200	(CEC, 1990)
EC-Ave.	608	Freezer	200	(CEC, 1990)
Indonesia	586	Refrig/Freezer	135	(Schipper and Meyers, 1991)
Ghana	900	N/A	N/A	(Sathaye, 1991)
Brazil	435	Refrig/Freezer	250-300	(Geller, 1991)
China	365	N/A	150-250	(Levine, 1991)
Denmark	350	Refrigerator	200	(Norgaard, 1989a)
Denmark	500	Freezer	250	(Norgaard, 1989a)
Denmark	1000	Refrig/Freezer	500	(Norgaard, 1989a)
Improved Technologies				
US	228	Refrig/Freezer	510	(UCS et al, 1991)
LER-200	90	Refrigerator	200	(Norgaard, 1989a)
Denmark	181	Freezer	250	(Norgaard, 1989a)

Based on estimates of current refrigerator energy use and saturation in various regions, and a reasonable rate of penetration of the improved refrigerator design[14], the average regional refrigerator unit consumptions and saturations over time are shown on Table 6.2c. We have assumed that refrigerator saturation will reach a target level of 100 percent, equivalent to one refrigerator per household. Additional stand-alone freezers are accounted for in the other appliance category below.

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13 The marginal cost of saved energy is an important cost measure that can be generalized to other regions, with certain qualifications. The average cost of saved energy is based upon the entire energy savings accrued when moving from an average current US appliances to an improved one. For instance, the improved refrigerator "saves" about 727 kWh relative to its current counterpart; the savings of course will be lower if one starts with a more efficient (not just smaller) unit. However, the marginal cost of saved energy shows the benefit accrued from installing the last measure. In the case of the refrigerator described here, it corresponds to the benefit in installing a vacuum insulation rated at R-58 in an already very efficient refrigerator (374 kWh/year), which saves an additional 146/kWh at a cost of $140 ($1990 U.S. $). Assuming the equivalent of a global free market in energy-efficient technologies, and a real discount rate of 3 percent, the R-58 insulation is cost-effective where that electricity costs more than $.064 per kWh. (1990 U.S. $)

14 As with other appliances, the refrigerator penetration rates are based on experience with technology dissemination and conservation programs in the U.S. (UCS et al., 1991)

Lighting: A most promising technology for improving lighting efficiency is the compact fluorescent light bulb, which uses one-quarter of the electricity to provide the same level of lighting as standard incandescent bulbs, and lasts approximately ten times longer (see Technological Leapfrogging text box). In many developing countries, the use of standard fluorescent fixtures in urban households is already fairly common. Although relatively bulky, compact fluorescent bulbs can be adapted for nearly every household lighting fixture, as well as provide a more aesthetically pleasing light spectrum than standard fluorescents. Other major opportunities for lighting savings include: improved daylighting, skylights, daylight and occupancy sensors.

Our analysis for lighting efficiency improvements parallels the methods used for refrigeration. In this case, a target of 240 kWh per year was chosen based on full use of compact fluorescents in a relatively large dwelling. The European Community indicates the potential to decrease annual lighting electricity use even further to 121 kWh/yr.

Current levels of lighting energy use and potential improvements are shown in Table 6.2e. For developing countries, we assume that all electrified households have access to electric lighting. A considerable number of households currently rely on kerosene for lighting. Although we considered this usage in our model, its overall contribution to energy use and carbon emissions is very small.

Table 6.2e

Household Lighting Electricity Use

Country	Annual Electricity Use (kWh/yr)	Source
Current Averages (Illustrative Examples)		
US	1295	(UCS et al, 1991)
Ghana	1000	(Sathaye et al, 1991)
Brazil	340	(Geller, 1991)
Venezuela	517	(Sathaye et al, 1991)
Denmark	860	(Norgard, 1989a)
Improved Technologies		
US	240	(UCS et al, 1991)
Denmark	301	(Norgard, 1989a)
EC	121	(CEC, 1990)

Other Appliance Use: This category includes clothes washers, dish washers, clothes dryers, televisions, video-cassette recorders, freezers, and other miscellaneous appliances. For this diverse grouping, a relatively high target level was selected, reflecting current U.S. appliance amenities, the highest among all regions, at 2916 kWh/year[15]. A set of cost-effective improvements were applied to this bundle of appliances, to yield savings of 75 percent and a target level of 744 kWh/year. Several of these measures and their savings are shown in Table 6.2f.

This analysis does not necessarily suggest uniform adoption of the same set of appliances in all countries; it merely reflects a level of energy use equivalent to that required for appliance amenities currently typical in the U.S. Depending on local preferences and culture, items such as TVs, coffee makers, rice cookers, fans, irons, and so on, may be more or less relevant. The relatively high appliance amenity levels (current U.S.) leave room for new appliances to emerge, if adoption of the U.S. type appliances (e.g. clothes dryers) is less than global. However, a major increase in energy use from new home appliances, appears unlikely. Most of these devices, such as telephone answering machines and home computers, are electronic

15 Based on personal communication with Robert Mowris, the base consumption values include cooktops and ranges that consume 1059 kWh/yr, clothes washers that consume 539.8 kWh/yr, and freezers that consume 797 kWh/yr as well as other miscellaneous appliances, all at different saturation levels. This category also includes an additional 2.29 GJ of other fuel use for fueled appliances; these too were subject to cost-effective improvements.

Table 6.2f
Residential Electric Appliance Improvements for the U.S.
Measures and Costs of Saved Energy (for year 2020)

End-Use	Unimproved Unit Consumption (kWh/yr)	Improved Unit Consumption (kWh/yr)	% Savings	Example of Technical Measures	Cost of Saved Energy: Average of All Measures ($/kWh)	Cost of Saved Energy: Marginal of Last Measure ($/kWh)
Refrigerator-Freezer	955	228	76%	Condenser anti-sweat heater Demand Defrost sensor and Microprocessor High Efficiency Fans 5.3 EER Compressor R-58 Vacuum Insulation	0.035	0.064
Lighting	1000	240	76%	Replace Incandescent with compact fluorescent	0.023	0.027
Water Heat-Electric	4048	1017	75%	Water-saving Showerhead + aerators Reduce Standby Losses Horizontal Axis Clothes Washer Add-on Heat Pump (COP=2.5)	0.027	0.043
Clothes Dryers-Electric	1059	151	86%	Moisture Termination Insulation Increase washer spin speed (600 to 1200 rpm) Heat-Pump Dryer	0.033	0.069
Stove-Electric	745	455	39%	Bi-Radiant Oven	0.024	0.038
Freezer	797	218	73%	5.3 EER Compressor Condenser anti-sweat heaters R-58 Compact vacuum insulation	0.036	0.054

Source: Analysis done by Robert Mowris for "America's Energy Choices," UCS, 1991.

Table 6.2f (cont.)
Residential Gas Appliance Improvements for the U.S.
Measures and Costs of Saved Energy

End-Use	Unimproved Unit Consumption (GJ/yr)	Improved Unit Consumption (GJ/yr)	% Savings	Example of Technical Measures	Cost of Saved Energy: Average of All Measures ($/GJ)	Cost of Saved Energy: Marginal of Last Measure ($/GJ)
Water Heater-Gas	23.7	12.5	47%	Water-saving Showerhead + aerators Reduce Standby Losses Horizontal Axis Clothes Washer Submerged Combustion plus flue baffle Electronic Ignition	3.9	11.1
Clothes Dryer-Gas	3.8	1.5	59%	Insulation Moisture Termination Increase washer spin speed (600 to 1200 rpm)	4.7	4.7
Stove-Gas	2.2	1.2	45%	Infrared Burner	4.2	4.2

Source: Analysis done by Robert Mowris for "America's Energy Choices," UCS, 1991.

with relatively low energy use characteristics compared with other standard appliances (Schipper and Meyers, 1992).

Space Heating

Space heating accounts for up to 60-80 percent of current household energy use in industrialised countries (Goldemberg et al., 1988, Schipper et al., 1985, Schipper and Cooper 1991). The only developing region with a high level of space heating use is Centrally Planned Asia. In China, approximately 36 percent of all households heat their homes, mostly with coal (Zhang, 1991).

Among the more important recent factors affecting space heating trends are:

- Widespread adoption of central heating in most industrialised countries. Therefore, this end use can be considered as relatively saturated, except possibly in the U.K. and Japan. (Schipper and Meyers, 1992)

- Growth in per-capita dwelling size, and in the area that needs to be heated (or cooled). This effect results in part from the declining number of persons per household. Increases in per-capita dwelling size are thus implicit in our scenario due to the continuing decrease in persons per household in all regions. Schipper and Meyers (1992) suggest that while significant in the recent past, the effects of dwelling size growth is likely to diminish in impact in the future, among most OECD countries, with the possible exception of Japan.

Numerous measures can be taken to greatly reduce space heating demand in both new and existing residential buildings, by improving heating equipment and building thermal integrity. Well insulated houses can reduce heat requirements by 70 to 90 percent, compared with average buildings in Sweden and the U.S.; evidence suggests that the net additional cost may be relatively small compared with the total cost of conventional houses (Goldemberg et al., 1988). Electric heat pumps and improved furnaces (e.g. condensing gas) offer the potential for considerable savings as well. Incorporation of passive solar designs in new buildings can offer additional energy use reductions. The savings potential is high for both existing and new construction.

Furthermore, other innovative automated energy management technologies can further reduce energy use. For instance, improved windows can automatically adjust their opacity depending on season and time-of-day, and so-called *superwindows* contain a vacuum or transparent gel between two panes to achieve insulation levels similar to well-insulated walls. According to one source, such windows may cost from 20-50 percent more than conventional windows, but provide a payback within 2 to 4 years (Bevington and Rosenfeld, 1990).

Regional space heating intensities are shown in Table 6.2g. For North America and Western Europe, we project that savings on the order of 65 percent (71 percent electricity; 58 percent fuel) can be achieved over the next 40 years. Subsequently, we assume modest improvements of approximately 0.5 percent per year, as new innovations and increased use of passive solar design enable a continued decline in heating energy use. Our projected savings targets are supported by several studies, in particular the recent detailed analysis for the U.S. For instance, in the U.S. cost-effective heating energy savings for existing and new residential buildings range from 52 percent (retrofit multi-family, fuel heat) to 88 percent (retrofit single family, electric heat) by 2030 (UCS et al., 1991). These projected savings for the U.S. are based on a combination of measures that include low energy windows, heat pumps, and improved insulation. These savings also consider the reduction in incidental heat gains from the increase in household appliance efficiency. By comparison, looking at the entire OECD region (JANZ, U.S.,WE), Schipper and Meyers (1992) project under a scenario of moderate effort (marginal cost pricing, removal of subsidies, incorporation of externality costs), savings of over 50 percent on a per capita basis are possible over 25 years. `Vigorous effort'/'comprehensive' retrofits programs, higher energy prices) could achieve 65 percent savings in 25 years. With declining persons per household, in the OECD, savings on a per household basis would be even higher.

In Eastern Europe and the USSR, the highly inefficient use of space heating has beenwell documented (Schipper and Cooper, 1991; Chandler et al., 1990). We have assumed that improvements to the levels found in Western Europe are easily possible, suitably adjusted for climatic differences.[16] In JANZ, we expect that the increases in interior dwelling size and potential increases in indoor temperature will offset all but minor (10 percent) energy intensity (per household) reductions from the already relatively low space heating energy use in this region.

For China, our estimates are based on two recent studies (Zhou, et al., 1989, Zhang, 1991). Increased dwelling size and higher comfort levels offset most building efficiency improvements and result in only minor energy intensity improvements.

Table 6.2g

Space Heating Energy Intensities (GJ/Household)

Region		1988	2030
CPA	Fuel	16	15
	Electricity	-	8
EE	Fuel	47	20
	Electricity	37	11
JANZ	Fuel	15	14
	Electricity	12	11
U.S.	Fuel	68	29
	Electricity	54	16
USSR	Fuel	64	33
	Electricity	52	18
WE	Fuel	47	20
	Electricity	38	11

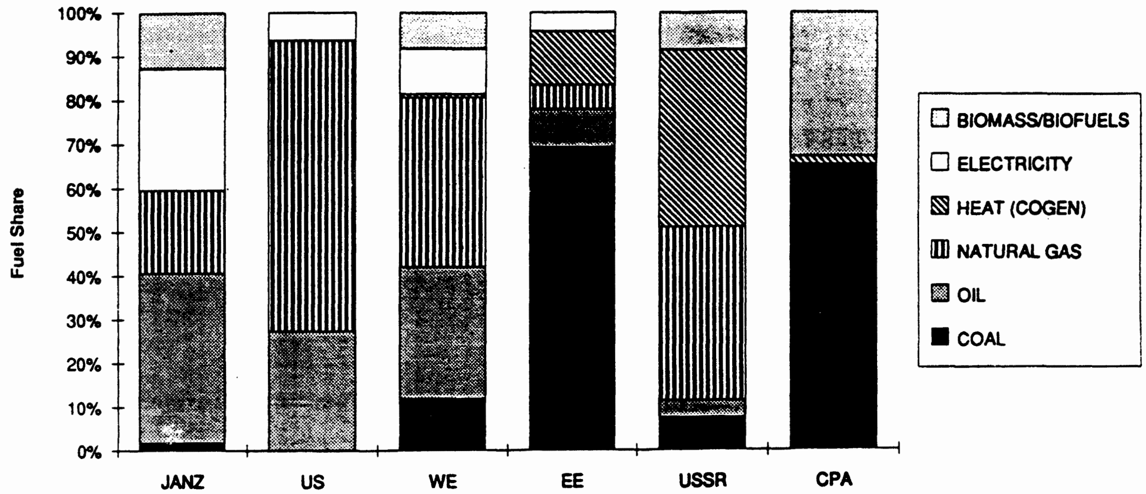
In the industrialized regions, 75 percent of the 1988-2030 space heating intensity reductions are achieved by 2010. In CPA, approximately 50 percent of the 1988-2030 reductions are reached by 2010.

Since space heating accounts for a large fraction of direct fossil fuel combustion in the residential sector, fuel switching opportunities are very important. This scenario embodies a rapid transition to lower carbon fuels for space heating, as illustrated in Figure 6.2f. Natural gas provides an important substitute for oil and coal, particularly in Eastern Europe and the former USSR, over the next 40 years. Electricity can also play an important role in reducing carbon emissions, provided that it is used with high-COP (coefficient of performance) heat pumps, and in regions where renewable sources provide a significant fraction of the electricity requirements. The transition to electricity is more pronounced after 2010 when renewable sources and high efficiency fossil technologies come to dominate electricity supply in most regions.

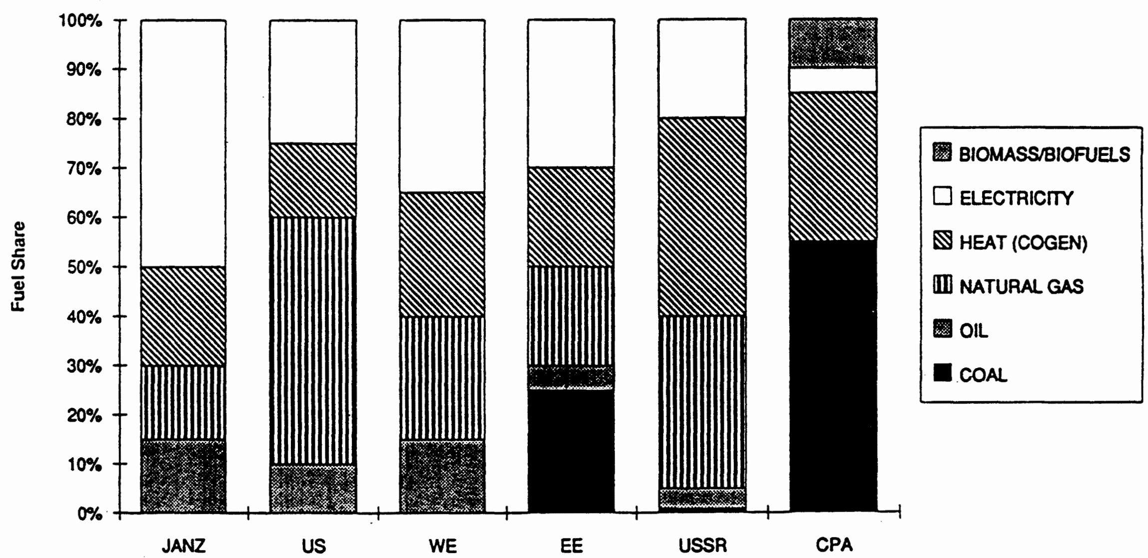
District heating can offer an important contribution in more densely settled areas, and in areas where district heating is already well established: Northern and Eastern Europe, Russia, and China. We have assumed particularly rapid growth in district heating in China, based on several studies (Zhang, 1991; Zhou, et al., 1989). For instance, the Chinese Institute for Nuclear Energy Technology suggests that the penetration of district heat could increase from 7 to 12 percent by the year 2000, while others project 40 percent by 2030 (Zhang, 1991). Small on-site cogeneration units, that could be used for multi-family complexes, are also included in this category.

16 According to Schipper and Cooper (1991), the annual heating degree days for the former USSR is 4600, based on an 18°C base, compared with an average of approximately 2760 for six European countries (Schipper et al, 1985). On this basis, we assume that heat requirements will remain higher in the former USSR by a factor of 1.66.

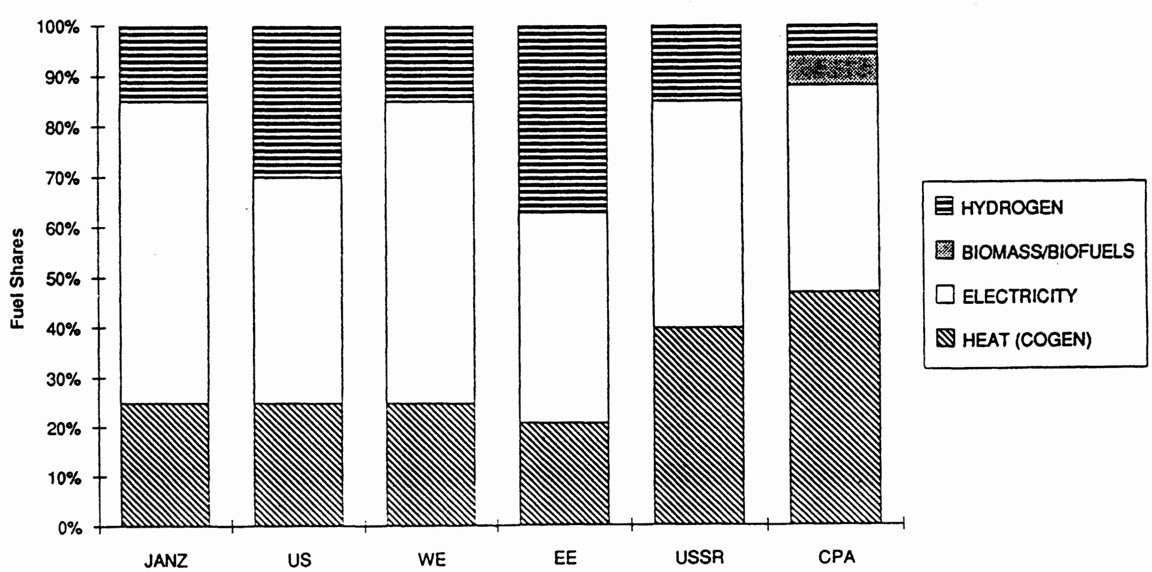
Figure 6.2f
1988 Space Heat Fuel Share by Region



2030 Space Heat Fuel Share by Region



2100 Space Heat Fuel Shares by Region



It is expected that the direct use of coal for space heating could be largely eliminated for most regions by 2030. In Eastern Europe and China, complete substitution is assumed to take until the year 2100, due to the current dominance of coal and policy emphasis on other sectors. Similarly, oil use decreases throughout the period.

Water Heating

Technologies for heating water differ significantly among regions: from the traditional biomass three-stone fires and stoves that are used in much of the developing world, to the point-of-use electric heaters used typically in Europe and many other regions, and the central storage water heaters that predominate in the U.S. For the purposes of this analysis, we have assumed convergence of hot water requirements to relatively high industrialised country levels consistent with the hot water requirements for household appliances such as dish and clothes washers.

There are great opportunities for improvement in all types of water heating. As an example, heat-pump water heaters can deliver up to 3 times the hot water per unit energy as current U.S. electric water heaters (UCS et al., 1991; Koomey et al., 1991). Heat pump water heaters may not make practical or economic sense in many regions. Numerous other measures, such as tankless or point-of-use systems, reduced distribution losses, and more efficient showerheads and faucets can all contribute to reducing energy use for water heating.

Table 6.2h

SOLAR WATER HEATING POTENTIAL

		-------- % of Population --------		
	Population (millions)	in Favourable Climate Zone	in Dispersed Housing	Saturation Potential*
AFR	575	100%	36%	36%
CPA	1070	90%	32%	35%
EE	115	35%	5%	15%
JANZ	140	100%	14%	14%
LA	415	100%	21%	21%
ME	110	100%	25%	25%
SEA	1535	100%	36%	36%
U.S.	240	100%	15%	15%
USSR	280	30%	6%	20%
WE	455	50%	9%	9%

* The saturation level is reached by 2030 in our analysis.

Source: Adapted from Dessus et al., 1991

Central storage gas water heating systems can also be improved by 47 percent, while point-of-use electric water heaters in Brazil can increase in efficiency by 16 percent (Geller, 1991; UCS et al., 1991).

Solar water heating shows great promise, particularly in sunnier regions. A Japanese study suggests that "with significant reductions in installation cost, about half of private homes are expected to be equipped with a solar photovoltaic system, and/or solar water heaters, by 2010" (Yamamura, 1991)[17]. A recent analysis by the Chinese Institute of Nuclear Energy Technology (1991) found that solar water heaters could provide one of the least expensive options for reducing carbon emissions. Our assumptions regarding solar heating potential to 2030 are drawn from Dessus et al. (1991), and are shown in Table 6.2h. These assumptions are relatively conservative over the long term, when solar water heating could achieve significantly deeper penetration. Using modern passive downpumpers and selective surfaces, solar water heating can be as cost-effective as fuel or electricity in most climatic areas[18].

Based on analyses of hot water requirements and efficiency improvements for the U.S., we assume a target energy intensity for electric water heating of 3.4 GJ/household (UCS et al., 1991, and Koomey et al., 1991). While the target for fuel and solar heating is approximately 10 GJ/household (UCS et al., 1991).

We assume a mix of sources for meeting future hot water demands that emphasizes solar and electric sources, with LPG, natural gas, and biofuels remaining important fuels over the next 40-50 years as illustrated in Figure 6.2g. In the developing regions, it is assumed that hot water requirements will be met increasingly from electricity, solar power, and biofuels, as the use of traditional biomass fuels declines. District heating can also be used effectively for hot water demands. The saturation of modern water heaters remains low in most developing countries, but we project this to rise significantly with income, to reach 100 percent by 2030 in urban areas, and 2100 in rural areas.

<u>Cooking</u>

Cooking energy intensities are specified separately by region, respecting differences in diet and staple foods and cooking practices. Most types of cooking devices show considerable potential for improved efficiency. Gas and electric stoves efficiencies can be improved by 45 percent and 39 percent respectively, as shown in Table 6.2f. These projected savings are extended to all regions.

During the transition to more convenient fuels, the dissemination and use of improved wood, charcoal, and residue stoves can play an important role in reducing stress on biomass resources, while potentially reducing labour time in fuel collection and the costs for purchased biomass fuels.

Improved stove programs have met with mixed success over the past 20 years, due to poor stove testing, ineffective dissemination programs and other problems. Recent efforts have begun to overcome some of the cultural and institutional barriers, with a better recognition of local needs and practices. Particularly promising have been improved charcoal stove dissemination efforts in Kenya and Tanzania. In Kenya, a sustainable local stove production and marketing system has already distributed over 500,000 stoves, while in Niger and Burkina Faso, over 350,000 improved stoves have been disseminated (Davidson and Karekezi, 1991). Table 6.2i below shows the estimated improvement in traditional biomass use assumed in this scenario.

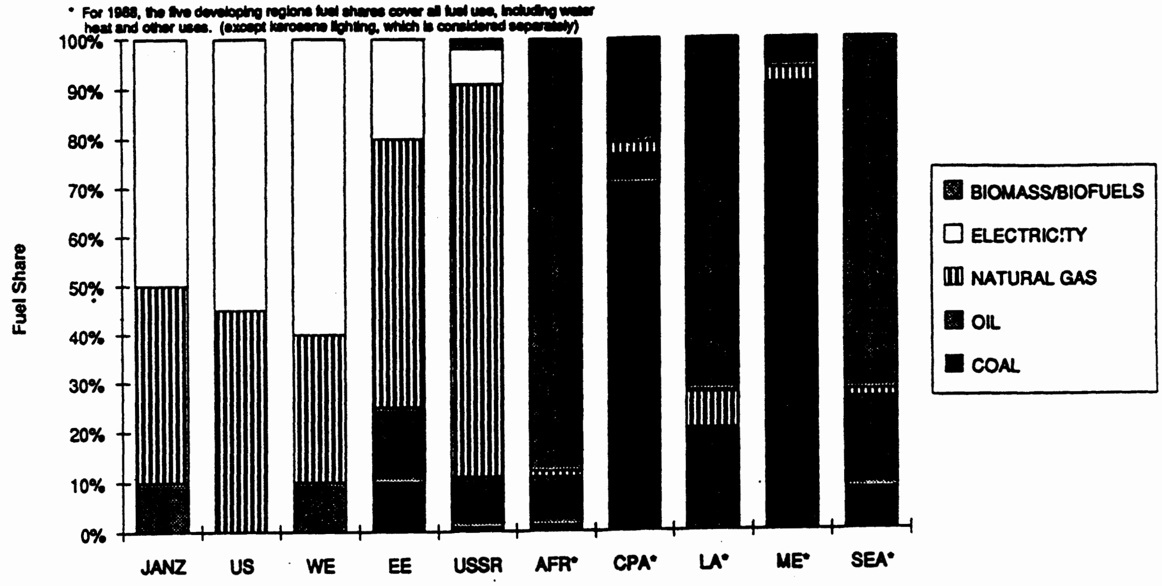
In terms of fuel switching, we assume some switching to electricity in most regions, but maintain a sizable fraction of households on gas fuels, through 2100, as shown in Figure 6.2h. By 2100, we assume for modelling purposes one-third hydrogen, one-third biofuels,

17 Attributed to "Japan's Energy Supply and Demand Outlook", Nov. 1990.

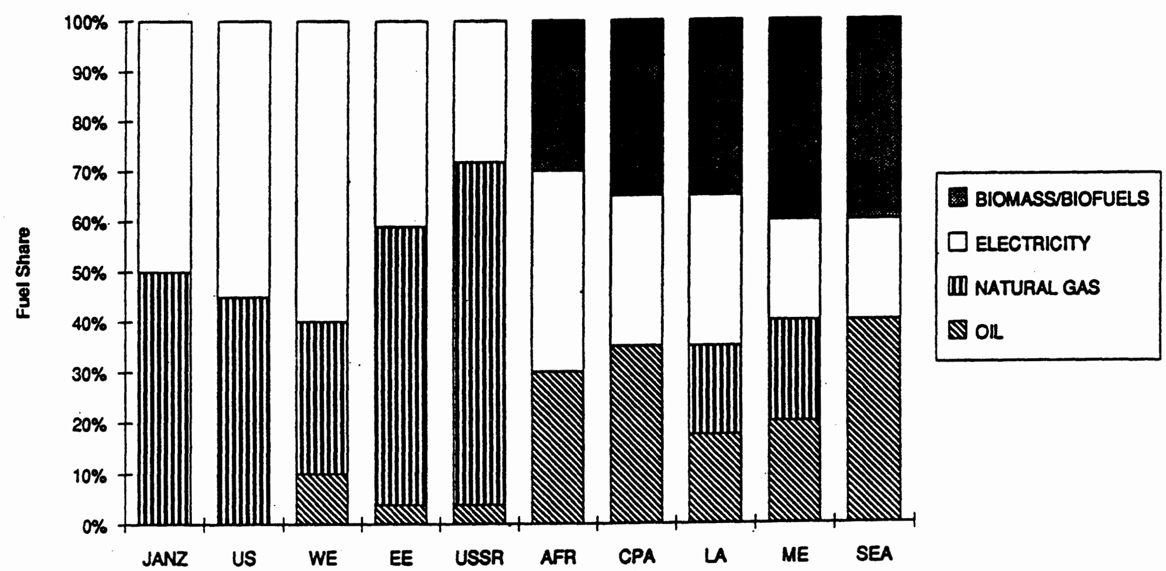
18 Based on personal communication, Amory Lovins. Data from 'The State of the Art: Water Heating', Rocky Mountain Institute, Snowmass, Colorado.

Figure 6.2h

1988 Cooking Fuel Shares by Region



2030 Cooking Fuel Shares by Region



2100 Cooking Fuel Shares by Region

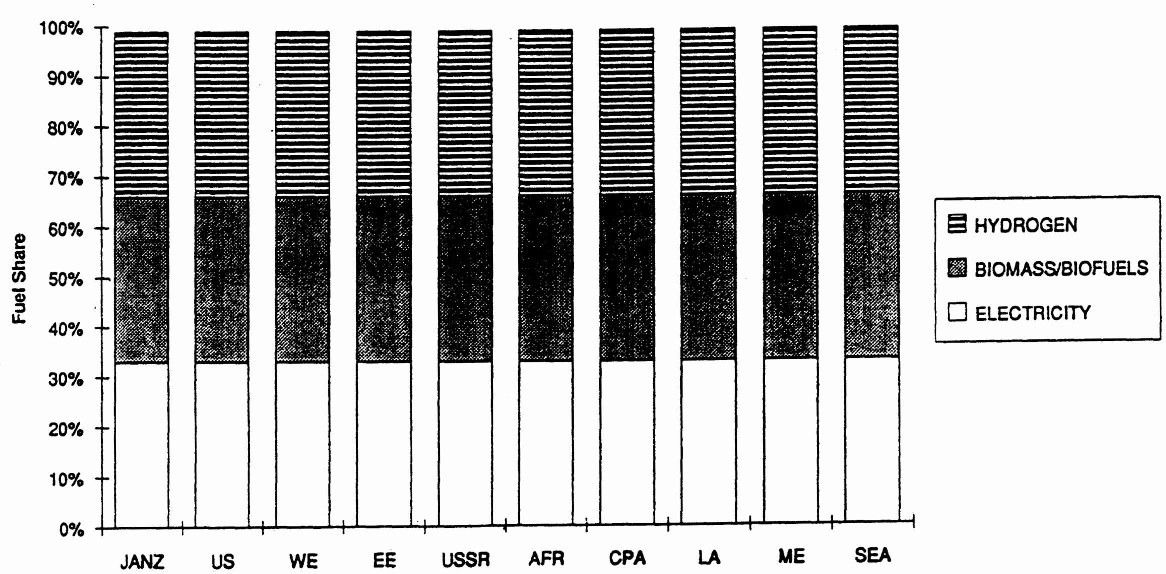
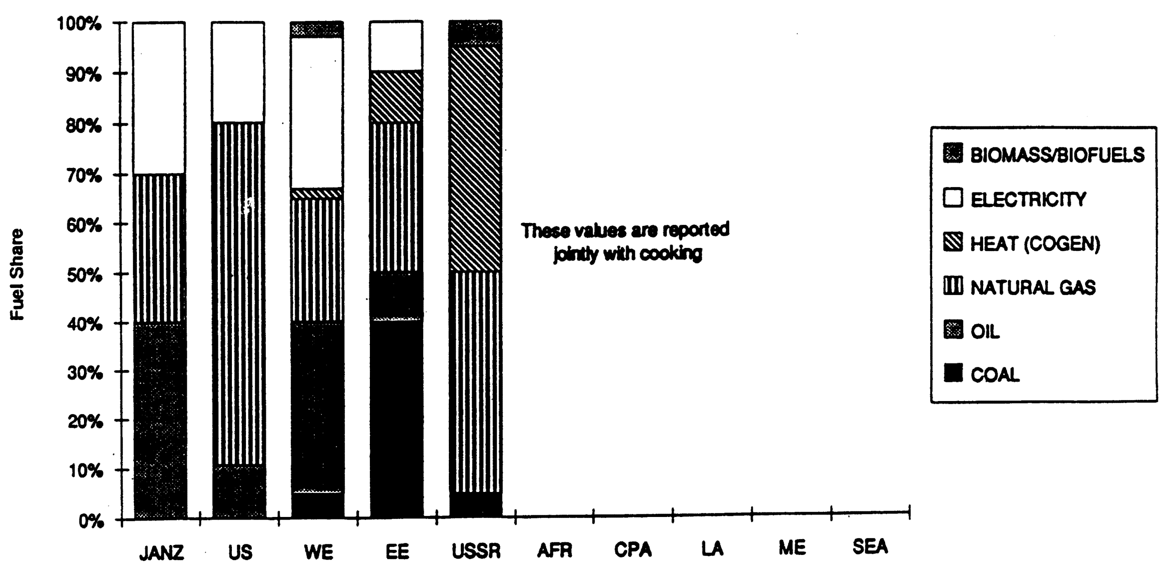
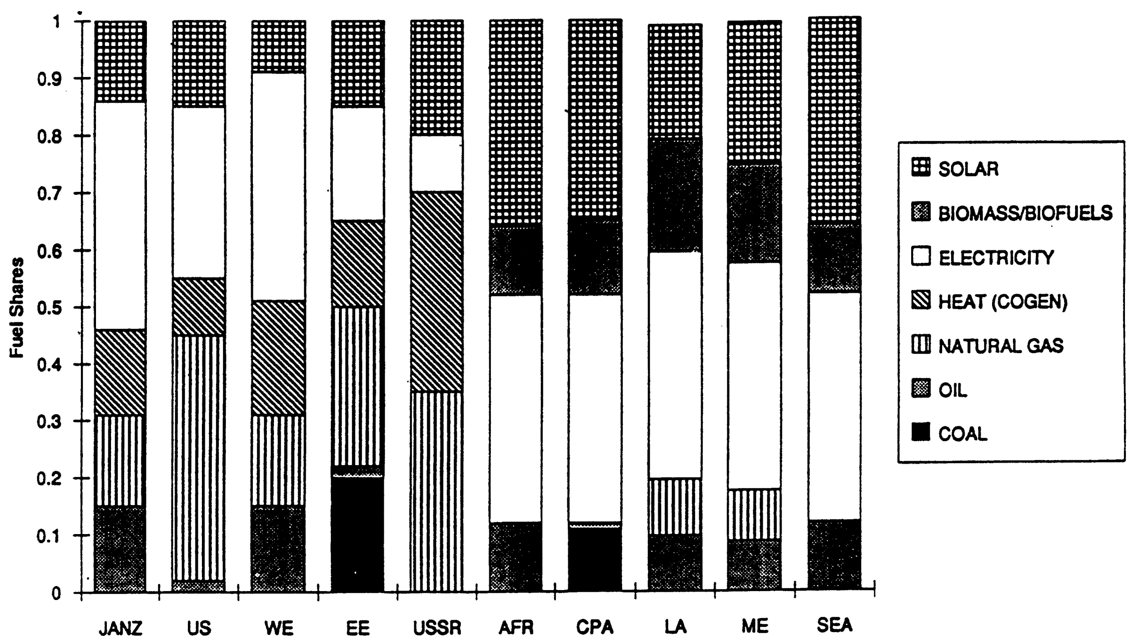


Figure 6.2g

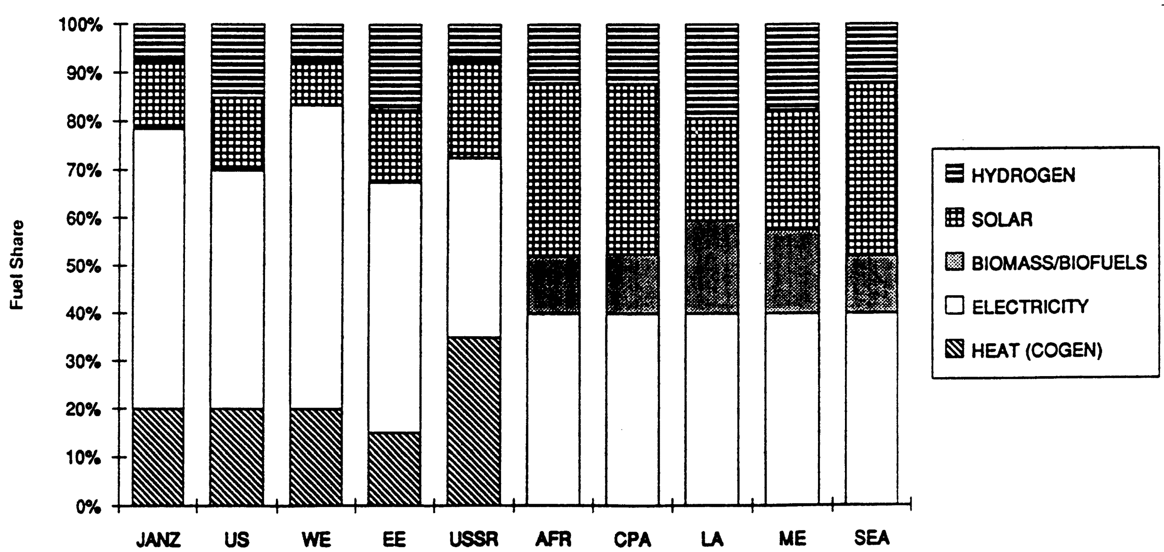
1988 Water Heat Fuel Shares by Region



2030 Water Heat Fuel Shares by Region



2100 Water Heat Fuel Shares by Region



and one-third electricity.

Table 6.2i

Regional Efficiency Improvements In Traditional Biomass Use

Region	2025 Efficiency Improvement
Centrally Planned Asia	47%
Middle East	53%
Africa	62%
Latin America	57%
South/South East Asia	50%

Adapted from Sathaye, et al., 1989.

Space Cooling

Residential space cooling is currently a relatively insignificant end-use, except in warmer regions of the U.S., and among higher income residents of tropical countries. However, with rising incomes in developing countries, the potential exists for a rapid increase in air conditioner ownership and resulting electricity use[19]. Among industrialised countries, on the other hand, major increases in the penetration of air conditioners will likely be more limited, and are expected here primarily in southern regions of Europe and the former USSR.

Many space cooling measures are relatively simple. For instance, a well shaded house (e.g., using trees), with reflective or light-coloured paint can reduce cooling load from 50 to 80 percent on a hot afternoon (Bevington and Rosenfeld, 1990). Passive cooling design measures that encourage night radiation of heat and good ventilation can also improve comfort levels, particularly in tropical climates, where such measures have often been practised in sophisticated traditional architecture. In temperate climates, many of the building shell measures that reduce heating requirements, such as insulation and superwindows, also help to reduce cooling load.

Current and projected saturation levels and electricity intensities for air conditioning are shown in Table 6.2c. In our analysis, we assume that the saturation of air conditioners will rise to significant levels among developing regions, ranging from 20-90 percent by 2100. For the U.S., average energy savings of 66 percent can be achieved in a cost-effective manner; we also assume that air conditioner ownership levels already reflect full saturation (UCS et al., 1991). In Japan, air conditioner ownership has grown dramatically, up from 12 percent in 1973 to 63 percent in 1988 (Schipper and Meyers, 1992). At the same time, average unit (household) consumption dropped from 352 to 299 kWh. We assume an increase to 80 percent saturation of JANZ region households and 25 percent saturation in Eastern Europe and former USSR households by 2030, at the current average unit consumption of 300 kWh.

19 For example, air conditioner ownership in Taiwan increased from 12 to 29% during the 1980s (Schipper and Meyers, 1992). As discussed below, Busch (1990) points out that in Thailand, cultural factors such as dress and acclimation to a warmer climate, lead to higher measured temperature and humidity comfort levels among building occupants. Also the more open building designs typical in tropical countries incorporate many passive cooling features. These effects could temper the potential growth in cooling demands.

6.3 Service Sector

6.3.1 Methods

This sector includes all demand-side activities not included in the industry, transport, and residential sectors. While it includes agriculture, we refer to this category as the service sector throughout most of the report, since with a few notable exceptions, agriculture accounts for only a small fraction of total `modern' energy use. We assume energy use in this category is governed primarily by trends for service activities and building stock.

The service sector, including both government and private activities, is a major component of the OECD economies, and of rapidly growing importance in centrally planned and developing countries. The service sector comprises a mix of office (government and private), retail, education, health care, entertainment establishments that use energy for lighting, cooling, heating, ventilation, refrigeration, and other end-uses. In our service sector model, we do not explicitly distinguish among building types and end-uses, as the globally available data do not allow such distinctions, particularly among developing countries. Nonetheless, we do capture end-use differences in our estimates of energy efficiency improvements, as discussed in Section 4, which are based on analysis of savings by end-use in typical service sector buildings[20]. Furthermore, data suggest that differences in energy use (per unit area) among service sub-sectors are not significant or stable enough (among countries) to justify disaggregation[21].

Our model for projecting service sector energy use is thus, as follows, for each region:

$$E_{t,f} = GDP^s_t * EI_{t,f} * FS_{t,f}$$

where,

E is the service sector energy use in time t and energy source f,
GDP^s is the GDP for the service sector (1985 U.S. $),
EI is the energy intensity in year t, either for fuels or electricity (GJ/1985 U.S. $),
FS is the fuel share of energy source f, for non-electric consumption, in year t.

Since energy use in the service sector is determined by the building stock, total building floor space (e.g., in square meters) would be a better indicator of service sector energy use than economic activity. Total building floor space indicates the area that needs to be heated, cooled, or illuminated. We implicitly assume that building floor space increases proportionately with economic activity as reflected in GDP. This assumption is conservative and overestimates floor space, as more efficient use of space (greater opening hours for service establishments) and higher value added activities in the future could be expected to decrease the ratio of floor space to service GDP. In fact, recent data for the U.S. and U.K. suggest that

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20 In projecting efficiency improvements, we utilize several country-level studies that distinguish among end-uses, e.g., for Brazil (Geller, 1991a), Thailand (Busch, 1990), and the US (UCS et al, 1991).

21 According to data from Schipper and Meyers (1992), subsectoral energy intensity in the US in 1986 ranged between about 600 MJ/m2 for assembly and warehouse to about 1200 MJ/m2 for offices and 1500 MJ/m2 for "other", with an overall average of about 1000 MJ/m2. Although these differences appear significant, all are within 40-50% of the average, and variations among countries (e.g. with Japan) seem to indicate that meaningful, large differences among subsectors would be difficult to justify and largely unnecessary for long-term global projections. This is partly due to differences in how services, such as education, are organized and delivered, (classroom sizes, hours of schooling, etc). Country-level studies would be far more useful for identifying service subsector trends and effects.

floor area has been increasing less rapidly than value added[22]. In the U.K., service sector value added grew twice as fast as floor space from 1975 to 1985. A continuation of these trends, which would appear quite likely, would drive service sector energy requirements considerably lower than those projected here.

In several developing countries, where agriculture remains a major fraction of total economic activity, the energy consumed by agriculture can be significant. Considerable biomass resources can be used for crop curing and drying. In countries heavily reliant on irrigation such as India and Pakistan, water pumping can account for up to about 20 percent of total electricity use (Levine et al., 1991; Tata Energy Research Institute, 1988). Declining ground water resources impose limits on future growth of this end-use (Reddy, 1991), although over the short-term and with deeper wells, this use could increase. Our estimates of conservation potential for the service sector implies improvements similar to those attainable for irrigation pumpsets[23]. Overall, the lack of disaggregation of the agricultural energy use within the service sector, given the structural shifts of economic development over the long-term, does not significantly affect our final results.

6.3.2 Service Sector Results and Analysis

Our scenario shows service sector energy demand increasing faster than any other sector (1.1 percent per year) from 1988-2100. Total service sector energy consumption grows over 3-fold, from 30 EJ in 1988 to almost 100 EJ by 2100, due in large part to structural economic shifts to the provision of services from primary production and manufacturing (see Table 6.3a). In the North, this shift is already underway. In the South, rapid growth in services would be expected to accompany industrialization and the sector dominates overall energy demand thereafter[24]. The evolution of service sector energy consumption by region is shown in Figure 6.3a.

As in other sectors, service sector energy use in the scenario is characterized by a shift from the North to the South. OECD service sector energy use declines throughout the scenario, from 16 EJ in 1988 to 13 EJ in 2100. In the countries of the former USSR and Eastern Europe, service sector energy use initially increases about 24% from 7 EJ to 10 EJ reflecting structural shifts into the sector before declining to 6 EJ as efficiency measures dominate. In the South, service sector energy use rises throughout the scenario. Energy use more than doubles between 1988 and 2030 from 6 EJ to 17 EJ. From 2030 to 2100, energy use increases an additional 4.7 times to 80 EJ due to the combined effects of economic growth and structural shifts.

Future service sector activity and hence energy use will depend on the nature of services utilized: business services (accounting, finance, etc.), restaurants, hotels, retail stores, and so on. In this scenario, we have not attempted to distinguish future changes in the mix of services. As noted above, the variation in energy intensity among sub-sectors is far less than that found within the industrial sector.

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22 F.W. Dodge data for the U.S. as referred to in Schipper, 1991. For the U.K., based on personal communication with Gerald Leach (ETSU report).

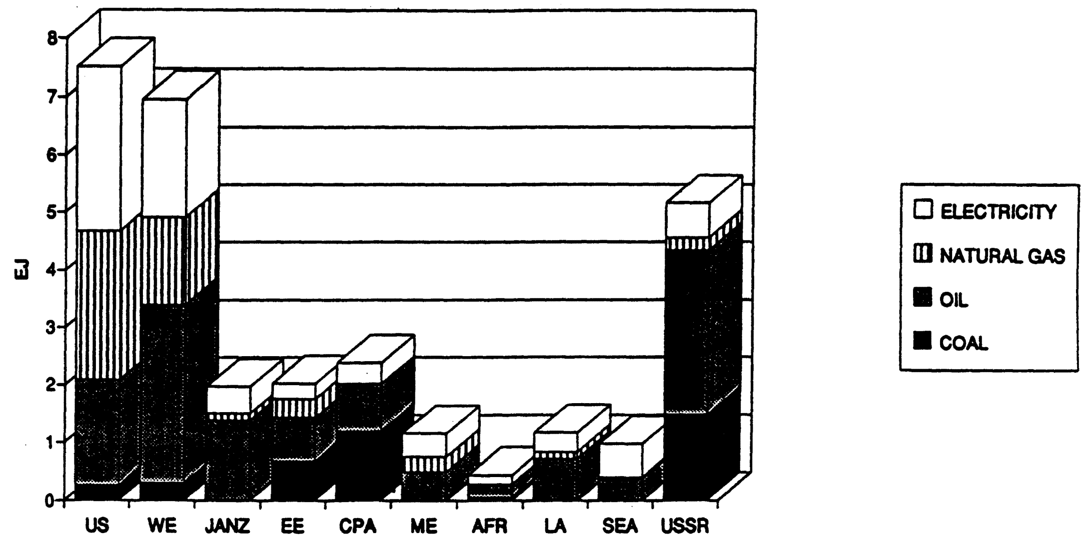
23 Studies have shown the potential for significant improvements in pumpset efficiency. In Pakistan, pumps operate at efficiencies 70 percent below what is technically achievable and 20 percent below what could be attained with cost-effective retrofits (Levine et al, 1991).

24 For instance, Brazil's electric utility, Electrobras, expects more rapid economic growth in services than manufacturing over the next 20 years (Geller, 1991b).

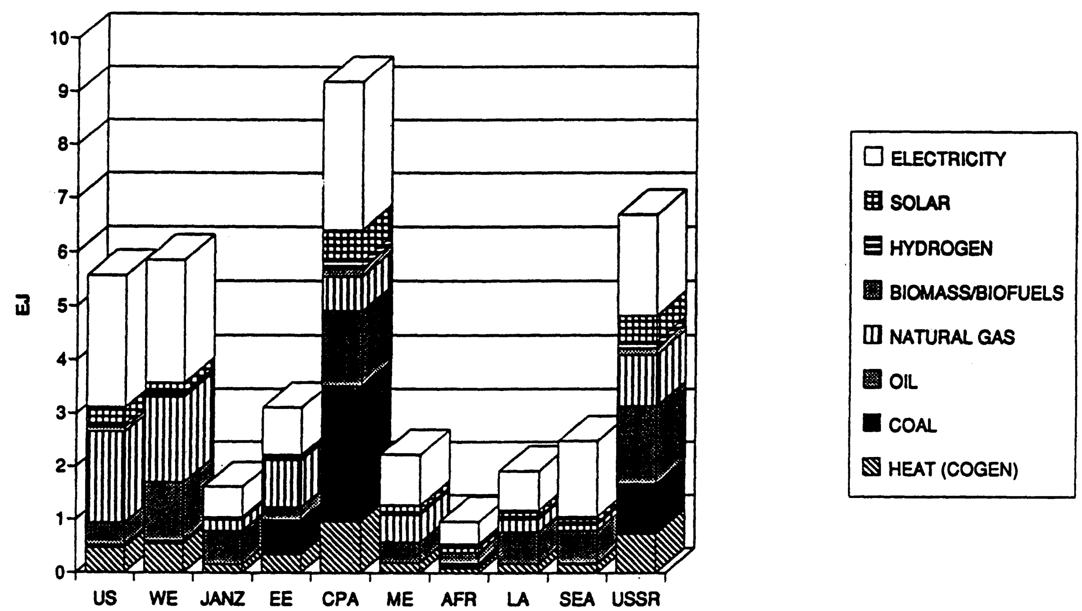
Table 6.3a
Service Sector Energy Consumption
by Region
EJ

	1988	2000	2010	2030	2100
AFR	0.44 *(1%)*	0.53 *(2%)*	0.61 *(2%)*	0.97 *(2%)*	23.59 *(24%)*
CPA	2.39 *(8%)*	3.93 *(12%)*	5.21 *(16%)*	9.19 *(23%)*	14.59 *(15%)*
EE	2.03 *(7%)*	2.24 *(7%)*	2.40 *(7%)*	3.12 *(8%)*	1.47 *(1%)*
JANZ	1.97 *(7%)*	1.90 *(6%)*	1.84 *(6%)*	1.62 *(4%)*	2.16 *(2%)*
LA	1.17 *(4%)*	1.37 *(4%)*	1.53 *(5%)*	1.92 *(5%)*	7.75 *(8%)*
ME	1.16 *(4%)*	1.40 *(4%)*	1.61 *(5%)*	2.23 *(6%)*	5.13 *(5%)*
SEA	0.98 *(3%)*	1.31 *(4%)*	1.58 *(5%)*	2.49 *(6%)*	28.69 *(29%)*
US	7.52 *(25%)*	6.91 *(22%)*	6.44 *(19%)*	5.57 *(14%)*	4.38 *(4%)*
USSR	5.16 *(17%)*	5.71 *(18%)*	6.10 *(18%)*	6.69 *(17%)*	4.89 *(5%)*
WE	6.98 *(23%)*	6.47 *(20%)*	6.07 *(18%)*	5.86 *(15%)*	6.71 *(7%)*
TOTAL	29.81	31.77	33.39	39.65	99.34

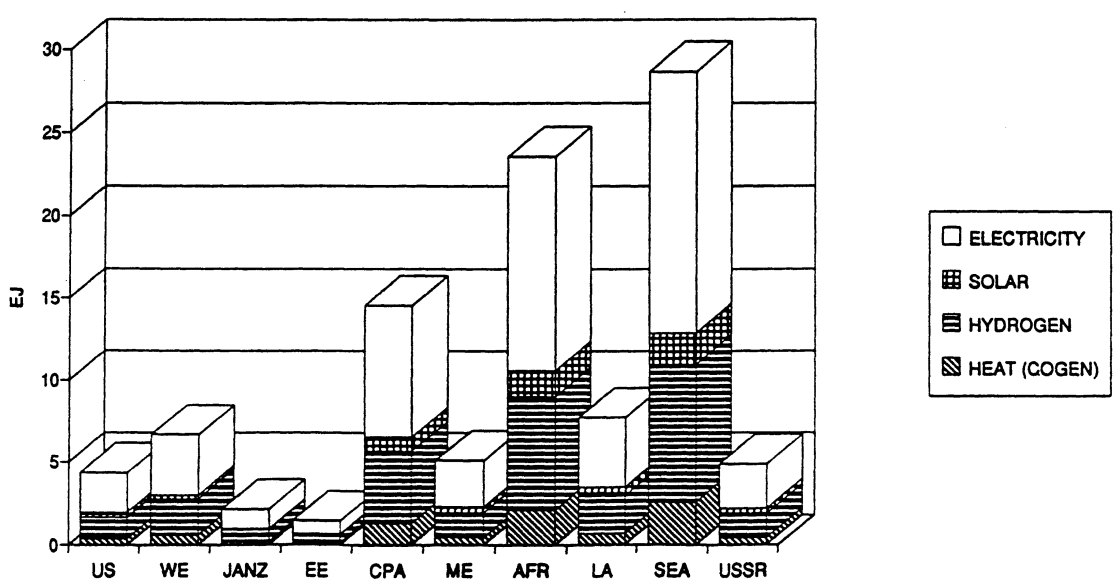
Figure 6.3a
1988 Service Sector Delivered Energy Consumption (EJ)



2030 Service Sector Delivered Energy Consumption (EJ)



2100 Service Sector Delivered Energy Consumption (EJ)



Energy Efficiency

Service sector buildings currently use energy more intensively than residential ones per unit area for lighting, space heating, and cooling. In general, the services tend to be inefficiently distributed to building occupants (Goldemberg et al., 1988). Service sector buildings present excellent opportunities for cost-effective energy savings. Energy costs can typically represent 30 percent of a building's operating budget (Bevington and Rosenfeld, 1990).

Table 6.3b

Service Sector Efficiency Improvements

Country/Region	End-Use	Energy Source	Savings vs. Current Stock	By Year	Annual Savings*	Source/Notes
US, Existing	All	Electric	61%	2030	2.2%	(UCS, et al, 1991)
US, New	All	Electric	66%	2030	2.5%	(UCS, et al, 1991)
US, Existing	All	Fuel	41%	2030	1.2%	(UCS, et al, 1991)
US, New	All	Fuel	37%	2030	1.1%	(UCS, et al, 1991)
Brazil	Lighting	Electric	60%	2010	4.1%	(Geller, 1991)
Brazil	A/C	Electric	40%	2010	2.3%	(Geller, 1991)
OECD	All	Fuel	55%	2010	3.6%	(Schipper&Meyers, 1992)
OECD	All	Electric	65%	2010	4.7%	(Schipper&Meyers, 1992)
Thailand, Office	All	Electric	45%			(Busch, 1990)
Thailand, Hotel	All	Electric	51%			(Busch, 1990)
Thailand, Retail	All	Electric	56%			(Busch, 1990)
US, Sweden	HVAC	Fuel	75%			(IEA, 1987)
US, Large Office	All	Fuel	63%			(IEA, 1987)
US	Lighting	Electric	50%			(IEA, 1987)
US, Existing	Shell	Fuel	40%	2000	4.2%	(OTA, 1991)
US, New	Shell	Fuel	75%	2015	5.0%	(OTA, 1991)
US, New	Lighting	Electric	60%	2015	3.3%	(OTA, 1991)
US, Replace	Lighting	Electric	50%	2015	2.5%	(OTA, 1991)
US	Off. Eqt	Electric	80%	2015	5.8%	(OTA, 1991)
US, Sample Bldg		All	76%			(Goldemberg, et al, 1988)
Sweden, Sample Bldg		All	76%			(Goldemberg, et al, 1988)

* Where not reported, base year assumed to be 1988. Goldemberg, et al data is historical; the remaining sources are projected efficiency improvements.

Many of the same types of measures discussed above for the residential sector (Section 6.2) apply equally to the service sector for improving building thermal integrity and efficient lighting -- and other building comfort-related energy uses. Similarly, near-term energy and CO_2 savings for service sector buildings can be derived largely from retrofitting existing buildings in the North, while elsewhere implementing improvements in new building stock is paramount, particularly in the rapidly industrializing countries.

Several estimates of future service sector energy savings potentials and recently achieved results are shown in Table 6.3b. The results range up to around 75 percent for sample U.S. and Swedish buildings. Even deeper reductions have been shown cost-effective in recent building designs. For example, 74 to 90 percent savings are expected for a California research building designed as part of a local utility pilot project.[25]

Typical measures include:

* utilizing natural thermal storage capabilities of buildings, cutting air conditioning costs by 30-70 percent (Bevington and Rosenfeld, 1990).

* good insulation, that together with thermal storage, can virtually eliminate the need for central heating systems, by using the heat generated by equipment (computers, lights, etc.) and people, even in a climate such as Sweden's (Bevington and Rosenfeld, 1990).

* natural lighting, using light wells, atriums, and superwindows, or adjustable shading to balance heat and light gains.

* more efficient lighting.

* natural shading, using trees.

* heat pumps for water and space heat

* adjustable speed drives in heating, ventilation, and air conditioning (HVAC) equipment.

In an emissions control scenario for the U.S. Congress, the Office of Technology Assessment has estimated that approximately 40 percent of total building (combined residential and service sector) energy use could be reduced in the year 2015. A combination of efficiency improvements and service sector cogeneration could yield net benefits to the economy of up to 28 billion dollars (OTA, 1991). For the service sector, OTA assumed that new building shells could be 75 percent more efficient than 1987 U.S. average, while retrofits could achieve 40 percent improvements in building shell efficiency by 2000. A combination of high efficiency bulbs, ballasts, reflectors, and daylighting can reduce energy use by 50 percent in existing and 60 percent in new buildings (OTA, 1991). Other estimates have indicated lighting savings for U.S. buildings from 70 to 90 percent, using improved fixtures and dimming technologies (Fickett et al., 1990).

In warmer regions, service sector energy use tends to favour electricity, as cooling and lighting tend to be the big energy users. In Sao Paulo, Brazil's largest city, approximately 44 percent of service sector electricity use provides lighting, while air conditioning (20 percent), refrigeration (17 percent), and cooking (8 percent) account for most of the remainder (Geller, 1991b). In Thailand, lighting accounts for 31 percent of total service sector energy use (Busch, 1990).

More efficient lighting generates less heat, and can result in significant additional benefits in terms of reduced cooling loads. Not surprisingly, this phenomenon is most marked in hotter climates. In Thai office, hotel, and retail buildings, lighting improvements can reduce lighting energy use by 70 percent, while at the same time reducing energy needs for cooling (12 to 33 percent, depending on building type), and ventilation (13 to 26 percent) (Busch et al., 1991). The estimated costs of saved energy for these measures are all at or below $.04/kWh

25 Pacific, Gas, and Electric's ACT2 experiment. Personal communication, Amory Lovins.

(1991 U.S.$).

Analysis of energy end uses in Thai commercial buildings found that efficiency measures could cut electricity and on-peak usage, and resulting electricity bills, in half. All of these measures were found to be cost-effective, based on a tariff of $.05/kWh, $9.16/kW (Busch, 1990). Using a detailed electric utility financial model, investments in conservation were shown to be 75 percent less capital intensive than avoided electric capacity investments (Busch, 1990).

Designing commercial buildings to accommodate local needs and preferences in developing countries can also help reduce energy use. For instance, Thai buildings are typically designed to meet American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) standards, which are based on comfort levels acceptable to a white, male, college age population (Busch, 1990). In contrast, Thais consider higher indoor temperatures and humidity levels to be acceptable, and are comfortable 4 degrees Centigrade above the ASHRAE standard (Busch, 1990). Clothing is an important factor; not surprisingly, adopting Western-style dress -- business suit and tie -- can require greater levels of air conditioning.

While increasing use of computers, faxes, and other office equipment could increase electricity use and cooling loads (due to the heat that they generate), efficiency improvements could well offset such increases. As part of their U.S. study, OTA found electronic office equipment could be 80 percent more efficient than current models, based on reduced idle time and improved technology.

Based upon our review of the literature, we find that service sector energy efficiency in the South could improve at an annual rate of 2.5 percent from 1988-2010 and 1.8 percent from 2010-2030, thus yielding a 60 percent reduction in energy intensity by the year 2030. Evidence from detailed studies of Brazil and Thailand shown above that indicate that such rapid improvements are both technically feasible and economically advantageous. In the North, we assume the same 60 percent reduction in energy intensity by 2030, but at a faster rate of 3.0 percent per year through 2010, due to greater ability to implement efficiency improvements and political pressure to reduce carbon emissions. After 2030, we assume a much slower rate of 0.5 percent per year efficiency improvement in all regions.

Cogeneration

Cogeneration makes good sense for many larger commercial buildings, particularly where heating demands are significant. The heat generated can also be used in absorption chillers for air-conditioning systems. In the longer term, with the advent of widely available fuel cell technology (see Section 7 below), roof-top cogeneration systems utilizing biofuels or solar hydrogen as feasible options. During the near term, existing combustion turbine, and soon, steam-injected aeroderivative turbines, offer feasible cogeneration technologies.

The Office of Technology Assessment estimates that 25 GW of cogeneration could be installed in commercial buildings by 2015 (OTA, 1991), at a cost premium of $.02 to .05 per kWh (1987 U.S. $)[26]. This cost translates to $80 to $210 per tonne of carbon saved. We believe that these estimates likely overstate the technical costs of cogeneration systems. Using somewhat conservative assumptions, gas-fired bottoming turbines can produce electricity at a levelized cost of only $.05/kWh (1990 U.S. $), net of heat demand, which is comparable to

26 In OTA's Tough Controls Scenario, total fuel use (excluding electricity) in the combined residential and commercial sectors is about 8-9 EJ. Assuming an 85% capacity factor, and 30% efficiency of electricity production, 25 GW of cogeneration would account for approximately 2 EJ or about 25% of combined residential fuel use in 2015. (See p.324)

electricity costs in the U.S. and elsewhere[27]. In Thailand, payback periods of 1.9 to 6.8 years for service sector cogeneration systems are possible, depending upon whether the system operates to meet building electric load (3.5 to 6.8 year payback) or to its maximum capacity, with sales back to the utility (1.9 to 2.1 years) (Busch, 1990).

Based on OTA, and the high potential payback of cogeneration systems in developing countries with similar energy costs to Thailand, we assume that by 2010, 10 percent of all fuel use is in cogeneration applications, while by 2030 the fraction increases to 20 percent. With the greater need for fuel use for heating in the North, we assume a greater penetration of cogeneration systems up to 30 percent of on-site fuel use in the year 2100.

Renewable Fuels and Fuel Switching

As in other sectors, we simulate a transition away from coal to available renewables and natural gas, and eventually to renewable-based electricity and fuels. Given the availability of low-cost coal resources, and infrastructures based around coal production, we have tempered the transition in China and East Europe, and anticipate coal use to remain high in Africa, where significant resources have begun to be tapped.

We introduce modest levels of active solar heating systems for various service sector building types with large low-grade heat demands such as laundries, combined with available surface area, such as in case of schools and universities. For the U.S., UCS et al. (1991) found introduction of direct solar heating to be cost-effective in meeting 8-10 percent of service sector fuel consumption in 2030 (and 4-5 percent of total demand). In this scenario, we assume that direct solar applications could displace up to 10 percent of 2030 consumption, depending on relative insolation levels of different regions. By 2100, we assume this rises to a maximum of 20 percent in the sunniest regions.

Electricity is assumed to gradually grow to 55 percent of total service sector energy use by the year 2100, based on the advantages of improved electric technologies for space heating, and its high overall convenience[28]. Finally, biofuels and hydrogen offer the renewable fuel options assumed to fully displace fossil fuels by the end of the 21st century. The changing fuel shares are illustrated in Figure 6.3b.

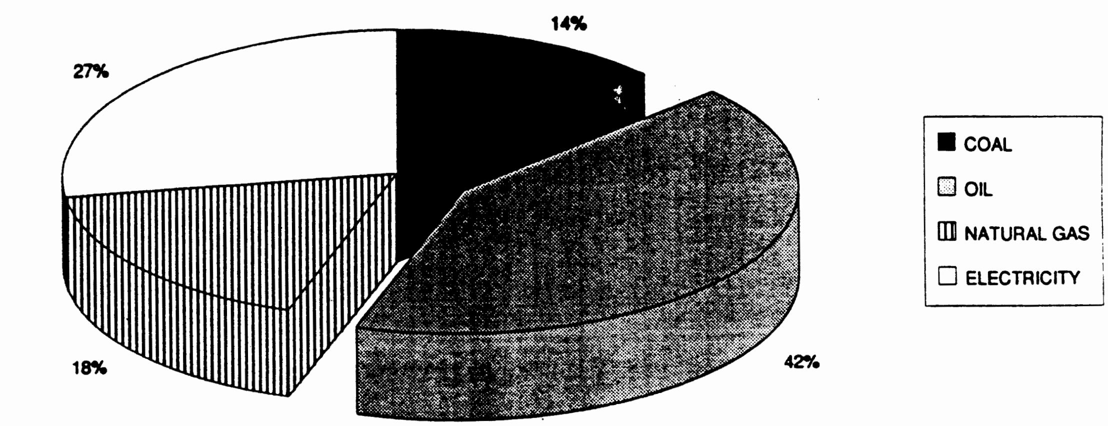
Changes in the Value of Services

In this scenario, we apply improvements in energy intensity on the order of 60 percent due to efficiency improvements alone through the year 2030. As noted in Section 4, our improved equity-based scenario yields income levels in all regions above current OECD levels. Therefore, we expect a related increase in the value added of services to reflect a shift toward higher GDP-yielding service sector activity in developing countries. As examples, consider the rising salaries of teachers, the increasing role of finance-related service sector activities, and more sophisticated health care facilities: all have the effect of increasing service sector value-added per unit of energy consumed. To reflect this effect, we assume a convergence to the same target energy intensity in all regions by the year 2100. This target -- 0.6 MJ/U.S.$(1985) -- embodies the types and values of services currently found in OECD countries, adjusted for efficiency improvements described above. This approach, in effect, represents what many energy models incorporate with income elasticities; in contrast, in keeping with scenario

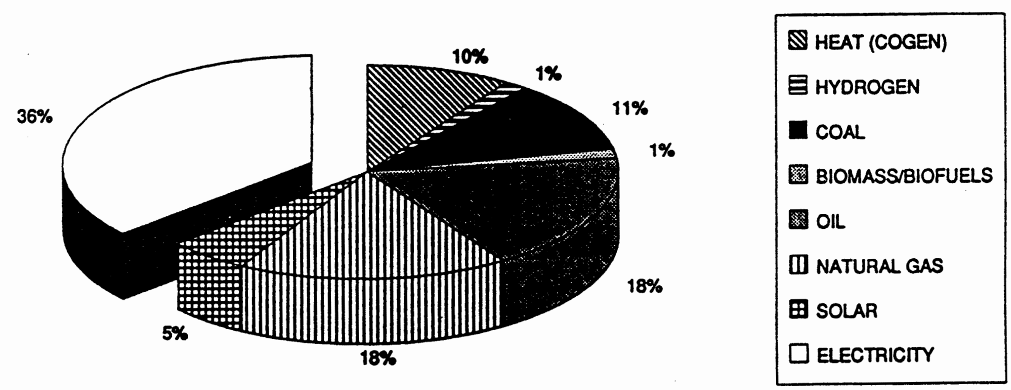
27 See Appendix Table G-8.

28 For instance, an increase in electric share from 40 to 54 percent from 1988-2030, was found to be part of a cost-effective set of improvements for the US commercial sector (UCS et al., 1991).

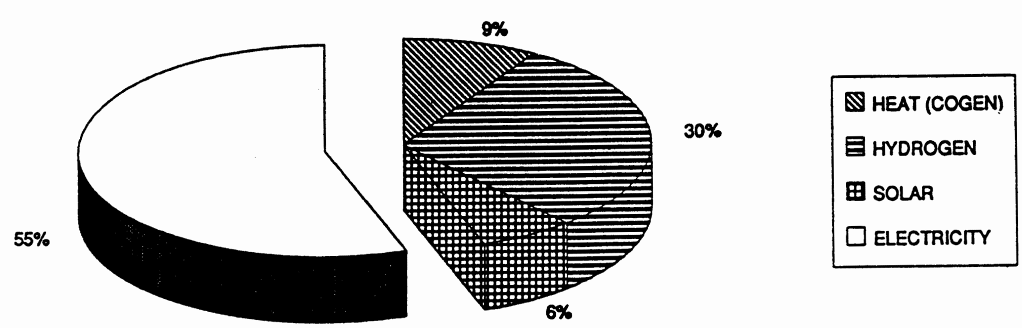
Figure 6.3b
1988 Service Sector Fuel Shares



2030 Service Sector Fuel Shares



2100 Service Sector Fuel Shares



assumptions of technology transfer, it results in standard energy intensities for all regions.[29]

6.4 Industrial Sector

The industrial sector, as defined here, comprises a range of economic activities from primary production to the manufacture of consumer goods. In 1988, the industrial sector accounted for 35 percent of global final energy consumption, more than any other sector.

6.4.1 Approach

We disaggregate the industrial sector into the five most energy intensive sub-sectors[30] -- iron and steel, non-ferrous metals, non-metallic minerals, paper and pulp, and chemicals -- and a sixth category for all other industry. This category includes food processing, textiles, machinery, mining, and other productive sub-sectors[31]. Energy intensiveness here is given as energy use relative to economic activity.

As shown in Table 6.4a, the first five sub-sectors accounted for 61 percent of global industrial energy use in 1988. Figure 6.4a compares the relative proportion of industrial GDP and energy use in these six sectors. In both the South and the North, the five energy intensive sectors account for only 30 - 40 percent of GDP in contrast to 50 - 70 percent of industrial energy use. The structure of disaggregation allows the analysis to reflect the effects of saturation of demand for basic materials and structural shifts in the industrial sector.

Overview

Two sets of factors will influence future energy use and CO_2 emissions from industry. The first set relates to the characteristics of the future industrial sector -- overall economic activity levels, shifts among industrial sub-sectors, and the changing set of products within each sub-sector. The second set relates to how energy is used for production processes -- energy efficiency, process technology and fuel mix. At an aggregate level, we represent these factors using two variables -- *economic activity* (GDP) and *energy intensity* (GJ/GDP) for each sub-sector.

Changes in sub-sectoral economic activity and energy intensity in the scenarios are governed by three considerations: *increasing equity, technological improvements*, and what we will refer to as *standardized industrialization*.[32] Increased equity considerations suggest that by the year 2100 all regions will have reached or exceeded current OECD per capita GDP with corresponding levels of materials consumption. Over the next century, assuming improved inter-regional equity, technological improvements and transfers can enable all regions

29 The source of any differences in existing models would likely be a result of the different starting year intensities.

30 Petroleum refineries are often considered an energy intensive industrial subsector. In our analysis, refinery energy use is accounted for in the energy supply analysis.

31 Significant manufacturing activity in the South currently takes place within the "informal sector." This activity is not well captured by national income and energy statistics, and thus is difficult to assess in terms of energy requirements.

32 In addition, price will affect demands. These effects are considered in the Edmonds-Reilly economic equilibrium model analysis in Section 9.

Table 6.4a

Subsectoral Distribution of Industrial Energy Use (1988)

	Iron and Steel	Non-ferrous Metals	Stone, Clay Glass	Paper & Pulp	Chemicals	All Energy Intensive	All Other
JANZ	32%	6%	9%	4%	9%	61%	39%
USSR	21%	7%	12%	1%	16%	57%	43%
EE	35%	1%	3%	0%	10%	48%	52%
US	20%	0%	5%	13%	14%	53%	47%
WE	23%	4%	12%	8%	19%	67%	33%
AFR	19%	5%	9%	4%	14%	52%	48%
CPA	39%	5%	19%	3%	14%	80%	20%
LA	35%	10%	11%	5%	18%	79%	21%
ME	20%	2%	29%	5%	24%	80%	20%
SEA	34%	1%	11%	3%	15%	65%	35%
WORLD	27%	4%	11%	5%	15%	63%	37%

Note: In the US, non-ferrous metals are included in the iron and steel sector.

Table 6.4b

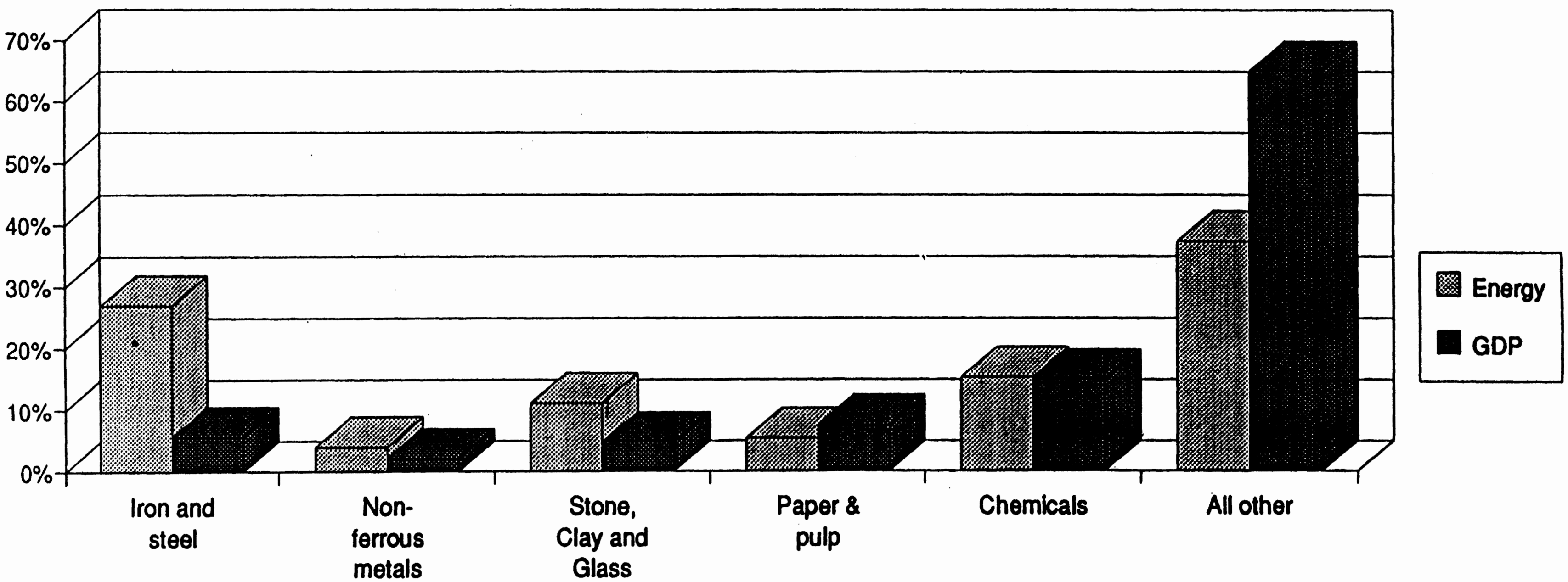
Indicator Commodities By Industrial Subsector

Subsector	ISIC	Commodity	% Sectoral Energy (WE avg.)
Iron&Steel	371	Crude Steel	95%
Non-ferrous Metals	372	Aluminum	42%
Stone, Clay and Glass	361, 362, 369	Cement	50%
Paper&Pulp	341, 342	Paper & paperboard	84%
Chemicals	351, 352, 355, 356	NA	NA
All other	3; 230;290;(-353, -354)	NA	NA

Sources: Howarth and Schipper, 1991; IEA, 1987.

Figure 6.4a

World Industrial Subsectoral Distribution of Global Energy Use and GDP (1988)



Sources: IEA, 1990; Summers and Heston, 1991; UN, 1990.

to reach similar levels of high industrial energy efficiency.

A principle of standardized industrialization implies a model of industrial development in the South that follows the basic pattern observed in the North, the transition from a reliance on primary materials to a more diversified industrial economy. This transition encompasses not only the shifts from industry to services, described earlier, but also among industrial sub-sectors, and within each sub-sector itself.

Given these three considerations, we project energy intensities and per capita economic activity levels to converge across regions, by the end of the next century. In order to adequately project this evolution over time, we have done the following:

1) based the levels of and shifts in economic activity among industrial sub-sectors (e.g. GDP in iron and steel sub-sector), upon changes in the physical production/consumption of indicator commodities (e.g. tonnes steel).

2) over the shorter term (the next 40 years), improved regional energy intensities by sub-sector based upon potential efficiency improvements, using a standard of cost-effectiveness wherever possible. The discussion of potential efficiency improvements can be found in Section 6.4.2.

3) over the longer term, adjusted regional sub-sector energy intensities to match future intensities attained in OECD countries.

4) introduced cogeneration and fuel switching to lower carbon content fuels. This is discussed in further detail in Section 6.4.2 below.

Sub-sectoral Activity Levels

The economic activity within a sub-sector is based on overall economic growth, the proportion of the economy within the industrial sector, relative growth among sub-sectors and the changing activity mix within sub-sectors. While it is possible to use economic indicators alone to *implicitly* reflect these changes, the high degree of aggregation that this leads to can obscure, rather than illuminate, the driving forces of structural change. For example, economic indicators can not explicitly represent the changing mix of products as economies achieve a post-industrial structure. This last shift is of particular importance when determining sub-sectoral energy intensities. For example, in the steel sector in developing economies we expect to see a transition from low carbon steels to higher value specialty alloy steels. In this case, we would expect greater economic activity without a parallel increase in energy use.

While it is beyond the scope of this study to detail all of the changing product needs that are embodied by shifts both between and within sub-sectors, we have selected a simple proxy that allows us to explicitly track representative components of structural change. Where possible, we have chosen an indicator commodity for each energy intensive sub-sector (see Table 6.4b). These commodities generally represent a majority of the energy use in each sub-sector. The table also shows the percent of sub-sectoral energy used for each commodity in Western Europe, ranging from over 90 percent for steel to closer to 50 percent for aluminum and cement. As will be discussed more fully below, the trends in sub-sectoral GDP growth and energy efficiency are derived from projected changes in these indicator commodities, including their relative proportion of sectoral economic activity. For those sub-sectors lacking an adequate representative commodity -- chemicals and all other industry -- we use GDP/sub-sector exclusively.

Currently, materials production is dominated by the industrialised countries of the North. Table 6.4c and Figure 6.4b show relative per capita production of primary materials for

Table 6.4c

Per Capita Production of Primary Materials (1988)
(kg/capita)

	Steel	Aluminum	Cement	Paper&Pulp
AFR	22	1.0	75	3
SEA	32	0.4	88	4
CPA	55	0.5	38	2
LA	100	3.7	200	21
ME	40	4.5	558	4
US	368	16.0	288	241
WE	436	12.7	543	122
EE	381	2.9	354	30
USSR	575	8.6	489	30
JANZ	786	10.1	590	140

Sources: UN 1990; UN 1990; UNCTAD, 1990

Table 6.4d

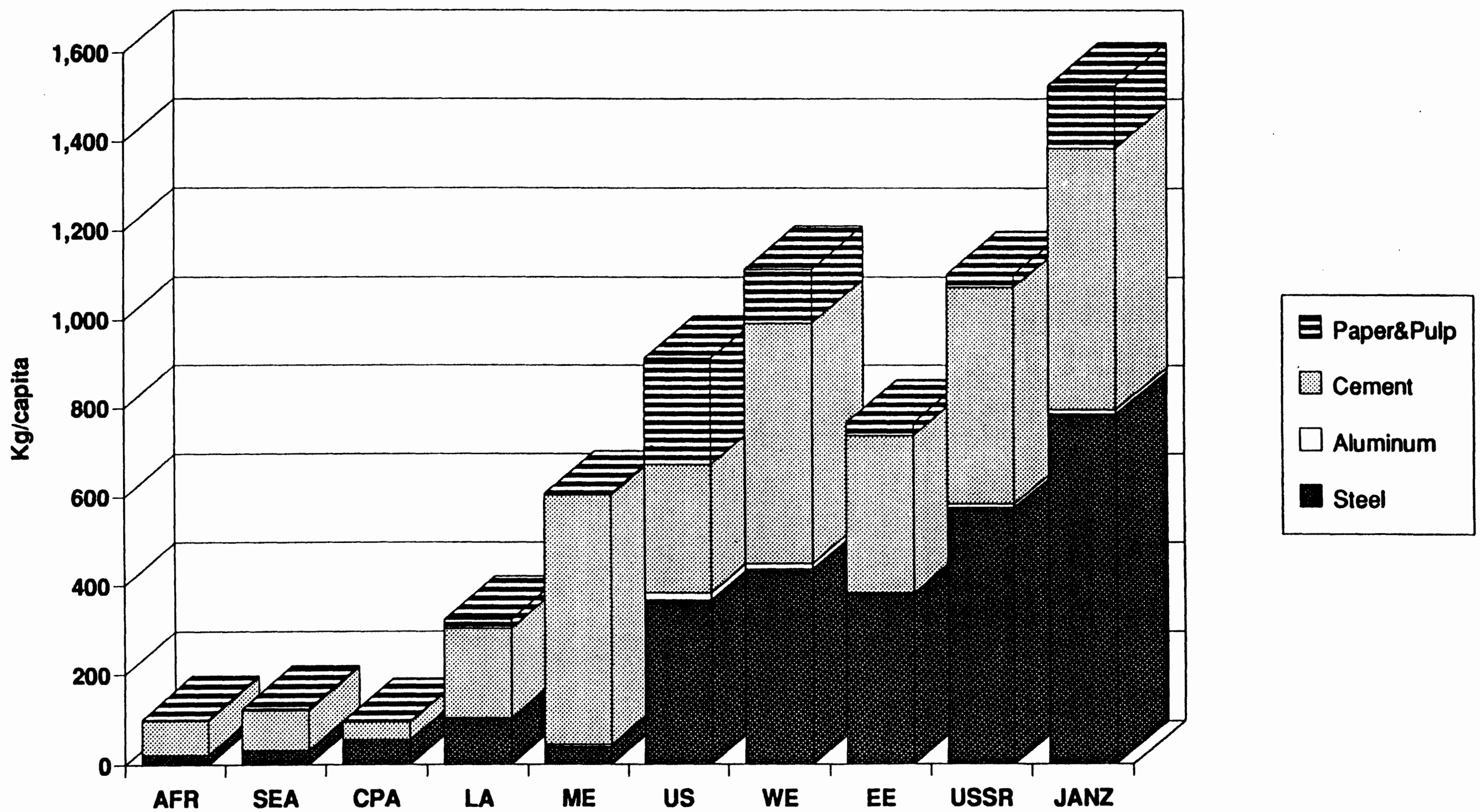
Per Capita Production of Primary Materials
Scenario Years
(kg/capita)

		1988	2030	2100
OECD				
	Steel	477	421	334
	Aluminum	13	14	14
	Cement	474	397	280
	Paper&Pulp	161	162	160
USSR/EE				
	Steel	511	446	334
	Aluminum	7	9	14
	Cement	445	384	280
	Paper&Pulp	30	79	160
SOUTH				
	Steel	45	142	334
	Aluminum	1	6	14
	Cement	93	156	280
	Paper&Pulp	5	58	160

Sources: UN 1990; UN 1990; UNCTAD, 1990

Figure 6.4b

Per Capita Production of Selected Primary Materials (1988)



various regions. In the steel sector, for example, we find that the countries of Western Europe produce about 436 kg/cap while those in Latin America produce about 100 kg/cap and in Africa only about 22 kg/cap.

How will these patterns and levels of production alter over the coming century? We tie activity in the energy intensive sub-sectors to changes in per capita consumption of our indicator commodities and to population growth. We also assume that consumption equals production, i.e., all regions become self-reliant in primary materials[33]. While this is neither true nor likely to fully occur in the future, we take this approach for two reasons. First, an analysis of future trade patterns and regional production advantages is beyond the scope of this project. Secondly, this approach implicitly assigns regional responsibility for energy use and emissions based on consumption.

Given this framework, we can now address regional specific methodologies. In the North, we expect to see a decline in per capita consumption of most primary materials. As Williams et al. (1987) and others have demonstrated, industrialised countries appear near saturation in terms of materials use per capita for specific commodities. Figure 6.4c illustrates this pattern in the U.S.

This is expected to be the case for two reasons. First, the most materials-intensive phase of development historically has been the construction of basic infrastructure - roads, bridges and buildings. Secondly, as technology advances, the same services can be performed with both less materials use as well as a wider variety of traditional or new materials. The classic case is the automobile. In the U.S., for example, the average weight of a car declined from about 1700 Kg in 1975 to about 1450 Kg in 1983 (about 16 percent). At the same time, the low carbon steel content declined even faster, from about 970 Kg to about 680 Kg (about 29 percent) to be replaced by high strength steel and plastics (Curlee, 1988). New materials, particular composites and plastics, can drive even this figure dramatically lower. For example, GM recently introduced a 5-passenger car, the Ultralite, weighing only about 640 Kg lb (Lovins, personal communication).

Accordingly, over the course of the next century we track both changes resulting from declines in materials use and shifts between industrial sub-sectors as we observe materials substitution. Table 6.4d shows the target materials consumption for our energy intensive sectors. We assume relatively constant per capita materials consumption targets for aluminum and paper and pulp at 14Kg/cap and 160 Kg/cap respectively. Per capita cement consumption decreases 40% to 280 Kg/cap while steel consumption drops 30% to 334 Kg/cap, consistent with the above discussions and previous studies (Goldemberg et al, 1988; IPCC, 1992; Lashof and Tirpak, 1990). Note that these figures are for total, not virgin, materials requirements. As discussed below, we assume increased recycling in all sub-sectors.

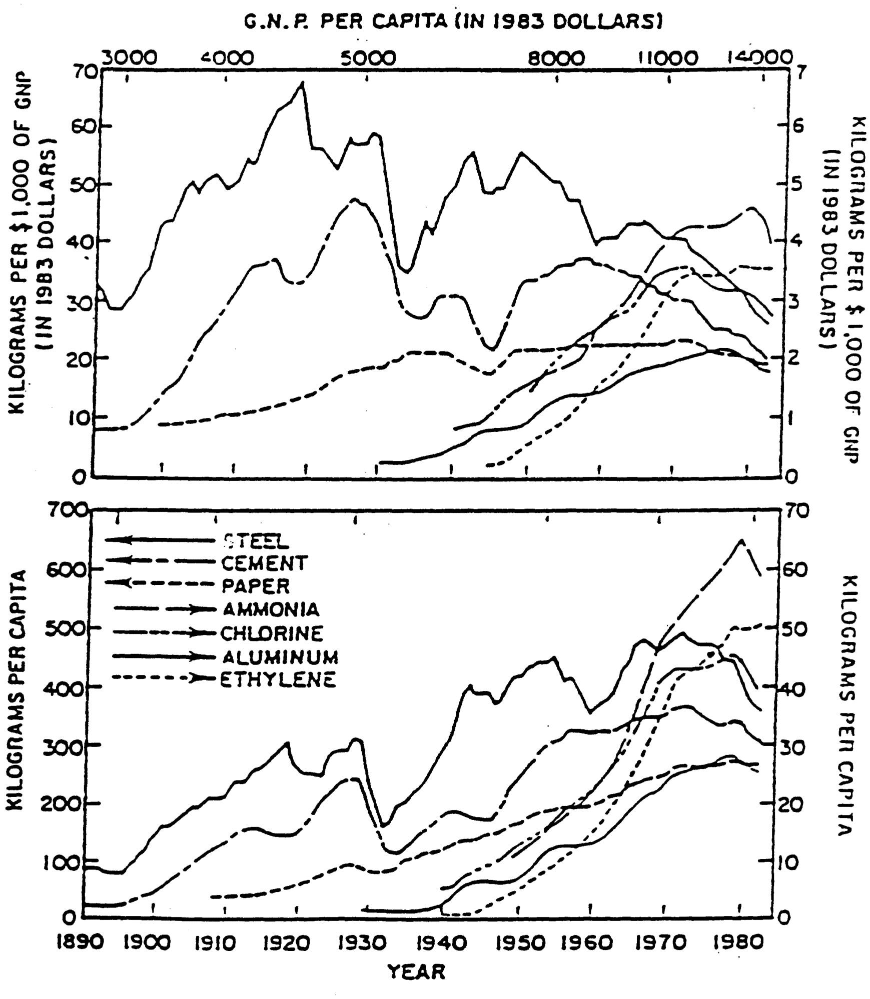
In the South, it is assumed that global consumption patterns will converge in keeping with the scenario assumption of approaching equity with all regional GDPs above current OECD levels by 2100.

We turn these consumption targets into sub-sectoral growth rates. In doing so, we want not only to allow the sub-sectors to grow to accommodate consumption targets, we also want to show the global convergence to a post-industrial structure. These structural changes primarily reflect an increasing proportion of higher quality materials and a reduction of the sub-sectoral activity accounted for by the indicator commodity. This structure can be simply

33 Assuming production equals consumption in primary materials neglects the trade in finished goods (i.e. we are measuring steel not cars). In this sense we may underestimate consumption in certain importing countries (for example, the US) while overestimating it in exporting ones (for example, Japan). This effect is expected to become less pronounced as the scenario converges towards equitable consumption targets.

Figure 6.4c

Trends in Apparent US Consumption of Selected Materials



Source: Williams, Larson and Ross, 1987. Reprinted with permission from Annual Review of Energy.

represented as a structure factor $S_{T,S}$. $S_{T,S}$ is an index that represents the ratio between the regional sub-sectoral structure and that of the OECD countries. Although all regions do not achieve the same final income level, all do reach or exceed current OECD levels, hence for all regions the structure parameter is set equal to 1 in 2100. For each energy intensive sub-sectoral GDP, we calculate:

$$GDP_{T,S} = GDP_{1988,S} * (P_{T,S} / P_{1988,S}) * S_{T,S} \quad (1)$$

where $P_{T,S}$ is the production of the indicator commodity in the target year. $P_{T,S}$ in turn is calculated from population (POP) and consumption per capita ($C_{T,S}$):

$$P_{T,S} = C_{T,S} * POP_T \quad (2)$$

We note that the use of the structure parameter $S_{T,S}$ means that GDP in energy intensive materials sectors in the South will increase more than it would if we kept sub-sectoral structure constant.

Matching GDP Targets

As discussed above, we determined the overall level of economic growth by adjusting the IPCC's projected growth rates to ensure increased global equity by the year 2100. Industry's share of this total varies by region over time to reflect anticipated shifts between the service, agricultural and industrial sectors. Given the economic activity levels for the energy intensive sectors calculated above, we calculate the growth of the non-energy intensive sub-sector to meet the desired overall industrial economic growth described above.

Converging Energy Intensities

Regional energy intensities are improved over time to a final global target energy intensity through sub-sectoral-specific improvements in energy efficiency. Section 6.4.2. describes the analysis of energy efficiency improvements, recycling potential, fuel switching to renewable fuels, and cogeneration.

Our paradigm of standard industrialization makes this convergence possible. Energy intensity as we have defined it represents both the amount of energy needed to produce a given material or product, as well as the mix of products and processes within any sub-sector. For example, the energy intensity in the paper and pulp sector represents the efficiency of particular plants, the amount of recycling within a region and the percentage of GDP in that sector that results from less energy intensive activities like printing and publishing. We would thus only expect to see a convergence of energy intensities if we also observe a convergence of sub-sectoral structure.

Resulting Energy Use

Pulling together our analysis gives us enough information to calculate energy use in a target year. For each sub-sector:

$$E_{T,S} = E_{1988,S} * EFF_{T,S} * A_{T,S} \quad (3)$$

Here $EFF_{T,S}$ is the efficiency of the target year energy use relative to the base year and $A_{T,S}$ is the target year activity level index given by

$$A_{T,S} = GDP_{T,S} / GDP_{1988}. \quad (4)$$

$GDP_{T,S}$ is obtained from eq. (1).

Finally, the energy is distributed to a target fuel mix $FS_{T,S,F}$

$$E_{T,S,F} = E_{T,S} * FS_{T,S,F} \quad (5)$$

6.4.2 Results and Analysis

In the scenario, global industrial energy use grows from 90 EJ in 1988 to 196 EJ in 2100, a total increase of 118 percent or an average of 0.7 percent per year. As illustrated in Figure 6.4d, most of this increase occurs after 2030, after most of the savings from efficiency improvements have been captured. This figure also shows the trend in energy intensive sub-sectors; their fraction of total industrial energy use declines from 63 percent to 39 percent from 1988 to 2100. As a result of industrialization in the South, the production of basic energy-intensive materials increases two and one-half to ten times during the same time period. Global production of steel increases 3.8 times; aluminum, 8 times; cement, 2.4 times; and paper and pulp, 10 times[34].

In the short-term (to 2030), the currently industrialised countries continue to dominate global industrial energy use (see Figure 6.4e and Table 6.4e). By 2100, however, industrialization and population growth in the South lead to a major change in the relative regional energy shares. Industrial energy use in the countries of the former USSR and Eastern Europe declines 35% from 27 EJ to 17 EJ between 1988 to 2030 and an additional 28% to 12 EJ in 2100. The OECD declines less dramatically from 35 EJ in 1988 to 24 EJ in 2100. In the South, the situation is reversed. Population and production growth drive energy use up 1.3 times from 28 EJ to 38 EJ by 2030, and another 4.3 times to 160 EJ (82% of total global industrial energy use) in 2100.

In the absence of substantial energy efficiency improvements, increased recycling of basic materials and a transition to a post-industrial economy, industrial energy use would be considerably greater. Efficiency improvements in the industrial sector vary by sub-sector, but by 2100 could be expected to range between 20 percent and 60 percent of base year levels in industrialised countries. Because energy efficiency improvements are integrally linked to the level of materials recycling, these levels will be addressed within each energy intensive sub-sector. Base year and target sectoral energy intensities (GJ/GDP) are shown in Table 6.4f. As will be discussed more fully below, these energy intensities include both efficiency and structural effects. Final energy intensities are about 24 percent of the base year in the iron and steel sub-sector, 18 percent for non-ferrous metals, 18 percent in stone, clay and glass, 31 percent in paper, 24 percent in chemicals and 33 percent in all other.

The types of fuels used to meet this demand also change (see Figure 6.4f). In 1988, about 71 percent of industrial energy came directly from fossil fuels, another 17 percent from electricity, currently supplied predominantly by fossil fuels, and only 12 percent from renewable fuels or heat. By 2030, direct fossil fuel use declines to 24 percent, renewable fuels and cogeneration rise correspondingly to 32 percent and greater electrification of industry brings electricity's share to 45 percent. In 2100, the proportion of electricity use remains almost constant at 45 percent, but renewable fuels and cogeneration account for the remainder of industrial energy use.

34 The GES scenario evaluates the energy consequences of this level of materials production. Other important considerations, such as materials availability and environmental consequences of materials production, are beyond the scope of this study.

Figure 6.4d
Global Industrial Energy Use by Sector

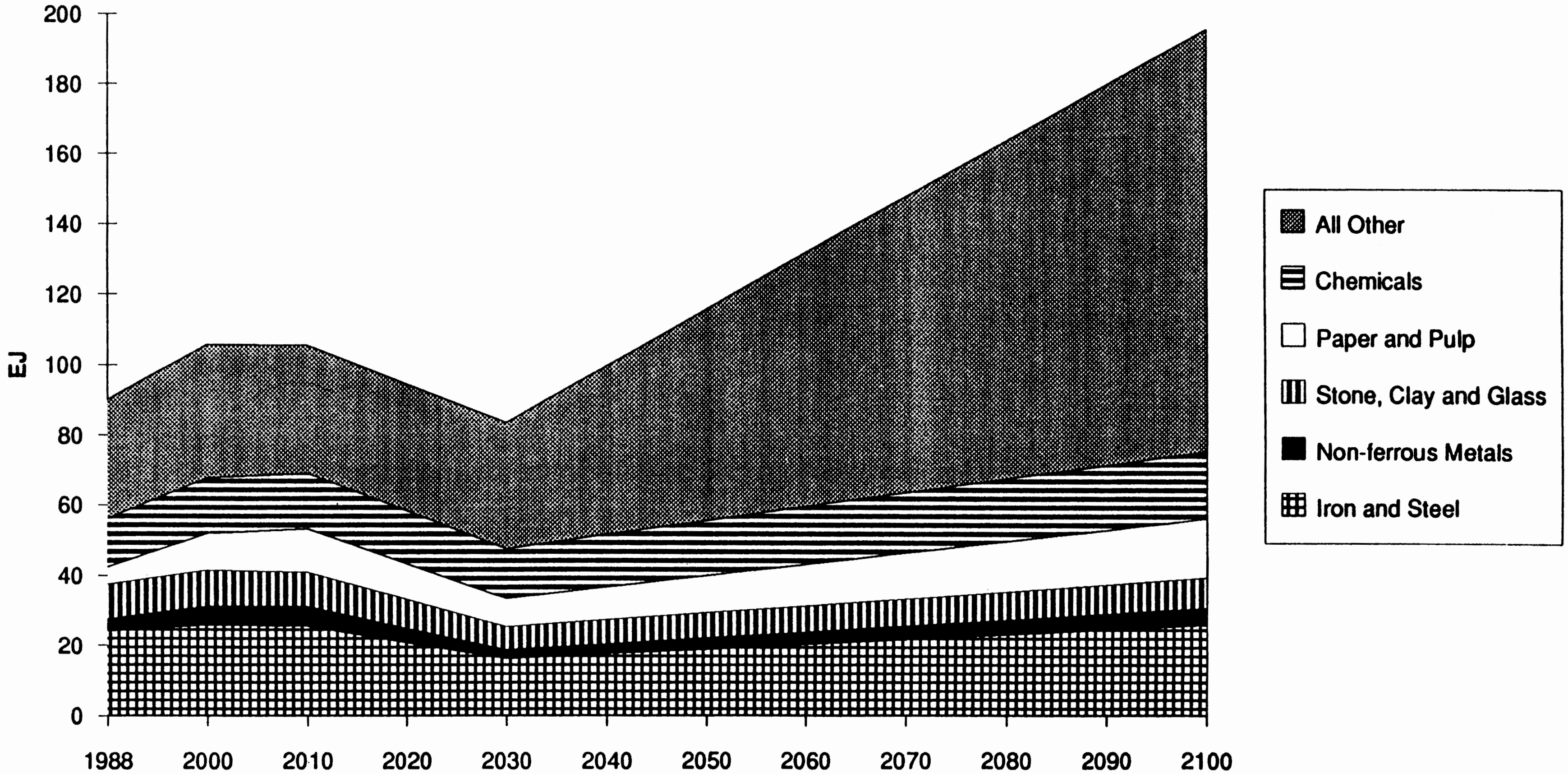
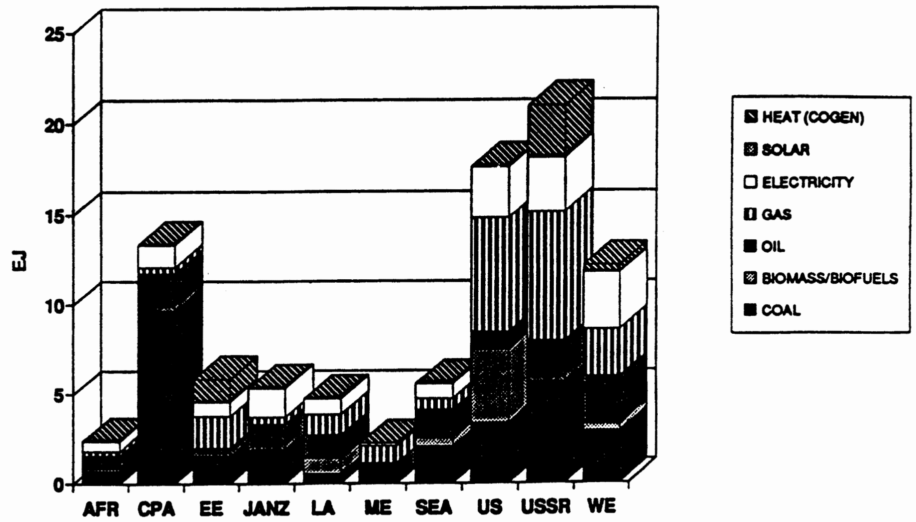
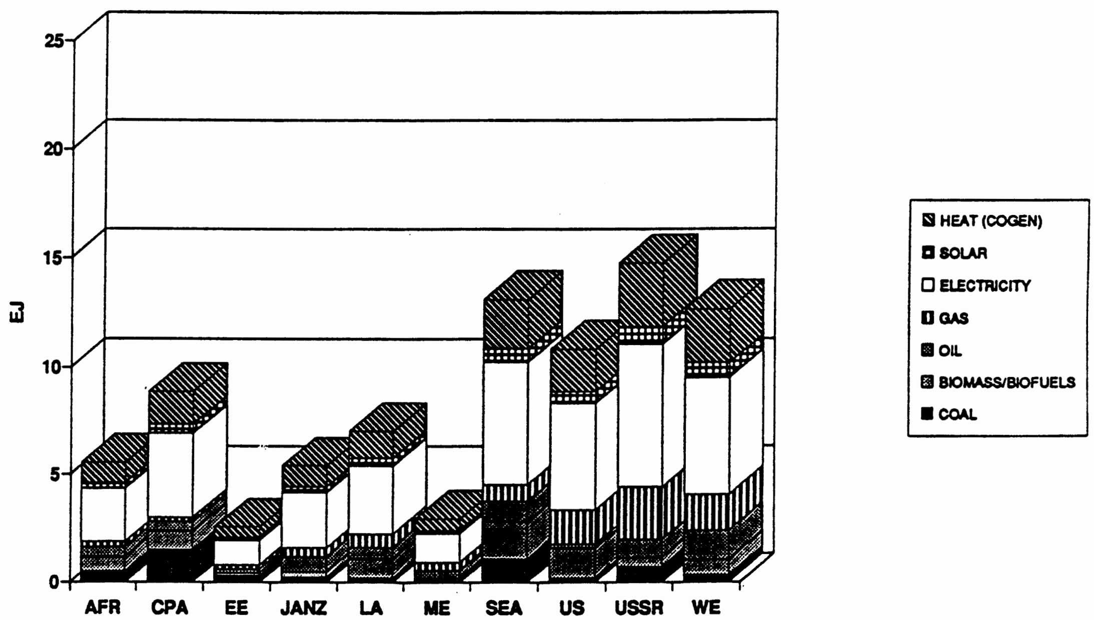


Figure 6.4e
1988 Industrial Sector Delivered Energy Consumption (EJ)



2030 Industrial Sector Delivered Energy Consumption (EJ)



2100 Industrial Sector Delivered Energy Consumption (EJ)

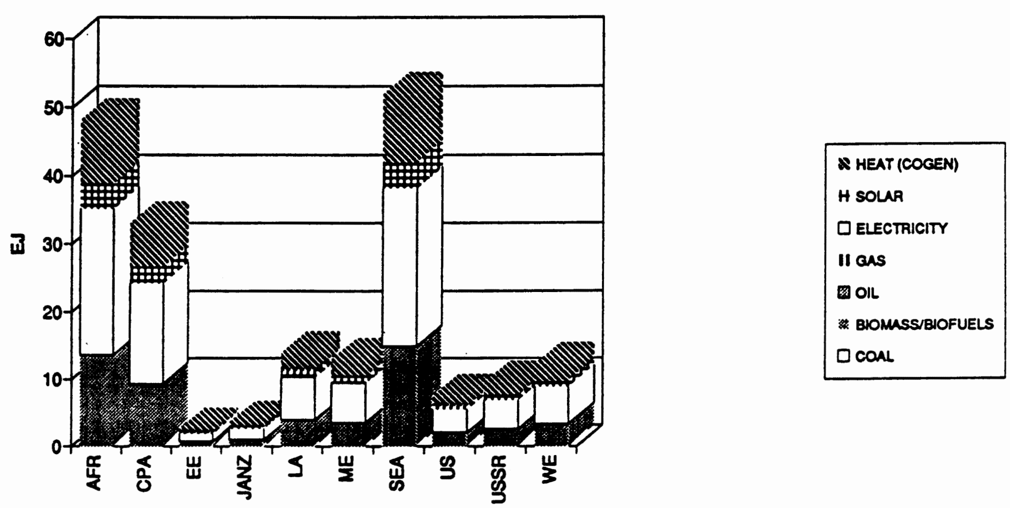


Table 6.4e

Industrial Sector Delivered Energy Consumption by Region (EJ)

	1988	2000	2010	2030	2100
AFR	2.37 *(3%)*	3.83 *(4%)*	4.72 *(4%)*	5.56 *(7%)*	48.16 *(25%)*
CPA	13.34 *(15%)*	21.71 *(20%)*	23.77 *(23%)*	8.87 *(11%)*	33.19 *(17%)*
EE	5.84 *(6%)*	5.34 *(5%)*	3.63 *(3%)*	2.56 *(3%)*	2.63 *(1%)*
JANZ	5.34 *(6%)*	5.92 *(6%)*	6.07 *(6%)*	5.41 *(6%)*	3.67 *(2%)*
LA	4.74 *(5%)*	6.05 *(6%)*	6.73 *(6%)*	7.03 *(8%)*	14.04 *(7%)*
ME	2.23 *(2%)*	3.57 *(3%)*	4.33 *(4%)*	2.95 *(4%)*	13.08 *(7%)*
SEA	5.58 *(6%)*	10.00 *(9%)*	12.72 *(12%)*	13.10 *(16%)*	52.01 *(26%)*
US	17.66 *(20%)*	15.87 *(15%)*	13.63 *(13%)*	10.85 *(13%)*	7.66 *(4%)*
USSR	21.00 *(23%)*	20.68 *(20%)*	17.00 *(16%)*	14.76 *(18%)*	9.59 *(5%)*
WE	12.17 *(13%)*	12.95 *(12%)*	12.95 *(12%)*	12.67 *(15%)*	12.38 *(6%)*
TOTAL	90.28	105.92	105.55	83.77	196.40

Table 6.4f

Energy Intensities* by Region and Subsector

(Subsectoral GJ/subsectoral GDP in 1985 US$)

		All Industry	Iron and steel	Non-ferrous metals	Stone, Clay, Glass	Paper & pulp	Chemicals	All other
1988	JANZ	8.41	48.74	29.52	16.60	4.53	5.32	5.03
	USSR	23.14	58.48	58.16	54.56	9.68	27.91	15.19
	EE	54.28	257.26	14.13	29.86	4.32	50.56	37.74
	US**	18.01	157.50		31.05	20.04	18.77	12.45
	WE	9.80	44.64	16.69	22.08	8.61	10.85	5.51
	AFR	20.54	101.75	46.43	47.01	17.54	20.67	13.93
	CPA	74.24	361.44	202.00	166.97	74.54	73.44	22.88
	LA	19.75	97.91	42.46	45.60	16.12	20.06	7.09
	ME	54.12	268.14	111.08	124.22	45.14	54.56	20.44
	SEA	31.54	156.24	76.29	72.18	28.62	31.75	16.05
	WORLD	19.52	96.31	37.72	45.02	14.13	19.83	11.28
2030	JANZ	60%	64%	25%	69%	>100%	>100%	64%
(Fraction of	USSR	27%	44%	11%	22%	50%	30%	34%
base year	EE	14%	20%	55%	89%	>100%	14%	14%
energy intensity)	US	35%	23%		33%	32%	46%	42%
	WE	56%	68%	51%	58%	70%	92%	61%
	AFR	44%	30%	21%	59%	28%	43%	37%
	CPA	11%	11%	4%	7%	7%	12%	23%
	LA	41%	28%	18%	47%	47%	52%	73%
	ME	16%	9%	29%	22%	7%	24%	25%
	SEA	36%	23%	24%	58%	31%	29%	32%
	WORLD	36%	34%	27%	41%	44%	47%	41%
2100	JANZ	50%	46%	22%	50%	94%	88%	73%
(Fraction of	USSR	18%	38%	11%	15%	44%	17%	24%
base year	EE	8%	9%	46%	28%	99%	9%	10%
energy intensity)	US	23%	14%		27%	21%	25%	29%
	WE	43%	50%	39%	38%	49%	43%	66%
	AFR	22%	22%	14%	18%	24%	23%	26%
	CPA	6%	6%	3%	5%	6%	6%	16%
	LA	23%	23%	15%	18%	26%	23%	52%
	ME	8%	8%	6%	7%	9%	9%	18%
	SEA	15%	14%	9%	12%	15%	15%	23%
	WORLD	23%	23%	17%	19%	30%	24%	32%

Sources: IEA, 1990; Summers and Heston, 1991; UN, 1990, UNIDO, 1990.

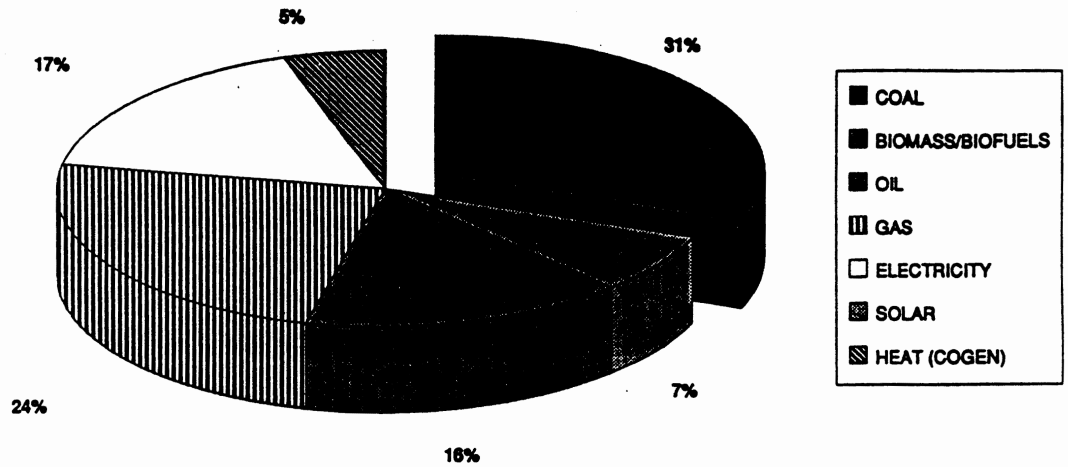
* Energy intensities are dependent on subsectoral definitions. In order to accord with international energy statistics, printing and publishing were included in paper and pulp, lowering the observed intensity. (Energy in the EE pulp and paper sector appears excessively low because biomass usage was not included due to inadequacy of data well as statistical aberations resulting from extremely low production levels levels in the subsector.) Finally, changes in energy intensity reflect both efficiency improvements and structural change.

** In the US, non-ferrous metals were included in the iron and steel sector in order to take advantage of detailed US energy efficiency data (UCS et al, 1991).

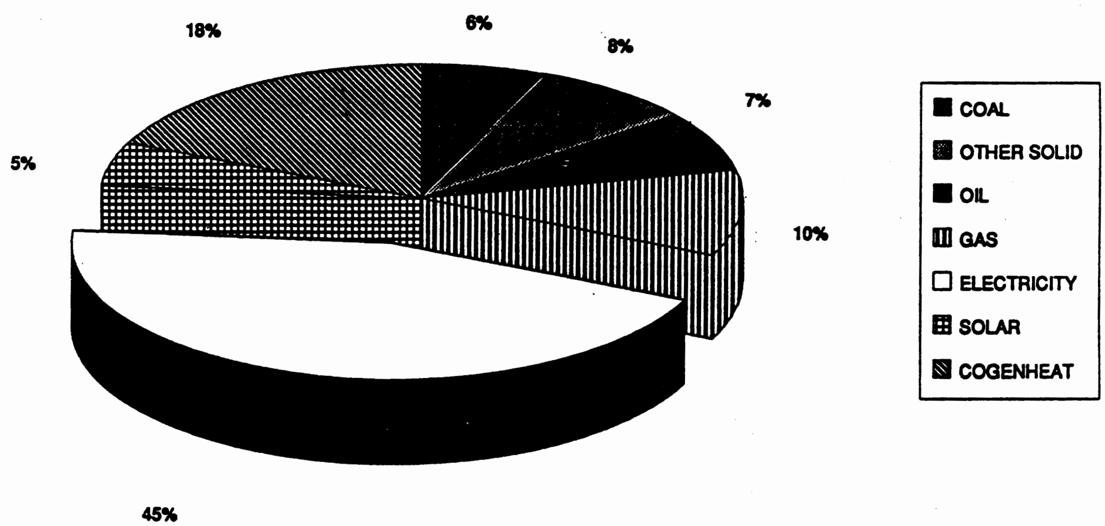
*** In industrialized regions, 75 percent of the 1988-2030 intensity reductions are achieved by 2010. In developing regions, approximately half are reached by 2010.

Figure 6.4F

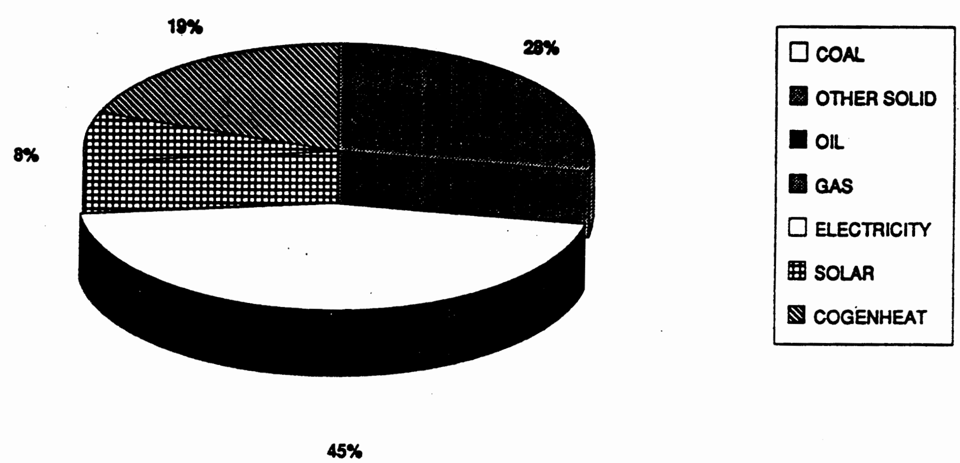
1988 Industrial Sector Fuel Shares



2030 Industrial Sector Fuel Shares



2100 Industrial Sector Fuel Shares



Advanced cogeneration units provide 90 percent of all industrial steam requirements, and account for 40 percent of total industrial fuel use by 2030 and 2100. While not observable from our results for final demand, the widespread adoption of cogeneration systems significantly reduces primary energy requirements.

Calculating Energy Efficiency Improvements

Energy intensity improvements were considered separately for the energy intensive materials and for all other industry. For all sectors, however, the same general methodological steps were followed:

1) Energy intensity improvements were developed for the industrialised countries for the year 2030 of the scenario.

2) From 2030-2100, an additional 0.5 percent/year of non-specified efficiency improvements were applied. This estimate is considerably lower than the current historical average of about 2.5 percent per year (Schipper, 1991). The resulting targets remained well above the theoretical limits for the indicator commodities examined.

3) These 2030 and 2100 energy intensities were used as targets for all regions, weighted to account for relative regional structural changes.

For non-energy intensive materials, we relied heavily on previous studies of the possible range of energy improvements across all sectors (UCS et al, 1991; Schipper and Meyers, 1992; Sathaye and Goldman, 1991). This was supplemented by an analysis of specific technological improvements that can be applied generically. Some of these are listed in Table 6.4g. Improvements in electricity efficiency of almost 30 percent, for example, can result from the use of more efficient motors, variable speed motors, efficiency improvements in electric furnaces and in electrolytic processes, where applicable (Geller, 1987). Other estimates have suggested that the potential savings from improvements in drive systems alone could be between 34-39% (Lovins and Lovins, 1991). More efficient lighting can reduce electricity consumption 50-60 percent (OTA, 1991). Automated controls can substantially reduce energy use. Finally, changes in production processes, in particular, the capture of waste streams of heat, materials and water can dramatically reduce energy requirements[35].

Quantifying these potential energy improvements across the wide number of production processes is difficult. Some historical trends are suggestive. Between 1973-1987, for example, 8 OECD countries saw energy intensity in an `all other' manufacturing sector decline 32 percent (Schipper, 1991). Projections for the next 40 years suggest a continued decline, ranging from 20 to over 45 percent in the industrialised world to 10-75 percent in various countries of the South (Sathaye, 1989; Schipper and Meyers, 1992, OTA, 1991). We assume a 2030 target of 35 percent of current OECD intensities based on detailed studies of the sub-sectors in `all other' (UCS et al., 1991).

For the energy intensive sub-sectors, we calculated the percent increase in energy efficiency for production of our indicator commodities which could result from technology improvements and increased recycling. The specific measures used for each commodity are discussed in some detail below. These efficiency improvements were then applied to the energy intensity of the entire sub-sectors in industrialised countries. This method assumes that efficiency improvements in the less energy-intensive activities of each sub-sector will be able to

35 Capture of heat has proven particularly promising. In the chemical industry, much of recent 70% energy savings resulted from the application of "pinch technology" - the thermodynamic optimization of production processes (Lovins and Lovins, 1991).

Table 6.4g

Generic Industrial Conservation Technologies

Heat Exchangers
Heat Pumps
Cogeneration
Systems control and sensors
Scrap Recycling
Insulating Materials
Separation processes
Drying Technologies
High-efficiency electric motors
High efficiency air motors
High-efficiency pumps
High-efficiency lighting
Pinch technology (Thermodynamic optimisation of production processes)
High-efficiency, high-temperature burners
Improved refrigeration
Genetic engineering technologies
Direct forming processes

(Source: from De Renzo, 1985, p. 355)

Table 6.4h

Energy for Steel Production
(Selected Countries)

Country	Year	GJ/ton	Source
Brazil	1,984	27.6	(Sathaye et al, 1989)
Canada	Late 80s	24.2	(Elliot, 1991)
China/India	Mid-80s	45-53	(OTA, 1991)
Hungary	1988	29	(Chandler, 1990)
Japan	1985	17.6	(IEA, 1987)
Sweden	1982	18.6	(Eketorp, 1987)
US	Late 80s	20.4	(Elliot, 1991)

keep pace with the changes in the representative materials. The resulting energy intensities served as targets for developing country energy intensities in 2100.

The convergence of energy intensities is consistent with the assumption of standardized industrialization, discussed above. The energy intensity (GJ/$GDP) embodies the energy efficiency of production technologies, the mix of products within the sub-sector and the dollar value of the goods. The latter two effects are considered in the structural index $S_{T,S}$. Although the data used to derive this index do not permit disaggregation of the two effects, the convergence of $S_{T,S}$ guarantees that both forces are implicitly captured.

Steel

In 1988, the iron and steel sub-sector accounted for 27 percent of global industrial energy, the largest share of any single sub-sector.

There are two primary methods for producing steel from iron ore -- the blast furnace-basic oxygen furnace (BOF) process or the direct reduction iron-electric arc furnace (EAF) process. A third method, the open-hearth furnace, also produces steel from ore, but is rapidly disappearing due to its high inefficiency. In the mid-1980s, an average European BOF plant required about 23 GJ/tonne of raw steel, the EAF less than half that amount (IEA, 1987). Much of the energy differential between the two processes results from the relative proportion of scrap in the charge to the furnace. In the BOF, typically 25-50 percent of the charge is scrap. In the most efficient EAF units, the figure is 100 percent. Seventy percent of the total energy is used for iron and steel-making, 20 percent for rolling and 10 percent for the remainder.

Current energy per tonne of crude steel for selected countries is given in Table 6.4h. Values range from a low of 17.6 GJ/tonne in Japan to a high average of 50 in China and India. With notable exceptions such as Brazil and South Korea, steel production in the South is in general twice as energy intensive as in the North. Plants in the South are less likely to be integrated, hence the metal has to be reheated several times during the production process with resulting decreases in process efficiencies. Chinese steel production is particularly inefficient due, inter alia, to the high proportion of small facilities and relatively high proportion of cast iron production. In addition, non-OECD countries are likely to have less of their productive capacity in the inherently more efficient EAF. As shown in Table 6.4i, in 1982 about 12.5 percent of Eastern European steel production came from EAF as compared to 28.6 percent in Western Europe and 30.2 percent in North America. As the table illustrates, however, in all regions there is an increase over time in the EAF's share of production.

Future improvements in energy intensity can come from basic housekeeping improvements, a transition to newer plant types -- both finishing the phase-out of open-hearth furnaces, particularly in the countries of the former USSR and Eastern Europe, and switching to the EAF where scrap steel is available -- and other process improvements. Process improvements are possible in both the steel making and rolling and finishing stages. In the BOF, possible improvements for the former include dry coke quenching and the use of sinter cooling air for combination. For the EAF, energy efficiency improvements include the use of bottom pouring ladles, the feeding of preheated scrap and the use of continuous tapping. In the rolling and finishing stages, significant energy savings can be realized by continuous casting methods, producing ingots at near net shape and using computer quality control to permit sending of adequate slabs directly to rolling mills without cooling.

A mix of 50 percent EAF/50 percent BOF is projected for 2030. Eketorp (1987) has calculated a target of 15.4 GJ/tonne for the BOF and 5.7 for the EAF. Averaging these to achieve a 50/50 mix, we select a combined target of 10.5 GJ/tonne in 2030. Other studies have suggested the energy intensity of the BOF might be closer to 13.6, suggesting a combined

Table 6.4i

Trends in Steelmaking Processes

Region	Year	Basic Oxygen Furnace (%)	Open Hearth Furnace (%)	Electric Arc Furnace (%)	Other (%)
Eastern Europe					
	1960	3.1	85.0	9.1	2.8
	1982	30.5	56.5	12.5	0.5
Japan					
	1960	11.9	67.9	20.2	0.0
	1982	73.4	0.0	26.6	0.0
North America					
	1960	3.2	87.0	8.7	1.1
	1982	60.8	9.0	30.2	0.0
Western Europe					
	1960	3.4	48.8	11.2	36.6
	1982	69.2	2.2	28.6	0.0

Source: Adapted from Meunier and de Bruyn Kops, 1984, p. 8.

Table 6.4j

Energy for Aluminum Production
(Selected Countries)

Region	Year	kWh/ton
North America	1981	16,500
Europe	1981	16,500
East Asia*	1981	14,800
Other Asia	1981	17,500
Oceania**	1981	16,000
Africa	1981	16,300
Latin America	1981	17,400

*Japan, South Korea, Taiwan

**Austrailia, New Zealand

Source: Adapted from OECD, 1983, p. 27.

target of 9.6 GJ/tonne might be possible (IEA, 1987). We allow 0.5 percent additional efficiency improvements per year, resulting in a target of 7.4 GJ/tonne. This value is about 90 percent higher than the theoretical limit of 3.9 GJ/tonne (7 GJ/tonne from ore; 0.7 GJ/tonne from scrap) (Goldemberg et al., 1988).

Aluminum

In 1988, the aluminum sector accounted for about 6% of total industrial energy use.

Alumina refining, accounting for about 16 percent of the total energy use, requires about 18 GJ of steam for the digestion phase, 9 GJ of heat for calcination and about 400 kWh of electricity per tonne of aluminum produced. Alumina reduction, the most energy intensive step, uses some 16,800 kWh per tonne or 75 percent of the total energy requirements. As so much of the energy for aluminum production is used in these early processing steps, secondary aluminum (from scrap) needs only about 5-10 percent as much energy per tonne produced.

Current average regional energy intensities for aluminum production display less variance than those for steel. Table 6.4j shows average power consumption per tonne of aluminum for market economies in 1981. The values range from about 14,800 kWh in East Asia (Japan, South Korea and Taiwan) to about 17,500 kWh/tonne in other parts of Asia, less than a 20 percent differential. The high performance of plants in developing economies primarily reflects their newer vintage. In 1980, slightly over 70 percent of total production capacity in the South was in plants less than 10 years old. In contrast, at the same time only 45 percent and 20 percent of European and North American plants respectively were of such recent vintage (OECD, 1983).

Future energy efficiency improvements are expected from three main sources - retirement and replacement of older plants, minor process modifications and increased recycling.[36] Aluminum plants have a typical operating life of 20-30 years (IEA, 1987). Expected stock turnovers in the North could show 20 percent reductions in energy intensity in the next two decades. New European plants, for example, require only 13,500 kWh per tonne aluminum. Process changes in the reduction stage, notably a switch from the vertical Soderberg cells to the more efficient horizontal ones, could reduce this figure an additional 10 to 20 percent. We assume a conservative 10 percent, yielding a target of 12,125 kWh/tonne.[37]

Finally, as discussed above, the use of recycled aluminum holds the potential for dramatic reductions of energy intensity. Increased use of aluminum scrap appears feasible. In general, well-segregated aluminum based scrap falls within appropriate composition limits for most applications (Bureau of Mines, 1985). Although contamination of scrap with other materials - either those potentially jeopardizing product quality such as stainless steel or magnesium or those affecting plant pollutant emissions such as paint, oil or plastics - can complicate the production of secondary aluminum, high levels of recycling are possible now (see Figure 6.4g). Furthermore, cleaner production technologies could well reduce scrap contamination. From 1970-1981, Japan increased its use of secondary aluminum from 30 percent to 49 percent. Other regions unfortunately followed the opposite trend. In Europe, for example, the use of secondary aluminum fell from 30 percent to 25 percent.

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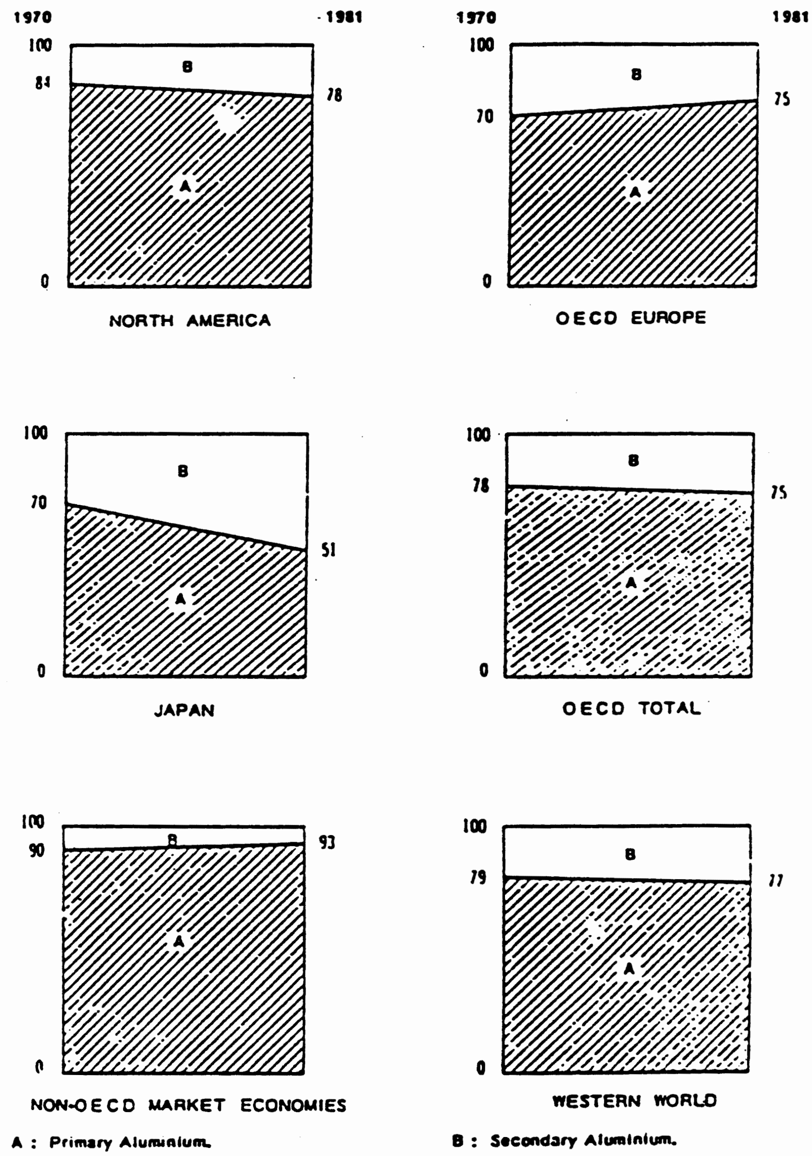
36 Larger scale process changes currently under development but still unproven (for example, reducing aluminum directly from bauxite) could dramatically reduce energy requirements but were not included in this study due to uncertainties about their future feasibilities.

37 Recent studies suggest this estimate may be quite conservative. EPRI (1990) finds a 30-50% potential reduction of 30-50% from bipolar cells, inert anodes and wettable cathodes, or between 8,000-11,000 kWhr/ton aluminum.

Figure 6.4g

Relative Shares of Primary and Secondary Aluminum
1970-1981
(%)



Source: OECD, 1983. Reprinted with permission from OECD.

Studies of future recycling potential concur that higher levels are possible, with estimates ranging as high as 90 percent (UCS et al., 1991). While it is clear the level of recycling can increase, the limits are as yet unknown. We thus select a conservative estimate of 50 percent recycling in 2030, doubling the OECD average recycling but staying within proven feasible levels. This yields an additional 30 percent improvement in Western European energy efficiency over the technological changes described above.

Assuming this level of recycling, the 2030 target is thus 8500 kWh/tonne, 40 percent below current best Western European technology or 47 percent below the Western European average.

The target in 2100 is 5950 kWh/tonne resulting from unspecified energy efficiency improvements of 0.5 percent per year. Even with no additional efficiency improvements over the 2030 target, achieving the 90 percent recycling rate discussed above would yield a total energy use of about 2900 GJ/tonne, 50 percent below the more conservative target selected.

Cement

The cement sub-sector consumed 11 percent of global industrial energy in 1988. Infrastructure building in the South will require substantial increases in cement production with a dual impact on carbon dioxide emissions from both energy and materials use.

There are three main stages in cement manufacture -- preparation of raw materials (crushing, grinding and mixing), burning the materials (the pyroprocess stage) and grinding of the pyroprocess end product, clinker. Although the specific share of total energy use in each stage depends on the production process, in general the grinding and pyroprocess stages are the most energy intensive, requiring about 12-18 percent and 80-87 percent of the total energy, respectively (Tresouthick and Mishulovich, 1991).

There are two main methods of cement production -- wet and dry. In the wet process, water is added to the prepared materials before they are injected as a slurry into the kiln. In the dry process, the materials are fed into the kiln in their dry state. The additional energy required for evaporation of water from the slurry in the wet process makes it inherently less energy efficient than the dry. The theoretical limits of energy intensity for cement production are 3 GJ/tonne for the wet process and 1.5 GJ/tonne for the dry (IEA, 1987).

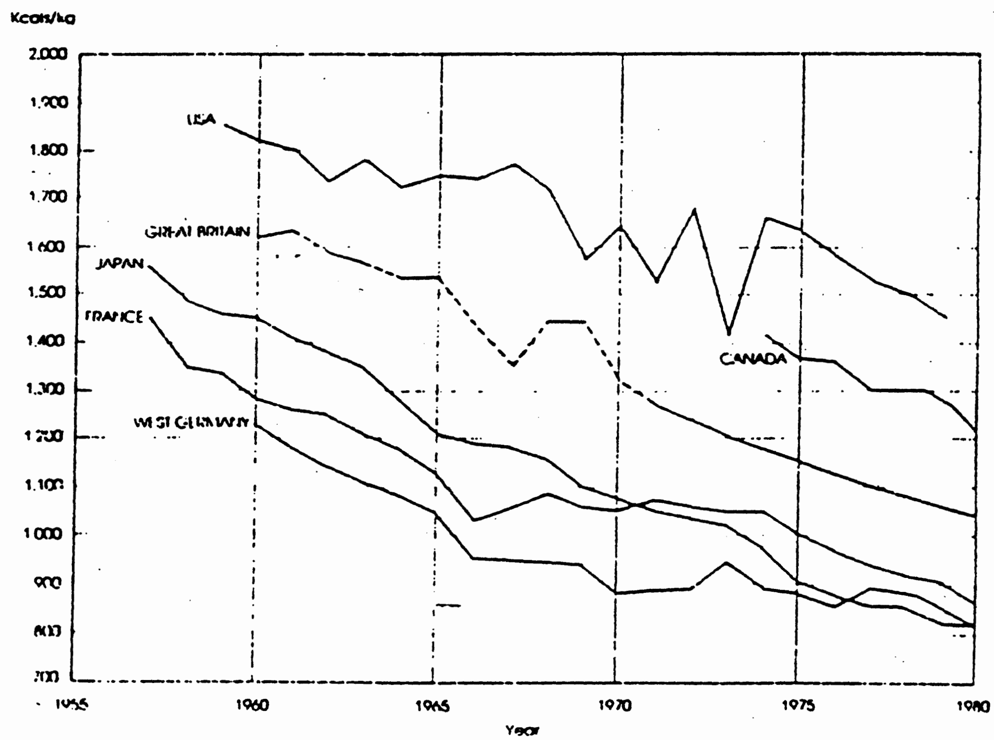
Current energy use for cement production varies widely across countries, ranging from a low of 3.7 GJ/tonne in much of Western Europe to over 7 GJ/tonne in India and Pakistan (see Table 6.4k). Much of this difference reflects the proportion of cement manufactured using the wet process. The historical results of a transition away from the wet process for selected industrialised countries can be seen in Figure 6.4h. By 1972, for example, 92% of West German cement plants had already been converted to the dry process.

The structure of the world's cement industry suggests similar reductions ought to be possible elsewhere. In 1980, Germany and France utilized the dry process for 97 percent and 90 percent of their cement production respectively. In comparison, on average the dry process accounted for 60 percent of production in Africa, 54 percent in Latin America, 52 percent in South East Asia, 42 percent in the Middle East and only 15 percent in the countries of the former USSR (Fog and Nadkarni, 1983; Schipper and Cooper, 1991).

There are three main areas for improved energy efficiency in the cement industry -- housekeeping measures, the transition to the dry process and process improvements. In the short-term, there are a number of measures that are not capital intensive but can substantially

Figure 6.4h

Trends in Thermal Energy Consumption for Cement Production (Selected Countries)



Source: Fog amd Nadkarni, 1983, p. 16.

Table 6.4k

Energy for Cement Production
(Selected Countries)

Country	Year	GJ/ton	Source
Brazil	1984	4.5	(Sathaye et al, 1989)
China	1988	4.7 dry/5.57 wet	(Levine and Liu, 1990)
France/UK/Switz/Germ avg.	mid-80s	3.7	((IEA, 1987)
India	1978	7.3	(Fog, 1985)
Japan	1985	4.1	((IEA, 1987; Goldemberg, 1988)
Pakistan	1978	7.1	(Fog, 1985)
Phillipines	1979	5.9	(Fog, 1985)
Portugal	1977	6	(Fog, 1985)
Tunisia	1981	4.6	(Fog, 1985)
US	mid-80s	6.1	(Levine, et al, 1991)
USSR	1985	7	(Schipper and Cooper, 1991)

Table 6.4l

Sample Energy Savings in Cement Production
(Based on US technology)

Process step	Measure	Sample Savings
Grinding	High Efficiency Classifiers	15%
	Roll Press	20%
	Controlled particle size distribution	27%
	Advanced mill internals	50%
	Separate grinding of components	5%-10%
	Computer control	15%
Pyroprocess	Computer control	3-10%
	Fluidized-Bed Reactor	10-30%
	Relaxed alkali specifications	2-4%
	Low pressure-drop preheaters	5%
	Advanced sensors	2-5%
	Advanced preheater/precalciner kilns	5-10%
	Use of waste combustibles as fuels	5-50%
	New mineralogical content of clinker	5-30%

Source: Adapted fromTresouthick and Mishulovich, 1991, p. 402.

reduce energy consumption[38]. Over the longer term, the most substantial improvements can be obtained by a transition to the dry process. We assume this transition is completed by 2020 as the average plant operating life is about 10-30 years.

Finally, additional process improvements are possible in the energy intensive grinding and pyroprocess steps. Sample improvements and their potential energy savings in the U.S. are outlined in Table 6.41. For the grinding stage, these measures include the use of roller mills instead of ball mills, high efficiency classifiers and controlled particle size distribution and computer control to both improve efficiency and ensure a uniform product. For the pyroprocess stage, energy efficiency improvements include computer control coupled with advanced sensors, improvements of the preheater/precalciner stage and changes in the mineralogical content of cement (incorporation of fly ash, slag or other substances).

As in the case of steel, total energy efficiency will depend on the mix of measures chosen. Current average new stock in Western Europe incorporating some of these measures is already substantially more efficient than the global average, requiring only about 3.3 GJ/tonne, but it appears at least an additional 13 percent improvement is possible (IEA, 1987)[39]. We thus select our 2030 target as 2.9 GJ/tonne or about 20 percent below current Western European averages. Applying the scenario standard efficiency improvement of 0.5 percent/year to 2100 yields a target of 2 GJ/tonne in that year, about 33 percent higher than the theoretical minimum for the dry process.

Paper

Energy requirements for the pulp and paper industrial sector in the FFES are based on the current corporate assumption that wood fibre will continue to be the basis of paper making. This assumption is challenged by Greenpeace and others. The present rate of wood extraction from primary forests and the practise of plantation forestry for the purpose of pulping are in themselves unsustainable environmentally. Alternative fibre for paper making is likely to be required. If the paper industry moves to regionally appropriate fibre sources, energy use could be dramatically reduced. Alternative fibres would allow for closed loop manufacturing systems, less chemical inputs, and water savings. Each of these factors would reduce energy use beyond the assumptions on which this report is based.

The pulp and paper sector currently uses about 5 percent of total global industrial energy. The sub-sector as a whole has potential to use large amounts of energy as projected future production growth rates are high, particularly in the South. Thus, efficiency improvements are likely to be of particular importance in the future.

There are two stages in paper production, pulping and paper forming. Most paper production in industrialised countries takes place in integrated plants that produce both pulp and paper. The chemical pulping process requires approximately 3.5-4 GJ of heat and 50-110 kWh of electricity per tonne of paper produced, or about 14 percent of the total process energy. The paper making stage is the most energy intensive step, requiring about 36 percent of the total.

38 Possibly the most important is careful management practices that ensure continual plant operation. Optimum energy efficiency is not obtained for 30 minutes to several hours following a cold plant restart. Additionally, preventing heat losses is of prime importance. Measures can include improving internal heat transfer, reducing the moisture content of wet slurries, enhancing kiln insulation and recuperation of waste heat from the cooler and clinker shell. These can result in savings of 10-15% (Fog and Nadkarni, 1983)

39 New plants are assumed to be 100% dry process.

Table 6.4m

Energy for Paper Production
(Selected Countries)

Country	Year	GJ/ton	Source
Japan	1985	23	(IEA, 1987)
US	1982	31	(Ewing, 1984)
Sweden	1979	21	(Ewing, 1984)
Columbia	mid 80s	46	(Ewing, 1984)
India	mid 80s	101	(Ewing, 1984)
Pakistan	mid 80s	54	(Ewing, 1984)
Indonesia	mid 80s	46	(Ewing, 1984)
Thailand	mid 80s	23	(Ewing, 1984)
USSR	1985	36	(Schipper and Cooper, 1991)

Table 6.4o

Sample Long-term Energy Savings in Paper and Pulp Production
(Based on average industrialized countries, mid-seventies)

	Sample measures	Estimated Savings
Currently Available Technologies	Counter pressure drying of pulp	80%
	Pressurized groundwood pulping	45%
	Oxygen Bleaching	35%
Developing Technologies	Dry paper forming	High
	Biodegradation of Lignin	High

(Sources: Goldemberg et al, 1988; Ewing, 1984)

Table 6.4n

Sample Short-Term Energy Savings in Paper and Pulp Production

(Based on average industrialized countries, mid-seventies)

Process step	Sample measures	Estimated Savings
Wood Handling	Whole log chipping	
	Mechanical barking instead of hydraulic	
	Belt instead of pneumatic conveyance	
Chemical Pulping	Continuous instead of batch processing	
	Indirect rather than direct heating	
	Increased liquor strength	
	High consistency of pulp washing	
Bleaching	High consistency of bleaching and washing	
Pulp drying and paper making	Closed circulation water systems	
	High efficiency mechanical water removal	
General	Good insulation	
	Reduced pumping distances	
	Minimized water use	
	Efficient motors, pumps, fans, etc.	
Total internal energy savings		**10%**
Efficient heat recovery sytems	Use of hot effluents to heat incoming process water	
	Heat recovery from: digesters, chemical recovery sytems, etc.	
Improved Waste Utilization	Adequate initial furnace capacity	
	High solid content of black liquors	
	Combustion of wood wastes	
Total additional savings from heat recovery		**5-15%**

(From Ewing, 1984)

Paper production in the South is generally estimated to be twice as energy intensive as that in industrialised countries (see Table 6.4m). Differences reflect not only relative energy efficiencies, but also the structure of the industry, particularly the relative production of pulp and paper, plant size, design and operational considerations (Ewing, 1985). Developing country mills tend to be much smaller, averaging 5-20 percent of industrialised country mill capacities and do not generally incorporate available energy efficiency measures. For example, chemical recovery systems are best suited for plants larger than 20,000 tonnes per year. Due to initial capital cost consideration, oil-fired burners may be chosen over more expensive combination dual-fuel burners capable of using wood wastes. There are three main areas for energy efficiency improvements in the paper and pulp industry -- housekeeping improvements, replacement of outdated machinery and process improvements and alterations. In the South in particular, the first category will be important in the short run. Table 6.4n details some specific short-term measures. Options range from overall insulation improvements and minimization of water use to the use of continuous instead of batch pulping in the chemical pulping process to high efficiency mechanical water removal in the forming and pressing stages. These simple measures could be expected to yield 10 percent thermal energy efficiency improvements and 5 percent electricity intensity improvements over the sample plants of the seventies. As detailed in the above table, on a slightly longer time scale, additional efficiency gains can be made though incorporating better heat recovery and improved waste utilization. The latter can include cogeneration, discussed in more detail below. These steps can result in additional savings of 5 to 15 percent.

As in other energy intensive materials, stock turnovers can bring average energy efficiencies up to new technology levels in an estimated 20-30 years. In particular, the installation of integrated plants in the South can cut fuel use through appropriate synergies. Waste heat from pulp production, for example, can be used for drying. In addition, newer plants can incorporate a broader range of process improvements. Table 6.4o lists some longer term options. Counter-pressure drying of pulp can save over 80 percent of the energy in Kraft pulp digestion or about 11 percent of the total energy. Pressurized ground wood pulping (now available) could save 45 percent of the energy use for thermo-mechanical pulping. Drivepower savings alone could save some 28%-60% of total energy for production (Lovins, personal communication). Some of the more advanced technologies under development offer large but as yet unspecified potential energy efficiency improvements. These include biodegradation of lignins for pulp formation or new dry forming technologies that produce paper without wet-forming sheets.

While recycling of paper products is more important from a materials point of view than an energy point of view, it can contribute to energy efficiency. Recycled pulp uses approximately only 55 percent as much energy as virgin materials. As pulping uses about 14 percent of total energy for paper production, 100 percent recycling would save about 6 percent of total energy for paper production. Perhaps more importantly, recycling decreases pressures on forests and potentially leaves more land available for biomass fuel production (see Section 7.4, below).

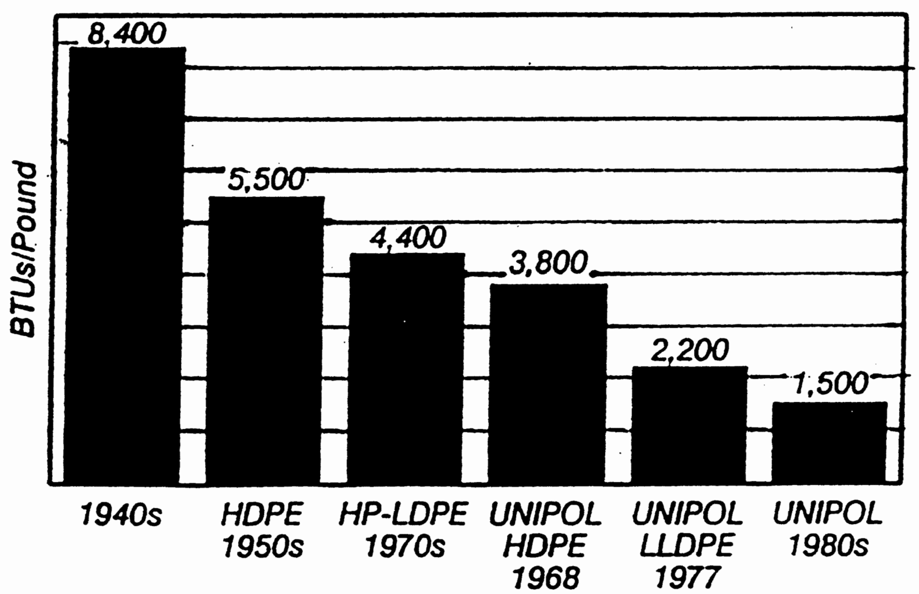
As in the other sub-sectors, the total energy savings will reflect the mix of measures chosen. We target energy efficiency levels in 2030 in industrialised countries to 30 percent below current Western European levels (IEA, 1987) and an additional 0.5 percent/yr of unspecified improvements over the period to 2100. This latter target is consistent with the developing technologies discussed above.

Chemicals

The chemical sub-sector is the most diverse of the energy intensive sectors. Accordingly, we look at trends in energy efficiency for representative products and process

Figure 6.4I

Trends in Energy Consumption for Polyethylene Production (US)



Source: Joyce, 1991, p. 433.

efficiency improvements that can be applied generically across the sector.

Large reductions in energy use have taken place in the chemical industry in the past. In the U.S., for example, energy for polyethylene production decreased over 80 percent from the 1940s to the 1980s (see Figure 6.4i). In the same time period, energy requirements for soda ash production decreased 10 percent, for chlorine about 25 percent and for ammonia about 50 percent (Goldemberg, et al., 1988). Substantial reductions are continuing. From 1972-1985, sub-sectoral energy use decreased 36 percent (OTA, 1991).

Much of these improvements historically came from measures applicable across various chemical industries, including better waste heat recovery, increased use of catalysts, more efficient distillation and better product integration. An example of the latter is the UNIPOL integrated process for the manufacture of both high and low density polyethylenes. This process integration was largely responsible for the energy reductions observed in Figure 6.4i.

According to Goldemberg et al. (1988), future large scale energy efficiency improvements are most likely to come from reaction chemistry and changes in separation and concentration processes. Improvements in reaction chemistry could come from increased use of catalysts and new developments in laser and biotechnologies. The first has been demonstrated successfully in the past, for example reducing the energy requirements for ammonia production to 1/3 their former value. Laser chemistry could potentially be even more effective by supplying only the specific energy required to break chemical bonds. Finally, biotechnological processes can save energy by combining multiple chemical processing steps into a single biological one and performing these at low temperatures and pressures.

The separation and concentration phases of chemical production currently consume some 80 percent of sectoral energy use (Goldemberg et al., 1988). Potential process alterations are suggestive of dramatic improvements in energy efficiency. The use of membrane separation techniques can reduce energy requirements of this stage some 80 percent, as demonstrated through the desalination of sea water. Separation using supercritical fluids (fluids at temperatures and pressures above the critical point) can be 50 percent more efficient than distillation. Alternatively, the use of freeze crystallization can reduce separation energy requirements by 75-90 percent over requirements for distillation.

These figures suggest it is reasonable to assume substantial continued energy efficiency improvements in industrialised countries. A scenario target of 50 percent of the current OECD energy intensities by 2030 as the target level is both plausible, given the efficiency improvements discussed above, and consistent with other studies (UCS et al., 1991). The 2100 target reduces energy intensity an additional 0.5 percent/year or about 30 percent overall, consistent with the more ambitious efficiency improvements described above.

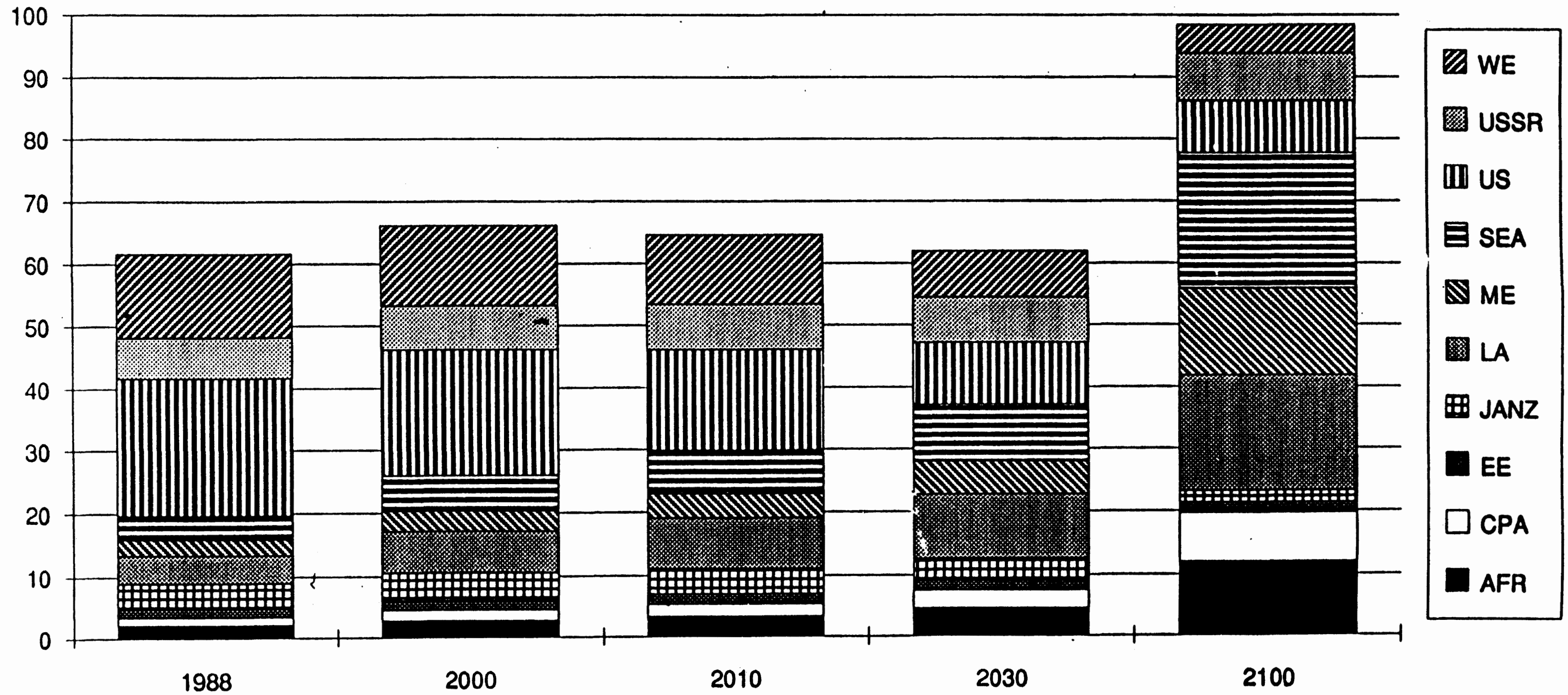
Fuel Switching and Cogeneration

It is possible to reduce carbon emissions in the industrial sector beyond levels obtainable through energy efficiency improvements alone by altering the fuel mix utilized by the sector. In the scenario, we alter the fuel mix first by increasing the share of heat obtained by cogeneration and second by switching between fuel types.

Cogeneration of steam and electricity is assumed to meet 20 percent of the steam demand in 2000, 60 percent in 2010 and 90 percent in 2030 and 2100. These figures are consistent with previous studies (OTA, 1991; UCS et al., 1991). Steam demand was assumed to be 45 percent of fuel use (Meyers, 1984).

For direct fuel use, fuel shares shift over time (see Figures 6.4e-g). In the near term (to 2030), renewables substitute for coal where available and natural gas substitutes for coal in

Figure 6.5
Transport Sector Delivered Energy
Consumption, 1988-2100, by Region



those cases where coal is not an integral part of the production process. The share of renewable fuels increases to around 8 percent on average. 20 percent of the fossil fuel share of total energy use was switched to electricity in industrialised countries, consistent with previous studies (Ross, 1991). In developing countries, this last shift occurred more slowly, resulting in a global convergence of fuel and electricity shares in 2100. The proportion of the emissions reductions resulting from the shift to electricity is obviously dependent on the electricity supply technology.

In the short term, process heat can be provided by solar energy. Relatively simple solar energy technologies, such as the solar parabolic trough, can produce process heat efficiently at low temperatures (<270° C) (Meyers, 1984). Approximately 30 percent of industrial process steam and heat needs fall below this temperature. In addition, in many other applications, solar heating could be used to preheat water for conventional boilers, making solar a potential option for about 50 percent of industrial process needs (Myers, 1984). Because the actual use of solar energy is dependent on a number of factors, particularly available land area and insolation, penetration of solar technologies to this level is unlikely in the medium term. A more conservative estimate, based on U.S. data, indicates that solar energy could meet 10 percent of process steam and heat needs in 2030 in a cost effective manner (UCS et al., 1991). In the longer-term, additional improvements in solar process heat, for example, the use of highly selective surfaces capable of high heat retention, will make the technology more attractive (Lovins and Lovins, 1991). We selected scenario targets of 10% in 2030 and 15% in 2100. This estimate was applied to all regions.

In the longer term (to 2100), all fossil fuel use can be replaced by renewable fuels. In the paper industry, 90 percent of fuel needs are met by its own biomass starting in 2030. In other sectors, final penetration of all renewable fuels averaged closer to 60 percent of fuel needs. Fuel mixes in steel and chemicals are not changed as specific fossil fuels are an integral part of the sub-sectoral product.

6.5 Transport Sector

The transport sector results in this report are based upon a companion analysis by Michael Walsh. The transport analysis embodies the economic and population growth assumptions discussed in this report. It reflects vehicle efficiency improvements and other emission reduction measures. The fuel shares shown below are consistent with the policy approaches and technology options described in the companion report.

	2030	2100
Oil	40%	0%
Biofuels	30%	20%
Electricity	20%	40%
Hydrogen	10%	40%

Transport sector results are shown in Figure 6.5. See companion analysis (Appendix F) for a discussion of underlying assumptions and analysis.

Section 7: Detailed Results of FFES: Energy Supply Assessment

7.1 Overview and Results

The size and characteristics of future energy systems will be crucial determinants of our ability to meet global targets for reducing greenhouse gas emissions and global warming impacts. The demand assessment in Section 6 provides a sense of the size of the energy system required to support a world growing in affluence, equity, and population. Here, the supply assessment presents a possible picture of its characteristics and evolution. It reflects an analysis of electricity and fuel production using the LEAP system. The technical assumptions and methods underlying this analysis are presented in Sections 7.2 to 7.4 below, with further detail on the modelling framework and input assumptions in Appendices G and H. Most estimates of near-term renewable potentials and future technology characteristics were drawn from recent literature, with guidance from Greenpeace regarding policy assumptions (see Section 1). We made a number of broad assumptions in order to construct a plausible long-term scenario for the evolution of a low carbon emission energy system. Most important to the success of such a scenario will be the implementation of policies that enable the technology development and penetration envisioned here. Such policies are described in the companion policymakers report, which appear in abstract form as Section 10.

The demand-side analysis showed the potential for end-use measures to provide substantial reductions in fossil fuel use and CO_2 emissions through 2030. Similarly, the supply analysis emphasizes near-term efficiency improvements in electricity generation and petroleum refining to 2030, while the full transition from fossil fuels to renewable energy sources occurs over the longer-term by 2100. Together, these demand-side and supply-side measures demonstrate the technical and economic feasibility of reaching ambitious CO_2 emission reductions, as shown in Figure 5.1. This transition to a renewable energy system, as illustrated in Figure 5.3 and Table 5.2, becomes possible over the 110 year time scale considered. Components of the current energy infrastructure -- electric systems, energy extraction facilities, energy-using equipment -- have several economic lifetimes over this period. During the most critical near-term period, emission reductions rely largely on improving the efficiency of both energy production and use, and on proven, cost-competitive lower-carbon and renewable sources.

In the FFES scenario, fossil fuels, which currently comprise over 80 percent of primary energy supply, remain at over half of total energy supply through 2010. By 2030, renewable energy sources begin to dominate primary energy supply.[1] In 1988, oil accounted for 116 EJ or 34 percent of total primary energy use, more than any other primary resource. In comparison, coal use accounted for 93 EJ (27 percent of total energy use), and natural gas use for 65 EJ (19 percent). Rapid growth in Asia, where new energy supplies are likely to be heavily coal-reliant, offsets fuel switching away from coal in the North, and world coal use remains at 93 EJ though 2000. Coal use continues to grow in some developing regions through 2010, after which efficiency gains and fuel switching to natural gas and renewable sources results in a decline in coal use in all regions. Globally, coal use declines to 85 EJ by 2010, and 29 EJ by 2030.

Natural gas use continues to rise through 2010, to 105 EJ from 65 EJ in 1988 as the result of fuel switching from coal and oil in all sectors, including electricity generation. Its

1 See Explanatory Notes following Section 10 for discussion of primary electricity conversion efficiency used for solar, wind, hydro, geothermal and nuclear sources.

share of total primary energy drops from 26 to 15 percent from 2010 to 2030, as alternative fuels and solar/wind electricity become widely available. Due to their well-developed natural gas infrastructures, the U.S. and the former USSR remain the largest natural gas users through 2000. With assumed supplies of Russian and Northern European natural gas, and strong emphasis on emission reductions, Western European consumption of natural gas doubles by 2010 to 24 EJ, then drops to 11 EJ by 2030.

Oil use remains roughly constant at 110-120 EJ through 2000, as efficiency improvements and decreased use of petroleum products for electricity generation offset otherwise increasing demands. In addition, oil use increases in the South roughly balance decreases in the North, as shown in Table 7.1. Table 7.2 shows primary supply in greater detail by region and resource.

Hydroelectric and geothermal resources are relatively limited in site availability, but offer important well-proven and economic low-emission options. Their combined contribution increases to 34 EJ (9 percent) by 2030, and remains roughly constant thereafter, as the environmental concerns regarding the preservation of river and other ecosystems limit available sites[2].

Solar and wind resources have far greater site availability. Solar technologies, while requiring significant land area per unit energy produced, do not present the level of potential land use conflicts as those that could arise between biomass and agricultural or wilderness preservation. Furthermore, many sites can be integrated with other applications (e.g., rooftops), thereby further decreasing land use requirements.

Naturally, regions do not possess equal levels of solar insolation, and relative land use requirements and economics of solar energy will thus vary among and within regions. The geographical, seasonal, and daily distribution of solar resources do not necessarily match the distribution of energy demands. Storage and transmission, in particular conversion to hydrogen, can help to overcome this obstacle in the long-run. Near-term solar potentials are thus highly dependent on proximity of insolation and the energy user, as reflected in the assumptions for water heating (Section 6.2) and electricity below.

With limited near-term economic applications in remote and selected high resource sites, solar and wind combined grow to 5 percent (20 EJ) of primary energy in 2000, and 9 percent (36 EJ) in 2010. Decreases in the cost of solar photovoltaic electricity generation, as shown in Figure 7.1, render it increasingly cost-competitive with fossil resources during the 2010-2030 period, particularly in higher solar resource regions.[3] (The example of photovoltaics in Western Europe in Figure 7.1 shows the improving economics even at relatively high latitude and with considerable cloud cover.) Decreases in the cost of wind systems similarly increase its competitiveness in more abundant, lower wind speed regimes during this period. Finally, the development of advanced storage facilities enable intermittent solar and wind resources to follow a greater part of electric system loads. Overall, solar and wind resources grow from about 30 percent to almost 80 percent of total primary resources

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2 The drop from 2030 to 2100 is in primary "fossil equivalent" energy, not actual hydroelectric/geothermal production. This is due to the increasing efficiency of "fossil equivalent production." See Explanatory Notes.

3 Documentation for this figure can be found in Appendix G. These costs are based largely on a study of the U.S. (UCS et al., 1991), and fossil prices are based on official U.S. DOE forecasts for the utility sector. Although these data are largely U.S. specific, and relative fuel prices and resource availability will differ somewhat among regions, this figure illustrates the cost-competitive nature of renewable electric options that could be further stimulated by policies such as energy taxes or externality costs.

Table 7.1

Primary Energy Supply, 1988-2100
Comparison of Current Developing and Industrialized Countries by Source
(EJ)

		Oil	Coal	Natural Gas	Hydro/ Geo*	Biomass	Solar/ Wind*	Nuclear*	Total
1988:									
	Developing	33	32	8	8	14	0	1	96
	Industrialized	83	61	56	16	8	0	18	242
2000:									
	Developing	40	48	19	9	20	8	1	144
	Industrialized	72	45	77	17	17	12	11	252
2010:									
	Developing	40	50	24	10	29	17	0	170
	Industrialized	53	35	81	18	23	20	0	229
2030:									
	Developing	28	20	18	14	49	61	0	190
	Industrialized	31	9	39	17	42	57	0	194
2100:									
	Developing	0	0	0	12	148	622	0	783
	Industrialized	0	0	0	15	33	156	0	204

*Solar, wind, hydro, geothermal and nuclear energy converted from electricity to primary energy using then-current average fossil/biomass plant efficiencies (see Explanatory Notes following Section 10).

Table 7.2
Primary Energy Supply, by Region and Resource, 1988-2100
(EJ)

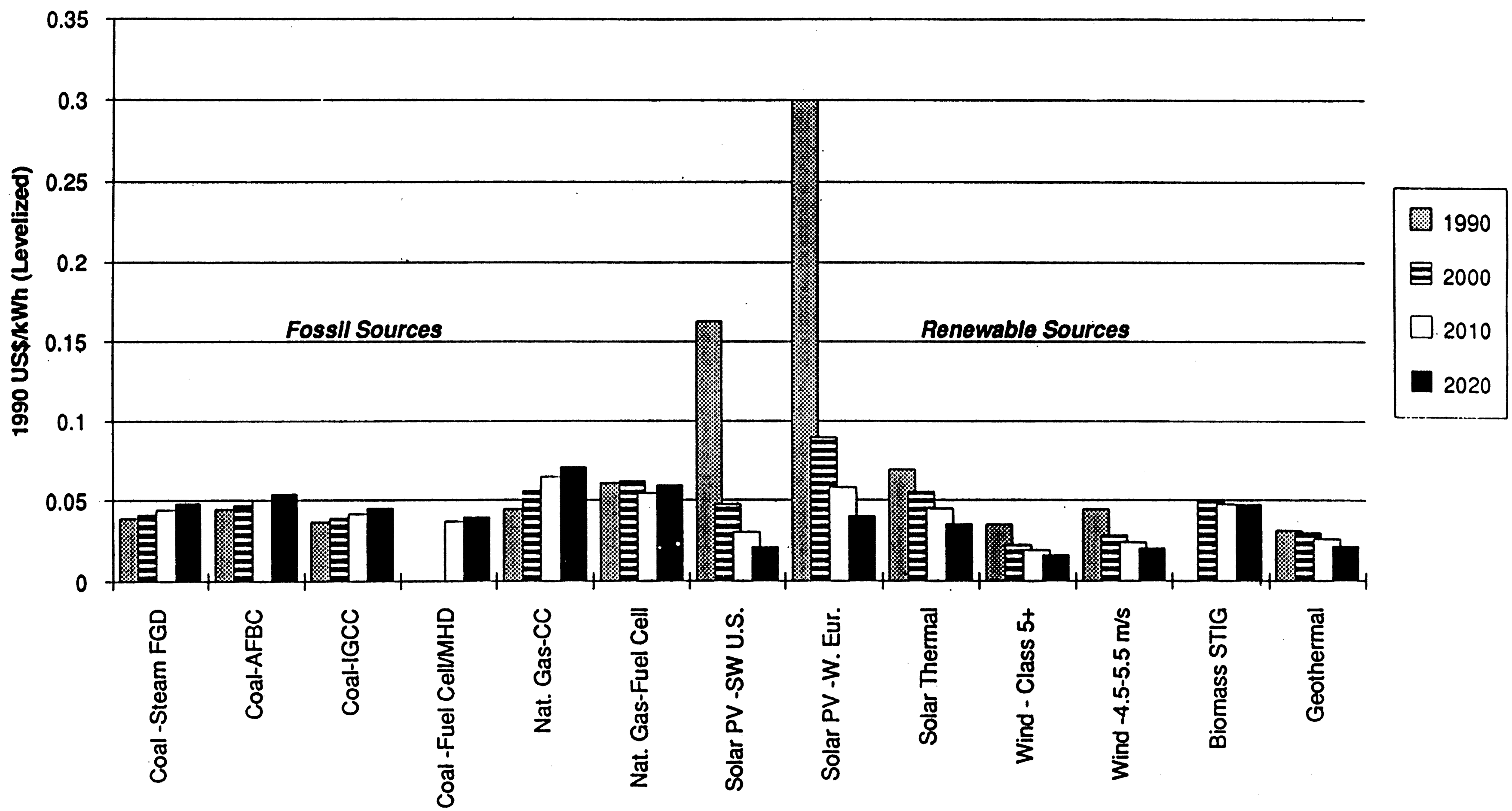
		Oil	Coal	Natural Gas	Hydro Geo*	Biomass	Solar/ Wind*	Nuclear*	Total
1988:	AFR	4.2	2.7	1.0	0.6	3.6	0.0	0.1	12.2
	CPA	4.8	22.0	0.5	1.5	2.1	0.0	0.0	30.9
	EE	3.6	7.9	3.4	0.5	0.0	0.0	0.5	15.9
	JANZ	9.8	4.2	2.8	1.5	0.2	0.0	1.9	20.3
	LA	9.0	0.8	2.6	4.0	4.0	0.0	0.1	20.5
	ME	6.3	0.2	2.6	0.2	0.0	0.0	0.0	9.3
	SEA	8.3	6.3	1.8	1.3	4.7	0.0	0.9	23.3
	US	29.3	19.8	19.2	2.8	5.6	0.1	5.6	82.2
	USSR	14.9	13.2	19.8	2.3	0.5	0.0	2.0	52.6
	WE	25.6	15.6	11.1	8.7	1.4	0.0	8.3	70.6
	TOTAL	115.6	92.6	64.6	23.3	22.1	0.1	19.4	337.7
2000:	AFR	4.7	4.6	2.0	0.7	4.3	0.9	0.1	17.3
	CPA	8.7	30.7	3.2	1.9	3.9	2.5	0.0	50.8
	EE	4.0	6.0	4.9	0.5	0.7	0.8	0.4	17.2
	JANZ	8.1	2.6	6.5	1.4	1.7	1.5	1.2	22.9
	LA	9.6	1.5	4.3	4.4	5.3	1.4	0.0	26.4
	ME	6.6	0.4	4.7	0.2	0.8	0.7	0.0	13.5
	SEA	10.2	10.9	4.4	1.9	6.3	2.3	0.5	36.5
	US	23.0	16.6	22.6	3.1	8.0	3.7	3.5	80.6
	USSR	15.9	9.0	23.9	4.0	2.9	3.5	1.0	60.3
	WE	20.7	10.5	19.1	8.3	4.2	2.7	5.1	70.5
	TOTAL	111.5	92.7	95.6	26.4	37.9	20.0	11.8	396.0
2010:	AFR	4.7	5.5	2.6	0.9	5.1	2.0	0.0	20.7
	CPA	9.8	29.8	4.9	2.1	6.8	5.3	0.0	58.6
	EE	2.8	5.4	3.7	0.5	1.0	1.1	0.0	14.5
	JANZ	5.7	1.2	8.3	1.4	3.0	3.1	0.0	22.7
	LA	9.0	1.8	5.1	4.7	6.8	2.8	0.0	30.2
	ME	6.2	0.6	6.0	0.1	1.7	1.6	0.0	16.2
	SEA	10.6	12.4	5.9	2.3	8.3	5.1	0.0	44.6
	US	16.0	14.4	24.6	3.3	7.7	5.1	0.0	71.1
	USSR	13.2	8.5	20.2	4.8	4.7	5.3	0.0	56.6
	WE	15.3	6.0	23.7	8.0	6.7	4.9	0.0	64.6
	TOTAL	93.3	85.3	105.0	28.0	51.8	36.3	0.0	399.8

Table 7.2 (cont.)
Primary Energy Supply, by Region and Resource, 1988-2100
(EJ)

		Oil	Coal	Natural Gas	Hydro Geo*	Biomass	Solar/ Wind*	Nuclear*	Total
2030:	AFR	4.0	2.3	1.9	1.6	8.0	10.1	0.0	27.9
	CPA	6.5	11.5	4.8	3.0	10.6	15.1	0.0	51.4
	EE	1.9	2.1	2.5	0.4	2.6	3.6	0.0	13.2
	JANZ	4.0	0.3	3.4	1.2	4.3	6.7	0.0	20.0
	LA	6.3	0.7	3.0	6.0	11.4	9.2	0.0	36.6
	ME	3.6	0.4	4.5	0.1	3.6	7.3	0.0	19.5
	SEA	7.8	4.8	4.1	2.9	15.6	19.3	0.0	54.4
	US	7.3	2.2	11.1	3.0	13.1	17.3	0.0	53.9
	USSR	9.3	2.9	11.1	5.2	10.2	14.1	0.0	52.9
	WE	8.4	1.3	10.5	6.9	11.8	15.4	0.0	54.2
	TOTAL	59.0	28.5	56.8	30.4	91.1	118.2	0.0	384.0
2100:	AFR	0.0	0.0	0.0	1.5	37.3	167.3	0.0	206.1
	CPA	0.0	0.0	0.0	2.7	29.0	126.1	0.0	157.9
	EE	0.0	0.0	0.0	0.4	2.5	12.0	0.0	14.9
	JANZ	0.0	0.0	0.0	1.1	3.0	14.4	0.0	18.5
	LA	0.0	0.0	0.0	5.5	23.5	62.5	0.0	91.5
	ME	0.0	0.0	0.0	0.1	10.7	66.3	0.0	77.1
	SEA	0.0	0.0	0.0	2.6	47.8	200.0	0.0	250.4
	US	0.0	0.0	0.0	2.7	9.3	42.4	0.0	54.5
	USSR	0.0	0.0	0.0	4.8	9.3	41.6	0.0	55.6
	WE	0.0	0.0	0.0	6.3	9.0	45.6	0.0	60.9
	TOTAL	0.0	0.0	0.0	27.6	181.4	778.3	0.0	987.2

*Solar, wind, hydro, geothermal and nuclear energy converted from electricity to primary energy using then-current average fossil/biomass plant efficiencies (see Explanatory Notes following Section 10).

Figure 7.1
Projected Busbar Costs of Electric Generation Technologies, 1990-2020



Busbar costs are based on projected fuel costs for the U.S See appendix table G-2 for details. See explanatory notes for acronyms.

from 2030 to 2100.[4]

Biogenic Sources of Carbon: The Role of Biomass for Energy and Afforestation

There are two elements in the role of biomass within the the overall Greenpeace study. The first is the retention of current primary forests and halting significant deforestation; the second is afforestation, the development of environmentally sustainable forests and other biomass resources. We only considered the potential for biomass energy resources, and the associated land use requirements. Kayes dealt with afforestation, in a separate report for Greenpeace (Kayes, 1992).

Deforestation and land use changes are estimated to release approximately 1.6 Gt C per year (± 1Gt C per year) into the atmosphere (IPCC, 1992). There is currently a major imbalance between deforestation and afforestation. Greenpeace commissioned analysis by Kayes to assess possible future carbon releases from deforestation and afforestation in a range of policy scenarios. In this analysis it was projected that net losses to forest sources of carbon would cease before the year 2020, and actual deforestation of major tropical rainforest and boreal forests would cease by 2025, due to international action through a Forestry Convention. These assumptions were utilised by Waide, with the FFES, in the climate analysis.

Developing sustainable biomass plantations will be critical to the success of a high-biomass energy scenario such as the FFES. Evidence of sustainable biomass plantations in Africa, Latin America and Northern countries was obtained and assessed. It was decided to reject assumptions of very high-yield biomass plantations; though such assumptions reduce the land area required, they raise a range of questions. These include the implications of high inputs of fertilizers and pesticides, the necessity of special breeds of plants, increased water demands, and the extent to which such plantations can be sustained in the longer-term. Unlike natural forests, very intensive biomass plantations may have a limited period of sustainability. As a result, only mid-range estimates were assumed for biomass yields. There is evidence that biomass yields at the levels assumed in the FFES might be sustained in widescale applications throughout the world (Hall, 1991a; Johansson et al, 1993)

Key ingredients for developing sustainable biomass energy systems which require low or zero artificial inputs, include the need to plant several species at each site, the inter-planting with nitrogen-fixing species, and careful choice of species which are matched to local water availability and soil types (National Audubon Society, 1991). The question of biodiversity depends on the previous use of the land. If natural forests are replaced, then biodiversity is clearly reduced. If degraded lands or surplus modern farmland is replaced, biomass plantations could improve bidiversity both above and below ground. As a result of the trade-off for lower yields and lower chemical inputs, land-use requirements for biomass for energy plantations are quite high (see discussion in 5.2.4).

Biomass use grows steadily throughout this scenario, despite the decreasing use of traditional biomass resources in developing regions. Biomass energy sources include short-rotation trees and grasses, wood from conventional forestry, wood wastes, agricultural residues and surpluses, and landfill methane.The initial rise in biomass use is relatively slow, limited by the need to develop the infrastructure for large-scale biomass energy production and its conversion and use as liquid biomass, particularly for transport. By 2010, biomass accounts for almost 13 percent of total energy supply, up from 7 percent in

4 We do not explicitly assign the relative contributions of solar and wind or the contributions of particular solar and wind technologies, such as PV vs. solar thermal electric. These contributions will depend upon the evolution of the technologies and their costs.

Table 7.3

Land Use Requirements of Renewable Resources in the FFES[d]
(Million Hectares)

	2000	2010	2030	2100
Solar/Wind				
Current Efficiencies[a]	2	4	15	105
% of global land area	(0.0%)	(0.0%)	(0.1%)	(0.8%)
Doubling Efficiencies by 2030[a]	2	3	8	53
% of global land area	(0.0%)	(0.0%)	(<0.1%)	(0.4%)
Biomass				
At Base Productivities[b]	156	215	384	721
% of global arable/pasture/forest/wood land:	(1.8%)	(2.5%)	(4.4%)	(8.2%)
w/25% of Recov. Residues by 2030[c]	136	179	316	652
% of global arable/pasture/forest/wood land:	(1.6%)	(2.0%)	(3.6%)	(7.4%)
2x Base Prod., 25% Resid. by 2030[b]	106	118	158	326
% of global arable/pasture/forest/wood land:	(1.2%)	(1.3%)	(1.8%)	(3.7%)

a Based on an average annual site insolation of 175 W/M2. Insolation levels range from 270 W/M2 at good U.S. sites (SW U.S., Ogden and Williams, 1989), to 210-250 W/M2 in Australia (Charters, 1991), to 146 W/M2, at a cloudier, higher latitude site (Vermont, NE U.S., Ehrlich et al., 1977), to 80-120 W/M2 in Northern Europe (Charters, 1991). A proxy of solar PV is used for this land use estimate, assuming cell efficiency of 15 percent and a ground to collector ratio of 2.04. This yields a land use coefficient of 246 hectares/PJ-yr of captured solar/wind energy. "Captured energy" refers to the solar/wind energy captured as electricity (eg PV, the proxy used here) or applied heat, some of which is subsequently lost during storage and conversion to hydrogen. The solar/wind energy balance, Appendix Table G-9, shows the captured energy calculation. Wind land area per unit energy assumed to be roughly equivalent to solar. (See Figure 7.3) Direct solar thermal applications, such as water heating, will have a lower land use per unit of delivered energy, due to their higher overall efficiencies, but the higher land use for PV was used in the calculation. To account for possible overestimation of land use requirements, figures are shown above for a doubling of overall efficiency assumptions. This doubling could reflect improved PV cell efficiency, a reduction in average collector to ground area, and/or a greater provision of delivered energy from direct solar, rather than solar PV-electric applications.

b See discussion of biomass productivity levels in Section 7.4. No use of biomass residues other than sugar cane residues for cogeneration are assumed here. Biomass production was assumed to occur in the region of biomass demand at the productivities shown in Appendix Table G-4. Recoverable residues of 16 EJ (25% of 65 EJ) displace a total of 69 million ha. by 2030 at doubled productivity. Both the utilisation of residues and the doubling of productivity are phased in over the 40 year period.

c Based on current recoverable residues of 65 EJ (Hall et al, 1992; see Table 7.9).

d Land use requirements fall considerably in variants to FFES (see section 5.2 and end of section 7)

1988.[5] Biomass plays a particularly important role as a source of emission reductions from 2010 to 2030, displacing fossil fuel use, as it grows from 51 EJ to 91 EJ, over 20 percent of

5 As noted earlier, our estimates for 1988 biomass use are based on UN data, which are low by a factor of 2 compared with other estimates.

global primary energy by 2030. By 2100, primary energy from biomass doubles to 181 EJ, while its share of total primary energy remains at roughly 20 percent.

Land use requirements for solar and wind electric systems are considerably less than those for biomass resources throughout the scenario, as shown in Table 7.3. The land use requirements for biomass could rise to between 2-4 percent of total present global arable, pasture, and forest and woodland area by 2030, and to 4-8 percent by 2100. Smaller land use needs for solar and wind energy -- less than 1 percent of global land area to meet 80 percent of world primary energy in 2100 -- could nonetheless pose conflicts in some areas. It is important to keep in mind that the land use for coal and oil shale extraction could present far more detrimental potential land use and pollution impacts. In the comparison of land use associated with electricity production from various sources shown in Table 7.3, the land requirements associated with coal facilities are similar to that for existing solar and wind installations. Furthermore, solar PV cells could be incorporated in roofing materials, vehicle bodies, and other surfaces, greatly reducing land use requirements in comparison with the central PV stations shown in Figure 7.2. Direct solar applications for low-temperature heat in buildings and industry can also employ rooftop or multiple-use land area. Wind turbines typically use less than 15 percent of the land occupied by multi-turbine wind farms, while the remaining land can be used, where appropriate, for crops and pasture (Gipe, 1991).

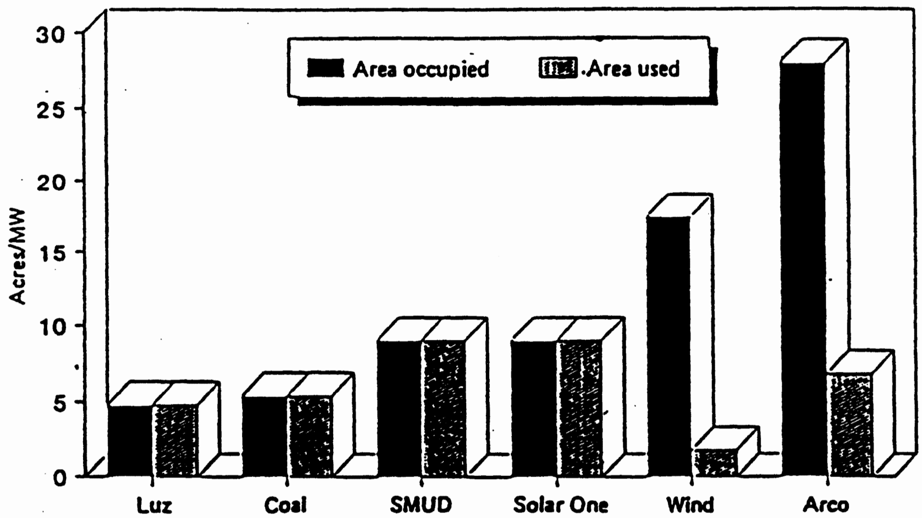
Environmentally sound, extensive biomass use will require minimizing risks to soil fertility and biodiversity. Cropping and harvesting systems will need to maintain the characteristics of diverse ecosystems and avoid potentially excessive water and fertilizer use requirements.[6] These reasons, plus the need to minimise competition with food production and avoid displacing indigenous people, explain our conservative base estimates on future biomass productivity and use; higher levels of productivity have been achieved, but this might require practices that are unsustainable over the time scale envisioned here (Cook et al., 1991). Table 7.3 also presents land use requirements assuming productivities can be doubled without unacceptable adverse consequences.

As noted in section 1, a constraint on the FFES placed by Greenpeace is the unacceptability of nuclear power as a sustainable energy option. This view is based on more than 30 years of global experience with the technology, and the significant risk factors from catastrophic accidents, nuclear weapons proliferation, and the unresolved problems of radioactive waste management. Nuclear power stations, accounting for 19 EJ (5 percent of primary energy) in 1988, are phased out over a 20-year period in the FFES. Nearly 70 percent of current nuclear reactors will have reached the end of their planned life by this date (data from Nuclear Engineering International, 1991). In addition, safety concerns over reactors in Eastern Europe and the former Soviet Union are assumed to accelerate the closure of many stations. The remaining reactors are assumed to be phased out due to public concern. Power from nuclear fusion is considered too remote and speculative for consideration in this assessment.

6 See Cook et al., 1991 for fuller discussion. Many years experience with eucalyptus plantations in Brazil has led to improved sustainability practices such as contiguous strips of fallow lands for native species. (Personal communication, David Hall)

Figure 7.2

Land Use for Electricity Generation



"LUZ = solar parabolic troughs, Kramer Junction, CA, USA. Coal = includes mining; SMUD = two 1 MW photovoltaic plants at the Sacremento Municipal Utility District's Rancho Seco nuclear station; Solar One = 10 MW central receiver near Barstow, CA, USA; Arco = MW Carizzo Plains photovoltaic plant." (Gibe, 1991).
Barstow, CA, USA;

Source: Gipe, 1991, p. 764.

N.B. Pasquallth et al (1984) give land-use requirements of 7-13 acres/MW for mid-western (US) opencast coal mines.

7.2 Electricity Generation

As shown in Figure 7.1, the cost of generating electricity from several renewable sources is already cost-competitive with fossil resources under certain conditions: at the best solar thermal and wind sites, some remote photovoltaic installations (not shown in the figure), and at numerous hydroelectric (not shown) and geothermal sites.[7] Over the next 40 years, decreasing costs could make wind and solar electricity cost competitive at more abundant sites, enabling their installation in all regions, particularly at or near the site of energy use (e.g., rooftop photovoltaics) (SERI, 1990). In fact, recent research indicates that within the 1990s, significant technical improvement in large-scale electricity generation from solar thermal technology and major reductions in costs appear feasible. Preliminary economic estimates suggest that electricity from solar thermal stations could be produced at an average cost of 4 to 6 cents per kWh by the end of the decade, making it cost competitive in many regions of the world.[8] A largely renewable, low-emission electricity supply system can thus be envisioned for the remainder of the next century.

On the path to a fully renewable electric system, several options to decrease greenhouse gas emissions will need to be pursued. The options pursued in this scenario, and the assumptions and modelling of future electricity generation can be summarized as follows:

1) **Description of existing system.** The current electricity resource mix for each region was assessed based on IEA data (IEA, 1990), and used as the starting point for further analysis.

2) **Retirement of existing fossil and nuclear units.** Existing centralized fossil-fuelled electric capacity is gradually phased out by the year 2020. This 30-year period approximates the economic lifetime of standard facilities, assuming no major life extension. In Western Europe and JANZ, currently existing central fossil stations are retired or retrofitted to improved efficiencies (combined cycle equivalent) by 2010, in order to meet Toronto target reductions. Nuclear units are retired more rapidly (by 2010) according to assumptions provided by Greenpeace.

Nuclear fusion is disregarded in this analysis. Since even the most optimistic advocates do not see commercial prototypes before the middle of the 21st century, with independent authorities more skeptical, the prospects of fusion making any noticeable impact on CO_2 emissions over the next century are low. A number of safety and environmental problems are outstanding (STOA, 1991).

3) **Increased cogeneration for on-site thermal applications and district heating systems.** Cogeneration and district heat potentials for industrial, service and residential sector applications are discussed in the demand sections above. Currently, technical limitations on cogeneration (e.g., site limitations) tend to be the exception rather than the rule. The primary reasons why cogeneration systems have not been exploited to their full technical potential are primarily institutional. In particular, unwillingness or the lack of mechanisms for the purchase of electricity by utilities from cogenerators, and the design of electricity tariffs, have masked the positive economics

7 Documentation for Figure 7.1 can be found in Appendix Table G-2.

8 Based on personal communication, David Mills, University of Sydney, Australia. See paper to be published in Energy, 1992, by Keepin and Mills, and paper for the 1992 ANZSES conference (Mills, 1992). With a backup fuel such as natural gas (for 10-30 percent of load), and inexpensive hot rock beds providing 8 to 10 hours of thermal storage, the load following capability of these facilities are greatly enhanced.

of cogeneration for many applications. The removal of these impediments should lead to a large expansion of cogeneration systems. The UK has experienced such an expansion in industrial cogeneration in the three years since the privatization of the electricity industry.

In the model used here, the demand for cogenerated or district heat determined in the demand analysis drives the operation of cogeneration systems. The generation of electricity is then assumed to offset the requirement for additional capacity and generation from other sources. Petroleum products and natural gas are initially assumed to fuel cogeneration systems. In part, this assumption reflects the greater flexibility and availability of these fuels. In addition, it is assumed that policy measures that encourage cogeneration as an emission reduction measure will also promote fuel switching from coal as new equipment is installed. The initial fuel mix for cogeneration is assumed to match the current industrial mix of petroleum product and natural gas use in the industrial sector in each region (with the exception of JANZ, where a 50/50 oil/natural gas mix is achieved by 2010). By 2030, the fuel mix for cogeneration is assumed to be 35 percent for both oil and natural gas, 20 percent for biomass and liquid and gas biofuels, and 10 percent for hydrogen (produced from solar and wind resources as discussed below). The fuel mix for cogeneration moves increasingly toward hydrogen and biofuels for the remainder of the century until it reaches 80 percent hydrogen/20 percent biofuel mix by 2100.

Including both electricity and useful heat generation, the assumed overall efficiency of cogeneration systems is 69 percent (thermal and electricity out/energy in). A ratio of 30 percent electricity to 70 percent heat production is assumed for all input fuels, based on the analysis of a low-cost steam load-following gas turbine, as shown in Appendix Table G-7. The gas-turbine analysis is simply an example to show the technical and economic characteristics of cogeneration units. The choice of cogeneration technologies will be application-specific in many cases, small internal combustion engines will be preferable. Other systems, such as aeroderivative turbines (e.g., steam-injected gas turbines, or STIGs), and fuel cells would likely be even more advantageous than the sample technology selected, due to a higher ratio of electricity production to steam production. With the implementation of advanced technologies, such as modular fuel cells and aeroderivative turbines, these efficiencies gradually improve through 2030, when they are assumed to reach 80 percent for gas and petroleum products, and 85 percent for hydrogen.

4) **Near-term renewable potentials (to 2020)**: Region-specific potentials for several near-term renewable electricity options -- hydro, wind, solar, and biomass residues -- were derived from three existing projections (Dessus et al., 1991, Odgen et al., 1990; Hall et al., 1992). The analysis by Dessus et al. is based on several geographical, social, and economic considerations, and provides accessible renewable reserves for solar, wind, and hydro during the 1990s and by 2020. We adopted these reserve levels, but delayed full implementation for the 1990 reserves until 2010 to reflect the time scale of the retirement of existing fossil and nuclear capacity. The specific levels of introduction are shown for each resource in Appendix Table G-5.

As noted in Section 1, the environmental considerations limit the full implementation of the renewable potentials. In particular, new hydro development was reduced 35 percent below the technical/economic potentials determined by Dessus et al., with original basis in World Energy Conference estimates. This fraction reflects an estimate of the higher-impact large hydro developments included in the Dessus et al./WEC potentials.

Biomass Waste Cogeneration: The total energy resource from current recoverable biomass residues has been estimated at 65 EJ (Hall, et al, 1992). We have considered here only a small fraction of this potential: the use of sugar cane refining wastes for on-site cogeneration. The use of pulp and paper wastes, another major source of biomass residues, has been considered within the analysis of the industrial sector above. A discussion of the large, economic potential of biomass waste use with biomass integrated gasifier steam-injected gas (BIG-STIG) turbine cogeneration systems can be found in several recent reports by researchers at Princeton University (Ogden, et al., 1990; Williams and Larson, 1991; Fulmer, 1990). BIG-STIG cogeneration systems offer a relatively low-cost versatile option for utilizing biomass resources. Average overall (combined thermal and electric) efficiency is estimated at 62 percent, with a ratio of electricity to steam production of 48 percent to 52 percent.[9] Future sugar residues and their generation potentials by region were derived from the same source (Odgen et al., 1990). A more conservative estimate of 25 percent of estimated sugar residue cogeneration potentials was adopted for 2030, with a gradual increase from now until then, and constant levels thereafter.

5) **Improved efficiency of new fossil units (`1st generation').** With the retirement of existing fossil-fired electric capacity, new, higher efficiency fossil units are introduced to meet growing electric demands that are not otherwise met by renewables or cogeneration units. The initial generation of new fossil electric supply operates at improved efficiencies of 37 percent for coal and 44 percent for gas, based upon a proxy of combined cycle technologies.[10] Other newer combustion technologies, such as fluidized bed systems for coal use and aeroderivative turbines could offer similar levels of improvements. These technologies are implemented through 2010, when fuel cells begin to dominate new fuel-based capacity.

6) **Fossil fuel mix: Increased natural gas, decreased oil use.** The installation of new oil-based units, except for peaking purposes, is highly unlikely in most regions. The future mix of coal and natural gas is based on the 1988 ratio and assumptions regarding regional availability. The share of natural gas for newer capacity increases somewhat relative to the current mix in each region, based on assumed climate stabilization policies. The fuel mix for these new units is shown in Table 7.4 below. In the OECD and the USSR, the coal to natural gas mix is assumed to be 60 percent to 40 percent. However, in JANZ new capacity was assumed to be

Table 7.4

Fuel Mix Assumed for New Fossil Capacity in Each Region (2010)

	AFR	CPA	EE	JANZ	ME	SEA	US	USSR	WE
Coal	70%	90%	75%	5%	10%	70%	40%	40%	40%
Gas	30%	10%	25%	95%	90%	30%	60%	60%	60%

95% natural gas (largely liquified natural gas, due to limited local coal resources), due to the current high levels of coal use, and political commitments to emissions stabilization. In Asia and Africa, the ratio of coal to gas remains high, particularly in China, where 90 percent of this new generation is expected to be coal-based.

7) **Fuel cell technology (`2nd generation').** Fuel cells (and

9 Based on an average of the 3 BIG/STIG systems (LM-5000, LM-1600 and GE-38) described in Table 5 of Ogden et al., 1990.

10 Efficiency estimates based on EPRI (1989).

magnetohydrodynamics, MHD) provide a second generation of efficiency improvements in electricity production, starting in the year 2000, and representing all new fuel-based capacity (fossil, biofuel, and hydrogen) after 2030 (EPRI 1989; Fisher, 1990). The efficiency of these units starts at 50 percent and grows to 57 percent by 2030. For coal, the efficiencies are 10 percent lower, representing the losses from coal gasification. For coal, MHD could provide similar efficiency improvements at similar costs to fuel cells.

Fuel cells have considerable flexibility in their technical configuration, operating characteristics and fuel input requirements. Fuel cells are modular, hence allowing for a phased installation, and smooth retrofit potential. The retrofit potential allows for central or decentralized fuel cells to accept different input fuels as their availability evolves. Such a retrofit could be accomplished at the time of fuel cell stack replacement, and could simply entail fuel processor replacement.

These modular characteristics enable a more rapidly changing fuel mix for fuel cell operation. Initially, fuel cells have the same fossil mix assumed for other new fossil additions above. By 2030, approximately half of fuel cell capacity utilizes renewable fuels, approximately 40 percent biofuels and 10 percent hydrogen from renewable sources. By 2100, this ratio increases to 80:20 biofuel/hydrogen.

8) **High-efficiency biomass generation.** Gasification of biomass at 85 percent energy efficiency provides the fuel input to fuel cells. If fuel cell technology does not prove to be the optimal technology for use of biomass resources for electricity production, then other efficient technologies such as gasified combined cycle or STIGs could be used.[11] The biomass resources utilized for both electricity and biofuel production are discussed below. The only region in which biomass does not displace up to 40 percent of fossil fuel inputs by 2030 is the Middle East, where no biomass is assumed due to plentiful fossil and scarce biomass resources.

9) **Long-term solar and wind supply.** The near-term renewable potentials for solar and wind (2010 and 2030) noted above, are limited to the use of highest resource sites and remote locations. Wide-scale application of solar PV, solar-thermal electric, and wind technologies at more abundant, lower resource sites is not expected to be cost-competitive until sometime around the 2010-2030 period, as illustrated in Figure 7.1 and noted above. The long-term solar and wind resource is phased into the energy mix, starting slowly in 2010.

We assume that solar and wind resources could provide up to 40 percent of direct electric loads, i.e. without storage requirements, by 2100. Grubb provides a detailed discussion of grid penetration and integration issues for renewables, wherein he points out that, a few caveats regarding PVs notwithstanding, concerns over the integration of renewable sources have been grossly exaggerated. "Contributions of perhaps 20 percent of the demand could be obtained from one type of variable [e.g., renewable] source with only a modest reduction in the value of the energy, and contributions of 30-40 percent would seem to be feasible before the penalties become severe, even neglecting storage and possible power exchanges with other systems" (p.684, Grubb, 1991).

In addition to Grubb's analysis, several additional factors suggest that solar and wind resources could provide even greater share of direct electric load than assumed here. First, the demand for electricity in many areas, particularly those with good solar

11 For instance, BIG/STIGs may prove better at handling a low quality biomass gas supply. While the electric efficiencies of these systems may be lower, they are highly compatible with waste heat capture, and the overall energy efficiency of cogeneration could well increase above 62% as cited above for near-term technology.

resources, correlates well with solar resource availability. Second, the electric load from a large fleet of storage-equipped electric vehicles could be shifted to periods of excess supply (20 to 40 percent of vehicles are electric from 2030 to 2100 in this scenario). Third, the load-following capability of other base and intermediate load generation technologies will improve compared to the poorer load-following capability of current boiler technology as the supply mix switches to a more flexible mix of sources including fuel cells, combined cycle units, and small cogeneration units (internal combustion engines, gas turbines, and fuel cells).

Beyond the 40 percent of load met directly, the remainder of solar and wind resources are assumed to require storage. For modelling purposes we assume hydrogen will play this role, although other storage (compressed air, battery, hot rock beds, etc.) and transmission modes are also possible, and could prove more efficient and cost-effective. Solar thermal, PV, and wind capacity must be sufficient to produce hydrogen for use in high efficiency fuel cells during hours when solar insolation or wind power is not available. As shown in Appendix Table G-9, fuel cells using hydrogen could operate at 70 percent efficiency, as assumed here. An 84 percent conversion (electrolysis) efficiency from electricity to hydrogen is assumed[12] (Ogden and Williams, 1989).

Long-distance transcontinental electricity transmission offers the potential for significantly reducing storage requirements beyond what is envisioned here, particularly with successful development of superconductors for low-loss transmission. In particular, east-west transmission would increase the diversity of wind and solar resources available to follow electric system loads. The future balance between long-distance transmission and storage will depend not only on the evolution of technologies and their costs, but on other considerations such as desires for local resource self-sufficiency.

Solar and wind generation could develop in both central station (e.g., large solar thermal stations and wind farms) and decentralized, on-site (e.g., integrated PV cell roofing materials) modes. We do not attempt to establish here which mode would dominate.

10) **Reduced transmission and distribution losses.** By the year 2030, electricity losses are assumed to have fallen to 6 percent in each region, a level already observed in the OECD Pacific region (Japan, Australia, and New Zealand). Electricity losses are left unchanged in 2030 and beyond. This estimated improvement is highly conservative; losses could be even lower given the potential development of superconductor technology, the reduced transmission requirements due to increased on-site cogeneration, and greater reliance on hydrogen storage, if it proves to be a more efficient long-distance transmission carrier than electricity.

Discussion of Power Sector Results

As a consequence of the assumptions outlined above, the electric supply mix changes over time from the current dominance of conventional fossil fuel and nuclear facilities to cogeneration, biomass, solar, and wind systems, as shown in Table 7.5. Solar and biomass slowly penetrate the electric mix by 2010, each accounting for 3 percent of global supply. Between 2010 and 2030, solar/wind supply increases rapidly, with assumed maturation of technology, a drop in costs relative to fossil fuel alternatives, and full retirement of current fossil and nuclear capacity. Solar and wind resources produce 9,100 TWh or one-third of global

12 The efficiency of the H2 fuel cell storage system is approximately 59% (84% electrolysis efficiency * 70% fuel cell efficiency). Thus, 1.7 kWh of primary (as available) electricity is required to produce 1 kWh of stored (as needed) electricity.

electricity in 2030. By 2100, solar and wind account for over two-thirds of global electricity supply, including the 80 percent of cogeneration that is assumed to be hydrogen-based. A solar/wind `balance' is included as Appendix Table G-9; our assumptions regarding storage, cogeneration, and hydrogen generation and use should be viewed as one possible solar-wind future, not necessarily the optimal one.

From 2010 onwards, cogeneration produces 15 percent of global electricity, based on demand-side assumptions regarding cogeneration potentials for buildings, industry, and district heating. The fuel mix is initially fossil-based, and accounts for much of fossil fuel use (gas and oil) for electricity generation after 2010. The category of `fossil fuels' shown in Table 7.5 includes a short-term expansion of coal use between 1988 and 2000, due to rapid growth in electricity demand in regions with considerable coal reserves and less developed natural gas infrastructure and availability, i.e. much of South, Central, and East Asia and parts of Africa. After 2000, coal use begins to decline, and by 2030 accounts for less than 10 percent of global electricity. Despite the scenario assumption that no new major oil-fired centralized electric capacity will be built, oil use for electricity generation continues through 2030 due to rapid growth in cogeneration applications.[13]

The shift from centralized fossil and nuclear stations to on-site cogeneration and renewable energy resource creates a core electric system that may appear more constrained in the load following capability. However, with fuel cells and combined cycle systems replacing traditional boilers, the operational flexibility (and load following characteristics) of fuel based systems is greatly improved. Direct solar/wind systems never exceed about 40 percent (2100) electricity production. Furthermore, the diversity and dispersion of many small renewable resources over a wide area can lead to decreased vulnerability to large plant outages. Indeed, in the absence of traditional boiler systems, the flexibility of the system envisioned here may prove superior to the current one.

7.3 Fossil Fuels

Refinery efficiency. Current petroleum refineries operate at a global average efficiency of 94 percent (petroleum product energy out / crude oil energy in) (IEA, 1990). Losses and energy used in refining processes accounted for about 7 EJ in 1988.[14] Refinery improvements can significantly reduce these losses. Based on an analysis of cost-effective refinery savings potential (UCS et al., 1991), a reduction in losses by 2 percent annually over the base level to 2000, and 0.9 percent annually from 2000 to 2030, was assumed. This yields an average refinery efficiency of 97 percent; no further improvements are assumed after 2030. Due to the difficulty of tracking refinery capacity among regions, the analysis of refinery losses is global, with each region assigned refinery losses and associated emissions in proportion to its petroleum product consumption.

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13 Note that the oil shown in Figure 7.2 includes fuel that is "switched" from direct heat/boiler to cogeneration applications in end-use sectors, rather than "new" oil use per se.

14 Electricity use at refineries was accounted for separately. See Appendix G.

Table 7.5

Electricity Generation By Source, 1988-2100

(ExaJoules)

Source	1988	2000	2010	2030	2100
Hydro/Geothermal	7.7 *(19%)*	10.0 *(17%)*	11.8 *(17%)*	15.2 *(18%)*	15.2 *(10%)*
Solar/Wind	0.0 *(0%)*	1.5 *(3%)*	2.9 *(4%)*	29.8 *(35%)*	83.1 *(55%)*
Biomass	0.1 *(0%)*	0.4 *(1%)*	2.1 *(3%)*	10.5 *(12%)*	19.8 *(13%)*
Nuclear	6.4 *(16%)*	4.5 *(8%)*	0.0 *(0%)*	0.0 *(0%)*	0.0 *(0%)*
Cogeneration*	0.1 *(0%)*	7.1 *(12%)*	9.6 *(14%)*	14.5 *(17%)*	33.1 *(22%)*
Fossil Fuels (total)	25.4 *(64%)*	33.8 *(59%)*	43.1 *(62%)*	15.2 *(18%)*	0.0 *(0%)*
Total	39.7	57.3	69.5	85.3	151.2

*Note: The fuel mix for cogeneration changes from all fossil fuel in 1988 to a mix of fossil, biomass and hydrogen (solar/wind) over the course of the scenario, as described in the text. Due to inconsistent reporting conventions, actual levels of cogeneration in 1988 could be higher than shown here.

Oil and Natural Gas Reserves. The cumulative global consumption of natural gas and oil in the FFES is 6200 EJ and 6600 EJ, respectively. According to one recent analysis, global natural gas reserves are sufficient to meet 1990 production levels (75 EJ/yr) for another 60 years, or 4500 EJ, somewhat less than the cumulative natural gas use in this scenario.[15] However, past reseve estimates have been consistently low. Natural gas reserves have increased over the past 20 years. Until recently, however, emphasis has been placed on oil exploration rather than gas, hence new reserves are likely. The cumulative oil and natural gas supply estimates through 2100 in the FFES are less than half those projected by U.S. EPA in its Rapidly Changing World scenario.

7.4 Renewable Fuels

In this scenario, hydrogen produced from solar and wind resources, and various fuels derived from biomass, comprise the renewable fuels that eventually displace fossil sources for gas, liquid, and solid fuel applications. Hydrogen production from solar and wind resources is described above. For simplicity of analysis, we have assumed that hydrogen satisfies most gas fuel demands, and that biofuels are largely used for liquid fuel applications. However, other assumed fuel patterns would be roughly compatible with our overall results, such as heavier use of gaseous biofuels, hydrogen from biomass, or `blended' gas supply that might consist of a mix of biogas, hydrogen, and a decreasing fraction of natural gas over time.[16]

Biofuels

Liquid biofuels include ethanol, methanol, and synthetic gasoline. With several conversion technologies under development, such as enzymatic hydrolysis for ethanol production, it is too early to say which fuels and processes will prove most practical and economic. Cost estimates for each, as shown in Table 7.6, indicate that they all could be cost-competitive with gasoline within the next 20 years. With further development in conversion technologies, and increase in petroleum product costs, costs should drop sufficiently for renewable fuels to effectively compete with other petroleum products in other applications. For example, based on distillate oil and natural gas price projections by the U.S. Department of Energy, biofuels could readily compete with petroleum products for residential, service, and industrial sector applications by early in the next century.

A conversion efficiency from biomass feedstock to all biofuels of 50 percent (energy basis) was assumed, based upon equal or higher estimates from other sources (SERI et al., 1990; Cook et al., 1991). Conversion efficiency is assumed to rise to 60 percent by 2010, a lower assumption than cited in some other sources. For instance, the recent EPA Policy Options study assumes an increase to 75 percent by 2010, based on U.S. DOE analysis (EPA, 1990).

Biomass Resources

Various biomass feedstocks and biofuels could contribute to meeting future energy

15 Reserves estimates are derived from an analysis by Jonathan Stern, August 1991, in a report to Greenpeace International.

16 Uwe Fritsche, personal communication, 1992.

Table 7.6

ILLUSTRATIVE PRODUCTION COST ESTIMATES FOR BIOFUELS

Fuel (Process)	Year	Production Cost including feedstock ($/GJ, 1990 US$)(1)	Conversion Efficiency	Source
LIQUID FUELS				
Ethanol	2000-2020*	$7		SERI, et al., 1990
(enzymatic hydrolysis and fermentation of woody biomass)				
Methanol	1995-2010*	$10		SERI, et al., 1990
(thermal gasification of woody biomass)				
Methanol	current	$14	54-57%	DeLuchi et al., 1991
(WM gasifier)				
Synthetic Gasoline	2000*	$10	50%	SERI, et al., 1990
	2010-2020*	$7	57.6%	
(pyrolysis of woody biomass)				
Gasoline (3)	*2000*	*$8*		*DeLuchi et al., 1991*
Gasoline/JetFuel (4)	*2010*	*$10*		*UCS et al., 1991*
Diesel (4)	*2010*	*$9*		*UCS et al., 1991*
Fuel Oil (4)	*2010*	*$7*		*UCS et al., 1991*
GAS FUELS				
Hydrogen current		$10	63-67%	DeLuchi et al., 1991
(gasification from biomass).				
Natural Gas (4)	*2010*	*$7*		*UCS et al., 1991*
SOLID FUELS				
Biomass	1990-2030	$3		UCS et al, 1991
Biomass	2000-2010	$2		SERI, 1990
Biomass	current	$3		DeLuchi et al., 1991
Coal (4)	*2010*	*$2*		

NOTES:
(1) Costs are levelized. For SERI, data costs assumed levelized to 1990 US$ (not clearly given).
(2) SERI estimates: earlier dates achievable with R,D, and D emphasis or in some US regions before others.
(3) Based on refinery crude oil acquisition cost of $28 per barrel, as projected by US Department of Energy for the year 2000 (as cited in DeLuchi et al., 1991).
(4) Levelized over 20 years, except for vehicle fuels (gasoline, diesel), which are levelized over 10 years. Based upon US Department of Energy price projections for the US.

needs. Table 7.7 illustrates the relative productivity of different feedstocks, the efficiency of conversion to more convenient fuels, and the land use per unit of biofuel produced.

For this analysis, we assume that most biomass feedstocks for fuel conversion are produced from herbaceous and short-rotation woody biomass plantations. Since feedstocks from dedicated woody biomass crops and plantations would likely be unavailable in large quantities before 2010, most biomass feedstocks resources until then are assumed to come from biomass residues and existing forest resources.

We conservatively estimate long-run biomass productivity of 10 tonnes of woody

Table 7.7

Energy Yields From Biomass (Mid-Range Estimates)

Fuel	Feedstock	Feedstock Yield Tonne/Ha/Yr	Fuel Yield Kg per Tonne feed	Heat content MJ/kg fuel	Fuel Yield GJ/Ha/yr
SOLID FUELS (2)					
	Temperate Wood	10	N/A	20	200
	Moist Tropical Wood	20	N/A	20	400
	Dry Tropical Wood	4	N/A	20	80
Charcoal					
	Wood	15	200	32	95
LIQUID FUELS					
Ethanol					
	Sugar Cane	58	58	28	93
	Cassava	12	145	28	48
	Sorghum	63	55	28	96
	Sugar Beet	31	26	28	22
	Maize	4	284	28	28
	Wood	15	360	28	150
	(enzyme hydrolysis)			0	
Vegetable Oils					
	Oil Palm	10	180	40	72
	Ground nut	1	462	40	24
Methanol					
	Wood	15	474	21	150
Synthetic Petroleum					
	Wood	15	250	40	150
GASEOUS FUELS					
Producer Gas (CO + H2)					
	Wood	15		N/A	201
Biogas					
	Dung	N/A	N/A	N/A	N/A
	Stillage wastes	N/A	N/A	N/A	N/A

(1) Ranges and sources given in Table G-3.

(2) Wood yields in dry tonnes, all other yields are as harvested.

Table 7.8
Wood Biomass Productivity Estimates

		Dry tonnes/ha-yr	Source
Tropical Areas			
Natural Land			
	Existing Tropical Rain Forest	8	(Dessus et al, 1991)
	Existing Dry Tropical Forest	2	(Dessus et al, 1991)
	Existing Savanna, maquis	1	(Dessus et al, 1991)
Managed Land			
	Estimated existing yields from long rotation forests	10-12	(Hall, et al, 1992)
	Estimated existing yields from short rotation woody crops	20-30	(Hall, et al, 1992)
	Experimental Small Plot in Puerto Rico	28	(Hall, et al, 1992)
	Experimental Eucalyptus grove in Brazil	40	(Hall, et al, 1992)
	Currently "Obtainable"*	20-25	(Hall, et al, 1992)
	Future Energy Plantation Estimates (A)**	49	(Lashof and Tirpak, 199(
	Future Energy Plantation Estimates (B)**	74	(Lashof and Tirpak, 199(
	Future Energy Plantation Estimates (C)**	99	(Lashof and Tirpak, 199
Temperate Areas			
Natural Land			
	Temperate Forest	3	(Dessus et al, 1991)
Managed Land			
	Currently "Obtainable"*	10-15	(Hall, et al, 1992)
	Existing US Energy Plantations	13-18	(Hall, et al, 1992)
	Present production in European Forests	5-20	(Hall, et al, 1992)
	Short Rotation hardwood plantations on small plots in North America and Europe	16-19	(Hall, et al, 1992)
	Estimated existing yields from long rotation forests	4-8	(Hall, et al, 1992)
	Estimated existing yields from short rotation woody crops	9-12	(Hall, et al, 1992)
	Future Energy Plantation Estimates (A)**	25	(Lashof and Tirpak, 19
	Future Energy Plantation Estimates (B)**	37	(Lashof and Tirpak, 19
	Future Energy Plantation Estimates (C)**	49	(Lashof and Tirpak, 19
Unspecified/Other			
	Taiga	2	(Dessus et al, 1991)

* Currently obtainable "with good management, research, and species/clone."

** Based on U.S. DOE analysis, as cited in U.S. EPA (1990), "with scenario A assuming a 65% improvement in current energy plantation productivity estimates, scenario B assuming a 150% improvement, and scenario C assuming an improvement of over 500% (a level potentially achievable by 2050)". (p.B-27, Technical Appendix).

biomass per hectare in temperate regions; 20 tonnes per hectare in moist or irrigated tropical regions, and 4 tonnes per hectare in semi-arid tropical regions (all tonnes given here are dry tonnes). Our assumptions are based on review of biomass productivity estimates from various sources as shown in Table 7.8[17], and constitute the *base* productivity levels shown in Appendix Table G-4, and used in Table 7.3. These productivity levels are considerably lower than those projected to be achievable by U.S. EPA (Lashof and Tirpak 1990), and are well within the range of productivities currently achieved on managed lands. We have chosen relatively conservative estimates, since very high yielding biomass plantations might be unsustainable (and unrealistic) due to high nutrient and water requirements, and potential lack of ecological diversity. Also shown in Table 7.3 are the decreased land use requirements that would result from a steady improvement of productivity to double the base levels by 2030. Such higher levels have already been achieved in practice -- 40 tonnes per hectare in tropical regions (Brazil) and 18-20 tonnes per hectare in temperate regions (high end of range for U.S. and Europe) -- as shown in Table 7.8.

Table 7.9

Global Current Land Area by Category

	Million Hectares
Cropland	1,473
Permanent Pasture	3,215
Forest and Woodland	4,074
Other Land	4,314
Total Land Area	13,077

Source: World Resources Institute, 1990

Freshwater availability by region serves as a rough guide on the extent of available land area that could be available for higher, moist/irrigated productivity compared with lower, semi-arid productivity. Based on relative regional freshwater availability, weighted average biomass productivities were determined. In terms of land use per unit biomass, regions range from a low of about 3 million ha/EJ in South and East Asia and Latin America to a high of about 9 million ha/EJ (See Appendix Table G-4). In comparison, the biomass productivities assumed by U.S. EPA in their *Policy Options* study, imply land use of only 0.8 to 1.5 million hectares per exajoule. (See Tables 7.8 and 7.10)

Comparison with other biomass energy potential and land use estimates shown in Table 7.10 is characterized by differing productivity assumptions and target dates. Two independent estimates -- Dessus et al., 1991 and Hall, 1991 -- both arrive at current or near-term potentials of approximately 70 EJ, relying largely on the current biomass productivities of natural, unmanaged lands (1-8 dry tonnes/hectare). Longer-term projections look towards management and research efforts to optimize biomass yields.

As noted earlier, our base productivity assumptions are relatively conservative in this regard, and as a result, biomass plantations could occupy over 700 million hectares, or about 8 percent of current crop, pasture, forest and woodland land area by 2100. Assuming biomass productivity could be improved two-fold by then, and that a significant percentage (25%) of recoverable residues can be captured, land requirements drop to around 3 percent of the

17 And personal communication with Gerald Leach and David Hall.

Table 7.10
Comparison of Biomass Potential Estimates

Year	Land Area (Mha)	Total Biomass Energy (EJ)	Report	Basis	Productivity (dry tonnes/ hectare)
N/A	873	66	Hall et al, 1992	10% of Crop, Forest, and Pasture Area at given productivity	4*
N/A		65	Hall et al, 1992	Currently Recoverable Biomass Residues (not including above)	N/A
N/A	556	338	Lashof and Tirpak, 1990	10% of Crop, Forest, and Woodland Area-Low Productivity Plantation	25 to 49
N/A	556	506	Lashof and Tirpak, 1990	10% of Crop, Forest, and Woodland Area-Medium Productivity Plantation	37 to 74
N/A	556	675	Lashof and Tirpak, 1990	10% of Crop, Forest, and Woodland Area-High Productivity Plantation	49 to 99
2100		467	Lashof and Tirpak, 1990	Results of EPA's RCWR Scenario (land area not reported)	
2000		95	Dessus et al., 1991	Wood Reserves, Biomass Crops, and Residues	N/A
2020		129	Dessus et al., 1991	Wood Reserves, Biomass Crops, and Residues	N/A
2030	124 - 384	91	Greenpeace, 1992	GES Scenario: Current Productivity Levels (and 25% of residues)**	4 to 20
2100	292 - 721	181	Greenpeace, 1992	GES Scenario: Increased Productivity (and 25% of residues)**	8 to 40

* Reported as 5 tonnes/hectare, 20% moisture content.

** Based on Hall et al, 1992 as shown above.

combined land areas. In either case, it is important to emphasize that these high land use requirements are not simply a result of the choice of biomass as a supply source, but of the underlying assumptions of this analysis: maintaining current industrialized patterns of consumption in a world of over 11 billion inhabitants. Modifying these assumptions reduces the need for energy and land use considerably, as discussed in Section 5.2.4.

Section 8: An Alternative Macro-Economic Modelling Approach: Atmospheric Stabilization Framework (ASF)/Edmonds-Reilly

Introduction

[This abstract was based on a seperate report by Paul Waide for Greenpeace: 'Towards a Fossil Free Energy Future: Economic Issues', which is available as an appendix].

The end-use approach employed for the FFES takes no direct account of pricing mechanisms upon energy consumption patterns in the modelling work produced through LEAP. Assumptions over the cost-effectiveness of both energy efficiency and renewable energy sources was made on the basis of a wide range of national, regional, and global studies which assessed the relative costs of such options. To address the pricing mechanism question a complementary analysis was performed using an adapted macro-economic global energy model, the Atmospheric Stabilisation Framework (ASF). This model, which has been used extensively by the IPCC and USEPA, was used to evaluate the cost of secondary energy under the FFES. [Further details of the analysis is included in the Appendix available from Greenpeace with this report]

Summary Model Overview

The ASF (ICF 1989) is a suite of models designed to explore the relationships between human economic activity, the emission of greenhouse gases and global warming. Simulation of the energy sector is performed using an adaptation of the IEA/ORAU Long-Term Global Energy-CO_2 model, (Edmonds & Reilly, 1986), more commonly known after its authors as the Edmonds-Reilly model. Both the ASF and the Edmonds-Reilly models have been extensively utilised for long-range energy assessments (EPA 1990a; Edmonds & Reilly, 1985; IPCC 1990; 1991).

In broad terms, the Edmonds-Reilly model may be described as a global macro-economic energy model which balances estimates of energy supply and demand through iterative adjustment of energy prices. In this respect it constitutes an alternative modelling framework to the LEAP model end-use, or "bottom-up", approach employed in the construction of the FFES. Macro-economic formulations of supply and demand are constructed from projected levels of population, wealth generation, energy resources, technological change and energy production, refinement and transportation costs. Within each time frame and region the initial projections of energy supply and demand are adjusted until they balance, using a partial equilibrium routine to modify the energy prices. The adjustment process obeys conventionally accepted economic precepts concerning the role of price in determining energy supply and demand, and thus the final prices are an estimate of the prices which might be expected under market conditions. The supply component of the model permits estimates of future supply from both conventional and unconventional fossil fuels, nuclear, hydro and solar electricity, synthetic fuels and biomass. These supply options compete with one another for market share based upon price forecasts and ability to satisfy demand. Inter-regional trade is permitted for fossil fuels, such that a region may be a net exporter or importer of energy. The model tracks emissions of radiatively significant gases from the energy sector, and in particular CO_2, to give a picture of the overall release of greenhouse gases from the energy sector.

The ASF adaptation of the Edmonds-Reilly model differs primarily in its use of exogenously *derived end-use model demand data up to 2025. This feature fixes the energy demand to match the exogenously determined demand for secondary fuels and electricity for the first 40 years, during which time the supply and demand are matched through supply-side adjustment only. After 2025, the model operates in pure macro-economic mode, with adjustment of both supply and demand being possible for equilibrium to be reached. The ASF variant was favoured in order that demand might be maintained at the FFES level while supply could be optimised as a function of cost.*

Methodology and Assumptions

In order that the relative costs of fossil fuel could be ascertained under the FFES, it was important that the ASF should be made to simulate the same demand for secondary energy as in the FFES. The procedure followed was to ensure that the income and population levels were consistent between the end-use formulation and the ASF analysis, and then to adjust the specification of the exogenous energy efficiency by end-use sector until demand was matched. However, by itself this would not be enough to ensure parity of demand between the two analyses, because the quality or type of secondary energy is also important. In order for demand to be matched by secondary energy type, a new set of secondary energy fuel share weights were calculated using initial estimates of secondary energy prices. This procedure was followed iteratively, using the latest set of price estimates to compute the subsequent set of fuel share weights until approximate demand convergence by secondary energy type was attained.

The cost curves for each supply type are of crucial importance in an analysis of this type. For the purposes of comparison, all the inputs concerning the resources, and production, transportation, refinement and distribution costs of fossil fuels were taken from the IPCC (1990, 1991) studies. These are considered to give 'middle-of-the-road' projections of the likely costs of fossil fuels. The costs of hydro power were also taken from the IPCC studies, but the ultimate development of the resource base was limited to less than 65% of its estimated potential, because of concerns over the environmental impact of large scale hydro. Geothermal energy was included in the hydro component, but is not significantly expanded because of environmental consequences in some instances. As in the FFES, nuclear power is phased out by 2010. The costing treatment reflects a proxy for the additional cost of nuclear energy due to environmental and safety concerns. Synthetic fossil fuel cost and resource estimates are identical to those used by the IPCC.

The FFES relies heavily upon all forms of solar energy and upon biomass to meet supply needs by the end of the next century. For this analysis we use the solar energy costs given in Appendix G as the starting point to formulate the regional cost curves for solar energy. Solar hydrogen is used as a storage medium and the solar energy vector within the FFES. The cost of the conversion, which contributes to the solar energy costs within the ASF, is based upon the work of Ogden and Williams (1989). The cost of transporting the H_2 to the end-use point is drawn from the same source, while the proportion of solar energy converted to H_2 is identical to the FFES. Regional estimates of solar energy costs are derived from simple inspection of annual insolation levels and/or wind speeds to adjust the initial estimate of solar electricity. A more sophisticated analysis based upon integrating the cost over regional fluctuations in the resource base was beyond the scope of this study. Implied discount rates used in the ASF analysis were those utilised for elements of the FFES. A discussion on appropriate discount rates is found on page 51.

The next most important energy source under the FFES is biomass. For the preliminary analysis, the conversion costs of biomass were taken from the USEPA Rapidly Changing World with Reductions scenario, which accords with an optimistic assessment of the development of biomass conversion technologies. However, the scale of the biomass resource *was limited to about a third of that used in the RCWR scenario, because of a revaluation of the pressure for land in a world of 11 billion people. The result is a much more conservative estimate of the costs of biomass. Nonetheless, the development of solar and biomass energy proceeds at a far greater rate than under any "business-as-usual" projection. This reflects the belief that a sustained political commitment to environmentally benign renewable energy sources will speed their development and produce lower prices at a far faster rate than under "business-as-usual" (BAU) conditions. If the institutional barriers to renewable energy are lifted and R,D&D is intensified for example, then there are good reasons for anticipating improvements of this scale.*

After the ASF analysis was completed a 'Renewables-Intensive Global Energy Scenario' by Johansson et al was published. (Johansson et al, 1993.) This provided a very detailed economic analysis of a wide range of renewable technologies. This data in many instances validated the cost assumptions made in the ASF analysis, and also suggested that these were unduly conservative for biofuels and solar electricity.

Results

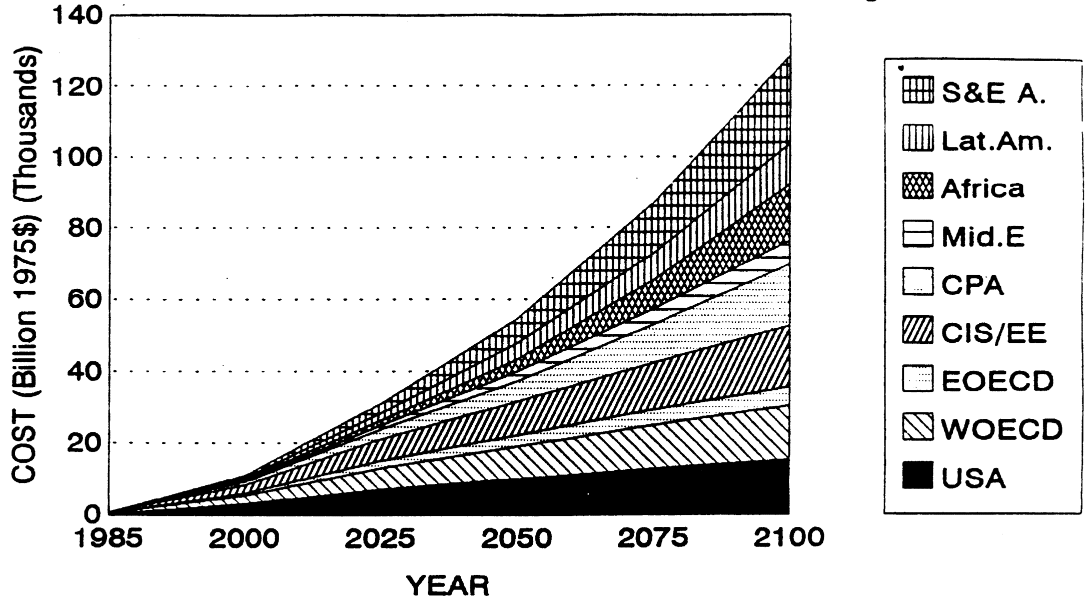
The demand for secondary energy by end-use sector, region and period was successfully matched to the FFES results. The demand for secondary energy by type did not precisely match the FFES across end-use sector, but it did match overall, thus the quality of delivered secondary energy remained the same between the two analyses. Apart from curbing demand to a level well below BAU projections, fossil fuel reduction was attained by extensive fuel switching toward solar energy and biomass. This was achieved partly through lower renewable energy cost projections than the BAU, and partly through representing policy initiatives, such as carbon reduction targets, via fuel share weight adjustment. The preliminary results fell short of the complete eradication of fossil fuels by 2100, but this was finally attained by the introduction over 65 years of a \$150/tonne (1990\$) CO_2 tax. This level of tax was utilised on the basis of needing to meet ecological targets, rather than a reflection of any attempt to accurately value externalities.

Being satisfied that the scenarios were sufficiently close to the FFES, it was possible to calculate the cost for secondary energy paid by the consumer, by multiplying the secondary energy costs output from the ASF by the annual consumption of each energy type. These secondary energy costs are levelised costs taking account of the fixed costs of production, transportation, distribution and transformation of primary energy into secondary energy. They do not take account of the cost of end-use equipment. Figures 8.1 and 8.2 show the cumulative costs of secondary energy as paid by the consumer for \$17.2/tonne CO_2 tax and \$150/tonne CO_2 tax scenarios, while figures 8.3 and 8.4 show the same information generated from the USEPA's Rapidly Changing World (RCW) and Slowly Changing World (SCW) scenarios, which are indicative of "business as usual" scenarios in general. The cumulative costs of secondary energy in the FFES are appreciably lower than those for the SCW, and less than half as much as the costs in the RCW. If one assumes the average of the RCW and the SCW scenarios to represent the case whereby "business as usual" supply and efficiency options are followed at an equivalent level of world economic growth, then the cumulative costs of secondary energy paid for by the consumer under the FFES are approximately half those of the "business as usual".

The costs determined above do not take account of the expenditure necessary to improve efficiency or replace end-use equipment, which is a vital component of the fossil free strategy. Neither do they account for intensified renewables RD&D or the cost of regulatory enactment to encourage fuel switching. Furthermore they are only as valid as the input cost assumptions for all forms of supply. These important caveats aside, it is clear that the FFES may enjoy a *considerable leeway before the additional costs of efficiency and end-use equipment cause it to be less economic than the BAU. The costs utilised in this analysis take no account of conventional (non-CO_2) externalities applying to fossil fuels, nor the avoided costs of damage*

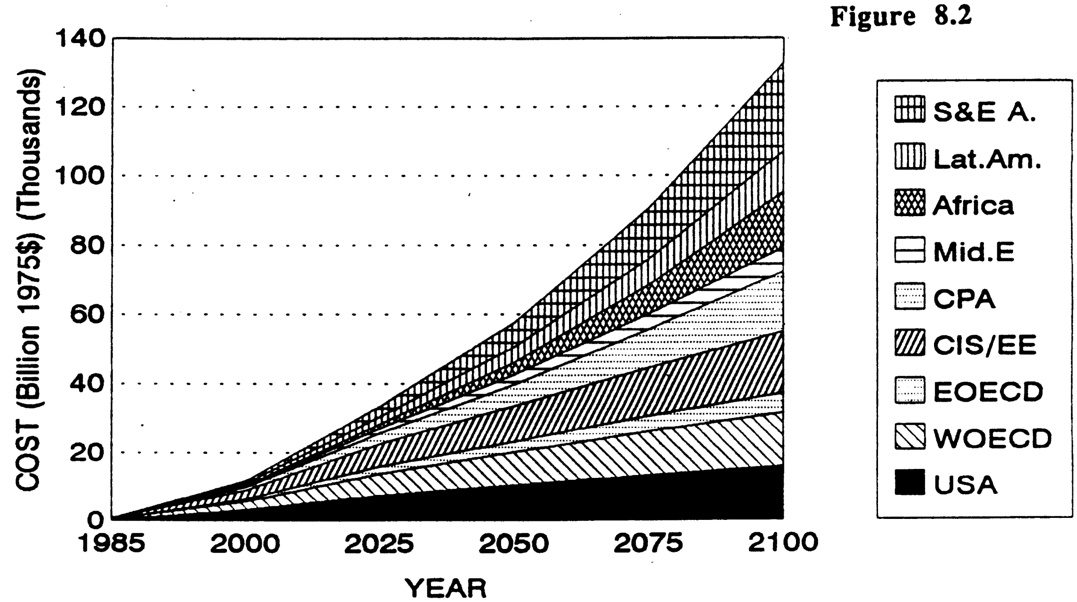
CUMULATIVE COSTS OF SECONDARY ENERGY CONSUMPTION FOR SCENARIO 1 [1]

Figure 8.1



CUMULATIVE COSTS OF SECONDARY ENERGY CONSUMPTION FOR SCENARIO 3 [2]

Figure 8.2

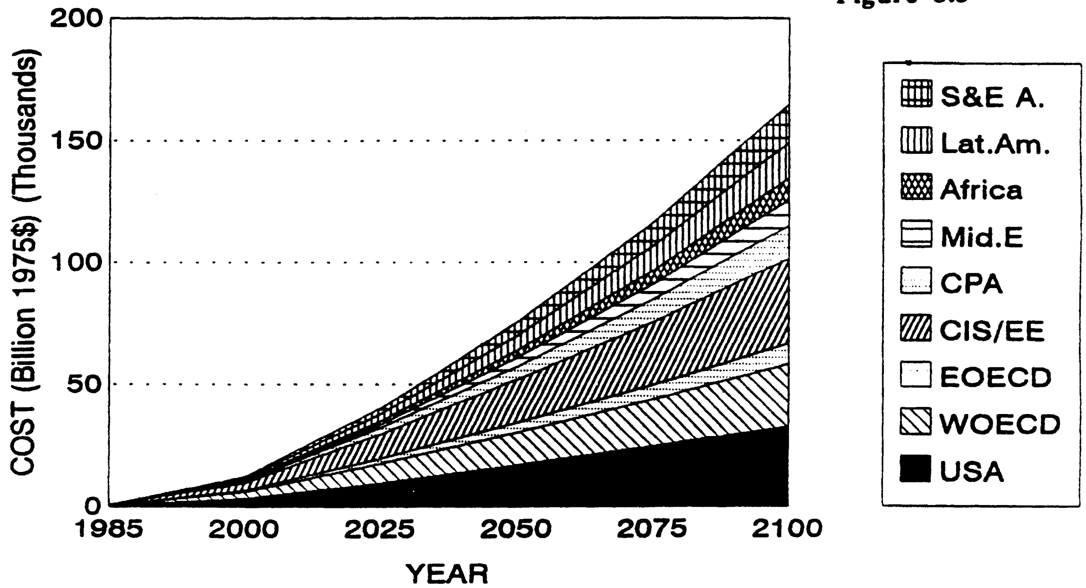


1. Very low carbon tax of $17.20/tonne carbon introduced over a 65 year period.

2. Carbon tax of $150/tonne carbon introduced over a 65 year period.

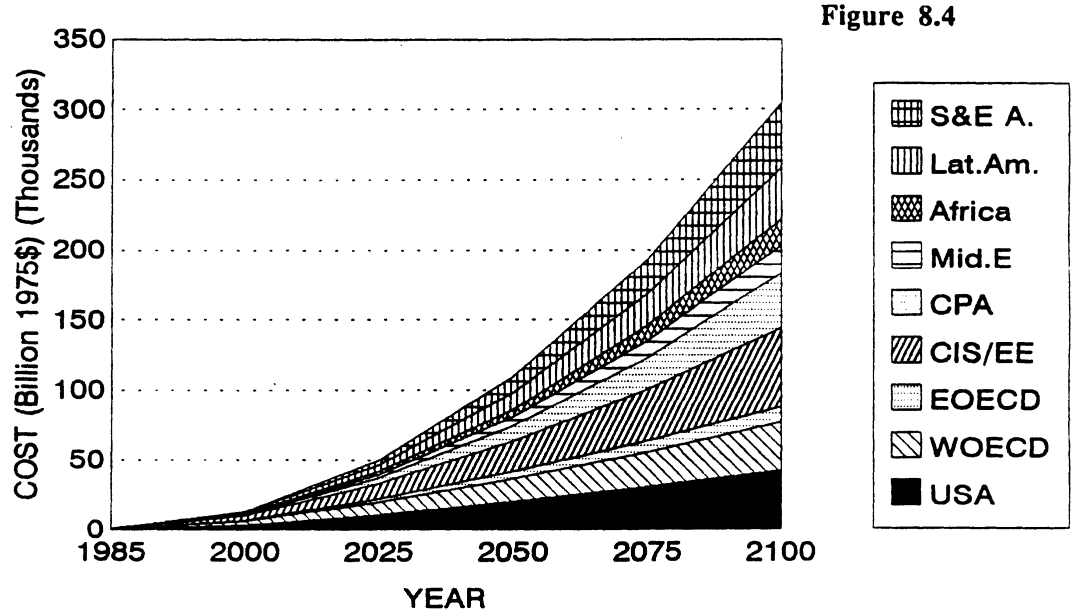
CUMULATIVE COSTS OF SECONDARY ENERGY CONSUMPTION FOR US E.P.A. SLOWLY CHANGING WORLD SCENARIO

Figure 8.3



CUMULATIVE COSTS OF SECONDARY ENERGY CONSUMPTION FOR U.S.E.P.A. RAPIDLY CHANGING WORLD SCENARIO

Figure 8.4



from global warming, thus the case presented for the FFES becomes even stronger. A recent study has suggested that the avoided costs of damage from global warming may be extensive, justifying strong policy responses (Cline, 1992).

Discount Rates

Among economists and policy makers there is much debate as to what is the appropriate discount rate to apply to energy technologies and other investments. Discount rates are used to assess the value today of economic benefits and the costs that may occur in the future. High discount rates of 10 to 15 percent[1], which reflect market perceptions of risk and rates of return, hence favour low capital cost technologies. Lower discount rates give more weight to the future than high discount rates do, and tend to favour higher capital cost options. Many, though not all, renewable energy options have high capital costs and low running costs.

The FFES has been based on a wide range of other studies, hence no consistent discount rate has been assumed throughout. The timing of the assumed cost-effectiveness of a range of renewable options has been based on several studies, including *America's Energy Choices,* which have low discount rates in the range of 3 to 6 percent. This is necessarily a compromise between opting for current market rates, and a zero discount rate which places the same value on future lives and environmental resources as present lives and environmental resources. Such rates - 2 to 5 percent - are sometimes described as 'social rate of time preference' (SRTP) discount rates, where the value of environmental costs and benefits to the public is given a somewhat higher priority than the investments of an energy utility.

Cline utilises a SRTP discount rate on the basis that actions over the next few decades may have very serious environmental implications over the next few hundred years. After reviewing the literature, he opts for an effective discount rate of 2 percent per year (Cline, 1992).

A 3 percent discount rate reflects the cost of capital to society based on the long term average yield on US treasury bonds, and the rate selected for analysis of energy efficiency policies by public institutions such as the California Energy Commission and the Northwest USA Power Planning Council. A lower discount rate can also be justified on the basis of imperfections in capital markets due to credit restricitions and/or tax distortions, and differing perceptions of risk from private and public perspectives.

America's Energy Choices did test the robustness of its analysis by reworking the net cost and savings of its scenarios using a 7 percent real discount rate. Though overall savings fell, the scenarios remained robust. This is a conclusion shared by European analysis where the role of renewable technologies only diminished significantly once the discount rate moved beyond a rate of 8 percent (CEC, 1990).

Most of the energy efficiency investments implied in a large number of the studies utilised for the FFES would be cost-effective even under higher discount rates of 8 to 12 percent.

The six-fold increase in CO_2 tax between the scenarios in Figures 8.1 and 8.2 does little to impact upon the cumulative cost of secondary energy, while causing a marked reduction in CO_2 emissions. This is because the cost of renewable energy supply is sufficiently cheap under the FFES as to be competitive with even the cheapest fossil fuels at some point within the next century. It is an important result that the aggregate cost of secondary energy per unit

5 All discount rates are 'real' discount rates, corrected for general inflation. Thus a 12 percent discount rate at a time of 6 percent inflation is a 6 percent real discount rate.

consumed for the FFES is in-between and similar to the values for the RCW and SCW respectively. This is in spite of a far greater proportion of electrification under the FFES, which is the most expensive secondary fuel per unit. The result is explained because the higher demand for fossil fuels under the BAU scenarios, combined with more expensive renewables, causes the cost of fossil fuels and total energy to rise substantially.

Sensitivity tests were carried out to ascertain the impact of higher solar energy prices (increases of 30% and 50%), and lower fossil fuel costs (25% and 50% lower production costs). Assuming higher solar costs indicates that CO_2 taxes would need to be increased beyond the \$150/tonne CO_2 level required for near complete fossil fuel phase-out under the FFES assumptions, or that regulatory initiatives would need to be stronger. The additional incurred cumulative costs of secondary energy are only a few per cent higher than the main FFES. Lower fossil fuel costs leads to a slow down in the shift away from fossil fuels, leading to higher CO_2 emissions. Higher CO_2 taxes would once again be needed to increase fossil fuel prices and to phase out fossil fuels.

Conclusions

The analysis described goes some way toward illustrating the economic viability of a fossil free energy future. In particular, it has been demonstrated that the delivered cost of secondary energy is liable to be significantly cheaper under the FFES than a "business as usual" strategy.

such a conclusion is of course dependent on the assumptions fed ito the nodelling exercise. It is also dependent on the enactment of policies, such as enhanced renewables R&D programmes and a range of fiscal measures which would have the effect of lowering effective discount rates for these supply side options. The principal environmental aim of CO_2 emission reduction has been achieved by a combination of end-use efficiency improvement and fuel switching.

It has been shown that under the prevailing conditions of the FFES the addition of a significant CO_2 tax has made little impact upon energy prices, but caused a substantial reduction in emissions. Furthermore, the ambition of zero CO_2 emissions has been achieved without a dramatic expansion of hydroelectric or geothermal supply, the untenable expansion of biomass supply, or the use of nuclear power. However some important questions remain unanswered. The solar supply cost assumptions are heavily dependent upon continued technological and organisational progress, while the precise costs of additional end-use efficiency measures and alternative end-use equipment are also uncertain. It is likely that a future suggested by the FFES can only materialise if appropriate non-fiscal incentives are enacted which, aside from environmental benefits, may act to rationalise the energy markets and help optimise costs. Certainly, a major reason for anticipating more optimistic renewable supply costs under the FFES than the BAU lies with the much stronger statement of intent which would greatly stimulate R,D&D, not to mention liberate institutional and capital barriers. Under these circumstances, environmentally responsive energy strategies need not be uneconomic and may even be cheaper than conventional strategies.

Section 9: Climate Implications of the Fossil Free Energy Scenario and Variants

[The following is an abstract of the analysis by Paul Waide - 'Greenhouse Modelling and Emission Targets' - based on a Greenpeace report available as an Appendix to this report.]

Results From The FFES

The final CO_2 emission figures from fossil fuel consumption generated in the FFES energy modelling exercise are given in Table 9.1. The table also includes the final CO_2 emissions/uptake from biotic sources derived by Kayes (1992) for use in the FFES. The fossil fuel and deforestation emission figures are summed with the afforestation uptake figures to give the total emissions under the FFES.

Normalising the Historic CO_2 Record

Before conducting a greenhouse simulation based upon these emissions, it is necessary that the emissions input into STUGE are properly normalised such that the model would accurately reproduce the historic atmospheric CO_2 concentration record. The total emissions figures need to be adjusted such that the 1990 emissions total matches the STUGE value of 6.2 Gt C/yr. This means that the 1990 figure needed to be modified downwards, and all subsequent values need to be adjusted too. The most appropriate method is to take the absolute difference between the IPCC 1990 emissions and the STUGE 1990 emissions and to subtract that difference from all emissions. This is the practice followed for the results labelled "absolute difference method". However it is by no means certain that the cause of the imbalance will continue to operate at a constant level. The absolute difference technique leads to very low emissions and high uptake levels of CO_2 under the FFES scenario. For completeness, an alternative approach, the "percentage difference method", is also examined. Under this adjustment, the value of the difference between the FFES 1990 emissions and the STUGE 1990 emissions as a percentage of the total FFES emissions is subtracted from all FFES emissions, i.e. the fractional difference is conserved rather than the absolute difference. For a more detailed discussion of the emissions adjustments see Waide (1992b).

Net CO_2 Emissions under the FFES

The FFES CO_2 emission data as input into STUGE is illustrated in Figure 9.1, prior to the combination of the fossil and biotic emissions components within the FFES, along with the upper and lower Greenpeace CO_2 emission scenarios generated from the target setting exercise (see Section 3). It is interesting to note how the extensive afforestation programme, in conjunction with the steady phase out of fossil fuels, actually causes a net uptake of CO_2 from the atmosphere beginning at some time between 2050 and 2080. This outcome is of course highly dependent upon the cause and behaviour of the imbalance in the model forecast and independently estimated global anthropogenic CO_2 emissions in 1990. Given present knowledge it is prudent to state that if the measures proposed under the FFES were carried out, the actual range of outcomes is likely to be between the FFES absolute and percentage differences method results.

The Climate Impacts of FFES

The radiative forcing by greenhouse gas under the FFES is shown in Figure 9.2, using the absolute differences method to calculate the CO_2 emissions (Atmospheric CO_2

CO_2 EMISSIONS UNDER THE FFES

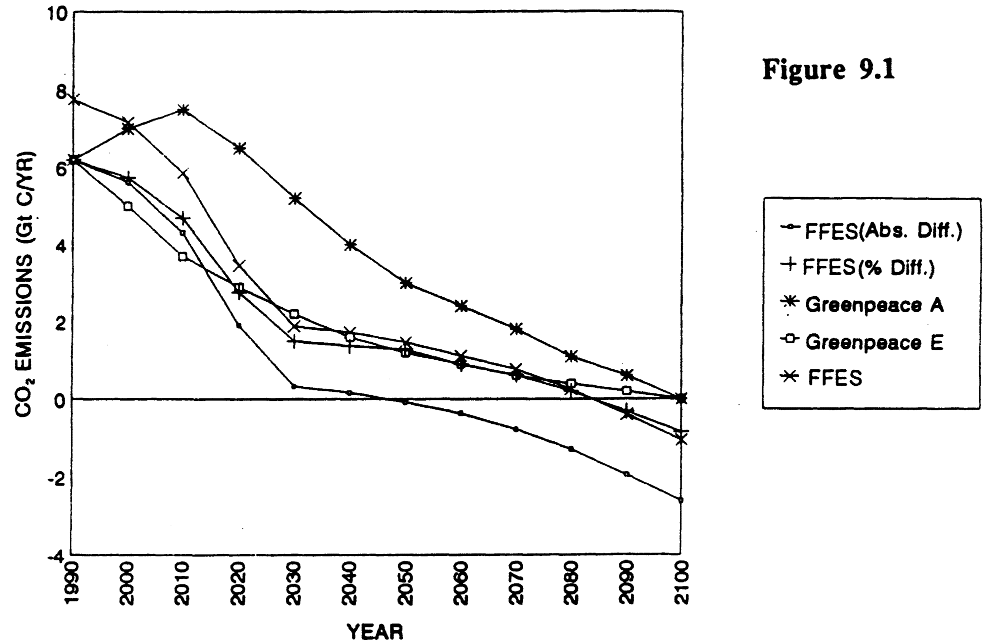


Figure 9.1

RADIATIVE FORCING BY GREENHOUSE GAS[1] UNDER THE FFES CO_2 COMPUTED VIA ABSOLUTE DIFFERENCE METHOD

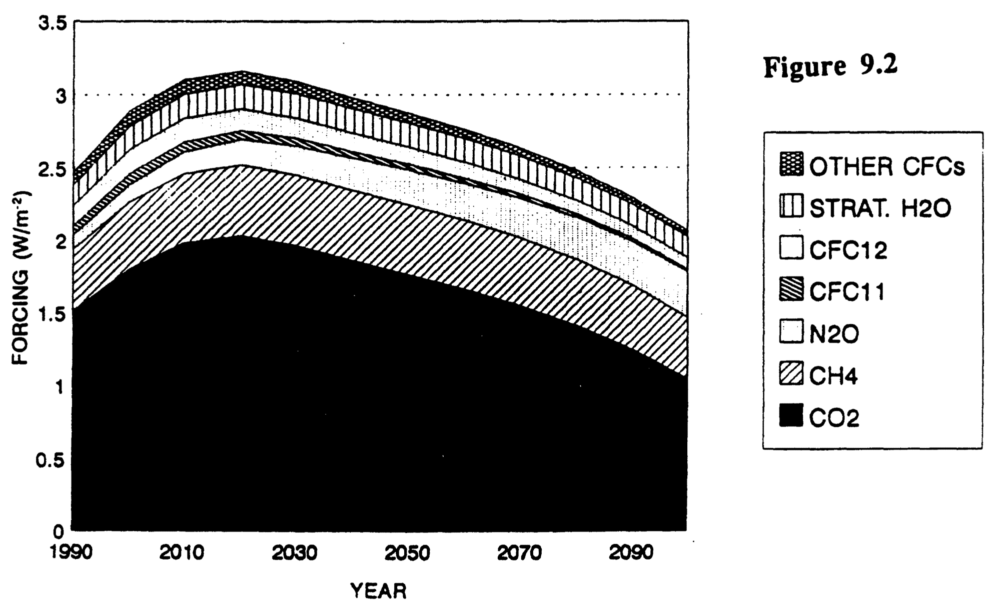


Figure 9.2

HCFC-22 HAS NEGLIGABLE CONTRIBUTION

1 The revised IPCC scientific assessment (1992) points towards a net zero radiative forcing impact from CFCs and substitutes. In view of the relatively small contribution of these in the FFES, and the major uncertainties in the new scientific evidence, the scenario was not re-run through the STUGE climate model.

concentrations of the FFES and several of the initial target CO_2 emission scenarios are shown in Figure 9.3). The urgency for immediately phasing out the halocarbons is demonstrated, because in spite of an immediate halt in emissions, the radiative forcing contribution from this source only declines slowly (see however the footnote to Figure 9.2 and Footnote 1 in Section 3 concerning changing scientific views on the contribution of CFCs and substitutes).. Nonetheless the FFES ensures that the forcing for global warming levels off and begins to return to pre-industrial norms from 2020 onwards.

Figure 9.4 illustrates the change in global mean temperature for the IPCC range of climate sensitivities using the absolute differences method for calculating CO_2 emissions. Global mean temperature stabilises between 2030 and 2050, at a level between 0.90^{o}C and 2.15^{o}C above the pre-industrial level (1.4 °C under a 2.5 °C climate sensitivity). If the absolute differences method is assumed for calculating CO_2 emissions then the peak temperatures are fractionally lower. This analysis illustrates that if appropriate policies and practices are adopted it is still possible to meet the climate and emissions targets used in this study (AGGG, 1990).

Table 9.1

CO_2 Emissions From Fossil and Biotic Sources in the FFES
(All emissions in Gt. C/YR)

Deforestation (Mid-Range Values)

Year	1990	2000	2010	2020	2025
	2.35	1.68	1.01	0.34	0

Afforestation

Year	1990	2000	2010	2020	2030	2040	2050	2100
	-	-0.19	-0.41	-0.57	-0.67	-0.78	-0.88	-1.06

Fossil Fuels & Biomass

Year	1988	2000	2010	2030	2100
	5.1	5.7	5.6	2.6	0.0

Total Emissions Under The FFES

Year	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
	7.75	7.17	5.86	3.46	1.88	1.72	1.47	1.12	0.77	0.26	-0.4	-1.06

Total Adjusted To Match STUGE 1990 Using Absolute Differencing Method

Year	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
	6.2	5.62	4.31	1.91	0.33	0.17	-0.08	-0.37	-0.78	-1.29	-1.95	-2.61

Total Adjusted To Match STUGE 1990 Using Percentage Differencing Method

Year	1990	2000	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
	6.2	5.74	4.69	2.77	1.50	1.38	1.28	0.89	0.61	0.21	-0.32	-0.85

ATMOSPHERIC CO_2 CONCENTRATIONS UNDER THE FFES

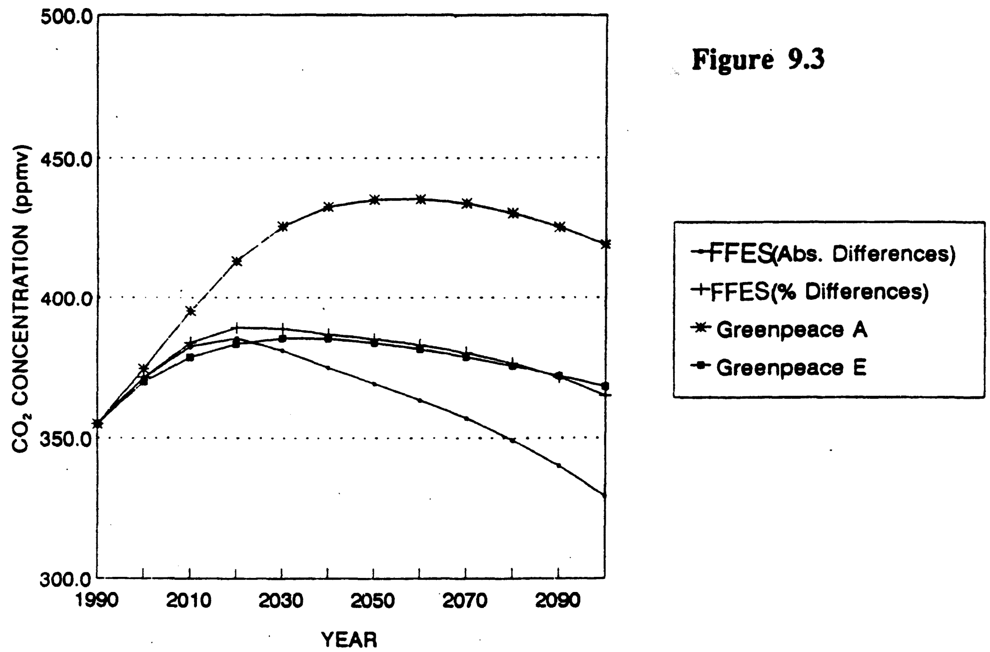


Figure 9.3

STUGE FORECAST GLOBAL MEAN TEMPERATURE RISE FROM PRE-INDUSTRIAL TIMES FOR THE FFES SCENARIO AT THREE CLIMATE SENSITIVITIES

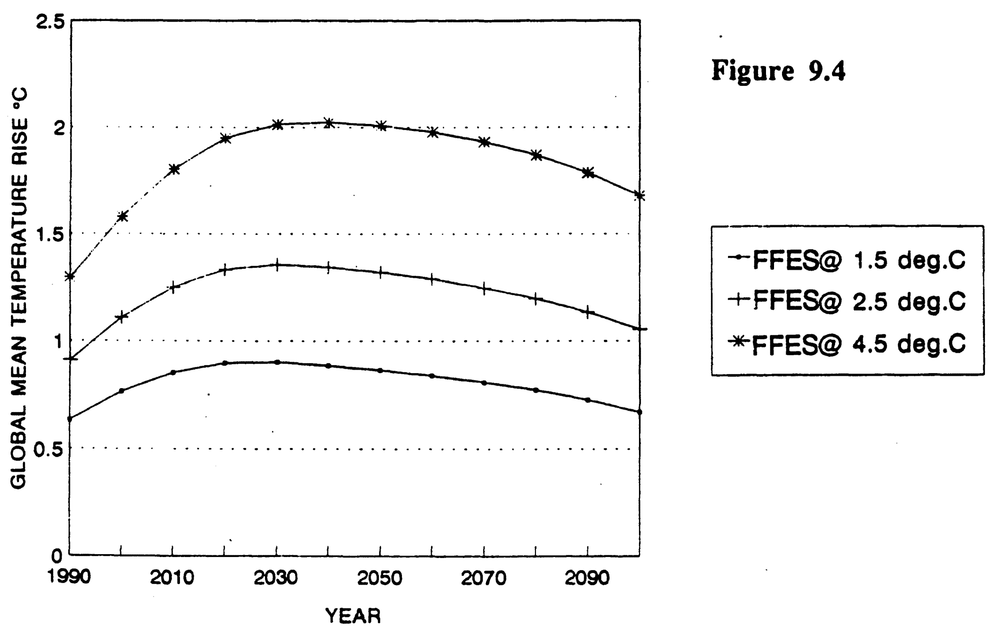


Figure 9.4

USING ABSOLUTE DIFFERENCES METHOD

The STUGE forecast for decadal warming under the FFES is shown in Figure 9.6, using the absolute differences method to calculate CO_2 emissions. The importance for immediate and strict control of greenhouse gas emissions is strongly underlined, because in spite of the steep emissions reductions engendered in the FFES, the target of 0.1 °C temperature rise per decade is only reached between 2007 and 2030 (2020 under a 2.5 °C climate sensitivity). The extent to which ecosystems can tolerate the intervening years of temperature rise is still highly uncertain.

Global mean sea-level rise under the FFES is illustrated in Figure 9.5 using the absolute differences method of calculating CO_2 emissions. The thermal lag of the oceans means that sea-level continues to increase after the date that surface global mean temperatures are falling again. Under the FFES, sea-level is forecast to stabilise between approximately 2100 and about 2130 at levels not in excess of 50cm above the 1990 level, which satisfies the upper sea-level rise limit recommended under the target. Importantly, the rate of sea-level rise is cut dramatically over the BAU, hopefully negating the worst environmental damage to marine ecosystems.

The Impact of Delaying Policy Responses

Finally, the impact of delaying the implementation of the FFES is illustrated for global mean temperature rise in Figure 9.7. The figure assumes the mid-range value for climate sensitivity (i.e. 2.5 °C for a doubling of pre-industrial CO_2 levels), and that the BAU (derived from the average emissions of the US EPA Rapidly and Slowly Changing World scenarios) is enacted until the FFES policies are implemented. Despite the lower than mid-range climate sensitivity assumed, the serious consequence of delaying action is clear (around 0.4 °C for every ten year delay in implementing policy changes to reduce CO_2 levels). These results contradict the assertion of Schlesinger and Jiang (1991) that the consequences of delaying action are minor. The comparative difference is fundamentally a function of the extent of emissions reductions envisaged. If only slight reductions are to be enacted (as they are under Schlesinger and Jiang) then delaying enactment will result in a small comparative loss. The fact that even the FFES does not satisfy all desired climate criteria under all circumstances suggests that prudent climate policies require deep and immediate cuts.

Conclusions

This study has clearly shown the urgent need to address anthropogenic global warming and the likely climatic consequences of ignoring that need. It has been shown that if humanity enacts policies and behaviour akin to those envisioned under the FFES, then global warming can be halted and much, though not all, of the potential damage can be avoided. It has also been demonstrated that these actions satisfy most of the desired climate criteria under the worst circumstances of extreme climate sensitivity (4.5 °C) or when natural climate 'feedbacks' come into play. Given the major uncertainties of such 'feedbacks', and the warming that the planet is already committed to, this suggests that a prudent approach would require deep and immediate cuts in emissions.

STUGE FORECAST GLOBAL MEAN DECADAL WARMING RATE FOR THE FFES SCENARIO AT THREE CLIMATE SENSITIVITIES

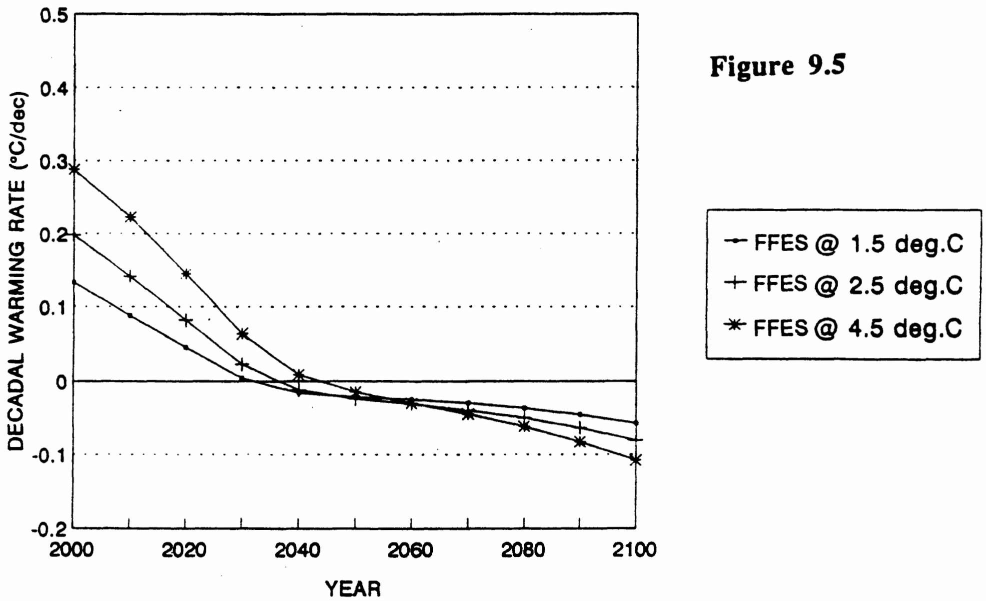


Figure 9.5

USING ABSOLUTE DIFFERENCES METHOD

STUGE FORECAST GLOBAL MEAN SEA LEVEL RISE FROM 1990 FOR THE GES SCENARIO AT THREE CLIMATE SENSITIVITIES

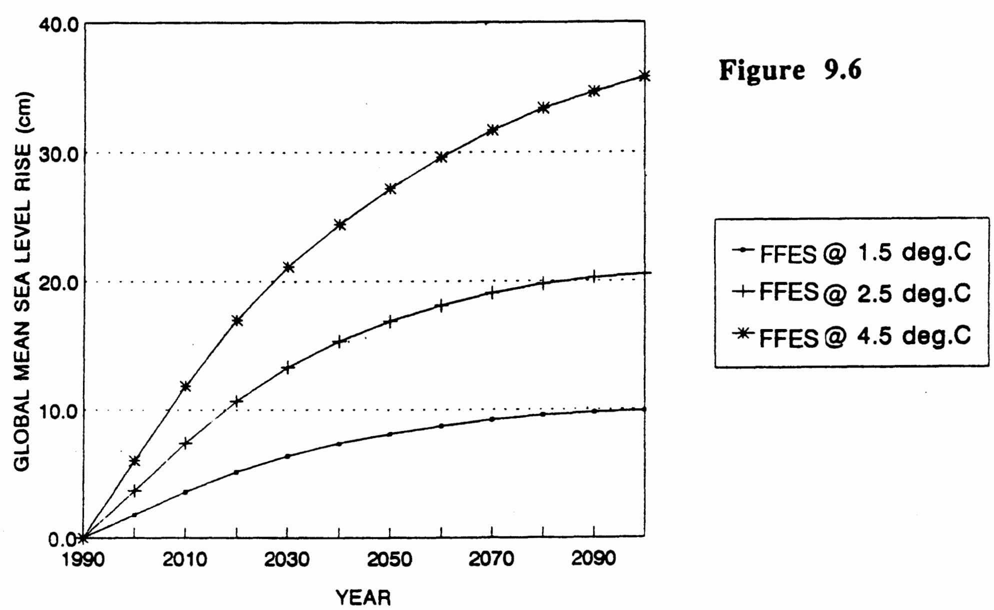


Figure 9.6

USING ABSOLUTE DIFFERENCES METHOD

SURFACE TEMPERATURE RISE SINCE PRE-INDUSTRIAL TIMES FOR DELAYEDFFESIMPLEMENTATION SCENARIOS*

ABSOLUTE DIFFERENCES METHOD

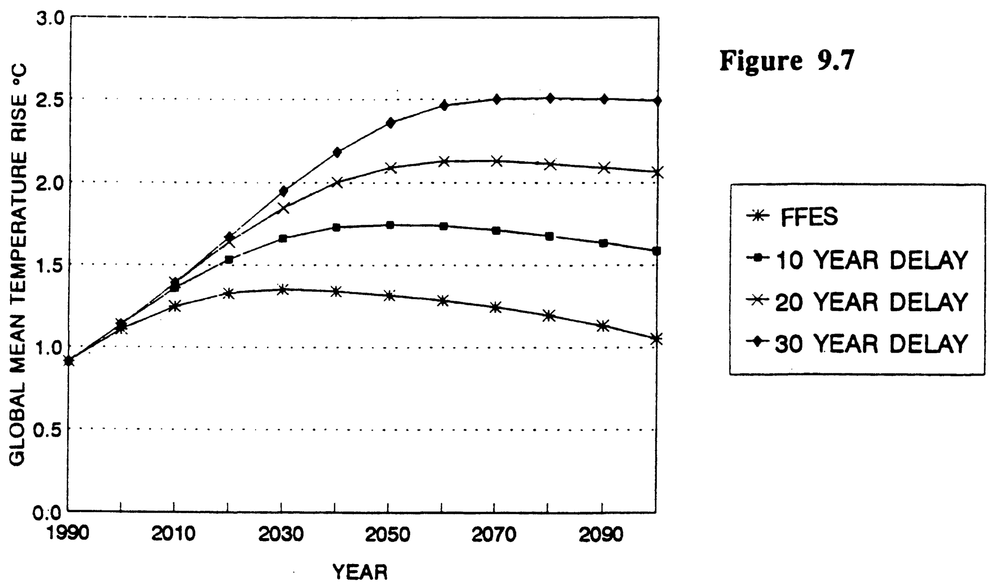


Figure 9.7

CLIMATE SENSITIVITY = 2.5°C

Section 10: Policy Options

[This abstract was written by Stewart Boyle, Greenpeace Energy Policy Director. It is based on a more detailed discussion of policy issues contained in the Policymakers Summary: 'Fossil Fuels in a Changing Climate', available from Greenpeace]

Introduction

Energy use, and specifically the burning of fossil fuels, is the main cause of global warming. Currently causing 60 percent of warming, this is set to grow to more than 70 percent as CFCs and related compounds are phased out. The role of CO_2 may be even hihger if the IPCC view that CFCs have no net radiative forcing is accepted (IPCC, 1992). In order to follow the 'precautionary principle' and avoid serious impacts from global warming, dramatic improvements in energy conservation, and fuel switching from fossil fuels to renewable energy sources will be necessary.

Historically, it has taken new fuels some 50 years to capture 10 per cent of the global energy market (Marchetti, 1989). In the FFES, renewable energy sources increase from their current 14 per cent of total energy supplies to 60 per cent within the next 40 years. Energy efficiency improves at the rate of 2.5 percent per annum for nearly 40 years, a rate which has only been seen in a few countries for several years in the period 1973-1985. Strong policies will be needed to reach these targets.

International Climate Protection Policies

One hundred and fifty-four nations signed the International Climate Convention at the Earth Summit in June, 1992. The Convention unfortunately failed to commit nations to specific reductions in carbon dioxide emissions and other greenhouse gases. Article 2 of the Convention did commit signatories to the stabilisation of concentrations of the greenhouse gases in the atmosphere. Achieving this will require a range of strong Protocols, assisted with tough national and regional CO_2 reduction targets.

A priority follow-up Protocol to the Convention would be an Energy Efficiency Protocol committing signatory countries to achieving annual improvements in energy efficiency over the next few decades. A challenging target would be 2.5 per cent per year. A Renewable Energy Protocol should also be enacted, committing signatory countries to expanding all environmentally sound sources of renewable energy. A challenging target would be 5 per cent per year.

Pricing Policies

The perfect energy market does not exist. Government and industry interfere with the market in numerous ways. In the last fifty years, legislation, pricing, and institutions have developed to favour fossil fuels and nuclear power. These now form market barriers, preventing producers and consumers from using new technologies to save money and utilise cleaner and sustainable energy systems (Boyle, 1992).

Realistic energy pricing will not on its own solve global warming. As part of a wider strategy, however, it is important in sending the correct signals for investment choices and removing subsidies.

Policies to encourage this should include:
a) the introduction of energy taxes on all non-renewable forms of energy to reflect the full

economic costs of environmental damage caused by fossil fuels and nuclear power. Despite the major uncertainties of calculating externalities, which may never be reasonably accurate (Stirling, 1992), a phased increase of energy costs to a level double the current oil price equivalent, perhaps even more, could be justified (Hohmeyer, 1988, PACE, 1990);
b) the introduction of tax credits for renewable energy developers (this is already occurring in Germany, Italy, the Netherlands, Denmark, and several states in the USA);
c) ensuring that utilities buy clean renewable energy at a reasonable price (as occurs in parts of the US, Italy, the UK, and Germany);
d) changing the regulations under which gas and electricity institutions operate; specifically removing the financial incentives to sell increasing quantities of gas or electricity.
e) removing the subsidies from the fossil fuel and nuclear industries - $44 billion per year in the USA alone (1984 prices) (Heede, 1986);
f) ending oil and gas exploration tax breaks, as well as a range of other subsidies such as corporate car tax relief, and capital write-offs for old oil and gas infrastucture and decommissioning.

The net effect of a), e) and f) above should, among other things, be to reduce the incentives to explore for and develop new sources of fossil fuels. In addition, fossil fuel developments should be excluded from all sensitive marine and land-based ecosystems. Where opportunities for energy efficiency and renewable energy technologies exist, new fossil fuel exploration should be discouraged.

Intervening in the Market

In addition to realistic energy pricing, regulation is needed to prevent cartels forming, the market from being manipulated, and to overcome market barriers. Regulation has already been shown to work in the US, Japan, and most Western European countries, in areas such as building standards, appliance efficiency, and safety. Policies should include:

a) new mandatory efficiency standards for appliances, vehicles, buildings, industrial motors and other technologies, should be set at ambitious levels. Efficiency standards have already been successfully implemented in several countries, including Germany, Denmark, Japan, and the US;
b) integrated resource planning (IRP), in which gas and electricity utilities are required to compare the cost of supplying energy (including the environmental costs) with the cost of minimising demand before building new power stations, could be introduced. This is a systematic way of ensuring that unnecessary power plants receive no investment while cost effective energy efficiency opportunities exist;
c) Demand Side Management (DSM) programmes should be encouraged, in which utilities meet energy demand by helping customers use less energy, rather than by building new power stations. DSM spend is doubling from $3 billion per year in the US to some $7 billion by 1995. $10-20 billion per year could be justified (Prindle, 1992. UCS, 1992);
d) national and local government purchasing programmes for efficiency and solar equipment could help establish initial markets;

Research and Development

There are a number of reasons why certain technologies achieve success and capture a large portion of the energy market, not all of which reflect inherent advantages of the technology in terms of costs, efficiencies and low environmental pollution (Thompson, 1990). Improving efficiencies and reducing costs are important objectives for accelerating the impact of renewable energy technologies, and enhanced research, development and deployment (R,D & D) can assist in this. One study has estimated that an expenditure of some $3 billion over the next few decades could double the projected contribution of renewable energy in the USA over the

Breakdown of IEA Government Energy R&D Budgets from 1979-90 (%)

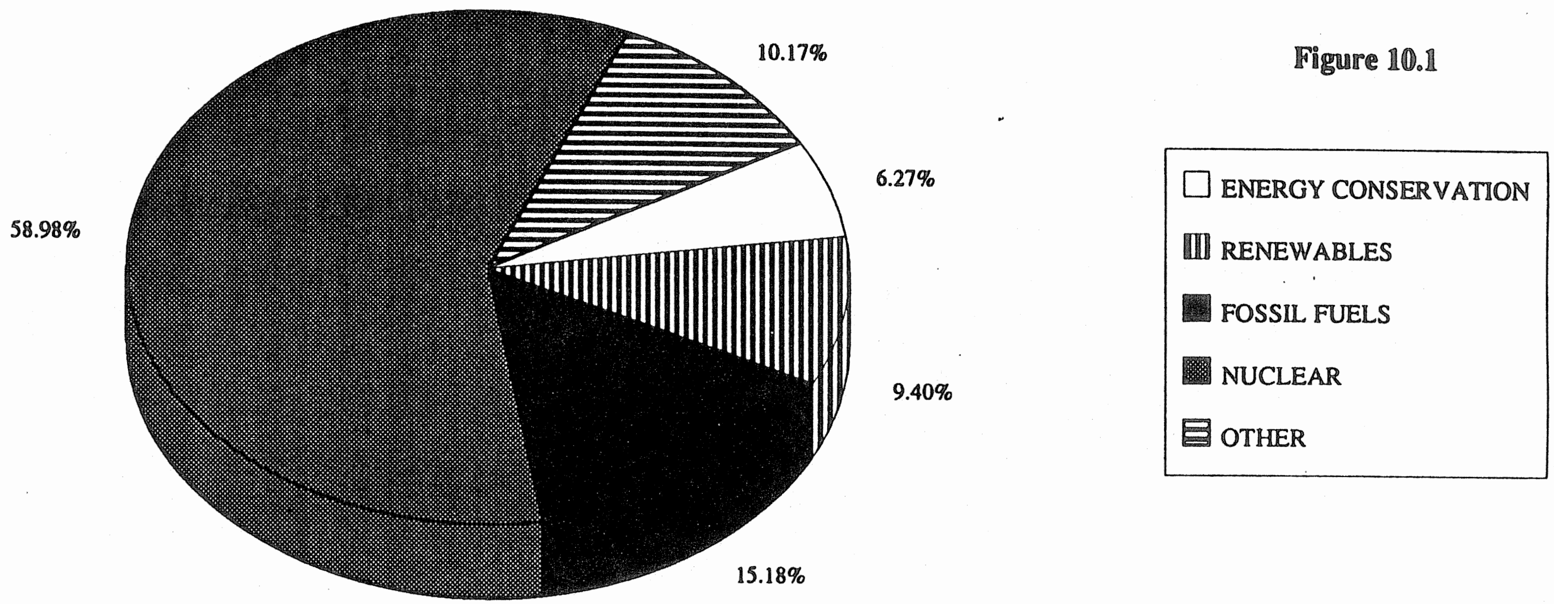


Figure 10.1

period (SERI et al., 1990). Another has suggested that increasing overall levels of government R, D & D by a factor of three is justified(Fulkerson, 1990).

A new approach towards energy Research and Development is needed. International Energy Agency governments' energy R & D budgets are currently heavily skewed in favour of fossil fuels and nuclear power. Only 12.5 per cent of the total budget of $7,675 million is allocated to renewables and energy conservation: over 70 per cent is allocated to fossil fuels and nuclear power (see Figure 10.1). Given that fossil fuel combustion and nuclear power are so-called 'mature' technologies, no government R & D should in future be provided except for the safe decommissioning of old plant, and ensuring appropriate waste management systems and techniques for existing stockpiles of waste. R & D should be substantially re-directed to energy efficiency and renewables, with a challenging target of 50 per cent wihtin five years.

Changing Institutions

None of the current energy institutions are guided by environmental concerns. At the international level, organisations exist to promote and develop oil use (OPEC), coal (the International Energy Agency), and nuclear power (the International Atomic Energy Agency). Transnational corporations promote and lobby for oil, coal, gas, and nuclear power. No international organisations exist for energy efficiency and renewable energy.

In the past ten years, energy loans from multilateral development banks such as the World Bank have totalled more than $50 billion. Less than 1 per cent of this energy lending went to improving end-use energy efficiency, despite the better rates of return such investments give when compared to paying for new energy supplies.

A major reassessment of energy institutions is needed if global energy policies are to change. New lending criteria for power sector loans which encourage energy efficiency investments, would be a start. The creation of a new international agency for the development and promotion of technologies for renewables and energy efficiency (TREEs) has been proposed by Greenpeace and others.

A TREEs agency could provide a focus for energy funding, R&D collaboration, technology transfer, education and information supply. It could also ensure that the other United Nations agencies, development banks, and other organisations develop appropriate policies and actions for a low-CO2 future. A tax equivalent to $1 per barrel on all non-renewable energy sources, applied in industrialised countries, could raise more than $50 billion per year to fund the agency (Goldemberg, 1990).

National and regional centres of excellence for energy efficiency and renewables should be developed. Training, information dissemination, designing finance programmes and providing seed funding should be a major part of the work of these centres.

North-South Policies

Twenty-five per cent of the world's population in the North currently consume 72 per cent of the world's commercial energy. Over a billion people, primarily in the South, have only limited access to energy for cooking, heating, light and power, and their primary objective is day-to-day survival. While this situation persists, energy and environmental security will be impossible to attain: it will not be the prime objective of sufficient numbers of people, or their governments.The single most useful policy to improve North-South relationships would be to wipe out the debt burden. Much of this arose due to inappropriate loans encouraged by the North. The South currently owes $1.4 trillion and the interest and capital repayments of this amount to a net annual outflow from South to North of some fifty billion dollars a year.

Carrying this weight of debt, it is impossible for many countries to even feed their own citizens. Investing in energy efficiency and renewable energy, though providing long-term savings, simply could not be afforded.

The World Bank spends $3 to $4 billion a year on energy sector projects and leverages a further $20 billion a year. The majority of energy sector loans go to large-scale hydro dams, coal stations, and roads - energy inefficient and environmentally damaging megaschemes. Less than one per cent of funding goes to energy efficiency (IIEC, 1991). The criteria for energy sector lending needs to change to re-orientate investment towards 'least cost' options, including environmental costs, which will dramatically encourage energy efficiency and smaller scale renewable energy options.

A number of countries in the South are being sold cheap but polluting technology from the North. Financial measures are needed which prevent such technology dumping, and which allow Southern countries to have access to newer technologies from the North.

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